# Cargo Handling Technologies Final Report

**Prepared for** 

# Task 1.2.3.2

## for the Center for Commercial Deployment of Transportation Technologies

by

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# List of Abbreviations

AAIT	Agile Automated Identification Technology
AAS	Average Actual Speed
AGV	Automated Guided Vehicle
AIR	Average Idle Rate
AIT	Automatic Identification Technology
APL	American President Lines
APS	Automatic Positioning System
AS/RS	Automated Storage and Retrieval multi-story System
ASPH	Automatic Seaborne Pallet Handling
CCDoTT	Center for Commercial Deployment of Transportation Technologies
CE	Cell Elevator
CPT	Compact Pallet Transfer
DCM	Double Cycle Mode
DGPS	Differential Global Positioning System
DoD	U.S. Department of Defense
DOF	Degree Of Freedom
GPS	Global Positioning System
DoT	U.S. Department of Transportation
EAT	Estimated Arrival Time
ETV	Elevating Transfer Vehicle
FCFS	First Come First Serve
LEO	Low Earth Orbit
HSS	High-Speed Sealift
IR	Idle Rate
ISO	International Standards Organization
KIPD	
JIT	Kaoshiung International Port Development project Just In Time
JWD	Jordan-Woodman-Dobson
LO/LO	Load On/Load Off
LMTT	Linear Motor-based Transfer Technology
LMS	Linear Motor-conveyance Systems
M	Million(s)
MARAD	MAritime ADministration
MEO	Medium Earth Orbit
MFCFP	Modified First Come First Pass
MMWR	MilliMeter Wave Radar
MPH	Miles Per Hour
MTS	Multiple Trailer System
NIST	National Institute of Standards and Technology
NIT	Norfolk International Terminal
NFESC	Naval Facilities Engineering Service Center
OCR	Optical Character Recognition
P/D	Pick-up/Delivery
PSA	Port of Singapore Authority
RF	Radio Frequency
RFID	Radio Frequency IDentification
RMG	Rail-Mounted Gantry
RO/RO	Roll On/Roll Off
RTG	Rubber-Tired Gantry
RTCM-SC104	Radio Technical Commission for Maritime services, Special Committee 104
RTK/OTF	Real-Time Kinematic/On-The-Fly
SCM	Single Cycle Mode
SRM	Storage and Retrieval Machine

TAV	Total Asset Visibility
TC	Transfer Car
TCS	Transfer Car System
TETRA	TETrahedral Robotic Apparatus
TEU	Twenty-foot container Equivalent Unit
VIT	Virginia International Terminals
UPS	United Parcel Service
USPS	U.S. Postal Service
USTRANSCOM	United States TRANSportation COMmand

## **ES.0 EXECUTIVE SUMMARY**

The purpose of this Task is to select and evaluate state of the art cargo handling technologies for both commercial and military operations. The emphasis of the study is on the quantitative assessment of the performance of existing, emerging and conceptual, commercially developed technologies for terminal operations.

Existing, emerging and conceptual technologies have been identified through a variety of sources. These sources include marine industry magazines and publications, organizations, associations and cooperative programs, port and terminal personnel, technology vendors, the internet and discussions and correspondence with other researchers.

The major categories of cargo handling technologies studied are:

- 1. Storage and Retrieval Systems. These include ship and yard loading/unloading cranes, anti-sway systems, cell elevator, etc.
- 2. Equipment Tracking Technologies.
- 3. High Speed Sealift (HSS) Specific Ship-loading Technologies.
- 4. Multiple Trailer Systems.
- 5. Container Technologies.
- 6. Automated Guided Vehicles (AGVs) for Yard Operations.
- 7. Linear Motor Conveyance Systems for Yard Operations.
- 8. Automated Storage and Retrieval Multi-Story Systems (AS/RS) for Yard Operations.

In each category we discuss current and future developments, current use, current and future performance expectations and where possible we discuss cost and secondary issues.

The technologies studied motivated three preliminary automated container yard concepts that are studied and evaluated. These are:

- Automated container yard using AGVs.
- Automated container yard using Linear Motor Conveyance Systems.
- Automated container yard using AS/RS.

The above concepts were simulated and their performance is compared with a base scenario of manual operations at the Norfolk International Terminal.

#### <u>Main Findings</u>

The main findings of this study are the following:

- The scarcity of land in most U.S. ports together with increasing demand for more capacity dictates the use of advanced technologies to make existing port and terminal facilities more efficient.
- The trend for using advanced technologies and automation for terminal operations has already started in Europe and Asia. Even though, in the U.S., labor agreements are a big obstacle to any type of automation that affects the labor force, in the long run the trend for automation will prevail in order to deal with the problem of land usage saturation and meet global competition.

- Advances in crane and cargo storage and retrieval technologies such as megacranes, robotic cranes, smart spreaders, cell elevators and others that are in the design or experimental phase could have a significant effect on the efficiency of terminal operations once properly implemented. Estimates of the expected throughput of the most advanced cranes can be as high as 75 to 100 moves per hour.
- The minimization of sway in most cranes could lead to significant improvement of loading/unloading operations. Existing anti-sway systems are based on simplified models and their performance is not satisfactory. A new anti-sway control system is designed using recently developed nonlinear control techniques whose performance is shown to be superior to existing ones.
- The use of Total Asset Visibility (TAV) systems to determine location of the assets, identify the assets and to access and deliver the information about the assets would play a significant role in improving the efficiency of commercial and military port operations. TAV is a rapidly changing area in both technology and business environments. The wise use of TAV systems depends on a certain amount of standardization, which is difficult to establish due to the volatility in the development of TAV technologies. An agile automated identification technology developed by August Design Inc. is designed to overcome some of the problems of standardization by being able to interface with a wide range of different TAV technologies.
- Automated guided vehicles for terminal operations offer potential for improving throughput considerably if properly used with other equipment. The interface of automated and manual operations should be designed properly in order to avoid delays that could significantly reduce the benefits of automation and maintain safety.
- Linear motor conveyance systems that have been successfully used for non-port applications offer a strong potential for application to container terminals.
- Automated storage and retrieval multi-story systems (AS/RS) for yard operations may be proven to be an ideal solution to areas where land is very limited. They could be very practical and cost effective especially if they are used to store empty containers or relatively lightweight cargo.
- The use of advanced technologies to automate all terminal operations could lead to significant improvements in throughput. Two automated container yards one using AGVs and the other linear motor conveyance systems are designed and simulated. Their throughput is shown to be more than double of that of a similar terminal with manual operations.
- A preliminary AS/RS system for a container yard is designed and evaluated. Simulations are used to demonstrate its effectiveness for yard operations where land usage is very limited.
- The use of automation in terminal operations will eliminate most of the randomness due to manual operations and allow the use of optimization techniques to further improve performance.

### Future Work

The three preliminary automated container yard concepts need to be considered further. The details of the design of each equipment and its operation need to be specified. The operations need to be optimized for performance by taking into account cost, utilization and other constraints. The interface of the proposed automated container yards with the gate and manual operations needs to be specified and analyzed.

## **1. INTRODUCTION**

This report describes the work performed and results developed by the Center for Advanced Transportation Technologies of the University of Southern California under a subcontract with the California State Long Beach Foundation for Sub-Task 1.2.3.2 entitled "Select and Evaluate State of the Art Handling Technologies" for the Project entitled "USTRANSCOM/MARAD/Center for Commercial Deployment of Transportation Technologies". It provides an engineering evaluation of existing, emerging and conceptual cargo handling technologies. The report emphasizes the quantitative assessment of the performance of existing, emerging and conceptual, commercially developed technologies for terminal operations and proposes three preliminary automated container terminal concepts that employ advanced technologies.

The competitive world economy, needs of the military and the increasing performance expectations of customers lead to a demand for low cost, rapid and dependable shipping of cargo. The saturation of land usage in most ports together with the competitiveness for higher capacity and efficiency put pressure on port authorities and terminal operators to make existing port terminal facilities more efficient through the use of advanced technologies. The development of efficient, automated, high-tech loading/unloading equipment and associated cargo handling and tracking technologies has the potential of considerably improving the performance of terminal operations. The commercial sector is driving these developments in an effort to improve competitiveness and provide additional services in operations associated with cargo handling. U.S. Department of Defense (DoD) has an opportunity to encourage, stimulate, and leverage the development and commercial application of such technologies in order to facilitate the rapid deployment of the force.

The major categories of cargo handling technologies studied include storage and retrieval systems, equipment tracking technologies, High Speed Sealift (HSS) specific ship-loading technologies, multiple trailer systems, container technologies, automated guided vehicles (AGV), linear motor conveyance systems, automated storage and retrieval multi-story systems (AS/RS). For each category we examine current and future developments, performance, cost and other specific issues associated with each technology. The current and future technologies for terminal operations studied are used to motivate preliminary designs for three automated container yards, which are, studied and evaluated using simulations. These include the automated container yard using AGVs, the automated container yard using linear motor conveyance system and an AS/RS yard.

The main findings of this report are summarized as follows:

- The scarcity of land in most U.S. ports together with increasing demand for more capacity dictates the use of advanced technologies to make existing port and terminal facilities more efficient.
- The trend for using advanced technologies and automation for terminal operations has already started in Europe and Asia. Even though in the U.S. labor agreements are a big obstacle to any type of automation that affects the labor force, in the long run the trend for automation will prevail in order to deal with the problem of land usage saturation and meet global competition.
- Advances in crane and cargo storage and retrieval technologies such as megacranes, robotic cranes, smart spreaders, cell elevators and others that are in the design or experimental phase could have a significant effect on the efficiency of terminal operations once properly implemented. Estimates of the expected throughput of the most advanced cranes can be as high as 75 to 100 moves per hour.

- The minimization of sway in most cranes could lead to significant improvements of loading/unloading operations. Existing anti-sway systems are based on simplified models and their performance is not satisfactory. A new anti-sway control system is designed using recently developed nonlinear control techniques whose performance is shown to be superior to existing ones.
- The use of Total Asset Visibility (TAV) systems to determine location of the assets, identify the assets and to access and deliver the information about the assets would play a significant role in improving the efficiency of commercial and military port operations. TAV is a rapidly changing area in both technology and business environments. The wise use of TAV systems depends on a certain amount of standardization, which is difficult to establish due to the volatility in the development of TAV technologies. An agile automated identification technology developed by August Design Inc. is designed to overcome some of the problems of standardization by being able to interface with a wide range of different TAV technologies.
- Automated guided vehicles for terminal operations offer potential for improving throughput considerably if properly used with other equipment. The interface of automated and manual operations may introduce delays that could significantly reduce the benefits of automation.
- Linear motor conveyance systems that have been successfully used for non-port applications offer a strong potential for application to container terminals.
- Automated storage and retrieval multi-story systems (AS/RS) for yard operations may be proven to be an ideal solution to areas where land is very limited. They could be very practical and cost effective especially if they are used to store empty containers or relatively lightweight cargo.
- The use of advanced technologies to automate all terminal operations could lead to significant improvements in throughput. Two automated container yards one using AGVs and the other linear motor conveyance systems are designed and simulated. Their throughput is shown to be more than double of that of a similar terminal with manual operations.
- A preliminary AS/RS system for a container yard is designed and evaluated. Simulations are used to demonstrate its effectiveness for yard operations where land usage is very limited.
- The use of automation in terminal operations will eliminate most of the randomness due to manual operations and allow the use of optimization techniques to further improve performance.

The details of the above findings are presented in the following sections.

## 2. STORAGE AND RETRIEVAL SYSTEMS

Since the introduction of containerization into our nation's marine terminals, there have been few changes in how cargo is moved between the storage facility and the ship and between the storage facility and the entrance/exit gates. In the case of containerized cargo, containers are moved to and from the yard through the use of manually operated pieces of yard equipment (combinations of hostlers, bombcarts, straddle carriers, rubber tired gantry cranes, sidepicks, or wheeled operations).

There are a number of interesting developments underway which seek to make these operations much more efficient. These initiatives include the use of Automated Guided Vehicles (AGVs), multiple trailer systems, automated container stacking systems, inland terminals combined with a highly efficient ship interface, and linear motor-driven conveyance systems. These technologies will be discussed, and analyzed for their relevance to the Agile Port concept in subsequent sections.

There are currently two general types of storage and retrieval systems in use at U.S. marine terminals: wheeled and grounded. Although wheeled operations are more efficient in terms of the amount of effort required to move the container through the yard, this operation is very inefficient in the utilization of space and equipment, since the containers are parked on chassis. Grounded operations, on the other hand, are very efficient in terms of space, since the containers can be stacked as much as 4-5 high when full, and even higher when the containers are empty. Grounded operations, however, require much more equipment to remove the container from chassis and place it in stacks and vice versa. These processes and the associated equipment are illustrated in Figures 2.1 and 2.2.

A wheeled operation is one in which the container is brought into the container yard on a chassis, and then brought to the ship on the same chassis, and lifted off. This empty chassis can then be used for inbound containers. The wheeled operations, where possible, are more efficient than the grounded ones in terms of loading and unloading rates as they require no container transfer and are random access. In addition the lower cost for labor and equipment for wheeled operations make these operations more desirable than grounded ones at places where land is inexpensive.

Grounded operations require much effort in the storage and retrieval of containers, since the container must be transferred via lifting equipment, and often, multiple lifts are required in the yard where containers are stacked on top of one another. Grounded operations usually require that the ground be reinforced to support the stacks of containers and the cargo handling equipment. However, the "throughput per acre" for grounded operations is typically much higher than that of wheeled operations. Grounded operations use hostlers, chassis, bombcarts, gantry cranes, straddle carriers, and reachstackers (see Figure 2.2) for the movement of containers within the yard.

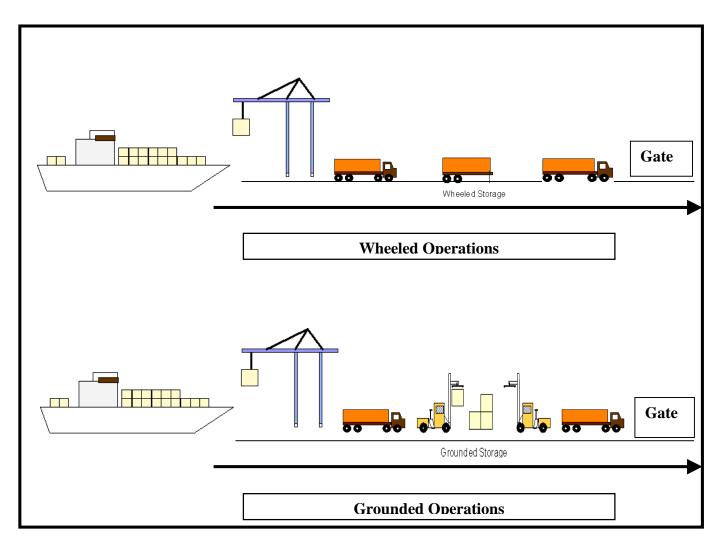


Figure 2.1: Wheeled and grounded operations.

As shown in Figure 2.1, containers are stored on chassis for wheeled operations, and cannot be stacked. This can be fairly costly if the land on which the terminal sits is expensive. On the other hand, significantly less equipment is required for a wheeled yard, since no container stacking equipment is required. In the United States, both of these operations are used at container terminals. Combinations of these operations are also found.



### **Chassis and Bombcarts**

Chassis are the wheeled platforms upon which containers are placed for transport. Chassis can be either flatbed trailers, which are meant for transport along roads and highways, or bombcarts, which are designed only for yard operations. Bombcarts are much easier to load, from the perspective of a crane operator.

## Hostlers

Hostlers are yard tractors that pull chassis (with or without containers) to and from the container yard. These are not legal vehicles for public road transit.

## **Straddle Carriers**

Straddle Carriers are rubber tired lifting units that are used to place and pick containers from stacks within container yards. They are manually driven, and typically are capable of lifting a container 4 container-heights high (one–over-three).

## **Gantry Cranes**

Gantry Cranes are used for the sorting and stacking of containers within the yard. They can be either rubber-tired, as shown in the photo, rail mounted, or fixed. One common trade name for this equipment is the Transtainer.

## **Toplifts, Sidepickers, Reach Stackers**

This type of equipment is used for container sorting and hostler loading within the yard. Typically, they can reach 4+ containers high.

## Figure 2.2: Yard equipment.

In both wheeled and grounded operations, the processes by which containers are moved through the yard are the same. For outbound cargo, the containers are: 1. Processed through the gate, 2. Stored in the yard, 3. Retrieved from the yard, and brought to the ship, 4. Loaded onto the ship. For inbound cargo, the containers are: 1. Unloaded from the ship, 2. Stored in the yard, 3. Retrieved from the yard, 4. Processed through the gate. In some cases the storage in the yard can be skipped for both inbound and outbound cargo. The above processes are the same for all containerized cargo whether is commercial or military.

The main performance measures for evaluating ship/yard loading/unloading equipment are presented below:

#### Performance Measures and Factors for Evaluating Loading/Unloading Equipment

Probably the most commonly used measurement of performance of loading/unloading equipment is the average loading cycle time measured in **moves per hour** (or minutes per move). The average cycle or **move** is defined as the average time [19] required for the loading/unloading equipment to acquire a container, pick the container up from the hold, move it out of the hold onto the dock-mounted vehicle, release the container and return to the hold position ready to acquire another container. Moves per hour can be used to either evaluate the performance of a single loading/unloading equipment or for evaluating the productivity of the terminal. In the last case, the throughput of the terminal is measured in moves per hour per ship crane. The throughput of the terminal may be lower than the maximum throughput that can be achieved when the ship cranes are operating at maximum capacity. For example ship crane, due to delays in transferring the containers to and from the yard, queues formed under the ship cranes, etc. The terminal throughput cannot, however, exceed the average best ship crane performance. Another measure used for the evaluation of the productivity of a terminal is the **cost per move** defined as the total cost including equipment purchase, terminal development, equipment maintenance and labor divided by the average number of the ship crane moves.

Other factors being considered for evaluating the performance of loading/unloading equipment are:

- Possibility for higher productivity, i.e., the possibility of increasing productivity by appropriately modifying the equipment
- Expandability of layout to cover total yard
- Automation capability
- Marketing value
- Environmental benefits
- Ability to serve intermodal rail
- Safety
- Civil cost
- Equipment cost
- Maintenance cost
- Labor cost
- Reliability

In this report we use the measure of "moves per hour" as the dominant performance measure. Since we are mostly dealing with future technologies that have not been implemented or tested, this measure is easier to quantify than the other measures. In our analysis, however, we do address the other measures where information and data are available to make reasonable assessments. Performance measures and characteristics specific to each piece of equipment considered are also presented and discussed in this report.

#### 2.1 Ship Loading/Unloading Equipment

PRC Inc. completed a research project and wrote a report in August 1993 for the Department of Transportation, Maritime Administration, on Assessment of Cargo Handling Technology [19]. This report presents a large inventory of cargo handling equipment, which is in use or could be used for military and commercial operations at ports. The purpose of this section is to use the PRC Inc. report as a starting point and focus on the performance characteristics of cargo handling equipment described in the report [19] and in other references [20, 22, 23, 24, 25, 26]. For each piece of equipment a brief description and summary of performance characteristics are provided.

The crane is the main equipment used for ship loading/unloading. Cranes can be either located on the dock (dock cranes) or mounted on the ship (ship-mounted cranes). While ship-mounted cranes provide flexibility with regard to the port facilities and equipment, dock cranes have better performance characteristics. Moreover, ship-mounted cranes increase the ship weight and the operating cost of the ship. Ship-mounted cranes, however, become very useful when ports are not well equipped. Such situations may easily arise in the case of military deployment at ports of underdeveloped countries or in areas where ports are not well developed.

Below we define and explain the various terms and names used to describe the characteristics of the cranes.

A crane is said to be operating in **single cycle mode** when it picks up the container from the hostler (resp. ship), loads it to the ship (resp. hostler) and returns empty to pick up the next container. In the **double cycle mode** the crane picks up the container from the hostler (resp.), loads it to the ship and then picks up a new container from the ship and loads it to the hostler.

The **outreach** and **backreach** of the crane denote the efficient length at which the trolley can move containers in the front and the back of the bridge crane, respectively. The **gage** of the crane denotes the length between the legs of the crane.

In the following subsections we present the main types of dock cranes and ship-mounted cranes and their characteristics.

#### 2.1.1 Dock-mounted Cranes

The majority of modern container dock cranes are rail gantry cranes (although rubber-tired cranes are sometimes used), which are mainly used for container loading/unloading. Longitudinal motion is achieved by a transverse beam supported at each end by rail-mounted columns while transverse motion and hoisting are accomplished by a trolley that travels along the beam [19].

Modern gantry cranes are capable of reaching any point in a ship's hull. Their throughput rates are in the range of 25-35 moves per hour and can reach as high as 75 moves per hour. Below we briefly present the main types of dock cranes and their characteristics.



#### **Type:** Conventional and modified A-frame Cranes

Figure 2.3: Conventional gantry cranes.

**Brief Description:** The conventional and modified A-frame crane with a single trolley and one operator is the workhorse of the industry [20]. The A-frame gantry crane takes its name from its "A"-shaped noticeable when observed from the bridge [19]. Modified A-frame gantry cranes are either low-profile or articulated-boom gantry cranes. Most of the modern conventional and modified A-frame cranes have 50 ft backreach, 100 ft gage, and 145 to 160 ft outreach. They usually service 16 container wide post-Panamax ships, but they can also service 18 wide post-Panamax ships using an outreach extension. Some ports, such as the Virginia International Terminals (VIT), are planning to use outreach extensions so that 21 wide post-Panamax ships will be served. Their production capabilities are in the range of 20-35 moves per hour [20].

The main hoist can be either on the trolley or on the frame. For extreme outreach cranes, the former design is more appropriate. The modern conventional and modified A-frame post-Panamax cranes are as productive as the Panamax cranes mainly because they use faster motors and better antisway control systems. Their cost is usually in the range of \$5-7 million, but can go 50% higher for articulated boom or low-profile cranes.

**<u>Performance</u>**: The performance characteristics of the conventional and modified A-frame gantry cranes are summarized below:

Moves per hour	20-35
Backreach (feet)	~50
Outreach (feet)	145 -160
Ships served	16-18 wide Post-Panamax, planning for 21
Cost in Millions (M)	\$5-7M (conventional A-frame), \$7-11M (modified)
Cycle mode	Single and Double
Development Status	Currently in use

#### Table 2.1: Performance Characteristics of Conventional and Modified A-frame Cranes

#### **<u>Type:</u>** Dual hoist single trolley cranes

**Brief Description:** Dual hoist cranes are conventional cranes with a second hoist added over the wharf. The second hoist could increase productivity by about 50% but it will also increase the initial costs by 30%-50%. It requires one more operator and that increases the operating cost [20]. The operation of the crane can be briefly described as follows: in the case of unloading, the trolley picks up the container and delivers it to the shuttle which in turn moves landward towards the second hoist. The second hoist picks up the container and loads it on the chassis. The process of loading is exactly the opposite. The container is delivered from the trolley to the shuttle at the portal beam elevation. With dual hoist single trolley cranes, containers can be handled only in the single-mode.

**<u>Performance</u>**: The performance characteristics of the dual hoist single trolley cranes are summarized below:

Moves per hour	30-55
Backreach (feet)	~50
Outreach (feet)	145 - 160
Ships served	16-18 wide Post-Panamax
Cost	130-150% of the conventional crane.
	Needs one more operator
Cycle mode	Single
Development Status	Currently in use

Table 2.2: Performance Characteristics of Dual Hoist Single Trolley Cranes

### **<u>Type:</u>** Dual hoist elevating platform cranes

**Brief Description:** The dual hoist elevating platform cranes are the same as the dual hoist single trolley cranes except the shuttle runway elevates to the ideal elevation [20]. The operator's cab is not in the trolley but on a separate runway next to the trolley. The productivity of dual hoist elevating platform cranes is at least the same as the productivity of the dual hoist single trolley cranes [20] but the modification done in the shuttle runway and the operator's cab increase cost.

**<u>Performance</u>** The performance characteristics of the dual hoist elevating platform cranes are summarized below:

Moves per hour	30-55
Backreach (feet)	~50
Outreach (feet)	145-160
Ships served	16-18 wide Post-Panamax
Cost	130-150% of the conventional crane.
	Needs one more operator
Cycle mode	Single
Development Status	Currently in use

**Table 2.3: Performance Characteristics of Dual Elevating Platform Cranes** 

#### **<u>Type:</u>** Dual hoist elevating girder cranes

**Brief Description:** This is a conventional crane except that the entire trolley runway elevates [20]. The boom and trolley girder can be set to the ideal elevation depending on the particular vessel and load. Single and double cycle modes can be handled. The feasibility of this type of crane (conceived by Mr. C. Davis Rudolf III and Mr. Anthony Simkus of VIT who applied for patent coverage) is currently being investigated by two manufacturers [20]. The crane is expected to be appropriate for ports that service a wide variety of vessels ranging from post-Panamax container ships to barges. According to [21] the dual hoist elevating girder crane is 50%-75% more expensive than a single hoist crane. No specific productivity measures were found for these cranes. However, since these cranes are conventional cranes modified so that the trolley runway elevates, it is expected their productivity to be at least the same with the productivity of the fast conventional cranes.

**<u>Performance</u>**: The performance characteristics of the dual hoist elevating girder cranes are summarized below:

Moves per hour	30-40 (conservative estimate)
Backreach (feet)	~50
Outreach (feet)	145-160
Ships served	Wide range of ships.
	From Post-Panamax to Barges.
Cost	150-175% of the conventional crane.
	Needs one more operator.
Cycle mode	Single and Double
Development Status	Design stage

Table 2.4: Performance Characteristics of Dual Hoist Elevating Girder Cranes

#### **<u>Type:</u>** Dual hoists and dual trolley cranes

**Brief Description:** This crane, conceived by Paceco Inc., is similar to a conventional crane with one trolley runway, except that it has two trolleys and a shuttle that operate on the runway with a chassis guide system that operates at the portal tie [20]. At least two operators are required. The operation of the crane can be summarized as follows [20]: The one trolley (ship trolley) parks over the container stack on the ship and the chassis guide is under the second trolley (shore trolley). For unloading, the ship trolley picks up a container from the ship, lifting the container to full height to get above the shuttle. The shuttle, which must be wide enough to clear the longest container, moves under the ship trolley and travels to the shore trolley. The shore trolley picks up the container and when clear, lowers the container into the chassis guide and onto the chassis. For loading, the cycle is reversed. Containers can only be handled in the single cycle mode. According to [20] dual hoist dual trolley cranes are expected to produce twice as many moves per hour.

**<u>Performance</u>**: The performance characteristics of the dual hoist dual trolley cranes are summarized below:

Moves per hour	50-70 (estimate)
Backreach (feet)	~50
Outreach (feet)	145-160
Ships served	Wide range of ships.
	From Post-Panamax to Barges.
Cost	Increase cost wrt the conventional
	crane. At least two operators are
	needed.
Cycle mode	Single
Development Status	Design stage

#### **Type:** Megacranes

**Brief Description:** With the introduction of larger than post-Panamax ships, the megaships, orders for dockside megacranes to service these ships are increasing [22]. Thus cranes (megacranes) with larger outreach, backreach, lift height and total height are required. The biggest challenge in designing these cranes is to preserve, if not increase, productivity with respect to the existing smaller cranes. There are two design approaches to achieve the desired performance for megacrane projects [22]. The first approach uses an extremely rigid structure to avoid crane deflections, vibrations induced by the crane movements. The second approach uses a structure similar to the existing ones (in terms of rigidity) and advanced load control systems to control the load and accommodate the crane deflections and vibrations. No specific productivity measures were found for these cranes. Since the emphasis for these designs is larger outreach, backreach, lift height and total height subject to maintaining productivity

similar to that of the smaller cranes we expect the throughput of the megacranes to be around 40-50 moves per hour. The arrangement for a megacrane is similar to that of a conventional crane. The result of the increased crane size is a heavier structure.

**Performance:** The performance characteristics of megacranes are summarized in Table 2.6.

Moves per hour	40-50
Backreach (feet)	65
Weight (tones)	1150-1300 (about 30% heavier than
	conventional crane)
Height (feet)	~230 (about 130% of the
	conventional crane)
Outreach (feet)	170
Ships served	Megaships (>7,000 TEU)
Cost	No Data
Cycle mode	Single and Double
Development Status	Design stage

**Table 2.6: Performance Characteristics of Megacranes** 

#### 2.1.2 Ship-mounted Cranes

Ship-mounted cranes provide flexibility with regard to the port facilities and equipment but do not achieve the high productivity rates that the dock cranes achieve. Moreover, ship-mounted cranes increase the ship weight and the operating cost of the ship. Ship-mounted cranes, however, become very useful when ports are not well equipped or when loading/unloading from ship to ship is required. Such situations may easily arise in the case of military deployment at ports of underdeveloped countries or in areas where ports are not well developed. In the following the main types of ship-mounted cranes and their characteristics are presented.

#### **Type:** Ship-mounted Gantry Cranes

**Brief Description:** There are three different main types of ship-mounted gantry cranes: The A-type, C-type and Jib-type cranes. The A-type or A-frame gantry crane is similar to the A-frame dock crane with its two legs at each end of the ship [19]. A trolley rides on a gantry bridge girder supported by the crane's legs (Figure 2.4). The bridge is extended beyond the side of the ship.

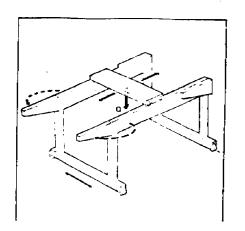


Figure 2.4: A-type crane [19].

The C-type gantry crane (Figure 2.5) is similar to the A-type except that it has a single leg at each end. The main advantage of this type of crane is that it can be rigged to operate with another C-type crane in a twinned operation. This is extremely useful when heavy or long pieces of cargo are required to be handled.

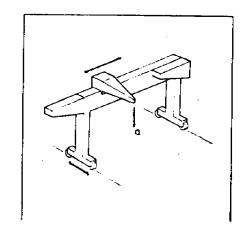


Figure 2.5: C-type crane [19].

The jib-type gantry crane is either similar to the C-type in that it has only a single bridge girder supported by single legs at each side of the ship or it has only one single leg (Figure 2.6). The jib-type crane does not use outriggers. This results in weight savings for the ship. This crane is particularly suitable when the deck track is short and a low crane weight is required [19].

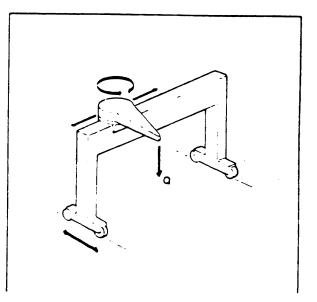


Figure 2.6: Jib-type crane[19].

### **Type:** Pedestal Cranes

**Brief Description:** Pedestal or revolving cranes are mounted on a pedestal that contains the crane machinery. The boom follows a circular path during crane movements. The pedestal crane is built as a single unit and has slewing, hoisting and luffing capabilities [19]. Several pedestal cranes are usually needed to serve all of the ship's hold.



Figure 2.7: Pedestal cranes.

**Performance of ship-mounted cranes:** Ship-mounted gantry cranes operate as fast as 25-30 moves per hour. The performance of the ship-mounted pedestal cranes varies considerably based on the crane model, year of production, cargo being carried, boom length, etc. However, it seems that today's pedestal cranes' performance range is about 10-20 moves per hour. Twin pedestal cranes with adjustment for off-center achieve an average of 3 moves per hour when they are used for loading/unloading special or extremely heavy lift [19].

Comparing ship-mounted gantry cranes and pedestal cranes, the former outperform the latter ones in the number of moves per hour. According to [19], most ship owners assume that one gantry crane has the same productivity as two pedestal cranes. In addition, gantry cranes have a better lifting efficiency. However, the gantry cranes cost more than the pedestal cranes, and they are heavier, adding extra weight to the ship. Finally, the pedestal cranes have the advantage that when one of the cranes is "down", loading and unloading can be continued with the others. This is a significant advantage over gantry cranes, since the average time a crane is "down" is estimated to be 2% for both gantry and pedestal cranes [19]. The following table summarizes the performance characteristics of ship-mounted cranes.

Table 2.7.a: Performance Characteristics of Ship-Mounted Cranes

Crane	Moves/hour	Twin	Down Time	Handling special
type		Operation		cargo
A-type	25-30	No	2%	No
C-type	25-30	Yes	2%	No
Jib	25-30	Yes	2%	No
Pedestal	10-20	Yes	2%	Yes

Crane type	Crane Purchase Cost	Crane Installation Cost	Crane Weight Tons	Crane Total Installed Weight Tons
A-type	\$1.9 M	\$3.1 M	210 T	300 T
C-type	\$1.9 M	\$3.1 M	195 T	275 Т
Jib	\$3.0 M	\$4.3 M	275 T	350 T
Pedestal	\$750 K	\$1.35 M	75 T	120 T

There are many other types of ship-mounted cranes [37] such as:

- 1. **Pillar Crane**. A fixed crane consisting of a vertical member held in position at the base to resist overturning moment with constant-radius revolving boom supported at the outer end by a tension member.
- 2. **Pillar Jib Crane**. A fixed crane consisting of a vertical member held at the base with a horizontal revolving arm carrying a trolley.

- 3. **Portal Crane (Whirley Type).** A gantry crane without trolley motion, which has a boom attached to a revolving crane mounted on a gantry, with the boom capable of being raised or lowered at its head (outer end). Portal cranes may be fixed or mobile.
- 4. **Traveling Jib Crane**. A jib crane with the vertical member running on a track, its upper end guided by a parallel overhead track.

The four ship cranes described above, and many others are variations of those presented in Tables 2.7.a and 2.7.b and have similar performance characteristics.

#### 2.1.3 Semi-automated and Automated Cranes

Although there are many different ways to classify cranes (e.g., mechanical design characteristics, weight, performance, etc), in this section cranes are classified with respect to their degree of automation. Three different types of cranes are defined: the *conventional* or *manually-operated*, the *semi-automated*, and the *automated* cranes. Conventional or manually-operated cranes are those whose performance depends mostly on the capabilities of the human operator. The semi-automated cranes are those which are equipped with advanced control systems and sensors that enhance the human operator's decisions in order to achieve better performance. For example, the control system of a semi-automated crane could control the speed of the crane's components for sway avoidance and fine-positioning of the spreader. This is extremely important since, according to a recent study [23], about 30% of each manual crane move is spent eliminating sway and fine-positioning of the spreader. Automated cranes are those that are equipped with advanced and intelligent control and measurement systems and require no human operatior.

#### **Type:** Cranes with Anti-Sway Systems

**Brief Description:** These cranes are equipped with special control systems for killing sway. Most antisway systems can be installed without requiring major modifications of the crane. An industrial computer reads the operator's speed and position commands from the control stick and sends appropriate modified commands to the motor drive to control sway while allowing the operator to maintain manual control. The computer measures the acceleration and deceleration of the trolley to match the pendulum period, so that the crane catches the load with no sway at the end of the move. Automatic moves to position the spreader are handled in a similar way. The Virginia International Terminal/Wagner anti-sway system is an example of such a system [23]. It operates in four different modes: (1) the manual anti-sway, in which case the computer senses the operator's control speed requests and provides with proper motor control signals to achieve the requested speed and prevent sway, (2) the long move mode, in which case the trolley returns at full speed to a position marked by the operator, (3) the short move mode, in which case the trolley moves one container width inshore or offshore, and (4) the anti-sway off mode, in which case the anti-sway system is inactivated to allow for very fine control of position (e.g. 6 inches).

Anti-sway devices are not without controversy. Most crane operators at commercial ports around the world are highly skilled and take great pride in their ability to work productively. According to a number of operators and crane maintenance personnel interviewed by August Design Inc., some types of anti-sway devices are disruptive to the crane operator in that the devices take control away from the crane operator, sometimes unexpectedly. In these cases the crane operator would be trying to make a move and the anti-sway device would kick in causing the load to move differently than the operator expected. The perception to the crane operator is that something is wrong with the crane controls. It is not uncommon for the anti-sway devices to be permanently disabled in order to satisfy the crane operator. It is possible that, given enough time and patience, the crane operator would become used to the feel of the anti-sway control system. However, the pressures of marine shipping is such that patience is not common.

Anti-sway devices are likely to gain more acceptance in training new operators, in military applications and in cases where the cranes are automatic and semi-automatic.

Anti-sway devices are available from a number of manufacturers including: Caillard, Noell, VIT, Innocrane Oy, AEG, Siemens, Mitsui, Oostwouder Engineering Consultants, GIAT Industries, Hagglunds, NKK Corporation, and ARC Electronique.

#### **Type:** Cranes with Automatic Positioning Systems

**Brief Description:** One of the main causes of delays during container loading/unloading is the positioning of the chassis so that container and chassis properly mate or the positioning of the container so that the flippers on the spreader bar can mate precisely. The current positioning technique involves the cooperation of the hostler or crane operator with human spotters who communicate with each other with hand and voice signals.

A technology called automatic positioning systems (APS) have been introduced which minimizes this positioning difficulty [23]. Both Wagner and August Design have demonstrated systems that measure the relative position of chassis and container beneath cranes. Matson and others have used vision systems to position straddle carriers beneath cranes. The automatic positioning systems are equipped with sensors such as cameras and machine vision systems with specially designed software. In the August Design system, the machine vision processes the images provided by the cameras and locates the twist locks on the chassis. Using this information a control signal is transmitted to the crane or hostler operator using either LED displays or other means of communication. The control signals transmitted provide the crane operator with information on how to move and do the alignment.

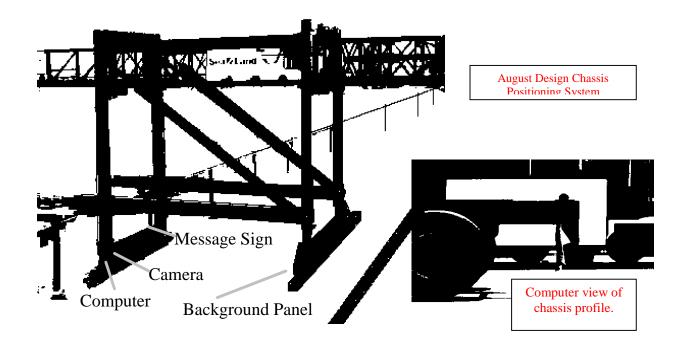


Figure 2.8: August Design chassis positioning system.

#### **Type:** Automatic and Smart Spreaders

**Brief Description:** Another technique for reducing the positioning difficulty of the spreader bar is the so-called automatic spreader. Automatic spreaders are equipped with electro-hydraulic controls for automatic rotation of the twistlocks by 90 degrees for locking the spreader into the container.

The most advanced technology in this area is the Bromma Smart Spreader [35] used for loading/unloading two twenty-foot containers simultaneously. Seven sensors located at the center of the specially designed spreader are used to detect the existence of any gap between the containers. Using the information provided by the sensors, the spreader expands or retracts accordingly. Special attention is given for impact avoidance. The automatic positioning system automatically adjusts the length positioning of the spreader in the event of an impact. If a particularly hard impact causes the telescopic ends of the spreader to be pushed in or out, the spreader will automatically expand or retract to return the spreader to its original position.

The DARTS spreader codesigned by Bromma and August Design takes the technology a step further by allowing the spreader to pick up and place two twenty-foot containers that are positioned up to 5 feet apart. This allows direct access to containers on flatcars, and also allows the placement of two twenty-foot containers in a 45-foot hatch.

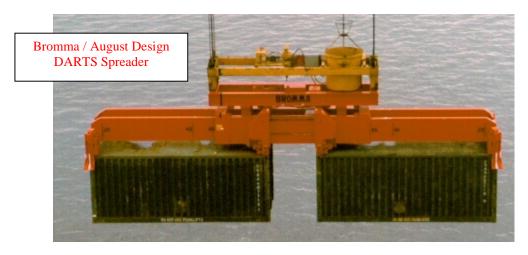


Figure 2.9: Bromma/August Design DARTS spreader.

### **<u>Type:</u>** NIST Robocrane

**Brief Description:** The design of the National Institute of Standards and Technology (NIST) robocrane is based on the following concept [25]: "By attaching the cables to a work platform and keeping all cables in tension, the load is kinematically constrained, and the work platform resists perturbing forces and moments with equal stiffness to both positive and negative loads. The result is that the suspended load is constrained with a mechanical stiffness determined by the elasticity of the cables, the suspended weight, and the geometry of the mechanism". Based on this concept several prototypes have been designed, developed and tested (Figure 2.10).

A gantry resembling an octahedron geometry [25], shown in Figure 2.10 (a), is used for housing the work platform. The work platform is connected to the octahedron via cables. Each of the triangular legs of the platform rotates about each member of the upper triangle. The rotation of the legs controls the position of the work platform. The forces and torques applied to the work platform are translated to compression in the legs.

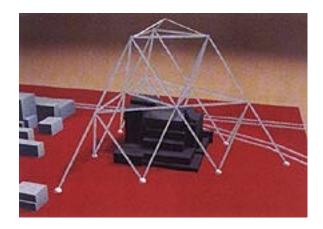
The above design – accompanied with appropriate control algorithms for leg movement – has been shown to produce higher payload-to-weight ratios than conventional cranes. Moreover, the NIST robocrane design completely overcomes the problem of sway. Therefore, the NIST robocrane does not require highly skilled operators, since no sway is present. Moreover, the NIST robocrane allows even a novice operator to position the load with accuracy of few millimeters and to control orientation without oscillation to within one degree in roll, pitch and yaw [25]. A down side to the crane is its need for a wide frame and cables at wide ranges. The wide frame provides stability of the cables, but it is likely to interfere with the infrastructure on most ships. The wide frame and the relatively extreme angles of the cables prevent the system from entering a hatch or reaching between stacks of containers without added capability.

A very interesting application of the NIST robocrane concept is the TETrahedral Robotic Apparatus (TETRA) project [26] for helicopter external cargo handling and rescue applications. In this project the idea is to attach the octahedron of the NIST crane at the bottom of the helicopter, with the legs attached to the helicopter. The work platform used for loading and unloading is attached at the top of the octahedron and a cable connects the center of the work platform with the bottom of the helicopter [26]. The height of the octahedron could be in the range of 75-200 feet. Using similar mechanisms as in the NIST robocrane, the pilot of the helicopter will be able to position the work platform with high accuracy and without any sway present.

The TETRA concept could be proven very useful for military applications at places where no port facilities are available.



(a)



**(b)** 

Figure 2.10: NIST Robocrane.

#### **Type:** August Design Robotic Crane

**Brief Description:** August Design has developed a one-tenth scale working model of a robotic container crane [24]. In full-scale operation, the robotic container crane would have a horizontal reach of 140 feet, and a vertical reach of 150 feet. The robotic crane is essentially a large scale combination of a SCARA robot, a rigid hoist, and a 6 degree of freedom (DOF) spreader bar (Figure 2.11). The lightweight SCARA arm is rigid horizontally, but articulated in two sections. It is able to rotate about the "shoulder" and "elbow" joints. The rigid hoist transports the spreader bar vertically and eliminates swaying movement due to cables. The 6 DOF spreader bar is an inverted Stewart platform and allows the spreader to move in a controlled fashion to follow the target container. Machine vision is employed to automatically track the moving target and guide the spreader into the proper position to pick up or place the container. In addition to the automatic pick-and-place capability, the system also permits telerobotic control by human operators in the control loop.

It has been estimated [24] that a 140-foot long robotic crane can be used to unload a container ship with a throughput of approximately 75 containers per hour. In addition to increased productivity, the robotic crane has several other advantages:

- It can operate well in high winds due to its rigid structure and lack of long swaying cables.
- It can operate in high sea states by utilizing a 6 DOF spreader bar that can adjust to the motions of the vessel.
- The use of machine vision reduces the level of manpower required.
- Because of the system's high productivity, it is likely that commercial shipping companies would use the robotic crane on both the pier and the vessels themselves.

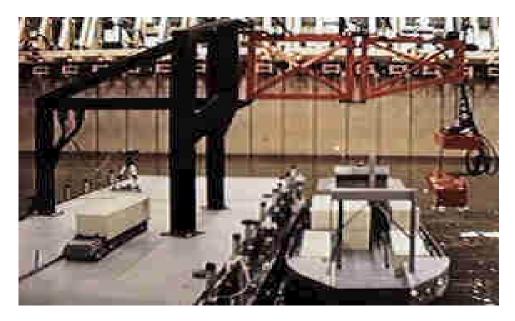


Figure 2.11: August Design robotic crane.

**<u>Performance</u>**: We summarize the performance characteristics of the August Design Robotic Crane in the following table.

Moves per hour	75 (estimate [24])
Vertical Reach (feet)	150
Outreach (feet)	140
Ships served	16-18 wide Post-Panamax
Cost	\$10.8M (estimate [19])
Cycle mode	Single and Double
Development Status	Design Stage

<b>Table 2.8: Performance</b>	Characteristics of	August Design	Robotic Crane
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### 2.1.4 Summary of Performance Characteristics

In the following table we summarize the performance characteristics of the ship loading/unloading equipment presented in this section.

Technology	Moves/hour	Cost	Advantages	Disadvantages	Development status
Conventional gantry	20-35	\$5-7M \$7-11 M	1.Work horse of the industry 2.DCM	1. Low performance	In use
Dual hoist Single trolley	30-55	130-150% of the conventional needs 2 operators	1.5 times faster than conventional cranes	1.SCM	In use
Dual hoist elevating platform	30-55	130-150% of the conventional 2 operators	1.5 times faster than conventional cranes	1.SCM	In use
Dual hoist elevating girder	30-40	150-175% of the conventional. Two operators	1. DCM	1. Increased cost (compared to conventional cranes)	Design Stage
Dual hoist dual trolley	50-70	Increased cost wrt conventional (no other data)	1.SDM	1. Increased cost (compared to conventional cranes)	Design Stage
Megacrane	40-50	No data	1.Serving Mega-Ships 2.DCM		Design Stage
Ship-mounted A-type	25-30	\$3.1M		1.Low-productivity 2.Adds weight to ship	In use
Ship-mounted C-type	25-30	\$3.1M	1. Twin operation	1.Low-productivity 2.Adds weight to ship	In use
Ship-mounted Jib	25-30	\$4.3M	1. Twin operation	1.Low-productivity 2.Adds weight to ship	In use
Ship-mounted pedestal	10-20	\$1.35M	<ol> <li>1.Twin operation</li> <li>2.Handling special cargo</li> <li>3.Low cost wrt to gantry</li> </ol>	1.Low-productivity 2.Adds weight to ship	In use
Crane w/ APS	5% improvement	No data	1.Improves loading/unloading time		In use

#### Table 2.9: Summary of Performance Characteristics of Ship Loading/Unloading Equipment

Technology	Moves/hour	Cost	Advantages	Disadvantages	Development status
Crane w/ Anti-	Small or no	No data	1.Minimizes sway	1.Experienced operators avoid using it	In use
sway	performance improvement		2.Suitable for non- experienced operators 3.Does not require major modifications in the crane design	2. Most of existing designs are based on simplified crane dynamics models	
Crane w/ Automatic Spreader	5% improvement	No data	1.Improves loading/unloading time		In use
Crane w/ smart spreader	5% improvement	No data	1.Improves loading/unloading time		In use
NIST robocrane	75-100	No Data	1.Eliminates sway 2.Dock-mounted or ship mounted 3.Operation in high- winds/seas 4.Remote control/completely automated 5. No need for experienced operators	<ol> <li>Increased manufacturing cost</li> <li>Not suitable for large loads</li> <li>Need for a wide frame and cables at wide ranges</li> </ol>	Design Stage
August Des. Robotic crane	75	10.8 M	1.Eliminates sway and cables2.Advanced Machine vision systems3.6 DOF spreader bar4.Dock-mounted or ship mounted5.Operation in high- winds/seas6.Remote control/completely automated7. No need for experienced operators	<ul><li>1.large inertia, low flexible structure mobility.</li><li>2.Increased manufacturing cost</li></ul>	Design Stage

### Table 2.9 (Continued)

1. DCM = double cycle mode 2. SCM = single cycle mode

# 2.2 Yard Loading/Unloading Equipment

In this section we present the various types of equipment for loading and unloading containers in the yard.

# **<u>Type:</u>** Rubber-Tired Gantry (RTG)

**Brief Description:** This type of crane, shown in Figure 2.12, refers to traveling cranes used for the movement and positioning of containers in a container yard. RTGs may also be used for loading and unloading containers from rail cars. One common trade name for this equipment is the Transtainer.



Figure 2.12: Rubber-tired gantry crane.



Figure 2.13: Straddle carriers.

# **<u>Type:</u>** Straddle Carrier

**Brief Description:** Straddle carriers, shown in Figure 2.13, are rubber tired lifting units that are used to place and pick up containers from stacks within the yard. They are manually driven and typically are capable of lifting a container 4-6 container-heights high (one-over-three to one-over-five).

# **Type:** Rail-Mounted Gantry (RMG)

**Brief Description:** This is the same as the rubber tired gantry except that is rail-mounted.

**Type:** Bridge Crane



Figure 2.14: Bridge crane.

**Brief Description:** Bridge cranes (also known as traveling overhead cranes) consist of a "bridge" structure and a trolley as shown in Figure 2.14. According to [37] it is a crane on a pair of parallel elevated runways, adapted to lift and lower a load and carry it horizontally parallel to, or at right angles to, the runways or both. It consists of one or more trolleys operating on the bridge which in turn

consists of one or more girders or trusses mounted on trucks operating on the elevated runways. The operation of the bridge crane is limited to the area between the runways.

## Performance characteristics of yard loading/unloading equipment

JWD (Jordan-Woodman-Dobson) performed a study on behalf of Virginia Intermodal Terminal, the operator of Norfolk International Terminal (NIT), that involved a comparison of the above different types of yard loading/unloading equipment [41] for a terminal equipped with three dual-hoist dock cranes, each capable of 45 moves per hour. The results of the study are summarized in the following table.

Crane	Feeding 3	Yard Cranes	Feeding	No of moves per	Cost
Туре	Dock		Yard	hour per crane	(\$/move)
	Cranes			loaded in the ship	
Rubber-	18	7 Rubber-tired	7 Hostlers	28	89.49
tired	Hostlers	Gantry's			
Gantry					
Straddle	9 Straddle	Not	7 Straddle	32	92.04
Carrier	Carriers	Applicable	Carriers		
Rail-	9 Straddle	7 Rail-	4 Hostlers	32	89.83
mounted	Carriers	mounted			
Gantry		Gantry's			
Bridge	9 Straddle	7 Bridge	3 Straddle	30	90.79
Gantry	Carriers	gantry's	Carriers		

Table 2.10: Productivity under Four Different Scenarios for the NIT

As it can be seen from the above table, for each type of yard loading/unloading equipment different types of equipment for serving the dockside cranes and feeding the yard were chosen. For instance, in the case where rubber-tired gantry cranes are used, the dockside cranes and the trucks are served using hostlers.

It is worth noticing that the results summarized in the above table are applicable only to NIT. The performance and cost estimates may be different in other terminals. However, the estimates presented in the above table provide a rough estimate of the capabilities of today's yard loading/unloading equipment and can be used as a base scenario for the comparison of current yard loading/unloading equipment with yard loading/unloading equipment that employs advanced technologies.

The productivity of yard loading/unloading equipment varies depending on whether the container to be picked up is in the top, middle or bottom tier. Below we present some estimates of the productivity of the yard loading/unloading equipment depending on the position of the container:

**Rubber tired gantry crane**. It is assumed that the rubber tired crane is over the stack of interest and the chassis where the container is to be placed is aligned properly below the crane. The lateral speed of the crane is 5 miles per hour. Moreover it takes about 15 seconds to line up the crane with the stack. The time required to load/unload a container is:

- best case (container is on the top tier): 30 seconds.
- worst case (digging out a container form the bottom of a cell without redressing the cell): 150 seconds.
- average: 50 seconds.

The above performance numbers are the same for **rail mounted gantry cranes**.

**Straddle carrier.** It is assumed that the straddle carrier is within 40 feet away from the container scheduled to be picked up. The time required to load/unload a container is:

- best case (picking the top container in a two container stack): 20 seconds.
- worst case (picking the lower container in a two container stack): 60 seconds.
- average: 30 seconds.

The average moving speed of the straddle carriers is about 15 miles per hour.

**Bridge Crane**. It is assumed that the crane is within 40 feet away from the container scheduled to be picked up and placed on a chassis. It is also assumed that the lateral speed of the crane is 5 miles per hour and it takes about 15 seconds to line up the crane with the stack. The time required to load/unload a container is:

- best case (move from the ground to a chassis): 35 seconds.
- worst case (pick up a container buried two down): 120 seconds.
- average case (move a container from a stack to a chassis): 45 seconds.

Equipment	Loading/Unloading Time			Assumptions	Speed	
Туре	Best case	Worst case	Average			
Rubber-tired Gantry	30 seconds	150 seconds	50 seconds	Chassis is aligned properly below the crane	5 mph lateral speed Needs 15 secs to line up with the stack	
Rail- mounted Gantry	30 seconds	150 seconds	50 seconds	Chassis is aligned properly below the crane	5 mph lateral speed Needs 15 secs to line up with the stack	
Straddle Carries	20 seconds	60 seconds	30 seconds	Within 40 ft of the container	15 mph	
Bridge Crane	35 seconds	120 seconds	45 seconds	Within 40 ft of the container	5 mph lateral speed Needs 15 secs to line up with the stack	

### 2.3 The Sway Problem

### 2.3.1 Anti-Sway Systems

An important problem of today's crane technologies is the sway. Before we analyze the problem further let us present a simplified description of the sway problem [23]. More precisely, let us consider a simplified crane model consisting of a weight suspended on a long string or cable. Such a system acts very much like a pure pendulum. In a frictionless environment, once the weight is offset from the vertical, it will swing back to a point just as far on the other side and keep doing that forever. The length of time it takes for the weight to get back to the same position on every cycle is called the pendulum period. The period is dependent only on the length of the pendulum and has nothing to do with how much weight is attached. In the real world, there is always some air friction on the string and the weight, so the heavier the weight, the more it acts like a frictionless pendulum. If the weight is stationary and the top of the cable (called the fulcrum) starts to move, then sway occurs also. If the fulcrum now stops suddenly, then there will be residual sway. Unless there is significant friction or something else to stop it, it will keep swaying for a long time. With well timed fulcrum movements, it is possible to reduce this residual sway but it takes time. When an actual crane is operated, the unavoidable movements of the trolley and the container lead to sway and the operator has to trade off speed and fine positioning with sway.

One way to reduce the effects of sway is by designing appropriately the mechanical components of the crane. An example is the NIST robocrane, where the mechanical design provides with flexiblestructure mobility. Another example is the August Design robotic crane, where the sway problem is overcome by replacing the standard crane configuration by a robotic arm with no cables. However, such a method gives rise to other problems, such as mechanical systems with large inertia and low flexible-structure mobility and expensive operating cost due to the use of powerful motors.

Another way to reduce the effects of sway is by introducing advanced control systems like the anti-sway systems described before. Returning back to the simple example, let us see how current anti-sway systems work according to [23]. The simplest method for eliminating sway is called "bang-bang" control. In this case, the fulcrum is first accelerated to half the speed and, one-half pendulum period later, it is accelerated to full speed. If this is done precisely, then the weight will be hanging straight down below the fulcrum. Stopping without sway is just the reverse procedure: slow to half speed and then wait one-half pendulum period before stopping. In other words, the acceleration is in two pulses, allowing the load to catch up with the trolley. The deceleration is also in two pulses, letting the load first get ahead of the trolley and then the trolley catches up with the load. The load is lowered rapidly at the end of the move.

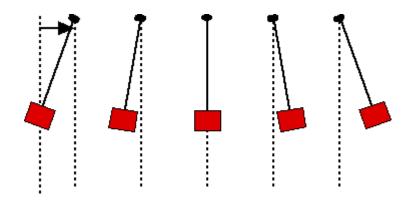


Figure 2.15: The sway problem (taken from [23]).

The above simple bang-bang control technique or similar techniques are used by most existing anti-sway systems. However, an actual crane is not as simple as a pendulum. The actual crane dynamics are highly nonlinear and - due to the effect of the human operator - quite unpredictable. This has two implications: (i) Due to the system nonlinearities and operator interference the anti-sway system may not improve and in some cases worsen the crane performance. Actual measurements collected by a member of our group at the Port of Tacoma indicate that in many cases, the use of antisway systems has a negative effect on productivity, which leads the operators to switch the anti-sway off. (ii) From a mathematical point of view, simple control designs like the bang-bang one, may lead to instabilities or poor performance when applied to complicated nonlinear systems. Advanced control methods have recently been proposed for killing anti-sway and/or automatically controlling the movements of the crane. Although those methods should be expected to perform better than the ones used by the current anti-sway systems, they still cannot guarantee system stability and good performance. The complicated nature of the crane dynamics makes the control design a very difficult problem with no satisfactory solution, so far. In the next subsection we present a method, developed by our group, that uses advanced nonlinear techniques for designing efficient anti-sway systems. This approach is shown to guarantee global stability and outperform the existing approaches.

## 2.3.2 New Nonlinear Control Anti-Sway System

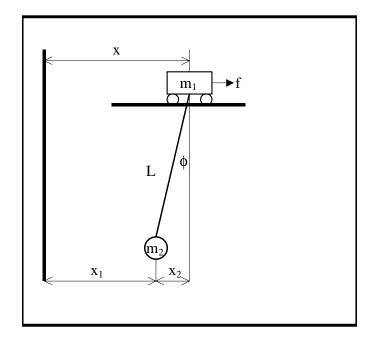


Figure 2.16: Simplified model of a crane.

Consider the model of a crane shown in Figure 2.16. In Figure 2.16  $m_1$  denotes the mass of the trolley,  $m_2$  is the mass of the load, L is the length of the suspending rope,  $\phi$  is the angle between the suspending rope and the vertical taken as positive in the clockwise direction, x is the displacement of the trolley's mass of gravity,  $x_1$  is the displacement of the mass of center of the load and  $x_2$  is the displacement of the center of the gravity of the load with respect to the center of gravity of the trolley. The displacements x,  $x_1$ ,  $x_2$  are with respect to a fixed coordinate system.

The crane model of Figure 2.16 is not complete since it does not incorporate the dynamics of the trolley and hoist motors. However, any control approach designed for the crane model of Figure 2.16 can be easily modified to be applicable to crane models that include the dynamics of the trolley and hoist motors. This is true, since if  $T_1$  and  $T_2$  denote the torques applied to the trolley and hoist motors, respectively, then the force f applied to the trolley and the force  $f_1$  applied to the suspending rope are related to  $T_1$ ,  $T_2$  through a mapping of the form

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = F(\bullet) \begin{bmatrix} f \\ f_l \end{bmatrix}$$

where  $F(\bullet)$  is a nonlinear function that depends on  $x_1$ ,  $x_2$  and L and on the crane geometric and inertia characteristics. Thus, one can use the proposed control design for calculating f and  $f_1$  and then compute  $T_1$  and  $T_2$  using the above equation.

If X denotes the 4-dimensional vector whose entries are  $x_1$ - $x^*$ ,  $x_2$  and their velocities, respectively, where x- $x^*$  denotes the desired travel distance and  $x^*$  denotes the desired destination point it can be seen [33] that the crane dynamics are governed by the following differential equation

$$\frac{d}{dt}X = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ g & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} X + \begin{bmatrix} 0 \\ 0 \\ 1/m_1 \\ 1/(m_1 + m_2) \end{bmatrix} f$$
(1)

The element g in the above equation is a nonlinear function that depends on many factors such as L, the angle  $\phi$  as well as their first and second time-derivatives and the masses m<sub>1</sub>, m<sub>2</sub>. In other words, g is a function of L, sL, s<sup>2</sup>L,  $\phi$ , s $\phi$ , s<sup>2</sup> $\phi$ , m<sub>1</sub>, m<sub>2</sub> where s denotes the differential (Laplace) operator, i.e, sL=dL/dt, s<sup>2</sup>L=d<sup>2</sup>L/dt<sup>2</sup>. In the sequel, we will write g(L, sL, s<sup>2</sup>L,  $\phi$ , s $\phi$ , s<sup>2</sup> $\phi$ , m<sub>1</sub>, m<sub>2</sub>) when we want to stress the fact that g is a nonlinear function of the quantities in the argument. Notice that due to hoisting the rope length L is not a constant and sL, s<sup>2</sup>L are not necessarily zero. Therefore the crane equations depend on the nonlinear and time-varying function g. The presence of g in the crane equations is the main reason why the crane control design is not an easy task. The function g makes the crane dynamics nonlinear and time-varying to a control problem that is difficult to solve due to the lack of control techniques for such a class of systems.

Let us now rewrite equation (1) in the following compact form

$$\frac{d}{dt}X = AX + Bf \tag{2}$$

where A and B are defined as

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ g & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1/m_1 \\ 1/(m_1 + m_2) \end{bmatrix}$$

Note that A is a nonlinear, time-varying function due to the presence of the term g.

In the past the following two approaches for crane control design have been pursued. In the first one the crane dynamics are linearized around an operating point leading to a linear time-invariant system. Then linear control techniques are used to design a control system based on the linear simplified model. The second approach uses gain-scheduling control design techniques. In this case the crane dynamics are approximated by a number of linear time-invariant systems each corresponding to different values of the vector X. For each of these linear systems a different linear controller is designed. The actual controller switches between these linear controllers depending on the particular value of the vector X. Both of the above approaches suffer from the drawback that the approximation modeling errors due to linearization affect dramatically the performance and stability of the controller. In the following we present an antisway control design which is based on recently developed nonlinear

and neural network control techniques that are suitable for the class of dynamics that is similar to the crane ones.

The proposed control design is a multi-step procedure described as follows:

<u>Step 1</u>: Let (Q(j), q(j)), j = 1, 2, ..., M, where Q(j) is a 4x4 symmetric positive definite matrix and q(j) a positive design constant, be chosen as follows: each of the pairs (Q(j), q(j)) is associated with the functional [38]

$$J(j) = \int_0^\infty (x'Q(j)x + q(j)f^2)dt$$

Thus, given a state trajectory x(t) and a control trajectory f(t), each of the functional J(j) provides with a different measure of the performance of the closed-loop system. The particular choice of (Q(j), q(j)) corresponds to different performance objectives. Let the pairs (Q(j), q(j)) be chosen as follows: the first pair (Q(1), q(1)) is chosen so that it corresponds to a closed-loop performance with ideal transient performance and steady state error characteristics, the second pair (Q(2), q(2)) corresponds to a closedloop performance that is slightly worse than the one that corresponds to the first pair, and so on.

**Step 2**: Compute the matrix  $A=A(g)=A(g(L, sL, s^2L, \phi, s\phi, s^2\phi, m_1, m_2))$  around N points Z(1), Z(2), ..., Z(N) where each of these points corresponds to different values of L, sL, s<sup>2</sup>L,  $\phi$ , s $\phi$ , s<sup>2</sup> $\phi$ . Let A(1), A(2), ..., A(N) denote the values of the matrix A that correspond to the points Z(1), Z(2), ..., Z(N). The points Z(1), ..., Z(N) must be chosen so the corresponding values g(Z(1)), ..., g(Z(N)) are uniformly distributed at the space of all the possible values that the function g can take.

<u>Step 3</u>: For each A(1), A(2), ..., A(N) find N\*M matrices P(i,j) that solve the Algebraic Ricatti Equations (ARE)

$$A'(i)P(i, j) + P(i, j)A(i) - \frac{1}{q(j)}P(j)BB'P(j) = -Q(j), i = 1, 2, ..., N, j = 1, 2, ..., M$$

where P(i,j) is a symmetric positive definite matrix. The Matlab Control System Toolbox can be used to solve the above AREs.

#### Step 4: Define

$$K(i, j) = \frac{1}{q(j)} B' P(i, j), i = 1, 2, ..., N, j = 1, 2, ..., M$$

Train a neural network NN(g,Q,q) so that the difference

$$NN(g(Z(i)),Q(j),q(j)) - K(i,j)$$

is minimized. In other words, the neural network is trained to approximate the input-output mapping

$$g, Q, q \to k$$

given by the solution of the ARE. It can be shown that such a mapping is continuous provided that g does not change sign. It can be seen (see the simulation section) that g remains always negative, and

thus the mapping is continuous. The proposed controller is then as follows: at each time-instant t, find the minimum integer j that satisfies

$$\lambda_{\min}(Q(j) - dP(j)) > 0$$

where  $\lambda_{\min}$  denotes the minimum eigenvalue and dP(j) is defined as follows:

$$dP(j) = \frac{\partial NN}{\partial x} (g(Z(t)), Q(j), q(j)) \left[ A(g(t)) - \frac{1}{q(j)} BB' NN(g(Z(t)), Q(j), q(j)) \right]$$
$$+ \frac{\partial NN}{\partial L_a} (g(Z(t)), Q(j), q(j)) \frac{dL_a}{dt}$$

where  $L_a=[L, sL, s^2L]$ . The control force applied to the trolley is chosen according to the control law

$$f = -NN(g(Z(t)), Q(j), q(j))X(t)$$

The advantages of the proposed control design over the existing ones are the following:

• The proposed technique guarantees global closed-loop stability whereas the existing methods guarantee only local stability. The proposed control design takes into account the nonlinearities of the system whereas the existing methods do not, which is the reason why they are susceptible to instabilities due to even small nonlinearities [36].

• The function V=x P(j)x can be used in order to calculate bounds on the performance of the proposed controller. When these bounds are not satisfactory we can redesign the controller by changing the pairs (Q(j), q(j)) in step 1 and/or by increasing the number N in step 2. More precisely, it can be shown that the function V satisfies the following differential inequality

$$\frac{d}{dt}V \le -x'(Q(j) - dP(j))x + n$$

where n is a term that is proportional to 1/N. In other words, the term n can be made arbitrarily small by increasing the number N of points Z(1), ..., Z(N). By solving the above differential inequality, we can relate the performance of the proposed control design to the matrix P.

• The proposed technique can be easily modified in order to be suitable for more complex – and thus more realistic – crane models.

• It is demonstrated using simulations that the proposed approach outperforms the existing ones. In particular, the proposed approach requires at most half the time to move the container from one point to another, compared to the existing approaches. Moreover, while the existing approaches guarantee good performance and stability only for the case of small lifting/lowering velocities (less than 1.2 m/sec), the proposed approach guarantees good performance and stability for lowering/lifting velocities of up to 50m/sec.

#### **Simulations**

We demonstrated the performance of the proposed controller by means of simulations. For comparison purposes, we used the same parameters and initial conditions as the ones used in [33]

where an advanced gain-scheduling technique is simulated for the control of cranes. The approach of [33] is the best we found in terms of performance and stability.

Similar to [33] the simulation parameters are as follows: the trolley mass is 6 tones and the container mass is 42.5 tones. These values are those of a container crane at the port of Kobe, Japan. The maximum and minimum suspending rope lengths are 10 meters and 2 meters, respectively. Moreover, the maximum allowable control force applied to the trolley is  $10^5$  N.

As in [33], we used the proposed controller to move the trolley at a distance of 5 meters, assuming that there is initially sway that corresponds to a value for  $x_2$  of 1.5 meters. We performed three different simulation tests. In the first, we simulated the proposed controller under no hoisting, in the second one, we simulated the controller under lifting with constant velocity of 50 m/sec and in the third we simulated the proposed controller for lowering with constant velocity of 50 m/sec. We mention here that the approach of [33] guarantees stability only for lowering/lifting velocities that are less than 1.2 m/sec. In the simulations of [33] a constant velocity of 0.5 m/sec is used. In our simulations we use the very large value of 50 m/sec for lowering/lifting velocity to demonstrate the efficiency of our approach.

Figures 2.17-2.22 summarize the three different simulation experiments. The blue curves correspond to the closed-loop system performance under the proposed controller while the red curves correspond to the closed-loop system performance under the controller of [33]. In all three cases, the proposed controller outperforms the one of [33] both in terms of settling time and overshoot. In all three cases the proposed controller requires at most 6 seconds settling time, while the controller of [33] needs 16-20 seconds settling time. On the other hand, the overshoot corresponding to the proposed controller is 1.5-2.5 meters for  $x_1$  and no overshoot for  $x_2$  while the controller of [33] produces an overshoot of 2-4 meters for  $x_1$  and 1 meter for  $x_2$ . Table 2.12 summarizes the simulation results.

	<b>Proposed Controller</b>	Existing Controller
Settling Time (No Hoisting)	5.5 sec	20 sec
Overshoot (No Hoisting)	$x_1$ : 1.4 meters $x_2$ :0 meters	$x_1$ : 2 meters $x_2$ :0.4 meters
Settling Time (Lifting)	5.5 sec	18 sec
Overshoot (Lifting)	$x_1$ : 1.2 meters $x_2$ :0.1 meters	$x_1$ : 2 meters $x_2$ :0.3 meters
Settling Time (Lowering)	5.2 sec	17 sec
Overshoot (Lowering)	$x_1$ : 2.4 meters $x_2$ :0.3 meters	$x_1$ : 4 meters $x_2$ :0.9 meters

Table 2.12: Comparison of Existing and Proposed Controllers

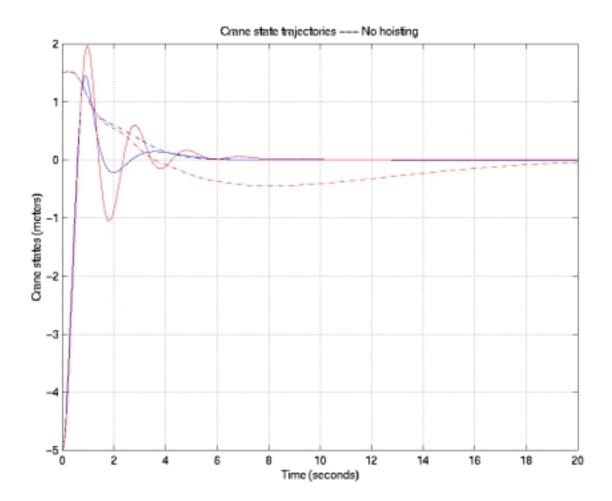


Figure 2.17: Crane states history (x(1): solid curve, x(2): dashed curve; the blue curves are for the proposed technique and the red curves for the existing technique) --- No hoisting.

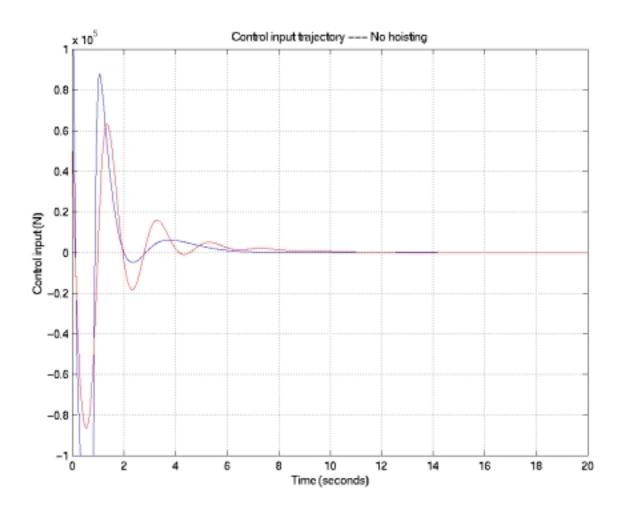


Figure 2.18: Control Input (blue curve: proposed technique, red curve: existing technique)---No hoisting.

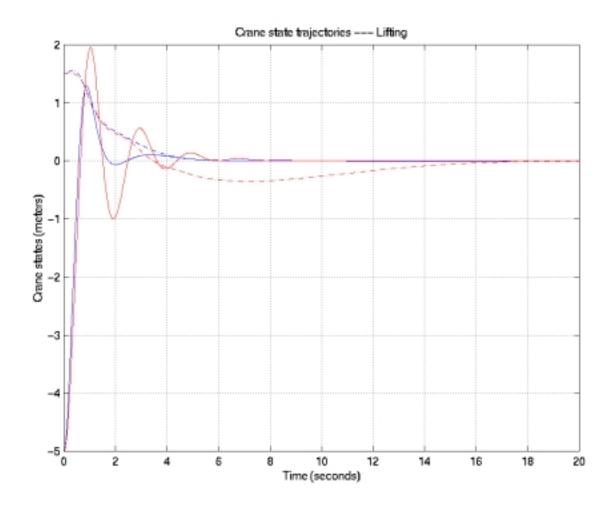


Figure 2.19: Crane states history (x(1): solid curve, x(2): dashed curve; the blue curves are for the proposed technique and the red curves for the existing technique) --- Lifting .

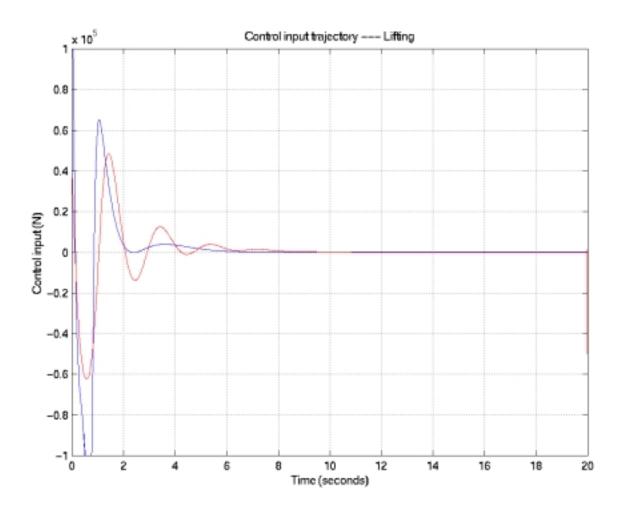


Figure 2.20: Control input curves (blue curve: proposed technique, red curve: existing technique) --- Lifting.

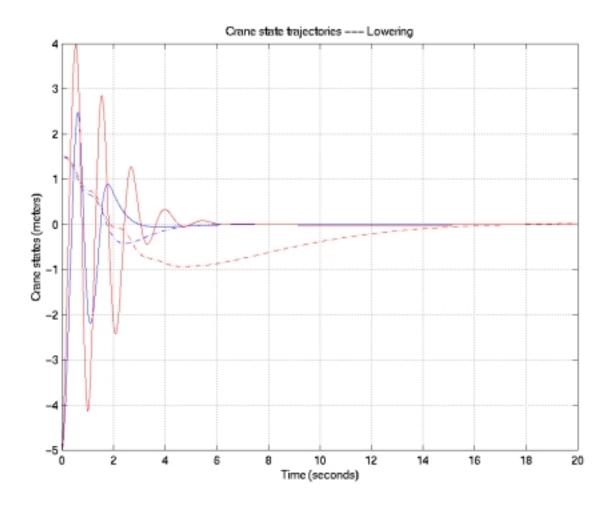


Figure 2.21: Crane states history (x(1): solid curve, x(2): dashed curve; the blue curves are for the proposed technique and the red curves for the existing technique) --- Lowering.

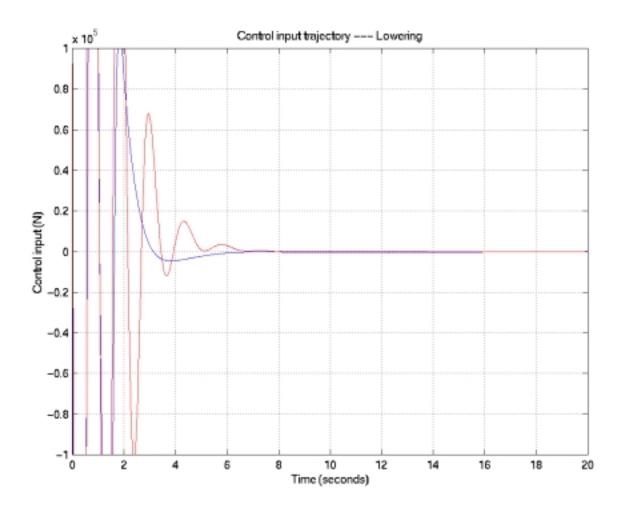


Figure 2.22: Control input (blue curve: proposed technique, red curve: existing technique) ---Lowering.

## 2.4 Cell Elevator

One of the most difficult moves for a crane operator is to place the spreader bar into the hold of a container ship. Despite mechanical gathers at the top of hatch cells, even the best of operators must make several failed attempts before finally entering the cell. This problem is even more pronounced in the military sealift environment because of vessel movement, and the need to operate in harsh environments.

August Design, Inc. is currently developing a concept called the cell elevator (CE). The purpose of the device is to raise the top container in each cell to deck level where the crane can easily access the container. Once the crane removes the container, the in-cell device will retrieve the next container and raise it above deck. The system would also work in reverse; that is, the crane operator could place a container above deck and the in-cell mechanism would stow the container below deck. Such a device should increase productivity significantly because it would ease the task of picking and placing containers. Since the device works in parallel with the crane, it would eliminate the need for the crane to enter the hatch, a major portion of the crane cycle.

During the product development cycle, August Design Inc. plans to investigate several methods to implement the lifting device. The concepts will include devices that would be built into each cell, requiring modification of the ship, but much more promising are devices that can be moved from cell to cell by the crane, requiring little or no ship modification. Preference will be given to devices that will require no modification to the ship and can be used on any vessel carrying containers below deck. Ideally the system will work with 20-foot, 40-foot, and even 45-foot containers.

A system that would not require modification of the vessel would be movable from cell to cell. A movable system would be placed in position on the ship using the existing crane and spreader bar. Once at the cell, the device would move a grasping mechanism down the cell guides until it reached the top container. At that time, the device would lock into the top corner posts of the container and proceed to slowly lift the container to the top of the cell. With such a system, multiple devices could be deployed at one time so that a container is always available for the crane.

The following sketches illustrate how the system might function. Please keep in mind that the sketches are artist's concepts only. Figure 2.23 shows the full CE system. For illustrative purposes the CE shown in Figure 2.23 is 20 feet long, but the CE can be 40 or even 45 feet long. It will be shown how a 40-foot CE can deal with dual 20-foot containers.

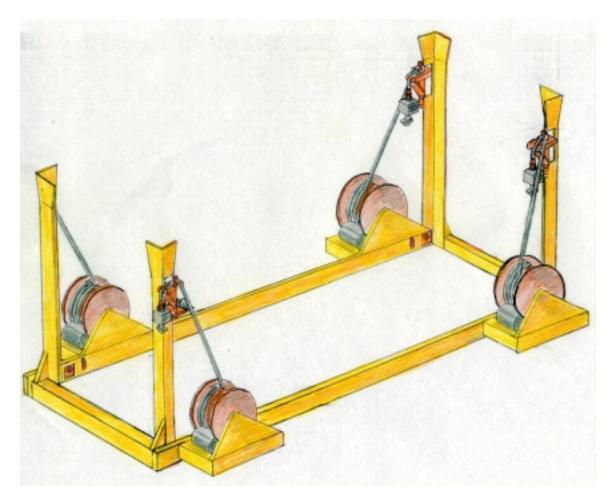


Figure 2.23: Illustration of full CE System.

In operation the CE would be lifted by a standard spreader bar and placed at the top of a ship's cell. Figure 2.24 shows one corner of the CE in place over a hatch. The cell guide of the ship's hatch can be seen below the CE in Figure 2.24. The CE itself includes what is in effect an extension of the cell guide that extends vertically above deck. The very top of the extension is flaired to provide a funnel effect to allow containers and the spreader to easily enter into the CE. In the illustration, the flair is slight, but in practice it could be more pronounced in order to ease the task of entering the CE (and subsequently the cell of the ship). Figure 2.24 also points out a number of the components of the CE: winch, twist lock stowage rotator, twist lock with magnetic rollers, container sensor, and lower corner casting pin. The purpose of each of the components will be discussed below.

Figure 2.25 shows one corner of the CE in the stand-by mode. The winch has drawn its cable in fully, causing the twist lock with magnetic rollers to rise to its highest level. The twist lock stowage rotator is rotated behind the cell guide extension by the use of a small linear actuator. In other words the cell guide path is clear for a spreader or container to enter. The lower twist lock pin is in the retracted position, leaving the opening to the ship cell clear for a spreader or container. The container sensor, as shown in the illustration, is a spring loaded switch. The purpose of the sensor is to detect the presence of a container and in particular the lower edge of the container. In practice one or more

sensors maybe used and they may be some other type of sensor rather than the mechanical one shown. In the illustration no container is present, so the sensor would indicate such.

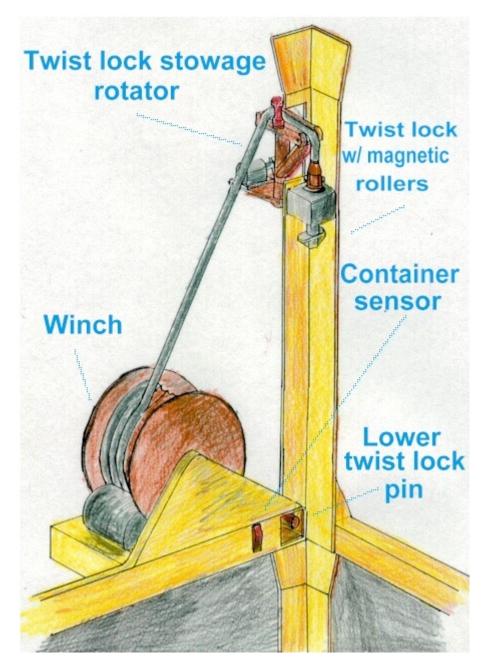


Figure 2.24: Corner of the CE with component labels.

To pick up a container from inside the cell, the actuator would move the twist lock stowage rotator, as shown in Figure 2.26.



Figure 2.25: CE in the standby position.

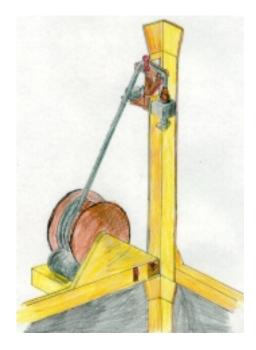


Figure 2.26: CE in start position to pick up a container.

The idea of the magnetic rollers is to keep the twist lock mechanism aligned in the cell guide as it is lowered by the winch. (Note that it is recognized that the pulleys shown on the twist lock stowage rotator are very much undersized in the drawing for the purpose of illustration.)

Figure 2.27 shows the twist lock with magnetic rollers being lowered into the hatch, while clinging to the extension. As the twist lock is lowered into the cell it continues to grip the cell guide. A sensor in the mechanism would detect that the twist lock has entered the corner casting of the container in the cell. When all four twist locks are engaged, the winches would reverse direction and in synchronism raise the container up the cell guide. If the twist lock is not properly in place a jogging mechanism would activate to nest the twist lock. While it is possible for the twist lock to be self-powered, it is envisioned that the lifting cable will contain power and signals.

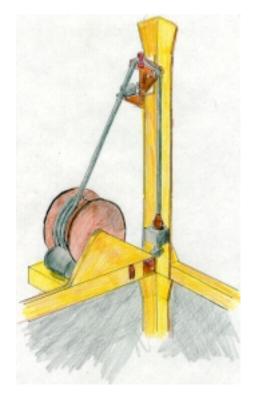


Figure 2.27: CE lowering a twist lock with magnetic rollers into the hatch.

In Figure 2.28 the container is shown lifted above the hatch, but still held within the in the extension of the cell guide that is part of the CE. The container sensor has detected the bottom of the container allowing the lower corner casting pin to extend and lock into the lower corner casting of the container. Sensors would recognize that the container is supported by all four pins and all four twist locks with magnetic rollers would disengage. The twist locks would then be rotated out of the way to provide a clear path for a spreader to lock onto the container.



Figure 2.28: CE after lifting a container to the deck of the ship.

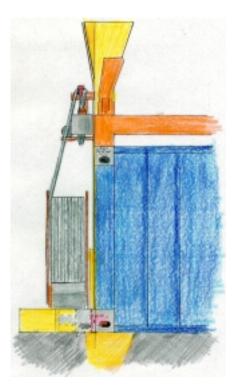


Figure 2.29: Spreader accessing a container in the CE.

Figure 2.29 shows that the spreader bar has been guided onto the container by the flair at the top of the CE's cell guide extensions. The spreader would lock onto the container as it normally would. Once the spreader has locked onto the container, the lower corner casting pins of the CE would be retracted, allowing the container to be lifted by the spreader.

The CE could then retrieve another container, accept a container for placement in the cell or can be moved by the spreader to another cell.

Accepting a container is very similar to removing a container. The twist lock with magnetic rollers is rotated out of the way, the spreader lowers the container into the CE, a sensor detects the container, and the lower corner casting pins engage and support the container. The spreader disengages from the container and the crane moves the spreader to the next task while the CE is left to stow the container. The CE twist lock with magnetic rollers is rotated into the CE cell guide extension, lowered onto the container and connected to the corner casting. When all four twist locks are engaged, they support the container allowing the lower corner casting pins to be retracted. The winches then lower the container into the cell. When the container has reached the lowest position, indicated by the tension in the winch cables, the twist locks are disengaged and raised back to the top of the cell by the winches.

Figure 2.30 shows how a spreader can be used to move the CE from one cell to the next. When it is time to move the CE, the twist lock with magnetic rollers is rotated out of the way and the mechanism that contains the lower corner casting pin is extended out to its fullest, causing a "corner casting" to be revealed. The Spreader is lowered into the CE until the spreader's twist locks are seated in the four corner castings. Once the twist locks are engaged the CE can be lifted by the crane and positioned onto another cell of the ship or moved out of the way until a new cell is available.

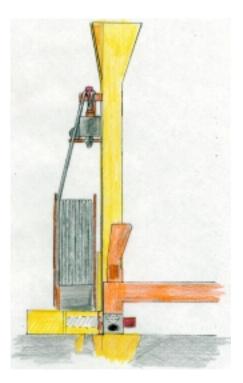


Figure 2.30: Spreader bar preparing to move the CE to another location.

Twin twenty containers can be handled with the CE in a number of ways. One way is to add additional winches midway on the CE at the locations where the twin twenty containers meet. A more economical way would be to use a mechanism to lock the two containers together. One example of many possible mechanisms is illustrated in the following Figures.

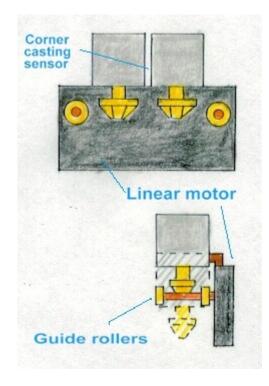


Figure 2.31: Front and side views of the twin twenty adapter mechanism.

Two twin twenty adapters would ride down to the container top on two of the twist locks with magnetic rollers. Once at the container top, the twist locks with magnetic rollers would lock into the corner posts of the containers, as they normally would. By doing so they would place the twin twenty adapters into a position where half of the adapter mechanism is on the roof of the container supported by the rollers, and the other half would be positioned along the side of the container. Once seated on the edge of the container roof, the adapter would energize its motor and detach from the twist lock with magnetic rollers. The motor which might be a linear induction motor, would provide forces to propel the adapter along the edge of the container towards the other end of the twenty-foot container or some other type of device. At the same time the motor would produce the magnetic force to keep the adapter attached to the container.

When the adapter reaches the gap between the two containers, a sensor would recognize the situation and the two twist locks integral to the adapter would be lowered into the corner castings of the twenty-foot containers and locked in. The mechanical design of the adapter would be such that the two twenty-foot containers could be lifted as though they were a single forty-foot container by the four corner twist locks with magnetic rollers, while the two sets of adapters lock the two twenty-foot containers together.

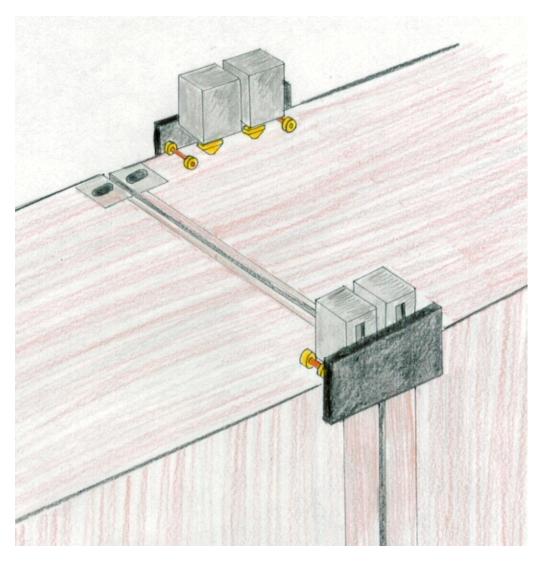


Figure 2.32: Twin twenty adapters moving into position on container roofs.

August Design Inc. believes a successful design would revolutionize container handling and become essential standard equipment. The device would create a new market parallel to the spreader bar market and could dramatically increase container crane productivity.

August Design Inc. believes that the CE would greatly improve productivity; improve safety; reduce damage to equipment; allow operations to continue in a harsh environment of rough seas and limited visibility. August Design Inc. believes the system is a logical step in the progression towards fully automated crane systems. The system would be useful for military and commercial operations and would have application in any ship crane system.

# **3. EQUIPMENT TRACKING TECHNOLOGIES**

### **3.1 Introduction**

Total Asset Visibility (TAV) [1] is a concept to provide the ability to determine, in real-time, the location of items anywhere in the world. TAV will be used primarily to keep track of cargo shipments, but it can be used to locate equipment such as trucks, chassis, containers, generator sets, locomotives, rail cars, cranes, etc. TAV systems will have the ability to gather information regarding shipments located in depots, as well as cargo in-transit. In its ideal form TAV will be location independent. It will provide information equally to a user located thousands of miles from the cargo as well as the user within feet of the cargo. With the ideal TAV system for containers, a user will be able to determine such information as the location of a specific container, its point of origin, its destination and a manifest of the current contents of the container.

TAV is a rapidly changing area in both technology and business environments. The technology of virtually all of the components related to TAV are changing and evolving constantly. Generally these changes are for the good as technological improvements will improve the performance of any TAV subsystem. However, because TAV is a system, and a worldwide system at that, it is dependent on a certain amount of standardization, but it is difficult to standardize in such a volatile environment. To complicate matters further, the business environment is evolving as rapidly as the technologies. Significant companies related to TAV technologies are formed very often, constantly adding to the choices available to a TAV system architect. Many of these start-up technology companies merge or are acquired by larger companies. The addition of new competitive technologies and the constant evolution of the companies that work in the industry also lead to very volatile prices for hardware and services.

In the paragraphs below, information is presented regarding the technologies, and companies involved with TAV. Because of the rapid changes in the industry, this information should be considered a snapshot of the situation at the time this report was written.

There are three key technological components of TAV: systems to determine location of the assets, systems to identify the assets, and communications technologies to access and deliver the information.

## **3.2 Communications**

Communication systems used in TAV include satellite, packet radio, cellular, and the internet and will all play important roles in transporting the shipment information from place to place.

Satellites are of the most interest for tracking equipment worldwide because a single satellite provider can often cover the entire world, or very large parts of it. A number of different types of satellites exist: Geostationary, Non-Geostationary, Low Earth Orbit (LEO), and Medium Earth Orbit (MEO). Each type has its own advantages and disadvantages regarding coverage, bandwidth, equipment size and portability, service availability and cost.

Satellite communications providers include: AT&T Skynet, COMSAT, GE, Hughes Communications, Lockheed Martin, TRW Space & Electronics Group, ICG Satellite Services, Inc., Iridium, Orbcom and Teledesic.

Qualcomm, a leader in truck tracking employs satellites in its Omnitracs system. Over 100,000 trucks use Omnitracs according to Qualcomm. Omnitracs cost approximately \$4000 per truck, with a cost of about \$50 - \$80 per month depending on the number of transactions. The components of the Omnitracs system include: satellite receiver/transmitter, communications unit, antenna (LORAN-C), display and keyboard in the truck cab.

The most promising of the technologies for TAV are the constellations of LEOs, because they promise low power, low cost, high bandwidth and global coverage. These are very new systems and their success is yet to be determined. Two leading providers are Iridium and Orbcomm.

In November of 1998, Iridium became the first company to offer worldwide telephone service. Orbcomm has launched over 30 LEOs and provides data messaging service virtually worldwide.

Another very interesting LEO company which expects to go into service in 2002 is Teledesic. Backed by cellular phone pioneer McCaw and Microsoft's Gates, the Teledesic constellation will consist of several hundred LEOs and will provide broadband coverage. According to Teledesic company literature the system will provide an "Internet in the Sky" having "fiber optic quality" with the ability to provide two-way broadband connections for voice, data, video, and high performance internet access.

The same satellites used for communications can determine the location of the earth transmission (cargo), but the resolution is on the order of 1/4 mile. For many applications this is sufficient. As will be discussed in more detail later in this chapter higher resolution location information can be determined by using Global Positioning System (GPS) satellites.

While satellites provide excellent global geographical coverage, currently they cost more than terrestrial forms of communication in both the cost of user hardware and transactions. They are the only form of communications that can be used globally in the open seas. While satellite companies need to negotiate agreements with each country in which their systems communicate, this has not been a problem for users. A disadvantage is the need to have near line of site connection with the satellite to establish the proper communications. It is difficult if not impossible to communicate with a satellite if the cargo is in a tunnel, in the hull of a ship, in a garage and in the middle of a city with tall buildings that block the view of the sky. These systems could be used at a port to communicate with truckers, cranes, hostlers, ships, trains, etc. in the day to day operations of the port. The advantage is that the communications backbone already exists, but the disadvantage, for the time being, is the cost of equipment and the cost per transaction and the latency (delay) in the delivery of the messages.

A terrestrial form of communications that is used by many trucking companies is packet data radio over nationwide privately developed networks. In 1980 Federal Express established the first US nationwide wireless network for their private use. ARDIS and RAM Mobile Data (now part of Bell South) have established nationwide packet radio networks for use by subscribers. These systems are very similar in concept to cellular telephone networks in that they are based in microcells of coverage. However, unlike cellular networks a single company operates the networks nationwide. The networks cover about 80% of the US geographically, but claim to cover over 90% of the businesses.

Unlike satellites, packet data radio networks do not need line of site communications and have good coverage inside buildings and within large cities. However, the systems are national and although similar systems exist in countries in Europe and elsewhere, the transmission frequencies are different and the systems are owned by different companies. So while the systems are seamless in the US and may be good for truckers, ports and railroads, worldwide coverage is problematic.

While these networks are designed for nationwide use, they could also be used at ports and terminals. Similar to the satellites, the advantage is that the communications backbone is already in place, but, to date, ports and terminals have opted for local radio networks citing the transaction costs involved with the national packet radio networks.

Cellular telephone networks are very similar to packet data radio networks, however they are not operated on a national basis so there are some complications in tracking cargo or equipment nationally and internationally, but for the most part within the US these complications are invisible to the user except in the billing which may include a variety of charges form various cellular providers.

Most of the cellular systems were designed to be analog systems for transmitting voice, unlike data packet radio networks which were specifically designed for digital data transmission; so they are not optimized for data transmission. However, a great deal of work has been performed over the last few years converting many systems to digital, which will improve the ability of the systems to transmit data, improve speed, accuracy, security and reliability.

Nationwide cellular systems have been developed by Sprint, and AT&T. A consortium consisting of Ameritech, Bell Atlantic, Contel Cellular, GTE Mobilnet, and Nynex have formed a nationwide cellular service system as well.

Although few if any ports and terminals have used cellular systems for operations, primarily due to air time costs, it is possible to use cellular as the communications portion in port equipment tracking.

All of the systems mentioned above are currently being used to track cargo [2, 3]. Cellular radio [4] methods can be used within the US and satellite [5,6] methods can be used in remote areas of the world. United Parcel Service (UPS) uses a cellular network [7] to track its trucks and packages. UPS has equipped 50,000 trucks with the equipment to provide its "TotalTrack" service. Smaller truckers are following suite with cellular networks. The cost is about \$2000 for installation and about \$80 per month per truck for air time.

Satellite tracking is also becoming common in the industry [1, 8, 9, 10]. For example in San Diego, Galaxy has installed a satellite reporting system in its trucks. The trucks link up with satellites and can collect data from the truck, as well as determine its position within a quarter of a mile. The cost of the Galaxy system is about \$4000 with \$80 per month air time costs.

### 3.3 Identification

The second major component in a TAV system is identification of the asset. In its most common form, automatic identification technology (AIT) provides the means to locally gather shipment serial number information and pass that information on to other components within the TAV system. For example, at a container port, AIT will record the serial number of the container as it enters the terminal via the gate. The container serial number will be automatically passed into the shipping company's data base where it will be matched with booking information such as the customer's name, and the destination of the container. Many shipping companies perform AIT at every interface point within the transportation system. Interface points include entry to or exit from the terminal via highway, rail, air or ship.

The traditional means of equipment identification is the recording of the container numbers using a pad and pencil, or directly keying the number into a computer (hand-held or otherwise). While the traditional systems work, AIT is much faster, and usually more accurate.

There are a number of techniques that can be employed to perform AIT including Radio Frequency (RF) tags, smart cards, bar codes, and Optical Character Recognition (OCR).

Today, the most popular means of AIT for intermodal transportation equipment is the use of Radio Frequency Identification (RFID) tags that are on thousands of rail cars and containers. Bar codes are also very popular in shipping, but currently typically used for smaller items such as individual packages. Bar codes were used several years ago on both railcars and containers. Many railcars still carry bar codes, but only very few and very old containers are bar coded.

Matron Navigation, American President Lines (APL) and the Class 1 US Railroads employ tags for containers and railcars. Companies such as Federal Express and the US Postal Service (USPS) use bar codes for tracking individual packages and envelopes. The Naval Facilities Engineering Service Center (NFESC) has been experimenting with the use of radio frequency (RF) tags for both containers and the cargo within the containers.

RFID tags are small transponders that when activated, usually by a radio signal, can transmit, via RF, information that has been stored in the tag. In the transportation industry, the tags usually provide the serial number of the container or railcar bearing the tag. The more sophisticated tags have non-volatile read/write memory in the tag to allow it to store transient information (such as owner, contents of the container, destination, etc.) Unlike bar codes, tags do not require line of sight, however, tags that must be read over a range of more than a few feet away require batteries.

RFID tag systems consist of two basic components: the RFID tag, and the interrogator. The tag is attached to the asset, and, when triggered, broadcasts a signal that contains the information stored on the tag. The interrogator is used to read, and sometime write, the tag. The interrogator is able to decode the signals sent by the tag and convert the signals into a computer usable format. The interrogator can be mounted in a logical location such as a marine terminal gate, or the spreader of a container crane. The tags have a data capacity ranging from about 128 bits for the basic Amtech tag to

over 64,000 bytes. While they can be supplemented with additional capability, basic tags have a range of a few inches to hundreds of feet.

Although the Automatic ID News Directory lists over 80 suppliers of RFID tagging systems, currently there are two key producers of RF tags in the US: Amtech and Savi. Amtech is currently a division of Intermec. Savi was a small business that was purchased by Texas Instruments and is now part of Raytheon.

Amtech tags employ the microwave backscatter technique, while Savi uses two way FM radio. The tags are not compatible.

The Amtech tag is the basis for an ISO standard, a fact that is controversial in some quarters [11]. Most of the railroads have standardized Amtech tags, as well as many of the marine container shippers including Matson and APL. Amtech has been producing 100,000 tags per month [12].

While the tags have not been adopted by all shippers, the technology is proven, though expensive to purchase and install. It has been estimated that the cost to tag a container using Amtech tags is \$130 [13]. This includes two tags and installation. Unfortunately the expense is not a one-time cost. The vast majority of Amtech tags have batteries that must be replaced in three to five years.

Amtech claims their system can read tags mounted on vehicles moving at over 60 MPH. The manufacturer's literature also claims a maximum range of 240 feet and lists the working range as 70 feet. Observation of actual installations suggests a much smaller range as the actual practical working range. Most installations have the interrogator's antenna within three or four feet of the vehicle's tag as it passes. In all cases, the interrogator's antenna must be aimed at the tag as the technique is directional.

Amtech tags operate in the microwave range and employ a backscatter technique. With this method the RF energy is modulated and reflected back to the interrogator. During the reflection process, the Amtech tags modulate the interrogator's signal. The information stored in the tag is added to the reflected signal creating an amplitude modulated signal. In the US, the Amtech system requires a license under FCC Part 90.239.

The Amtech interrogators are most commonly used at the gates of intermodal terminal facilities and alongside railroad tracks. At the gate, they reduce processing time by providing automatic input to the computer systems. Coupled with the terminal's computer information system, they also help produce an inventory of the terminal. Hand held or truck mounted readers are used to check the inventory of the terminal. By correlating the location of the mobile interrogator with the tagged item, the location of an asset within the terminal can be determined.

An RFID tag product, produced by Savi, has a more versatile tag design. The system uses FM radio under FCC Part 15 for unlicensed operation. It produces an omni-directional signal and the interrogator can read tags located within a 10,000 square foot area, although it cannot determine the location of the tag [14]. The system can communicate two way, between the tag and the interrogator, at a rate of 9600 baud. The Savi tags have a serial interface so they can download data directly into a hand held computer.

In an attempt to meet perceived user needs, Savi has added a few interesting features. For example the tags have a "beeper" feature. With this feature, the interrogator can ask a specific tag to emit an audible beep. The idea is to help a person find the tag. In the marine terminal environment, with noisy trucks and 50 acres or so of land to cover, it is questionable that such a feature would be useful at a port.

Savi has an RF direction finder that is supposed to help locate a tag. With this system, the tag must continue to transmit while the use hunts the tag down employing an electronic form of divining rod. This seems to be a tedious process that would be very taxing on the tag's battery.

Savi has a number of tag styles. Two styles tags that are incompatible with one another are: the SealTag and the TyTag. In the container application, the SealTag would be used to mark the container, while the TyTag would mark the packages inside the container. At approximately \$100 per TyTag it is unlikely that tagging every carton or pallet would be cost effective. The SealTag costs are also high, running about \$200 each. The costs do not include installation, which could easily double the price.

The range advantage Savi has over Amtech is not seen as a major feature in a port application. Unless the system can pinpoint the location of the tag to a parking slot, it doesn't really matter if the tag can be read 6 inches away or 6 miles away. The only real apparent advantage Savi tags have over the standard Amtech tags is their ability to read and write data. This is a very desirable feature for TAV. In the case of a container for example, the inventory of the container could be downloaded into the tags, as well as the owner, destination, route, etc.

Generally speaking, the Amtech tags have been adopted by many commercial shipping organizations throughout the US and the world, while the military has shown more interest in the Savi system. The Amtech system requires that the interrogator antenna be within a few feet of the tag. Amtech reportedly has sold over 7 million tags and 14,000 readers. The Savi system, in contrast, can obtain information from Savi tags located within about 200 feet of the interrogator's antenna.

Because of its relatively wide range, each Savi interrogator is able to automatically perform a bulk inventory of tagged containers located on approximately 1 acre of land. For reference, Sea-Land's Elizabeth New Jersey terminal is approximately 100 acres and would require 100 Savi interrogators if the bulk inventory feature were desired. The inventory provides a list of what equipment is in the area, but does not provide location information (other than knowing which acre of land holds the container.)

Under the Amtech system, an "automatic" container inventory is taken while driving a vehicle containing an Amtech interrogator and antenna past the containers in the area. If the path of the vehicle is known, or if tags are used to mark each parking location, the inventory can be identified with specific locations within the terminal. With this technique, a single mobile interrogator can cover an entire terminal regardless of size. Most commercial intermodal terminals perform an inventory reconciliation approximately once per day and are coupled with visual inspection of the equipment-- which is necessary to perform regardless of the need to perform an inventory reconciliation.

Smart cards are read / write devices that are about the size of a credit card. They contain microchips that can transfer data to a reader and can hold vast amounts of data. Because they require contact to be read, the smart cards do not require batteries, the reading device can provide the power.

In the TAV application, compared to RF tags, smart cards are smaller, less expensive and require no batteries. However, they require contact in order to transfer information. This would preclude the ability to read the ID of passing vehicles.

A more passive means of tagging equipment is with bar codes. There are several producers of bar code readers throughout the world. Most readers employ the UCC standards, however, standards [15] are still evolving. New linear coding methods such as UCC/EAN-128 [16] and two dimensional codes [17] such as Maxi Code, Data Matrix are addressing the needs of the industry to provide the detailed information needed track, identify and manage shipments throughout their entire life cycle. These new bar codes include detailed information such as order number, shipper, container number, pallet number, and box number. Linear codes usually employ laser scanners, although a video camera can be used. The two dimensional codes require a video camera. Depending on their design, bar code readers require that the code be within inches of the reader to several feet.

Bar codes are very common items today. Everything seems to have a bar code from the morning newspaper to a can of soda. Optical readers are able to scan the bars and encode the data much more quickly and accurately than a human. The bar code represents a number of characters or symbols that identify the item bearing the code. In the shipping industry, codes are often used to record the origin and destination of a carton or pallet, as well as the contents. Any data that can be used to track or control the movement of the item can be included in the bar code. Some codes are permanent in that they are created at time of manufacture and are virtually indelible, while others, such as those used for shipping boxes, are created at certain point in the life cycle of an item and are intended to be temporary.

Identifying the item optically can be performed using Optical Character Recognition (OCR). This technique is similar to Bar Code reading because it uses passive symbols printed on the asset to provide information. These symbols can be permanent markings or can be added for a specific reason, such as shipping. Unlike Bar Codes, OCR symbols are able to be read by humans. This is a big advantage over Bar Codes and RFID Tags, because if the system is broken for some reason, a human can always get out a paper and pencil and record the markings on the object.

Bar codes and OCR have a major advantage over most RFID tagging systems in that they are passive and require no power source. An additional advantage in the military climate is that bar codes and OCR also do not employ RF techniques which may produce signals that could be detected or jammed by the enemy.

OCR has further advantages. OCR is much more economical in that electronic tags or special bar codes because they do not have to be added to each container or piece of cargo. The cost, logistical problems and maintenance problems involved with tagging millions of shipping containers (7,000,000 containers worldwide), trailers, chassis and railcars (1,200,000 railcars in the US), and, possibly, billions of packages are avoided with OCR technologies.

In operation, a camera scans the characters to be recognized, digitizes the image and feeds it to a computer containing OCR software which performs the pattern recognition. The characters can then be used by the computer as though they were typed in by a user.

OCR shows promise in the future, but currently it is not commonly used in the shipping industry. This is primarily because of the wide variety of conditions under which it must operate. In the shipping industry, OCR would have to operate with a wide variety of containers and packages, under a wide variety of environmental and lighting conditions.

OCR is used extensively by the USPS to sort mail, but other than a few installations it has not been widely adopted by the shipping industry to track equipment or cargo. Perceptics, a company now owned by Northrop Grumman, is a leader in license plate identification and has developed a container equipment number identification system. Hi-tech Solutions of Israel offers a system called "See Container". August Design Inc. and Bromma are teaming on the development of a spreader-based system.

#### **3.4 Location**

The third major component in a TAV system is the means to identify the location of the item being tracked. In nationwide tracking system, the simplest way is for the trucker to call in every few hours to report position. Similarly in a port, the simplest and most common way to know the cargo location is to record the location when it is placed in the depot or moved within the depot.

The process can be by paper and pencil, voice radio, or RF data terminal. When coupled with an occasional physical inventory, the technique is very accurate, however, it is usually not very timely, and is impractical to be performed in near real time on a move by move basis.

Using RF terminals in the cabs of the hostlers or crane where the operator has the opportunity to enter the location of the equipment works, however, it is difficult for a hostler or crane operator to work efficiently and safely if they need to enter data with each move, therefore, a means to automatically record the position of the cargo with little or no involvement from the hostler or crane operators is ideal.

The GPS offers a solution. GPS is the most accurate worldwide all-weather navigation system in use today but it still has significant errors. GPS receivers determine position by calculating the time it takes for the radio signals transmitted from three or more GPS satellites to reach earth. Radio waves travel at a known speed (the speed of light). The time a signal travels from the GPS satellite to the earth can be determined by the GPS radio receiver using code matching techniques. Couples with the known location of the satellite relative to the earth as reported in the signal received from the satellite, the distance to the satellite can be determined. By using the distance to three or more satellites and trigonometry, the GPS receiver can determine its location on earth.

GPS position accuracy depends on the receiver's ability to accurately calculate the time it takes for each satellite signal to travel to earth. There are primarily five sources of errors: multi-paths, receiver clock inaccuracy, ionosphere/troposphere effects, satellite orbital position error, Department of Defense (DoD) induced errors.

The DoD error is called "Selective Availability (SA)" and is intended to prevent adversaries from exploiting highly accurate GPS signals and using them against the United States or its allies. SA accounts for the majority of the error budget.

Typical accuracy is then about 100 meters. This accuracy is generally fine for tracking cargo across country, but fairly useless in a port operation. Fortunately, many of these errors can be reduced using differential GPS (DGPS).

DGPS works by placing a GPS reference receiver station at a known fixed location. Since the location of the receiver is known, it can determine the errors in the satellite signals. The difference between the measured and calculated location is the total error which can be transmitted to mobile users with their own GPS receivers. The error signal is subtracted out to provide a very accurate measurement. The correction message format follows the standard established by the Radio Technical Commission for Maritime Services, Special Committee 104 (RTCM-SC104). Receivers can then produce an accuracy of 1 meter or less.

For example, Del Norte Technology, Inc. designs and manufactures a system that claims to provide sub-meter dynamic positioning in real time using DGPS techniques with patented RTK/OTF (Real-Time Kinematic/On-The-Fly) algorithms. Fugro Starfix also claims submeter positioning globally. The Starfix system employs corrections broadcast from over 60 reference stations worldwide via the Inmarsat satellite communication system to provide global coverage.

Other manufacturers include: Trimble, Absolute GPS Systems, Adventure GPS, MAGEC Software, Motorola, North Coast Resource Management, PosNAV and The Explorer Company.

### **3.5 Equipment Tracking Using Information Technology.**

Using the communications, identification and location technologies described above, assets can be tracked locally, such as at a port and globally. But the information needs to be made accessible to the user. Many intermodal companies provide tracking information via the internet. Below is a selection of companies and web sites that allow customers to track shipments:

APL:	http://www.apl.com/content/trace/trace.html
Columbus Line:	http://www.columbusline.com/tracker.htm
Crowley Maritime:	http://www.crowley.com/scripts/tys_request.asp
Evergreen:	http://www.evergreen-america.com/ct0f.htm
Hanjin:	http://www.hanjin.com/
Hyundai Merchant Marine:	http://juliet.hmm.co.kr:8890/hw_index.html
Sea-Land:	http://www.sealand.com
Maersk:	http://www.maerskline.com/Cargo01.htm
BNSF:	http://www.bnsf.com/cws/eqptrace/

Each of the companies listed above has their own systems for tracing and tracking assets. Some third party companies offer a similar service on a subscription basis. One such company is Euro-Log.

Euro-Log offers communication and information services for shipment flow management. Euro-Log states that their "services bridge the gaps which still exist in the information chain between shippers, logistics service providers and consignees by means of advanced information processing and communications technology." Using the system authorized personnel can track the current status of shipments at any time.

### 3.6 Agile Automated Identification Technology (AAIT)

From the 1970's technology of bar codes [18] to today's RFID transponder tags, the major problems remain unsolved: the cost of installation, the cost of readers, cost of maintenance, and, most importantly, the need for universal acceptance and application of the technology. Advancing technology and obsolescence is also emerging as a problem for today's AIT systems. For example, by the time a fleet of containers or other assets are tagged, it is not unlikely that a new generation of technology will be available, making the existing systems obsolete. Compounding the problem is a lack of agreement and coordination between commercial and military shippers.

The US industry has spent hundreds of millions of dollars tagging railcars, containers and chassis in order to provide competitive, efficient and reliable shipping services. For similar reasons, the US military is in the process of tagging a large number of assets. The need for such systems is well established. Unfortunately, in spite of published standards, the various AIT systems are not compatible. An AIT interrogator developed by one company cannot read the tagging system developed by another company. In some cases the incompatibility even exists within a single company's product line.

Even if all the major companies and the military implement the ISO (International Standards Organization) standard AIT, there will still be a large number of assets that are not tagged and those tagged will most likely not be compatible. Incompatibility is permitted under the ISO standard. Tags produced by the same manufacturer are not always compatible between product lines.

It is inevitable that AIT will continue to evolve. New techniques for tags, bar codes, OCR, etc. will be introduced with regularity. It is believed that the only way to deal with the evolution is with a revolution in the AIT interrogator system.

It is clear that one of the major problems with AIT is the lack of standardization. August Design Inc. has proposed the development of an agile automated identification technology (AAIT) system that would, if perfected, be able to deal with a number of identification technologies. The paragraphs that follow explain the concept.

The goal of AAIT is to read any RF tag, any bar code, and, employing optical character recognition (OCR), the serial numbers on any ISO shipping container (regardless of whether it is also tagged or bar coded). In addition, AAIT would be designed with an open architecture enabling it to deal with new technologies as they are introduced.

The ideal AAIT system would consist of an interrogator capable of reading any asset identification system, from any manufacturer. The system would be capable of interrogating any RFID tag, bar code system, and, employing optical character recognition (OCR), be able to read serial numbers. The

system would be designed with an open architecture so that it would be capable of adapting to future AIT technologies. The system would also provide a common interface so that the details of the various AIT systems would be transparent to the user.

The basic advantages of an agile reader are summarized below:

- □ The system would be designed so that it could deal with any type of existing AIT tagging/marking system, i.e., radio, microwave, linear bar code, two dimensional bar code, alphanumeric symbols, etc.
- □ The system would be designed with an open architecture so that it can adapt to any future models or type of AIT.
- □ While the agile reader will likely cost more than any one type of reader, it will cost much less than the purchase of a reader for each type of AIT system. The goal will be to keep the cost for the agile reader as close to the cost of a standard reader as possible.
- □ While the agile reader will be capable of reading any AIT tag or marking system, it will present the common interface to external computer systems. The type of AIT system employed on a particular asset would be irrelevant to the external computer system.
- □ With some modification, the system could also be used to perform other tasks such as damage inspection and act as feedback elements for automated materials handling devices.
- □ The most important advantage is that the system would require no cooperation from customers, competitors or compatriots. The system is stand-alone, and could be added to a single depot or port at a time, independently. The system would be very useful for temporary military operations.

## 4. HSS SPECIFIC SHIP-LOADING TECHNOLOGIES

A great deal of interest today in the cargo world is with high speed sealift (HSS). The competitive world economy, the needs of the military and the increasing performance expectations of customers are causing the rise of just in time (JIT) manufacturing, custom built orders, a desire for freshness perishable goods and other time critical cargo. All of these parameters lead to a demand for low cost, rapid and dependable shipping of cargo.

Because of rising military, consumer and business demands for rapid economic cargo several organizations around the world are investigating the use of high speed ship technologies for cargo ships. Many of the HSS concepts are totally new designs that will have specially developed method of loading and unloading cargo. Other concepts are based on modification of existing designs of high speed ferry boats and smaller sports boats that originally were not designed to carry a variety of cargo.

Moving cargo across the sea at high speed is only half of the problem, the other half is getting cargo on and off of the vessels rapidly. There is little sense in increasing the speed of travel if the speed of loading / unloading operations and moving cargo through the port are not also dramatically increased.

Certainly some of the HSS concepts will use shiploading concepts that are similar to those used today such as container cranes and roll on/roll off (RO/RO) ramps. But even the methods that appear similar to today's cargo handling are going to have to improve in speed. Concepts such as the cell elevator (described earlier in section 2.4), the Robocrane (section 2.1.3), dual hoist cranes (section 2.1.1), anti-sway devices (section 2.3.1), telepresence, machine vision, and crane automation will increase throughput. Other methods that have been proposed specifically for HSS will be presented in the paragraphs that follow. In addition some high speed and high density methods to store and retrieve the cargo at the port will be discussed as they are critical components in rapid loading / unloading of HSS and rapid storage and access in the yard.

#### 4.1 RO/RO Methods

Many of the HSS under consideration have RO/RO capability. In order to perform rapid RO/RO a number of improvements over existing systems have been proposed.

Aside from the internal design of the RO/RO ramps to minimize bottlenecks, protect cargo, provide ventilation, one of the most commonly suggested concepts is that of a convoy or train of wheeled cargo. The concept is simply to have a cargo on wheels (such as chassis) linked together to form a train-like string of cargo that can be pulled or pushed by a powered vehicle. In this way several pieces of cargo can be taken on or off the ship at once, presumably by a single operator driving a single hostler ("locomotive").

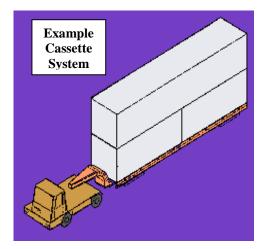


Figure 4.1: Example cassette systems.



Figure 4.2: TTS-CP Train.

A similar idea using "cassettes" of cargo is a popular concept. A cassette is a wheeled platform holding multiple units of cargo. TTS of Norway has proposed a concept known as CPT (compact pallet transfer).

TTS and FastShip Atlantic have proposed a very sophisticated train type system for pre-staging stacked containers in the terminal on specially designed flatcars and loading cargo onto HSS. The TTS system is known as the CP-train.

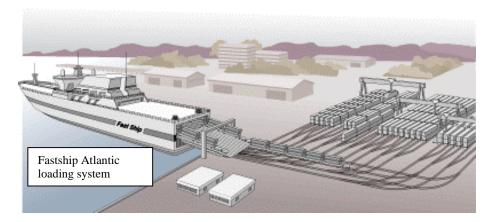


Figure 4.3: Fastship Atlantic loading system.

A number of innovations have been proposed for external RO/RO ramps, primarily to allow them to rapidly interface with the ports, adjust for tides and any relative motion between the ship and the dock.



Figure 4.4: VibTech floating Ro/Ro ramps.

VibTech has proposed floating ramps that provide all weather RO/RO capability for almost any situation.

## 4.2 LO/LO Concepts

Systems such as the DARTS spreader, the intelligent spreader bar and the cell elevator are methods to improve the speed of load on / load off (LO/LO) vessels, high speed or otherwise. A commonly proposed solution for rapid loading and unloading of vessels is the design of a berth such that cranes can work both sides of the ship. Some existing, though not commonly used, commercial cranes may prove of particular value for HSS. Though not new designs, these concepts include the split trolley, dual hoist, Matson "mousetrap", Matson bridge crane, and the O&K double jointed deck cranes.

The split trolley gantry crane separates the operator's cab from the hoist trolley. Both units can trolley over the deck and the dock, but under different controls and at different rates. In this way the hoist trolley can be designed for maximum acceleration and velocity without concern for the comfort of the crane operator.

Dual hoist cranes have two hoisting mechanisms, one for shipside and one for landside. A common area between the two hoist mechanisms is used to transfer cargo from one to the other. While one hoist is working the dock, placing a container on a chassis for example, the other hoist is working the ship, such as picking up a container from a ship cell. While two operators are required, time saving parallel operations are performed. In addition the crane operation becomes less dependent on the timing of the yard operation in that, given space to buffer one or more containers, the shipside crane does not have to wait for a chassis before performing more ship operations.

The Matson mousetrap and bridge crane together provide an extreme example of the dual hoist crane. The mousetrap is a platform that moves with the port's gantry crane to provide a container buffering system that can accumulate several containers (e.g. 5) in a horizontal plane. The crane operator is able to pick up or place from any of the mousetrap's container locations. In this way the crane operator working the ship can select from one or more containers in order to keep to the stow plan. In addition system lends itself to loading and unloading the ship at the same time.

The Matson bridge crane is a very large gantry crane similar in general concept to a commonly used Transtainer, but with a coverage of over 300 feet, the crane is able to straddle many more stacks of containers. The bridge crane is able to straddle, perpendicular to the ship, many container stacks in the yard. It is also able to gantry parallel to the ship in order to cover many more container stacks. The hoisting mechanism is able to trolley the length of the bridge crane in order to access any of the stacks of containers below. When the bridge crane is positioned over the mousetrap the trolley and hoist is able to deliver or pick up container to / from the mousetrap. The system was designed, built and proven in the 1980's. Updates of the design using the latest technology has to offer would likely result in an effective means to rapidly load and unload vessels.



Figure 4.5: O&K double jointed crane.

O&K double jointed cranes, employed on several vessels and ports, are similar to August Design's Robotic Crane concept (section 2.1.3). Both cranes have articulated horizontal arms able to rotate about the shoulder and elbow joints. This allows them to access very large areas rapidly and with little movement enabling high throughput rates. The August Design Robotic Crane has the additional feature of using a rigid hoist instead of cables.



Figure 4.6: Automated all-weather cargo transfer system.

In addition to advances in crane systems for LO/LO operation, several concepts have been proposed for using overhead rail systems for loading and unloading ships. Sea-Land's GRAIL system is an example, as well as a system proposed by MIT in the late 1980's. The latest version of this theme is the SpeedPort. In SpeedPort container straddle carrier-like devices, called Spiders, bring cargo alongside the ship and move over the deck of the ship. The spiders along with their cargo attach themselves to overhead rails. And move over the deck of the ship. In the concept, the hoisting mechanism in the spiders is able to pick up and place cargo from the ship. Once the spiders reach the

other side of the ship, they lower themselves to the ground where they are able to travel to the yard to pick up the next container.

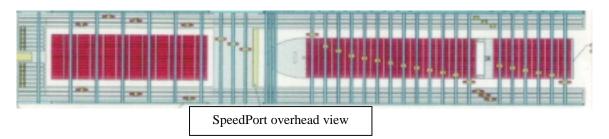


Figure 4.7: SpeadPort overhead view.

Another interesting concept for rapid cargo handling has been proposed by KSW. KSW, a joint venture of Kaefer, Sabroe, and Westfalia, has developed the Automatic Seaborne Pallet Handling (ASPH) system. The ASPH was specifically designed for refrigerated cargo that is often the cargo of economic choice in high speed transport. ASPH consists of a ship that combines containers and a below deck automated pallet storage system. While the physical infrastructure required in the ship may limit its potential in a HSS, a version of the concept may prove useful.

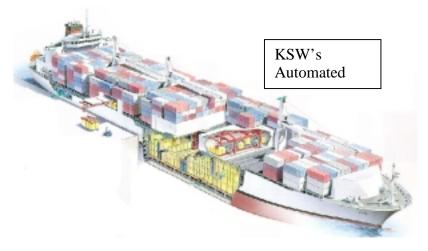


Figure 4.8: KSW's Automated Seaborne Pallet.

# **5. MULTIPLE TRAILER SYSTEMS**

A multiple trailer system (MTS) (also called multi-trailer system) is one where a towing vehicle transports more than one container to and from the container yard. Also known as elephant trains, these systems can save appreciable labor in the transport of containers. A typical MTS is capable of towing between 3 to 5 trailers, each with a capacity of 2 TEUs. The concept of a multiple trailer system is that it is cheaper to use one manually operated vehicle to tow multiple containers, instead of one hostler per container. A sketch of a generalized MTS is shown in Figure 5.1. An example of a MTS is shown in Figure 5.2.

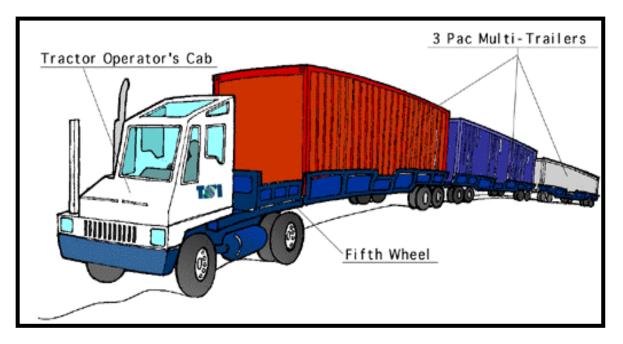


Figure 5.1: Sketch of an MTS.

MTS's are known to be in use at the Ports of Vancouver (Canada), Rotterdam, Gioia Tauro (Italy), and Felixstowe (UK). In the United States these systems are currently prohibited from use due to existing labor agreements with existing ports. The Vancouver MTS, shown in Figure 5.2, is capable of transporting three 45-foot containers. The entire system consists of a tractor capable of pulling 154 tons, and the trailers, each with a 2 TEU capacity. Vancouver currently operates 13 MTS's. The company responsible for the development of these systems is Magnum Trailers and Equipment Inc. of Abbotsford, British Columbia.

The European Combined Terminal (Port of Rotterdam) also employs the use of MTS's, along with an automated guided vehicle (AGV) system. This MTS, shown in Figure 5.3, uses a combination of one tractor to 5 trailers, for a total transport capability of 10 TEUs per system. The braking of the rear trailer is slightly stronger than that of the trailer in front of it, and so on. This ensures the proper spacing between the trailers when the platoon comes to rest.

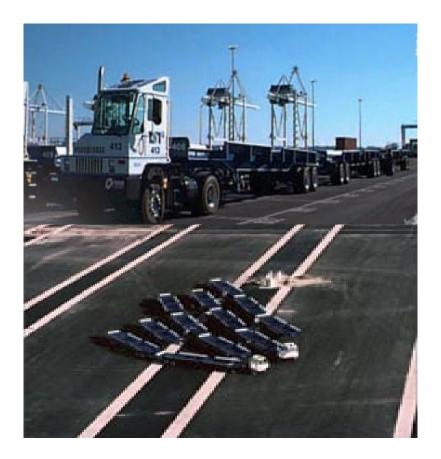


Figure 5.2: The Port of Vancouver MTS.



Figure 5.3: The Port of Rotterdam MTS.

# 6. Container Technologies

## 6.1 Introduction

Containerization has grown remarkably since the Korean War in the 1960's. Today approximately 70% of seaborne cargo is carried out in containers [43]. Among the advantages of containerization is that containers come in standard forms and that only a few types of handling equipment are needed, no matter what kind of cargo is carried inside the container. With containerization many small packages are combined to a larger unit to simplify the handling and reduce the handling costs. Moreover, it is also likely that fewer damages occur, compared to non-containerized cargo and the containerized goods are safe in the container during strorage of the container in the warehouse and during transportation. This is especially important when the cargo contains explosive material or goods that need to be kept in either low or high temperatures.

On the other hand, containers are expensive to purchase and maintain and a large number is required to establish a frequent and efficient level of service. If trade between particular regions is unbalanced, the number of empty, therefore non-profitable, containers may grow drastically in the region which has a deficit in export. Thus the use of containers is ideal in traffic between two regions when the materials flow is equally great both ways.

## **6.2** Container Types

The following classification of containers is due to [43].

## **6.2.1 General Cargo Containers**



Figure 6.1: General cargo containers.

General cargo containers are any type of containers which are not intended to be used in air mode transport and which are not primarily intended for the carriage of cargo such as liquid, gas or dry bulk cargo. General cargo containers are divided into general purpose containers, specific purpose containers and specific cargo containers.

#### a. General Purpose Containers

General purpose containers are totally enclosed and weather-proof with rigid roof, floor and sidewalls. These containers are intended to be suitable for the transport of the greatest possible variety. The majority of general purpose containers are 20' and 40' long with 8'6''height. According to [44], in 1992, there were 3,160,000 20' long 8'6'' high general purpose containers, representing 49% of the world container fleet and 1,650,000 40' long 8'6'' high general purpose containers, or 26% of the world container fleet. Another type of containers that share a significant portion in the world container fleet are 9'6'' high containers (high cube containers). These 20' and 40' long high cube general purpose containers represented 7% of the total number of containers worldwide (457,000 containers) in 1992 [44]. High cube containers provide additional volume capacity for light, voluminous cargo for more convenience and efficiency. There are also 45' long high cube containers; actually, most of 45' containers are high cube. General purpose containers are made of aluminum or steel. Aluminum containers have a slightly larger capacity than steel, while steel containers have a larger payload than aluminum containers.

### **b.** Specific Purpose Containers

Specific purpose containers have special constructional features. Their dimensions are usually compatible with those of the general purpose containers so that they can fit in the cells of a conventional container-ship and they can be handled by conventional loading/unloading equipment. Below we describe various types of specific purpose containers.

### **Closed vented/ventilated containers**

Closed vented/ventilated containers (example shown in Figure 6.2) are similar to the general purpose containers, but are designed to allow air exchange between the interior of the container and the outside atmosphere. Vented containers have passive vents at the upper part of the cargo space. Ventilated containers, however, have a ventilating system designed to accelerate and increase uniformly the natural convection of the atmosphere within the container.



Figure 6.2: Closed vented/ventilated containers.

#### **Open top containers**

Open top containers (example shown in Figure 6.3) are similar in all respects to a general purpose containers except that they have no rigid roof. The roof may be flexible and movable or removable and can be, for example, made of polyvinyl cloride (PVC). Open-top containers allow cargo to be loaded from the top and are therefore suited to bulky cargo such as machinery.



Figure 6.3: Open top container.

### **Platform-based containers (Flatracks)**

Platform-based containers (example shown in Figure 6.4) have no side walls but have base similar to that of a platform container. Platform-based containers, also called flatracks, are suited to heavy loads or for cargo that must be loaded from the top or sides such as pipes and machinery. There are three different types of platform-based containers: (i) Platform-based containers with complete superstructure that have a permanently fixed longitudinal static and dynamic type load-carrying structure between ends at the top. (ii) Platform-based containers with incomplete superstructure and fixed ends that have no permanently fixed longitudinal static and dynamic type load-carrying structure between ends other than at the base. (iii) Platform-based containers with incomplete superstructure and folding ends that have folding end frames with a complete transverse structural connection between corner posts and no permanently fixed longitudinal superstructure other than at the base.



Figure 6.4: Flatrack.

## **Platform containers**

Platform containers (example shown in Figure 6.5) are loadable platforms that have no superstructure but have the same length and width as the base of a container equipped with top and bottom corner fittings.



Figure 6.5: Platfrom container.

## c. Specific cargo containers

Specific cargo containers are types of containers which are primarily intended for the carriage of particular categories of cargo. Similar to the specific purpose containers their dimensions are usually compatible with those of general purpose containers. Below we briefly describe the main types of specific cargo containers:

- **Thermal containers:** Thermal containers are built with insulating walls, doors, floor and roof which reduces the heat transmission between the inside and the outside of the container.
- **Insulated containers:** Insulated containers have insulated walls, doors, floor and roof but have no use of devices for cooling or heating.
- **Refrigerated containers:** Refrigerated containers use ice, dry ice or liquefied gases for cooling. These containers have no external power supply or fuel supply.

- **Mechanically refrigerated containers:** Mechanically refrigerated containers (see example in Figure 6.6) have a refrigerating appliance such as a mechanical compressor unit or an absorption unit.
- **Heated containers:** Heated containers are similar to mechanically refrigerated containers but have a heat producing appliance instead of a refrigerating appliance.
- **Refrigerated and heated containers:** Refrigerated and heated containers have both a refrigerating appliance and a heat producing appliance.

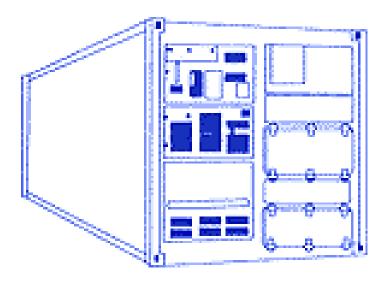


Figure 6.6: Mechanically refrigerated container.

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Figure 6.7: Tank container.

## **6.2.2 Other Container types**

There are three main types of containers that do not belong to the general cargo container category:

• **Tank containers:** Tank containers (see example in Figure 6.7) have two basic elements, the tank or tanks and the framework. These containers are primarily used for the carriage of liquefied cargo.

- **Dry bulk containers:** Dry bulk containers are intended to use for the carriage of dry solids in bulk without packaging. Dry bulk containers consist of a cargo-carrying structure firmly secured within the framework.
- **Named cargo containers:** Named cargo containers are various types of containers such as automobile containers, livestock containers and hangertainers which are also known as garmentainers. Hangertainers are specifically designed for shipping hanging garments.

#### 6.3 Competing Container Dimensions and Container Standardization

The use of container standards continues to be one of the most important factors influencing the development of intermodal transport. It is commonly recognized that the standardization of containers is a very crucial issue for the efficient development of container transportation worldwide. The world container fleet has increased 4 times in the period 1980-1983 with 90% of them being 20' and 40' long containers with 8'6" height [44].

Despite the fact that the majority of the containers are 20' and 40' long with 8'6" height the problem of container standardization is still an open issue. Several factors such as the development of ship cranes that can handle bigger and heavier containers than the old cranes and the advances in railway and automotive industry, make it possible for the design of containers with larger than the standard dimensions. Bigger containers are in many cases preferable since they can carry larger volumes and heavier cargo, increasing therefore the percentage of the total volume and weight that is occupied by the container.

Among the containers that are not 20' or 40' long with 8'6" height, the most popular are those of 9'6" height. Containers of such height are gaining popularity and their share in the total world container population was in 1992 more than 7% while it was less than 3% in 1983. Many of the 9'6" high containers are 45' long and a big number of them are flatracks or refrigerated containers. Other container classes (which will be called thereafter non-standard containers in order to distinguish them from the class of 20' or 40' long with 8'6" height and the class of containers with 9'6'' height) include:

- 48' long containers which are mostly used for domestic purposes.
- 53' long containers. These containers tend to be deployed in specific city-to-city corridors and are tailored primarily to individual customers' requirements.
- Swap-bodies and inland containers with different lengths and with a width of 8'2'' are used in the European logistics systems in conjunction with palletized goods. It is estimated that an equivalent of about 200,000 TEUs of such units are presently in operation. Among them the so-called "cellular pallet-wide containers" (CPC) should be mentioned as gaining popularity in short-sea and coastal trades. The main feature of these containers is that they have 8' wide endframes and a width of 8'2'' along the sidewalls. They may thus be carried in standard containership cells while at the same time they provide side-by-side stowage of 3'11''-wide pallets. The fact that the attention of leasing companies has recently been attracted to such containers suggests that they are gaining popularity.
- As an exceptional example of a specific case of non-standard containers one may cite the use of 25'3'' long and 10'2'' high containers by a European company supporting the trade between Antwerp and Romania by railway. The use of specialized rolling stock which has a loading platform height of only 3'1'' above the railhead permits transportation of these containers by the

European railways. The company has deployed this equipment in an effort to maximize the volume of a unit load in the trade with long frontier delays and a big potential risk of pilferage.

Non-standard containers are, in general, in use only in specific international trades where high volume, low-density cargo is prevailing. The share of such containers in the world container population is negligible and there is no universal use of these containers; only one third of the ports were using such containers in 1992 while the total number of such containers represented only the 3.8% of the total number of containers at the same year [46]. Moreover, the orders of most non-standard containers are declining, while many seaport terminal operators have completely abandoned the use of such containers. However, there are examples of port and terminal operators that initially decided not to accept non-standard containers and later were forced to change their decisions and their container handling equipment so that they can handle non-standard containers. The reason they did so is that they did not want to lose their share of the market, since many of their customers are using non-standard containers.

Several issues regarding the use of non-standard containers and container standardization are discussed next:

- Accepting non-standard containers needs a serious upgrading of the facilities and the cargo handling equipment. An area in the terminal might be required to be allocated.
- Most of the developing countries do not handle non-standard containers.
- In many States 53' containers cannot be legally moved by road.
- Unlike highways, railways are not regulated by the government in the U.S. and other countries. Therefore, in many cases, over-height, over-length containers are introduced. Railways introduced 53' long containers in connection with the development of double-stack container trains. In the United States double-stack container trains are considered profitable when the distance of transportation is in excess of 800 miles. Below this distance the cost of managing chassies and of terminal handling seems to outweight the advantages of long-haul transportation by rail.
- One-third of containers shipped in the U.S. may exceed the prescribed weight limit. This results in serious road damage and creates safety problems in connection with their movements. The problem is so serious that a special law has been adopted requiring shippers to give road carriers written information about the nature and weight of the cargo carried inside the container.
- Reconsideration of the present motorway construction standards with the aim of increasing the lane width will require more land and will lead to a further degradation of the environment. In this respect, the introduction of wider and longer containers than the standard ones may be considered as environmentally harmful.
- According to a study conducted for the European Union [44] the introduction of new generation containers is unacceptable for Europe. As an example considering the European railways, the study concluded that the introduction of larger containers "will clearly have a negative effect on rail transport, at least in the short run, due to the difficulties and costs linked to the need to enlarge the loading gauge, adapt structures and terminals, invest in new rolling stock and operate a wider variation of different intermodal loading units".
- Though many ports in recent years have ordered ship-to-shore container cranes with spreaders capable of handling longer-than-40'-containers, the majority of the cranes presently in service are not suitable for handling over-length containers. About one third of all container cranes capable of

handling over-length containers are located in North America. European ports, despite their large share in the world container trade, hold under one fifth of such cranes. Ports in South East Asia have the largest share of container cranes equipped with spreaders capable of handling 40'-plus containers. Here the over-length units outnumber the conventional ones by 2 to 1. This indicates that most Asian terminals have been equipped during recent years mainly to handle 45'-long containers coming from United States ports. Contrary to this and although the European ports have recently made big purchases of such equipment, the small proportion of such cranes presently in service in Europe, suggests that port operators in Europe are not convinced of the necessity of 40'-plus spreaders, since they have not experienced sufficient traffic of long containers to justify the additional investments.

Special reference should be made to containers used for military purposes. In this case the objective is not to reduce the overall cost of cargo transport but rather to develop container technologies that allow for faster cargo handling in emergency situations. Therefore, there are cases where non-standard containers are designed. As an example we refer to the design of a flatrack (called the A-frame flatrack because of the shape of its fixed endwall) which is larger than the conventional flatracks [47]. The A-frame flatrack is used to quickly pick up and drop off loads of ammunition from trucks and trailers using a load handling system installed on the truck. The A-frame flatrack was initially designed so that its dimensions are suitable for the load handling system. Due to its dimensions it cannot be stacked in the cell of a conventional container ship. A study was performed by the U.S. Army regarding the redesign of the A-frame flatrack so that its dimensions are compatible with those of a conventional flatrack [47]. According to this study, to meet both user battlefield requirements and intermodal specifications, the weight, complexity, and cost of the new flatrack are significantly greater than those of the A-frame flatrack.

# 7. AUTOMATED GUIDED VEHICLES FOR PORT APPLICATIONS

### 7.1 Introduction

One of the most interesting cargo handling equipment developments are those related to the Automated Guided Vehicles (AGVs). AGVs have enjoyed a period of explosive growth in the last decade, primarily in the area of industrial automation. The promise in AGVs lies in their high controllability, and the degree to which they can perform the same tasks that currently require significant labor. In the case of container operations, AGVs are well suited for interfacing with an automated storage and retrieval facility. There are currently applications of AGVs in ports such as Rotterdam, The Netherlands, and Thamesport, England. Initiatives are underway at the Ports of Singapore, and Kaoshiung, Taiwan.

The AGV system (shown in Figure 7.1) consists of the vehicle, an onboard controller, a data link with a centralized management system, and a navigation system. The vehicles are typically electrically powered, and constructed from off-the-shelf components. The onboard controller manages the propulsion, steering, braking, and other functions of the vehicle. The management system deals with dispatching, routing and traffic control. The navigation system is used by the vehicle for guidance to its destination.

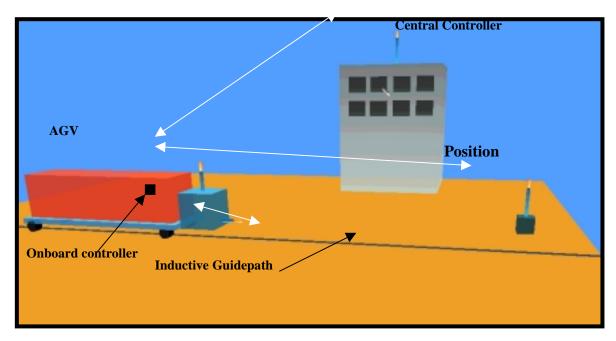


Figure 7.1: Example of a basic AGV system.

## 7.2 AGV Control and Management System

While operating within a manufacturing or service environment, the AGVs require on-board and/or centralized computer control to coordinate the movements relative to other material handling devices or other AGVs. Therefore, we need to look at the *AGV System* as a supervisory system which has a hierarchical structure [27,28,29,30,31,32].

The lowest level in this hierarchy belongs to the vehicle control, which consists of the drive system control (e.g. motors, transmission, brake, etc.) and navigation system. The higher-level system control is responsible for management and vehicles interaction. It consists of the planning, the scheduling, and the execution function.

### • Navigation Systems

The navigation systems of AGVs are transitioning from wire guided to free ranging. Until recently, AGVs followed an inductive guide wire (Figure 7.1) or an optical visible line, painted or made with tape, on the floor. AGVs now may utilize new methods such as laser scanners, microwave transponders, inertia gyros, ultrasonic sensors, embedded magnets, camera vision systems, etc. Below we present a number of technologies that are used or could be used by AGVs for guidance and control.

- 1. *Wire Guidance System.* The majority of automatic vehicles used today are designed to follow a wire buried in the floor. An AC current produces an electromagnetic field around the wire. Passing vehicles detect the magnetic field by using two magnetic coils located at the sides of the vehicle. The difference between the voltages of these coils is used to issue the control command for the vehicle steering actuator. Among its technical advantages, wire guidance is robust proven, and relatively simple. However, wire guidance is expensive to repair, disruptive to install, infrastructure intensive and inherently inflexible as it requires the presence of a wire path to any location that a vehicle may need to reach.
- 2. *Magnetic Systems*. Similar to the guided wire system, the underlying guidance principle of magnetic trails is to provide a path in the pavement for a vehicle to easily follow. Magnetic bars (systems) are reliable and can be used in all weather but they are inflexible, vulnerable to magnetic interference, and could cause pavement problems.
- 3. *Free Range On Grid.* This system uses a grid that is marked on the floor with transponders at nodes to transmit "labels" containing a unique ID and position data. Each time a vehicle encounters a line in the grid, it compares that information with its calculated position, then corrects itself. This navigation system, deployed in Rotterdam, is flexible and has accuracy up to  $\pm 3$  cm. It is disruptive to install, though and transponders may shift in bad weather.
- 4. *Laser Guidance*. The vehicle uses laser beams and reflectors to calculate its distance from fixed points using triangulation. A minimum of three targets must be detected at each time during travel. Normally there should always be five visible targets. The vehicle can then use its onboard map to determine and correct its own location. This system is flexible, accurate, and imposes low infrastructure cost. However, it is affected by adverse weather, needs large number of reflectors, and has a long set-up time.
- 5. *Millimeter Wave Radar (MMWR)*. A rotating MMWR detects the presence of beacons at known locations in the yard to determine the vehicle's position. The beacon observations are then processed to constantly update the vehicle's position. MMWR is accurate up to  $\pm 10$  cm, but it is expensive, needs long set-up time, and a large number of reflectors.
- 6. *Differential GPS*. Differential GPS (DGPS) systems could be used for navigation within the yard despite some critical issues regarding the satellite coverage, and reliability of the signal for commercial AGV operations in ports. A DGPS system is accurate up to  $\pm 5$  cm, it has a relatively low cost installation, and requires few modifications to the yard.
- 7. *Dead Reckoning*. Dead Reckoning is a free path, relative positioning guidance method. In this method vehicle-mounted motion sensors precisely detect vehicle direction and speed. Given a

known starting position, the integration of speed data over time allows the location of the vehicle to be determined. Because errors accumulate with distance traveled, these systems become inaccurate and unreliable unless the vehicle's position is periodically corrected by some other means. Dead Reckoning is simple, flexible, inexpensive, and easy to accomplish in real-time.

- 8. *Machine Vision*. This system uses image processing to provide guidance. Machine vision systems require little or no infrastructure modifications. They have been shown to provide excellent positional data for vehicle guidance, and may be configured to perform many different tasks (from lane keeping to collision avoidance to road sign reading, etc.). Some disadvantages are: current system expense, complexity, and inherent limitations of the basic sensor (camera), which can only provide information on the scene immediately visible to it.
- 9. *Magnetic Nails*. Small magnets in the form of a solid cylinder of diameter that of a quarter and length about 10 cm are inserted in holes at the center of the lane path at a distance of a meter or less apart. Magnetometers installed under the car sense the magnetic field and provide an estimate of the lateral error from the center of the lane to be used for steering. Static information, such as the geometry of the path, location of crucial slopes, change of lanes could be coded by changing the polarity of the magnets. PATH and Caltrans installed magnetic nails on a part of Interstate I-15 in order to demonstrate automated vehicle driving using 10 vehicles in a platoon formulation at speeds as high as 65 mph in August of 1997. The use of magnetic nails for AGVs at ports is expected to be easier due to the lower speeds.

#### • Planning

Planning involves selecting an appropriate vehicle and determining the appropriate routing for that vehicle. Planning is often referred to as routing and dispatching in the context of AGVs. *Dispatching* is the process of selecting and assigning tasks to vehicles. Two situations are possible when a request is received to assign a task to a vehicle: *work center-initiated* task and *vehicle-initiated task assignment*. In work-center task assignment, a vehicle is selected from a set of competing idle vehicles. Different rules can be employed for assigning priorities to vehicles for dispatching. Random vehicle rule, nearest vehicle rule, and least utilized vehicle are among these rules. In vehicle-initiated task assignment, a work center will be assigned to a vehicle from a set of competing work centers. There are several rules to assign a task to a vehicle. It includes random work center, shortest travel time/distance rule, maximum outgoing queue size rule, and modified first come first served rule. *Routing* is the selection of specific paths taken by vehicles to reach their destinations. An AGV system network can be modeled as a graph consisting of nodes connected by set of arcs. Given the location of an AGV and its prescribed destination, the route manager can find the sequence of nodes that specify the path of the vehicle. Alternative routes can be evaluated based on the aggregate cost of traversing the sequence of arcs.

#### • Scheduling

Scheduling involves combining all of the individual vehicles' routes into an overall sequence of vehicle segments. In other words, the planning is responsible for breaking down the individual vehicle paths into smaller segments, and scheduling is responsible for sequencing the vehicles' access to each segment. The scheduling function is also responsible for resolving vehicle *conflicts* or *deadlocks* and generating/updating expected start and finish times for the selected routes.

### • Execution

Execution provides the interface between the physical system (drive system control and navigation) and the higher-level control system. Therefore, it is responsible for interfacing with the subordinate vehicle controllers, initiating start-up and shut-down procedures, issuing commands for assigned activities, and monitoring for error detection and recovery.

### 7.3 Commercial Applications

AGVs are making initial inroads for port applications in other parts of the world. It was found that significant effort has been expended by American firms in marketing heavy lift AGVs for port applications, but these efforts have had no success. Furthermore, U.S. companies have had little or no success in marketing these products to foreign countries, for primarily political reasons. The most well known American AGV company, Mentor AGVs, built, tested, and actively tried to market AGV units for port applications in early part of the decade, but cut back its efforts to actively pursue this growing market. Current commercial applications of AGV technology include systems at the Ports of Rotterdam, Thamesport, Singapore, Kawasaki, and Kaoshiung.

### Rotterdam

The Deltaport terminal at Rotterdam uses AGVs (shown in Figure 7.2) in transporting containers from the stacked storage area (served by rail-mounted gantry cranes) to the apron. The total fleet size is 105 vehicles. Electronic positioning devices align the wharf gantry crane with the units for rapid loading and discharging of the vessel. An onboard computer in each AGV communicates with a control center to enable free ranging navigation to any point within the terminal.



Figure 7.2: The Deltaport container terminal at Rotterdam.

### Thamesport

Thamesport is a Greenfield container terminal in Southeast England, and is thought to potentially be the world's first fully automated container terminal. Built in 1992, Thamesport uses fully automated

yard stacking equipment (gantry cranes), and has been testing prototype AGVs, built by Terberg Benschop (The Netherlands) for the past 4 years. They have since gone out for bids for a 20-30 vehicle system.

### **Port of Singapore**

The Port of Singapore Authority (PSA) let a contract for 5 prototype AGVs to Kamag, and Mitsui in late 1994. In talks with representatives from Mentor AGVs, the only U.S. company to actively pursue this market, it was found that PSA was interested in procuring perhaps as many as 1,000 to 2,000 AGVs eventually. Shown in Figure 7.3, the vehicles are designed to be able to accelerate from 0 to 5 meters per second in less than 10 seconds, with a top speed of 7 meters per second. Also, they can accept either 20- or 40-foot containers.



Figure 7.3: Port of Singapore prototype AGVs.

## Port of Kawasaki

The Port of Kawasaki has bought AGV test units from Mitsui (a Japanese company), and one test unit from a German firm, Schueulre.

## Port of Kaoshiung

The Port of Kaoshiung also has a commitment to automate its terminals in order to meet the demand of expected future growth. In the final report from the Kaoshiung International Port Development Project (KIPD), it is recommended that the Number 5 Terminal be completely automated for the purpose of container handling. It is known that the Port of Kaoshiung has various automated technologies under review, although details are currently scarce.

#### Virginia Inland Port and Mentor AGVs

Mentor AGVs, partnered with Raytheon, is attempting to secure funding for the development of a prototype AGV system at the Virginia Inland Port (VIT). Funding would come from the DoT, although the consortium is open to additional funding alternatives. Mentor has already developed a working prototype (shown in Figure 7.4), and boasts having built the largest AGV in the world for the Boeing Co.



Figure 7.4: A Mentor AGV prototype.

Mentor, the only U.S. company pursuing this market, has attempted on numerous occasions to win contracts from overseas ports. Unfortunately, the company found that winning an AGV contract for a foreign port is difficult.

Table 7.1 on the following page shows the various AGVs offered for terminal operations, and their respective performance and cost measures.

## 7.4 AGV Characteristics

Company and	Vehicle Type	Guidance Used	Communication System	Load Capacity	Travel Speed	Battery	Towing Capacit	Approx Weight	Drive Confi	Price Range
Product			System	(lbs.)	(ft./min.)	Туре	y (lbs.)	(lbs.)	guration	(\$)
MENTOR AGVs INC.	Tractor, Unit-Load Carrier, Fork Lift	Inductive Wire, Dead Reckoning, Laser Triangulation	Inductive Wire, RF Transmission, Optical Infrared, DGPS	300,000	To be specified based on customer' s request	To be specified based on customer's request	To be specified based on customer 's request		Electric or Hydrostatic	Varia- ble
RAPISTAN DEMAG DC-300 Unit Load AGV	Unit-Load Carrier	Inductive Wire, Other	Inductive Wire, RF Transmission	30,000	0-200	Lead Acid		8,000	Hub-Mounted Drive, (F & R)	175K
RAPISTAN DEMAG DT-100 Automatic Guided Tow Vehicle,	Tractor	Inductive Wire, Other	Inductive Wire, RF Transmission		0-225	Lead Acid	50,000	2,000	Dual Rear Wheel	65K
Elwell_Parker	Tractor, Unit-Load Carrier, Fork Lift	Inductive Wire, Internal Guidance	Inductive Wire, RF Transmission	25,000- 250,000	0-200	Lead Acid, Gell Cell	15,000		4_wheel	100K- 400K
Frog Navigation Systems	Tractor, Unit-Load Carrier, Light-load Carrier, Fork Lift	Inductive Wire, Optical Guidance, Laser Triangulation, Internal Guidance	Optical Infrared, RF Transmission	100,000+	0-225	NiCad, PH Acid				
AGV PRODUCTS INC. Automated Guided Vehicle	Tractor, Unit-Load Carrier, Light-load Carrier, Fork Lift	Inductive Wire, Laser Triangulation, Internal Guidance	Inductive Wire, Optical Infrared, RF Transmission	50,000	0-220	Lead Acid, NiCad	10,000		Tricycle, Dual Steer, Differential	40K - 100K
CONTROL ENGINEERING CORP. Heavy Load Handling Vehicle,	Unit-Load Carrier, Fork Lift	Inductive Wire, Internal Guidance	RF Transmission	65,000- 100,000	0-200	Lead Acid, NiCad		31,000	4-Wheel Drive/Steer	250K- 350K
CONTROL ENGINEERING CORP. Heavy Load Handling Vehicle,	Unit-Load Carrier	Inductive Wire, Internal Guidance	RF Transmission	250,000	0-200	Lead Acid, NiCad		71,500	4-Wheel Drive/Steer	400K- 600K

## Table 7.1: Current AGV Manufacturers, and Product Specifications for Terminal Operations

Table 7.1 shows that the approximate purchase cost of automated vehicles ranges between \$100,000 and \$600,000 per unit. The initial capital cost for AGV systems is high, as are the various maintenance costs, which include the powering of the vehicles, and other mechanical maintenance. However, because the labor operating cost is negligible, these costs should be mitigated over the life cycle of the system. Moreover, the accuracy of loading, transporting and unloading can improve efficiency. It reduces the cost of misconducting, missing and delaying. The benefit is potentially significant. Also, there is value in the flexibility an unmanned system offers over conventional systems.

#### 7.5 Future Trends and DoD Applications

AGVs are likely to have promise to the DoD. AGVs are less subjected to environmental interference. The unmanned vehicle can work in bad weather or other tough environments, 24 hours a day. These capabilities could be useful to the DoD during times of crisis. Moreover, AGVs can perhaps move loads more accurately and efficiently, which could be of additional value to the DoD. Also, AGVs can perform functions considered unsafe for human labor. Security is also easier to maintain in an automated container handling yard.

AGVs offer a safe, reliable alternative to human operators in environments where material transport requirements are well-defined and reasonably static. The paths, however, are difficult and expensive to change, particularly in the case of the wire guided systems. In dynamic environments, the fixed-path vehicles may not be practical. Toward that end, a new generation of material handling vehicles is emerging which are more autonomous than the AGVs of the past. These machines do not require that a continuous guide path be installed, but find their way around the plant by means of internal maps and periodic sighting of landmarks whose position in the environment is known. One can expect that with time, increasingly sophisticated and "intelligent" control systems onboard AGVs will allow more autonomous operations, and better system performance.

#### 7.6 Summary

Over time, automated systems may be accepted into U.S. terminal operations, but currently these technologies do not appear to be feasible from a political standpoint because of labor use. Automated systems could have value for the DoD, because of their high degree of reliability, their value in performing cargo handling tasks which would be unsafe for human operators, and the higher degree of security, cargo enjoys in an automated container yard.

It would behoove the DoD to support, to the extent appropriate, U.S. initiatives in AGV development for port and terminal applications, since this technological industry is clearly growing in other parts of the world, and the U.S. has clearly fallen behind. In the future, the intellectual capital associated with AGVs enterprises could prove to be very valuable to American industry.

# 8. LINEAR MOTOR-CONVEYANCE SYSTEMS

Another technological concept that has demonstrated significant promise for the transfer of containers to and from the yard is based upon linear motor-conveyance system. Linear motor-driven conveyance systems (LMS) could have significant advantages over AGV systems, due to their relatively low maintenance cost, and possibly lower capital cost. One prototype "linear motor terminal" has been constructed in Germany, and the preliminary results seem to be very promising.

#### 8.1 The Technology

A linear induction motor operates on the same basic principles as a conventional, rotary induction motor, except that instead of the coils being wound around a shaft, the entire assembly is "unwound" into a linear configuration. Running current through the coil still induces motion in the shaft. By controlling an array of linear motors that are placed underneath a platform, one can accurately move the platform (given that it is on a sliding or rolling surface). The concept of a linear motor is demonstrated in Figure 8.1.

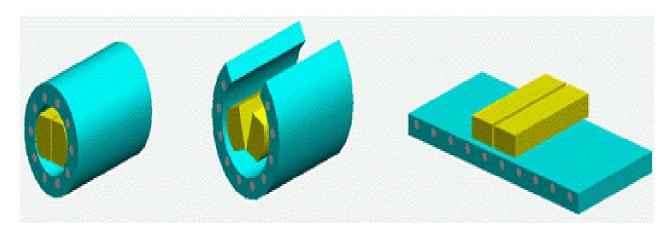


Figure 8.1: "Unrolling" a conventional motor to create a linear motor.

Linear motor systems have some very attractive characteristics: The motors themselves consist of no moving parts, are very reliable, and last a long time. Platforms, which are conveyed via linear motors systems, are unmanned and have very few moving parts. The wheel assembly on the platform is the only moving part. Also, no power is required onboard the platform. These characteristics make linear technology very promising for a wide array of applications, including container conveyance at marine terminals.

In practice, linear motors are currently used widely for smaller scale, manufacturing applications, such as conveyance systems for sorting systems or assembly plants. However, the technology is scaleable to larger tasks, including container transfer within marine terminals. One can imagine a very large linear motor-driven system for container transport at marine terminals. It would consist of large rolling pallets, with a fixed aluminum/steel plate on its underside, a fixed guideway, linear motors, and a central control system. Shown in Figure 8.2, such a system could be used for the transfer of containers to and from a storage yard.

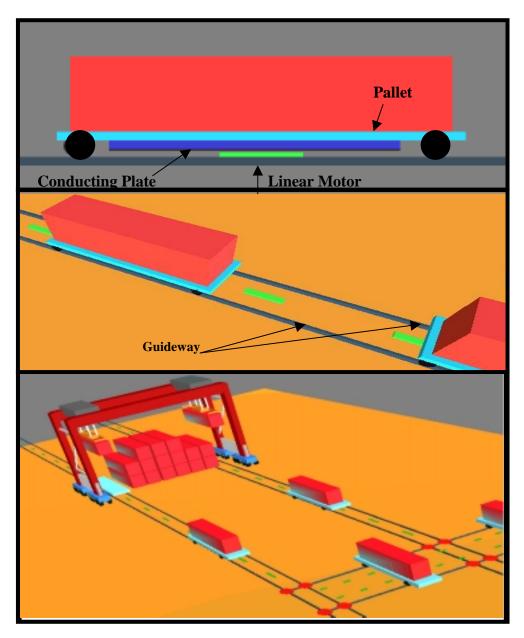


Figure 8.2: A Linear motor conveyance system.

A system such as this could be ideally suited for port and terminal operations. Once the necessary infrastructure is in place (fixed guideway, motors), and the pallets to carry the containers are constructed, the system could be operated autonomously without any constraints on the hours of operation, and at a very low cost. The critical issues regarding the implementation of this technology for container transfer operations are discussed later in this section.

## 8.2 Current Applications (Non-Port)

#### Skytrain (Vancouver, Canada) -

Skytrain was built by Metro Canada (UTDC) for the World's Fair in 1988. Completed in 1986, the train system is the biggest known application of linear technology. Shown in Figure 8.3, Skytrain uses a complimentary approach to the theory posited above. Instead of mounting linear motors on the ground underneath the moving platform, Skytrain uses linear motors mounted on the underside of the platforms themselves. System Specifications are given in Table 8.1 below.



### Figure 8.3: Skytrain, Vancouver, B.C.

Length Height Width Weight	41 ft. 8 in. 10ft. 2 in. 8 ft. 2 in. 13.75 tons
Train Formation	2-car units 2X2 axle bogies per car
Power Required	600V (dc) side collection
<b>Operating Speed</b>	50 mph

### Table 8.1: Skytrain System Specifications

The Skytrain has now been in operation for more than 10 years.

#### Disneyworld (Orlando, Florida) -

Disneyworld used linear technology for its People Mover system in the mid-seventies. The system consists of the multi-unit passenger cars (very similar to a typical roller coaster train), the track, and linear motors mounted between the guiderails underneath. The system was designed such that three linear motors are underneath a train at all times, thus ensuring a continuous force on the vehicles. Also, a fairly sophisticated control system, whereby the "on/off" status of the electromagnets (linear motors) are monitored and managed, is used for the train. The system also features an automatic collision avoidance system, and an air gap monitoring system. It is very important to maintain a constant air gap between the plates mounted on the bottom of the cars, and the linear motors. According to the manufacturer of the motors, Northern Magnetics (Southern California), the system ran without flaw for nearly twenty five years, with the exception of one motor failure after 10 years of the operation, that was caused by a lightning strike.

### **8.3 Port Applications**

In 1994, the German Federal ministry for Research and Technology in Bonn commissioned a "Study of the General Framework and Concepts for a Container Transport System of the Future". As result of this study, Preussag Noell GMBH developed a linear motor-driven system which transports containers from the gantry cranes to the storage yard. A prototype of this system has been constructed at the Eurokai Container Terminal, Hamburg. The purpose of the prototype was to test the functioning capabilities of the entire system, the weather resistance under extreme wind /temperature/humidity conditions, reliability, and maintenance. The system, shown in Figure 8.4, consists of: 1. A substructure (it includes guiderail, linear motors), 2. Shuttle cars, 3. A control system, which positions the cars under the gantry cranes in both the yard and at the ship quay. The operating data of the prototype system are listed in Table 8.2.

Effective Load	48 Mg max
Speed	3 m/s
Acceleration	0.3 m/s^2

Table 8.2: Operating Characteristics of the Eurokai LM Transfer System

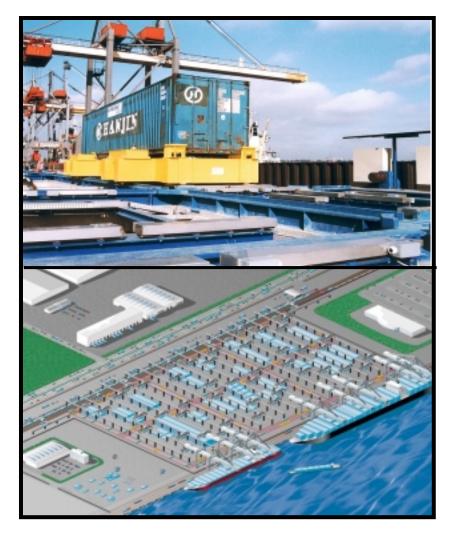


Figure 8.4: Top Picture: The Linear motor conveyance system at the Eurokai container terminal. Bottom Picture: The "container terminal of the future" concept.

One interesting element of this system is that the container shuttles are designed to make right angle turns. This is accomplished by designing the shuttles such that the wheels can be turned 360 degrees individually. At the corners of the track, the wheels rest on four "turntables" which are turned 90 degrees, so that the shuttle can continue on its new path. The entire terminal concept is automated. The yard is serviced by automated overhead (gantry) cranes, and can stack containers 7 high. According to the designers of this system, the capital costs associated with this terminal are comparable to building a conventional terminal, but the operating costs are "considerably lower."

Critical design issues in using linear motor technology involve, primarily, the interface between the guide-rails, and the shuttle cars. Since a very small gap must be consistently maintained between the plate on the underside of the shuttle, and the linear motors, this becomes a critical design requirement. Also, for a right-angle turning system, the design of the turntables to reposition the wheels underneath is another critical design question. The Eurokai/Noell engineers successfully designed and implemented the turntable system.

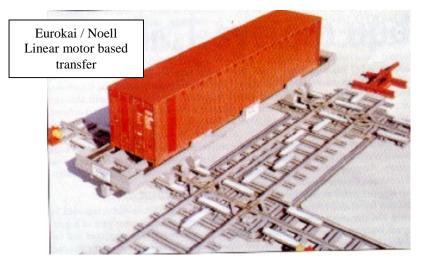


Figure 8.5: Eurokai/Noell linear motor based transfer.

The Port of Tacoma, Eurokai, and Noell are investigating innovative AGV-like systems employing linear motors embedded in the ground to propel containers throughout a storage yard. In the Eurokai and Noell system (see Figure 8.5), known as LMTT (linear motor-based transfer technology), the container is placed in what is called a palette wagon. The palette wagon acts as a reaction plate to the linear induction motors and is propelled by the magnetic force of the motors.

Sea-Land's proposed GRAIL system (see Figure 8.6) also uses linear induction motors, but the motors are located on overhead shuttles that move along a monorail above the terminal. The containers are stacked beneath the monorail and can be accessed and brought to the ship as needed. Sea-Land has a portion of this system running in its highly successful Hong Kong terminal.

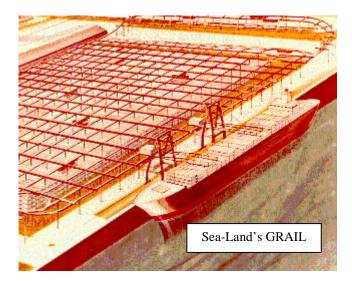


Figure 8.6: Sea-Lands GRAIL.

#### 8.4 Linear Motor Systems vs. AGV Systems

Linear motor driven systems could be proven to be more attractive than AGV systems for marine terminal applications. The comparison matrix in Table 8.3 was used to assess the relative merits of each technology.

System Attribute	AGVs	Linear Motor Systems
Speed	0-15 mph	0-15 mph
Capital Cost	Medium/High (relative to conventional terminal)	Medium/High (relative to conventional terminal)
Operating Cost	Low	Low
Maintenance Cost	Medium/High	Low
Reliability	Medium	High
Routing Flexibility	High	Low

Table 8.3: Comparison of AGV and Linear Motor Conveyance Systems

*Speed:* Both AGVs and LMS have comparable speeds. Each could attain speeds higher than the range listed in Table 8.3, but this is the range of speeds for normal operations.

*Capital Cost*: Both AGVs and LMS have high capital outlays. An AGV system requires the construction and testing of not only each vehicle, but also requires installation of a navigation system.

*Operating Cost:* For both types of systems, the operating cost is low, compared to conventionally equipped terminals.

*Maintenance Cost:* A linear motor system would enjoy an appreciably lower maintenance cost than an AGV system primarily due to the simplicity of the system. Also, an AGV system uses powered vehicles, and the navigation system is prone to hysteresis (creep). This must be constantly recalibrated to ensure the optimum performance of the system.

*Reliability:* Both types of systems are capable of reliable operations. Linear motors are expected to be more reliable as demonstrated by the Disneyworld application.

**Routing Flexibility:** Due to the fixed guideway associated with linear motor systems, AGV systems could be much more flexible in terms of their ability to travel on numerous paths depending on the navigation concept used. This is seen to be an issue, which will be critical to terminal owners in choosing between these two systems. In general, however, it is probably not critical for most terminal operations that the container transfer vehicles be able to travel anywhere within the yard. Typically, the vehicles travel on set paths.

# 9. AUTOMATED STORAGE AND RETRIEVAL MULTI-STORY SYSTEMS FOR YARD OPERATIONS

#### 9.1 Automated Storage and Retrieval Multi-Story Systems (AS/RS)

In recent years the AS/RS has had an important impact on storage and warehousing operations. These high-rise storage modules are becoming commonplace in companies that deal with numerous items in large volumes. For those enterprises with limited storage space, high labor costs, and sensitivity to accuracy of order deliveries, AS/RS is an attractive solution. Today, the average shipping accuracy in US warehouses is 99%, the Japanese standard of one error per 10,000 shipment is rapidly becoming the acceptable standard. Location assignment and inventory planning and control in AS/RS are maintained by the computer. A random access system stores and retrieves the loads. In such a dense environment, the storage capacity of the warehouse is expanded twofold to fivefold by using the same floor space. Such a fully mechanized system requires very little labor to operate. It also minimizes material handling by reducing the average distance traveled and by being accurate in identifying the location of items.

An AS/RS (automated storage and retrieval system) is defined by the AS/RS product section of the Material Handling Institute as a storage system that uses fixed-path storage and retrieval machine running on one or more rails between fixed arrays of storage racks. A unit load AS/RS usually handles loads from 1,000 to 100,000 pounds. The number of systems installed in the US is in the hundreds, and installations are commonplace in all major industries.

An AS/RS has four major components; Storage and Retrieval Machine (SRM), the rack structure, horizontal material handling system, and planning and controls. The SRM simultaneously moves horizontally and vertically to reach the desired location. It travels on floor-mounted rails guided by electrical signals. Pick up and delivery either on the Pick-up/Delivery (P/D) stands or on the storage racks are automated, and are controlled by the computer.

The SRM usually picks up a load at the front of the system, transports the load to an empty location, deposits it in the empty location, and returns empty to the P/D stand. Such an operation is called Single Command (SC) operation. Single command accomplishes either storage or retrieval between successive visits to the P/D point. A more efficient operation is a Dual Command (DC) operation. A DC involves the SRM picking up a load at P/D point, traveling loaded to an empty location, depositing the load in the empty location, traveling empty to the location of the desired retrieval, picking up the load, traveling loaded to the P/D point, and depositing the load. The key idea is that in the double command mode, one store and one retrieve takes place in each cycle.

The Storage Racks interface with the SRM, and in doing so, require very close tolerances in their construction. The guide rails within it must allow SRM to move in and out freely, stopping exactly at the required cubbyhole. A typical unit load AS/RS configuration would include unit loads stored single deep, in long narrow aisles, where each aisle contains one SRM. The P/D point would be located at the lowest level of the storage and at one end of the system. Such a P/D location system is referred to as end of aisle order picking. However, there are potential modifications in such a prototype configuration for AS/RS. One variation is to store loads in two deep racks. This could be beneficial if the variety of loads stored in the system is relatively low, throughput requirements are moderate, and the number of

loads to be stored is high. A second variation in the typical configuration is the number of locations of P/D stands. Throughput requirements or facilities design constraints may mandate multiple P/D stands at locations other than the lower corner of the rack structure. Multiple P/D points might be used to separate inbound and outbound loads and/or to provide additional throughput capacity. Alternative P/D locations are at both ends of the racks as well as at middle points. Load characteristics, activity rate, and limitations imposed by the cost of construction are the important factors in the overall design of the rack structures.

The horizontal material handling system interfaces with SRM for receiving and shipping. These material handling equipment in the port operations can be trucks, Automated Guided Vehicles (AGVs), and Transfer Cars (TC). Note that in port operation, shipping also plays the role of receiving, and receiving plays the role of shipping too. Automated Guided Vehicle System (AGVS) and Transfer Car System (TCS) can be made interactive with the AS/RS to achieve maximum flexibility and rapid real-time response.

The planning and control mechanisms are key to the control of AS/RS. Unit loads to be stored in the racks arrive randomly. They are then transferred via SRM to an open location in the rack. The computer keeps track of where each unit load is placed in the rack. Requests for retrieval of items also arrive randomly. Two measures usually used to describe the arrival of the loads are Estimated Arrival Time (EAT) of the ships, and the probability density function of truck (and train) inter-arrival time. When these incoming and outgoing flows are combined with material storage policies, an additional stochastic factor - the location of items in the rack- is introduced. In recent designs, the single computer is replaced by a distributed system. This results in simplicity of design, operation, and faster response.

#### 9.2 AS/RS in Container Terminals

The material handling process re-engineering is now a critical issue for industry and military logistics managers, airlines and shipping lines, terminal and warehouse operators, intermodal carriers and airports around the world. Faced with substantial increases in container traffic, limited land availability, increasing vessel sizes and the need to become cost competitive, the high density storage system will play an important role in the future success of many of container terminal activities. Implementing AS/RS in a container terminal to automatically store, retrieve, shuffle (in two deep systems), sort containers, and reposition them to maximize productivity, would improve many key strategic variables of container terminal operations such as:

- 1- **Space utilization**. The high rise high density AS/RS structure reduces the required space by 1/3 to 1/2.
- 2- Cycle time reduction. The cycle time of AS/RS is shorter than that of a gantry crane. Furthermore, the random access capability results in no re-handling (false shuffling). This obviously leads to higher productivity and throughput.
- 3- **Flexibility**. The AS/RS can retrieve the desired containers with the desired attributes (content, destination, weight, etc.) in the desired sequence. It could have random access for expedited intermodal hand-offs and 24 hour on demand service with ATM card.
- 4- Horizontal material handling fleet size reduction. Whether AS/RS is served by truck, AGVS, or TCS, in all cases, replacing the conventional port storage block layout by AS/RS results in a smaller fleet size.

- 5- Quality. The potential of picking wrong containers is minimized.
- 6- **Expandability**. Additional modules can be added easily.
- 7- Management control. High value containers are well tracked and securely stored.

In general, material handling means providing the right amount of the right material, in the right condition, at the right place, at the right time, in the right position, in the right sequence, by the right method, and for the right cost. It seems AS/RS dominates present conventional block container layouts in all the above directions except in the initial investment cost.

### 9.3 High Density High Productivity Port Storage Systems

Three high rise, or pigeon hole, storage and retrieval systems have been proposed by Seaport Container Storage Systems in association with Transact, Earl's Group, and Krupp. Though at first glance each system looks similar, the detailed operations and techniques used provide each with unique pros and cons. August Design Inc. has written a computer model to study the Seaport and Earl's systems.

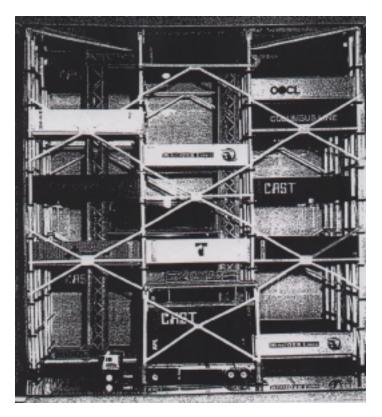


Figure 9.1: A view of the physical model developed by Seaport.

The Seaport system (see Figure 9.1) is based on the Transact design of automated air cargo handling systems employed at a number of airports. Seaport describes the system as a "high-rise, random access storage system for marine containers." The Seaport literature provides the following additional description for one variation of the system:

"The main component, a fully automatic Elevating Transfer Vehicle (ETV) is the key element of the system. A proprietary design based on Transacts over 25 years of experience in the air cargo industry is adapted to meet specific needs of handling marine containers. The ETV is a stacker crane that interfaces horizontally and vertically with the storage position (bins) in the bays. The shuttle mounted on the ETV cradle is the mechanism that stores and retrieves the containers from the storage positions. A bay is a module of self supporting structure 41.5 feet long, 44 feet wide, 127 feet high. The bay, 10 levels high, with 4 storage positions on each level creates an aisle for the ETV. Each level accepts two containers on each side of the ETV aisle. In order to achieve 501 container storage capacity, 13 bays are used. The inlet/outlet is an interfacing system. An automatic overhead crane with a 40-foot spreader provides the means to receive and deliver containers to and from the trucks or AGVs. It is located at the front of the system approximately in the middle bay in place of 6 storage bins."

Earl's is a leading manufacturer of container spreader bars, and through private investment and funds from the Canadian government has built a full scale prototype of the handling system with a small number of storage bins. The Earl's system is known as the Computainer (see Figure 9.2). The following description is taken from Earl's advertising literature:

"The Computainer System offers terminal owners and operators a means to greatly reduce acreage needed for container storage, and the capability to sort and stage containers more efficiently and less expensively than previously imagined.

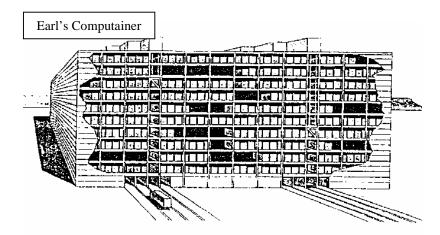


Figure 9.2: Earl's Computainer.

The Computainer System, is a multi-story steel structure providing for inventory management of containers. Less than 4 acres of land, for example, are needed for 2,000 forty-foot full size containers and related access and truck queuing areas. Multiple access bays are provided for rapid truck turn around. The Computainer System includes an integrated hoist transfer system based on proven technology. Its straightforward mechanical design and operational simplicity endures its on time performance and long term dependability.

Proven computer control technology provides many functions:

- Fast track positioning loading and unloading
- Real time inventory and location information
- Operations and maintenance records
- Low cost sorting and positioning for rapid ship loading."

According to Earl's estimations the maximum time to store a container, from the time of pick-up from the truck to the location in allocated bay, is 2 minutes. Simulations performed by Earl indicate that the throughput per acre using computainer is about 1400 TEU per acre, while the throughputs for the same terminal equipped with either 5 or 8 rubber tired gantries is about 450 and 800 TEU/acre.



Figure 9.3: Krupp fast handling system.

Krupp is a manufacturer of marine cranes, mineral processing, materials handling and mining. They are located in Germany with offices throughout the world. The "Krupp Fast Handling System" (see Figure 9.3) is an automated system designed specifically for intermodal rail terminals, but can be adapted for marine terminals. The system includes a high rack storage system. Krupp has a portion of the system installed as a prototype at the terminal in Duisburg-Rheinhausen. The following descriptions have been extracted from the Krupp literature:

"The Krupp Fast Handling System features the following advantages:

- Extremely fast handling
- Modular design for more efficiency
- Short waiting time for trucks
- Space requirement is far less compared with conventional systems

The high-rack store has a modular structure and comprise:

- The warehouse end and center modules
- Storage bays and
- The high-rack handling device and the channeling vehicles

The storage bays for the containers are on the lower level of the high-rise system to avoid having to lift bulky loading units unnecessarily and effort-intensively. Apart from height they have the same dimensions as all the other rack bays.

The high-rack handling device moves along the transverse aisle on running and guide rails. It consists of a lifting frame, lifting cross-beam, turning device and channeling vehicles. The high-rack handling device mainly serves to transport the loading units vertically to the storage levels.

## **10. AUTOMATED CONTAINER TERMINAL CONCEPTS**

In the previous sections we presented numerous technologies associated with container terminal operations as well as examples where these technologies were applied. The most accurate evaluation of these technologies in a container terminal environment is to actually implement them in full scale and collect data during operations. This however is not possible due to the fact that some of the technologies are in the design stage and others need to be evaluated or the obstacles (often non-technical) need to be overcome before an actual implementation becomes feasible. The evaluation of concepts or systems using models and simulations, in order to assess expected performance and examine feasibility is the first step towards implementation.

In the following sections 11, 12, and 13, we analyze three different automated container terminal concepts employing the latest equipment technologies discussed in the previous sections, and evaluate the performance of each concept by means of simulations. The results of the study performed by [41] for the Norfolk International Terminal at Virginia Port and data collected [42] are used to develop a base scenario for manual operations. The performance of the proposed automated operations was then compared with that obtained from manual operations.

#### **10.1 Base Scenario: Manual Operations**

The Norfolk International Terminal (NIT) is used as a base scenario for manual operations. It is equipped with three dual-hoist ship cranes capable of 45 moves per hour. The yard of the terminal is divided into two main parts, the wheeled storage area and the gantry crane storage area. The wheeled storage area is used for short-term container storage. The containers in this area are mounted on chassis and are dropped off or picked up by over-the-road trucks. The containers are moved from the dock to the wheeled area or from the wheeled area to the dock by terminal tractors (hostlers). The gantry crane storage area, which is closer to the dock than the wheeled area, is equipped with rubber tired gantry cranes which load and unload the terminal hostlers.

Despite the fact that the dock cranes at NIT are capable of 45 moves per hour, the average current terminal productivity is about 30 moves per hour. Thus, as mentioned in [41], the problem is not with the cranes but with the yard operations. According to the analysis presented in [42], despite the fact that the average operating speed of manually-operated hostlers is about 17 mph (25 ft/sec), a hostler moves approximately 6 containers/hour (10 minutes per move), where a move is defined as the movement of a container from the initial pick-up point to a destination point (including the time the hostler waits to get loaded or unloaded). By using the fact that the average distance traveled by a hostler is 1500 ft, we conclude that the *Average Actual Speed (AAS)* in ft/sec of the hostler can be approximated as follows

	Average Distance	1500
AAS = -		=
	Average Move Time – Loading Time – Unloading Time	600-Tl-Tu

where Tl= time needed for the hostler to be loaded by the yard crane and Tu= time needed for the hostler to be unloaded by the ship crane.

JWD performed a simulation study in order to compare four different operation scenarios of manually operated yard equipment at NIT [41]. The results of their study are presented in Table 2.10 of section 2.2. The first scenario uses 7 rubber tired gantry cranes at the gantry crane storage area, 18 hostlers for serving the dock cranes and 7 hostlers for serving the wheeled storage area. Their simulation study showed that the average productivity achieved under this scenario is 28 moves per hour per dock crane. PCS performed a study on the use of AGVs for the same terminal [42]. The average operating speed of the AGVs is assumed to be 10 ft/sec (i.e., it is assumed that the AGVs average speed is 2.5 times less than that of a manually-operated hostler). Also, the study considered the problem of connecting the AGVs to chassis for wheeled operations and assumed that it takes on average 1 minute to connect the AGV to chassis. Connecting an AGV to chassis in the wheeled area requires safe backing and connection of their brake hoses. Both operations require human involvement, which in turn raises important safety issues and introduces additional delays.

The model we used to describe the container terminal operations and calculate throughput and other variables in sections 11, 12 is validated using the data provided in [41,42] for NIT. The model is so developed that if simulated with the equipment (e.g., cranes, hostlers) and yard characteristics given in [41,42], then the yard productivity generated by the model matches the measured productivity of the terminal. More precisely, when the yard operations are simulated using the same dock and yard crane characteristics as the NIT ones (e.g., the actual average speed of the hostlers is the AAS given above, the yard is equipped with the same number of hostlers and yard cranes as the ones considered in [41], etc.), then the yard productivity is close to 28 moves per hour, or the actual productivity observed in the terminal. No wheeled operations are assumed in our model. Such an assumption does not affect the compatibility of our analysis with the ones in [41,42] provided that the interference between the hostlers serving the wheeled area and the ones serving the dock cranes is negligible.

The simulation results obtained using the model for the manual operations and automated operations proposed in subsequent sections are presented in sections 11, 12.

## **11. AUTOMATED CONTAINER YARD USING AGVS**

We propose a container terminal serviced by advanced cranes and AGVs for automated container loading and unloading. The basic features of the proposed terminal that enable us to evaluate expected throughput are specified. Our goal is to estimate the increase in throughput that can be achieved by the proposed automated terminal compared with the throughput of similar terminals with manual operations.

The layout of the automated container yard employing AGVs is shown in Figure 11.1. The dimensions of the yard are 700 feet width and 1400 feet length.

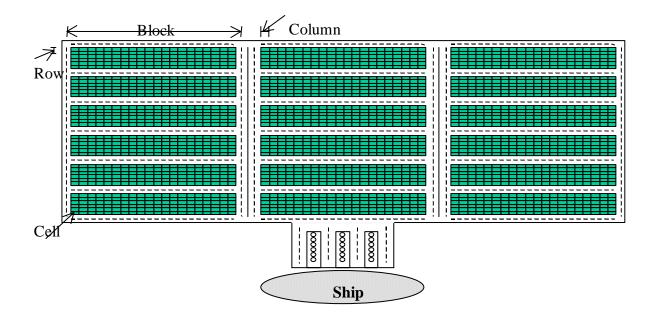


Figure 11.1: The layout of the automated container yard.

The yard consists of three major parts, which thereafter will be called *blocks*: left, middle and right. Each block has six storage stacks and each stack has 20 *columns*. In each stack, there are also 6 *rows*, which leads to 6 *cells* in each column. We assume that each cell can be stacked with up to three containers. Therefore, the capacity of the yard is 2,160(cells)x3 = 6,480 TEUs (Twenty-foot Equivalent Unit).

In each block, a two-lane road (aisle) referred to as the *working road (aisle)* separates stacks from each other. A four-lane road (aisle) referred to as *transit road (aisle)* separates blocks from each other. We also refer to the roads on the left and right borders (vertical roads), and the road adjacent to the ship cranes (horizontal one) to be transit roads. To prevent heavy congestion and blocking, we reserve the working roads for drop-off and/or pick up activities, while the transit roads are used to reach a specific working aisle or a ship crane. In each road we have at least two lanes in opposite direction to allow a smoother traffic in the yard. All the lanes in working and transit roads are considered to be unidirectional lanes, and an AGV is allowed to travel only on the right lane of a two-lane road. Each

working lane can be occupied by only one AGV at any time. Other requests, for occupying that lane, will be simply put in a queue until the lane is empty. This queue works on the first come first served (FCFS) basis.

We also assume that each stack has only one *yard crane*, and this crane is responsible to move containers to/from the two adjacent working lanes. That is we divide each stack into two sections, where each section contains three rows. The yard crane will load or unload a vehicle from/to the nearest part. We assume that a yard crane serves vehicles in two adjacent working lanes based on the first come first served rule (FCFS). There are also three *ship cranes* on the yard. Yard cranes are responsible for loading/ unloading the AGVs, whereas the ship cranes are responsible for loading/ unloading the ships and loading/unloading to/from AGVs. We also assume that the maximum number of AGVs waiting in a queue under each ship crane cannot exceed 6, and that they will be served within the first quarter of time slot that is needed for a ship crane to transfer a load to a ship. That is the service time for a vehicle is one fourth of the time that the ship crane needs to load a container. A ship crane is chosen by an AGV if its queue has the minimum number of vehicles compared to the other ship cranes' queues. The service rule for the ship crane queue is also based on first come first served rule (FCFS). The above protocols and rules for the movement of AGVs are not unique. They are based on intuition and may not satisfy optimality. In future work we plan to optimize these operations.

In our analysis and evaluation we assume the following characteristics of the yard equipment:

Performance of the yard cranes: The performance characteristics for rubber-tired gantries given in Table 2.11 are used.

Speed of the ship cranes: 45 to 75 moves/hour.

Speed of the loaded AGVs: 5 miles/hour.

Speed of the unloaded AGVs: 10 miles/hour.

The speed of the ship cranes is based on current and expected performance of advanced cranes which are either in use or in conceptual designs. The speed of the AGVs is chosen to be similar to those used at Rotterdam and suggested by manufacturers.

### **11.1 Control Logic for AGVs**

The control logic and protocols that dictate the motion of AGVs and loading/unloading processes are developed as follows: We first developed a database describing the yard layout (network). Next, we defined the intersections, and loading and unloading points as the *nodes* of the network. As it is mentioned before an AGV is only allowed to travel on the right lane of a two-lane road. Therefore, once the pick-up and drop-off points are assigned to a particular AGV, the *path* is uniquely determined by using the intermediate nodes.

The control logic algorithm must be able to resolve any possible conflict between AGVs. A *conflict* between two or more AGVs may occur during the following situations:

1. <u>Arriving at an intersection from different path segments at the same time</u>. A *segment* is defined as a part of a road located between two adjacent nodes. To resolve this type of

conflict, we introduce the '*Modified first come first pass*' (MFCFP) protocol. This protocol is similar to the '*stop sign*' protocol in urban traffic and is described as follows:

• If two or more AGVs arrive at an intersection at the same time, and there is no possible collision between them, all AGVs will proceed with their maneuvers simultaneously. For instance, for a typical intersection in the yard shown in Figure 11.2, consider the case where AGVs A and C arrive at an intersection at the same time and AGV A wants to make a right turn. In this case C can proceed with its either right or left turn maneuver since there is no possible collision.

• When two or more AGVs arrive at a particular intersection from different segments at the same time, the right of the way is given to the vehicle(s) in the transit lane. That is AGV F, in Figure 11.2, has priority over G in case G wants to make a left turn into the transit lane.

• Consider two AGVs arriving at an intersection at the same time from different segments of a transit road. If there is any possible collision between them, the priority of continuing their maneuvers will be given to the AGVs based on their intention and in the following order: 1) to go straight (top priority), 2) to make a right turn, and 3) to make a left turn. For example, if AGVs A and B, in Figure 11.2, arrive at a particular intersection and A wants to make a right turn while B wants to make a left turn, the right of the way will be given to A, since turning right has the priority over turning left.

• When two or more AGVs happened to be at the same segment at the same time, say A and H in Figure 11.2, and if the leading one, A, stops at an intersection, or in the middle of a segment, the following AGV, H, will stop at least 10 feet away from the leading one. If these two or more AGVs are traveling in different segments, say A and E (or D and A), and the leading AGV A(D) stops at an intersection (in the middle of a segment), the following AGV E(A) is barred from entering the next segment, which is occupied by the leading one. This rule is set to ensure that an intersection is always open to the through traffic.

• If an AGV begins its maneuver at a particular intersection, say AGV C has already started to make a left turn, other arriving AGVs at that particular intersection, say A and B, should wait at the intersection until the end of the maneuver.

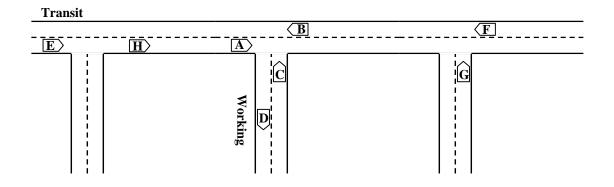


Figure 11.2: Typical intersections in the yard.

2. <u>Traveling along the same path with different speeds leading to potential collision</u>. As it is mentioned before only one AGV is allowed to occupy a working road at a specific time. Thus, a possible conflict can only occur in a transit road. To prevent this kind of collision, we define *Low Speed Zone(s)* in the portion(s) of transit lanes where two or more AGVs with different traveling speeds may exist. When a particular AGV enters the Low Speed Zone, it simply reduces its speed down to that of the loaded AGV which is 5 miles per hour.

For the container yard under consideration, the Low Speed Zone is the portion of the horizontal transit lane in Figure 11.1, which is located in the front of the ship cranes' area. Since an AGV travels on the right lane of a two-lane road in the yard, the other portions of the transit lanes in the yard will be occupied either by loaded or unloaded AGVs. That is there is no other area in the yard where unloaded vehicles, with speed 10 mph, and loaded vehicles, with speed 5 mph, will be on the same lane at the same time.

In the container yard where combined loading and unloading operations are taking place, the Low Speed Zone area is almost every transit lane in the yard. We elaborate more about this case when combined loading/unloading simulation is discussed in subsection 11.2, (simulation 3).

The flowchart in Figure 11.3 summarizes the control logic that governs the motion of the AGVs in the yard.

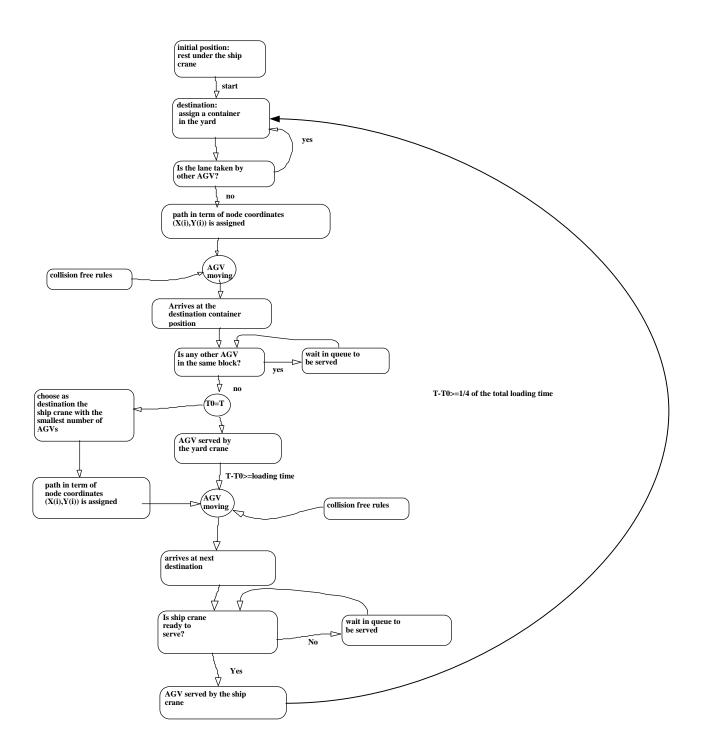


Figure 11.3: Flow chart of the control logic for AGVs.

### **11.2 Simulation of Control Logic**

The mathworks software packages "Stateflow", "Simulink" and "Matlab" are used to simulate the loading/unloading operations of the automated container terminal shown in Figure 11.1. The following definitions and measures have been considered to assess the performance of the simulated operations.

- **Definition 1:** *Busy Period of an AGV*. An AGV is called to be in its busy period if it is in one of the following situations:
  - 1. Being served by either a ship crane or a yard crane,
  - 2. Traveling in the yard to load/unload an assigned container.

If an AGV is not in its busy period, it is in *idle period*. For example, the idle period includes the times a particular AGV is waiting in the ship or yard cranes' queue to be served, plus the time during which it stops either at an intersection or in the middle of a segment to prevent possible collision.

- **Definition 2:** *Busy Period of a Ship Crane*. A ship crane is said to be in its busy period if it is occupied with the loading/unloading task.
- **Definition 3:** *Busy Period of a Yard Crane*. A yard crane is said to be in its busy period if it is occupied with the loading/unloading task.
- **Definition 4:** *Idle Period of an AGV, a Ship Crane, or a Yard Crane.* An AGV, a ship crane, or a yard crane is said to be in its idle period when it is not in its busy period.
- **Definition 5:** *Idle Rate (IR).* The idle rate (IR<sub>i</sub>) of equipment *i* is defined as

$$IR_i = \frac{Idle \ Period \ (i)}{Busy \ Period \ (i) + Idle \ Period \ (i)} \times 100\%$$
.

• **Definition 6:** Average Idle Rate (AIR). The average idle rate of N pieces of similar equipment is defined as

$$AIR = \frac{\sum_{i=1}^{N} IR_i}{N} \%$$

• **Definition 7:***Throughput.* The average number of containers being loaded/unloaded per hour per ship crane is referred to as the throughput of the terminal, i.e.,

 $Throughput = \frac{Total \ number \ of \ containers \ loaded \ and \ / \ or \ unloaded \ to \ / \ from \ the \ ship}{Total \ time \ elapsed \times Number \ of \ ship \ cranes}$ 

The following sets of simulations are performed:

### Simulation 1: Simulation of Automated Operations: Loading

The automated yard loading operations are simulated for different number of AGVs and ship crane speeds. Only the container loading operation from the yard to the ship is considered. We consider the cases where 6, 9, 12, 15, 18, 21, 24 and 27 AGVs are used. The ship cranes are assumed to work with four different speeds: 45, 50, 55 and 75 moves per hours.

Figures 11.4, 11.5 and 11.6 show the results of simulation 1. Figure 11.4 demonstrates that the faster the ship crane is, the more containers per hour can be loaded to a ship provided the number of AGVs used is sufficiently large. The number of AGVs is a very crucial parameter. If the number of AGVs used is small the throughput of the yard doesn't increase by using faster ship cranes. For instance, as shown in Figure 11.4, for 6 AGVs the number of the loaded containers is almost the same for all different ship crane speeds.

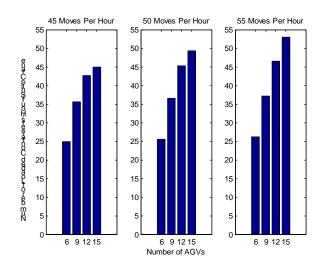
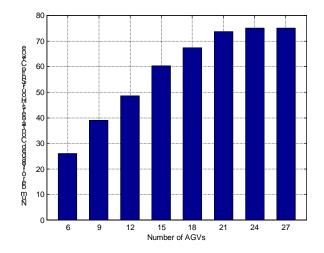


Figure 11.4: No. of loaded containers / hour / ship cranes vs. no. of AGVs for three identical ship cranes with different speeds 45, 50 and 55 moves per hour.

In addition, for a given ship crane speed, say 75 moves per hour as shown in Figure 11.5, as the number of AGVs increases the throughput of the yard increases until the saturation point is reached which is the point where the ship cranes reach their maximum speed. As expected, increasing the number of AGVs beyond the saturation point, around 21 AGVs in Figure 11.5, doesn't increase the throughput. Actually, by adding more AGVs in the yard, AGVs spend more time in the ship cranes' queues waiting to be served rather than traveling in the yard to do the next loading operation. Therefore from the practical point of view it is desirable to keep the number of AGVs as the lowest number for which maximum throughput is achieved. In this example the optimum number of AGVs is close to 21.



# Figure 11.5: No. of loaded containers / hour / ship crane vs. no. of AGVs (Ship cranes speed 75 moves/hr).

Figure 11.6 illustrates that the Average Idle Rate (AIR) of the AGVs has an increasing exponentiallike shape. That is, for small number of AGVs in the yard, say 6 or 9, the Idle Rate (IR) of an AGV which consists of the total time that an AGV stops due to the collision avoidance policy plus the total time it waits in the cranes' queues is very low. As the number of AGVs increases, the congestion rate of AGVs as well as the total time that an AGV spends in the cranes' queues goes up which leads to the increase of the AIR. In other words, increasing the number of AGVs in the yard results in decreasing the busy period of an AGV, and consequently increasing the AIR.

When the number of AGVs deployed in the container yard increases, more AGVs visit the yard and ship cranes; and consequently, the idle period of yard and ship cranes, as shown in Figure 11.6, decreases. As we discussed before the throughput of the ship cranes shown in Figure 11.5 reaches its maximum value, 75 containers per hour, for 21 AGVs in the yard. When the number of AGVs in the yard exceeds 21, the AGVs spend more time in the ship cranes' queues and make the ship cranes almost always busy. Figure 11.6 shows that the Average Idle Rate (AIR) of ship and yard cranes decreases before this point and is becoming almost constant at its minimum rate, after the saturation point.

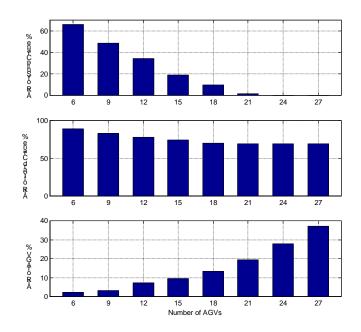


Figure 11.6: Average Idle Rates (AIR) in the yard for loading operations (Ship cranes speed 75 moves/hr).

### Simulation 2: Simulation of Automated Operations: Unloading

We simulated the automated yard for unloading operations which includes the transfer of containers from the ship to the yard. We divided the yard into two parts. The first part contains the upper 9 stacks (upper 18 rows) of the yard, and the second part contains the rest of the yard. The unloading containers from the ships are stored in the upper 3 storage stacks of each block since these stacks are close to the entrance to the yard. This choice is intuitive and is followed in most container terminals. In the simulation, 6, 9, 12, 15, 18, 21, and 24 AGVs were considered and the ship cranes speed was equal to 75 moves per hour.

Figure 11.7 shows the throughput of the yard for unloading operations. Comparing Figures 11.5 and 11.7 we can see that the throughput for the unloading operations is almost the same as that for the loading operations. For the large number of AGVs, say 21 and over, the saturation points for both yards are reached, that is the throughput of the ship cranes are at their maximum number, 75 moves per hour. The comparison also shows us that for the smaller number of AGVs in the yard, say 15, the throughput of unloading operations, 55 containers per hour per ship crane in Figure 11.7, is a little bit lower than that of the loading operations, 60 containers per hour per ship crane in Figure 11.5. The difference in the throughput is due to the longer distance that an AGV has to travel for unloading operations to reach the upper 9 stacks in the yard, which leads to decrease in the throughput of the yard.

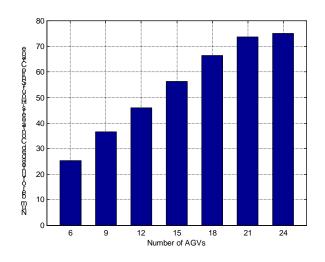


Figure 11.7: No. of unloaded containers / hour / ship crane vs. no. of AGVs (Ship cranes speed 75 moves/hr).

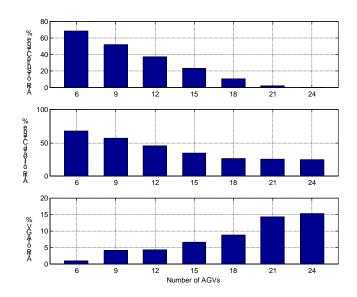


Figure 11.8: Average Idle Rates (AIR) in the yard for unloading operations (Ship cranes speed 75 moves/hr).

Figure 11.8 shows the Average Idle Rate (AIR) for ship crane, yard crane, and AGV. The AIRs in Figure 11.8 have similar shapes as those in Figure 11.6. Since an AGV travels longer distance to reach the upper 9 stacks the AIR of the AGVs is smaller for unloading operations than loading ones.

For the unloading operations, the ship cranes are not as busy as during the loading operations due to the fact that it takes more time for an unassigned AGV to go back to the ship crane area which results in a slightly increment in the AIR of the ship cranes. On the contrary, the AIR of the yard cranes for unloading operation reduces down noticeably as shown in Figure 11.8, since the yard cranes in the upper 9 stacks have to handle all the unloading operations. In our calculation for the AIR of the yard cranes associated with the upper stacks.

#### Simulation 3: Simulation of Automated Operations: Combined Loading/Unloading

We simulated the performance of the automated yard for combined loading and unloading operations. As in the unloading operation case, we divided the yard into two parts. The first part contains the upper 9 stacks (upper 18 rows) of the yard, and the second part contains the rest of the yard. The AGVs pick up containers from the first part of the yard (closer to the ship cranes) and transfer them to the ship cranes. The ship cranes unload the AGVs and load them with new containers – taken from the ship – which are brought and stored to the second part of the yard (closer to the exit from the yard).

Both loaded and unloaded AGVs may travel at the same time in the second part of the yard. Therefore, these portions of the transit lanes, which are located in the second part of the yard, are considered as Low Speed Zones for combined loading and unloading operations.

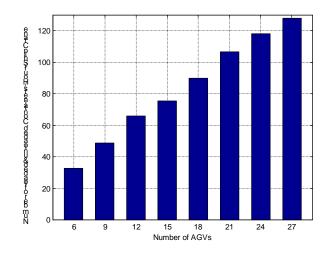


Figure 11.9: No. of combined loaded &unloaded containers / hour / ship crane vs. no. of AGVs (Ship cranes speed 75 moves/hr).

For combined loading/unloading simulation 6, 9, 12, 15, 18, 21, 24 and 27 AGVs are used. The ship cranes speed is assumed to be 75 moves per hour. The control logic for this part of simulations was the same as that in simulations 1 and 2, except that an AGV had to wait longer time under a ship crane due to delays introduced by the combined unloading/loading process. Thus, while in simulation 1, an AGV waits 25% of the time needed for the ship crane to complete the loading cycle, in this simulation, the vehicle waits 100% of the crane loading cycle to be loaded again.

Figure 11.9 shows the throughput of the yard for combined loading and unloading operations. Comparing Figure 11.9 with Figures 11.5 and 11.7 it is clear that the throughput of the combined operations yard has increased by at least 30%.

It is worth noticing that the throughput, in Figure 11.9, is not twice that of the loading or unloading operations shown in Figures 11.5 and 11.7, respectively. As explained before, in the case of combined operations, the Low speed zone is almost half of the yard which prevents unloaded AGVs to travel with their maximum speed in the second part of the yard. Another reason which accounts for not reaching twice the throughput of the loading and unloading operations is that in the case of combined operations an AGV stays longer under a ship crane to be served. That is, the ship crane has to complete the unloading operation first and then start to load the AGV with a new container.

Figure 11.10 illustrates the effect of the number of AGVs on the AIR of AGVs, ship cranes, and yard cranes. In the combined operations, we observe similar shapes of the AIRs as in the loading and unloading operations. Since the ship crane throughput has not reached its maximum value for the number of the AGVs deployed in the yard the yard has not reached the saturation point (see Figures 11.9 and 11.10); In this case more AGVs can be added in order to reach maximum throughput.

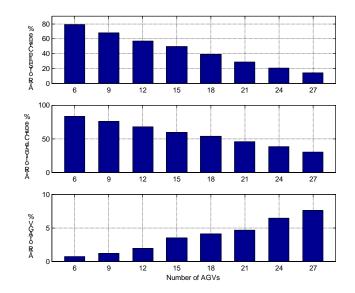


Figure 11.10: Average Idle Rates (AIR) in the yard for combined loading & unloading operations (Ship cranes speed 75 moves/hr).

### Simulation 4: Simulation of Manual Operations

In this part of simulations, we simulated the yard operations by using the data provided in [41,42] for manual operations. As we have already explained, this simulation study is needed to validate the simulation model using real yard operation. Similar to the first scenario used in [41], we used 18 hostlers whose average actual speed (AAS) is given in section 10.1. Despite the fact that the yard

layout of Figure 11.1 is slightly different from that of the NIT terminal and it has different number of yard gantry cranes, and different crane performance characteristics, our simulation results are realistic and compatible with the data provided in [41,42] due to the following factors:

- The time needed to load a hostler in the yard and to unload it by the ship crane is negligible compared to the time needed for the hostler to travel from the pick-up point in the yard to the drop-off point under the ship crane.
- Since the hostlers are traveling with average speed equal to AAS (defined in section 10.1) and the number of hostlers is the same as the ones considered in [41] the productivity of the two yards should be approximately the same despite the fact that the two yard layouts are different.
- The ship crane maximum throughput in our simulations is equal to 45 to 75 moves per hour, while the NIT crane throughput is 45 moves per hour. Again, this does not affect the compatibility of our results with the ones of [41,42] since in both cases the ship cranes do not reach the maximum throughput.

In Figure 11.11, we compare the throughput of the yard, for manual operations (simulation 4), automated operations for loading (simulation 1), automated operations for unloading (simulation 2) and automated operations for combined loading/unloading (simulation 3). In all simulations 18 vehicles were deployed and the speed of the ship cranes is assumed to be 75 moves per hour.

From Figure 11.11 it is clear that the use of automation employing AGVs could increase the throughput of the yard. The throughput of about 28 containers per hour per ship crane using manual operations involving 18 hostlers can be more than double by using 18 AGVs. Since high utilization of a container terminal is a generally accepted goal in maritime container terminal industry, this simulation shows that a very high utilization can be achieved by deploying AGVs in container terminals.

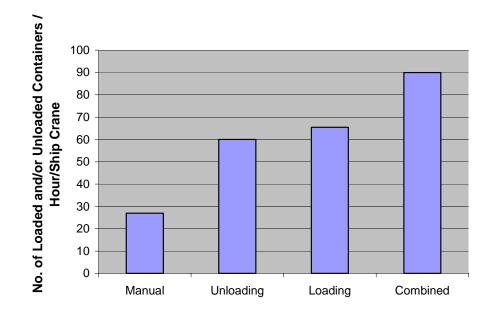


Figure 11.11: Comparison of throughput for manual, automated unloading, automated loading and automated combined loading & unloading operations. (Number of hostlers or AGVs 18, Ship cranes speed 75 moves/ hr).

The crucial problem of choosing the number of AGVs in the yard has already been discussed and illustrated in Figures 11.4 through 11.10. Choosing the optimum number of AGVs for best performance and maximum throughput is an important problem from the cost and performance point of view. We formulate and investigate the effect of the number of the AGVs on the productivity of the yard by using the following variables:

 $C_1$  as the Average Idle Rate (AIR) of the ship cranes,  $C_2$  as the Average Idle Rate (AIR) of the yard cranes, and  $C_3$  as the Average Idle Rate (AIR) of the AGVs.

Assume that the performance index of the yard, J, for loading operations is defined as the linear combination of  $C_1$ ,  $C_2$ , and  $C_3$  as follows:

$$J = \sum_{i=1}^{3} W_i \times C_i$$

where  $W_i$  is the weighted penalty for  $C_i$ . Our objective is to find the number of the AGVs in the yard which minimizes the performance index *J*. Figure 11.12 illustrates the value of the performance index, *J*, for different values of the weighted penalty vector  $\underline{W}^{\mathrm{T}} = (W_l, W_2, W_3)$ .

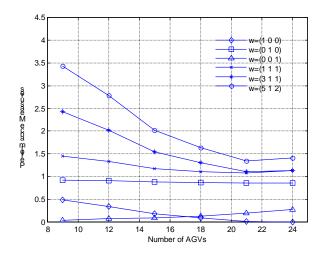


Figure 11.12: Yard performance indexes.

As Figure 11.12 shows the more AGVs we have, the more containers can be loaded into the ship; that is, the maximum number of AGVs, here 24, minimizes the performance index J with  $\underline{W}^{T} = (1,0,0)$ . For this choice of  $\underline{W}$  we minimize the idle time of the ship cranes only. As a result the larger the number of AGVs the smaller the J, i.e., the smaller the amount of time the ship remains idle. Obviously as we reach the capacity of the ship cranes the number of AGVs no longer has any effect on the performance index. For other performance indices that take the AIR of yard cranes and AGVs into account, the best performance is achieved with a smaller number of AGVs. As it is shown in Figure 11.12, and for  $\underline{W}^{T} = (3, 1, 1)$  or  $\underline{W}^{T} = (5, 1, 2)$ , the number of AGVs which minimizes the performance index is around 21. More elaborate performance index and/or cost functions could be used to choose the number of the various equipment subject to various constraints, that may include maximum cost, minimum acceptable performance, etc. Our future work in this area will involve the development of such performance indices and cost functions in an effort to optimize the choice of equipment and operations.

## **12. AUTOMATED CONTAINER YARD USING LINEAR MOTOR-CONVEYANCE SYSTEMS**

The layout of the automated container yard using linear motor-conveyance systems is shown in Figure 12.1. The dimensions of the yard are 700 feet width and 1400 feet length.

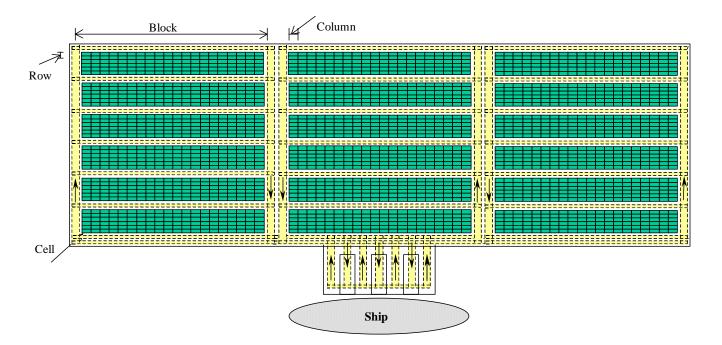


Figure 12.1: The layout of the automated container yard.

The yard consists of three major parts, which thereafter will be called *blocks*: left, middle and right. Each block has six storage stacks and each stack has 20 *columns*. In each stack, there are also 6 *rows*. We assume that each cell can be stacked with up to three containers. Therefore, the capacity of the yard is 2,160(cells)x3 = 6,480 TEUs (Twenty-foot Equivalent Unit).

Working roads (aisles) separate stacks from each other, while *transit roads* (aisles) separate blocks from each other. We consider the roads on the left border, right border (vertical roads), and the roads adjacent to the ship cranes (horizontal roads) to be the transit roads. The working roads are equipped with a single one-way guiderail, while the transit roads are equipped either with 1 or 2 one-way guiderail(s). All guiderails are unidirectional and the direction of movement is fixed (i.e., we cannot change the direction during operation of the yard). Arrows in Figure 12.1 show the directions of movement for vertical transit roads; the directions are chosen so that the travel distance of the loaded shuttles is minimum. To prevent heavy congestion and blocking, we reserve the working roads for drop-off and pick up activities, while the transit roads are used only to reach to a specific working aisle or to the ship crane area.

The container shuttles (carts) are designed to make right or left angle turns. This is accomplished by designing the shuttles such that the wheels can be turned 360 degrees individually. At the corners of the

track the wheels rest on four "turntables" which are turned 90 degrees, so that the shuttle can continue in its new path.

We also assume that each stack has only one *yard crane*, and this crane is responsible to load a container to/from the adjacent working lane. We refer to the first working lane above a particular stack in Figure 12.1 as the adjacent working lane. We assume that a yard crane serves vehicles based on the first come first served rule (FCFS). There are also three *ship cranes* on the yard. Yard cranes are responsible for loading and unloading the container shuttles, whereas the ship cranes are responsible for loading containers to/from the ships and from/to the shuttles.

In case where there is a shuttle waiting to be unloaded by a ship crane, a queue of shuttles is formed. We assume that the shuttles under the crane will be served within a fraction of time needed for a ship crane spreader to fetch a container located underneath the crane.

For the purpose of checking the control logic algorithms for the shuttles, we assume the following as characteristics of the equipment in the yard:

Performance of the yard cranes: The performance characteristics for rubber-tired gantries given in Table 2.11 are used. Speed of the ship cranes: 75 moves/hour. Speed of loaded shuttles: 5 miles/hour. Speed of unloaded shuttles: 10 miles/hour. Time for shuttles' wheels turning: 5 seconds.

The speeds of the ship cranes and shuttles are based on current and expected performance of advanced cranes and shuttles which are either in use or in the stage of conceptual design.

### **12.1 Control Logic for Container Shuttles**

When a shuttle (cart) becomes available, a container in the yard is chosen randomly to be picked up and is assigned to the shuttle. Meanwhile, the container identification number is added to the corresponding yard crane's queue. If there is no other container in the yard crane's queue, the corresponding yard crane starts the process of loading the container by moving laterally and longitudinally towards it, followed by the loading operation. This procedure saves time in loading operation, since the yard crane gets ready while the shuttle is on its way towards the container.

Once a shuttle is assigned to pick up a container, the position of the container is determined by its block number, stack number, and column number. Since all paths are unidirectional the path towards a container is uniquely determined. As mentioned before, the directions of the guide paths are chosen such that the travel distance for a loaded shuttle to the ship crane area is minimum.

When the shuttle arrives at the ship crane area, it selects one of the ship cranes. In our simulation, we compare two different scenarios:

- 1. The ship crane is chosen randomly,
- 2. The ship crane is chosen based on:

- a) the minimum number of shuttles in a ship crane's queue, and/or
- b) the minimum traveling distance between the shuttle and a ship crane.

In the second scenario, when a shuttle applies policy 2.a to find the best ship crane, it is possible that two or more ship cranes queues have the same minimum number of shuttles. In that case the shuttle will apply policy 2.b to select the appropriate ship crane.

The control logic of the linear-motor shuttles must be able to resolve possible conflict and deadlocks in the yard. For conflict resolution, we simply use a *safety zone* policy around each shuttle such that no other shuttles are allowed to enter the zone. This policy prevents any lateral or longitudinal collision between shuttles. For deadlock resolution, first we should investigate the situation where a deadlock may occur.

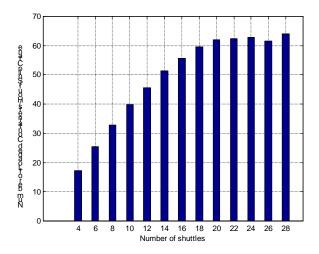
As it is mentioned before, when a container is chosen to be picked up by a shuttle, it will be added to the corresponding yard crane queue. When two or more containers in one stack have been assigned to shuttles, it is possible that the shuttles do not arrive at the working aisle according to the order of containers in the queue. For instance, assume that two containers x and y are in a yard crane's queue, and container x is in the head of queue. The corresponding crane has already started the process of moving laterally and longitudinally towards the container or it may have even finished picking up container x and is waiting for shuttle-x to arrive. If shuttle-y happened to reach the working aisle before shuttle-x, there would be a deadlock. To prevent this type of deadlock, we reassign the containers to the shuttles as soon as the first shuttle arrives at the corresponding working aisle. That is shuttle-y is assigned to x, if y arrives earlier. In such case, shuttle-x is assigned to container y instead.

#### **12.2 Simulation of Control Logic**

The software package "Matlab" is used to perform the control logic simulation. Two different scenarios have been investigated and compared for automated yard performing loading operations. In the first simulation, a ship crane is randomly chosen by a shuttle, and in the second simulation, a ship crane is chosen based on the minimum number of shuttles in the ship crane queue as well as the minimum travel distance between the shuttle and the ship crane. In each simulation several performance measures have been utilized and compared.

#### Simulation 1: Simulation of randomly selected ship cranes.

The automated yard operations are simulated by using different number of shuttles (carts), assuming that a shuttle chooses a ship crane randomly. More precisely, we deployed 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, and 28 shuttles in the yard. To ensure that the automated yard system has reached its steady state, we simulated 3 hours of the yard loading operations. Figure 12.2 shows the throughput of the yard.



# Figure 12.2: No. of loaded containers / hour / ship crane vs. no. of shuttles. Ship cranes are randomly selected, (Ship cranes speed 75 moves/hr).

As the number of shuttles in the yard increases, as shown in Figure 12.2, the ship cranes throughput increases provided that there is sufficient number of shuttles. When the number of shuttles in the yard increases to 20, the throughput of the ship cranes reaches its saturation point. That is increasing the number of shuttles beyond this point doesn't increase throughput any more. The policy of randomly selecting ship cranes adds uncertainty to the system, as it may be seen from the decrement of the throughput when 26 shuttles are deployed (Figure 12.2). We elaborate more about this phenomenon when we discuss the results of simulation 2 in this section.

As Figure 12.3 illustrates the Average Idle Rate (AIR) of the ship cranes, the yard cranes, and the shuttles have similar shapes, as those in section 12.2 (simulation 1), so the very same discussion is valid here too.

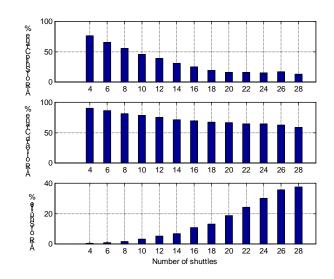


Figure 12.3: Average Idle Rates (AIR) in the yard for loading operations, ship cranes are randomly selected, (Ship cranes speed 75 moves/hr).

# <u>Simulation 2:</u> Simulation of selecting a ship crane based on minimum number of shuttles in the ship crane's queue.

The automated yard operations are simulated using different number of shuttles (carts), assuming that a shuttle selects a ship crane based on the minimum number of shuttles in the queue as well as the minimum distance between the shuttle and ship crane. We deployed 4, 6, 8, 10, 12, 16, 18, 20, 22, 24, and 26 shuttles in the yard. To make sure that the automated yard system reaches its steady state, the simulations were run for at least 3 hours.

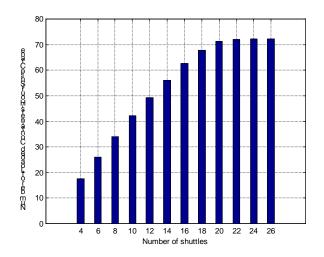
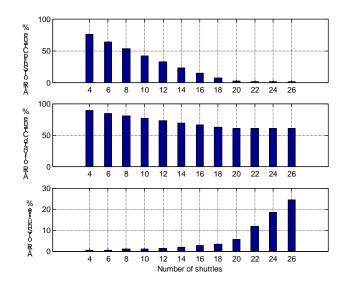


Figure 12.4: Throughput of ship cranes for loading operations; Ship cranes are selected based on the minimum number of shuttles in the ship cranes' queues; (Ship cranes speed 75 moves/hr).

As shown in Figure 12.4, increasing the number of shuttles in the yard results in an increase in the yard throughput. However, the maximum throughput is about 72 containers per hour per ship crane which is very close to the maximum number, 75, that is, the crane's maximum capacity. The difference is due to computational errors in the simulation.

Figure 12.5 shows several other performance measures such as the Average Idle Rate (AIR) of the ship cranes, yard cranes, and shuttles in the yard. Applying the minimum ship crane queue policy not only makes the container yard system more robust and reliable, but it also results in improvement of the yard throughput by about 20% (compare Figure 12.2 with Figure 12.4). It seems that this policy provides feedback to the system leading to better robustness and throughput. The policy also affects the AIR of the ship cranes, yard cranes and shuttles in the yard, as shown in Figure 12.5. As the number of the shuttles in the yard increases the effect of this policy becomes more tangible and observable. In some cases the average idle time reduces down to 50% due to this policy (compare Figure 12.3 and 12.5, AIR of ship crane for 20 or more shuttles).



# Figure 12.5: Idle rates in the yard for loading operations; Ship cranes are selected based on the minimum number of shuttles in ship cranes' queues; (Ship cranes speed 75 moves/hr).

Another important issue to be addressed is the number of shuttles in the yard. Choosing the optimum number of shuttles for best performance and maximum throughput is an important problem from the cost and performance point of view. To demonstrate the effects of the number of shuttles on several performance measures, we use the following variables

- $C_1$  as the Average Idle Rate of the ship cranes,
- $C_2$  as the Average Idle Rate of the yard cranes, and
- $C_3$  as the Average Idle Rate of the shuttles in the yard.

Assume that the performance index of the yard, J, is defined as the linear combination of  $C_1$ ,  $C_2$ , and  $C_3$  as follows:

$$J = \sum_{i=1}^{3} W_i \times C_i$$

where  $W_i$  is the weighted penalty for  $C_i$ . Our objective is to find the number of shuttles in the yard which minimizes the performance index. Figure 12.6 illustrates the value of performance index, J, for different values of weighted penalty vector  $\underline{W}^{T} = (W_1, W_2, W_3)$ .

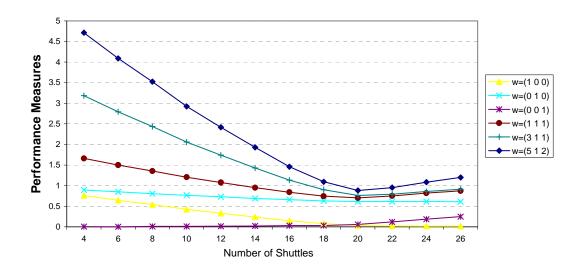


Figure 12.6: Yard performance indexes.

As Figure 12.6 shows the more shuttles we use, the more containers can be loaded into the ship; that is the maximum number of shuttles, here 26, minimizes the performance index J with  $\underline{W}^{T} = (1,0,0)$ . To be more realistic and precise, we may also want to minimize the AIR of the yard cranes and the shuttles. As Figure 12.6 shows that for  $\underline{W}^{T} = (3, 1, 1)$  or  $\underline{W}^{T} = (5, 1, 2)$ , the optimum number of shuttles which minimizes the performance index is 20. A more elaborate performance index with constraints may be used to optimize the number and type of equipment used and maximize performance. In our future work we plan to concentrate on extending these preliminary results to more complex but realistic performance indices and cost constraints.

## **13. AUTOMATED CONTAINER YARD USING AS/RS**

In this section we present a conceptual Automated Storage and Retrieval Structure (AS/RS), and develop a simulation model to evaluate its throughput.

### 13.1 Description of Proposed AS/RS

The proposed AS/RS is shown in Figure 13.1.

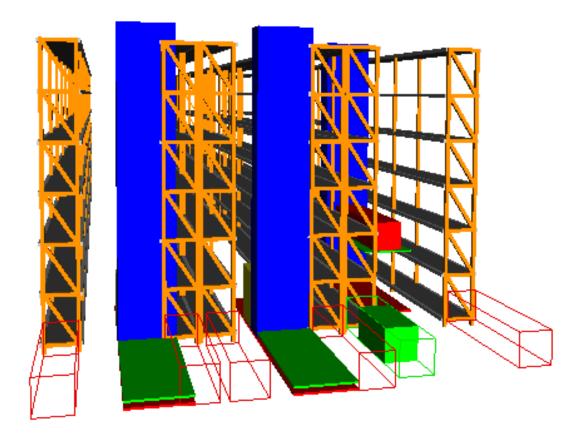


Figure 13.1: The proposed Automated Storage and Retrieval System.

The proposed AS/RS consists of three parallel substructures referred to as *modules*. Each module consists of two parallel *racks* used for the storage of containers and an *aisle* between the racks that is used for the movement of the Storage and Retrieval Machine (SRM). The SRM is the loading/unloading equipment used for loading and unloading containers to and from the AS/RS. Each aisle is equipped with a guide-rail parallel to the racks used for the horizontal movement of the SRM. Each rack is 6 levels high and consists of 60 *cells*, ten cells per level. The cells are used for the storage of forty feet containers and their dimensions are as follows: (i) length: 42 feet, (ii) depth: 12 feet and (iii) height: 12 feet. The width of the aisle is 16 feet, which brings the total width of each module equal to 40 feet. The above numbers bring the total area required by each module equal to 18,400 square feet,

while the total capacity of each module is 120 forty-foot containers, and therefore the total capacity of the whole AS/RS structure is 360 forty-foot containers or 720 TEUs (Twenty-Foot Equivalent Units). At the one end of each aisle a Pick up and Delivery Station (PD station) is located. The containers are temporarily located on the PD station, where they are picked up by either the SRM or a yard loading/unloading equipment (e.g. an AGV).

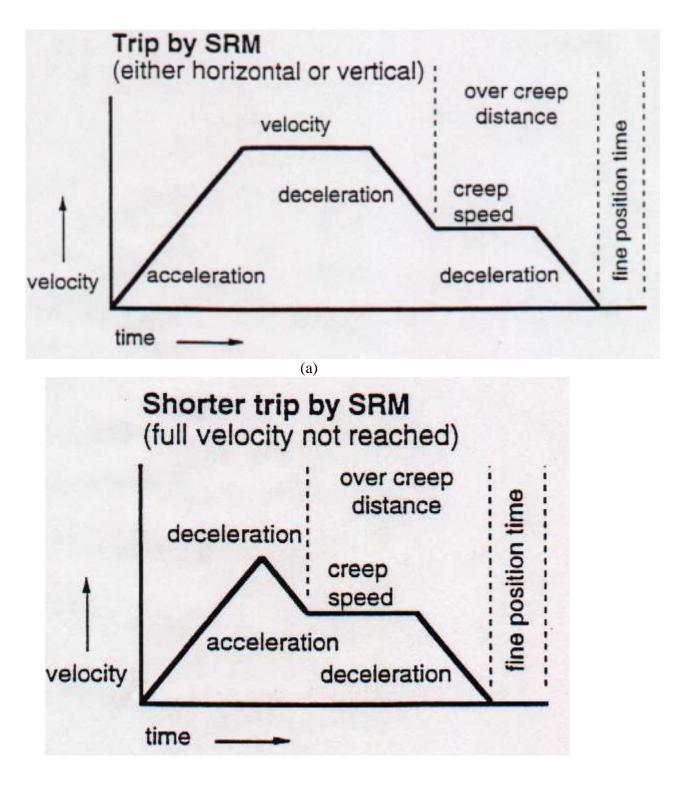
The SRM is a specially designed straddle carrier used for loading and unloading the containers to and from the cells of the AS/RS. The details of the SRM are presented in the next subsection. The SRM can be used either in Single Command (SC) mode or Double Command (DC) mode. When in SC mode, the SRM picks up a container from the PD station, delivers it to an empty cell and returns empty to the PD station. The opposite procedure holds for unloading. In the case of DC mode, the SRM picks up a container from the PD station, delivers it to an empty cell, moves to a loaded cell, picks up the container from the cell and delivers it to the PD station.

The design and construction of the storage racks to support the 40,000 lbs. containers 6 levels high is an interesting design problem. No actual cost data is available. The rough-cut cost estimate is around \$2,500,000 per module.

### 13.1.1 The Proposed Storage and Retrieval Machine (SRM)

The conceptual SRM is a specially designed straddle carrier. It is mounted on guide-rails where it can move in the horizontal (parallel to the racks) direction. The platform of the SRM moves in the vertical direction and it is equipped with a specially designed *shuttle* for loading and unloading the containers to and from the cells or the PD station. A SRM of approximately 80' high, designed to handle loads of 40000 lbs., would likely have a dead weight of approximately 150,000 lbs. Including the live load, the total load could approach 200,000 lbs.

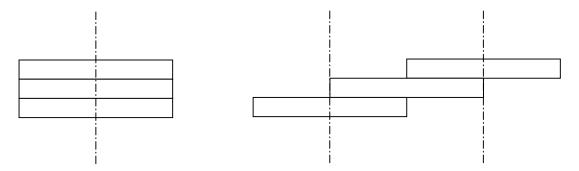
In our simulation model it is assumed that both horizontal and vertical trips are accomplished simultaneously, although one of the trips may last longer. Moreover, we assumed that the velocity profiles for horizontal and vertical trips are similar. The typical velocity profiles of the horizontal and vertical trips are shown in Figures 13.2. A typical trip involves increasing the velocity using constant acceleration until the maximum allowable velocity is reached, move with the maximum allowable velocity for some time interval, and decreasing the velocity with a constant deceleration until the SRM is within *creep distance* from the destination point. When the distance between the SRM and the destination point is equal to the creep distance the velocity follows the profile shown in Figure 13.2 in order to make sure that the SRM does not miss the destination point. An extra time may be spent for fine positioning of the SRM with the cell or the PD station.



(b)

Figure 13.2: Velocity profiles of horizontal and vertical movement of SRM.

When the SRM is fine positioned both in horizontal and vertical direction with the cell or the PD station, the specially designed shuttle is used for loading or unloading the container. This conceptual shuttle consists of three sections: base, intermediate, and top slide. The base is fixed to the vertical carriage. The intermediate extends by half of its width. The top slide is capable of extending one load width to either side of the aisle. This mechanism is very similar to a 3-section telescope. It can be stretched out full length or collapsed back to its minimum dimensions. A simple representation is given in Figure 13.3.



# Figure 13.3: Representation of the conceptual shuttle used for loading and unloading the containers.

### **13.2 Performance Measures**

The measure used for assessing the performance of the proposed structure is the *cycle time* measured in moves per hour. Similar to the ship cranes, a *move* is defined as the average time required for the SRM to acquire a container from the PD station, deliver it to a cell and return to the PD station to acquire a new container.

### 13.3 Estimates of Performance Characteristics of the SRM

In order to assess the performance characteristics and the cost of the proposed conceptual SRM the following SRM manufacturers have been contacted:

- HK (Harnischfeger Eng. & Kenway) Systems
- ACCO Systems
- Jervis B. Webb Co.
- Transact & Seaport

After discussions with people from these companies we estimated that the cost of the proposed conceptual SRM would be approximately \$1,000,000. Regarding the performance characteristics of the SRM there was a variety of different estimates presented below:

	Minimum Estimate	Maximum Estimate
Speed (loaded) in ft/min	300	600
Speed (empty) in ft/min	400	700
Acceleration in $ft/sec^2$	1	3
Deceleration in ft/sec <sup>2</sup>	1	3
Creep speed in ft/min	150	300
Creep distance in feet	0	10
Fine Positioning Time in sec	0	5

Table 13.1: Performance Characteristics of the Horizontal Trip of the SRM

Table 13.2: Performance Characteristics of the Vertical Trip of the SRM

	Minimum Estimate	Maximum Estimate
Speed (loaded) in ft/min	75	150
Speed (empty) in ft/min	90	175
Acceleration in ft/sec <sup>2</sup>	0.4	1
Deceleration in ft/sec <sup>2</sup>	0.4	1
Creep speed in ft/min	25	50
Creep distance in feet	0	3
Fine Positioning Time in sec	0	2

Finally the shuttle pick up and set down time was estimated to be in the range of 15 to 30 seconds.

### **13.4 The Simulation Model**

A simulation model was developed for the evaluation of the proposed AS/RS. Since all three modules are identical only one of the modules was simulated. The simulation policy was as follows:

We assumed a stochastic model for the arrival of containers to the PD station. Namely, we assumed that the containers arrive to the PD station randomly according to a Poisson distribution with arrival rate equal to  $\lambda$ . A similar stochastic model was used for the loading of the containers from the PD station to the yard shuttles. Once there is a container in the PD station, an empty cell is randomly assigned and the SRM picks up this container from the PD station and delivers it to the assigned cell. In the case of single command (SC) mode, the empty SRM returns back to the PD station and picks up the next container. In the case where there is no container in the PD station, the SRM waits until one arrives. The difference in the case of DC mode is that the SRM, after it delivers the container to the assigned empty cell, it moves to a randomly assigned loaded cell, picks up the container, delivers it to the PD station, and waits until the container is picked up by a yard shuttle and a new container is loaded to the PD station. The simulation model does not allow arrival of containers to the PD station while the SRM is performing the loading/unloading operation.

The arrival rate  $\lambda$  defines the throughput of all the operations that involve loading/unloading containers to/from the PD station, moving them to/from the ship cranes and loading/unloading them to

the ship. In our simulations, we made sure that  $\lambda$  is always larger than the throughput of the AS/RS module, so that the total time the SRM is idle (either waiting empty in an empty PD station or waiting loaded in a loaded PD station) is negligible.

The travel times for the SRM are calculated using the velocity profiles given in section 13.1.1. The range of values of the parameters (velocity, acceleration, creep speed, etc.) that specify these velocity profiles are given in Tables 13.1 and 13.2 of the previous section. In order to evaluate the AS/RS module performance with respect to the whole range of parameters given in Tables 13.1 and 13.2 a number of different simulation experiments was performed as detailed in the next section.

#### **13.5 Simulation Results**

Numerous experimental simulation runs, each with tens of replications were performed, covering the whole range of the model parameters. The calculated throughputs for a single AS/RS module were as follows:

Mode	Worst Case Scenario Throughput (moves per hour)	Best Case Scenario Throughput (moves per hour)
Single Command	23	45
Double Command	16	33

Table 13.3 Throughput of a Single AS/RS Module

In the above Table, the worst case scenario refers to the case where the worst parameters given in Tables 13.1 and 13.2 are used in the simulations (i.e., smallest velocities, accelerations, deceleration and creep speeds and the largest creep distances and fine positioning times), while the best case scenario refers to the case where the best parameters in Tables 13.1 and 13.2 are used in the simulations.

Sensitivity analysis with respect to a single parameter was also performed by changing one of the parameters and keeping the rest constant and equal to the ones of the best case scenario. Figure 13.4 plots the percentage decrease in throughput for the SC mode case versus the percentage decrease in horizontal and vertical speed, shuttle loading time and horizontal and vertical acceleration/deceleration (in the simulations both the horizontal and vertical speeds or accelerations were decreased by the same percentage). As it is seen in Figure 13.4, the horizontal and vertical speeds and the shuttle loading times are very crucial for the overall throughput, while the throughput is less sensitive to changes with respect to acceleration or deceleration. From Figure 13.4 it is seen that a decrease of either horizontal and vertical speed or shuttle loading time by x% results in a decrease of throughput that is approximately equal to x%. In other words, the SRM and shuttle speeds critically affect the throughput.

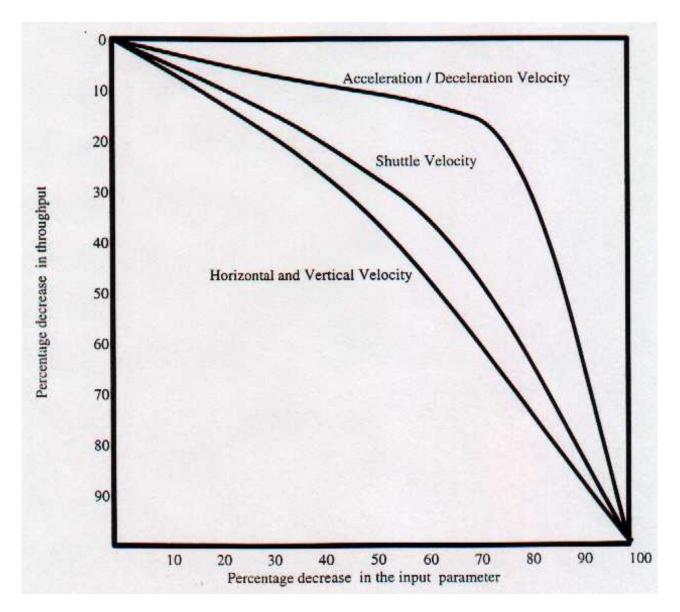
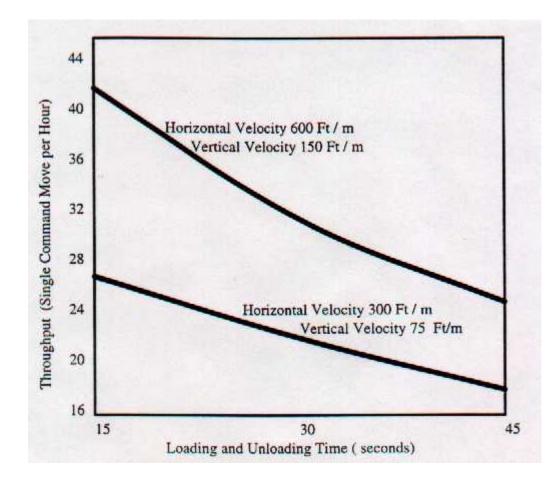


Figure 13.4: Percentage decrease in throughput versus percentage decrease in horizontal and vertical speed, shuttle loading time and acceleration/deceleration.

Figure 13.5 presents plots for the throughput in the case where the best case and the worst case speeds are chosen versus the shuttle loading/unloading time for the case of SC mode.



# Figure 13.5: Throughput versus shuttle loading and unloading time. In the upper plot the best case speeds are used while in the lower curve the worst case velocities are used.

As it seen, in both cases the shuttle loading and unloading time affects considerably the throughput.

### **13.6 Conclusions**

An Automated Storage and Retrieval Structure (AS/RS) concept has been proposed and evaluated by means of simulations. Estimates of costs and performance characteristics have been given based on discussions with AS/RS manufacturers. A critical component of the proposed AS/RS structure is the specially designed straddle carrier, or SRM, which uses a telescope-like shuttle for picking and delivering containers. The simulations showed that a single AS/RS module throughput ranges from 23 to 45 moves per hour for single command mode and from 16 to 33 moves per hour for double command mode, depending on the performance characteristics of the SRM. The SRM horizontal and vertical speeds as well as the shuttle loading and unloading times critically affect the throughput. Nevertheless, even if the worst case SRM parameters are assumed the total throughput of the proposed three-module AS/RS is about 70 moves per hour. Therefore if ship cranes capable of 75 or more moves per hour are used and automated guidance vehicles are used for picking and delivering the containers to/from the PD station, the terminal throughput could exceed 70 moves per hour.

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