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# Line Following Control of an Autonomous Truck-Trailer

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***Abstract*—This paper presents the line following control of a truck-trailer. The control architecture of the truck-trailer is also proposed. To cope with the autonomous application of the truck-trailer, the kinematics of truck-trailer is derived and the mapping of the control actuators in the head-truck, which are the steering angle and the traction to the posture of the trailer is conducted. The geometrical schematic between the truck trailer and the path to be followed is explored so that the error dynamics between the configuration of truck-trailer and the path are formulated. The path following control is designed based on the Lyapunov method, and the global asymptotic stability of the origin of error variables is shown. Optimization of the control parameters is performed to include the constraints of the truck-trailer maneuver. Simulation results of a truck-trailer following rectangular-shaped path are conducted to show the efficiency of the proposed method.**

***Keywords*—truck-trailer; nonholonomic system; line following control; mobile robot; Lyapunov-based method; nonlinear control.**

## I. Introduction

The control application of truck-trailer has been of special interest to logistic industry since it offers unmanned operation, in which increases the safety, reduces human error, and optimizes the efficiency. Ports and warehouses have implemented automated guided vehicles (AGVs) with special design to ease the implementation of development of autonomous material handling operation. Nowadays, the automatization of conventional truck-trailer is feasible as the design directs to drive-by-wire system: electro-hydraulic power steering, computerized traction engine, and electro-pneumatic brake system. All the systems are integrated in the electronic control unit (ECU). Hence, an autonomous container truck can be developed from a common manual human-operated truck. However, control of truck-trailer system is the most challenging problem in mobile robotics. The difficulties include the high non-linearity of the system, its non-holonomic constraint, and less inputs that are involved in controlling the under-actuated system.

Control of mobile robot are classified into three objectives which are stabilization, trajectory tracking, and path following controls [1]. In stabilization control, the mobile robot is intended to be driven from initial posture to another. The objective of trajectory tracking control is to track a desired trajectory. Meanwhile, the objective of path following control is to make the mobile robot follow a desired path, without any specific time. The path following control is common application in industry, because the mobile robots do not have to change the trajectory when an unwanted scenario happens, such as stopping due to obstacles, slip between the wheel and the surface, etc. Instead, the path can be regenerated with no constrain to time. Numerous industrial applications implement path following controls for their autonomous vehicles since it is necessary to have reliable performance and safe operation. The control architecture of an industrial vehicle between path regeneration, control, and obstacle avoidance is elucidated in [2].

Control methods of truck-trailers have been researched in many literature. A model-based fuzzy control method was utilized for stabilization of a truck-trailer [3], [4]. The control of truck-trailer systems has been summarized in [5].

We use a nonlinear approach as it assures the stability and robustness of the performance. Truck-trailer motion planning controllability was shown in [6]. The chained form [7], [8] is one of methods that can stabilize the nonholonomic systems. Recent development on the *N*-trailer mobile robot, which is consisted of unicycle head-truck followed by *N* passive trailer shows that the concept of Vector-Field-Orientation (VFO) control approach for the last vehicle trailer can be used to design a controller that stabilize the last-trailer posture [9].

In this paper, the realization of path following control of truck-trailer, in which the head-truck is considered as a car-like vehicle, as of the real container truck, is investigated. The mapping from the head-truck to the trailer is derived. The control objective is to control the last trailer aligned with a desired path. The distance and orientation errors between the posture of the last-trailer and the desired path are conducted. The path following control is designed based on the Lyapunov method, in such a way that the globally asymptotically stability of the origin of errors is achieved. An optimization method is utilized in order to determine the control parameters with the constraints of the ranges of steering angle and of the angle between the head-truck and the trailer. Simulation results of truck-trailer control

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following a rectangular path is shown.

This paper is organized as follows. Section II derives the modeling and desgins control design of the path following control of the truck-trailer. Simulation results are depicted in Section III, showing the effectiveness of the proposed methods. Section IV draws conclusions.

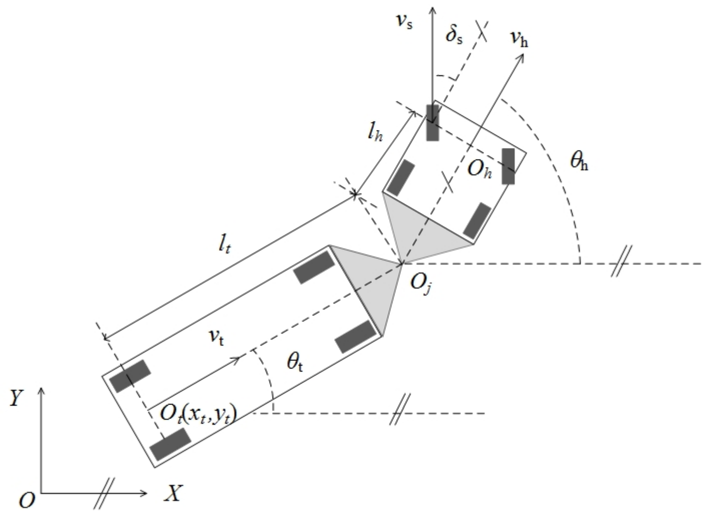


Fig. 1. Schematic model of the truck-trailer.

## II. Control of The Truck-Trailer

### A. Kinematics of the Truck-Trailer

Let the global coordinate be denoted as $OXY$-coordinate. The truck-trailer is controlled by implementing two inputs, which are the traction velocity $v_s$ and the steering angle $\delta_s$ which are driven the front-wheel (see figure 1). The center of the two steering wheels (left and right) is defined as point $O_h$. The joint between the head-truck and the container is denoted by the point $O_j$. Noted that the joint $O_j$ is not conducted with any actuation. The length from $O_h$ to $O_j$ is denoted as $l_h$ and that from $O_t$ to $O_j$ is $l_t$. The configuration of the truck-trailer is defined by $O_t(x_t, y_t)$, $\theta_t$, and $\theta_h$, where $O_t(x_t, y_t)$ is the coordinate of the trailer, $\theta_t$ is the angle between the $X$-axis with the line $O_t$-$O_j$, and $\theta_h$ is the angle between the $X$-axis with then line $O_j$-$O_h$. Despite of using $\theta_h$ as a concerned variable, we introduce $\delta_h$=$\theta_h$-$\theta_t$, where $\delta_h$ relates the heading of the head truck with respect to the trailer. We also introduce $v_h$ and $v_t$ as the head-truck linear velocity and as the trailer linear velocity, respectively. From Fig. 1, the kinematics of the truck-trailer is as follows:

$$\begin{aligned} \dot{x_t} &= v_s \cos\delta_s \cos\delta_h \cos\theta_t, \\ \dot{y_t} &= v_s \cos\delta_s \cos\delta_h \sin\theta_t, \\ \dot{\theta}_t &= \frac{v_s}{l_t} \cos\delta_s \sin\delta_h, \\ \dot{\delta_h} &= \frac{v_s}{l_h} \sin\delta_s - \frac{v_s}{l_t} \cos\delta_s \sin\delta_h. \end{aligned} \tag{1}$$

It is noted that $v_t = v_s \cos\delta_s \cos\delta_h$ and $\delta_s \in (-\pi/2, \pi/2) and \delta_h \in (-\pi/2, \pi/2)$.

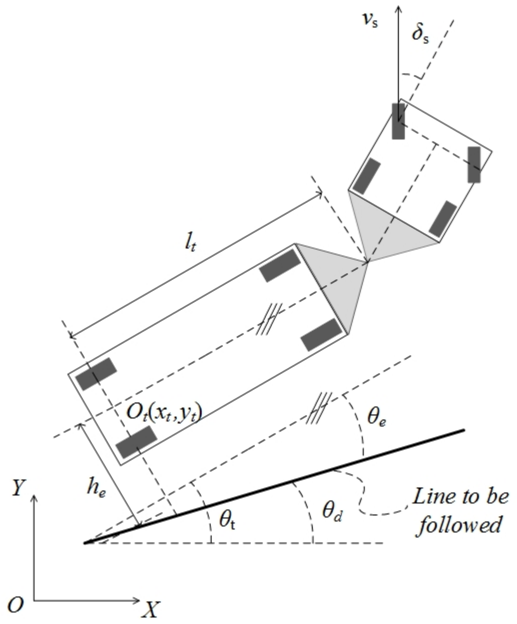


Fig. 2. Line following formulation.

### B. Line Following Control Problem

The line following control of truck-trailer system is formulated in this subsection. From the $x$-axis, the angle of desired line to be followed is denoted as $\theta_d$ (see figure 2). Two variables are introduced: the distance between the trailer and the line is defined as $h_e$, and the difference between the trailer orientation $\theta_t$ and the orientation of the desired line to be followed $\theta_d$ is denoted as $\theta_e$, $\theta_e = \theta_t - \theta_d$. Using (1) and from figure 2, The dynamics of these two variables is derived as:

$$\begin{aligned} \dot{h_e} &= v_s \cos\delta_s \cos\delta_h \sin\theta_e, \\ \dot{\theta_e} &= \frac{v_s}{l_t} \cos\delta_s \sin\delta_h. \end{aligned} \tag{2}$$

The problem of line following control problem becomes the stabilization problem of (2). Or on the other words, the truck-trailer follows the line if ($h_e$, $\theta_e$) goes to (0, 0).

### C. Steering Control

In this subsection, we assume that the linear velocity $v_s$ is any positive constant and the steering $\delta_s$ is the main concerned. The steering control for the line following control is derived based on the Lyapunov method. Let a Lyapunov function candidate $V$ be as follows:

$$\begin{aligned} V &= V_1 + V_2, \\ V_1 &= \frac{1}{2} h_e^2 + \frac{1}{2} \theta_e^2, \\ V_2 &= \frac{1}{2} \Delta\delta_h^2, \end{aligned} \tag{3}$$

where $\Delta\delta_h = \delta_h d - \delta_h$ and $\delta_{hd}$ is the desired value of heading angle $\delta_h$. At first, we will assume that $\delta_h d = \delta_h$ or $\Delta\delta_h = 0$.

*Theorem 1:* Consider equation (2). Suppose $v_s$ is any positive value and there exists a function of $\delta_s$ that drives $\Delta\delta_h$ to zero, or $\delta_{hd} = \delta_h$, and the $\delta_{hd}$ is set as

$$\delta_{hd} = -\arctan(\frac{l_t}{v_t}(k_{\theta_e}\theta_e + h_e v_t \frac{\sin\theta_e}{\theta_e})), \tag{4}$$

where $k_{\theta_e}$ is a positive constant and $v_t = v_s \cos\delta_h \cos\delta_s$. The origin of (2) is globally asymptotically stable.

*Proof*: Consider the Lyapunov function $V_1$. The time-derivative $V_1$ is

$$\begin{aligned} \dot{V}_1 &= h_e\dot{h}_e + \theta_e\dot{\theta}_e \\ &= h_e v_t \sin\theta_e + \theta_e v_s \tan\delta_h. \end{aligned} \tag{5}$$

Assuming $\delta_h = \delta_{hd}$ and using (4), (6) becomes

$$\begin{aligned} \dot{V}_1 &= h_e v_t \sin\theta_e - k_{\theta_e}\theta_e^2 - h_e v_t \sin\theta_e, \\ &= -k_\theta \theta_e^2 \leq 0. \end{aligned} \tag{6}$$

Since $V_1$ is a positive function and (6) is semidefinite negative, it can be concluded that $\theta_e \to 0$ as $t \to \infty$. Now, consider the closed loop equation of (2) with the use of (3).

$$\begin{aligned} \dot{h}_e &= v_t \sin\theta_e, \\ \dot{\theta}_e &= -k_{\theta_e}\theta_e - h_e\frac{\sin\theta_e}{\theta_e}. \end{aligned} \tag{7}$$

From the first equation (7), $h_e$ tends to a constant value when $\theta_e$ goes to zero. From the second equation (7), the term $\frac{\sin\theta_e}{\theta_e}$ goes to 1 as $\theta_e$ goes to zero. There is no change on the value of $\theta_e$ when it achieves zero, thus the $\dot{\theta}_e$ is also zero. Thus, the third term remains $h_e$ which is no other than zero. For equation (2), using (4) and assuming $\delta_{hd} = \delta_h$, we obtain $h_e \to 0$ and $\theta_e \to 0$ as $t \to \infty$, or the origin of the error is asymptotically stable. □

Now, we will derive the steering angle control so that the $\Delta\delta_h = 0$ is achieved.

*Theorem 2:* Let $v_s$ be a positive value, the desired steering angle $\delta_{hd}$ be defined as in (4), and the $\delta_s$ be as follows:

$$\begin{aligned} \delta_s &= -\arctan(\frac{l_h\cos\delta_h}{v_t}\Delta\delta_{hd} + \frac{1}{1+\dot{\delta}_{hd}}(\delta' + \delta'')), \\ \delta' &= -\frac{v_t}{l_h\cos\delta_h}\tan\delta_h, \\ \delta'' &= \frac{1 + h_e v_t(\theta_e\cos\theta_e - \sin\theta_e)}{l_t\theta_e^2} + v_t^2\frac{\sin\theta_e}{\theta_e}. \end{aligned} \tag{8}$$

$h_e$, $\theta_e$, and $\Delta\delta_h$ go to zero as $t$ go to infinity.

*Proof:* The proof of $h_e$ and $\theta_e$ go to zero as time goes to infinity has been affirmed in Theorem 1. Now, the proof of $\Delta\delta_h$ goes to zero is examined. The derivative of the Lyapunov function $V_2$ is

$$\dot{V}_2 = \Delta\delta_h\Delta\dot{\delta}_h, \tag{9}$$

The time-derivative of $\Delta\delta_{hd}$ is

$$\begin{aligned} \Delta\dot{\delta}_h &= \dot{\delta}_{hd} - \dot{\delta}_h, \\ &= \frac{1}{1+\dot{\delta}_{hd}}(\delta' + \delta'') - \frac{v_t}{l_h\cos\delta_h}\tan\delta_s. \end{aligned} \tag{10}$$

Substituting (8) and (10) into (9), we obtain

$$\dot{V}_2 = -\Delta\delta^2 \leq 0, \tag{11}$$

which conclude that the origin of $\Delta\delta \to 0$ as $t \to \infty$. □

## D. The Speed Control

In the previous subsection, the linear velocity input $v_s$ is defined as any positive constant. Here, the linear velocity input is designed to control the speed based on the pose of the truck-trailer with respect to the line to be followed. The speed should be reduced when the truck-trailer is far away from the configuration of the desired line and conversely the it should be increased when it is aligned. Thus, linear velocity $v_s$ is proposed as follows:

$$v_s = \frac{v_{s,max}}{1 + k_{v_s,\theta_e}|\theta_e| + k_{v_s,h_e}|h_e^2|}, \tag{12}$$

where $v_{s,max}$ is a determined maximum velocity of the truck-trailer, $k_{v_s,\theta_e}$ and $k_{v_s,h_e}$ are positive constants. From (12), the velocity $v_s$ is reduced whenever the error of the distance error $h_e$ or of the orientation $\theta_e$ is increased. When the errors $(h_e, \theta_e)$ are minimum,the velocity $v_s$ achieves the maximum speed.

The maximum velocity $v_{s,max}$ can be determined based on the performance of the truck-trailer. The parameters of speed control $k_{v_s,\theta_e}$ and $k_{v_s,h_e}$ and also parameter of the steering control $k_{theta_e}$ can be determined by an optimization method to achieve a specified performance.

## E. The Control Architecture

From the control design, we can determine the control architecture that should be implemented in the application of autonomous truck-trailer. In the control design, the control inputs are the linear velocity and the steering angle of the head-truck. The linear velocity can be directly set by manipulating the input to the traction engine, while the steering input can be achieved by accessing the hydraulic power steering. The feedback signals are the distance error $h_e$ and orientation error $\theta_e$ to the predetermined lines, and also the heading angle that is the angle between the head-truck and the trailer $\delta_h$. The error distance $h_e$ can be measured by magnetic, vision, or global localization sensors such as global positioning system (GPS), ultrasonic beam, etc. Magnetic sensors are the most common in the automated guided vehicles (AGVs) applications, in which the sensor magnetic measures the distance from the sensor to the magnetic line. The orientation distance $\theta_e$ and the heading angle $\delta_h$ can be obtained by implementing two amounts of those sensors.

The configuration of the sensors are shown in figure 3. Four sensors are placed, two are on the head-truck, $s_{h1}$

and $s_{h2}$, with distance of $l_{s,h}$ and two are on the trailer, $s_{t1}$ and $s_{t2}$, with distance of $l_{s,t}$. The sensors on head-truck measures the distance $h_{s,h1}$ and $h_{s,h2}$ and those of the trailer $h_{s,t1}$ and $h_{s,t2}$. The feedback signal $h_e$ is the same as the measured distance $h_{s,t1}$. The variables $\theta_h$, $\theta_e$, and $\delta_h$ are calculated using the following formula:

$$\begin{aligned} \theta_h &= \arcsin(\frac{h_{s,h2} - h_{s,h1}}{l_{s,h}}), \\ \theta_e &= \arcsin(\frac{h_{s,t2} - h_{s,t1}}{l_{s,t}}), \\ \delta_h &= \theta_h - \theta_e. \end{aligned} \tag{13}$$

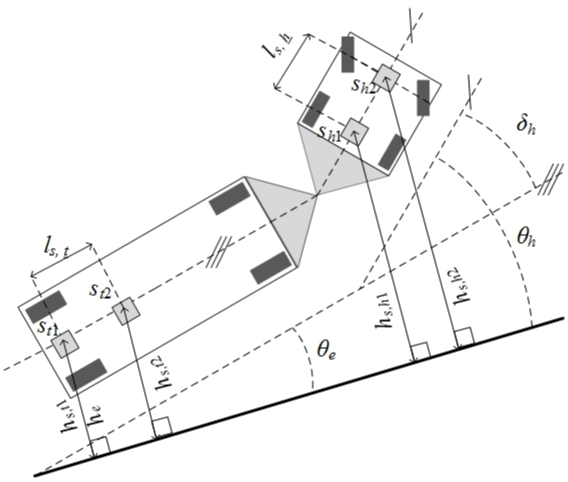


Fig. 3. The configuration of sensors for autonomous line following.

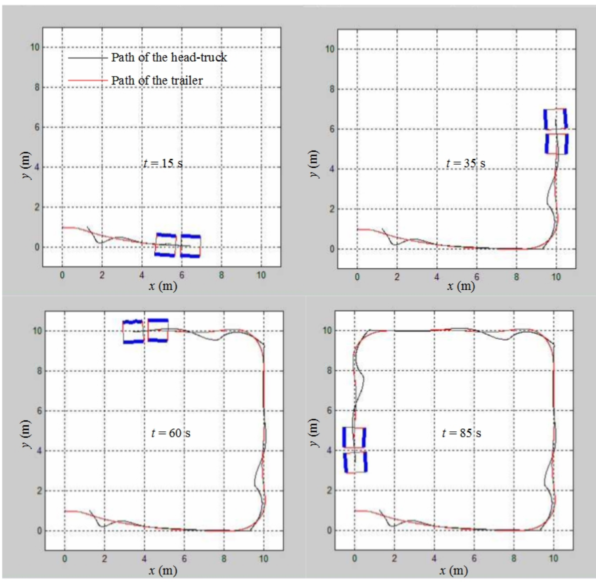


Fig. 4. The motion of truck-trailer following the rectangular line with the vertices of (0, 0), (0, 10), (10, 10), (0, 10). The black-line shows the path of the head-truck and the red line shows the path of the trailer

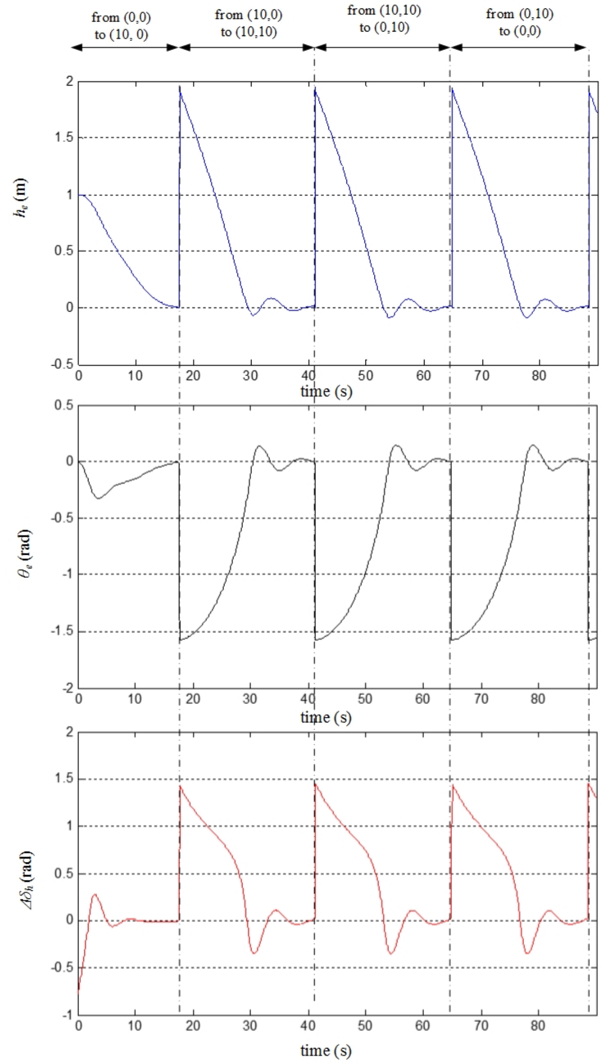


Fig. 5. The errors of the distance $h_e$ and of the angle $\theta_e$ between the truck-trailer to the desired line, and the error of the heading angle $\Delta\delta_h$ between the desired and the measured heading angle

## III. Simulation Results

In this section, a simulation of truck-trailer following a rectangular line is conducted. The vertices of rectangular ($x$m, $y$m) are (0, 0), (10, 0), (10, 10) and (0, 10). There is no a specified curvature assigned between edge. The switch from one edge to another is based on a simple finite-state-automata in which it will excited when the distance between the truck-trailer to the next line segment is 2 m. The steering angle $\delta_s$ and the heading angle $\delta_h$ are constrained with the range of (-0.78, 0.78) rad. The parameters are set by minimizing the trajectories of $h_e$ and $\theta_t$, as follows: $v_{s,max}$ = 0.67 m/s, $k_{v_s,\theta_e}$=3.73 $s^-1$, $k_{v_s,h_e}$=1.5 $s^-1$, $k_{\theta_e}$=1 rad. It is noted that the parameters does not affect to the stability of the closed-loop system and the asymptotic stability has been assured for any initial condition. The parameters however determine the performance of the truck-trailer movement.

The motion of the truck-trailer is depicted in figure 4. The initial position of the truck trailer is at $x_t(0)$=0m, $y_t(0)$=1m, $\theta_t(0)$=0rad, and $\delta_h(0)$=0rad. The first line that the truck-trailer should follow is the edge that conducts the vertices (0, 0) and (10, 0). The simulation shows that the truck-trailer can follow the desired rectangular line.

The ability of truck-trailer in following the predetermined line means that the errors of the distance $h_e$ and of the angle $\theta_e$ between the truck-trailer to the desired line converge to zeros as the truck-trailer moves. The difference heading angle $\Delta\delta_h$ between the designed and the measured heading angle also goes to zero. The facts are shown in figure 5. When the switch of desired line is excited, the errors tends to increase, however the control strategy brings the errors decrease to zero.

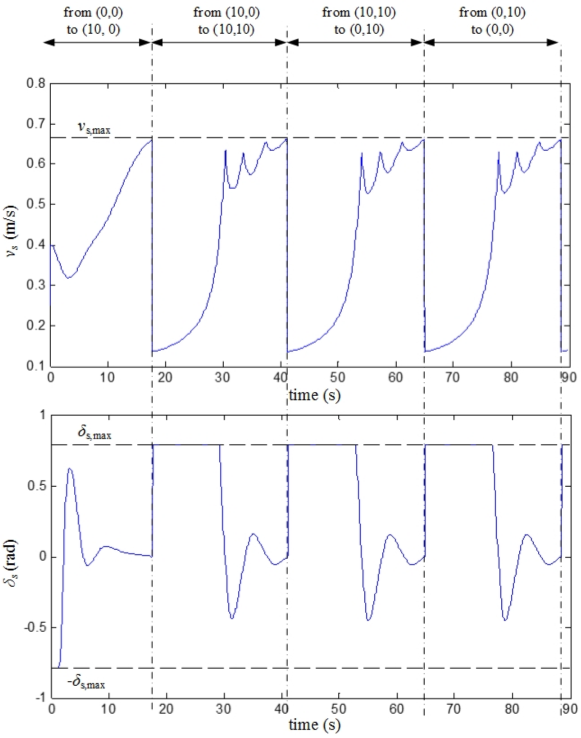


Fig. 6. The control inputs.

From the plot of control inputs in figure 6, we can find that the control inputs linear velocity $v_s$ can achieve the maximum velocity, however the linear velocity decreases whenever the configuration of the truck-trailer is not align with the desired line. The steering angle is also available to be maintained in the range of the steering angle that is $(-\delta_{s,max}, \delta_{s,max})$.

## IV. Conclusion

The line following control algorithm for truck trailer and its architecture have been presented. The design conducts the global asymptotic stability of the origin of the errors, which are the distance and orientation errors between the truck-trailer configuration and the line to be followed. The assurance of the asymptotic stability assures that the proposed algorithm drives the truck-trailer to follow any designated line. The control structure also allows the inclusions of constraints of the truck-trailer such as the range of linear velocity, the heading angle, and the steering angle that can be handled by a truck trailer. Simulation results show the effectiveness of the proposed controller, where a truck trailer is assigned to follow a rectangular which is not continuous at each vertex.

## V. Acknowledgment

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