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Path-tracking Control of a Tractor-aircraft System

Nengjian Wang, Hongbo Liu* and Wanhui Yang

School of Mechanical and Electrical Engineering，Harbin Engineering University, Harbin 150001, China

Abstract: An aircraft tractor plays a significant role as a kind of important marine transport and support equipment. It's necessary to study its controlling and manoeuvring stability to improve operation efficiency. A virtual prototyping model of the tractor-aircraft system based on Lagrange's equation of the first kind with Lagrange mutipliers was established in this paper. According to the towing characteristics, a path-tracking controller using fuzzy logic theory was designed. Direction control herein was carried out through a compensatory tracking approach. Interactive co-simulation was performed to validate the path-tracking behavior in closed-loop. Simulation results indicated that the tractor followed the reference courses precisely on a flat ground.

Keywords: path-tracking controller; aircraft tractor; preconcert route; fuzzy control; co-simulation
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1 Introduction

Automatic guidance of industrial articulated vehicles, such as mining trucks, earth-removal and road-paving vehicles, intercity bus travels, and automated guided vehicles (AGVs), (Lane *et al*., 1994; Larsson *et al*., 1994; Hirose *et al*., 1995; Rabinovitch and. Leitman, 1996; de Santis, 1997; Lamiraux *et al*., 1999); have over 80 years, received a great deal of attention from researchers. Recently, a study in intelligent control technology for maritime applications has prompted more research investigating. For more than 20 years the study of tractor aircraft systems has provided vital information for on researching maritime vessel transportation. The process has been noted as to being a complicated nonholonomic, under-actuated and nonlinear system. The path-tracking plays a significant role in improving operation efficiency (Rifford, 2004, 2006, 2008; Nakamura *et al*., 2001). Wang (1994) Aircraft tractors are essential tools for aircraft movement on large ships, as well as takeoff and landing. The mechanism is different from a shore-based allocation and transporting of an aircrafts; tractors on the ship are placed in less than ideal environments, narrow space and exclusive transportation facilities by Han *et al.* (2010). Relatively good transport efficiency and flexibility are required during these tasks. As a result, the lack of maneuverability has increased a higher rate of involvement in fatal accidents.

Through constant evolution and development of computer and sensor technologies, research on tracking control methods for two-wheeled and car-like mobile robots have increased significantly(de Wit *et al*., 1993; Kanayama *et al*., 1990, 1991; Murray and Sastry, 1993; Samson and Ait-Abderrahim, 1991a, 1991b) .

In addition, a few researchers have explored in greater detail the study of tracking control of trailer systems, which basically consist of a steering tractor and a passive trailer, linked with a rigid joint, such as a tractor-aircraft system. As noted in the references listed: (Lamiraux and Laumond, 1997; Sekhavat *et al*., 1997; Yuan and Huang, 2006) much of the interest driving experimentation, is the utilization of trailers on mobile robots. However, problems occur due to the controlling of the system from the viewpoint of the mobile robot and not a passive trailer. In 1994, de Santis, conducted a simple linear control study using a linearized model designed for a trailer system. The research is of great interest and a positive perspective on the study of tracking control systems guide points have been explored for future recommendations.

The study was divided into three components: First, analyzing the tractor aircraft systems, examining the marine transport equipment, and understanding the procedures of the maneuvering stability of a ship. Next, the research focused on guiding a path tracking controlled aircraft tractor into preconcerted routes and keeping a smooth motion, almost like a flat ground on a ship. Thirdly, the paper focused on analyzing the performance of the tractor in an automatic navigation system setting.

The research study utilized the fuzzy logic theory as a measuring tool in the designing of the controller for the tractor-aircraft system. The researcher also took into account factors for the adverse effects, caused by factors such as tire slippage. The direction control was performed through a compensatory tracking approach method.
The organizational flow of the research paper has been divided into five sections. In section II, the research focused on the kinematic and virtual prototyping model of the aircraft-tractor system. Section III, focused on the

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***Corresponding author Email:** lhbcims10@163.com

design of the fuzzy control system, while section IV contains simulation results. The paper concludes with remarks and recommendations in section V.

2 Model of a tractor-aircraft system

2.1 Kinematic model

The model is based on a rigid multiply body that consists of a tractor, a drawbar, the undercarriage and fuselage, ignoring, for the moment, the flexibility of the tractor suspension and undercarriage buffer system.

It is usually assumed that the wheels do not slip. The deformation of the tires is also ignored for the sake of simplicity. These assumptions are acceptable for tractor towing at low speeds:

(1) Calculate the lateral component of constraint force on the tractor-aircraft system junction.

(2) The relative angles between the various parts are small, and the tractor front wheel steering angle is small.

(3) Examine the wheels rolling resistance, back torque and air resistance. Primarily consider the lateral and the swaying motions of the tractor-aircraft system illustrated in Figure 1.

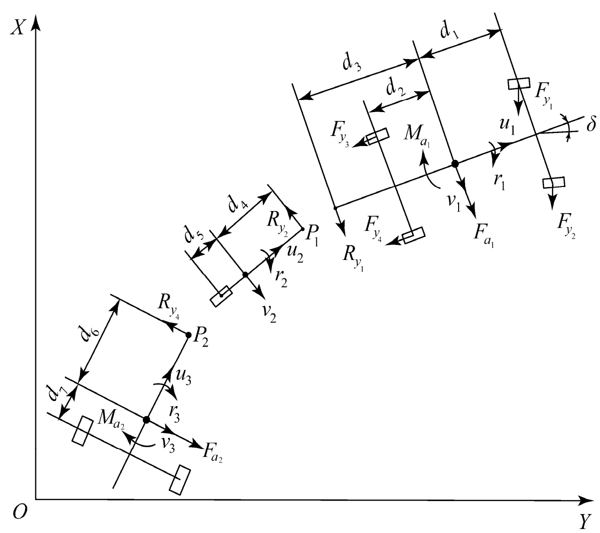


Fig. 1 Kinematic model of a tractor-aircraft system

Dynamical equations of the tractor are shown as the following.

$$m_1(\dot{v}_1 + u_1 r_1) = F_{y1}\cos\delta + F_{a1} + F_{y2} + R_{y1} \quad (1)$$

$$J_{1z}\dot{r}_1 = F_{y1}d_1\cos\delta - F_{y2}d_2 - R_{y1}d_3 + M_{a1} \quad (2)$$

The drawbar and the nose landing gear dynamical equations are depicted as:

$$m_2(\dot{v}_2 + u_2 r_2) = R_{y3} - R_{y2} + F_{y3} \quad (3)$$

$$J_{2z}\dot{r}_2 = -R_{y2}d_4 - R_{y3}d_5 - F_{y3}d_5 \quad (4)$$

Dynamical equations of the fuselage and the rear landing gear are founded with the expression

$$m_3(\dot{v}_3 + u_3 r_3) = F_{a2} + F_{y4} - R_{y4} \quad (5)$$

$$J_{3z}\dot{r}_3 = -R_{y4}d_6 + M_{a2} - F_{y4}d_7 \quad (6)$$

where m_i represents the mass (the subscript i=1,2,3 denotes the tractor, the drawbar and the aircraft respectively), u_i is the marching velocity, r_i is the sway rate and F_{yi} is the cornering force on the tractor wheel, R_{yi} is the lateral constraint reacting force on the articulation and the vertical moment of inertia is expressed with J_{iz}, F_{ai} and M_{ai} are the accessional lateral force and torque on the centroid, δ is the tractor front wheel steering angles, d_1, d_2 are the distances from the tractor centroid to the front and rear axle, d_3 is the distance from the tractor centroid to the anterior to the drawbar, d_4, d_5 are the distances from the drawbar centroid to its foreside and rearward, d_6, d_7 are the distances from the aircraft centroid to the front and rear axle.

Cornering force on the tractor wheels F_{yi} is defined as a function of the slip angle. When the lateral acceleration is less than 0.4g, the slip angle is generally no more than 4°-5°, the tire cornering properties are in the linear range.

Cornering force is given by $F_{yi} = k_i a_i$, where k_i is the cornering stiffness, its value is negative, a_i is the tire slip angle.

The state equation of tractor-aircraft towing operation can be described by means of:

$$\boldsymbol{K} \cdot \dot{\boldsymbol{X}} = \boldsymbol{L} \cdot \boldsymbol{X} + \boldsymbol{M} \cdot \boldsymbol{U} + \boldsymbol{N} \cdot \boldsymbol{T} + \boldsymbol{S} \cdot \boldsymbol{F} \quad (7)$$

2.2 Virtual prototyping model

Using the ADAMS/View program(Elliott, 2000), a virtual prototyping model is created as shown in Figure 2. A centralized quality tractor model is established, which includes the body, suspension and steering system, tires and other components.

The study shows evidence of a reduction in the drawbar to a cylindrical rod.. The aircraft model is mainly composed of the fuselage, undercarriage and employs spring-dampers. As a result, nonlinear elastic damping effects in the spline curve takes place in the undercarriage buffer system.

Fig. 2 Virtual prototyping model of the tractor-aircraft system

The parameters of the tire and road can be set in the Fiala tyre model and mdi_2d_flat road model, such as: the vertical stiffness, vertical damping of the tire, the friction factor, and graphics of the road.

2.3 Comparative analysis of kinetic model and virtual prototype model

A comparative analysis was conducted to set the tractor initial position on the ground coordinate system origin and zero degree for the initial direction. The simulation was carried out using a vertical speed of 5 km/h. The step input was given to a steering wheel with the function: step (time, 8, 0, 8.02, and 42*d*). The study compared the steady-state values of the kinetic model and the virtual prototype model, as shown in Table 1. It was established that the virtual prototype model is a good feature.

Table 1 Contrast of the Kinetics Parameters

Investigating variables	Yaw rate of the tractor/((°)·s^{-1})	Yaw rate of the drawbar/((°)·s^{-1})	Yaw rate of the aircraft/ ((°)·s^{-1})	Lateral velocity of the tractor/(mm/s)	Angle between the drawbar and the aircraft/(°)	Angle between the tractor and the drawbar/(°)
Simulation value	1.436	1.427	1.404	45.90	4.126	6.222
Theoretic value	1.507	1.507	1.478	46.60	4.395	6.549
Absolute error	0.074	0.080	0.074	0.700	0.269	0.327
Relative error	5.3%	5.6%	5.3%	1.5%	6.5%	5.2%

3Establishment of fuzzy control sysytem

Based on the virtual prototype model of the tractor-aircraft system a Mamdani fuzzy control system is established (Shukla and Tiwari, 2010). A block diagram of the fuzzy control system is visible in Figure 3. Distance deviation and angle deviation, which can be derived by drawing a comparison between the actual path, and the preconcerted routes are calculated as the input of the controller. The torque that controls the steering wheel angle sheers off betimes to eliminate the error is referred to as the output.

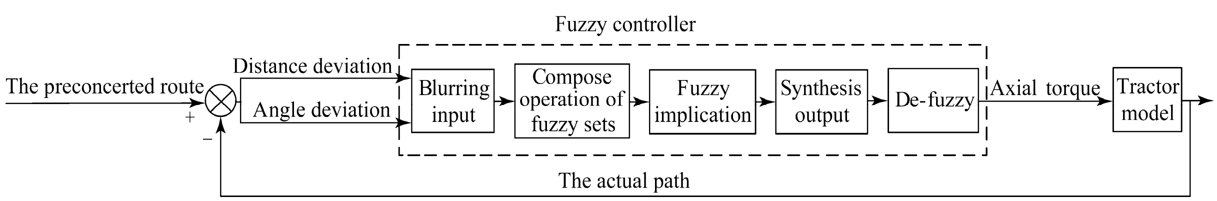


Fig. 3 Block diagram of the controller

3.1 Path Reference frame

Ubiety between the tractor and the preconcerted route is shown in Figure4. The ground coordinate system *OXYZ* is used to describe the trajectory, whereas vehicle coordinated system *oxyz* is used to calculate the distance deviation Ed and angle deviation *Ea*. Path point P_c (c=1, 2, 3, …n) connecting to the sequentially composed preconcerted path. The origin of the vehicle system of coordinates is (X_0, Z_0) on the ground coordinate and the relative angle between these two coordinated systems is φ .

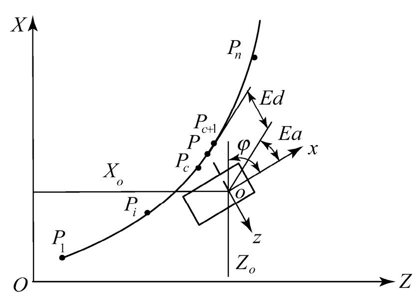


Fig. 4 Schematic diagram of the ubiety

3.2 Position Controller

The functions of the fuzzification interface are to perform the following steps: measure the values among the input variables from the data acquisition interface, quantifying in order to transform the range of the observed values into the corresponding discourse of the language variables, and transforming the input data into proper linguistic values, that can be regarded as a form of fuzzy set.

The subets of the in-out variables are decomposed into seven fuzzy partitions, denoted by *PB* (positive big), *PM* (positive medium), *PS* (positive small), *Z* (zero), *NS* (negative small), *NM* (negative medium), and *NB* (negative big), respectively. The domain of distance deviation, *Ed* is [–1000, 1000], Unit: mm and of angle deviation *Ea* is [−1.57, 1.57], Unit: rad. Control axial torque on the steering wheel has a basic domain of [−78400, 78400] which unit is N·mm. In-out variables in fuzzy set are on the fuzzy domain {−6, −4, −2, 0, 2, 4, 6}. Analyzing the basic domain and the compartmentalization of the hierarchy, quantization factor of distance deviation *Kd* comes to a value of 0.006 and that of angle deviation *Ka* is 0.267, while the control torque scale factor *Kt* is 13066.

The membership function of in-out is shown in Figure 5.

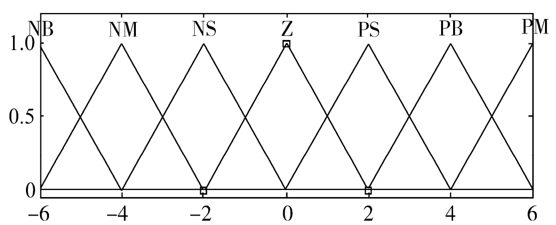


Fig. 5 Membership function

The rule table of fuzzy controller is shown in Table 2 and the output surface of fuzzy control rules can be illustrated as shown in Figure6. There are four conditions of the tractor current position and preconcerted route determined by the distance and angle deviation:

(a) $Ed \geq 0,\ Ea \geq 0$; (b) $Ed \leq 0,\ Ea \leq 0$;
(c) $Ed > 0,\ Ea < 0$; (d) $Ed < 0,\ Ea > 0$

Table 2 Rule table of fuzzy controller

Output					*Ed*			
Torque *U*		*NB*	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
	NB	*PB*	*PB*	*PB*	*PM*	*NS*	*NS*	*NS*
	NM	*PB*	*PB*	*PM*	*PS*	*NS*	*NS*	*NS*
	NS	*PB*	*PM*	*PM*	*PS*	*NS*	*NS*	*NS*
Ed	*Z*	*PM*	*PM*	*PM*	*Z*	*NM*	*NM*	*NM*
	PS	*PS*	*PS*	*PS*	*NS*	*NM*	*NM*	*NB*
	PM	*PS*	*PS*	*PS*	*NS*	*NM*	*NB*	*NB*
	PB	*PS*	*PS*	*PS*	*NM*	*NB*	*NB*	*NB*

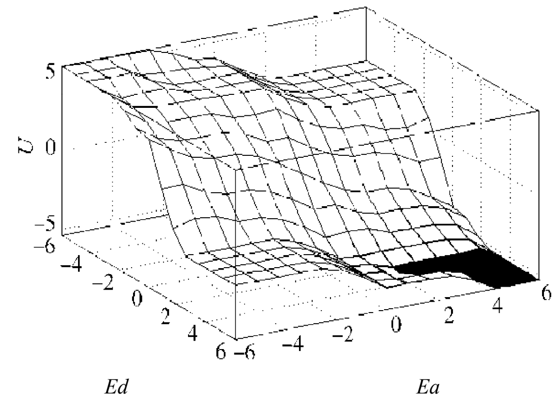


Fig. 6 Output surface of fuzzy rules

4 Tracking behavior simulation analysis

For verifying the efficiency of the proposed controller, we realize this system on the virtual prototyping model created in section Ⅱ. Define the in-out adopting ADAMS/Controls and establish the control algorithms in Simulink Model.

The study implemented control modules and designed software in the control system, and interactive simulation. The co-simulation model is shown in Figure7, which contains dynamic modules; path deviation calculation module, a fuzzy control module and a time limit module. The corresponding oscilloscope to record the distance and angle deviation and other important data were also established. Thus, the operations and some experimental results are presented in a series of pictures to demonstrate the efficiency of the proposed methods.

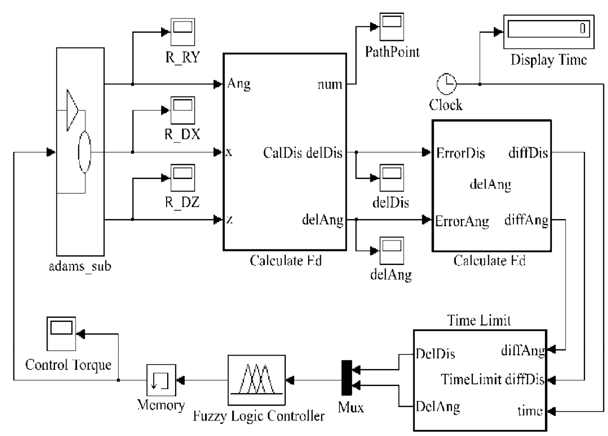


Fig. 7 Co-simulation model

4.1 Performance of the Virtual Prototyping Model

Given the tractor rear wheel, a axial torque with a step input: step (time,0,50000,180,1800000) and a drive function to the steering wheel with: step (time,0,0,1,168d), the simulation was carried out. The traction trajectory is shown in Figure 8.

The simulations illustrated in Figs. 7 and 8, results indicate that the under-steer system increased the tractor turning radius and lateral velocity. t. The tractor's turning radius and lateral velocity are greater than those of the aircraft. Aforesaid analysis proves that the virtual prototyping model has good maneuvering stability.

(a) Route of the Idle Load Tractor (b) Route of the Load-Carrying Tractor

(c) Route of the Passive Aircraft

Fig. 8 Traction Trajectory

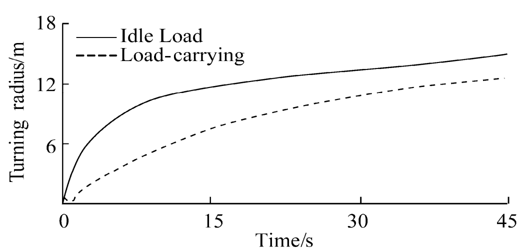


Fig. 9 Turning Radius of the Tractor

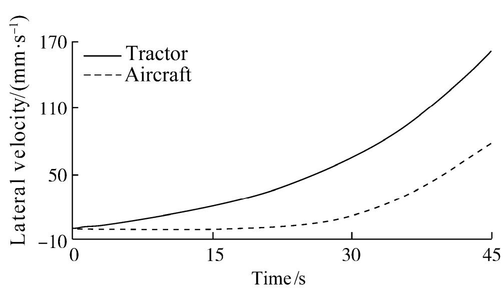


Fig. 10 Lateral Velocity Comparison

4.2 Tracking Behavior Under the Fuzzy Control

Towing the aircraft at the speed of 5.4 km/h along route 1(visible in Fig.11), simulations was carried out as follows:

(a) Running with a step input: step (time, 4, 0, 4.2, 42d)

(b) Control the system through co-simulation approach

We investigate the performance of the fuzzy control system. Figure 12 shows the tracking behavior under an operation of closed-loop input. The foundation of the fuzzy controller could make up some adverse effects caused by tire slippage, etc, to a certain extent. Also the establishment plays an important role in safe and efficient towing operation.

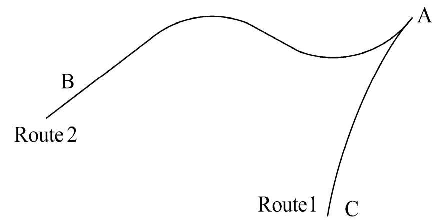


Fig. 11 Preconcerted Routes

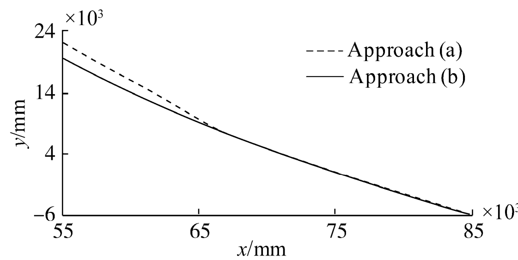
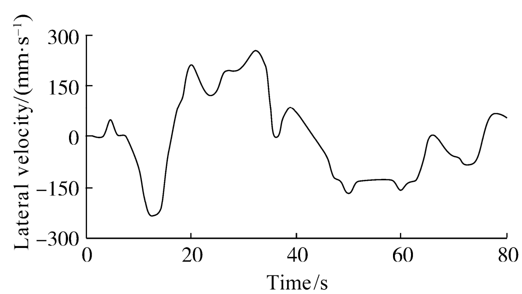


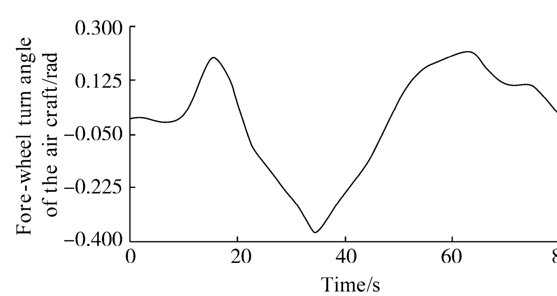
Fig. 12 Tracking Trajectories

The tractor drove in accordance with the intended route 2 as shown in Figure 13, pulling the aircraft from point A to destination B at the speed of 5.4 km/h. The tracking trajectories also obtained the kinetics parameters during the task from the co-simulation. Figure 12 shows the lateral velocity and turn angle of the aircraft for wheel values. The maximum kinetics parameters are also shown in Tab. 4 characterizing the towing performance.

Therefore, using the designed controller to guide the traction system tracking in an intended route under practical traction work conditions is safe.



(a) Lateral Velocity of the Tractor



(b) Turn Angle of the Aircraft Fore-wheel

Fig. 13 Kinetics Parameters

5 Conclusions

For the automatic guidance and stability control of the ship-based tractor-aircraft system, a fuzzy control system was designed. Firstly, taking into account lateral and the swaying motions, a nonlinear dynamic model is introduced. A virtual prototyping model, which has good maneuvering stability, is established. Furthermore, based on the fuzzy logic, the controller is derived based on the virtual prototyping model.

The simulation results confirm the fuzzy control system effectively enables the traction system to track the preconcerted path well. Under the control of the designed controller, the tractor-aircraft system provided a good description of the dynamic behavior.

References

De Santis RM (1994). Path-tracking for a tractor-trailer-like robot. *Int J Robot Res*, **13**(6), 533-543.

De Santis R (1997). Modeling and path-tracking for a load-haul-dump vehicle. *J. Dynam. Syst. Meas. Contr.*, **119**, 40-47.

De Wit C, Khennouf H, Samson C, Sordalen OJ (1993). Nonlinear control design for mobile robots, recent trends in mobile robots. *World Scientific Series in Robotics and Automated Systems*, **11**, 121-156.

Elliott AS (2000). A highly efficient, general purpose approach for cosimulation with ADAMS. *MDI North Amer, User Conf.*, MI,.

Han F, Yang BH, Wang HD, Bi YQ(2010). The optimizing research on aircraft handling workflow. *Science Technology and Engineering*, **10**(22), 5602-04.

Hirose S. Fukushima E, Tsukagoshi S (1995). Basic steering control methods for the articulated body mobile robot. *IEEE Contr. Syst. Mag.*, **4**, 5-14.

Kanayama Y, Kimura Y, Miyazaki F, Noguchi T (1990). A stable tracking control method for an autonomous mobile robot. *IEEE Int Conf on Robotics and Automation*, Cincinnati, OH, 384-389.

Kanayama Y, Kimura Y, Miyazaki F, Noguchi T (1991). A stable tracking control method for a non-holonomic mobile robot. *Int Conf on Intelligent Robotics Systems*, Osaka, Japan,1236-1241.

Lamiraux F, Laumond JP (1997). A practical approach to feedback control for a mobile robot with trailer. *IEEE Int Conf on Robotics and Automation, leuven, Belgium*, 3306-3311.

Lamiraux F, Sekhavat S, Laumond J (1999). Motion planning and control for Hilare pulling a trailer. *IEEE Trans. Robot. Automat*, **15**, 640-652.

Lane J, King R (1994). Computer-assisted guidance of an underground mine truck. *IEEE Int. Conf. Robotics and Automation*, San Francisco, 420-425.

Larsson U, Zell C, Hyppa K, Wernesson A (1994). Navigating an articulated vehicle and reversing with a trailer. *IEEE Int. Conf. Robotics and Automation*, San Francisco, 2398-2404.

Murray RM, Sastry S (1993). Nonholonomic motion planning: Steering using sinusoids. *IEEE Trans Automat Contr*, **38**(5), 700-716.

Nakamura Y, Ezaki H, Tan Y, Chung W (2001). Design of steering mechanism and control of nonholonomic trailer systems. *IEEE Transactions on Robotics and Automation*, **17**(3), 367-374.

Rabinovitch J, Leitman J (1996). Urban planning in Curitiba. *Sci. Amer.*, **274**(3), 46-53.

Rifford L (2008). Stabilization problem for nonholonomic control systems. *Geometric Control and Nonsmooth Analysis, Series on Advances in Mathematics for Applied Sciences*, **76**, 260-269.

Rifford L (2006). The stabilization problem on surfaces. *Control Theory and Stabilization II*, **64**(1), 55-61.

Rifford L (2004). The stabilization problem: AGAS and SRS feedbacks. Optimal Control, Stabilization, and Nonsmooth Analysis. *Lectures Notes in Control and Information Sciences*, **301**, 173-184.

Samson C, Ait-Abderrahim K (1991a). Feedback stabilization of a nonholonomic wheeled mobile Robot. *Int Conf on Intelligent Robotics Systems*, 1242-1247.

Samson C, Ait-Abderrahim K (1991b). Feedback control of a nonholonomic wheeled cart in cartesian space. *IEEE Int Conf on Robotics and Automation*, 1136-1141.

Sekhavat S, Lamiraux F, Laumond JP, Bauzil G, Ferrand A (1997). Motion planning and control for Hilare pulling a trailer. *IEEE Int Conf on Robotics and Automation, Leuven, Belgium*, 3306-3311.

Shukla S, Tiwari M (2010). Fuzzy logic of speed and steering control system for three dimensional lines following of an autonomous vehicle. *International Journal of Computer Science and Information Security*, **7**(3), 101-108.

Wang Y (1994). Development of aircraft-towing tractor. *Inter-national Aviation*, **11**(9), 18-20.

Yuan J, Huang YL (2006). Path following control for tractor-trailer mobile robots with two kinds of connection structures. *IEEE/RSJ International Conference on Intelligent Robots and Systems,* Beijing, China, 2533-2538.

Nengjian Wang was born in 1962. He has been a professor at Harbin Engineering University since 2003. He has been a supervisor for decades. His research covers a wide range of problems in modern manufacturing systems theory, workshop and logistics scheduling and optimization, computer-aided process planning and mechanical dynamics.

Hongbo Liu was born in 1987. She is working on doctoral degree at Harbin Engineering University. She mainly engages in computer simulation, analysis of aircraft traction system dynamics and stability control study.