Intelligent Transportation System for Container Movement between Inland Port and Terminals*

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In this paper we propose an intelligent transportation system for container movement between inland port and terminals, in which fully automated trucks are employed to transfer all the containers. The inland port is located a few miles away from the terminals and is used for storing and processing import/export containers before distribution to customers or transfer to the terminals. We design and analyze such an intelligent transportation system, with particular attention to the overall supervisory controller that synchronizes all the operations inside the automated system. We employ the technique of truck platooning in order to simplify the control of the overall system, and minimize the possibility of deadlocks, congestion and failures. A microscopic simulation model is developed and used to demonstrate the overall performance of the proposed system.

Key Words: intelligent transportation system, container transportation, automated truck, supervisory control, Petri nets

1. INTRODUCTION

In recent years, the global container trade has been growing at an annual rate of about 9 percent, and the corresponding U.S. rate has been around 6 percent. By 2010, it is expected that 90 percent of all liner freight will be shipped in containers. Thus every major port is expected to double or even triple its processed containers by 2020 [Liu et al. 2002]. In order to remain competitive, marine container terminals in metropolitan areas must meet the increasing demand for storage and processing capacity. Ports such as those of Los Angeles/Long Beach (LA/LB), which handle nearly one third of all U.S. foreign container traffic, are under a lot of pressure to meet projected capacity demand increases in order to remain competitive and avoid traffic congestion at the terminals and

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contiguous areas. As potential solutions for improving the performance of container terminals and meeting the challenges of the future in marine transportation, various automated container terminals have been proposed, among which the use of automated guided vehicles (AGVs) has attracted the most studies [Evers et al. 1996, Vis 2006 and the references inside]. The Delta Terminal at the Port of Rotterdam has been operating AGVs for transporting containers within the terminal, while the Ports of Singapore, Thamesport, Hamburg, Kawasaki and Kaoshiung are experimenting with similar systems. Other competitive concepts, including the Grid RAIL (GRAIL) and Automated Storage/Retrieval System (AS/RS), are also investigated [Liu et al. 2002].

Another feasible approach to reduce the pressure of increased storage capacity demand at terminals is the use of an inland port, which acts as an intermediate storage area before the cargoes are processed for export/import. Such an inland port could be made very efficient by automating all the tasks associated with processing, scheduling, storage, and transfer of containers between the inland port and the container terminals. As an important part of such an automated system, automated trucks are employed to transport all the containers. The use of automated trucks in container transportation has a lot of benefits, such as high container throughput, 24-hour continuous operation, reduced labor costs, high reliability and high safety standards. Since the automated trucks are required to transport containers between a terminal and an inland port, generally a few miles away, they will be expected to travel at much higher speeds than the AGVs operating inside container terminals, and the vehicle control problem becomes more challenging. The Center of Transport Technology in the Netherlands studied a container transport system, called “Combi-Road” [Scrase 1998], in which each container is pulled on a semi-trailer of an unmanned vehicle, and the vehicles are electrically driven along specially designed tracks. In the US, a lot of research efforts are currently under way to study the deployment of automated commercial trucks on highways, either in platoon formations or as autonomous vehicles [Chen and Tomizuka 1995, Hingwe et al. 2000, Tan and Kanellakopoulos 2002, Yanakiev and Kanellakopoulos 1995a, 1995b, 1998, Zhang and Ioannou 2006]. These results strongly suggest that automated commercial trucks may come into market in a near future. Despite past activities in the area of truck automation, there is currently no system that utilizes fully automated trucks at relatively high speeds, due to the human factors and liability issues.

In this paper, we design, analyze and simulate an intelligent transportation system for moving containers between inland port and terminals. Inside such a transportation system, fully automated trucks are employed to move containers between an inland port and terminals. The intelligent container transportation system, as shown in

Fig. 1, is composed of automated trucks, automated cranes and a supervisory controller that synchronize all the automated units inside the system. The supervisory controller contains all the information related to transportation tasks and road geometry, acquires the real time information and issues commands for all the automated units via communication devices. We design and analyze the supervisory controller using Petri Net [Murata 1989], and demonstrate the overall system work in a safe and efficient manner via microscopic simulations. We briefly present the design of on-board (longitudinal and lateral) controllers for automated trucks for the completeness of this paper. A feasible application of the intelligent system is in the Long Beach area between the Intermodal Container Transfer Facility (ICTF) (inland port) and different Piers (container terminals). Since our approach focuses on the deployment of automated trucks in a controlled environment where human being is not present, the use of automated trucks is free of the human factors and liability issues, which currently challenge the deployment of automated vehicles. Hence truck automation is strongly feasible and it will be acceptable provided its benefits can be established. The rest of the paper is organized as follows. In section 2, we introduce the basic concept for the intelligent container transportation system, and explain the design considerations and system layout. In section 3, we briefly investigate control designs for automated trucks. The supervisory controller is designed and analyzed in section 4. In section 5, microscopic simulations are carried out to demonstrate the performance of the overall system. The conclusions are given in section 6.

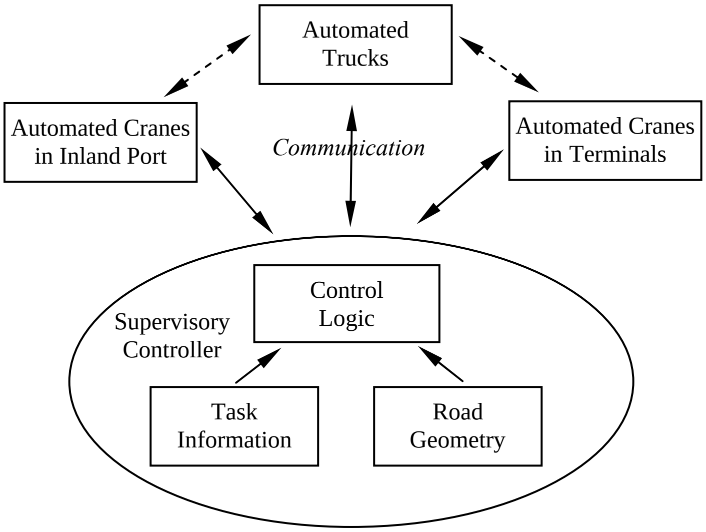


Fig. 1. Overview of the proposed intelligent transportation system for container movement.

2. INTELLIGENT CONTAINER TRANSPORTATION SYSTEM

The basic components of the proposed intelligent container transportation system are an inland port, terminals and an automated container transportation system. The inland port is located a few miles away from the terminals where land of lower cost is available, and is used to temporarily store and process import/export containers. Automated trucks are used to transport containers on a dedicated road inside the transportation system. The truck road may be dedicated for the automated trucks all the time or for time intervals, and the rest of the time could be used by manually driven vehicles. Inside the inland port and terminals, containers will be processed by automated cranes. As shown in Fig. 1, the supervisory controller will synchronize the movements of all the automated units inside the transportation system via wireless communication. An automated truck employed in the container transportation system will be assigned tasks such as carrying a container from the inland port, joining a platoon, speeding up to a desired speed and cruising while on the road, slowing down when entering the container terminal, positioning itself under a quay crane for unloading, then getting loaded with an imported container and driving back to the inland port, and vice versa. While being served by an automated crane, the automated truck is connected with the crane through communications, as indicated in Fig. 1.

In this section, we present the design considerations and a feasible system layout for the intelligent transportation system, which will used in the simulations presented in sections 4 and 5. The designs of the on-board controllers for automated trucks and the supervisory controller will be presented in sections 3 and 4, respectively.

2.1 Design Considerations

In the design of the proposed system, we consider the following operation conditions:

1. The container terminal is able to serve ships with capacity of 8,000 Twenty-foot Equivalent Units (TEUs). It is assumed that the ships arrive every 24 hours, which requires that the service time must be strictly limited to 24 hours or less. In our design, we further assume that the ship carries import containers up to 85% of its capacity and should be reloaded with the same number of export containers. The turnaround time for a ship with 85% load is restricted to 20 hours, so that the system is able to serve any ship within 24 hours even if the ship is fully loaded and some unexpected events take place.

2. All the import containers will be transported to the inland port before they are distributed to different destinations, and all the export cargoes will be preprocessed in the inland port before they are transferred to the container terminal. All the containers are of Forty-foot Equivalent Unit (FEU) type.

3. The cranes used in the inland port and terminals are identical and work in the dual mode (i.e. both loading and unloading). The maximum physical capacity of the cranes is assumed to be 42 moves per hour in the dual mode. A variance of 20% (uniformly distributed randomness) to the maximum capacity of the quay cranes is considered in the simulations, due to the uncertainties involved in the quay crane operations.

4. The automated trucks are able to work 24 hours per day. No fueling or maintenance time is considered for the trucks in this study.

The above conditions are used in this paper to demonstrate how to determine the minimum number of required cranes, and estimate some other specifications in the intelligent transportation system.

2.2 System Layout

Before we present the system layout, we need to determine how many cranes are required in the container terminal. A quay crane working in the dual mode transfers one export container from truck to ship and one import container from ship to truck in one moving cycle. If all the quay cranes operate at their maximum capacities, the smallest number of quay cranes required to accomplish the task proposed in section 2.1, N_{qc}, is given as

$$N_{qc} = \left\lceil \frac{N_{container}}{C_{qc} T_{ship}} \right\rceil \tag{1}$$

where $N_{container}$ is the number of containers to be unloaded from the ship (or loaded onto the ship), C_{qc} is the maximum physical capacity of the quay cranes, T_{ship} is the desired ship turnaround time, and • • • is the operator that rounds up the argument to the closest integer. Using the specifications in Section 2.1, it is found that five quay cranes are required in order to load and unload a mega-ship with 3,400 containers of FEU within 20 hours.

As shown in Fig. 2, the layout of the intelligent container transportation system consists of three parts: the container terminal, the inland port and the dedicated lanes connecting the inland port with the terminal. In this study, we assume the inland port is located at the ICTF and the container terminal is Pier G at Long Beach.

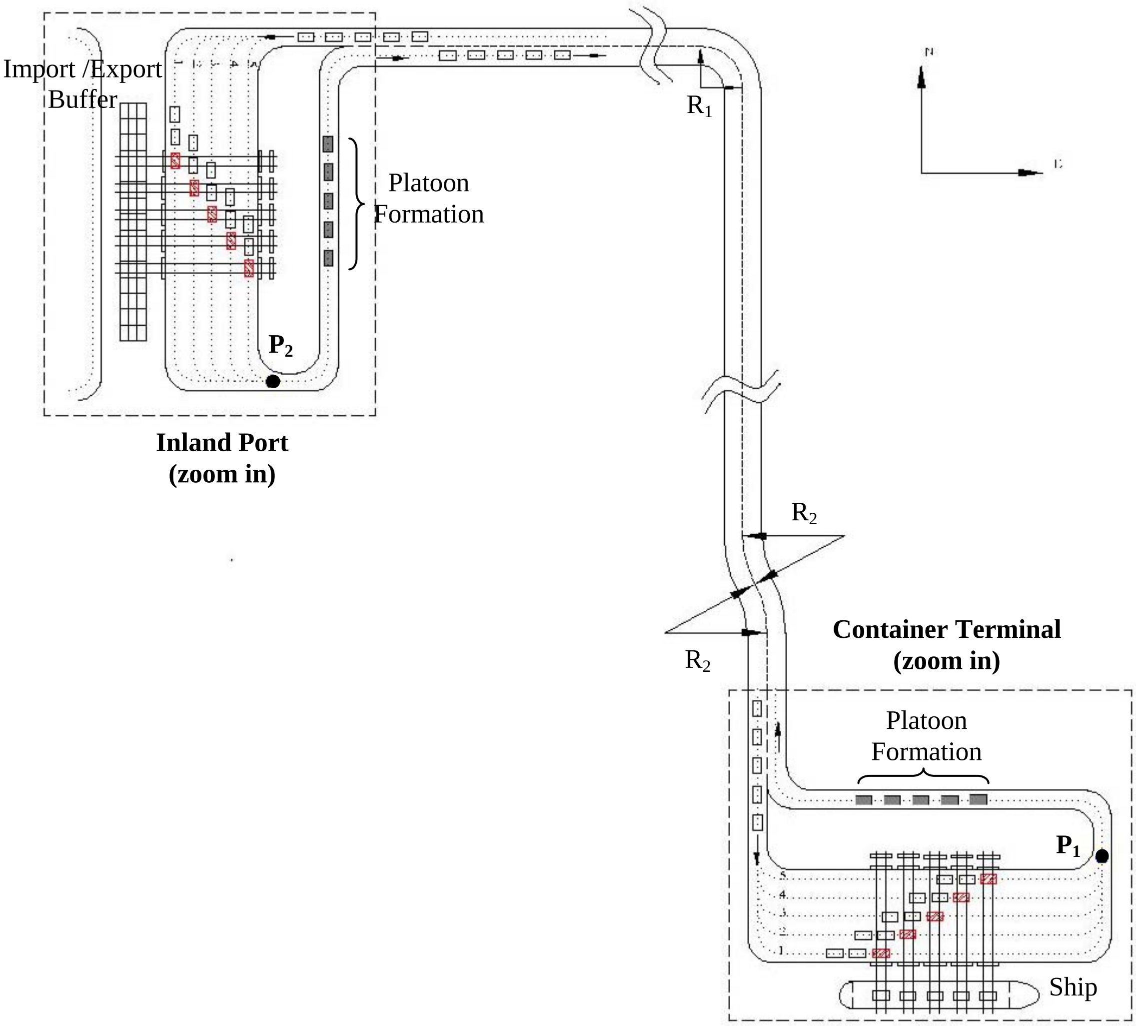


Fig. 2. Layout for the proposed transportation System.

The container terminal, shown on the right lower box, is the place where ships are to be loaded or unloaded. When trucks are following the lane center in this area, large transient lateral errors may occur due to the large road curvatures, which could lead to a collision between two trucks traveling in opposite directions. Therefore all paths inside the container terminal are designed to be uni-directional and wide enough so that large transient lateral errors will not cause any problems. In this layout, five quay cranes are available to serve the ship simultaneously, and each of the quay cranes can be accessed via the five service lanes under them. In this paper, each truck entering the container terminal will be assigned to one quay crane with the minimum number of trucks in the service queue. At point P_1 the five service lanes merge together. To avoid collisions at this point, a time-window T_{w1} is established.

When the system detects that one truck will reach P_1 at time t_1 while another truck will arrive at time t_2 and $|t_1 - t_2| < T_{w1}$, it will allow the truck closer to P_1 to pass first, while the other truck would wait until the collision possibility is eliminated. Platoon Formation (PF) is the location where automated trucks are organized to form platoons. If the PF is empty initially, the first truck that enters the PF will stay in pool 1, the second one that enters will stay in pool 2, and so on. After enough trucks have joined the platoon, the truck platoon will move towards the exit of the container terminal. In our case, we consider platoons of five trucks.

The inland port is shown in the left upper box of Fig. 2. It is almost identical to the terminal except that the ship is replaced by the import/export buffer. There are also five cranes working in the dual mode and each crane can be accessed via the five service lanes. Each truck entering the container terminal will be assigned to one crane with the minimum number of trucks in the service queue. Similar to the container terminal, all the paths inside the inland port are uni-directional and a time-window T_{w2} is also established for the merging point P_2. There also exists a PF at the inland port to organize the trucks into platoons.

The dedicated road between the inland port and the container terminal contains two uni-directional lanes of opposite directions, and automated trucks travel in platoon formations at relatively high speeds. Large road curvatures shown in Fig. 2 are known and this knowledge is used in the design of the lateral controllers of the trucks, while the small unknown curvatures are treated as disturbances by the control system. For example, R_1 =200m is known so that the curvature 1/200m^{-1} is taken into account by the lateral controller, while the road curvature associated with R_2=1,200m is treated as unknown disturbance.

3. AUTOMATED TRUCKS

In the proposed intelligent transportation system, fully automated trucks are used to transport containers on a dedicated road. These trucks are normal commercial heavy-duty vehicles equipped with communication devices, Differential Global Positioning System (DGPS), and on-board sensors such as Inertial Measurement Unit (IMU), radar (or lidar), wheel angle sensor et al. Through the communication devices, an automated truck receives commands from the supervisory controller to interact with the other units inside the system. The on-board sensors, together with the GDPS, provide the appropriate measurements that are used by the on-board longitudinal and lateral control systems in order to keep the truck at the center of the lane, track desired speeds, following preceding truck and stop for loading and unloading [Zhang et al 2002]. Since vehicle control is not a contribution of this paper, we only give a brief introduction on the truck dynamics and the design of the on-board controllers for the completeness of this work. Some similar results have been presented in various technical reports and papers [Ioannou and Xu 1994, Chen and Tomizuka 1995, Hingwe et al. 2000, Tan and Kanellakopoulos 2002, Yanakiev and Kanellakopoulos 1995a, 1995b, 1998]. The on-board controllers presented in this section, together with the truck dynamics, are simulated in section 4 to demonstrate that the use of automated trucks in the proposed system is feasible. Detailed information about the model parameters can be found in Zhang et al [2002].

3.1 Longitudinal Control Design

In our study, the technique of truck platooning is employed. Two longitudinal controllers are presented in this section, one for speed tracking and the other for vehicle following. When a truck platoon is formed, the lead truck operates in the speed tracking mode and follows the speed trajectory assigned by the supervisory controller, while the other trucks in the platoon operate in the vehicle following mode to tightly follow the preceding trucks. The longitudinal truck model used for simulations is proposed by Yanakiev and Kanellakopoulos [1995a, 1995b] and has been experimentally validated [Zhang and Ioannou 2006]. It is a complicated nonlinear model characterized by a set of differential equations, algebraic relations and look-up tables. The model used for control design is [Ioannou and Xu 1994, Yanakiev and Kanellakopoulos 1995a, 1995b]

$$\begin{cases} \dot{v} = -a\left(v - v_d\right) + b\left(u - u_d\right) + d \\ v_d = f_u\left(u_d\right) \end{cases} \tag{2}$$

where v is the truck speed, v_d is the desired speed, u_d is the corresponding desired fuel command, d is the modeling uncertainty, a and b are positive constant parameters that depend on the operating point, and f_u is a smooth function. In the vehicle following mode, the desired steady state speed is the speed of the lead vehicle v_l.

In the speed tracking mode, the longitudinal controller should regulate the vehicle speed v close to the desired speed v_d set by the supervisory controller.

Lemma 1 [Zhang and Ioannou 2006]: For the system represented in (2), the speed tracking controller

$$\begin{cases} u = f_u^{-1}\left(v_d\right) + k_{st,1}e_v + k_{st,2} + k_{st,3}\dot{v}_d \\ \dot{k}_{st,1} = \mathrm{Proj}\left\{\gamma_{st,1}e_v^2\right\}, \dot{k}_{st,2} = \mathrm{Proj}\left\{\gamma_{st,2}e_v\right\}, \dot{k}_{st,3} = \mathrm{Proj}\left\{\gamma_{st,3}e_v\dot{v}_d\right\} \end{cases} \tag{3}$$

where $e_v = v_d - v$ is the speed error, $k_{st,\mathrm{i}}$ (i=1,2,3) are the control gains, $\gamma_{st,i}$ (i=1,2,3) are positive design parameters, and Proj{·} is the projection function, can stabilize the closed-loop system. Furthermore, if v_d and d are constants, then e_v converges to zero as time goes to infinite.

□

Using (4) the fuel command is issued when u is positive, while the brake is activated when $u < -u_0$ (u_0 is a positive constant). Otherwise, the brake system is inactive and the fuel system is operating as in idle speed.

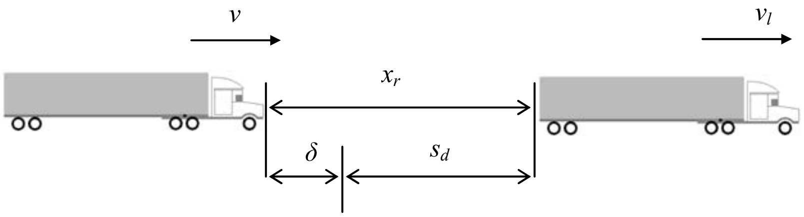


Fig. 3. Trucks in the vehicle following mode.

In the vehicle following control mode, as shown in Fig. 3, the longitudinal controller should regulate the vehicle speed v towards the speed of the lead vehicle v_l and keep the intervehicle spacing x_r close to the desired spacing s_d. Let us define the relative speed as $v_r = v_l - v$ and the separation error as $\delta = x_r - s_d$. With the time headway policy, s_d is given by $s_d = s_0 + hv$, where s_0 is a fixed safety spacing and h is the time headway. In [Yanakiev and Kanellakopoulos 1998], a variable time headway is proposed as

$$h = \mathrm{sat}(h_0 - c_h v_r) \tag{4}$$

where h_0 and c_h are positive design parameters, and sat(·) is the saturation function with an upper bound 1 and lower bound 0. This variable time headway is adopted in our study since it has been shown to be able to provide safe vehicle following with tight intervehicle spacing. The vehicle following controller is designed as

$$\begin{cases} u = k_{vf,1} v_r + k_{vf,2}\delta + k_{vf,3} \\ \dot{k}_{vf,1} = \mathrm{Proj}\left\{\gamma_{vf,1} v_r \left[(p_1 v_r + \delta) + (v_r + a_m k p_1 \delta + a_m \delta) H\right]\right\} \\ \dot{k}_{vf,2} = \mathrm{Proj}\left\{\gamma_{vf,2} \delta \left[(p_1 v_r + \delta) + (v_r + a_m k p_1 \delta + a_m \delta) H\right]\right\} \\ \dot{k}_{vf,3} = \mathrm{Proj}\left\{\gamma_{vf,3} \left[(p_1 v_r + \delta) + (v_r + a_m k p_1 \delta + a_m \delta) H\right]\right\} \end{cases} \tag{5}$$

where $k_{vf,1}$, $k_{vf,2}$ and $k_{vf,3}$ are variable control gains, a_m, k and $\gamma_{vf,i}$ (i=1,2,3) are positive design parameters, and $H = \partial s_d / \partial v$.

Lemma 2 [Zhang and Ioannou 2006]: For the vehicle following problem with the following vehicle dynamics described by (2), the adaptive controller (5) can locally stabilize the closed-loop system if the design parameters are chosen such that

$$\begin{cases} a_m p_1 > 1 \\ \dfrac{4 p_1 k}{a_m + a_m k p_1 - k} > \sup H \end{cases} \tag{6}$$

Furthermore, if v_l and d are constants, then $v_r, \delta \to 0$ as $t \to \infty$.

□

In the simulations in section 4.3, the parameters used in the variable time headway are chosen as s_0=3m, h_0=0.1, and c_h=0.2 [Yanakiev and Kanellakopoulos 1998]. We choose $a_m = 0.5$, $p_1 = 10$ and k=1.0 so that (6) holds when the lead truck operates under the maximum speed of 30m/s. The other control parameters are chosen based on simulations to achieve good vehicle following performance and are not presented here. According to (5), fuel and brake commands are issued in the same way as in the speed tracking control.

Remark 1: As shown in the previous studies [Ioannou and Xu 1994, Zhang et al 2006], the vehicle following performance is mostly determined by the spacing policy rather than the controller form. Hence we present only the spacing parameters in this paper.

3.2 Lateral Control Design

We design the lateral controller to generate steering commands by using the McFarlane and Glover loop-shaping method [Mcfarlane and Glover 1990], which has been implemented for lateral control of heavy-duty vehicles [Hingwe et al. 2000]. We use the same technique with different nominal values for trailer mass, longitudinal speed and road adhesion coefficient, which are appropriate for our specific applications.

The lateral model with respect to the road reference frame has the form [Chen and Tomizuka 1995]

$$M\ddot{q}_r + D\dot{q}_r + Kq_r = F\theta_w + E_1\dot{\varepsilon}_d + E_2\ddot{\varepsilon}_d \tag{7}$$

where $q_r = [y_r \;\; \varepsilon_r \;\; \varepsilon_f]^T$, y_r is the lateral displacement of tractor's center of gravity (CG) with respect to the road center line, ε_r is the yaw angle of the tractor relative to the road center line, ε_f is the relative yaw angle between the tractor and the semi-trailer (see Fig. 4), θ_w is the front wheel angle and $\dot{\varepsilon}_d$ and $\ddot{\varepsilon}_d$ are road curvature characteristics. The matrices M, D, K, F, E_1 and E_2 are related to the truck characteristics [Zhang et al 2002]. The steering system is approximated as a first-order system

$$\frac{\theta_w(s)}{\theta_s(s)} = \frac{1}{0.08s+1} \tag{8}$$

where θ_s is the steering angle. The transfer function from θ_s to y_r obtained from (7) and (8) contains a pair of poorly-damped zeros when the longitudinal velocity is high, which makes the lateral control difficult if the lateral error at the tractor's CG is the only signal used for feedback. This problem is solved by introducing a *look-ahead distance* d_s [Hingwe et al. 2000]. As shown in Fig. 4, it is assumed that a virtual sensor is placed at distance d_s ahead of the tractor's CG, and its measurement y_s is used for feedback. With

$$y_s = y_r + d_s\varepsilon_r \tag{9}$$

we can get $G_o(s)$, the transfer function from θ_s to y_s. Model uncertainties in $G_o(s)$ may be due to variations in trailer mass m_2, longitudinal speed v and road adhesion coefficient μ. The McFarlane and Glover loop-shaping method is applied here to handle the uncertainties. In our control design, d_s is selected to be 5m, and the nominal values for the variable parameters are m_2=15,000kg, v=20.1m/s and μ=0.8.

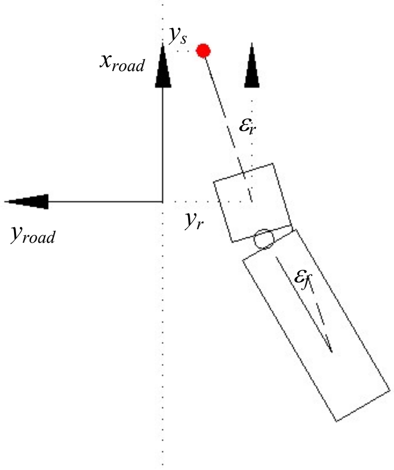


Fig. 4. A truck in the road reference frame.

4. SUPERVISORY CONTROLLER

In this section, we design and analyze the supervisory controller that dictates and synchronizes the movements of the trucks and cranes. The supervisory controller assigns new tasks to cranes, checks truck positions, generates proper speed trajectories and selects appropriate longitudinal/lateral actions for the trucks under different situations. As shown in Fig. 5, the supervisory controller is composed of two units: the Information Center and the Control Logic. All necessary information, such as path information, ship arrival and departure times, tasks to be performed and so on, are stored in advance in the Information Center. Every unit in the transportation system provides its updated status to the Information Center by direct communication. The Control Logic requires information from the Information Center and instructs all the units in the transportation system. We also investigate the performance of a platoon of trucks under the guidance of the supervisory controller through simulations.

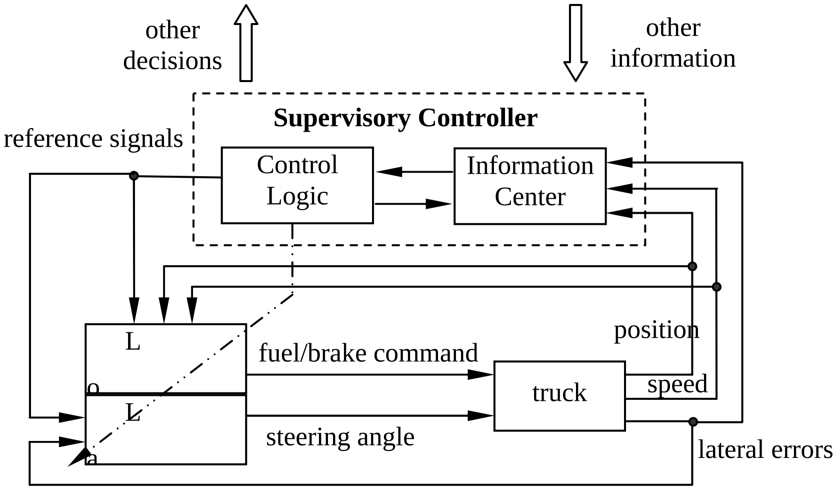


Fig. 5. Interaction between the supervisory controller and a truck.

4.1 Control Logic

In the proposed container transportation system, a platoon with import containers slows down as it enters the inland port, checks which service lane is available, then splits so that the trucks operate in the individual mode. Individual trucks position themselves under the assigned cranes in the Import/Export Buffer to get unloaded and loaded, move toward PF and wait there until a platoon is formed. The newly formed platoon moves towards the exit of the inland port, speeds up to a desired speed while cruising on the dedicated lanes, slows down to enter the container terminal, allows splitting of the trucks in such a way that each truck will be assigned to one quay crane with the minimum number of trucks in the service queue. After being unloaded, a truck picks up another container and moves towards the PF to form the next platoon. The new platoon moves back to the inland port and the same process is repeated for all platoons.

In the intelligent container transportation system, the basic requirement for the supervisory controller is to guarantee operations with no collision, no congestion and good performance. There are three possibilities for two trucks to collide in the system: (i) when two trucks are merging simultaneously at the point P_1 or P_2 in the layout shown in Fig. 2, (ii) when the trucks are moving on different lanes, but they may interfere with each other due to large lateral errors and (iii) when two trucks are traveling on the same lane and the intervehicle spacing between them is unsafe. The first possibility has been automatically excluded by establishing the two time windows T_{w1} and T_{w2} so that two trucks will never merge at the same time. The second possibility is eliminated too by designing robust lateral controllers that always keep the trucks very close to the center of the lane. The collision between two trucks traveling on the same lane is avoided by using intervehicle spacing that is safe under the worst stopping and accelerating conditions. This consideration leads to the following intervehicle spacing

$$S_{safe} = \begin{cases} S_{\min}, & v \le 3.6\text{m/s} \\ \eta S_{stop}, & \text{otherwise} \end{cases} \tag{10}$$

where S_{safe} is the safety spacing, S_{stop} is the stopping distance obtained based on the simulated characteristics of the truck, the constant η is set as 1.2 in our simulations, and $S_{\min}$ is set equal to η times the stopping distance for a truck traveling at 3.6m/s (about 8 miles/hour, which is the nominal speed for trucks in the inland port and terminals). Once a truck detects that there is another truck ahead in the same lane and the distance between them is less than S_{safe}, it will decelerate until a safe intervehicle spacing is reached. Once the supervisory controller properly selects the longitudinal controllers and speed trajectories, the system safety can always be guaranteed.

The layout shown in Fig. 2 and operations are designed for congestion-free environment. There will be no deadlock in the system if the supervisory controller has no deadlock. It is clear that the longitudinal behavior of the automated trucks is an important issue in the intelligent container transportation system, and that the longitudinal control logic is the most critical component of the overall control logic. According to the longitudinal speed command, a truck in the individual mode is considered to have four states: acceleration, deceleration, cruise or stop. In the acceleration state, the supervisory controller generates a smooth increasing speed trajectory to be followed.

The desired acceleration is varies from 0.5m/s^2 to 0.2m/s^2 depending on the truck load and speed. In the deceleration state, the supervisory controller generates a decreasing speed trajectory to be followed, which has an acceleration of -2m/s^2. In the cruising case, the truck follows a constant speed. In the stop state, the brake is always on so that the truck keeps still all the time. For a platoon, the leading truck is considered as operating in the individual mode by tracking assigned speed trajectories, but the following trucks are considered as operating in the vehicle following mode.

4.2 Petri Net Modeling and Analysis

Petri Net is a graphic and mathematical modeling tool applicable to many systems. In this paper we use it to model the supervisory controller since the graphic presentation makes the controller easy to understand. The Petri Net model of the supervisory controller consists of two sub-modules, one for trucks and one for cranes. We investigate the liveness and safeness properties of the modules individually and for the overall system. The system is dead-lock free and will not lead to conflicted decisions if it is live and safe. The basic definitions and theory of Petri Nets can be found in references such as Murata [1989].

4.2.1 Crane Module

As shown in Fig. 6, the control logic for a dual-mode crane in the container terminal and inland port has two places:

1. *crane_idling*: no truck is assigned or the crane is waiting for the next coming truck.
2. *serve_truck*: the crane unloads an export container from the truck, moves it to the ship, stacks it, moves back with an import container and loads it onto the truck.

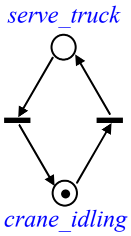


Fig. 6. Petri Net module for a dual-mode crane.

It is easy to see that each of the three crane modules is a strongly connected State Machine (SM) with only one token. Therefore, they are live, safe [Murata 1989]. It can also be seen that a live and safe SM (N, M_0) is reversible, since a token that leaves a place can always go back to the same place.

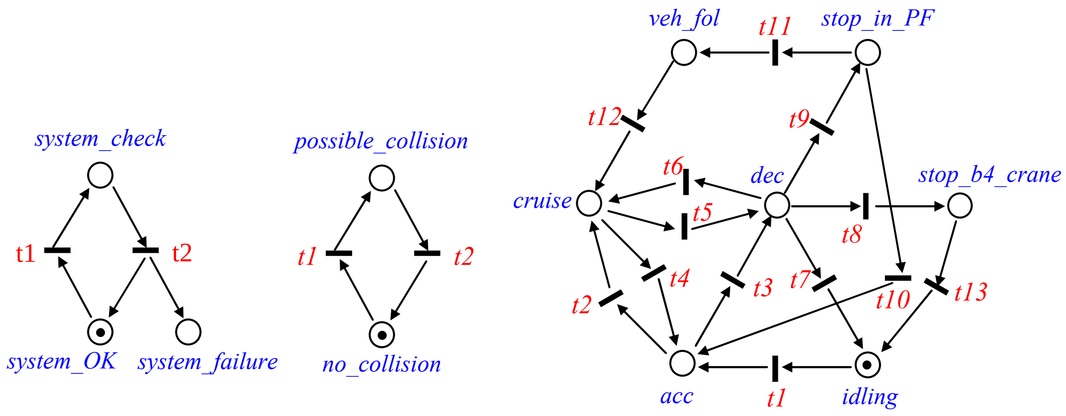
4.2.2 Truck Module

The control logic for an automated truck can be divided into three parts. As shown in Fig. 7, they are "system check", "safety check" and "decision control". In fact, the control decisions, such as which on-board controllers to be used and what kind of speed commands to be generated, are all decided by the key part "decision control". The first two parts are employed to assist "decision control", and will not generate any control decision directly. In other words, they can be implicitly included into the transitions of "decision control" as we will discuss later. The first part "system check" is used to check the functional status of the on-board systems and it has three places:

1. *system_OK*: A token is put in this place when all the on-board systems operate properly.

2. *system_check*: It is checking the on-board systems continuously, until all the containers have been transported. It is assumed that this check is almost instantaneous and does not introduce significant time delays.

3. *system_failure*: A token is put in this place once a system failure is detected.



(a) system check (b) safety check (c) decision control

Fig. 7. Petri Net module for an automated truck.

The second part “safety check” incorporates the safety policy in (10) into the supervisory controller, and it has two places:

1. *no_collision*: A token in this place indicates the safety policy is not violated.

2. *possible_collision*: A token in this place indicates that the truck gets too close to another truck ahead and collision possibility exists if the current speed is maintained.

The third part, which is also the key part of the supervisory controller, is used to select appropriate controllers for trucks and provide reference signals if necessary. As shown in Fig. 7(c), it has seven places and thirteen transitions. The seven places in fact represent seven truck working states:

1. *idling*: The truck stays still in this state. This happens when possible collision exists ahead or no job is assigned. The brake is always on during this state.

2. *acc*: The truck tracks a desired increasing speed trajectory and the longitudinal controller in (3) is engaged.

3. *cruise*: The truck tracks a constant speed and the controller in (3) is engaged.

4. *dec*: The truck tracks a decreasing speed trajectory and the controller in (3) is engaged.

5. *stop_b4_crane*: The truck stops before the assigned crane and waits until the service is complete. The brake is always on during this state.

6. *stop_in_PF*: The truck stops in PF and waits until the platoon is formed. The brake is always on during this state.

7. *veh_fol*: The truck is part of a platoon, but not a leader. In this case, it follows the preceding truck. The longitudinal controller in (5) is engaged.

The thirteen transitions that represent different logic operations are:

1. *t1*: If the truck stops to avoid a possible collision, and the possibility of this collision has been eliminated, then the truck will begin to accelerate.

2. *t2*: If the truck has reached the speed limit, then it will track this limit speed.

3. *t3*: If the truck detects a collision possibility during acceleration, it will slow down.

4. *t4*: If the truck has been cruising at a speed below the speed limit for some reason (we will come to this point at *t6*), and there is no collision possibility, then it will speed up.

5. *t5*: If the truck has detected a possible collision ahead or it needs to slow down to enter the service destination, it will decelerate until the collision possibility vanishes or it reaches the destination.

6. *t6*: If the truck decelerates because of possible collision and this collision possibility has vanished, then it will cruise at the current speed for a few seconds. During this cruising period, if the collision possibility reappears, then *t5* will take the truck back to *dec*. Otherwise, *t4* will transition the truck to the *acc*. There is no direct transition from *dec* to *acc*, because it may cause chattering.

7. *t7*: If a collision possibility exists during *dec*, then the truck will come to a complete stop.

8. *t8*: When the truck arrives at the service destination point, it will stop and wait there until it is served.

9. *t9*: When the truck enters the PF point, it will stop and wait until the platoon is formed.

10. *t10*: If the truck is the leading truck in a formed platoon, then it can transition to *acc* in a similar fashion as a truck in the autonomous mode.

11. *t11*: When the truck is within a formed platoon, then it will enter *veh_fol*.

12. *t12*: When the truck separates from a platoon, it will enter *cruise*.

13. *t13*: After the truck is served by a crane, it will enter *idling*.

As mentioned before, the sub-module “system check” has been incorporated into the transitions in “decision control”. A token inside *system_OK* means any transition in “decision control” is executable, while a token inside *system_failure* forbids all transitions except *t3, t5* and *t7*. Thus the truck must come to a complete stop and wait to be towed away. Since the truck with failure will be removed from the system eventually, it can only affect system performance but not system liveness. Similarly, in “safety check”, a token inside *possible_collision* will disable all the transitions except *t3*, *t5* and *t7*. But when the collision possibility disappears, the token will move back to *no_collision*, which will make all transitions valid again. In our analysis, we refer to the part “decision control” as the main control logic for trucks.

It is easy to see that the truck module is a state machine, but not live. It is not strongly connected since there is no path from *stop_b4_crane* to any other node. However, if the place *stop_b4_crane* and the transition *t8* are removed from the truck module, the remaining part is a strongly connected state machine and contains only one token, which means that the remaining part is live and safe.

4.2.3 Supervisory Controller

Although the truck module and the crane modules can be modeled and analyzed independently, they are not completely isolated. There is a “dynamic transition” between a truck and a crane, which dynamically links trucks and cranes together. This link exists only when one truck is under the service of the assigned crane, as shown in Fig. 8. After the service is completed, this connection will automatically disappear. Such a "dynamic transition" will not appear until the truck is assigned to another crane. The following lemma tells that the supervisory controller is live and safe.

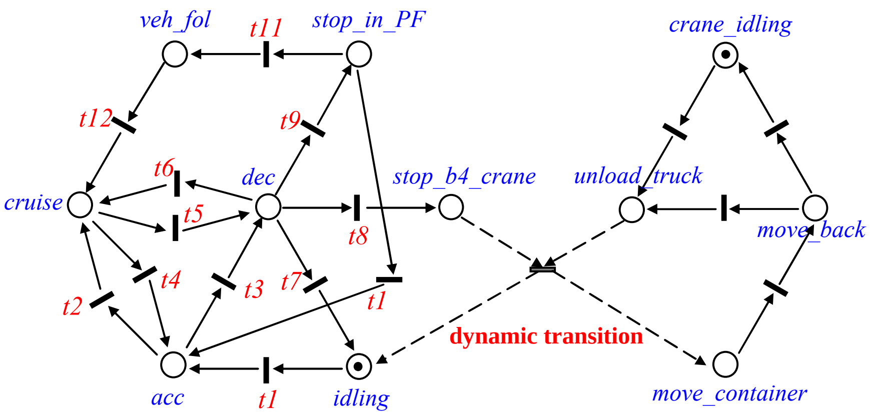


Fig. 8. Dynamic transition between an automated truck and a single-mode crane.

Lemma 3: With the dynamic transition shown in Fig. 8, the supervisory controller modeled with Petri Nets involving automated trucks and cranes is live and safe.

Proof: Suppose at some time point, the overall system is not live, i.e. there exists at least one deadlock in the overall system. This deadlock would correspond to one of the following three cases:

1. A token inside *system_failure* causes a deadlock for the truck. In this case, as soon as the system failure is detected, the truck comes to a stop and keeps idling. It may block the road in the system and cause deadlock. However, the system liveness will be recovered once the failed truck is removed from the system.

2. A deadlock exists inside the "decision control" module for an active truck. From the previous analysis, we know that this could only happen when no crane is assigned to serve that truck. However, in our design, this is not possible as each truck entering the container terminal or inland port will be assigned to one and only one crane, and each truck can follow one and only one assigned lane.

3. There is a deadlock in one crane module. From Fig. 6, we can see that this deadlock may happen when there is no truck assigned to that crane. Since we have designed the service lanes so that any crane is accessible to any truck

in the system, no truck assigned to the crane means the crane has broken down or the path to it is blocked for emergency. However, it will not affect the liveness of the whole system since the other cranes still work. Once we properly revise the dispatching rule so that all the trucks are assigned only to the active cranes, the system is still live. This point is verified using microscopic simulations, where a crane that cannot work properly is simulated.

Given the above discussions we can conclude that the overall system is live. The control logic in the supervisory controller can be viewed as a collection of relatively independent sub-modules connected by the dynamical transitions. Furthermore, since a token in the overall system is always inside one sub-module, the Petri Net model for the overall system is safe.

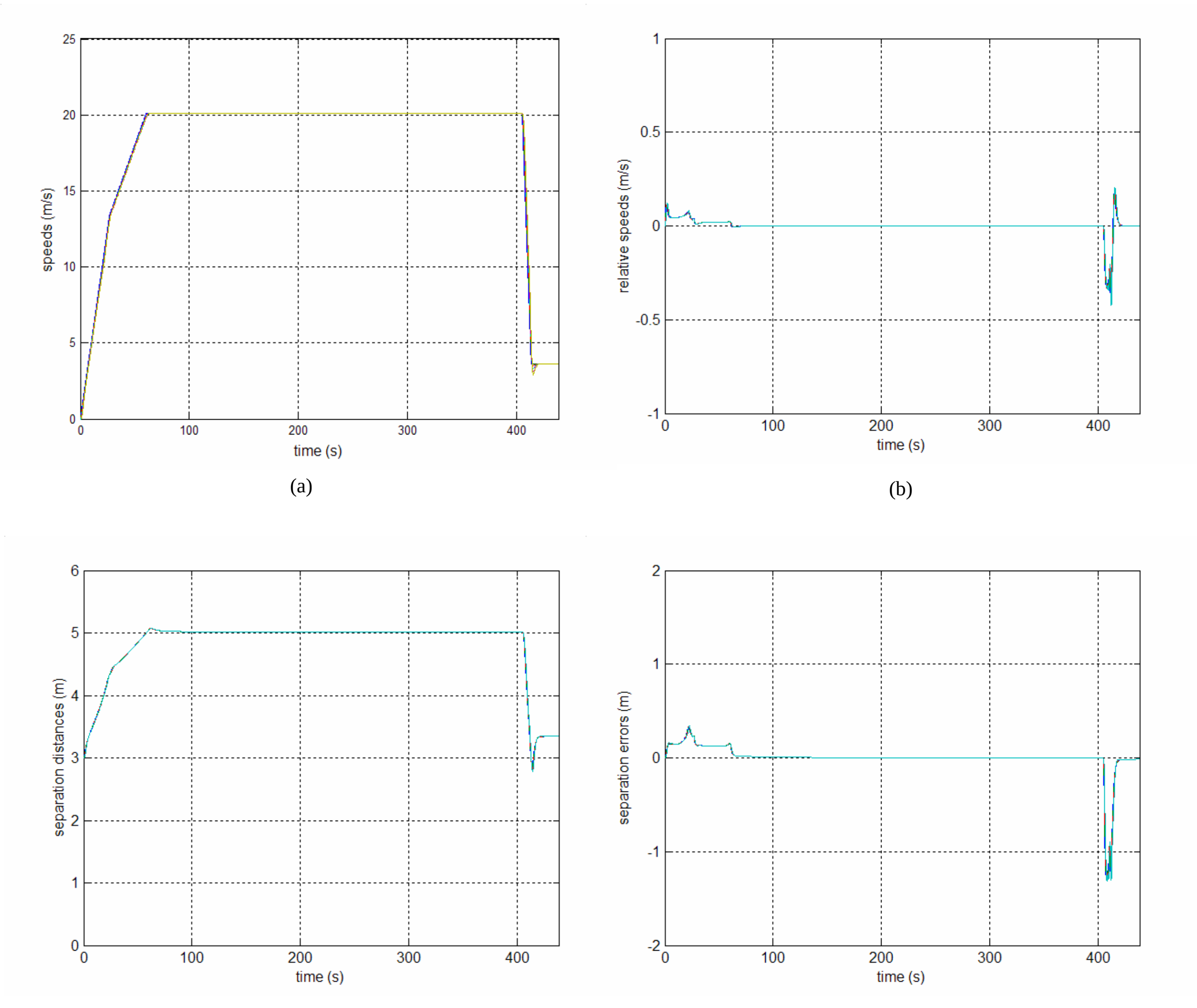
□

Remark 2: In this work, we consider all the containers are temporally storied and processed in the inland port. Hence optimization of the traffic is not an issue for the considered system. In the case that some containers are processed and stored in the terminals, the results presented in Liu et al [2002] and Kozan [2000] can be applied.

4.3 Illustrative Simulations

Using the developed supervisory, longitudinal and lateral controllers, we study the behavior of one platoon in the container transportation system, which has the layout in Fig. 2. In the simulations, the length of dedicated road is about 4.3 miles, which is the distance between ICTF and Pier G. The platoon, composed of 5 trucks (simulated with the nonlinear models) loaded with FEU containers of 15 tons, speeds up to 20.1m/s (45 miles per hour), cruises with this speed towards the container terminal, and slows down to 3.6 m/s (8 miles per hour) to enter the container terminal. The speed, relative speed, separation distance and separation error responses are shown in Fig. 9. The speed, relative speed and separation distance vehicle responses indicate that the platoon can be viewed as a single moving unit. As the lead truck cruises at a constant speed, the relative speeds and separation errors within the platoon go to zero. Fig. 9(c) shows that the separation distance between any two adjacent trucks is larger than 2.8m even in the worst case, indicating a collision-free operation. Fig. 10(a) shows the steering angle responses of the five trucks, and Fig. 12(b)-(d) show lateral displacements from the lane center at the tractor front axis, rear axis and trailer rear axis. The lateral displacements are always small, which means that the trucks are kept within the dedicated lanes so that no collision could happen between two units operating on different lanes.

The simulation results demonstrate that there is no collision within the platoon under all possible maneuvers, and all trucks exhibit satisfactory speed responses. At the same time, all the trucks are kept close enough to the center of the dedicated lanes. After a truck is released from a platoon, it follows the assigned service lane, cruises at a speed of 3.6 m/s towards the assigned crane, stops under the crane and waits until it is served. It then moves to the PF point and waits for a platoon formation. The simulation results are not presented here, and interested readers are referred to [Zhang et al 2002].



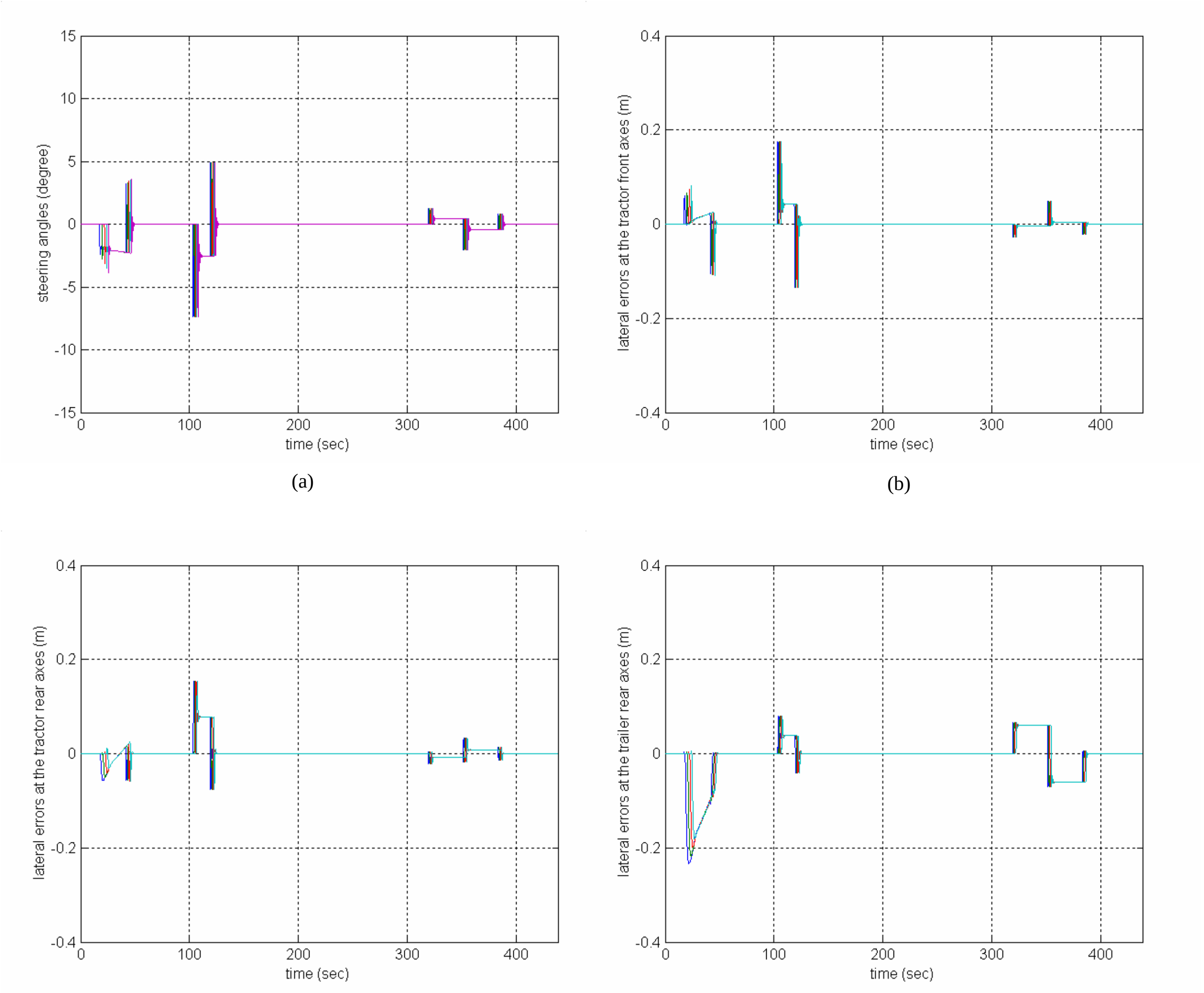
(a)

(b)

(c)

(d)

Fig. 9. (a) Speed, (b) relative speed, (c) separation distance and (d) separation error responses within the platoon.



(a) (b)

(a) (b)

Fig. 10. (a) Steering angle responses of the five trucks, and lateral errors at (b) the tractor front axis, (c) rear axis and (d) trailer rear axis of the five trucks.

5. EVALUATION OF THE PROPOSED INTELLIGENT TRANSPORTATION SYSTEM

We have demonstrated in section 4.3 that the trucks can always be kept within the dedicated lanes without colliding or getting off the assigned lane or position. In this section, we investigate the performance of the proposed container transportation system in different situations with a large number of trucks. In this case, the dynamics of the automated trucks have to be highly simplified to reduce the simulation complexity so that the simulation is computational feasible on a personal computer. Since the lateral behavior of a truck will not lead to collisions and has little effect on the truck traveling time, the lateral truck dynamics are neglected. Another simplification is to approximate the longitudinal behavior of an automated truck in the individual mode with a simple time delay

$$v(t) = v_d(t - \tau) \tag{11}$$

where $v(t)$ is the longitudinal speed of the truck, $v_d(t)$ is the desired speed and τ is a small time delay. An automated truck in the vehicle following mode is assumed to keep the intervehicle spacing close to the desired spacing. We use Matlab/Stateflow for the following microscopic simulations. The simplified truck model in (11) and the supervisory control logic presented in section 4 are used.

Before we present the simulation results, some key definitions are introduced. Let us define the truck turnaround time, T_{truck}, as the average time for one truck to transport one container from the inland port to the container terminal and transport another container back to the inland port when there is no traffic congestion. The efficiency of the ith quay crane can be evaluated by its busy rate $BR_{qc}(i)$, which is defined as

$$BR_{qc}(i) = \frac{Busy\ Period\,(i)}{Busy\ Period\,(i) + Idle\ Period\,(i)} \tag{12}$$

where *Busy Period*(i) represents the total time that the ith quay crane is engaged for loading/unloading trucks, and *Idle Period*(i) is the total time that the ith quay crane is not engaged in any job. The average busy rate of the quay cranes, BR_{qc}, is defined as

$$BR_{qc} = \frac{1}{N_{qc}} \sum_{i=1}^{N_{qc}} BR_{qc}(i) \tag{13}$$

The average busy rate of the cranes in the inland port, BR_{pc}, is defined in the same manner. The efficiency of the trucks can be similarly evaluated by their average busy rate, BR_{truck}, defined as

$$BR_{truck} = \frac{N_{container} T_{truck}}{N_{truck} T_{system}} \tag{14}$$

where T_{system} is the total time for the system to accomplish the assigned transportation task. If the intelligent container transportation system is designed properly, the busy rates of the automated cranes and trucks should be kept close to 1 and the ship turnaround time should be within the desired time window.

One question arises: how many automated trucks are required to keep the efficiency of the system high? Given the desired ship turnaround time T_{ship}, the minimum number of trucks required to transport all containers within the time window is obtained as

$$\underline{N}_{truck} = \left\lceil \frac{N_{container} T_{truck}}{T_{ship}} \right\rceil \tag{15}$$

However, if too many trucks are employed in the system, then terrible traffic congestion will show up and bring down the system efficiency. Hence the maximum number of trucks that should be employed is

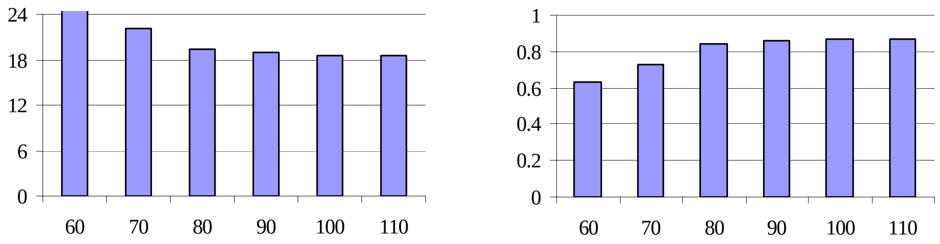
$$\overline{N}_{truck} = \left\lceil N_{qc} C_{qc} T_{truck} \right\rceil \tag{16}$$

which is just enough to keep the efficiency of the quay cranes close to 1. Since the number of the quay cranes, N_{qc}, is determined by (1), it is easy to see that $\overline{N}_{truck} \geq \underline{N}_{truck}$.

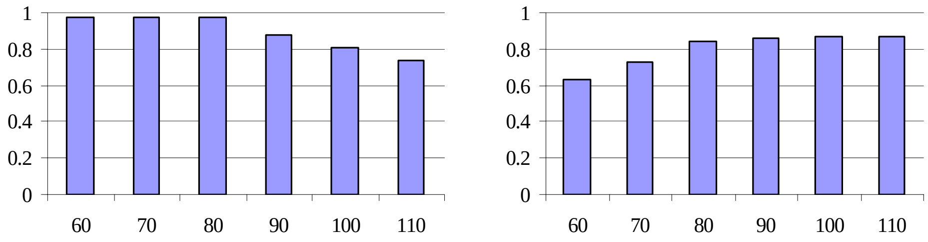
In the microscopic simulations, the layout of the intelligent container transportation system shown in Fig. 2 is simulated with the system description given in section 2.1. The layout in Fig. 2 corresponds to the area between the ICTF and Pier G in the Long Beach area. With the illustrative simulation results shown in section 4.3, we know the truck turnaround time T_{truck} is about 1590 seconds [Zhang et al 2002]. Hence we can predict that the system efficiency should be high when the number of trucks stays between $\underline{N}_{truck}$ =76 and $\overline{N}_{truck}$ =93. The simulation results are presented in Fig. 11. When the number of automated trucks is less than 80, the ship turnaround time keeps deceasing as the number of trucks increases. When 80 trucks are employed in the transportation system, the service for the ship can be done within 20 hours, which is the desired time window. At the same time, the traffic congestion is not serious since the truck busy rate is close to 1. When 90 or more trucks are employed, the ship turn around time is kept close to the minimum value and the busy rates of the cranes are also close to their maximum values. By increasing the number of trucks beyond 80, the ship turnaround time does not decrease significantly, but the traffic congestion becomes more and more serious, which means the system efficiency is decreasing. When 110 trucks are used, the truck busy rate gets down to 0.75, which means there are too many unnecessary stop-and-go motions. The simulation results in Fig. 13 show that 80 or more trucks are needed to accomplish the transportation task within 20 hours, and the optimum number of trucks does lie between $\underline{N}_{truck}$ and $\overline{N}_{truck}$. It can be noticed that BR_{qc} cannot get too close to 1 when the quay cranes operate in the dual mode, because it takes some time for a truck to position itself under the assigned quay crane, and the crane in the dual mode has to idle during that period.

With the truck number fixed at 90, simulations are performed for ships with different load ratios (load ratio: the ratio of shipload to ship capacity) and the results are given in Fig. 12. It is clear that there is a linear relation between ship turnaround time and the load ratio, which indicates that the system performance is insensitive to crane uncertainties. Furthermore, the ship turnaround time is much less than 24 hours for a fully loaded ship.

In all the simulations, no collision situation has ever been encountered. The simulation results demonstrate that the proposed system operates as designed during normal operations when the truck number is properly chosen.



(a) ship turnaround time (hours) vs. number of trucks. (b) quay crane busy rate vs. number of trucks.



(c) truck busy rate vs. number of trucks. (d) port crane busy rate vs. number of trucks

Fig. 11. Microscopic simulation results (ship is 85% loaded).

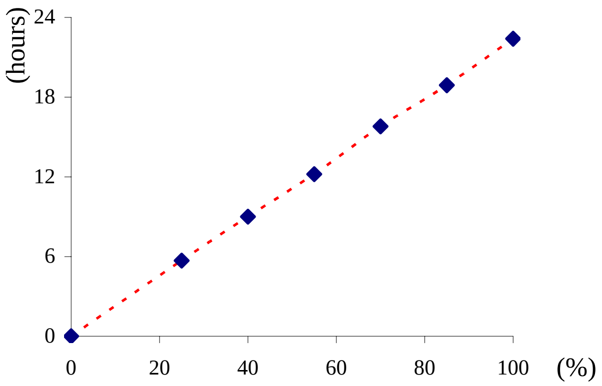


Fig. 12. Ship turnaround time vs. shipload ratio.

6. CONCLUSIONS

In this paper we introduce an intelligent container transportation system, which utilizes fully automated trucks to transport containers between inland port and terminals. We design, analyze and simulate the proposed system with emphasis on the supervisory controller that synchronizes all the movements inside the system. It is demonstrated that each subsystem in the system operates in a satisfactory manner and the overall performance is what is expected.

Our preliminary study indicates that the intelligent transportation system for container movement between inland port and terminal is feasible and could operate in an efficient manner. The issues that require further investigation are cost analysis and effectiveness as well as acceptance by terminals and other stakeholders. Furthermore technical issues such as particular choices of sensors, actuators, equipment based on cost, reliability and performance considerations need to be addressed by performing actual experiments and additional studies. Another important issue is the location of the container transportation system and the availability of land for an inland port and of dedicated lanes to connect the inland port with the terminals. Since our approach focuses on the deployment of automated trucks in a controlled environment where humans are not present, the use of automated trucks is free of the human factors and liability issues. Hence truck automation is strongly feasible and it will be acceptable in the proposed environment provided that its benefits can be established.

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