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Implementation of Motion Controller Based On Kinetic Constraints for Tractor-Trailer System

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Abstract

In our era, the science and technology have been developed significantly. One of the examples is the common appearance of robotic system in our lives. However, it does not only operate alone in workspace but also manipulate in a group of collaborators. As a result, there is an emergent need to develop the multi-agent system. The connected agents perform well in logistics, warehouse management or agriculture and brings many benefits for mass production. To support the operators, in this paper we present a method to control the system with respect to the coordinates of the trailer. Firstly, the construction of tractor-trailer AGV kinematics model is launched in the virtual environment of Matlab Simulink software via differential equations in order to simulate its response to the control signal which are the linear and agular velocity of the tractor itself. Secondly, the flatness-based representation of the model in order to establish the control law which stabilizing the linearization feedback error. This controller is then numerically analyzed and computed using Matlab, and later implemented in the model of the first part so that the efficiency of the controller can be evaluated. Under the impact of proposed controller, the tracking error of whole system tends to zero while the system stability is guaranteed. Several suggestions for future works are mentioned to support the other developers in the field of multi vehicles. It can be seen clearly that our approach is feasible, innovative and robust to the industrial applications in real world.

Index Terms— Model predictive control, connected agents, smart agriculture, linearization feedback, motion control.

I. INTRODUCTION

Recently, more and more attention has been paid to the tractor-trailer vehicle thanks to its capability of high transport efficiency and low-fuel consumption. In single AGVs, there are certain limits about the amount of loads it can carry and the risk of making the vehicle unstable. On the other hand, in the tractor-trailer model, the system will be able to function more effectively with higher number of loads within the trailer.

Moreover, the tractor-trailer AGV has been playing a vital role in many submissions of the industry such as indoor transportation and delivery systems because of its simplicity, efficiency and flexibility. The considered system involves of the tractor which is a classical robot with a swivel wheel and two active wheels controlled by two different wheel torques making the trailers tracking a feasible trajectory. By adding or releasing several trailers, the system can move payloads following a given path without changing any actuators. It is clear that the tractor trailer AGV includes many wheel mobile robots, therefore, it is still the nonlinear and underactuated system subjected to non-holonomic constraints, leading to significant complexity in control tasks. In the objective of this paper, the slave robots must track a desired position and orientation with a specified timing law. There were many controllers which were proposed to control single vehicle [13–16], but none of them can be applied directly or indirectly because of the variation in kinematic and dynamic model of the two types.

II. BACKGROUND WORKS

Controlling the systems perfectly is still a challenging problem because of its characteristic of an underactuated system. Many approaches have been taken to simulate the controller for tractor-trailer vehicles including using linear quadratic regulator (LQR) with linearized time-variant system or non-linear model predictive control (MPC) on the level of kinematics [1].

To achieve satisfactory control performance, several studies have focused on various control methods to implement trajectory tracking for this kind of vehicle system. A survey about this kind of connected vehicle system can be found in [7-9]. As for internal dynamics of the underactuated vehicle system, authors revealed that the number and type of interconnections will influence the nonminimum-phase effects for this system in [10], and then, a general trajectory tracking control solution was proposed for truly *N*-trailer robots comprising an unicycle-like tractor and arbitrary number of passive trailers with sign-homogeneous nonzero hitching offsets [11]. In [12], a Lyapunov-based kinematic control law and a feedback linearization-based dynamic controller were separately reported to make up a robust adaptive dynamic controller, by which a favorable tracking performance can be achieved. Admittedly, these investigations can achieve good control performance for the vehicle system, but finding an appropriate Lyapunov candidate is indeed a difficult matter for the control scholars.

Author(s)	Methodology	Advantage(s)	Limitation
Binh et al. [2]	Error tracking controller is designed with adaptive control to estimate the unknown parameters in tractor trailer wheeled mobile robot in both kinematic and dynamic model.	The approach is robust with regard to the ability to adapt thorough the variation of the parameters.	The trajectory was generated without considering the model.
Khalil Alipour et al. [3]	Sliding mode control is utilized with a view to ensuring the robustness and handling the constraints of the system.	The paper completely handles the geometrical constraints and the phenomenon of slipping wheels	The work requires various mathematical transformation before being applied, which may cause computational difficulties.
Asghar et al. [4]	The modeling of the system is based on geometrical data and the controller is Lyapunov-PID based.	The introduction of spherical wheels helps increase the robots' maneuverability and reduce non-holonomic constraints.	The dynamics model is not considered in the approach.
Khalaji et al. [5]	At the beginning, system dynamic equations are obtained. A non-model-based control algorithm using PD-action filtered errors has been used in order to control the wheeled robot. Non-model-based controllers are always more appropriate than model-based algorithms due to lower dependency on dynamic models, lower computational costs, and also robustness to uncertainties. Asymptotic stability of the closed-loop system then has been investigated using Lyapunov method and Barbalat's lemma.	Asymptotic stability of the system is mathematically guaranteed and a method of non-model-based control is introduced with its efficiency, reducing the computational burden.	As the model is not taken into account, the trajectory hence has no connection with the kinematics and dynamics of the model.

Table 1. Summary list of the state-of-art previous works

III. PROBLEM STATEMENT

As can be seen from the Table 1. Most of the researches separate the connection between the model and the trajectory. This is the issue where flat properties are needed. Hence, the trajectory will be generated after constructing the model.

Besides, with regard to the model, the load of the trailer is supposed to be constant, hence only kinematics model is considered.

IV. PROPOSED APPROACH

With regard to the controller, the approach applied would be flatness-based. With this method, the vehicle would be controlled by an explicit signal formed by the states of the systems and their derivatives. Roughly speaking, because the system is differentially flat, the inputs can be determined from a set of outputs without integration. Differentially flat systems were originally studied by M. Fliess [2]. Flatness-based control techniques have been developed and utilized in various industrial application with a great success in solving planning and tracking problems of desired trajectories such as thermal process control [3], motors control [4], chemical reactor control [5], crane control [6] etc. Hence, with a view to controlling the midpoint of the trailer (slave) to follow a desired path, the theory of differentially flat systems will be used to create the control signal. In other words, the objective of this design is to control the position of the passive trailer (the slave) by controlling the linear and angular velocity of the tractor, or the master. Finally, the results of previous work are summarized in Table 1.

The paper is organized in the following manner: Section V introduces the objective of the paper and includes the modeling of the tractor-trailer kinematic system. Then the trajectory generation and tracking will be covered in Section VI using the flat representation and also, a controller will be designed in this section using the control theory of linear system. The mathematic model and controller then will be simulated in Section VII with the help of MATLAB. Conclusion then summarize the paper in Section VIII.

V. MODEL CONSTRUCTION

In this section, we introduce the mathematic model of the tractor-trailer AGV and the control objective. Describing the model constraints, we use the transformation to eliminate this constraint to build the kinematic model. We design a desired trajectory and present several assumptions to find the linear and angular velocity of the system.

The modeling of the system will be depicted in Fig. 2 which includes the models of a tractor and a trailer with the centers of the two parallel plating wheels respectively named P and K (d=PK) as Table 2.

Consider $u = [v \quad \omega]^T$ as the system's input, where v is defined in Table. 1 as the linear velocity and ω is the angular velocity of the tractor, (or $\omega = \frac{d\varphi}{dt}$). Also, set $\boldsymbol{q} = [x, y, \varphi, \theta]^T$ as the states describing the entire model.

Similarly, the control system's schematic is illustrated in Fig.1 where the posture controller computes the control signal using the flat output and the reference of desired path.

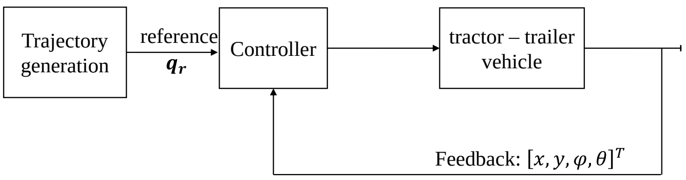

Fig.1 Schematic diagram of the control system

Finally, the kinematic model of the underactuated system is mathematically described as follows [1]:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta)\cos(\varphi-\theta) & 0 \\ \sin(\theta)\cos(\varphi-\theta) & 0 \\ 0 & 1 \\ \frac{1}{d}\sin(\varphi-\theta) & 0 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \qquad (1)$$

VI. TRAJECTORY GENERATION AND TRACKING

A. S-curve planning

Definition	Symbol (unit)
Coordinates of point K	$x, y\ (m)$
Distance between points P and K	$d\ (m)$
Orientation of the frame attached to tractor	φ
Orientation of the frame attached to trailer	θ
Angular velocity of tractor	ω
linear velocity of point P	v

Table 2. The parameters and variables of the investigated system

In this paper, because of the importance of the smoothness in the desired path, S-curve planning will be calculated in order to create an ideal reference. Moreover, to simplify the generation problems, third-order polynomial S-curve would be mathematically sufficient to create a path for point-to-point movement of the vehicle.

More specifically, let $x_r(t), y_r(t)$ and $\theta_r(t)$ be the reference function of the desired path and have the form as belows:

$$\begin{cases} x_r(t) = a + bt + ct^2 + dt^3 \\ y_r(t) = 3x_r(t) \\ \theta_r(t) = \arctan\frac{\dot{y}_r}{\dot{x}_r} \end{cases} \qquad (2)$$

However, to make the computing with Matlab Simulink more easily, $\theta_r(t)$ should be calculated from its derivative:

$$\dot{\theta}_r(t) = \frac{\ddot{y}_r\dot{x}_r - \ddot{x}_r\dot{y}_r}{\dot{x}_r^2 + \dot{y}_r^2}$$

In this case $\theta_r(t) = \arctan(3) = constant$

Finally, it is worth mentioning that the reference trajectory, namely $q_r = [x_r(t), y_r(t), \theta_r(t)]^T$, and the reference control inputs and their derivatives are all continuous and uniformly bounded.

With the equations in (2), it can be seen that the flat output of the system is $[x(t); y(t)]$, which means all the output and input can be described with the flat output and its derivatives.

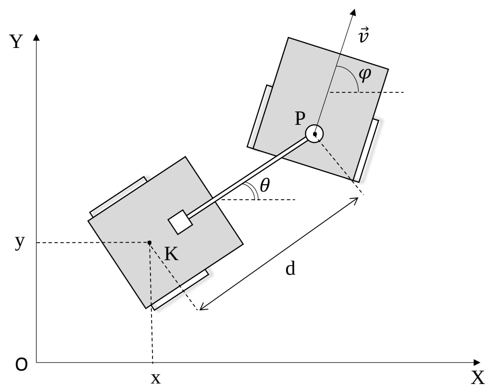

Fig 2. Illustration of tractor-trailer vehicle modeling

B. Tracking error dynamics

As we know, open-loop steering alone will usually not be enough to achieve satisfactory tracking along a reference trajectory unless the model is completely matching the system in reality (which is impossible). This suggests that a feedback controller must be introduced to assure that the actual trajectory follows the planned one, even if the initial conditions of the physical model do not coincide with those used for planning, and even if the model does not match the actual behavior very well.

Therefore, as mentioned above, a flatness-based controller will be designed in order to establish a closed loop control driving the vehicle to track the reference posture trajectory, together with the knowledge of tracking error dynamics in linear systems.

Recall the mathematical model in equation (1) we can have:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta)\cos(\varphi-\theta) & 0 \\ \sin(\theta)\cos(\varphi-\theta) & 0 \\ \frac{1}{d}\sin(\varphi-\theta) & 0 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

Then take the derivative of both sides, we have:

$$\begin{bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{\theta}\end{bmatrix} = R(\varphi,\theta)\begin{bmatrix}\dot{v}\\ v\dot{\theta}\\ v\dot{\varphi}\end{bmatrix} \qquad (3)$$

where

$$R(\varphi,\theta) = \begin{bmatrix}\cos(\theta)\cos(\varphi-\theta) & \sin(\varphi-2\theta) & -\cos(\theta)\sin(\varphi-\theta)\\ \sin(\theta)\cos(\varphi-\theta) & \cos(\varphi-2\theta) & -\sin(\theta)\sin(\varphi-\theta)\\ \frac{1}{d}\sin(\varphi-\theta) & -\frac{1}{d}\cos(\varphi-\theta) & \frac{1}{d}\cos(\varphi-\theta)\end{bmatrix}$$

On the other hand, the tracking error yields:

$$e(t) = \begin{bmatrix}x(t)-x_r(t)\\ y(t)-y_r(t)\\ \theta(t)-\theta_r(t)\end{bmatrix}$$

and we choose desired error dynamics as:

$$\ddot{e}(t) + K_1\dot{e}(t) + K_2 e(t) = 0 \qquad (4)$$

Here, K_1 and K_2 can be chosen as positive scalars with respect to the characteristic equation:

$$s^2 + K_1 s + K_2 = 0$$

We then can choose the roots (or the poles) of the equation in order to determine the error dynamics.

In order to establish the relation between our desired error dynamics and vehicle model, from (4) we derive expression for acceleration:

$$\begin{bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix}\ddot{x}_r\\ \ddot{y}_r\\ \ddot{\theta}_r\end{bmatrix} - K_1\begin{bmatrix}v.c\theta.c(\varphi-\theta)-\dot{x}_r\\ v.s\theta.c(\varphi-\theta)-\dot{y}_r\\ \frac{v}{d}.s(\varphi-\theta)-\dot{\theta}_r\end{bmatrix} - K_2\begin{bmatrix}x-x_r\\ y-y_r\\ \theta-\theta_r\end{bmatrix} \qquad (5)$$

With $c\theta = \cos(\theta)$; $s\theta = \sin(\theta)$;
$c(\varphi-\theta) = \cos(\varphi-\theta)$; $s(\varphi-\theta) = \sin(\varphi-\theta)$

As the right-hand sides of (3) and (5) must be equal we now have:

$$\begin{bmatrix}\dot{v}\\ v\dot{\theta}\\ v\dot{\varphi}\end{bmatrix} = R(\varphi,\theta)^{-1}\left[\begin{bmatrix}\ddot{x}_r\\ \ddot{y}_r\\ \ddot{\theta}_r\end{bmatrix} - K_1\begin{bmatrix}v.c\theta.c(\varphi-\theta)-\dot{x}_r\\ v.s\theta.c(\varphi-\theta)-\dot{y}_r\\ \frac{v}{d}.s(\varphi-\theta)-\dot{\theta}_r\end{bmatrix} - K_2\begin{bmatrix}x-x_r\\ y-y_r\\ \theta-\theta_r\end{bmatrix}\right] \qquad (6)$$

From here, the differential equations of the control input can be extracted to form the tracking control law.

More specifically, from the first and the third row of (6) we have:

$$\begin{cases}\dot{v} = \lambda_1(\varphi,\theta)\xi & (7)\\ \dot{\varphi} = \dfrac{\lambda_2(\varphi,\theta)\xi}{v} & (8)\end{cases}$$

With $\lambda_1(\varphi,\theta) \in \mathcal{R}^{1\times 3}$, the first row of $R(\varphi,\theta)^{-1}$

$$\lambda_1(\varphi,\theta) = \begin{bmatrix}\dfrac{\cos(2\varphi-\theta)+\cos(2\varphi-3\theta)+2\cos(\theta)}{\cos(\varphi-\theta)}\\ \dfrac{\sin(2\varphi-\theta)-\sin(2\varphi-3\theta)+2\sin(\theta)}{\cos(\varphi-\theta)}\\ d\sin(\varphi-\theta)\end{bmatrix}^T$$

Then $\lambda_2(\varphi,\theta) \in \mathcal{R}^{1\times 3}$, the third row of $R(\varphi,\theta)^{-1}$

$$\lambda_2(\varphi,\theta) = \begin{bmatrix}-\dfrac{\sin(2\varphi-\theta)+\sin(2\varphi-3\theta)+4\sin(\theta)}{\cos(\varphi-\theta)}\\ \dfrac{\cos(2\varphi-\theta)-\cos(2\varphi-3\theta)+4\cos(\theta)}{\cos(\varphi-\theta)}\\ d\sin(\varphi-\theta)\end{bmatrix}^T$$

And $\xi \in \mathcal{R}^{3\times 1}$,

$$\xi = \begin{bmatrix}\ddot{x}_r\\ \ddot{y}_r\\ \ddot{\theta}_r\end{bmatrix} - K_1\begin{bmatrix}v.c\theta.c(\varphi-\theta)-\dot{x}_r\\ v.s\theta.c(\varphi-\theta)-\dot{y}_r\\ \frac{v}{d}.s(\varphi-\theta)-\dot{\theta}_r\end{bmatrix} - K_2\begin{bmatrix}x-x_r\\ y-y_r\\ \theta-\theta_r\end{bmatrix}$$

In short, now the linear velocity required can be numerically calculated with the differential equation (7) and that value in turn will be used to calculate $\dot{\varphi}$ (or ω) in the equation (8).
The structure of the controlled system is depicted in Fig 3.

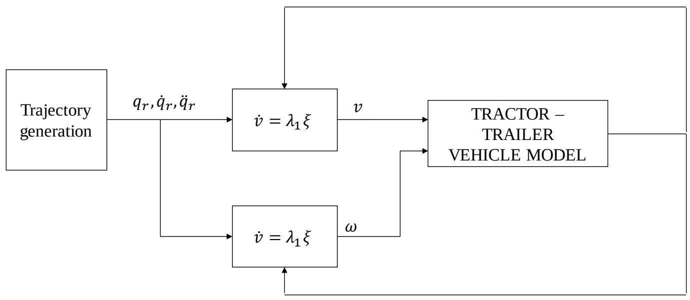

Fig.3 Structure of the tracking control loop for the vehicle model

VII. RESULTS OF STUDY

A. Trajectory generation and tracking performance.

The simulation of this model can be generated in MATLAB with the SIMULINK tools as Fig. 4-7. In this paper, the trajectory generation of the S curves will be constructed with the conditions below:

When $t = 0$ (s)

$$\begin{cases}x_r(0) = 0\\ \dot{x}_r(0) = 0\end{cases}$$

When $t = t_f = 5$ (s)

$$\begin{cases}x_r(t_f) = 5\\ \dot{x}_r(t_f) = 0\end{cases}$$

So, the parameters of $x_r(t)$ in (2) can be calculated as:

$$\begin{cases}a = 0\\ b = 0\\ c = 0.15\\ d = -0.01\end{cases}$$

And $y_r(t) = 3x_r(t)$

With the desired path, the results of the tracking of the vehicle are shown below:

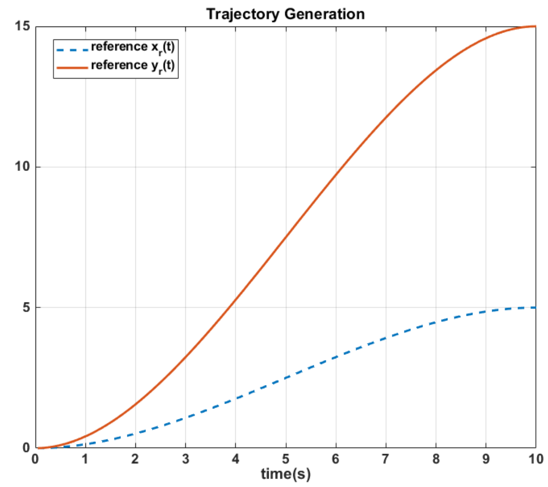

Fig.4 Trajectory generation of $y_r(t)$ and $x_r(t)$

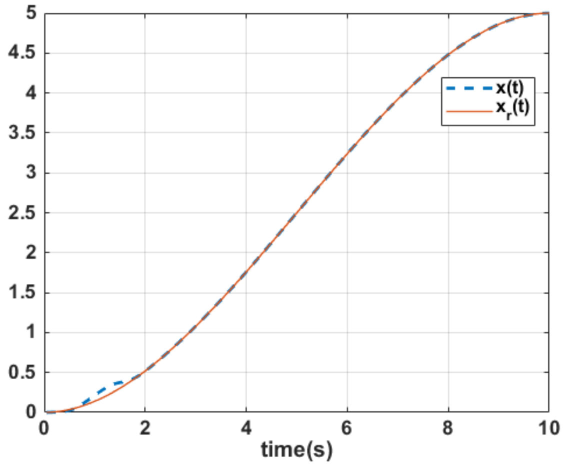

Fig.5 The tracking of $x(t)$ to $x_r(t)$ of the trailer (slave)

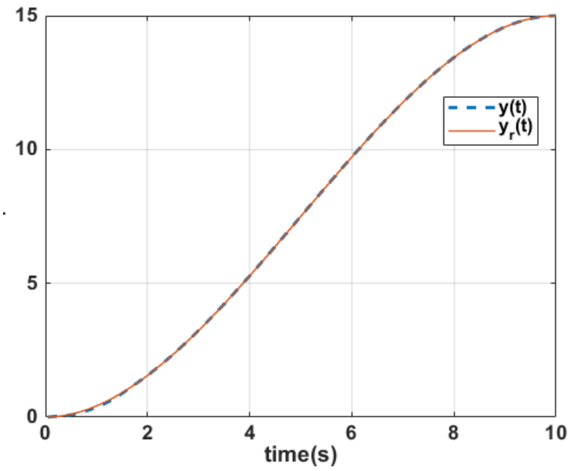

Fig.6 The tracking of $y(t)$ to $y_r(t)$ of the trailer (slave)

When it comes to the error dynamics controller, the behavior

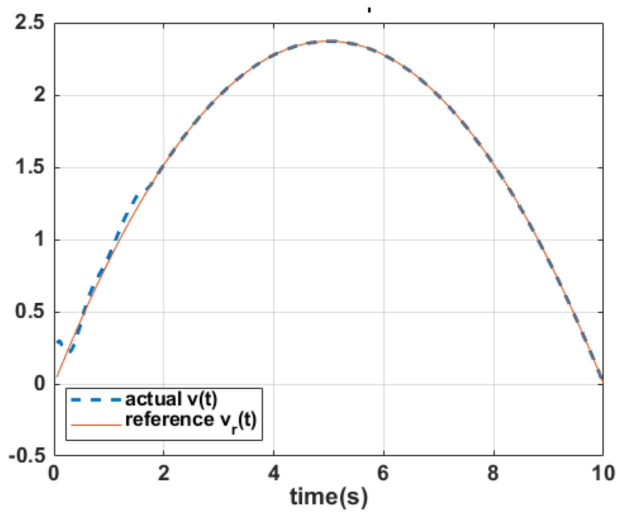

Fig.7 The tracking of $v(t)$ to $v_r(t)$ of the trailer (slave)

of this error is described with linear transfer function containing two poles at (-40, -40). Besides, it is important to physically limit the control signals to make the modeling more reasonable. In this case, the angular velocity will be limited in $\pm 1\frac{rad}{s}$.

Similarly, the steady error of the linear velocity is equal to zero with the controller proposed. In this experiment, the initial condition of the states can be expressed as:

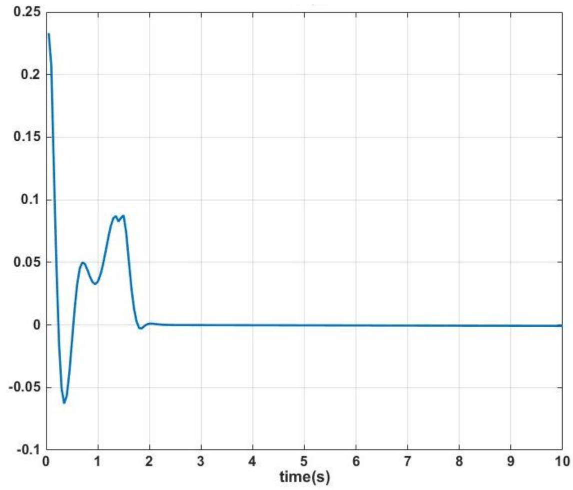

Fig.8 Error between $v(t)$ and $v_r(t)$

$$q(t=0) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

It can be noticed that, in the first few miliseconds, the system has to adjust its position and velocity in order to track the trajectory. Therefore, there is a peak near $t = 0\ (s)$.

B. *Error analysis*

In this section, the distribution of the error vectors will be calculated so as to evaluate the efficiency of the controller as

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Fig. 8-10.

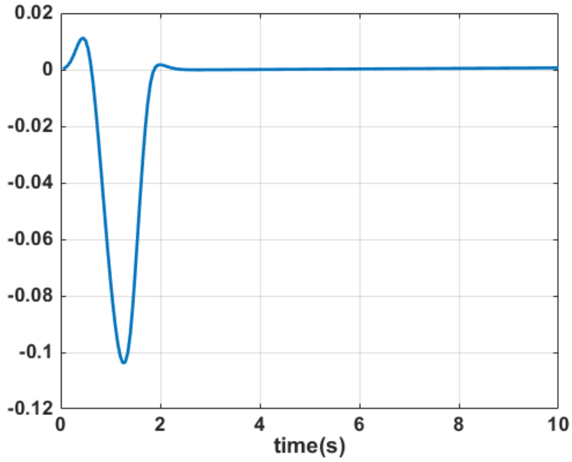

Fig.9 Error between $x(t)$ and $x_r(t)$

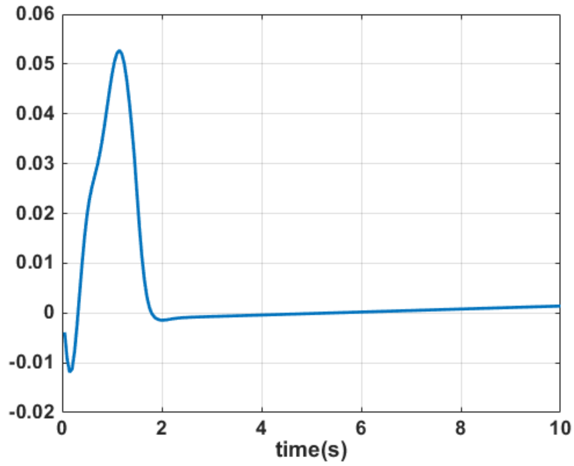

Fig.10 Error between $y(t)$ and $y_r(t)$

The root mean square definition will be introduced in order to evaluate the result: with a data set $X = \{x_1, x_2, x_3, \dots, x_n\}$ we have:

$$RMS(X) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}$$

Items	RMS	Min	Max
x *error* (mm)	23.56	1.2×10^{-4}	103.8
y *error* (mm)	13.1	0.001	52.74
v *error* (mm/s)	32.09	0.019	233.16

Table 3. Evaluation of the errors

The table suggests that the root mean square of the position error has the value of ~10-20 mm. Besides, the maximum value of the position errors is relatively acceptable (about 100 mm) compared to the path evaluated (5m and 15m). Finally, although the actual linear velocity eventually meets the trajectory path, the maximum error is still large compared to the velocity evaluated. This problem may be caused by the reaction of the system to the difference between the desired path and the initial actual condition.

VIII. CONCLUSIONS

Many approaches have been taken to control the tractor trailer system so that they can be applied to the AGV in factories with stronger capability of carrying loads. This paper is devoted to create a classic kinematic model of tractor trailer system and then design a controller using the theory of differentially flat system. The flatness-based control is used to generate the desired trajectory and to force the vehicle to follow it. Simulation results show the proposed algorithm efficiencies.

In this report, the design method is divided into two parts. Firstly, an appropriate reference trajectory is chosen to nominally establish a desired motion using polynomial functions. Hence, the corresponding control trajectories can be obtained with the controller. Second, the dynamics for the error on the flat output trajectory are designed based on the insight of the transfer function's poles in linear system. This control characteristic then is used to calculate the corresponding law based on the closed loop control model. These two steps may be applied to many flat systems.

However, the method may seem to be complicated due to the fact that there are so many values needed to be mesured in order to calculate the next control input. Hence, this method definitely needs further improvement. More specifically, thanks to the existing flat property of the tractor-trailer model, we can then take advantage of the flat representations of u via the function of the flat output. Then linearisation of tracking error should be implemented in order to stablise the whole system.

Finally, one important points that is ignored during this simulation is the constraints of the systems. They are barely mentioned in the saturation of the controller, however, there should be more than just the constraints of the controller. In real system, constraints can be in the limit of the wheels' angular velocity, the variation of the linear velocity and the limit of the angles (φ, θ).

In conclusion, the method proposed is applicable in terms of the use of AGV in industrial system but further improvement needs carrying out in terms of the modeling and the designing of the controller in order to fully describe the reaction of the vehicle in real application.

METHOD AND DISCUSSION

From the view of flatness-based control, the motion controller for tractor-trailer system is implemented. The high performance of tracking error and robustness has been validated by numerical simulations such that this system could follows the complicated trajectory in practical scenario. Several comments have been demonstrated in this paper for further development.

LIST OF ACRONYMS

AGV: Automated Guided Vehicle.
LQR: Linear Quadratic Regulator.
MPC: Model Predictive Control.
PID: Proportional Integral Derivative.
PD: Proportional Derivative.

RMS: Root-mean-square.

CONFLICT OF INTERESTS

There is no conflict.

AUTHOR CONTRIBUTIONS

The author fully contributes in this work.

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