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). Based on the analysis of its kinematics models, a motion planning method is proposed. The position and orientation of the end-effector is decomposed into two parts. In the first part, 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 the proposed approach.

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

I. 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 endows 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 an 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 quarter- nions 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 cannot 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 organized as follows. The configuration of the mobile manipulator and its task are described in Section 2. The models for the 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 presented in this section. Simulation results are shown in Section 5. Finally, Section 6 concludes the paper.

II. 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.

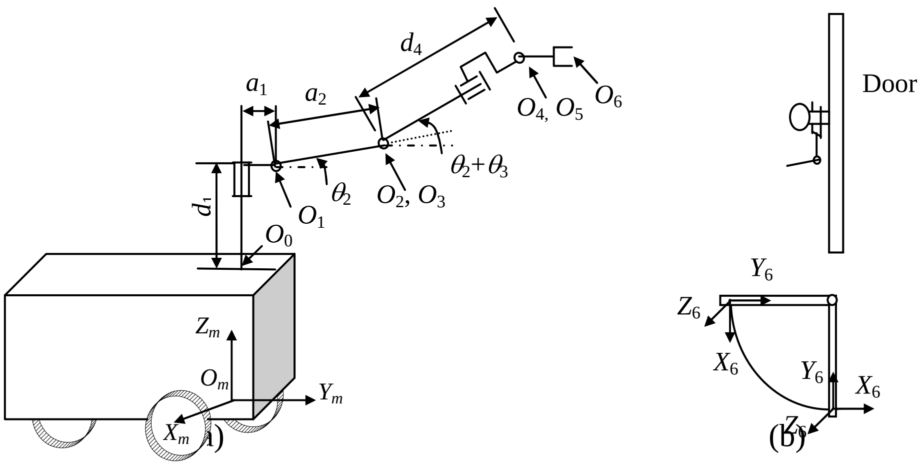

Fig.1. The mobile manipulator and its task. The configuration sketch of the mobile manipulator is shown in (a). The principle sketch of opening a door is shown in (b).

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.

III. 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, the transforms A_1-A_6 can be obtained. Then the position and orientation of the end-effector [11] are indicated as

$$ {}^0T_6 = A_1A_2A_3A_4A_5A_6 = \begin{bmatrix} \vec{n} & \vec{o} & \vec{a} & \vec{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

here $\vec{n} = \begin{bmatrix} n_x & n_y & n_z \end{bmatrix}^T$, $\vec{o} = \begin{bmatrix} o_x & o_y & o_z \end{bmatrix}^T$, $\vec{a} = \begin{bmatrix} a_x & a_y & a_z \end{bmatrix}^T$, $\vec{p} = \begin{bmatrix} p_x & p_y & p_z \end{bmatrix}^T$.

A. *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, which is taken as absolute reference frame. 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. θ^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).

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

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

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 α^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].

B. *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).

$$ {}^{w}T_6^i = {}^{w}T_0^i\,{}^{0}T_6 = {}^{w}T_m^i\,{}^{m}T_0\,{}^{0}T_6 $$
$$ = \begin{bmatrix} -n_x s\theta^i - n_y c\theta^i & -o_x s\theta^i - o_y c\theta^i & -a_x s\theta^i - a_y c\theta^i & -(p_x+m_y)s\theta^i - (p_y-m_x)c\theta^i + p_x^i \\ n_x c\theta^i - n_y s\theta^i & o_x c\theta^i - o_y s\theta^i & a_x c\theta^i - a_y s\theta^i & (p_x+m_y)c\theta^i - (p_y-m_x)s\theta^i + p_y^i \\ n_z & o_z & a_z & p_z+m_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where the up index *i* denotes the *i*-th sampling, ${}^{w}T_6^{i}$ denotes the position and orientation of the end-effector in the frame O_w, ${}^{w}T_0^{i}$ is the position and orientation of frame O_0 expressed in frame O_w. ${}^{m}T_0$ as Eq. (5) is the position and orientation of the frame O_0 in frame O_m.

$$ {}^{m}T_0 = \begin{bmatrix} 0 & -1 & 0 & m_x \\ 1 & 0 & 0 & m_y \\ 0 & 0 & 1 & m_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

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

IV. Deal with the Insufficient and Redundant DOFs Problem

A. *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.

B. Position and Orientation in Z-axis

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

$$ {}^{w}T_6^i = \begin{bmatrix} {}^{w}\vec{n} & {}^{w}\vec{o} & {}^{w}\vec{a} & {}^{w}\vec{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6) $$

where $\vec{n} = \begin{bmatrix} {}^{w}n_x & {}^{w}n_y & {}^{w}n_z \end{bmatrix}^T$, $\vec{o} = \begin{bmatrix} {}^{w}o_x & {}^{w}o_y & {}^{w}o_z \end{bmatrix}^T$, $\vec{a} = \begin{bmatrix} {}^{w}a_x & {}^{w}a_y & {}^{w}a_z \end{bmatrix}^T$, $\vec{p} = \begin{bmatrix} {}^{w}p_x & {}^{w}p_y & {}^{w}p_z \end{bmatrix}^T$. ${}^{w}n_z$, ${}^{w}o_z$, ${}^{w}a_z$ and ${}^{w}p_z$ are determined by the joint angles θ_2-θ_5 of the manipulator. Considering redundancy, the assignment θ_5=0 will be a good selection to simplify the realization of the position and orientation of the end-effector in the world frame. Hence, Eq. (7) is deduced from Eq. (4) and Eq. (6).

$$ \begin{cases} {}^{w}n_z = c_{23}c_4, & {}^{w}o_z = -c_{23}s_4 \\ {}^{w}a_z = -s_{23}, & {}^{w}p_z - m_z = -d_6 s_{23} - d_4 s_{23} - a_2 s_2 + d_1 \end{cases} \quad (7) $$

θ_{23} has two candidate solutions denoted as $\theta_{23\text{-}1}$ and $\theta_{23\text{-}2}$ from $s_{23}=-{}^{w}a_z$. Submitting $s_{23}=-{}^{w}a_z$ to the last equation in (7), two candidate solutions for θ_2, i.e. $\theta_{2\text{-}1}$ and $\theta_{2\text{-}2}$, are presented. Submitting θ_{23} to other equations in (7), θ_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, θ_4 can be assigned to any value in the working range of joint 4. However, it had better be evaluated with the consideration for θ_1 and θ^i.

C. Position and Orientation in X and Y axes

The orientation angle θ^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, ${}^{0}T_6$ is a known matrix as shown in Eq. (8).

$$ {}^{0}T_6 = {}^{w}T_0^{i-1}\,{}^{w}T_6^i $$
$$ = \begin{bmatrix} -{}^{w}n_x s\theta^i + {}^{w}n_y c\theta^i & -{}^{w}o_x s\theta^i + {}^{w}o_y c\theta^i & -{}^{w}a_x s\theta^i + {}^{w}a_y c\theta^i & -({}^{w}p_x - p_x^i)s\theta^i + ({}^{w}p_y - p_y^i)c\theta^i - m_y \\ -{}^{w}n_x c\theta^i - {}^{w}n_y s\theta^i & -{}^{w}o_x c\theta^i - {}^{w}o_y s\theta^i & -{}^{w}a_x c\theta^i - {}^{w}a_y s\theta^i & -({}^{w}p_x - p_x^i)c\theta^i - ({}^{w}p_y - p_y^i)s\theta^i + m_x \\ {}^{w}n_z & {}^{w}o_z & {}^{w}a_z & {}^{w}p_z - m_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8) $$

The resolving of θ_1 is based on Eq. (8) according to the values of θ_4 and θ_{23}. If c_4=0 and $c_{23}\neq 0$, the terms n_x and a_x can be employed to find θ_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 θ_1 is obtained as Eq. (9) in the condition θ_5=0.

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

where atan(y, x) is a function to calculate the arc tangent of y/x, the signs of both arguments x and y are used to determine the quadrant of the result.

The solutions for θ_1-θ_4 can be selected from the candidates according to the actual range of the joint angles and criterions in [11]. If θ_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, θ_4 could be calculated after the assignment of θ_1.

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

In other cases, i.e. $c_{23}\neq0$, θ_4 is uniquely determined. The parameter, what can only be adjusted, 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 θ_1 to θ_4 and θ_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). Then the desired direction angle and position of the mobile base are derived in Eq. (12).

$${}^wT_m^i = {}^wT_6^i\,({}^mT_0\,{}^0T_6)^{-1} = \begin{bmatrix} {}^wn_{mx}^i & {}^wo_{mx}^i & {}^wa_{mx}^i & {}^wp_{mx}^i \\ {}^wn_{my}^i & {}^wo_{my}^i & {}^wa_{my}^i & {}^wp_{my}^i \\ {}^wn_{mz}^i & {}^wo_{mz}^i & {}^wa_{mz}^i & {}^wp_{mz}^i \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\theta^i & -s\theta^i & 0 & p_x^i \\ s\theta^i & c\theta^i & 0 & p_y^i \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

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. ${}^wn^i$, ${}^wo^i$ and ${}^wa^i$ are the orientation vectors of ${}^wT_m{}^i$ and ${}^wp^i$ is its position vector.

$$\theta^i = \text{atan}({}^wn_{my}^i, {}^wn_{mx}^i),\ p_x^i = {}^wp_{mx}^i,\ p_y^i = {}^wp_{my}^i \tag{12}$$

V. Simulations and Results

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

The first simulation was designed for checking the effectiveness of the methods with real manipulator parameters. In this simulation, each joint angle was 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.

$$\begin{cases} {}^wp_x = 2500 - 2000\sin(2\pi t/360) \\ {}^wp_y = 2500 + 2000\cos(2\pi t/360) \\ {}^wp_z = 55 + t/20 \end{cases} \tag{13}$$

$$
{}^{w}T_{6} = \begin{bmatrix} 1 & 0 & 0 & {}^{w}p_{x} \\ 0 & -1 & 0 & {}^{w}p_{y} \\ 0 & 0 & -1 & {}^{w}p_{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)
$$

where t (=1,2,…,360) was 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 positions of the frame O_m of the mobile base, and the positions of the end-effector in the world frame in simulation. Trajectories of both the mobile base and the effector were 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.

The second simulation was designed to open a door. The distance from the knob to the turning axis of the door was set to 230mm. The height of the doorknob was set to 340mm. The Z_6-axis in the end-effector frame was keeping upward. The Y_6-axis was the direction from the doorknob to the turning axis of the door. In addition, X_6-axis was the tangent direction of the circle arc moved. When the

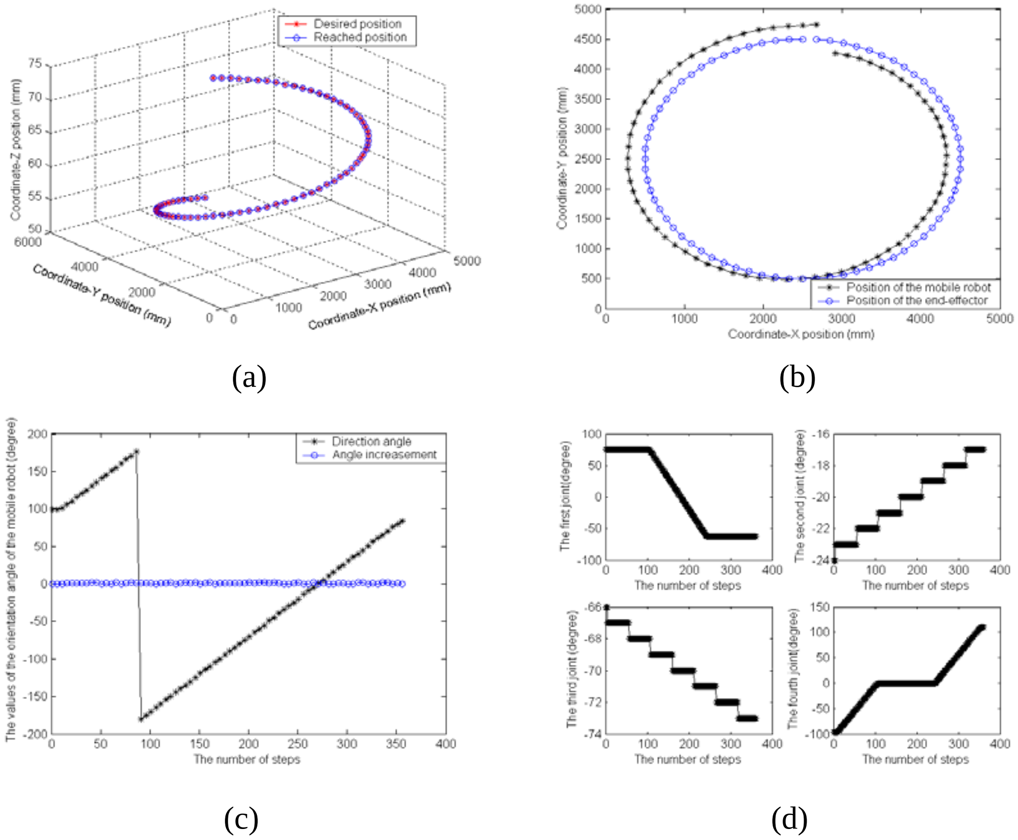

Fig.2. The results of the 1st simulation with real working range for manipulator joints. (a) gives the desired and reached positions of the end-effector in the world frame in 3D space. (b) shows the positions of frame O_m of the mobile base, and the positions of the end-effector in the world frame. The direction angles of the mobile base and their increments are shown in (c). The values of joint angles of the manipulator are shown in (d).

(a) (b)

Fig.3. The simulation results of opening a door with real working range for manipulator joints. (a) gives the desired and reached positions of the end-effector in the world frame in 3D space. (b) shows the positions of frame O_m of the mobile base, the positions of the wheels, and the positions of the end-effector in the world frame in 2D.gripper opened the door, its trajectory was a piece of circle arc. The simulation results of desired and reached positions of the end- effector in the world frame in 3D space are shown in Fig. 3(a). The positions of frame O_m of the mobile base, the positions of the wheels, and the positions of the end-effector in the world frame in 2D are shown in Fig. 3(b). The simulation results show the effectiveness of the proposed method.

VI. 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 the effectiveness of the proposed method. Moreover, the simulation results also 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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