CONTAINER TERMINALS USING AUTOMATED SHUTTLES DRIVEN BY LINEAR MOTORS

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Abstract: The emergence of huge containerships together with the scarcity of yard land put an enormous pressure on authorities to adopt advanced technologies to increase the throughput of current container terminals. Automated Container Terminals (ACT), using advanced material handling technologies, are recently considered as candidates for increasing the performance of manually operated yards. In this paper, an ACT that employs Linear Motor Technology is designed. A multi attribute decision making method is employed to find the optimum number of conveyor shuttles in the terminal. Simulations demonstrate a double increase in the throughput of ACT compared to the similar one with manual operations. Copyright © 2000 IFAC

Keywords: Automation, Automated guided vehicles, Linear motors, Multiple-criterion optimisation, Decision making, Marine systems.

1. INTRODUCTION

World container trade experienced a 9.5 percent growth per year between 1991-1995. In U.S., though it was not as rapid as its global one, the growth was around 6.0 percent per year during the same period. It has been estimated that U.S. container trade will experience a 7.8 percent annual growth through the year 2010. To handle this amount of freight and to reduce the cost per TEU slot, shipping companies are forced to order faster, larger and deeper ships. The scarcity of available lands for yard expansion is another issue of concern to port authorities. Many ports have already reached the limitation on landside pier area expansion (Vickerman, 1998).

Booming in the world trade, new massive containerships, and scarcity of the yard land put an enormous pressure on port authorities to use advanced cargo handling technologies and automation in order to increase the throughput of the current container terminals.

Automated Guided Vehicles (AGV) and Linear Motor Conveyor systems are among the technologies recently been considered for cargo handling. The Delta terminal at the Port of Rotterdam has deployed Automated Guided Vehicles (AGV) during the last 5 years, and prototype of linear motor conveyor system has been constructed and tested in Eurokai Container Terminal, Hamburg (Ioannou, et al.,1999).

The purpose of this paper is to design an automated container yard using conveyor shuttles propelled by linear motor technologies. The promise of employing linear motor technologies lies in its very high positioning accuracy, reliability, robustness of equipment, and very low operational costs. A control logic algorithm is designed to resolve any conflict as well as to ensure deadlock-free and smooth traffic in the automated yard. To optimize the number of conveyor shuttles in the port, a Multi Attribute Decision Making (MADM) method is employed.

Simulation results demonstrate that the container yard throughput can be doubled (when compared with that involving manual operations) by automating the yard using shuttles driven by a linear motor technology.

2. DEFINITIONS

The following definitions are adopted and used throughout the paper:

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**Definition 1:** Shuttle. A shuttle is referred to the conveyor cart propelled by linear motor technology and deployed in the yard to transfer containers.

**Definition 2:** Busy Period of a Shuttle. A shuttle is called to be in its busy period if it is in one of the following states: (1) Being served by either a quay crane or a yard crane, (2) Travelling in the yard to load/unload an assigned container.

**Definition 3:** Busy Period of a Quay Crane (QC)/Yard Crane (YC). A QC/YC is said to be in its busy period if it is occupied with the loading/unloading task.

**Definition 4:** Idle Period of a Shuttle, a QC, or a YC. A shuttle, a QC, or a YC is said to be in its idle period when it is not in its busy period.

**Definition 5:** Idle Rate (IR). The idle rate of machine \( i \), \( IR_i \), is defined as:

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

**Definition 6:** Average Idle Rate (AIR). The average idle rate of \( N \) similar machines is defined as follows:

\[
AIR = \frac{\sum_{i=1}^{N} IR_i}{N}.
\]

**Definition 7:** Throughput. The average number of containers being loaded/unloaded per hour per QC is referred to as the throughput of the terminal.

### 3. MANUAL CONTAINER YARD

The Norfolk International Terminal (NIT) is used as a base scenario for manual operations. It is equipped with three QCs 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 and the containers in this area are mounted on chassis. 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 tractors (hostlers).

Towery, et al. (1996) performed a simulation study in order to compare different scenarios of manually operated yard equipment at NIT. They used 7 rubber tired gantry cranes at the gantry crane storage area, 18 hostlers for serving the QCs and 7 hostlers for the wheeled storage area. Their simulation study showed that the average productivity achieved under this scenario is 28 moves per hour per QC.

According to analysis presented in (Larsen and Moses), despite the fact that the average operating speed of manually-operated hostlers is about 17 mph (7.6 m/sec), a hostler moves approximately 6 containers/hour. That is the average time for a move, which thereafter is called Average Move Time, is about 10 minutes. 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 0.284 mile (460 m), it can be concluded that the Average Actual Speed (AAS) in mph of the hostler can be approximated as follows:

\[
AAS = \frac{\text{Average Distance}}{\text{Average Move Time - Loading Time - Unloading Time}} = \frac{0.284}{0.167 - T_l - T_u}
\]

where \( T_l \) = Loading Time, and \( T_u \) = Unloading Time are the times (in hours) needed for the hostler to get loaded by the YC and get unloaded by the QC.

### 4. AUTOMATED CONTAINER YARD

#### 4.1 Linear Motor 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 unrolled, flattened stator moves a metal flat blank, which is placed above the stator, as though it is a rotor (Blease, et al., 1989). 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).

Linear motor systems have several attractive characteristics: The motors are very reliable, and last a long time. Platforms, which are conveyed via linear motor technology, are unmanned, and have very few moving parts. The wheel assembly on the platform is the only moving parts. Also, no power is required onboard the platform.

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 scalable to larger tasks. A system such as this could be ideally suited for port and terminal operations. Once the necessary infrastructure is in place, and the shuttles 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 technical feasibility of employing this technology in container terminal port was proved at Eurokai Container Terminal in Hamburg, Germany, where a pilot of fully operated container yard was constructed in 1997.
4.2 Yard Configuration

The layout of proposed automated yard is designed in such a way that it is similar to the currently operational yards (see Fig. 1). The dimensions of the yard are assumed to be 700 feet (213.36 m) width and 1400 feet (426.72 m) length.

The yard consists of two major parts: storage and dock area. Storage area consists of three blocks, and each block has six storage stacks. In each stack there are 20 columns and 6 rows which results in 2,160 cells in the yard. It is assumed that each cell can be stacked with up to three containers. Therefore, the capacity of the yard is 6,480 TEUs (Twenty-foot Equivalent Unit).

Each pair of dotted lines, in Fig. 1, represents a road in the yard. In order to have smooth traffic for transferring containers within the yard, the roads are divided into two types: working road (WR) and transit road (TR). In Fig. 1, all transit and working roads for the left block in the yard are marked by T.R. and W.R., respectively. To prevent heavy congestion and blocking, WRs are reserved for drop-off and pick up activities, while TRs are used only to reach to a specific WR or to the dock area. Shuttles are not allowed to travel along a particular working road unless they need to perform the pick up or drop off task in that road. All roads, in the yard, are considered to be unidirectional and are equipped with a one-way guiderail. The direction of the movement in each road is fixed and cannot be changed during the yard operations.

In the storage area, a YC is assigned to each stack. As the top view of the container yard in Fig. 1 shows, there are two adjacent lanes to each storage stack: one at the top, and the other one at the bottom. The first WR above each stack is referred as the corresponding adjacent WR.

To make our proposed container yard comparable to the NIT, three QC’s are deployed in the dock area. YCs are responsible for loading/unloading containers from/to a storage stack to/from the shuttles in the corresponding adjacent WR, whereas the QC’s are responsible for loading and unloading containers to/from the ships. It is assumed that YCs and QC’s serve shuttles based on the first come first served rule (FCFS).

Assuming that there is no congestion on the route, let’s model the path of Fig. 2a by a graph consisting of nodes connected set of arcs, as shown in Fig. 2b. The nodes represent the intersections and loading points on the path. Node 1 is the entrance/exit point to the block. Node 4, is the pick up node representing the location of the YC. Other nodes are illustrating the intersection points.

An arc represents the guide rails that a shuttle can take in moving from a node to another node. Associated with each arc is the distance between the two end nodes. The problem here is to assign the direction to each arc such that the total time that a particular shuttle needs to travel from node 1 to node 4 and goes back from node 4 to node 1 is minimum. Let’s define \( d_{ij} \) as the distance between two neighboring nodes \( i \) and \( j \). The distance between two neighboring nodes are fixed and does not depend on the direction of the movement, i.e. \( d_{ij} = d_{ji} \). Let’s assume that the speed of the loaded shuttle, \( v_l \) is less than that of the unloaded one, \( v_u \), i.e. \( v_u > v_l \). The problem of finding the shorter time direction can be formulated as follows:

\[
\min \left( t_{load} + t_{unload} \right)_{clockwise}, \left( t_{load} + t_{unload} \right)_{counter \_clockwise} \tag{2}
\]

Let’s define \( d_{12} = d_{1234} + d_{23} + d_{34} \) and \( d_{34} = d_{341} + d_{45} \). Knowing that \( d_{ji} = d_{ij} \), Eqn. 2 can be written as follows:

\[
\min \left( \frac{d_{1234}}{v_s} + \frac{d_{34}}{v_l} \right) = \left( \frac{d_{34}}{v_u} + \frac{d_{1234}}{v_l} \right) \tag{3}
\]

For any typical pick up point such as \( X \) in Fig. 2a \( d_{34} = d_{35} \) and \( d_{12} \geq d_{45} \) which results in \( d_{1234} = d_{35} + d_{45} \geq d_{34} \). Knowing that \( (1/v_u) > (1/v_l) > 0 \), the following inequality is obtained:

\[
(d_{1234} - d_{45}) \times \left( \frac{1}{v_l} - \frac{1}{v_u} \right) > 0 \tag{4}
\]

which results in,

\[
(d_{1234} \times \frac{1}{v_j} + d_{45} \times \frac{1}{v_u}) > (d_{1234} \times \frac{1}{v_u} + d_{45} \times \frac{1}{v_j}) \tag{5}
\]
Fig. 2: (a) The path to cell X in the container yard, (b) the associated graph.

Eqn. 5 indicates that for the loading operation and for travelling on a shorter time direction, the unloaded shuttle should travel from node 1 to node 4 via nodes 2 and 3 (solid lines in Fig. 2). After being loaded, the shuttle should continue its travel from node 4 to node 1 via node 5 (dotted lines).

4.3 Control Logic for Container Shuttles

The purpose of the control logic for the container shuttle is to establish and maintain a desired sequence of events. When a shuttle becomes available, a container in the yard is chosen to be picked and is assigned to the shuttle. Meanwhile, the container number is added to the corresponding YC’s queue. If there is no other container in the queue, the container number is added to the corresponding YC’s queue. To prevent this type of deadlock, the shuttle utilizes policy P2.b.

When two or more QCs’ queues are occupied with the same minimum number of shuttles, the shuttle utilizes policy P2.b.

5. OPTIMIZATION

The choice of the performance index would very much depend on the specific priorities of the terminal operation. In general, the performance index should be thorough and should be a function of many weighted variables. The choice of these weights would depend on the specific terminal objectives.

Multiple Attribute Decision Making (MADM) methods deal with problems that involve multiple, sometimes conflicting, criteria and take all the criteria of concern into account. MADM techniques try to establish rational “attributes” that can measure goal accomplishments. “Alternatives” are then constructed over the chosen attributes. Usually, all attributes are not of equal importance to a decision-maker; thus, appropriate weights should be assigned to attributes (Yoon and Hwang, 1995).

Let’s assume that  is the set of all attributes, and  is the set of all alternatives. A MADM problem can be concisely expressed in a matrix form. A decision matrix  is a  matrix whose element  is the outcome of alternative  with respect to the attribute  . The relative importance of each outcome is usually given by a weight . For each alternative , a value, , is computed as follows:

\[
V(A_i) = U_i(x_{i1}, x_{i2}, ..., x_{ij}, w_{j1}, w_{j2}, ..., w_{jk}), \quad i = 1, 2, ..., I \tag{6}
\]

where  is the value generator for alternative . Based on the values of alternatives,  the decision-maker selects the best alternative , which has the highest value among all alternatives as follows:

\[
A^* = \{A_i \mid \max_j V(A_i)\}, \quad i = 1, 2, ..., I \tag{7}
\]

Simple Additive Weighting Method (SAWM) is probably the best known, and the most widely used MADM method. In this method the relative importance weight is given to each attribute  rather than to each outcome . The SAWM can be written as follows:

\[
V(A_i) = \sum_{j=1}^{J} w_j x_{ij}, \quad i = 1, 2, ..., I \tag{8}
\]

\[
A^* = \{A_i \mid \max_j V(A_i)\}, \quad i = 1, 2, ..., I
\]

and \( \sum_{j} w_j = 1. \)
In this paper, the objective is to obtain the optimum number of shuttles in the yard for a specific cost function. Let’s assume that the overall structure is given in Fig. 1, the control logic is as described earlier, and the number of the YCs and QCs is given and fixed. For automated container yards the AIR of QCs, YCs and shuttles are chosen as attributes $X_i$, $X_j$, and $X_k$, respectively. The number of shuttles deployed in the yard (say $A_1, A_2, \ldots, A_l$) for loading or unloading operation is considered as alternatives. Thus, the elements of the decision matrix $D$ would be $x_{ij}$ (AIR of the QCs), $x_{ik}$ (AIR of the YCs), and $x_{jk}$, (AIR of the shuttles).

The SAWM method is employed to find the optimum number of shuttles with aforementioned attributes. In (8), $A'$ is the optimum number of shuttles deployed in the yard such that the sum of the weighted AIR (sum of the weighted utilization) of machines is minimized (maximized).

6. SIMULATIONS

The most accurate evaluation of current advanced 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 need to be overcome in advance. 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.

For manual operation, the container yard is simulated using the data provided in Towery, (1996); and Larsen and Moses. For automated yard operation, two scenarios P1 and P2 described earlier are investigated and compared. The following are assumed as characteristics of the equipment in the yard:

Performance of the YCs:
- 5-mph (2.24 m/s) lateral speed, needs 15 seconds to line up with the stack, and the average loading/unloading time is 50 seconds.
- Capacity of the QCs: 75 moves/hour.
- Speed of loaded shuttles: 5 mph (2.24 m/s).
- Speed of unloaded shuttles: 10 mph (4.48 m/s).
- Time for shuttles to turn at corners: 5 seconds.

Simulation 1: (Manual Operations). 18 shuttles are deployed for loading operation. The AAS of trucks is given in (1), and the speed of QCs and YCs are as described above. The throughput achieved in our

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Fig. 3. QCs are selected based on policy P1, (a). No. of loaded containers / hour / QC, (b) AIR of machines in the yard.

(1) Despite the fact that the QCs at the NIT are capable of 45 moves per hour, the average current speed of QCs is about 30 moves per hour. Thus, the problem is not with the cranes but with the yard operations. That is, the time needed to load a hostler in the yard and to unload it by the QC is negligible compared to the time needed for the hostler to travel in the yard. (2) Since the hostlers are travelling with average speed equal to AAS in Eqn. (1) and the number of hostlers is the same as the ones considered in (Towery, et al. 1996), the productivity of the two yards should be approximately the same despite the fact that the two yard layouts are slightly different.

Simulation 2: (selecting a QC based on policy P1). The automated yard operations are simulated by using different number of shuttles, assuming that a shuttle chooses a QC randomly. Fig. 3a shows the throughput of the yard for different number of shuttles. As shown in Fig. 3a, as the number of shuttles increases the throughput of the yard increases until the saturation point is reached which is the point where the QCs reach their maximum speed. By adding more shuttles in the yard, the shuttles spend more time in the QCs’ queues waiting to be served rather than travelling in the yard to do the next loading operation. Therefore from the practical point of view it is more desirable to keep the number of shuttles at the lowest number for which maximum throughput is achieved.

Fig. 3b illustrates the AIR of the QCs, YCs, and shuttles. For small numbers of shuttles in the yard (say 6 or 9) the Idle Rate (IR) of a shuttle is very low. As the number of shuttles increases, the congestion rate of shuttles as well as the total time that the shuttle spends in the cranes’ queues goes up which leads to the increase of the AIR. In other words, increasing the number of shuttles in the yard results in a decrease of the busy period of the shuttle, and consequently into an increase of the AIR of shuttles.

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1 The speed of the QCs is based on current and expected performance of advanced cranes which are either in use or in conceptual designs. The speed of the shuttles is chosen to be similar to that of the AGVs used at Rotterdam.
Fig. 4. QC's are selected based on policy P2, (a). No. of loaded containers / hour / QC, (b) AIRs of machines in the yard

Simulation 3: (selecting a QC based on policy P2)
Here a shuttle selects a QC based on the minimum number of shuttles in the queue as well as the minimum distance between the shuttle and QC. As shown in Fig. 4a, 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 QC which is very close to the capacity of QC. The difference is due to computational errors in the simulation.

Fig. 4b shows the AIR of the QC's, YCs, and shuttles in the yard. Applying policy P2 not only makes the container yard system more robust and reliable, but it also results in improvement of the yard throughput by about 20%. It seems that this policy provides kind of feedback to the system leading to better robustness and throughput.

Comparison of the throughput of manual (simulation 1) and automated yard (simulations 2 and 3) for similar operations, i.e. loading operations, while equal numbers of shuttles with similar characteristics are deployed in the container yard shows a great promise in increasing the throughput and achieving high utilization. To find the optimum number of shuttles in the yard, SAWM is employed. Our performance index was a weighted sum of the machines’ utilization. Since high utilization of the container yard is the generally accepted goal for container terminals’ authorities, automated container yards emerges as a candidate to substitute the currently low throughput container yards.

To find the optimum number of shuttles for simulation 3 the SAWM is employed. For convenience, weighted penalties is presented in the vector form, \( W^1=(w_1, w_2, w_3) \). Fig 5 illustrates the values of alternatives, \( V(A_i) \), for \( A_i \in \Psi \), \( \Psi = \{4,6,\ldots,26\} \), and for several weighted penalty vectors.

In graphs 1, 2, and 3 of Fig.5 the optimum number of shuttles is found for a single criterion decision making. That is, the intention is to minimize the AIR of either QC’s, \( W^3=(1,0,0) \), or YCs (0,1,0), or shuttles (0,0,1). As Fig. 5 shows, using single criterion decision making to minimize the yard performance index leads to choosing either the maximum or the minimum number of shuttles in \( \Psi \). In graphs 4, 5, and 6 in Fig. 5, all three attributes are taken into account. The number of shuttles which minimizes the Fig. 5. Yard performance for several penalty vectors.

performance index is around 20. It is worth mentioning that a more elaborate performance index and/or cost function could be used to choose the number of the various equipment subject to various constraints.

7. CONCLUSION

In this paper, an automated container terminal using linear motor technologies is designed. For similar operations, i.e. loading operations, and for equal number and similar characteristics of machines deployed in the container yard, linear motor technology demonstrated a great promise in increasing the throughput and achieving high utilization. To find the optimum number of shuttles in the yard, SAWM is employed. Our performance index was a weighted sum of the machines’ utilization. Since high utilization of the container yard is the generally accepted goal for container terminals’ authorities, automated container yards emerges as a candidate to substitute the currently low throughput container yards.

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