A Simple Control Method for Opening a Door with Mobile Manipulator

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Abstract: The home service robot supports human beings by performing various kinds of works at home. This paper presents a simple control method for opening a door from the viewpoint of the mobile manipulation. The simulation shows various results of path planning and motion planning for opening a door. The joint trajectories were generated by the simulation system. In general, a six-axis force/torque sensor at an end-effector is needed in order to maintain the static equilibrium of the manipulator. But we show another method. From three components of applied forces which was directly obtained by the three-axis force sensor and three components of applied forces which was indirectly estimated by the joint-torque sensors, all of joint torques that will exactly balance forces at the end-effector in the static situation can be found. It is more practical method than using a six-axis force sensor in a wrist. Experimental results have shown that the opening a door can be realized more effectively from the suggested control method of mobile manipulation.

Keywords: service robot, manipulator, compliance control, opening a door

1. Introduction

These days, a new application of robotics is appearing, e.g. the areas of field, hazard-work and service robot. Especially, a home service robot supports human beings at home by performing various tasks such as patrolling rooms, fetching and carrying things, opening a door, etc. The successful new area, when these kinds of robots and human beings live together, depends on the development of the safe and easy robot systems. For that reason, the robots have to ensure enough mobility and manipulation [10].

Various control methods are needed for diverse tasks. Force control and compliance control for simple tasks in industry are well studied and this technique works quite well [1]. However, sufficient robust, accurate and simple control methods are needed for real world tasks. These robots work mobile manipulation, the integrated control of a mobile base platform and manipulator, and these manipulators can perform various kinds of tasks like opening a door. Previous door opening approaches have been presented some methods. For instance, S. Yuta in the University of Tsukuba explains the method of opening a door. The robot previously computes the position of mobile base and the joint angles of manipulator for opening a door task. Yamabico-10, which was developed by University of Tsukuba, assumes that parameters of the door are well known [8]. L. Petersson presented another door opening system. It is supposed that door parameters such as the position and radius are unknown and these parameters are estimated by least square method from the motion of the robot when a compliance control is used [9]. O. Khatib presents a control method connected with dynamics. An end-effector dynamically decoupled motion and force control can be achieved by the control structure [10]. But those presented robots use a six-axis force/torque sensor at end-effector of a manipulator.

In this paper, we show another method for opening a door without a six-axis force/torque sensor. We use six components of applied forces obtained from a three-axis force sensor at the gripper and the joint-torque sensors at the first, second and third joints. This method has the advantage of design and cost. We use Hombot in an experiment. Hombot, a home service robot which was developed by the KIST, can expand its scope of working space with an equipped manipulator. The discussion in this article focuses a simple method for opening a door from the viewpoint of the mobile manipulation.

This paper is organized as follows. Section 2 explains kinematics analysis. Section 3 presents experimental system. Section 4 deals with the simulation results and discussion. Section 5 shows experiment and its result. Finally, conclusion is made in section 6.

2. Kinematic Analysis

The relationship between static forces and the corresponding joint torques is defined by the Jacobian matrix [1]. Generally, transforming the forces and torques acting on the end-effector into corresponding joint torques is described as follows:

$$t = \boldsymbol{J}^{\boldsymbol{T}} \boldsymbol{f} \qquad (1)$$

where t is the vector of joint torques of the manipulator and $\boldsymbol{f}$ is the vector of force acting on the end-effector. $\boldsymbol{J}^{\boldsymbol{T}}$ is the manipulator Jacobian matrix transpose. Because of the mechanism of DAUJ (Double Active Universal Joint) in manipulator [3], Eq. (1) can be divided into Eq. (2) and Eq. (4). Eq. (2) includes the mechanism of DAUJ but Eq. (4) dose not. t_1, t_2, t_3, $\boldsymbol{f_1}$, $\boldsymbol{f_2}$ and $\boldsymbol{m_3}$ are the known parameters and t_4, t_5, t_6, $\boldsymbol{f_3}$, $\boldsymbol{m}_1$ and $\boldsymbol{m}_2$ are the unknown. The forces and moments on the end-effector can be converted to corresponding joint drive torques using appropriate Jacobian.

The joint torques of manipulator are t_1 , t_2 , t_3 and t_4 as follows:

$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} = J_1^T \begin{bmatrix} {}^0R_7 & 0_{3\times3} \\ ({}^0p_7 \times)\,{}^0R_7 & {}^0R_7 \end{bmatrix} \begin{bmatrix} f \\ m \end{bmatrix} \quad (2)$$

where $J_1^T \in \mathbf{R}^{4\times6}$ is Jacobian matrix [2] such as

$$J_1^T = \begin{bmatrix} ({}^0z_1 \times ({}^0p_7 - {}^0p_1))^T & {}^0z_1^T \\ ({}^0z_2 \times ({}^0p_7 - {}^0p_2))^T & {}^0z_1^T \\ ({}^0z_3 \times ({}^0p_7 - {}^0p_3))^T & {}^0z_1^T \\ ({}^0z_6 \times ({}^0p_7 - {}^0p_6))^T & {}^0z_6^T \end{bmatrix} \quad (3)$$

and f is a 3×1 force vector and m is a 3×1 moment vector. The matrix ${}^iR_j$ denotes the rotation matrix of frame Σ_j from frame Σ_i , and the vector ${}^iP_j$ denotes the position vector of Σ_j 's origin from Σ_i 's origin. The notation $(\bullet\times)$ denotes the cross product matrix of the vector **p**.

Furthermore, t_4 and t_5 are the torques of fourth and fifth joints respectively.

$$\begin{bmatrix} t_4 \\ t_5 \end{bmatrix} = J_3^T J_2^T \begin{bmatrix} {}^0R_{a'} & 0_{3\times3} \\ ({}^0p_7 \times)\,{}^{a'}R_7 & {}^0R_{a'} \end{bmatrix} diag(1,\,1,\,0,\,1,\,1,\,0) \begin{bmatrix} {}^{a'}R_7 & 0_{3\times3} \\ ({}^{a'}p_7 \times)\,{}^{a'}R_7 & {}^{a'}R_0 \end{bmatrix} \begin{bmatrix} f \\ m \end{bmatrix} \quad (4)$$

where diag(1, 1, 0, 1, 1, 0) is diagonal matrix. It is determined by outer universal joint of DAUJ [3]. $J_2^T \in \mathbf{R}^{2\times6}$ is Jacobian matrix [2] such as

$$J_2^T = \begin{bmatrix} ({}^0z_a \times ({}^0p_{a'} - {}^0p_a))^T & {}^0z_a^T \\ ({}^0z_b \times ({}^0p_{a'} - {}^0p_b))^T & {}^0z_b^T \end{bmatrix} \quad (5)$$

and

$$J_3^T = \begin{bmatrix} \frac{1}{2} & -\dfrac{\tan f \sin\left(\frac{q_4 - q_5}{2}\right)}{1 + \tan^2 f \cos^2\left(\frac{q_4 - q_5}{2}\right)} \\ \frac{1}{2} & \dfrac{\tan f \sin\left(\frac{q_4 - q_5}{2}\right)}{1 + \tan^2 f \cos^2\left(\frac{q_4 - q_5}{2}\right)} \end{bmatrix} \quad (6)$$

where ${}^0p_{a'} - {}^0p_a = {}^0p_a - {}^0p_b = \mathbf{0}$ as the origins coincide.

Thus the transform matrix **K** in Eq. (7) calculated from Eq. (2) and Eq. (4). The matrix transforms the forces and torques acting on the end-effector into corresponding joint torques.

$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{16} & K_{13} & K_{14} & K_{15} \\ K_{21} & K_{22} & K_{26} & K_{23} & K_{24} & K_{25} \\ K_{31} & K_{32} & K_{36} & K_{33} & K_{34} & K_{35} \\ K_{41} & K_{42} & K_{46} & K_{43} & K_{44} & K_{45} \\ K_{51} & K_{52} & K_{56} & K_{53} & K_{54} & K_{55} \\ K_{61} & K_{62} & K_{66} & K_{63} & K_{64} & K_{65} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ m_3 \\ f_3 \\ m_1 \\ m_2 \end{bmatrix}$$

$$= \begin{pmatrix} \mathbf{A}_{3\times3} & \mathbf{B}_{3\times3} \\ \mathbf{C}_{3\times3} & \mathbf{D}_{3\times3} \end{pmatrix} (f_1 \;\; f_2 \;\; m_3 \;\; f_3 \;\; m_1 \;\; m_2)^T \quad (7)$$

Hence, the unknown parameters which are t_4 , t_5 , t_6 , f_3 , m_1 and m_2 are calculated according to follow equations.

$$\begin{pmatrix} f_3 \\ m_1 \\ m_2 \end{pmatrix} = \mathbf{B}^{-1}\left(\begin{pmatrix} t_1 \\ t_2 \\ t_3 \end{pmatrix} - \mathbf{A}\begin{pmatrix} f_1 \\ f_2 \\ m_3 \end{pmatrix}\right) \quad (8)$$

$$\begin{pmatrix} t_4 \\ t_5 \\ t_6 \end{pmatrix} = \mathbf{C}\begin{pmatrix} f_1 \\ f_2 \\ m_3 \end{pmatrix} + \mathbf{D}\begin{pmatrix} f_3 \\ m_1 \\ m_2 \end{pmatrix} = \left(\mathbf{C}\text{-}\mathbf{D}\mathbf{B}^{-1}\mathbf{A}\right)\mathbf{C}\begin{pmatrix} f_1 \\ f_2 \\ m_3 \end{pmatrix} + \mathbf{D}\mathbf{B}^{-1}\begin{pmatrix} t_1 \\ t_2 \\ t_3 \end{pmatrix} \quad (9)$$

3. Experimental system

The hardware configuration of Hombot is divided into two parts, i.e. a mobile base and an equipped manipulator. The system of Hombot is composed of two on-board computers. One of them is for motion control, the other is for vision. Hombot is interfaced with motion board using CAN-BUS in Windows system and has a mobile base with two-wheels driving. The mobile base of Hombot is also equipped with a stereo vision camera for visual servoing. The manipulator mounted on a mobile base of Hombot has six degree-of-freedom and has a three-axis force sensor at the gripper and joint-torque sensors at the first, second and third joints shown in Fig. 1.

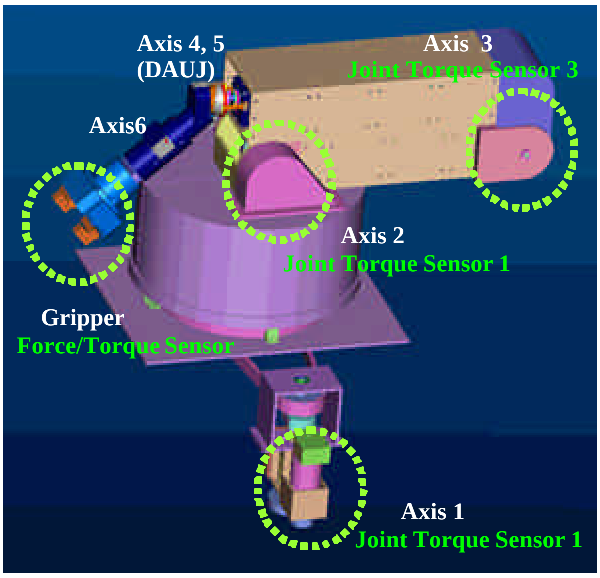


Fig. 1 Configuration of the Mobile Manipulator

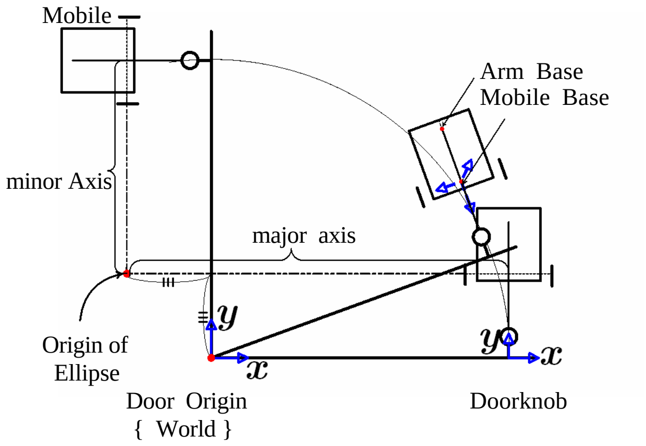


Fig. 2 Elliptical Trajectory of Mobile Base

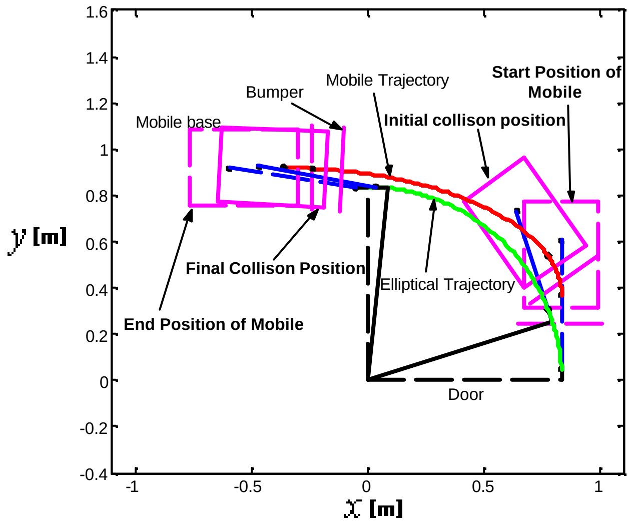


Fig. 3 Collision Path.

In general, a six-axis force/torque sensor at an end-effector is needed in order to maintain the static equilibrium of the manipulator. In Hombot, three components of applied forces can be obtained from the three-axis force sensor at the gripper, and three components of applied forces can be estimated from the joint-torque sensor at the first, second and third joints. Therefore, we can find all of joint torques that will exactly balance forces at the end-effector in the static situation. The collision is defined that a safe distance between the mobile base and a door is not ensure.

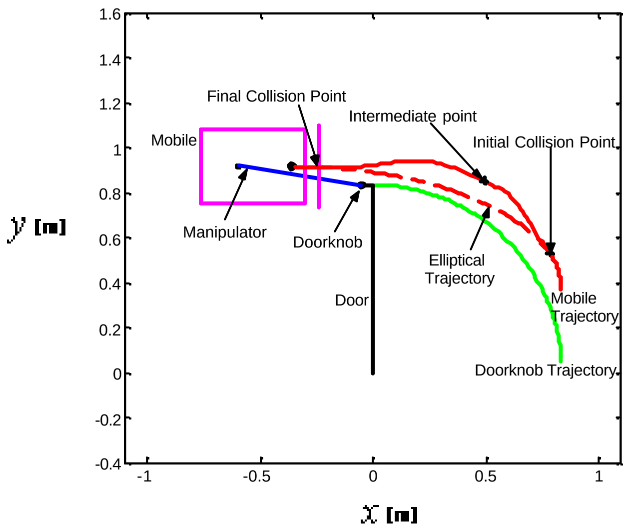


Fig. 4 New Collision Free Path Created by Simulation

4. Simulation Results

The simulation shows various results of path planning and motion planning for opening a door. To realize this motion, we assumed that 1) the manipulator system is rigid, 2) the gripper of manipulator follows the trajectory of the doorknob during opening a door, 3) the simulator is required predefined parameters such as the height, a radius and position about a doorknob for this work 4) the mobile base must avoid the collision with a door. In simulation, the collision is defined that a safe distance between the mobile base and a door is not ensured.

In the first method, the posture of the manipulator is changed and the mobile base follows the predetermined an elliptical path illustrated in Fig. 2. The elliptical parameters like the lengths of a major axis and minor axis are determined by the initial position where the mobile base is located in front of a door. But there is no solution for inverse kinematics during opening a door, because of the mechanical characteristic of manipulator.

In the second method, the posture of the manipulator is changed and the mobile base follows the predetermined path. This algorithm is shown in Fig. 2, Fig. 3, Fig. 4, and Fig. 5. Fig. 3 shows the collision path before the simulation. Fig. 4 illustrates the new collision free path with a door. Fig. 5 represents the joint angles of manipulator during opening a door task. The algorithm of a new collision free path is summarized as the following steps:

STEP1: Given a candidate posture of the manipulator, the mobile base follows the predetermined elliptical path. If no solution for inverse kinematics is found, the given posture is infeasible. So, change the posture of the manipulator. (Fig. 2)

STEP2: Check the collision points with a door. (Fig. 3)

STEP3: Draw a straight line from an initial collision point to a final collision point. And find a center point on the created straight line.

STEP4: Draw a perpendicular line through the center point.

STEP5: Generate a new path via any point on the perpendicular line

STEP6: After create a new path, it is needed to check that all the presented assumptions are satisfied.

STEP7: If the new path is not satisfied the supposed conditions, find another new path by next step

STEP8: If the mobile base collides with the door between the initial collision point and the intermediate point, the initial collision point is moved forward along the elliptical trajectory. Also, if the collision occurs between the middle point and the final collision point,

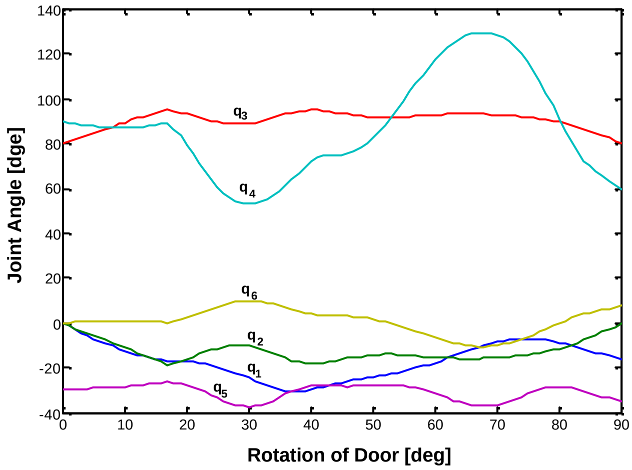


Fig. 5 Joint Angles of Manipulator

the final collision point is moved backward. (Fig. 4)

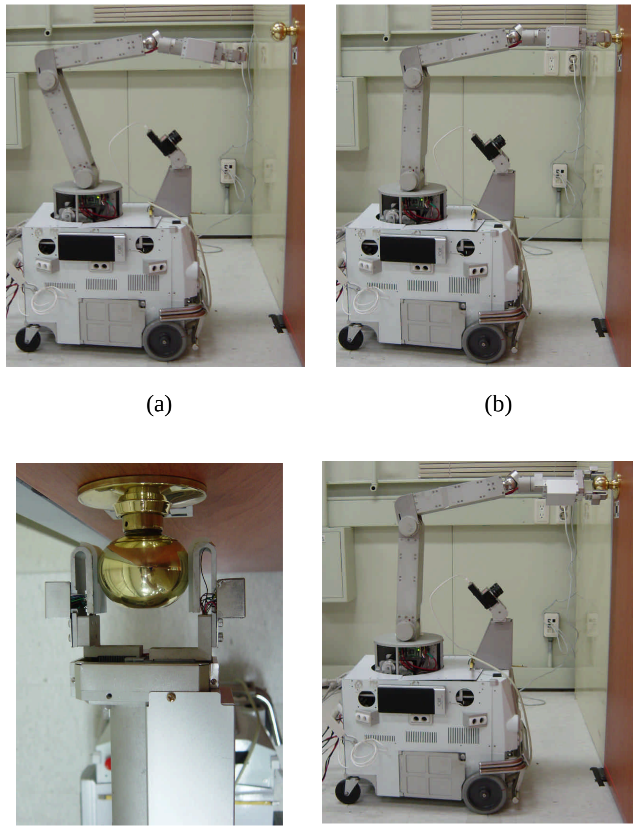
STEP9: Above steps are repeated until a new collision free path which is satisfied with the presented assumptions is generated.

And an angular velocity of the mobile base is influenced by a tangential angle. The speed of the mobile is set by a differential coefficient of the point.

4. Experimental Results and Discussion

In this section, experimental results of the behavior are shown. Using the proposed simulation, the process of opening a door follows next steps. First, the mobile base of Hombot is located in front of a door using the stereo vision system on the mobile base. Before opening a door task with visual feedback, the robot arm is posed for an appropriate position shown in Fig. 6(a). Second, the visual system on the mobile base sends a signal to manipulator controller. With this signal, the manipulator moves the end-effector to desired position shown in Fig. 6 (b). Third, after visual servoing, the center of gripper is aligned by the arm for closing a gripper. The manipulator grasps the doorknob to turn it. It is illustrated in Fig 6 (c). Fourth, Hombot arm pulls very little a doorknob. Before executing an actual motion, the simulator checks the planned motion. Sixth, the simulator makes a collision free path. Then the motion of the robot is used compliant control. The new collision avoidance path is generated by the simulator, again. Final, the robot mobile follows the collision free path generated by the simulator. The compliance control is begun to work for Hombot arm. It is represented on Fig. 6 (d).

We assumed that an end-effector's position of manipulator is fixed (perpendicular to a door), like Fig. 6 (b), but it is not used any situation. For example, the end-effector is not perpendicular when visual servoing of mobile base is at the wrong angle and the pulling trajectory of doorknob is not perpendicular. In our implementation, the path planning algorithm is very simple, there is no guarantee to find a path, because of the limits of joint and collision avoidance with a doorknob.



(a) (b)

(c) (d)

Fig. 6 Process of Opening a Door: (a) pose manipulator before visual servoing. (b) after visual servoing. (c) closing gripper. (d) turning and pulling a doorknob.

5. Conclusions

In this paper, a simple control method for opening a door with mobile manipulator was presented. The joint trajectories were generated by the simulation system. From three components of applied forces which was directly obtained by the three-axis force sensor and three components of applied forces which was indirectly estimated by the joint-torque sensors, all of joint torques that will exactly balance forces at the end-effector in the static situation can be found. It is more practical method than using a six-axis force sensor in a wrist.

Experimental results have shown that opening a door can be realized more effectively from the suggested control method of mobile manipulation.

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