

## Motion Planning for a Mobile Manipulator with Redundant DOFs

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**Abstract.** This paper investigates how to track a desired trajectory by a mobile manipulator that has redundant degrees of freedom (DOFs). Our approach is based on the analysis of its position and orientation. In the first part of the analysis, the manipulator contributes sub-vectors projected on the  $Z$  axis in the world frame, including position and orientation. In the second part, the mobile base and the manipulator move along the direction of the desired path and reach the sub-vectors on axes  $X$  and  $Y$  in the world frame respectively. Simulated results are presented to show the effectiveness of our approach.

**Keywords:** Mobile manipulator, Redundant DOFs, Insufficient DOFs, Path planning, Trajectory tracking.

### 1 Introduction

A mobile manipulator consists of a mobile base and a manipulator [1], which represents several advantages and various constraints [2]. The most important feature of a mobile manipulator is the flexible operational workspace in contrast with the limited workspace of a fixed manipulator. This feature endow a mobile manipulator with the ability to operate in a large scale of operation [3], such as handling and transporting parts from one place to another. However, there is an intrinsic problem with a mobile manipulator: the total number of degrees of freedom (DOFs) is generally greater than six DOFs. How to deal with the redundant DOFs attracts much attention in the robotics community recently [1-10].

Seraji [4] presented an approach to motion control of a mobile manipulator, in which both mobility and manipulation were put on the same frame with a equal treatment using the combined Jacobian matrix. Tanner et al [5] proposed a motion planning method for multiple cooperating mobile manipulators. Huang et al [6] introduced the Zero Moment Point to path planning for a mobile base, and to orientation planning for a manipulator with 5 DOFs. The orientation of the end-effector is not concerned except for avoiding instability in mechanics. Papadopoulos and Poulakakis [7] presented a model-based control and planning method for a mobile manipulator. Perrier et al [8] presented a global approach to motion generation for a non-holonomic mobile manipulator. Both homogeneous matrices and dual quaternion are respectively employed to generate a point-to-point trajectory for a mobile robot. Sugar and Kumar [3][9] provided a framework and algorithm for cooperating mobile manipulators to hold and transport large objects. Matsikis et al [10] proposed a behavior coordination manager based on Bayesian Belief Networks for a mobile

manipulator to estimate the effectiveness of its behaviors. It should be noticed all these mobile manipulators have enough DOFs such that the mobile base and the manipulator can be decoupled in the control design.

However, the mobile manipulator concerned in this paper consists of a differential driven mobile robot, Pioneer II, and a 5-DOF manipulator Pioneer Arm (PArm). It is impractical to decouple them since the 5-DOF PArm itself can not satisfy some desired positions and orientations of its end-effector. Hence, it is a real challenge to deal with the problem of insufficient DOFs for the PArm and redundant DOFs for the mobile manipulator, i.e. the integration of the Pioneer II and the PArm.

The rest of the paper is organised as follows. The configuration of the mobile manipulator and its task are described in Section 2. The models for our mobile manipulator are investigated in Section 3. In Section 4, a new strategy to deal with the motion control of the mobile manipulator is introduced based on its kinematics models. The method of freedom assignment for the mobile base and manipulator is given, and the resolve of joint angles for the PArm is deduced. The position assignment of the mobile base is also present in this section. Simulation results are shown in Section 5. Finally, Section 6 concludes the paper.

## 2 The configuration of the mobile manipulator and its task

The sketch of the mobile manipulator is as shown in Fig. 1(a). The manipulator PArm is on the top of the mobile base Pioneer II. A gripper is mounted on the end of the PArm, namely the end-effector in the rest of this paper.

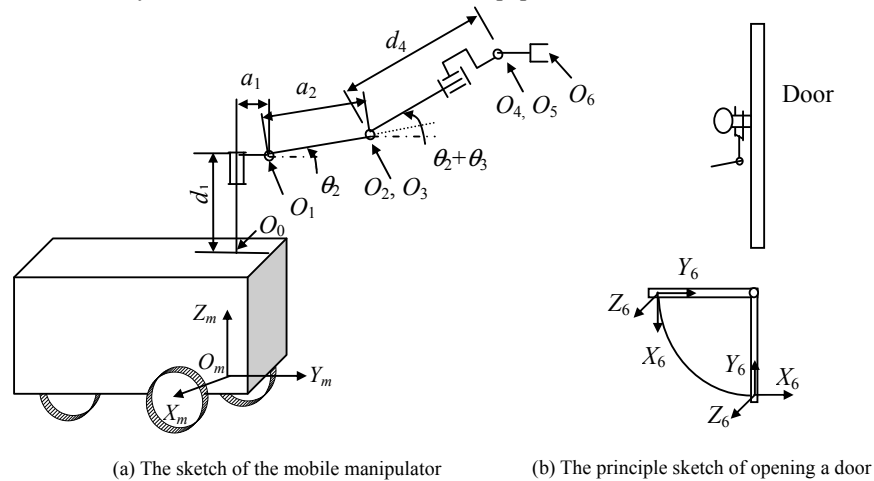


Fig.1 The configuration of the mobile manipulator and the principle sketch of opening a door

Assume that the robot's local frame  $O_m$  is at the center of the main axis connecting two driven wheels of the mobile base, and the PArm is located at  $(m_x, m_y, m_z)$  in the robot local frame.  $O_0$  is the base frame of the manipulator, and  $O_6$  is the end-effector's frame.  $O_1$  to  $O_5$  are the joint frames of the manipulator.  $a_1, a_2, d_1$  and  $d_4$  are the inherent parameters of the manipulator. More detail about the frame assignment can be found in [11][12].

The task of the mobile manipulator is to open a door, as shown in Fig. 1(b). The end-effector catches the doorknob in the upward orientation. In other words, the  $Z_6$ -axis in the end-effector frame is upward. The  $Y_6$ -axis is the direction from the doorknob to the turning axis of the door. When the end-effector opens the door, its trajectory is a piece of circle arc. This task can be described as: following the desired trajectory and orientation by a mobile manipulator. How to deal with its redundant DOFs is the key factor to ensure the PArm and the mobile base working reasonably.

### 3 The model of the mobile manipulator

Assume that  $c_i$  denotes for  $\cos(\theta_i)$ ,  $s_i$  for  $\sin(\theta_i)$ ,  $c_{23}$  for  $\cos(\theta_2 + \theta_3)$ ,  $s_{23}$  for  $\sin(\theta_2 + \theta_3)$ ,  $c$  for  $\cos$ , and  $s$  for  $\sin$ . The transform  $A_j$  between two neighboring frames, i.e.  $O_{j-1}$  and  $O_j$ , can be obtained from Denavit-Hartenberg parameters. Therefore, we can have transforms  $A_1$ - $A_6$ . Then the position and orientation of the end-effector [11] are indicated as:

$${}^0T_6 = A_1 A_2 A_3 A_4 A_5 A_6 = \begin{bmatrix} \bar{n} & \bar{o} & \bar{a} & \bar{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where  $\bar{n} = [n_x \ n_y \ n_z]^T$ ,  $\bar{o} = [o_x \ o_y \ o_z]^T$ ,  $\bar{a} = [a_x \ a_y \ a_z]^T$ ,  $\bar{p} = [p_x \ p_y \ p_z]^T$ .

#### 3.1 The model of mobile robot Pioneer II

Pioneer II is a mobile robot with two differential driven wheels and a caster.  $W_1$  and  $W_2$  represent the left and right wheel separately, along the forward direction of the mobile robot in the view of bird's eye. The world frame  $O_w$  is selected at a fixed position on the floor. Assume that  $O_m^i$  indicates the coordinate frame  $O_m$  of the robot at  $i$ -th sampling.  $r^i$  denotes its turning radius in the period between the  $i$ -th and  $i+1$ -th samplings, which is relative to  $W_1$ .  $\theta^i$  represents its direction angle at the  $i$ -th sampling.  $l$  is the distance between  $W_1$  and  $W_2$ .

The position and orientation of Frame  $O_m$  in the world frame at the  $i+1$ -th sampling,  ${}^wT_m^{i+1}$ , can be derived from  ${}^wT_m^i$  according to homogeneous transformation. Suppose  ${}^wT_m^i$  is as shown in Eq. (2).

$${}^wT_m^i = \begin{bmatrix} c\theta^i & -s\theta^i & 0 & p_x^i \\ s\theta^i & c\theta^i & 0 & p_y^i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$${}^wT_m^{i+1} = \begin{bmatrix} c\theta^{i+1} & -s\theta^{i+1} & 0 & p_x^{i+1} \\ s\theta^{i+1} & c\theta^{i+1} & 0 & p_y^{i+1} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c(\theta^i + \alpha^i) & -s(\theta^i + \alpha^i) & 0 & p_x^i - 2s(\theta^i + \frac{\alpha^i}{2})(r^i + \frac{l}{2})s\frac{\alpha^i}{2} \\ s(\theta^i + \alpha^i) & c(\theta^i + \alpha^i) & 0 & p_y^i + 2c(\theta^i + \frac{\alpha^i}{2})(r^i + \frac{l}{2})s\frac{\alpha^i}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The distance between Frame  $O_m^{i+1}$  and Frame  $O_m^i$  is  $2(r^i + l/2)s(\alpha^i/2)$ , and the rotation angle between  $Y_m^{i+1}$  and  $Y_m^i$  is  $\alpha^i$ . Then  ${}^wT_m^{i+1}$  can be derived as (3). More detail is available in [13]. Of course, Eq. (3) can be rewritten as a group of iteration equations that represent positioning with *Odometry* for the mobile robot [14].

### 3.2 The model of the mobile manipulator

The position and orientation of the end-effector in the world frame can be derived from homogeneous transform according to the position and orientation of the mobile robot in the world frame, that of the end-effector in the manipulator's base frame, and the transform between the mobile robot frame and the manipulator's base frame. The kinematics of the mobile manipulator can be described in Eq. (4).

$${}^wT_6^i = {}^wT_0^i {}^0T_6 = {}^wT_m^i {}^mT_0^i {}^0T_6$$

$$= \begin{bmatrix} -n_x s\theta^i - n_y c\theta^i & -o_x s\theta^i - o_y c\theta^i & -a_x s\theta^i - a_y c\theta^i & -(p_x + m_y)s\theta^i - (p_y - m_x)c\theta^i + p_x^i \\ n_x c\theta^i - n_y s\theta^i & o_x c\theta^i - o_y s\theta^i & a_x c\theta^i - a_y s\theta^i & (p_x + m_y)c\theta^i - (p_y - m_x)s\theta^i + p_y^i \\ n_z & o_z & a_z & p_z + m_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where the up index  $i$  denotes the  $i$ -th sampling,  ${}^wT_6^i$  denotes the position and orientation of the end-effector in the frame  $O_w$ ,  ${}^wT_0^i$  is the position and orientation of frame  $O_0$  in frame  $O_w$ .  ${}^mT_0$  as (5) is the position and orientation of the frame  $O_0$  in frame  $O_m$ .

$${}^mT_0 = \begin{bmatrix} 0 & -1 & 0 & m_x \\ 1 & 0 & 0 & m_y \\ 0 & 0 & 1 & m_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

where  $[m_x \ m_y \ m_z]^T$  is the offsets of the frame  $O_0$  in frame  $O_m$ , in axis  $X$ ,  $Y$ , and  $Z$  separately.

## 4 Deal with the insufficient and redundant DOFs problem

### 4.1 The freedom assignment for the mobile robot and the manipulator

As explained previously, the PArm has 5-DOFs, and the Pioneer II robot has 3-DOFs. Obviously, the mobile manipulator is with redundant DOFs. If the links of the PArm have enough length, or the desired moving range of the end-effector is adequate, the mobile manipulator will have 8-DOFs. In fact, the link length is limited and the desired range of the end-effector is large [15-20]. Therefore, how to distribute the desired 6-DOFs to the manipulator and the mobile robot is a key factor for the mobile manipulator to satisfy the desired position and orientation of the end-effector in an efficient and simple manner.

It is easy to find that the position and orientation of the Pioneer II base have no contribution to the position and sub-vectors of orientation for the end-effector in  $Z$ -axis of the world frame. Therefore, the manipulator can only satisfy these desired position and sub-vectors of orientation. This means that these 3-DOFs must be completely handed over to the manipulator. Other 3-DOFs should be the interaction results between the manipulator and the mobile base.

### 4.2 Position and Orientation in $Z$ -axis

Suppose the desired position and orientation of the end-effector in frame  $O_w$  is

$${}^wT_6^i = \begin{bmatrix} {}^w\bar{n} & {}^w\bar{o} & {}^w\bar{a} & {}^w\bar{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where  $\bar{n} = [{}^w n_x \quad {}^w n_y \quad {}^w n_z]^T$ ,  $\bar{o} = [{}^w o_x \quad {}^w o_y \quad {}^w o_z]^T$ ,  $\bar{a} = [{}^w a_x \quad {}^w a_y \quad {}^w a_z]^T$ ,  
 $\bar{p} = [{}^w p_x \quad {}^w p_y \quad {}^w p_z]^T$ .  ${}^w n_z$ ,  ${}^w o_z$ ,  ${}^w a_z$  and  ${}^w p_z$  are determined by the joint angles  $\theta_2$ - $\theta_5$ .

Considering redundancy, the assignment  $\theta_5=0$  will be a good selection to simplify the realization of the position and orientation of the end-effector in the world frame. Deduced from equation (4) and (6), we have

$$\begin{cases} {}^w n_z = c_{23}c_4, & {}^w o_z = -c_{23}s_4 \\ {}^w a_z = -s_{23}, & {}^w p_z - m_z = -d_6s_{23} - d_4s_{23} - a_2s_2 + d_1 \end{cases} \quad (7)$$

where  $\theta_{23}$  has two candidate solutions denoted as  $\theta_{23-1}$  and  $\theta_{23-2}$ . Submitting  $s_{23} = -{}^w a_z$  to the last equation in (7), two candidate solutions for  $\theta_{23}$ , i.e.  $\theta_{2-1}$  and  $\theta_{2-2}$ , are presented. Submitting  $\theta_{23}$  to other equations in (7),  $\theta_4$  is determined according to the sign of  $c_{23}$ .

Note that  $c_{23}=0$  is satisfied if and only if  ${}^w a_z = \pm 1$ . In this case,  $\theta_4$  can be assigned to any value in the working range of joint 4. However, it had better be evaluated with the consideration for  $\theta_1$  and  $\theta^i$ .

#### 4.3 Position and Orientation in X and Y axes

The orientation angle  $\theta^i$  of the mobile base can be calculated using the last position and the current desired one of the end-effector, which is a known variable. Therefore,  ${}^0T_6$  is a known matrix as shown in Eq. (8).

$${}^0T_6 = {}^wT_0^{-1} {}^wT_6^i = \begin{bmatrix} -{}^w n_x s\theta^i + {}^w n_y c\theta^i & -{}^w o_x s\theta^i + {}^w o_y c\theta^i & -{}^w a_x s\theta^i + {}^w a_y c\theta^i & -(p_x - p_x^i)s\theta^i + (p_y - p_y^i)c\theta^i - m_y \\ -{}^w n_x c\theta^i - {}^w n_y s\theta^i & -{}^w o_x c\theta^i - {}^w o_y s\theta^i & -{}^w a_x c\theta^i - {}^w a_y s\theta^i & -(p_x - p_x^i)c\theta^i - (p_y - p_y^i)s\theta^i + m_x \\ {}^w n_z & {}^w o_z & {}^w a_z & {}^w p_z - m_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

The resolving of  $\theta_1$  is based on (8) according to the values of  $\theta_4$  and  $\theta_{23}$ . If  $c_4=0$  and  $c_{23} \neq 0$ , the terms  $n_x$  and  $a_x$  can be employed to find  $\theta_1$ . If  $c_4=0$  and  $c_{23}=0$ , the terms  $n_x$  and  $o_x$  are employed. If  $c_4 \neq 0$  and  $c_{23} \neq 0$ , the terms  $o_y$  and  $a_y$  are used. If  $c_4 \neq 0$  and  $c_{23}=0$ , the terms  $n_y$  and  $o_y$  are selected. The solution of  $\theta_1$  is obtained as (9) in the condition  $\theta_5=0$ .

$$\theta_1 = \begin{cases} \text{atan2}[n_x \text{sig}(s_4), a_x/c_{23}], & \text{if } c_4 = 0, c_{23} \neq 0 \\ \text{atan2}[n_x \text{sig}(s_4), -o_x \text{sig}(s_{23}s_4)], & \text{if } c_4 = 0, c_{23} = 0 \\ \text{atan2}[a_y/c_{23}, -a_x s_{23}s_4/(c_{23}c_4) - o_x/c_4], & \text{if } c_4 \neq 0, c_{23} \neq 0 \\ \text{atan2}[n_y c_4 \text{sig}(s_{23}) - o_y s_4 \text{sig}(s_{23}), -n_y s_4 - o_y c_4], & \text{if } c_4 \neq 0, c_{23} = 0 \end{cases} \quad (9)$$

The solutions for  $\theta_1$ - $\theta_4$  can be selected from the candidates according to the actual range of the joint angles and criterions in [11]. If  $\theta_1$  is out of the working range, it is assigned to a maximum value. In other words, if  $\theta_1 > \theta_{1max}$  then  $\theta_1 = \theta_{1max}$ ; if  $\theta_1 < \theta_{1min}$  then  $\theta_1 = \theta_{1min}$ .

In the case  $c_{23}=0$ , we could calculate  $\theta_4$  after the assignment of  $\theta_1$ .

$$\theta_4 = \text{atan2}(n_x s_1 - o_x c_1 s_{23}, n_x c_1 s_{23} + o_x s_1) \quad (10)$$

In other cases, i.e.  $c_{23} \neq 0$ ,  $\theta_4$  is uniquely determined. The parameter, what we can only adjust, is the direction of the mobile base to satisfy the desired orientation of the end-effector. The reached  ${}^0T_6$  can be calculated using the values of  $\theta_1$  to  $\theta_4$  and  $\theta_5=0$ . Combining the desired position and orientation of the end-effector in the world frame

$O_w$  at the  $i$ -th control cycle, the desired  ${}^wT_m^i$  can be determined using Eq. (11). The desired direction angle and position of the mobile base are derived in (11).

$${}^wT_m^i = {}^wT_6^i ({}^mT_0^0 T_6^0)^{-1} = \begin{bmatrix} {}^w n_{mx}^i & {}^w o_{mx}^i & {}^w a_{mx}^i & {}^w p_{mx}^i \\ {}^w n_{my}^i & {}^w o_{my}^i & {}^w a_{my}^i & {}^w p_{my}^i \\ {}^w n_{mz}^i & {}^w o_{mz}^i & {}^w a_{mz}^i & {}^w p_{mz}^i \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\theta^i & -s\theta^i & 0 & p_x^i \\ s\theta^i & c\theta^i & 0 & p_y^i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

where  ${}^wT_6^i$  is the desired position and orientation of the end-effector in world frame at the  $i$ -th control cycle,  ${}^wT_m^i$  is that of the mobile base.  ${}^w n^i$ ,  ${}^w o^i$  and  ${}^w a^i$  are the orientation vectors of  ${}^wT_m^i$  and  ${}^w p^i$  is its position vector.

$$\theta^i = \text{atan2}({}^w n_{my}^i, {}^w n_{mx}^i), \quad p_x^i = {}^w p_{mx}^i, \quad p_y^i = {}^w p_{my}^i \quad (12)$$

## 5 Experimental results

In our simulations, the parameters of the mobile base and the manipulator are assigned respectively. For the mobile base, parameters are given as the wheel gauge  $l=320\text{mm}$  and the maximum velocity of the driven wheel  $v_{max}=0.5\text{m/s}$ . For the manipulator, we have the parameters  $a_1=68.75\text{mm}$ ,  $a_2=160.0\text{mm}$ ,  $d_1=120.0\text{mm}$ ,  $d_4=137.75\text{mm}$ , and  $d_6=113.21\text{mm}$  [21]. These are actual parameters of the PArm. The displacements of the frame  $O_0$  in the frame  $O_m$  are assigned as  $m_x=0\text{mm}$ ,  $m_y=155\text{mm}$ ,  $m_z=155\text{mm}$ . The wheel diameter is  $187.5\text{mm}$ . To verify the effectiveness of the methods proposed in Section 3, two simulations are designed.

The 1st simulation was designed for checking the effectiveness of the methods with real manipulator parameters. In this simulation, each joint angle is strictly limited to the real working range. The desired trajectory of the end-effector was generated with Eq. (13) and Eq. (14). Its positions varied with time, and its orientation was kept.

$$\begin{cases} {}^w p_x = 2500 - 2000 \sin(2\pi / 360) \\ {}^w p_y = 2500 + 2000 \cos(2\pi / 360) \\ {}^w p_z = 55 + t / 20 \end{cases} \quad (13)$$

$${}^wT_6 = \begin{bmatrix} 1 & 0 & 0 & {}^w p_x \\ 0 & -1 & 0 & {}^w p_y \\ 0 & 0 & -1 & {}^w p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

where  $t (=1,2,\dots,360)$  is an independent variable.

The simulation results are shown in Fig. 2. Fig. 2(a) gives the desired and reached positions of the end-effector in the world frame in 3D space. Fig. 2(b) shows the position of the frame  $O_m$  of the mobile base, and the position of the end-effector in the world frame in simulation. Trajectories of both the mobile base and the effector are smooth. The direction angles of the mobile base and their increments are shown in Fig. 2(c). Fig. 2(d) shows the values of joint angles of the manipulator. The distinguish angle value is one degree for each joint in the PArm. The direction of the mobile base varied smoothly. The simulation results verified the correctness of the methods provided in Section 4.

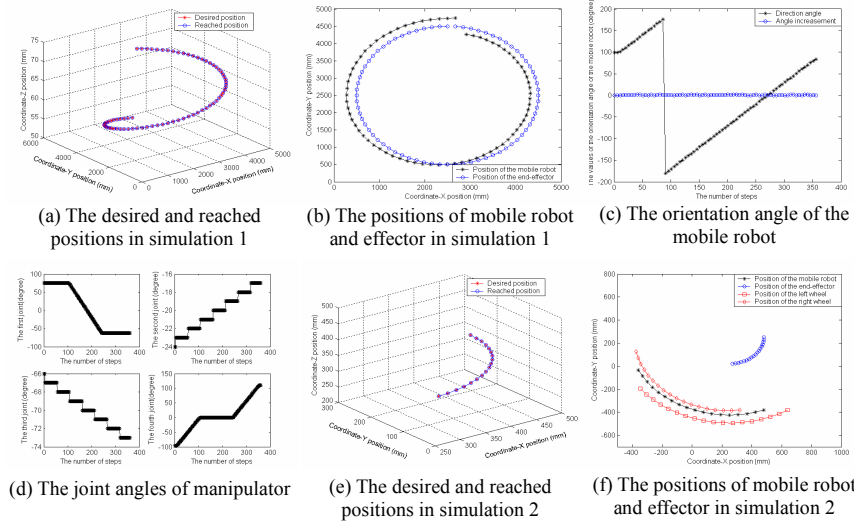


Fig. 2 The simulation results with real working range for manipulator joints

The 2nd simulation was designed to open a door. The distance from the knob to the turning axis of the door is set to 230mm. The height of the doorknob is set to 340mm. The  $Z_6$ -axis in the end-effector frame is keeping upward. The  $Y_6$ -axis is the direction from the doorknob to the turning axis of the door. And  $X_6$ -axis is the tangent direction of the circle arc moved. When the gripper opens the door, its trajectory is a piece of circle arc. The simulation results of desired and reached positions of the end-effector in the world frame are shown in Fig. 2(e). The positions, orientations and trajectories of the wheels of the mobile base are shown in Fig. 2(f). As we can see, the simulation results show the effectiveness of the proposed method.

## 6 Conclusions

In this paper, a new strategy is proposed to effectively deal with the problem in a mobile manipulator that has redundant DOFs. It decomposes the position and orientation of the end-effector into two parts. The manipulator realizes the sub-vectors projected on  $Z$ -axis in the world frame, including position and orientation. The mobile base and the manipulator are responsible for moving along the main direction of the desired path and the sub-vectors on axes  $X$  and  $Y$  in the world frame. The simulation results show that the little working ranges of the joints of the manipulator have seriously limited the application. A large working range for each joint is very helpful for the mobile manipulator to follow a desired trajectory with given orientations.

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