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An Omnidirectional Mobile Operating Robot Based on Mecanum Wheel

Yiqun Liu[1,2], Hao Li[1], Liang Ding[2,*], Leilei Liu[1], Tao Liu[1], Jianfeng Wang[1,2], Haibo Gao[2]

1. School of Automotive Engineering, Harbin Institute of Technology, Weihai, 264209, China
E-mail: lyq.new@163.com

2. State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, 150080, China
E-mail: liangding@hit.edu.cn

Abstract: Omnidirectional mobile operating robot not only expands the working space of manipulator, but also enhances the function of the omnidirectional vehicle. So, it has wide application prospect. This paper analyses the omnidirectional movement principle of Mecanum wheel, designs an omnidirectional moving vehicle based on Mecanum wheel, and establishes its motion control rules. A manipulator with six degrees of freedom is designed and its kinematic model is established. Simulation platform of omnidirectional mobile operating robot is developed, and the motion trajectory to cover the maximum moment and speed of joints as much as possible is designed. Simulation results show that the movement of omnidirectional vehicle is steady and the vertical fluctuation is small. The predetermined trajectory of manipulator is achieved, the movement of joints is smooth, and the force and energy consumption of each joint are reasonable, which verifies the feasibility of the omnidirectional mobile operating robot.

Key Words: Mecanum Wheel; Omnidirectional Vehicle; Manipulator; Mobile Operation; Performance Simulation

1. INTRODUCTION

Omnidirectional mobile operating robot which installs a manipulator on an omnidirectional vehicle, not only expands the working space of the manipulator but also enhances the function of the omnidirectional vehicle. However, in the design, this combination also increases the complexity of the whole robot system structure, while increasing the mobile robot's own weight and energy consumption. In order to complete complex work, the manipulator and omnidirectional vehicle must be in perfect harmony, and also need to reduce energy loss. Therefore, the study of omnidirectional mobile operating robot has important theoretical and practical value.

Omnidirectional movement refers to the movement system has three degrees of freedom in the plane, such devices can move independently at the same time in three directions. It can move forward, backward, left and right, and can also rotate in situ. So, it has obvious advantages in many occasions. The realization of omnidirectional movement depends on the use of omnidirectional wheels, typically with omnidirectional wheels, Mecanum wheels. Tavakoli, et al. [1] designed a climbing robot that uses an omnidirectional wheel to detect cracks and corrosion on tanks and pipes, and it can also be used for hull cleaning and painting. Bi, et al. [2] proposed a co-robot constructed by three-interval 120° omnidirectional wheels. Wang, et al. [3] analysed the conditions of the four-Mecanum-wheel system for omnidirectional motion. In addition to Mecanum wheel, there are some other omnidirectional wheels, such as Swiss wheel [4], orthogonal wheel [5] and ball wheel. These different types of wheels can use in different conditions according to their functional characteristics.

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Mobile robot is an important part of robot family, because of its flexibility and adaptability to the environment, can be given to the specific or extreme conditions of the task. Jerald, et al. [6], proposed a solution in the simultaneous arrangement of machines and automatic guided vehicles in flexible manufacturing systems (FMS) to minimize production time. In the logistics industry, Sprunk, et al. [7] has proposed an accurate positioning of the omnidirectional mobile robot navigation system for logistics. It can greatly improve the accuracy of navigation and security. In the military, US Marine Corps use four wheeled mobile detection vehicles instead of artificial to patrol military bases. In the medical, with the development of nanotechnology, nano-scale mobile operating robots gradually apply to remote surgery and diagnose disease [8].

At present, the domestic omnidirectional mobile device is mainly used in light carrying such as omnidirectional soccer robot, omnidirectional chassis inspection robot and so on. Alakshendra, et al. [9] proposed an adaptive second-order sliding model control of four mobile robots with four Mecanum wheels, which is the first time to imply high-order sliding mode control for trajectory tracking control of Mecanum mobile robots.

This paper proposes an omnidirectional moving vehicle based on Mecanum wheel, and establishes its motion control rules. A manipulator with six degrees of freedom is designed and its kinematic model is established. Simulation platform of omnidirectional mobile operating robot is developed. Finally, the validity and feasibility of the designed robot is verified.

2. OMNIDIRECTIONAL VEHICLE DESIGN AND MODELING

2.1 Kinematic model of omnidirectional vehicle

Mecanum wheels, needn't to change the body posture while completing the omnidirectional walk and they can rotate around its center at the same time. The edge of Mecanum wheel is quite different from the ordinary wheel, which consists of a set of rollers arranged around the wheel axis. Gfrerrer [10] described the geometry of these rollers in detail, and established the roll edge curves and roll surface shapes by parametric modeling. Each small roller can be freely rotated independently of its own axis, usually the roller axis and the wheel axis in the space into a 45° angle. Theoretically, the projections of all the small rollers in the direction of the Mecanum wheel axis can form an enveloped circle, so that Mecanum wheel can be continuously rolled.

Mecanum wheels can produce both rotation and axial movement characteristics. Each wheel of the mobile platform is driven by electric motor independently. The mobile platform can move in different directions when equipped with different rotating directions of the driven motor. For example, the principle of right movement is shown in Figure 1.

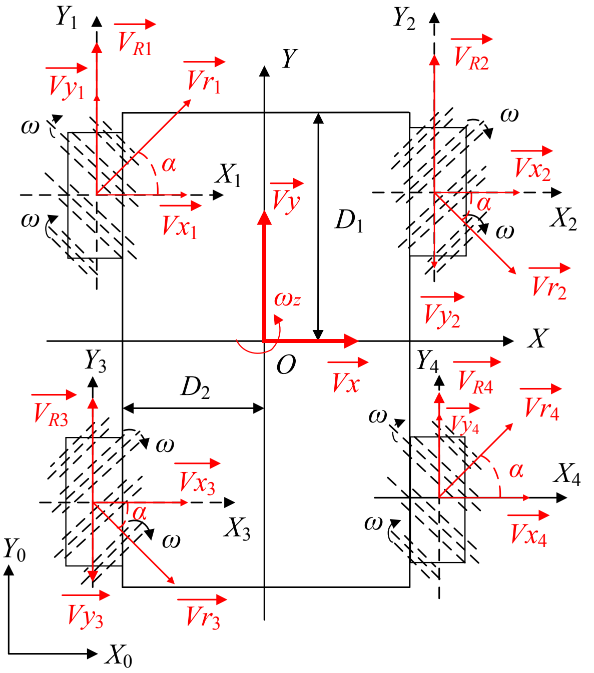

Fig 1. Principle of movement toward right.

Figure.1 shows the motion analysis of each wheel when the omnidirectional vehicle moves to the right. As can be seen from the figure, when the wheel is rotated in the direction of the figure, the velocity vector of each wheel is decomposed. It can be found that the forward and backward speeds are offset and the speed of the omnidirectional vehicle is directed to the right. By controlling the four-wheel steering, the vehicle can achieve all-round movement. The specific control methods of an omnidirectional vehicle with four Mecanum wheels are shown in Table 1.

Table1. Control Methods of Omnidirectional Vehicle

Number of wheel	1	2	3	4
Forward	+	+	+	+
Backward	-	-	-	-
Left	-	+	+	-
Right	+	-	-	+
Left front 45°	/	+	+	/
Right front 45°	+	/	/	+
Left rear 45°	-	/	/	-
Right rear 45°	/	-	-	/
Anticlockwise rotation	-	+	-	+
Clockwise rotation	+	-	+	-

The absolute coordinate system $\{X_0, Y_0, Z_0\}$ and the relative coordinate system $\{X, Y, Z\}$ of the mobile platform are established, as shown in Fig. 1. Speed of each Mecanum wheel can be described as:

$$\begin{cases} \vec{V}_{xi} = \vec{V}_{ri}\cos\alpha \\ \vec{V}_{yi} = \vec{V}_{Ri} + \vec{V}_{ri}\sin\alpha \end{cases} \quad (1)$$

where $\vec{V}_{xi}$ and $\vec{V}_{yi}$ (i=1, 2, 3, 4) are center speed of wheel i, $\vec{V}_{ri}$ is roller center speed of wheel i, and $\vec{V}_{Ri}$ is the relative speed of wheel center and roller center. Relationship of vehicle velocity and wheel velocity can be given by:

$$\begin{cases} \vec{V}_{xi} = \vec{V}_{x} + D_1\vec{\omega}_z \\ \vec{V}_{yi} = \vec{V}_{y} + D_2\vec{\omega}_z \end{cases} \quad (2)$$

where $\vec{V}_x$ and $\vec{V}_y$ are vehicle velocity in X and Y direction, $\vec{\omega}_z$ is vehicle angular velocity around Z axis. Angular velocity of each Mecanum wheel can be obtained as:

$$\dot{\theta}_j = \frac{1}{R}\left[\vec{V}_y + \vec{V}_x\tan\alpha + (D_1\tan\alpha - D_2)\vec{\omega}_z\right] \quad (3)$$

where $\dot{\theta}_j$ (j=A, B, C, D) is angular velocity of wheel j, R is radius of the wheel. Kinematics equation of omnidirectional vehicle can be described as:

$$\begin{bmatrix} \dot{X}_0 \\ \dot{Y}_0 \\ \dot{\theta}_z \end{bmatrix} = \frac{R}{4}\begin{bmatrix} -\cot\alpha & 1 & \dfrac{1}{D_1\tan\alpha - D_2} \\ \cot\alpha & 1 & \dfrac{-1}{D_1\tan\alpha - D_2} \\ \cot\alpha & 1 & \dfrac{1}{D_1\tan\alpha - D_2} \\ -\cot\alpha & 1 & \dfrac{-1}{D_1\tan\alpha - D_2} \end{bmatrix}^T \begin{bmatrix} \dot{\theta}_A \\ \dot{\theta}_B \\ \dot{\theta}_C \\ \dot{\theta}_D \end{bmatrix} \quad (4)$$

2.2 Design of omnidirectional vehicle

The omnidirectional car mainly includes body, Mecanum wheel, motor and reducer, drive control system, battery and other parts.

The selection of Mecanum wheel design is mainly based on the design weight of the manipulator and the design weight of the omnidirectional car to select the diameter of Mecanum wheel. The servo motor is chosen to be the driver because it is widely used in the robot industry with speed adjustable, positioning accurately. The design of each Mecanum wheel can be driven independently, and the motor model selection is based on the design speed of the omnidirectional vehicle. Combined with the reducer to match the appropriate reduction ratio, and ultimately determine the servo motor model and reducer model.

An advanced integration module is used to cooperate controller with driver. The specific components are: controller CPU, two input IO interface, two output IO interface, two modules in parallel into the two groups of communication and communication module, a total of five parts in series. Taking into account the source of energy needs to have high energy ratio, long life and environmental protection features, this design uses lithium batteries to meet the mobile platform needs.

The body is made of aluminum, with sheet metal bending plate for the bottom of the car. The other parts are assembled above it. The design of the omnidirectional vehicle model is shown in Figure 2.

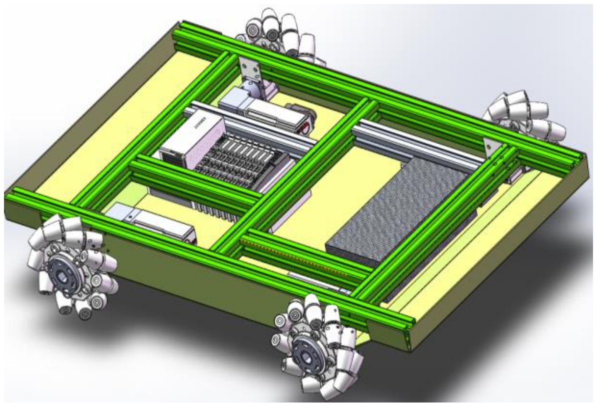

Fig 2. Omnidirectional vehicle model.

3. ANALYSIS OF MANIPULATOR

Manipulator design is mainly considered its length, work range and movement planning. The working range of the manipulator determines whether or not the kinematic solution exists. To the manipulator with the six rotating joints, the sufficient condition for the existence of the closed solution is that three adjacent joint axes intersect at one point. The existing 6-DOF manipulator has almost three intersecting axes. Axis 4, Axis 5 and Axis 6 are designed to intersect at one point in this design. Coordinate systems of the manipulator are shown in Figure 3. The D-H parameters of the manipulator based on the above coordinate systems are shown in Table 2.

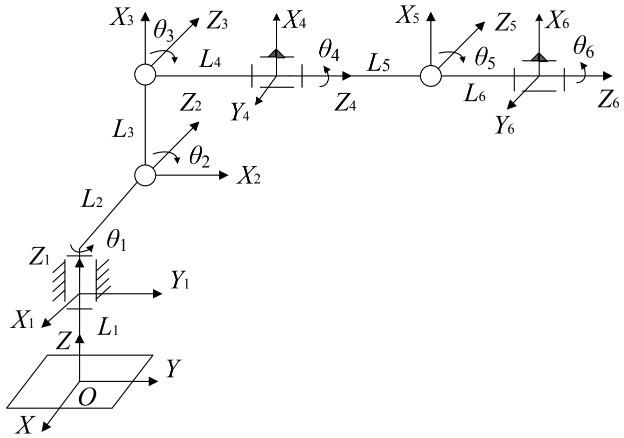

Fig 3. Coordinate systems of the manipulator.

Table2. D-H Parameters of Manipulator

Link i	θ_i	α_{i-1}	a_{i-1}	d_i
1	θ_1 (90°)	0°	0	0
2	θ_2 (0°)	-90°	0	L_2
3	θ_3 (-90°)	0°	L_3	0
4	θ_4 (0°)	-90°	0	L_4
5	θ_5 (0°)	90°	0	L_5
6	θ_6 (0°)	-90°	0	L_6

Select center point of omnidirectional vehicle O to establish reference coordinate system O-XYZ, the transformation matrix ${}^0T_6$ can be written as:

$$
{}^0T_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}
$$

Use 's' to represent 'sin', and use 'c' to represent 'cos', parameters of ${}^0T_6$ can be obtained by calculation. Therefore, kinematic model of the omnidirectional mobile operating robot can be described as:

$$
\begin{bmatrix} \dot{X}_F \\ \dot{Y}_F \\ \dot{Z}_F \end{bmatrix} = \begin{bmatrix} -\cot\alpha & 1 & 1\big/ D_1\tan\alpha\text{-}D_2 \\ \cot\alpha & 1 & -1\big/ D_1\tan\alpha\text{-}D_2 \\ \cot\alpha & 1 & 1\big/ D_1\tan\alpha\text{-}D_2 \\ -\cot\alpha & 1 & -1\big/ D_1\tan\alpha\text{-}D_2 \\ J_{15} & J_{25} & 0 \\ J_{16} & J_{26} & J_{36} \\ J_{17} & J_{27} & J_{37} \\ J_{18} & J_{28} & J_{38} \\ J_{19} & J_{29} & J_{39} \\ 0 & 0 & 0 \end{bmatrix}^T \begin{bmatrix} \dot{\theta}_A \\ \dot{\theta}_B \\ \dot{\theta}_C \\ \dot{\theta}_D \\ \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \\ \dot{\theta}_5 \\ \dot{\theta}_6 \end{bmatrix} \tag{6}
$$

$$J_{15} = -L_3 s_1 c_2 - L_2 c_1 + L_4\left(s_1 c_2 s_3 + s_1 s_2 c_3\right) + L_5(s_1 s_2 s_3 s_4 - s_1 c_2 c_3 s_4 - c_1 c_4) + L_6(s_1 c_2 s_3 c_5 - s_1 s_2 s_3 c_4 s_5 + s_1 s_2 c_3 c_5 + s_1 c_2 c_3 c_4 s_5 - c_1 s_4 s_5) \quad (7)$$

$$J_{16} = -L_3 c_1 s_2 - L_4\left(-c_1 s_2 s_3 + c_1 c_2 c_3\right) + L_5(-c_1 s_2 c_3 s_4 - c_1 c_2 s_3 s_4) + L_6(c_1 c_2 s_3 c_4 s_5 + c_1 s_2 s_3 c_5 - c_1 c_2 c_3 c_5 + c_1 s_2 c_3 c_4 s_5) \quad (8)$$

$$J_{17} = -L_4\left(c_1 c_2 c_3 - c_1 s_2 s_3\right) + L_5(-c_1 c_2 s_3 s_4 - c_1 s_2 c_3 s_4) + L_6(c_1 s_2 c_3 c_4 s_5 - c_1 c_2 c_3 c_5 + c_1 s_2 s_3 c_5 + c_1 c_2 s_3 c_4 s_5) \quad (9)$$

$$J_{18} = L_5(c_1 c_2 c_3 c_4 - c_1 s_2 s_3 c_4 + s_1 s_4) + L_6(c_1 c_2 c_3 s_4 s_5 - c_1 s_2 s_3 s_4 s_5 - s_1 c_4 s_5) \quad (10)$$

$$J_{19} = L_6(c_1 s_2 s_3 c_4 c_5 + c_1 c_2 s_3 s_5 + c_1 s_2 c_3 s_5 - c_1 c_2 c_3 c_4 c_5 - s_1 s_4 c_5) \quad (11)$$

$$J_{25} = L_3 c_1 c_2 - L_2 s_1 - L_4\left(c_1 c_2 s_3 + c_1 s_2 c_3\right) + L_5\left(c_1 c_2 c_3 s_4 - s_1 c_4 - c_1 s_2 s_3 s_4\right) + L_6(-s_1 s_4 s_5 - c_1 c_2 s_3 c_5 - c_1 s_2 c_3 c_5 - c_1 c_2 c_3 c_4 s_5 + c_1 s_2 s_3 c_4 s_5) \quad (12)$$

$$J_{26} = -L_3 s_1 s_2 - L_4\left(s_1 c_2 c_3 - s_1 s_2 s_3\right) - L_5(s_1 s_2 c_3 s_4 + s_1 c_2 s_3 s_4) + L_6(s_1 s_2 s_3 c_5 - s_1 c_2 c_3 c_5 + s_1 s_2 c_3 c_4 s_5 + s_1 c_2 s_3 c_4 s_5) \quad (13)$$

$$J_{27} = -L_4\left(s_1 c_2 c_3 - s_1 s_2 s_3\right) + L_5\left(-s_1 c_2 s_3 s_4 - s_1 s_2 c_3 s_4\right) + L_6(s_1 c_2 c_3 c_5 + s_1 s_2 s_3 c_5 + s_1 c_2 s_3 c_4 s_5 + s_1 s_2 c_3 c_4 s_5) \quad (14)$$

$$J_{28} = L_5\left(-c_1 s_4 + s_1 c_2 c_3 c_4 - s_1 s_2 s_3 c_4\right) + L_6(c_1 c_4 s_5 + s_1 c_2 c_3 s_4 s_5 - s_1 s_2 s_3 s_4 s_5) \quad (15)$$

$$J_{29} = L_6(c_1 s_4 c_5 + s_1 c_2 s_3 s_5 + s_1 s_2 c_3 s_5 - s_1 c_2 c_3 c_4 c_5 + s_1 s_2 s_3 c_4 c_5) \quad (16)$$

$$J_{36} = L_4\left(c_2 s_3 + s_2 c_3\right) - L_3 c_2 - L_5\left(c_2 c_3 s_4 - s_2 s_3 s_4\right) + L_6(c_2 s_3 c_5 - s_2 s_3 c_4 s_5 + c_2 c_3 c_4 s_5 + s_2 c_3 c_5) \quad (17)$$

$$J_{37} = L_4\left(s_2 c_3 + c_2 s_3\right) - L_5\left(c_2 c_3 s_4 - s_2 s_3 s_4\right) + L_6(s_2 c_3 c_5 + c_2 c_3 c_4 s_5 - s_2 s_3 c_4 s_5 + c_2 s_3 c_5) \quad (18)$$

$$J_{38} = -L_5\left(c_2 s_3 c_4 + s_2 c_3 c_4\right) - L_6(c_2 s_3 s_4 s_5 + s_2 c_3 s_4 s_5) \quad (19)$$

$$J_{39} = L_6(c_2 s_3 c_4 c_5 - s_2 s_3 s_5 + s_2 c_3 c_4 c_5 + c_2 c_3 s_5) \quad (20)$$

4. SIMULATION AND DISCUSSION

The 3D model of the omnidirectional robot is established, and the simulation platform of the robot is developed based on ADAMS software, as shown in Fig. 4. The simulation model includes two parts: the omnidirectional vehicle model and the manipulator model. The driving and constraint function is added to the simulation platform, and then the simulation parameters are set to carry on the simulation of the omnidirectional operating robot. During the simulation, the end of the manipulator moves from point A to point B shown in Fig. 4, and the associated movement of omnidirectional vehicle and the manipulator implements the spatial motion trajectory from point A to point B, which covers as much as possible the maximum moment of each joint or maximum speed conditions, so as to analyze the motion characteristics of the omnidirectional vehicles and the manipulator.

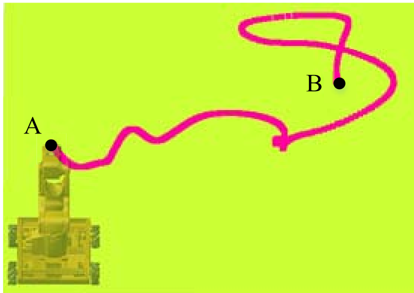

Fig 4. Simulation platform of the robot.

Moving process of omnidirectional operating robot in simulation is shown in Fig. 5. The robot is able to complete complex work by the coordinated actions of omnidirectional vehicle and manipulator.

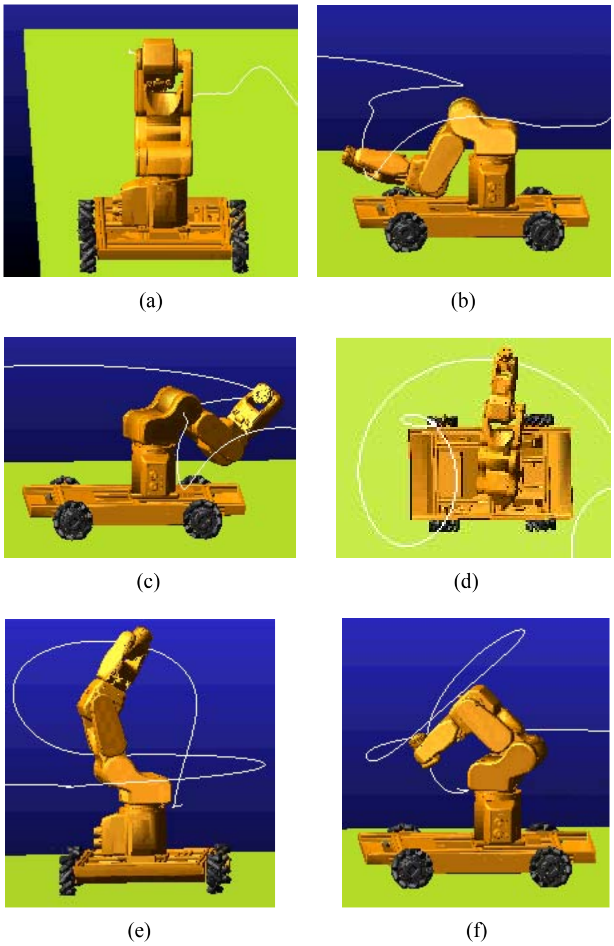

Fig 5. Simulation process of omnidirectional operating robot.

The simulation results that position curve, velocity curve and acceleration curve of the omnidirectional vehicle are shown in Fig. 6, Fig. 7 and Fig. 8. It can be seen from Fig. 6 that the omnidirectional vehicle moves smoothly in *x* direction and *y* direction, and the fluctuation in *z* direction is small. It can be found through Fig. 7 and Fig. 8 that the velocity of omnidirectional vehicle is continuous and smooth, and there is no severe impact of the acceleration.

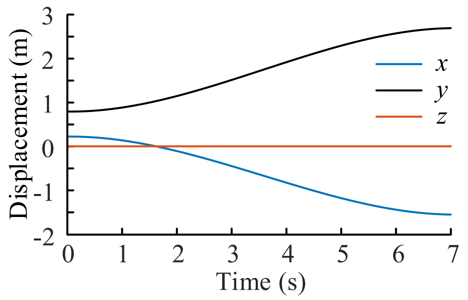

Fig 6. Position of the omnidirectional vehicle.

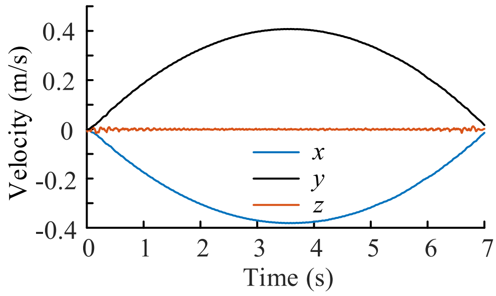

Fig 7. Velocity of the omnidirectional vehicle.

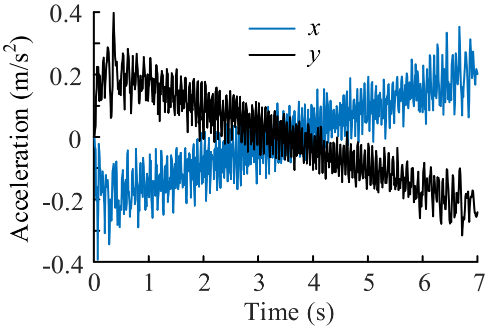

Fig 8. Acceleration of the omnidirectional vehicle.

Simulation results that the angular curves, angular velocity curves and angular acceleration curves of the manipulator's joints are shown in Fig. 9, Fig. 10 and Fig.11. It can be seen according to Fig. 9 that the joint movement is smooth, the end of the manipulator has achieved the predetermined trajectory, and the angle curves of joints are smooth. It can be found from Fig. 10 that joint angular velocity is continuous without sudden change. And based on Fig. 11, it can be seen that the joint angular acceleration is in a reasonable range.

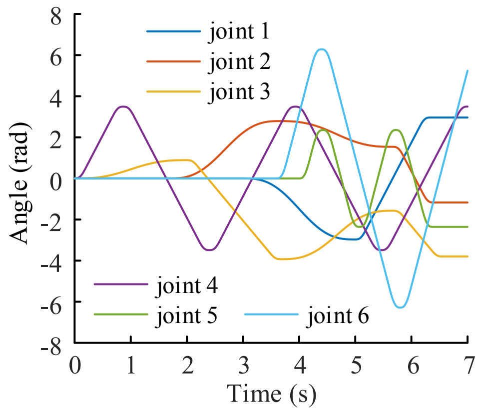

Fig 9. Joint angle of the manipulator.

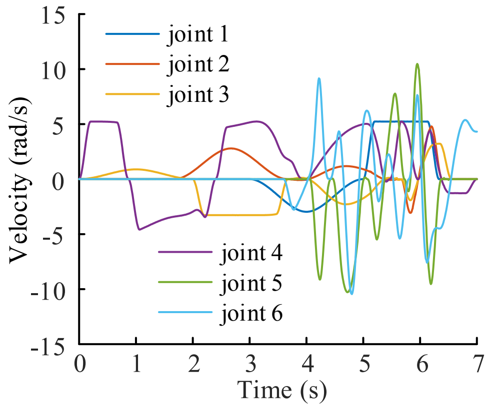

Fig 10. Joint angular velocity of the manipulator.

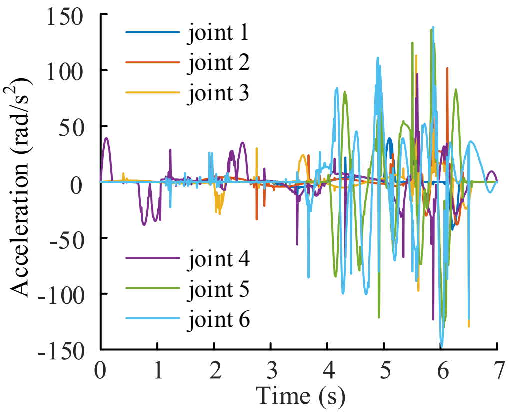

Fig 11. Joint angular acceleration of the manipulator.

The torque curves of each joint of the manipulator are shown in Fig. 12. It can be seen that the joint 1 and the joint 2 have the largest torque when the manipulator reaches the maximum wingspan, and the maximum torque is about 80 Nm. The torques of other joints are relatively small, so, the torque results meet the design requirements.

Fig. 13 shows the power curves of each joint of the manipulator. It can be found that the energy consumption of each joint during the movement of the robot is reasonable. Joint 2 has a peak power, and the value is about 400W. Other joints have relatively low power cost. The simulation results can be used as the basis for further design.

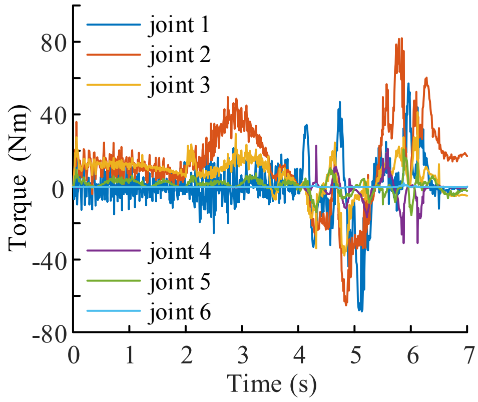

Fig 12. Joint torque of the manipulator.

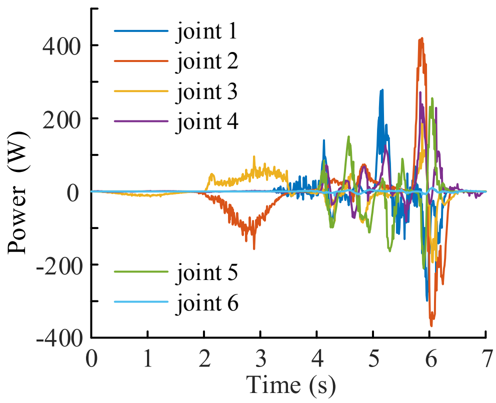

Fig 13. Joint power of the manipulator.

5. CONCLUSIONS

This article analyses the principle of omnidirectional movement of Mecanum wheel. An omnidirectional moving vehicle is designed based on Mecanum wheels, and the motion control rule of omnidirectional vehicle is proposed. A 6-DOF manipulator is designed and its kinematics model is established. Three-dimensional model of omnidirectional mobile operating robot is established.

The simulation platform of omnidirectional mobile operating robot is developed, and the motion trajectory is designed to cover the maximum moment and maximum speed of each joint as much as possible. Motion simulation of omnidirectional robot is carried out. The results show that the movement of the omnidirectional vehicle is smooth and the vertical fluctuation is small. The joint movement of the manipulator is smooth and the desired trajectory of manipulator is realized. Torque and energy consumption of each joint are reasonable. Finally, simulation results verify the feasibility of the designed omnidirectional mobile operating robot.

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