Research on Co-simulation of Omni-directional Mobile Platform Based on ADAMS and MATLAB

Wei Tang[a], Yong Liu[b], Cao Liu[c], Jinfeng Gu[d], Yaqiang Ji[e] and Xiangyong Liu[f]

School of Mechanical Engineer,

Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, China, 212003

[a]tangweisc@163.com, [b]tim4146@gmail.com, [c]lc13211@163.com, [d]kai00ge@163.com, [e]1742833890@qq.com, [f]1134271381@qq.com

Keyword: Omni-directional mobile platform; Fuzzy-PID; Co-simulation; ADAMS; MATLAB
Abstract. C

Introduction

Most of the conventional mobile platforms adopt the chassis structure based on multi-wheel layout, with the disadvantages of large turning radius, low space utilization and inflexible motion, the conventional platform may collide with the surrounding objects and even unable to work, especially when operated in narrow space. Mecanum wheel has the advantages of compact structure and flexible movement, the mobile platform based on Mecanum wheel can achieve the omni-directional movement by the cooperation of all the wheels. The omni-directional movement includes the vertical movement, the lateral movement and the spinning on the spot, and the other complex movements of free combination. With the movement characteristic of moving in any direction without changing its posture, the mobile platform with Mecanum wheels can overcome the conventional defects mentioned above, which especially suitable for the narrow space or the occasion where needs to turn round frequently.

At present, some research have been done by the domestic and foreign scholars on the omni-directional mobile system based on the Mecanum wheel technology, which mainly focused on the analysis of kinematic and control methods. M.de Villiers proposed an improved mathematical model for the change of the contact points between the Mecanum wheel and the pavement in the process of work [1]. Junmin Kim used inertial navigation as feedback of location to improve the position accuracy of Mecanum automatic guided vehicle [2]; Wang Yizhi analyzed and deduced the six-dimensional kinematic model which is adapted to uneven ground [3]; Zhang Xueling investigated a contour compensation method for roller design, by considering the problem that the roller, when being loaded, has a deformation which results in the instability [4].

However, because of its unique structure, all the Mecanum wheels installed on the omni-directional mobile chassis need to be operated with each other. It will take a long time to manufacture the physical prototype to prove the theoretical analysis results, and some error sources can be brought during the machining and assembling process. In order to the improve the design and development efficiency of the omni-directional mobile platform, multi-body dynamics simulation model of the platform is built, and the synchronous control system for wheels based on fuzzy PID algorithm is designed in MATLAB/Simulink environment, and the co-simulation of the system is accomplished with the bidirectional data connection. By far, the related results of theoretical analysis have been validated reasonably in the engineering prototype.

Omni-directional moving system with Mecanum wheels

Structure of the Mecanum wheel

Mecanum wheel was first developed by the Swedish engineer Bengt Ilon in 1973, as shown in Fig.1，which consists of a hub carrying a number of free moving rollers angled at 45 ° around the hub's circumference. The rollers are shaped such that the overall side profile of the wheel is circular, so as to ensure the consistency and stability of the wheel in contact with the ground. Partial force of wheel can be converted to the perpendicular direction by rollers. With the cooperation of speed and direction of the wheels, a torque in arbitrary direction is synthetized.

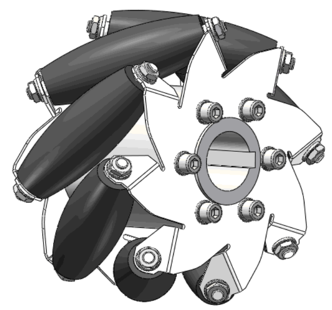

Fig.1 Structure of the Mecanum wheel

Wheels group layout and its optimization

The wheels group layout of omni-directional mobile platform with four Mecanum wheels has the following several typical forms, as shown in Fig.2. In the picture, axes of the rollers which touch the ground are presented.

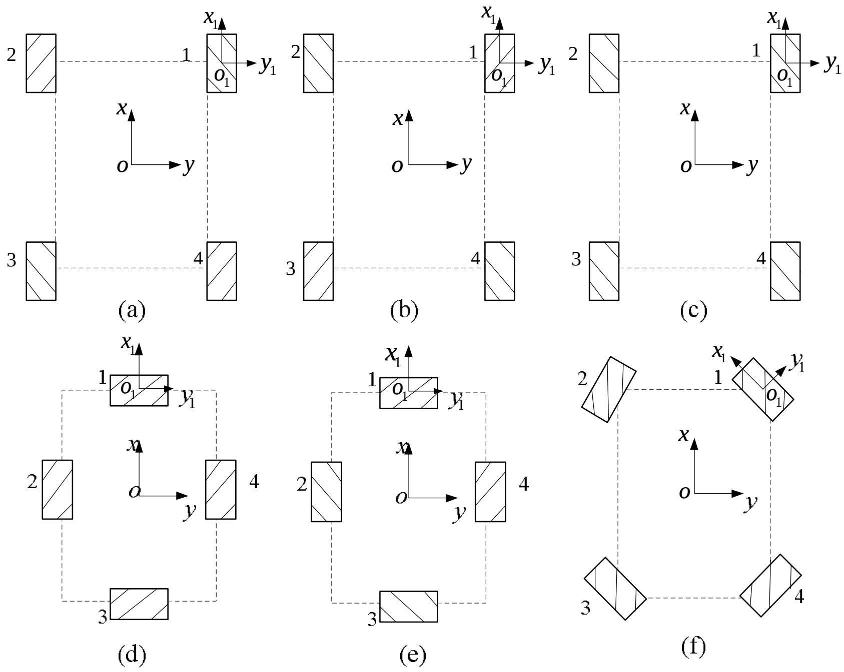

Fig.2 Typical layouts with four Mecanum wheels

According to paper [5], Wang Yizhi analyzed the group layout with four Mecanum wheels and the general inverse kinematic equations of the six typical layout forms are derived:

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = -\frac{1}{R} \begin{bmatrix} \frac{\sin(q_1 - a_1)}{\sin a_1} & \frac{\cos(q_1 - a_1)}{\sin a_2} & \frac{W_1 \sin(q_1 - a_1) - L_1 \cos(q_1 - a_1)}{\sin a_1} \\ \vdots & \vdots & \vdots \\ \frac{\sin(q_4 - a_4)}{\sin a_4} & \frac{\cos(q_4 - a_4)}{\sin a_4} & \frac{W_4 \sin(q_4 - a_4) - L_4 \cos(q_4 - a_4)}{\sin a_4} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ w_z \end{bmatrix} \tag{1}$$

q_i is the rotating angle between the platform center coordinate system and the omni-directional wheel coordinate system. a_i is the offset angle of the roller. L_i and W_i are the distances from the platform coordinate system to the Mecanum wheels in the x- and y-axis direction respectively. Eqs.(1) can be noted as $\dot{w} = K \cdot \dot{x}$, in which K is a Jacobian matrix (4×3) above.

From the control perspective, if the platform intends to achieve the desired motion state, only four wheels are assigned a combination of reasonable and unique speed then it will realize the omni-directional movement. On the other hand, after the speed of four wheels are given reasonably, the movement state of the platform must be determined. So the movement state of the platform and the speed of four wheels should be a one-to-one mapping relationship, as is shown in equation $\vec{w} = K \cdot \vec{x}$, that when $\vec{w}$ is known, if the solution of $\vec{x}$ is unique, the K must be full rank, namely, rank (K) =3. After calculation, only (a) and (b) of the six layouts in fig.2 can meet the requirement. In particular, if the center of the four wheels in Fig.2 (b) composes a square, the resultant speed of four wheels' center will precisely pass through the center of the platform. In this case, the platform can't realize the movement of spinning around, so Fig.2 (a) is the best layout of four-wheel form.

Modeling of the system

Kinematic model of the four Mecanum wheels system

According to the results of the above analysis, the layout is designed in Fig.3.

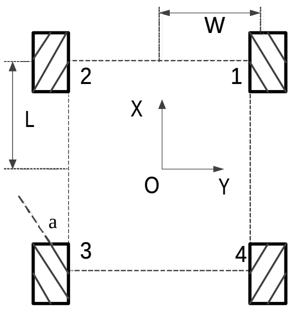

Fig.3 Layout of the platform

Kinematic model is built under the reference of Jorge Angeles's rotation vector method [6]. At last, the inverse kinematic model of the omni-directional mobile platform is derived:

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \frac{1}{R} \begin{bmatrix} 1 & -1/\tan\alpha & (W\tan\alpha + L)/\tan\alpha \\ 1 & 1/\tan\alpha & -(W\tan\alpha + L)/\tan\alpha \\ 1 & -1/\tan\alpha & -(W\tan\alpha + L)/\tan\alpha \\ 1 & 1/\tan\alpha & (W\tan\alpha + L)/\tan\alpha \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ w_z \end{bmatrix} \tag{2}$$

In Eq.(2), w_1、w_2、w_3、w_4 are the rotate speeds of four Mecanum wheels, R is the radius of the wheel, a is the offset angle of the roller, W、L is the size of the platform, v_x、v_y、w_z is the component velocity of the omni-directional mobile platform.

It can be seen from the inverse kinematic model that the platform can realize an omni-directional movement by the cooperation of the four wheels with different speed. Compared with other types of mobile systems, the steering mechanism is not needed in the omni-directional mobile platform, so that the structure is relatively simple.

Virtual prototype in ADAMS

The omni-directional mobile platform with Mecanum wheels is complicated on assembling, and curve of the roller surface is complex which makes it difficult to model in ADAMS. Therefore, the platform is modeled and assembled by the use of 3D modeling software Pro/E. The modeling of roller is referred to the parameter equation made by Gfrerrer A [7].

$$\begin{cases} x^*(q) = d\dfrac{\cos^2 a}{\sin a}\tan q + r\sin a \sin q \\ z^*(q) = -\sqrt{\cos^2 a \tan^2 q + 1}(r\cos q - d) \end{cases} \tag{3}$$

In Eq.(3), d is the length of the public vertical line between axes of the hub and the roller, a is the offset angle of the roller's axis, r is radius of the bottom surface of the cylinder of the roller's envelope, q is a free variable, $x^*(q)$ is the axial distance of roller, $z^*(q)$ is the radius of roller.

The simulation model of omni-directional mobile platform for co-simulation is established in ADAMS/View. Firstly, the assembly model of Pro/E is saved in the format of Parasolid which can be imported into ADAMS, then the material, constraint and contact are defined and the drive of wheels is added, At last, the related inputs and outputs state variables are defined in the co-simulation.

For the convenience of machining, sheet metals of aluminum alloy are assembled in the omni-directional platform. In order to increase the friction force with ground and reduce slippage, roller is made of rubber. The mechanical structure is designed as simplified single-portrait suspension system. By the using of spring damper, the shake of vehicle would be relieved when the roller 'beats' the ground by turns while running which improves the stability. Fig.4 shows the virtual prototype and its structure parameters are: R=30mm, W=125mm, L=134mm.

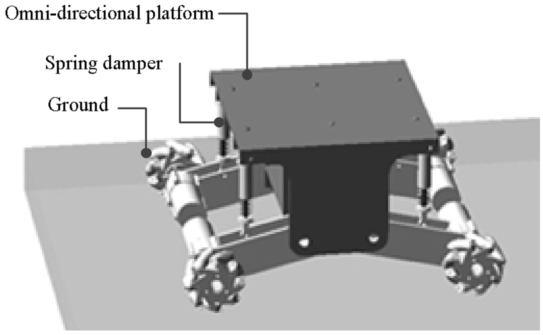

Fig.4 3D model of omni-directional platform

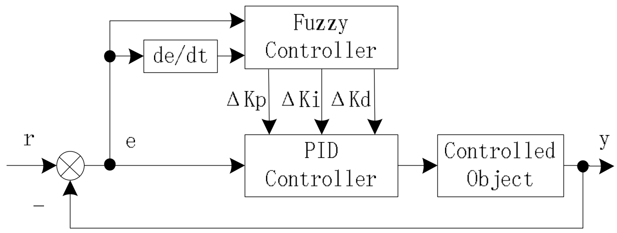

Fig.5 Structure of fuzzy PID controller

Co-simulation of control system

The omni-directional platform actualizes omni-directional movement by the coordinated work of four wheels with different rotation rate. The movement accuracy depends on control accuracy of rotation rate. When the system is time varying or has large disturbance, in contrast with the conventional PID controller, the fuzzy PID control show a higher following performance and interference immunity. For improving the stability, a synergic controller of four wheels based on fuzzy PID control is built in the SIMULINK environment on MATLAB.

Design of fuzzy PID controller

On the basis of conventional PID controller, a two-dimensional fuzzy PID controller which refers to systematic error and change rate of systematic error is designed in the paper. This controller can make online autoturing for PID parameter K_p、 K_i and K_d so as to adjust to different working condition, and the structure of fuzzy PID controller is shown in Fig.5. The process of fuzzy controller includes: fuzzification, fuzzy reasoning and defuzzification.

Fuzzification is to transform the exact value of current error and change rate of error to fuzzy domain by multiplying quantization factor. Then, according to membership function, fuzzy linguistic variables are obtained, namely, E and EC. The most frequently used method of membership function is trigonometric functions. The fuzzy subset in this system includes {negative big,negative middle,negative small,zero,positive small,positive middle,positive big},which are short for {NB,NM,NS,ZO,PS,PM,PB}. Based on E and EC, the process of fuzzy reasoning is in the form of "if-then", and comes to fuzzy linguistic variables of ΔK_p、 ΔK_i and ΔK_d. For example, if (E is PB) and (EC is PB) then (ΔK_p is NB) (ΔK_i is PB) (ΔK_d is PB), in which, the fuzzy reasoning rules reflect engineers' intelligence and experience.

Table 1 Fuzzy inference rule table of ΔKp、ΔKi and ΔKd

EC	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB NB PS	PB NB NS	PM NM PM	PM NM NB	PS NS NB	ZO ZO NM	ZO ZO PS
NM	PB NB PS	PB NB NS	PM NM NB	PS NS NM	PS NS NM	ZO ZO NS	NS ZO ZO
NS	PM NB ZO	PM NM NS	PM NS NM	PS NS NM	ZE ZO NS	NS PS NS	NS PS ZO
ZO	PM NM ZO	PM NM NS	PS NS NS	ZO ZO NS	NS PS NS	NM PM NS	NM PM ZO
PS	PS NM ZO	PS NS ZO	ZO ZO ZO	NS PS ZO	NS PS ZO	NM PM ZO	NM PB ZO
PM	PS ZO PB	ZO ZO NS	NS PS PS	NM PS PS	NM PM PS	NM PB PS	NB PB PB
PB	ZO ZO PB	ZO ZO PM	NM PS PM	NM PM PM	NM PM PS	NB PB PS	NB PB PB

The fuzzy control algorithm multiplies the result of fuzzy reasoning by scaling factor to transform the output from fuzzy domain to real physical domain. At last, values of three PID parameters, namely, K_p、K_i and K_d, are updated after adding actual values of ΔK_p、ΔK_i and ΔK_d[8]. Furthermore, variations of ΔK_p、ΔK_i and ΔK_d which obtained from inputs of E and EC satisfy PID parameters under different working conditions, so that the adaptability of fuzzy PID controller is improved.

Co-simulation of ADAMS and MATLAB

According to kinematics analysis, rotation rates of fours wheels in omni-directional mobile platform are set as the input variables, position and speed of the platform as the output variables, respectively, which aim to record and analyze the simulation data. The input and output state variables are listed in table 2. Then, the model file of controlled object is exported through module of ADAMS/Controls which can be called in MATLAB.

Table 2 Definition of input and output state variables

name	value	remark	name	value	remark
w1	0	Rotation rate of wheel 1	w2	0	Rotation rate of wheel 2
w3	0	Rotation rate of wheel 3	w4	0	Rotation rate of wheel 4
dx	DX(BODY.cm)	Displacement in X-axis	az	AZ(BODY.cm)	Angle in Z-axis
dy	DY(BODY.cm)	Displacement in Y-axis	vx	VX(BODY.cm)	Speed in X-axis
dz	DZ(BODY.cm)	Displacement in Z-axis	vy	VY(BODY.cm)	Speed in Y-axis
wz	WZ(BODY.cm)	Angular velocity in Z-axis			

Fuzzy PID controller is built in MATLAB/Simulink and the model of ADAMS sub is called for data exchange, four-wheel synchronous control system based on fuzzy PID algorithm is set up, which is shown in Fig. 6. The control system belongs to discrete system, in which the model of inverse kinematics is included in kinematic function. In order to realize a close loop control, every wheel is controlled by a fuzzy PID controller. After setting the block diagram and simulation parameters such as interval of data exchange and simulation, experiments of synchronous control system is practicable.

Analysis of simulation in typical working conditions

The co-simulation of ADAMS and MATLAB fully synchronizes the mechanical simulation model of omni-directional mobile platform with the four-wheel control systems, using the data exchange interface, which avoids the defect that the simulation of mechanical structure and control system can't be implemented synchronously in single software. Therefore, this method is more suitable for the complex mechatronics product. Virtual prototype model in the co-simulation of two software is so close to the physical prototype that the results of simulation are more meaningful [9].

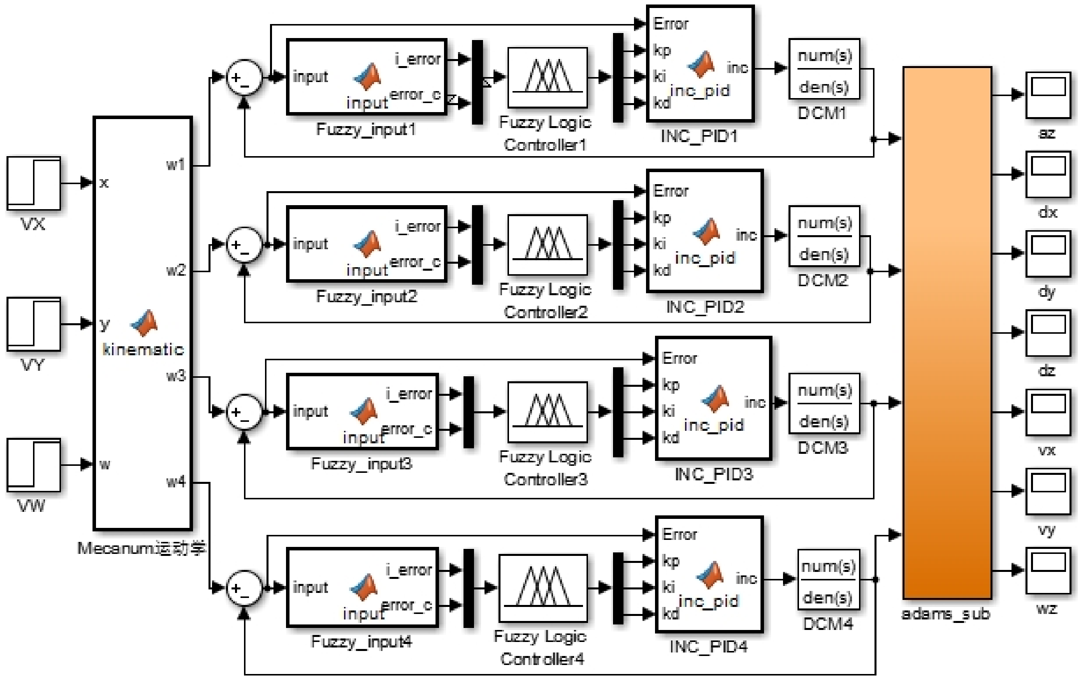

Fig.6 Block diagram of omni-directional mobile platform co-simulation

The mobile platform based on Mecanum wheel is capable of omni-directional movement within the plane. In this paper, only two motion forms including the lateral movement and the spinning around movement are discussed, and the motion performance of two different control strategies, the conventional PID and the fuzzy PID, are analyzed comparatively.

Lateral movement

Set the target speed of virtual prototype for v_x=0, v_y=15cm/s, w_z=0, and add an instantaneous interference at the time 2s, experiment of lateral movement in Y-direction was completed, Fig. 7 shows the speed curve of the moving platform. Fig.8 shows the deviation curve of yaw angle when the omni-directional mobile platform was moving in steady state for 5s laterally.

As shown in Fig. 7, it can be concluded that the rise time of the fuzzy PID controller was 0.13s, the variance of the steady-state value was 2.7, the average steady state value was 145.4mm/s; The rise time of the conventional PID controller was 0.44s, the steady state variance was 5.5, and the average steady state value was 145.3mm/s. Compared with conventional PID controller, the fuzzy PID controller has better dynamic and static performance, and the time of rise time was reduced by 70%, the stability was improved by 51%. Because of the control system is a semi-closed loop system, there was steady-state error about 3%.

Fig. 8 reflects the body angle of omni-directional mobile platform, the error accumulation of the control system using fuzzy PID algorithm was slower, and the cumulative deviation angle was about 4e-3 rad, which was 71% of the conventional PID in 5s.

Spinning around movement

Setting the target speed of the prototype as v_x=0, v_y=0, w_z=1rad/s, zero-radius rotary motion was tested. Positional distribution map about barycenter of mobile platform in the x-y plane is shown in figure 9, in which the coordinates (0, 0) is the initial position.

As shown in Fig.9, when the prototype was moving in stable rotation rate, two types of control systems deviated from the theoretical position (0, 0) without exception. The control system using Fuzzy PID algorithm deviated from the initial position of 0.31mm, which was significantly reduced than conventional PID algorithm of 0.68mm, therefore, the motion accuracy was greatly improved.

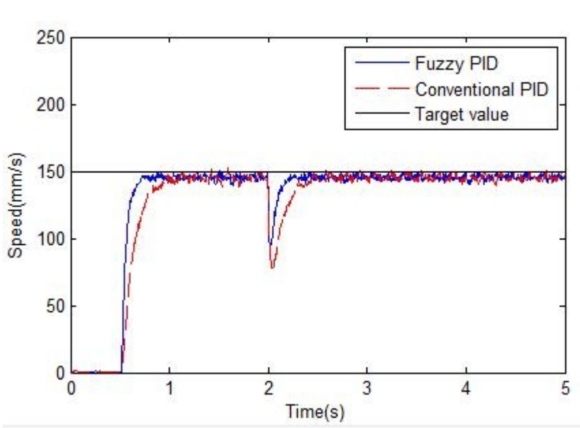

Fig. 7 Comparison of speed of lateral movement

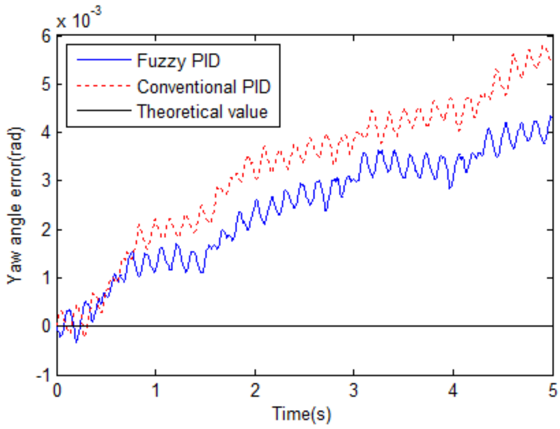

Fig. 8 Comparison of yaw angle error

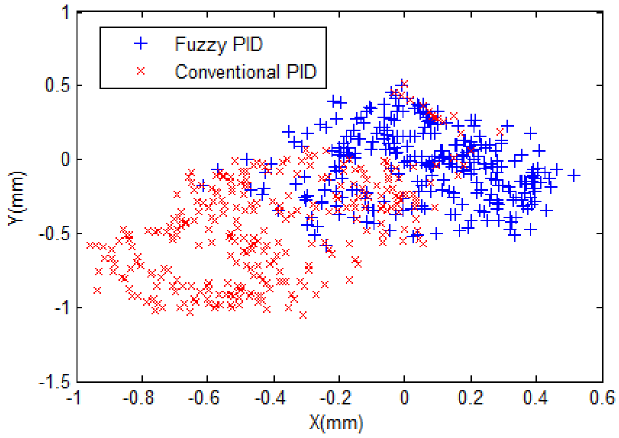

Fig.9 The position distribution of the barycenter

Error analysis

1) The actual radius of the wheel became smaller due to the deformation of roller. As roller's material is rubber (Young's modulus: 7.8 N/mm^2), it's easily deformed. Actually, radius of R is smaller than the theoretical value under the effect of gravity on the platform. Combined with the formula (2), it is easy to see that the actual speed will be decrease. Meanwhile, the larger the deformation is, the larger the steady error would be.

2) There is some influence on yaw angle caused by the continuous disturbance when the rollers touch the ground in turns. At the moment of rollers' switching, it would fluctuate the load torque; consequently, wheel speed is disturbed continuously. In this condition, the fuzzy PID controller shows a higher steady-state performance and makes the error of yaw angle smaller.

3) The mechanical configuration parameters of the omni-directional platform have a little change in the process of simulation. Independent suspension system is designed for the simulation model. In the process of simulation, spring damper is compressed under the effect of gravity which leads to the little change of the mechanical parameters W and L, as a result, the error of the kinematic model and the influence on the position of the center of mass are generated.

Method of improvement

1) The deformation of flexible roller under load is inevitable, and there are two ways to reduce the error. One is to join the compensation coefficient of the wheel deformation in the kinematic model, and the other is to design the roller's contour curve by considering the compensation of roller deformation.

2) The flexible suspension ensures the damping function of the omni-directional mobile platform, however, it reduces the accuracy of the geometric control. Optimizing the parameters of the spring damper can be considered in the practical use.

Conclusions

The Omni-directional mobile equipment with Mecanum wheels can realize the full range of motion in the plane, which has the unique movement flexibility and wide application prospect. In this paper, a virtual prototype of omni-directional mobile platform is built in ADAMS and the co-operative control strategy is designed in MATLAB/Simulink, and the co-simulation in ADAMS and MATLAB is completed. The results show that the control algorithm of wheels' speed based on fuzzy PID has a high dynamic and static performance, and the flexible movement performance of the omni-directional mobile platform can meet the practical requirements. In addition, the risk of prototype development and design cycle can be significantly reduced by the method of virtual prototype co-simulation.

Acknowledgment

This work was financially supported by the Research Innovation Program for College Graduates of Jiangsu Province, China, and the Grant No. was SJLX15_0524.

References

[1] M.de Villiers, N.S. Tlale. Development of a Control Model for a Four Wheel Mecanum Vehicle[C]. Transactions of the ASME. JANUARY 2012, Vol. 134/011007.

[2] Junmin Kim, Seungbeom Woo, Jaeyong Kim, et al. Inertial Navigation System for an Automatic Guided Vehicle with Mecanum Wheels[J]. International Journal of Precision Engineering and Manufacturing. Vol. 13(2012) No. 3, p. 379-386.

[3] Yizhi Wang, Degong Chang, Jinwu Qian. Configuration and Kinematics Model of Omni-directional Mobile Vehicle with Four Mecanum Wheels Suitable for Uneven Ground[J]. Journal of Mechanical Engineering. Vol. 20(2009) No. 9, p. 1130-1133.

[4] Xueling Zhang, Caihong Shi, Shaohua Kang, et al. Compensation Design for Roller Contour Surface Deformation of Mecanum Omni-directional Wheels[J]. Chinese Journal of Mechanical Engineering. Vol. 12(2014) No. 3, p. 213-217.

[5] Yizhi Wang, Degong Chang. Motion Performance Analysis and Layout Selection for Motion System with Four Mecanum Wheels[J]. Journal of Mechanical Engineering. Vol. 45(2009) No. 5, p. 307-310,316.

[6] Jorge A. Fundamentals of robotic mechanical systems, Theory, Methods and Algorithms[M]. Springer-Verlag NY USA, 1997.

[7] Gfrerrer A. Geometry and kinematics of the Mecanum wheel[J].Computer Aided Geometric Design. Vol. 25(2008) No. 9, p. 784-791.

[8] Ping Li, Feng Li, Hu Zhao, et al. The Design and Simulation of Fuzzy Self-tuning PID Controller[J]. Chinese Journal of Scientific Instrument. Vol. 25(2004) No. 4, p. 264-267.

[9] Pengfei Xiao, Zhenyu Xie. Co-simulation of Rotor System Supported by Magnetic Bearings Based on ADAMS and MATLAB[J]. System Simulation Technology. Vol. 7(2011) No. 1, p. 48-53.