2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

A Door Opening Method by Modular Re-configurable Robot with Joints Working on Passive and Active Modes

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Abstract— **In this paper, we study the problem of door-opening by using a modular re-configurable robot (MRR) mounted on a tracked mobile platform. The main concern of opening a door is how to prevent the internal forces that occur because of the positioning error or the imprecise modeling of the environment, i.e., the door parameters. Most previous research is based on compliant control, which makes the control system rather complicated. In addition, such approaches need expensive force/torque sensor to be implemented. With respect to the multiple working modes of the MRR modules, the complication has been avoided by switching the joints that has axis of rotation parallel to the door hinge to work in passive mode. As a result of this approach, the internal forces between the door and the mobile manipulator will vanish. Simulation results demonstrate the validity and efficiency of the proposed door opening strategy.**

Index Terms - Modular re-configurable robot, Door-opening, trajectory planning, hybrid control.

I. INTRODUCTION

Modern robot applications such as service robots make performance demands far beyond those of the assembly and repetitive task devices of the past. One of the prerequisites of a robotic system operating in a domestic environment is the ability to manipulate objects, patrol rooms, fetch and carry things, open doors, etc. This section describes past proposals and past results related to the door opening task.

Khatib *et al.* [1] [16] considered a mobile-manipulator system as a macro-micro manipulator and on the basis of this concepts they proposed an effective dynamic-behaviour models. Nagatani *et al.* presented general approaches to door-opening ([2] to [4]) and applied the concept of action primitives to open doors. In their method, they assumed that the door parameters are known and a robotic hand takes a firm hold of the knob and then a robotic arm opens the door through compliance control. Niemeyer *et al.* proposed a relatively simple control method of following the path of least resistance [5] to solve the problem of door opening. This approach does not require the kinematic model of the door. However, the velocity resolution should be sufficiently high. Otherwise, in the existence of large joint backlashes, the method is difficult to implement due to the error in the estimation of the direction of movement. Hanebeck *et al.* proposed simultaneous control of both the mobile base and the robot arm [6]. Petersson *et al.* proposed a high-level control approach, which used off-the-shelf algorithms of force/torque control, for door opening by mobile robot manipulators [7] . The aforementioned authors also proposed a hybrid dynamic system for the complicated task of opening a door. They demonstrated the intelligent control architecture from finding the doorknob by visual servoing and then estimating the door parameters [8] [9]. The difference between Nagatani and Yuta's work and that of Petersson *et al.* is that in the latter, the mobile robot moves along the estimated arc, and the manipulator configuration remains almost unchanged. Waarsing *et al.* investigated the possibilities that the behaviour-based hypothesis could offer when it came to mobile manipulation when they implemented a demo application for opening a door [10]. Kim *et al.* developed a special mobile robot called Hombot for opening a door [11]. Hombot is equipped with an anthropomorphous arm with a double active universal joint (DAUJ) to guarantee a compact size of the manipulator. A system employing behavior and sensor motor control that can push open doors was presented by Brooks *et al.* [14]. Kobayashi *et al.* have been developing a series of rescue robots named UMRS (Utility Mobile Robots for Search) since the Great Hanshin-Awaji earthquake in 1995. In their recent version, they implemented a door opening system using compliant mechanisms in [15].

All of the previous work was based on mobile robot manipulators equipped with fixed configuration arms with joints capable of working only in active mode. In addition, the used control approaches requires expensive force/torque sensor to be implemented. To the authors' best knowledge, the method presented in this paper is the first method to have solved the problem of door opening by using re-configurable robot with joints working in passive and active mode and complete the task with minimal sensing.

II. DYNAMIC MODEL OF THE MRR

A picture of the 5 DOF MRR robot is depicted on Fig. 1. Each joint module consists of a brushless DC motor, an encoder, a brake, homing and limit sensors and a harmonic drive with an integrated torque sensor and amplifier [22]. For the door opening problem studied in this paper, assuming that the MRR's end-effector has already grasped the door knob. Hence, the MRR is constrained during the door opening process. Referring to [17] and [18] the dynamic equation of an MRR with n joint modules can be derived as:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+f_d(q,\dot{q})+\Gamma^{-1}\tau_s=\tau+f \qquad (1)$$

This work is supported by a Collaborative Research and Development (CRD) grant by Natural Sciences and Engineering Research Council (NSERC) of Canada, Engineering Services Inc, the Canadian Space Agency, and in part by the Canada Research Chair program.

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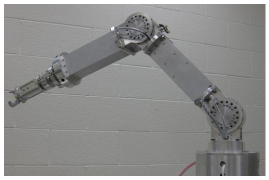

Fig. 1. 5 DOF MRR

where $q = [q_1, q_2, ..., q_n]^T \in R^n$ denotes generalized coordinates; q_i, $\dot{q}_i$, $\ddot{q}_i$ represent the rotation angle, angular velocity and angular acceleration of the i^{th} joint, respectively; $M \in R^{n\times n}$ denotes the inertia matrix; $C(q,\dot{q})\dot{q} \in R^n$ is a vector containing Coriolis, centrifugal forces; $f_d(q,\dot{q}) \in R^n$ is a vector representing frictional force; $\tau_s \triangleq [\tau_{s1}, \tau_{s2}, ..., \tau_{sn}]^T \in R^n$ and τ_{si} denotes the coupling torque at the i^{th} torque sensor location; $\Gamma \triangleq diag\{\gamma_1, \gamma_2, ..., \gamma_n\} \in R^{n\times n}$ and γ_i denotes the reduction radio of the i^{th} speed reducer ($\gamma_i \geq 1$); $\tau \in R^n$ is the actuation input; and $f \in R^n$ is the vector of constraint forces in the joint space. Here, referring to [17], f_d has the following expression,

$$f_{di} \triangleq b_{mi}\gamma_i\dot{q}_i + (f_{ci} + f_{si}exp(-f_{\tau i}\dot{q}_i^2))sgn(\dot{q}_i) \tag{2}$$

where I_{mi} denotes the moment of inertia of the i^{th} rotor about the axis of rotation; b_{mi}, f_{ci}, f_{si} ,$f_{\tau i}$ denote the vicious frictional coefficient, the Coulomb friction-related parameter, the static friction-related parameter, a positive parameter corresponding to the Stribeck effect, respectively. The sign function is defined as

$$sgn(\dot{q}_i) = \begin{cases} 1 & for \quad \dot{q}_i > 0 \\ 0 & for \quad \dot{q}_i = 0 \\ -1 & for \quad \dot{q}_i < 0 \end{cases} \tag{3}$$

Let $\varphi(q) \in R^m$ represent the constraint function, which include a set of m independent equations, we have

$$\varphi(q) = 0,\ \frac{\partial\varphi}{\partial q}\dot{q} \approx J_c(q)\dot{q} = 0 \tag{4}$$

The function $\varphi(q)$ is twice continuous differentiable [19] with a Jacobian matrix denoted by $J_c(q) \in R^{m\times n}$. The constraint force f can be expressed in terms of a generalized multiplier $\lambda \in R^m$ by the following equation.

$$f = J_c^T(q)\lambda \tag{5}$$

As a result of accumulated research efforts [20], it has been recognized that there exists a proper partition $q^1 \in R^{n-m}$, and $q^2 \in R^m$, such that $q = [q^1 \quad q^2]^T$. From (4),

$$J_c(q) = \begin{bmatrix} J_{c1}(q) & J_{c2}(q) \end{bmatrix} = \begin{bmatrix} \frac{\partial\varphi(q)}{\partial q^1} & \frac{\partial\varphi(q)}{\partial q^2} \end{bmatrix} \tag{6}$$

The kinematic constraints $\varphi(q) = 0$ and $J_c(q)\dot{q} = 0$ reduce the degrees of freedom from n to $(n-m)$ [21]. They also determine an implicit function q^2, whose derivative is given by $\dot{q}^2 = -J_{c2}^{-1}(q)J_{c1}(q)\dot{q}^1$ according to the theory of calculus. If an explicit function $q^2 = \rho(q^1)$ is available, then $-J_{c2}^{-1}(q)J_{c1}(q) = \frac{\partial\rho}{\partial q^1}$.
This fact enables one to write

$$q^2 = \sigma(q^1) \tag{7}$$

This enables one to write

$$\dot{q} = L(q)\dot{q}^1 \tag{8}$$

$$L(q) = \begin{bmatrix} I_{n-m} \\ -J_{c2}^{-1}(q)J_{c1}(q) \end{bmatrix} \tag{9}$$

where $I_{n-m} \in R^{(n-m)\times(n-m)}$ is an identity matrix. It is then easy to derive

$$L^T(q)J_c^T(q) = 0 \tag{10}$$

Substituting (5) and (8) into (1), we have

$$\begin{aligned} &M(q)L(q)\ddot{q}^1 + M(q)\dot{L}(q)\dot{q}^1 + C(q,\dot{q})L(q)\dot{q}^1 + f_d(q,\dot{q}) \\ &+\Gamma^{-1}\tau_s = \tau + J_c^T(q)\lambda \end{aligned} \tag{11}$$

Left multiplying $L^T(q)$ at both sides of (11) yields

$$\begin{aligned} &M_1(q^1)\ddot{q}^1 + C_1(q^1,\dot{q}^1)\dot{q}^1 + L^T(q)f_d(q,\dot{q}) + \Gamma_1^{-1}\tau_s \\ &= L^T(q)\tau \end{aligned} \tag{12}$$

where

$$M_1(q^1) \triangleq L^T(q)M(q)L(q) \tag{13}$$

$$C_1(q^1,\dot{q}^1) \triangleq L^T(q)M(q)\dot{L}(q) + L^T(q)C(q,\dot{q})L(q) \tag{14}$$

$$\Gamma_1^{-1} \triangleq L^T(q)\Gamma_1^{-1} \tag{15}$$

III. CONTROL DESIGN

For the door opening task performed by the track driven type mobile robot, which is equipped with MRR consisting of multiple working modes modules, the decision on which and when a joint should be working on active or passive mode is critical because it determines the success and efficiency of door opening control to a great extent. In this section, we first address the unknown parameter estimation and the path planning, which are necessary for the subsequent door opening method. Second, we provide the control laws used in the hybrid control scheme, and the corresponding stability proof.

A. *Unknown Parameter Estimation*

In order to plan the path of the mobile robot base, we need to find the exact value of the door radius, r, the initial base position of the MRR, (x_1, y_1), and the knob height with respect to the base of the MRR, h. Here, we employ the method of least-squares estimation to solve this problem. Fig. 2 shows the initial configuration of the MRR, where J_i denote the i^{th} joint. The origin of the reference frame $\{G\}$ is set as the intersection point of the door hinge and the horizontal plane that crosses the origin of the reference frame of the MRR $\{O\}$. Since the MRR end-effector has already firmly grasped the door knob, we then in the estimation process, apply a small torque only to the 2^{nd} joint, until the unknown parameters are estimated. At the same time, the other joints are set in the passive working mode. How to set a joint in the passive working mode will be addressed in Section 3.D. The reason for applying a small torque here is to keep the door closed during parameter estimation. Let (x_e, y_e, z_e) denote the tip position of the end-effector in the reference frame, l_i denote the length of the i^{th} link, and q_i

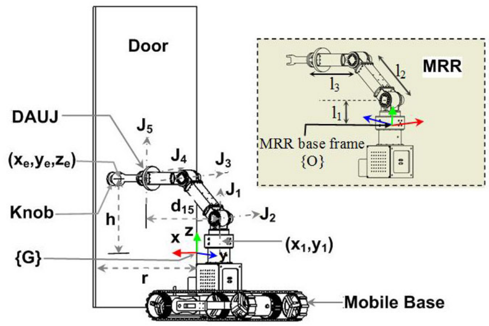

Fig. 2. The initial configuration of the MRR and the reference frames

denote the rotation angle of the i^{th} joint. From Fig. 2, with respect to the door radius, r, we have

$$x_e(t)^2 + y_e(t)^2 = r^2 \tag{16}$$

$$z_e(t) = h \tag{17}$$

With respect to the reference frame $\{G\}$ shown in Fig. 2 and coordinate transfer, we derive

$$\begin{aligned} x_e(t) = x_1 - &\left[\sum_{i=2}^{n-1} l_i sin\left(\sum_{j=2}^{i} \theta_j(t)\right)\right] cos\theta_1(t) \\ &-l_n sin\left(\sum_{i=2}^{n-1} \theta_i(t)\right) cos[\theta_1(t) + \theta_n(t)] \end{aligned} \tag{18}$$

$$y_e(t) = y_1 - l_1 + \sum_{i=2}^{n-1} l_i cos\left(\sum_{j=2}^{i} \theta_j(t)\right) \tag{19}$$

$$\begin{aligned} z_e(t) = - &\left[\sum_{i=2}^{n-1} l_i sin\left(\sum_{j=2}^{i} \theta_j(t)\right)\right] sin\theta_1(t) \\ &-l_n sin\left(\sum_{i=2}^{n-2} \theta_i(t)\right) sin[\theta_1(t) + \theta_n(t)] \end{aligned} \tag{20}$$

For simplicity, let us introduce the two function definitions $L_x(t)$ and $L_y(t)$,

$$\begin{aligned} L_x(t) \triangleq - &\left[\sum_{i=2}^{n-1} l_i sin\left(\sum_{j=2}^{i} \theta_j(t)\right)\right] cos\theta_1(t) \\ &-l_n sin\left(\sum_{i=2}^{n-1} \theta_i(t)\right) cos[\theta_1(t) + \theta_n(t)] \end{aligned}$$

$$L_y(t) \triangleq -l_1 + \sum_{i=2}^{n-1} l_i cos\left(\sum_{j=2}^{i} \theta_j(t)\right)$$

Substituting $L_x(t)$, $L_y(t)$ into (18), (19) and the resulted equations into (16) and rearranging each term, we have

$$L_x^2(t) + L_y^2(t) = r^2 - x_1^2 - y_1^2 - 2x_1 L_x(t) - 2y_1 L_y(t) \tag{21}$$

Let us define

$$P = \begin{pmatrix} 1 & 2L_x(t) & 2L_y(t) \\ \vdots & \vdots & \vdots \end{pmatrix}, \quad W = \begin{pmatrix} L_x^2(t) + L_y^2(t) \\ \vdots \end{pmatrix},$$

$$\lambda = \begin{pmatrix} r^2 - x_1^2 - y_1^2 \\ -x_1 \\ -y_1 \end{pmatrix}$$

Equation (21) can be re-written as

$$\lambda = (P^T P)^{-1} P^T W \tag{22}$$

A straightforward least squares approximation is then performed.

$$\lambda = (P^T P)^{-1} P^T W \tag{23}$$

where λ is used to solve for the estimated parameters r, x_1, and y_1. Once x_1 and h are estimated, the desired rotation angle of the 2^{nd} joint can be calculated,

$$\theta_{2(d)} = tan^{-1}(h/y_e) \tag{24}$$

At that moment, the axis of rotation of the third and the forth joints of the MRR are located in the same plane that crosses the center of the door knob, and the axis of rotation of the first and fifth joint are parallel to the door hinge. The horizontal distance between J_1 and J_5 can be calculated as follows,

$$d_{15} = l_2 \cos(\theta_{2(d)}) + l_3 \tag{25}$$

B. Path Planning

In the method proposed in this paper, as the mobile base approximately follows the predetermined elliptical path illustrated in Fig. (3), the posture of the manipulator will changed freely because of the passive joints J_1 and J_5. The elliptical trajectory was chosen because it provides us with the freedom of choosing the major and minor axis independently so that initial and final positions of the mobile base can be satisfied. The distance between J_1 and J_5 , (d_{15}) is always constant and can be calculated from (25). The elliptical parameters, like the lengths of a major and minor axis, are determined by the initial position where the mobile base is located in front of the door. The equations of the elliptical path of the mobile base, the circular path of the joint J_5 and the line from J_1 to J_5 are as follows,

$$(x_1 - h_e)^2/a^2 + (y_1 - v_e)^2/b^2 = 1 \tag{26}$$

$$x_5^2 + y_5^2 = dw^2 \tag{27}$$

$$(x_5 - x_1)^2 + (y_5 - y_1)^2 = {d_{15}}^2 \tag{28}$$

Here $x_5 = x_e$ and $y_5 = y_e + l_4$; x_e and y_e are calculated using (18) and (19) respectively. where: (x_1, y_1), (x_5, y_5) are the coordinates of J_1 and J_5 in the global frame $\{G\}$ at the start

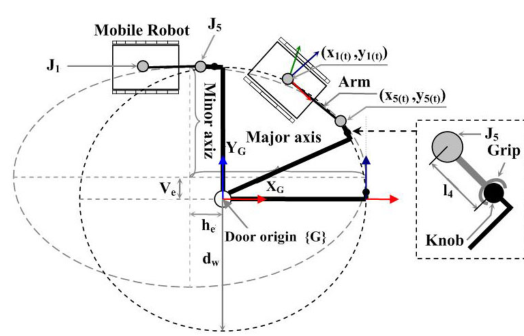

Fig. 3. Elliptical Trajectory of the Mobile Base

position of the mobile robot; a, b are the major and minor axis of the ellipsoid, respectively; dw is the distance from the origin of frame $\{G\}$ to J_5; d_{51} is the projection of the distance between J_1 and J_5 in the XY-plane. h_e and v_e are the horizontal and vertical displacement of the ellipsoid origin with respect to the global frame $\{G\}$ and they are chosen to be equal ($h_e = v_e = h$). By solving equations (26), (27), and (28) we obtain,

$$a = dw + h \tag{29}$$

$$b = dw - h \tag{30}$$

$$h = \frac{x_1 + y_1 - dw\cos(\theta) - dw\sin(\theta)}{\cos(\theta) - \sin(\theta)} \tag{31}$$

where, $\theta = \arctan(x_1/y_1)$

C. Door Opening Method

Based on the parameters estimation and the path planning, we propose a door opening method with two minimum assumptions. (i) the door opening direction is known (right-side open or left-side open); (ii) the robot base is located within the applicable door-opening area. Throughout the door opening task, the robot tip is constrained to the circular trajectory of the door knob. Therefore, in the case of using conventional robots with joints capable of working only in active mode, the occurrence of large internal forces is inevitable due to the positioning and modeling errors. These internal forces can cause damage to the robot or failure to the whole task if they have not been taken care of in the control design; thus compliant control algorithms are usually required for the door opening task. These control algorithms require force/torque measurements to be implanted. In addition, the high frequency component of the error cannot be covered by the active compliant control because of its slow response time and the direction error of the end-effector. Soft rubbers attached inside the gripper fingers are usually used to minimize the effects of the high frequency component of the error. Fig. 3 shows the directions in which a complaint control is needed. It is intuitive that the only direction where complaint control is not needed is on the axis direction of the door knob. On the contrary, in the method proposed in

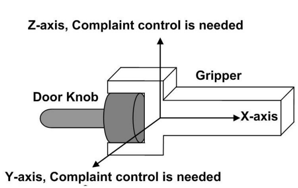

Fig. 4. Internal forces at the end-effector

this paper, we take advantages of the MRR joint modules that can switch between active and passive working modes. Based on the configuration after the parameter estimation; by setting the joints that have axis of rotation parallel to the door hinge, which are the first and DAUJ joint of the MRR to work in passive mode, the internal forces will vanish with no efforts. Since these joints will act like a rotating rod free at both ends, this will prevent the occurrence of the internal forces in the Y and Z axes. The movement of the mobile base along the predefined trajectory will generate the needed force for opening the door while the MRR robot is acting as a cable for pulling the door open. The proposed door opening method is summarized in the following steps:

1) Grasp the door knob.
   - The mobile robot navigates to front of the door.
   - All joints are set to work in active mode.
   - The MRR robot grasps and rotates the doorknob.
2) Estimate the door parameters.
3) Set the second joint to the desired angle calculated from the estimation process.
4) Keep the rotation angle of the second and third joints unchanged by switching to the post-active mode.
5) Switch the first joint (J_1) and the DAUJ (J_4,J_5) to work in passive mode.
6) The mobile robot base moves along the predefined trajectory to pull the door open.

D. Control Design

From the proposed door opening method, we may categorize the modes of MRR joints in three types: passive mode, active mode and post-active mode. Here the passive mode refers to the mode, in which a joint rotates freely with friction compensation; the active mode refers to the mode, in which the joint is moving under control; and the post-active mode refers to the mode, in which the rotation angle of the joint keeps unchanged. With respect to these three modes, a hybrid control scheme is proposed. For the joints working in the passive mode, friction must be compensated so that the output shaft of the joints can be moved freely. Referring to [22], based on the motion trend and the angular velocity of the passive joints, a feedforward torque can be applied to compensate the friction. Hence, the control law for the joints working in the passive mode can be expressed as follows.

$$\tau_i = -f_{mi}exp(-f_{\tau i}\dot{q}_i{}^2)sgn(\dot{q}_i) - b_{mi}\gamma_i\dot{q}_i \quad i = 2,...n \tag{32}$$

where f_{mi} represents the constant part of the friction and is less than the static friction f_{si} . Since the magnitude of constant friction part often dominates the overall magnitude of the total friction at lower speed, by applying τ_i expressed in (32) can thus substantially compensate the friction. For the joints working in the post-active mode, we employ the technique of position control, for example, a PD feedback control method. Define the position and velocity errors as

$$e = q - q^d, \ \dot{e} = \dot{q} - \dot{q}^d \tag{33}$$

The control law is

$$\tau_i = k_i e_i + k_d \dot{e}_i \quad i = 1...n \tag{34}$$

where k_i and k_d are constant proportional and derivative control gains. For the joints working in the active mode, the objective of the control is that given a desired joint trajectory q^d to determine a control law such that $q \to q^d$ as $t \to \infty$. Two vectors used in the control design are defined as

$$u = q^d - \Lambda e \tag{35}$$

$$r = \dot{e} + \Lambda e \tag{36}$$

where $\Lambda \in R^{n\times n}$ is a positive constant matrix. Let $B = diag\{b_{mi}\gamma_i\}$, $f_c = [f_{c1} \dots f_{cn}]^T$, $f_s = [f_{s1} \dots f_{sn}]^T$, $f_\tau = [f_{\tau 1} \dots f_{\tau n}]^T$, $\hat{B}$, $\hat{f}_c$, $\hat{f}_s$, $\hat{f}_\tau$ denote the nominal values of B, f_c, f_s, f_τ, respectively. Define

$$D(\dot{q}) = \begin{bmatrix} \dot{q} & sgn(\dot{q}) & \rho sgn(\dot{q}) & -\hat{f}_s \dot{q}^2 \rho sgn(\dot{q}) \end{bmatrix} \tag{37}$$

where $\rho \triangleq exp(-\hat{f}_\tau \dot{q}^2)$.

$$\tilde{f} = \begin{bmatrix} \hat{B} - B & \hat{f}_c - f_c & \hat{f}_s - f_s & \hat{f}_\tau - f_\tau \end{bmatrix}^T \tag{38}$$

In order to ensure the active joints follow their corresponding desired trajectories and satisfy the constraints, the control laws are defined as,

$$\tau = \tau_0 + D(\dot{q})u_p + \Gamma^{-1}\tau_s - J_c^T(q)\lambda^d - K_r r \tag{39}$$

where λ^d denotes the desired constraint force;

$$\tau_0 = M(q)\dot{u} + C(q,\dot{q})u + \hat{B}\dot{q} + (\hat{f}_c + \hat{f}_s\rho))sgn(\dot{q}) \tag{40}$$

$$u_p = -k\int_0^t D(\dot{q})^T r d\tau \tag{41}$$

Here u_p is designed to compensate for the effect of the constant parametric uncertainty $\tilde{f}$. $K_r \in R^{n\times n}$ is a constant gain matrix.

Substitute control law (39) into (1), we have the closed-loop equation as

$$M(q)\dot{r} + C(q,\dot{q})r = D(\dot{q})(\tilde{f} + u_p) + J_c^T(q)(\lambda - \lambda^d) - K_r r \tag{42}$$

Left multiplying $L^T(q)$ on both sides of (42), from (11), we derive the reduced equation, which is similar to (12),

$$M_1(q^1)\dot{r}^1 + C_1(q^1,\dot{q}^1)r^1 = L^T(q)D(\dot{q})(\tilde{f} + u_p) - L^T(q)K_r L(q)r^1 \tag{43}$$

Theorem 1: Given the system (12), the tracking error asymptotically converges to zero under the control law defined by (39∼41).

Proof: The Lyapunov function candidate is defined as

$$V = \frac{1}{2}r^{1T}M_1 r^1 + \frac{1}{2}k\xi^T\xi \tag{44}$$

where

$$\xi = \frac{1}{k}\tilde{f} - \int_0^t D(\dot{q})^T r d\tau \tag{45}$$

Since k and $\tilde{f}$ are both constant, we have

$$\dot{\xi} = -D(\dot{q})^T r \tag{46}$$

Differentiating (44) yields,

$$\dot{V} = \frac{1}{2}r^{1T}\dot{M}_1 r^1 + r^{1T}M_1\dot{r}^1 + k\xi^T\dot{\xi} \tag{47}$$

Combining (43), (45), (46), we have

$$\dot{V} = \frac{1}{2}r^{1T}\dot{M}_1 r^1 + r^{1T}(-C_1(q^1,\dot{q}^1)r^1 + L^T(q)D(\dot{q})(\tilde{f} + u_p) - L^T(q)K_r L(q)r^1) - k\xi^T D(\dot{q})^T r \tag{48}$$

Since $\frac{1}{2}\dot{M}_1 - C_1(q^1,\dot{q}^1)$ is a skew-symmetric matrix [23] and $r = L(q)r^1$, we have

$$\begin{aligned}\dot{V} &= r^{1T}(L^T(q)D(\dot{q})(\tilde{f} + u_p) - L^T(q)K_r L(q)r^1) - kr^T D(\dot{q})\xi \\ &= r^{1T}L^T(q)D(\dot{q})(\tilde{f} + u_p) - r^{1T}L^T(q)D(\dot{q})(\tilde{f} \\ &\quad - k\int_0^t D(\dot{q})^T r d\tau) - r^{1T}L^T(q)K_r L(q)r^1 \\ &= r^{1T}L^T(q)D(\dot{q})(\tilde{f} - k\int_0^t D(\dot{q})^T r d\tau) - r^{1T}L^T(q)D(\dot{q})(\tilde{f} \\ &\quad - k\int_0^t D(\dot{q})^T r d\tau) - r^{1T}L^T(q)K_r L(q)r^1 \\ &= -r^{1T}L^T(q)K_r L(q)r^1\end{aligned} \tag{49}$$

Since $V \geq 0$, $\dot{V} < 0$, from (44) and (49), it is evident that $\|r^1\|$ converges to zero, i.e., $e \to 0$ as $t \to \infty$. Also, $q^{2d} = \sigma(q^{1d})$, which implies $q^2 \to q^{2d}$, if $q^1 \to q^{1d}$. Therefore, using control law (39), (40), (41), the closed-loop system is globally asymptotically stable, and $q \to q^d$, as $t \to \infty$.

IV. Computer Simulation

Based on the proposed door opening method, the process of opening a door follows the following steps. First, the mobile base is located in front of the door. Then, the MRR robot arm is posed in an appropriate configuration as shown in Fig. 2. Second, using a vision system mounted on the mobile base, the MRR end-effector grasps the door knob and turns it. Third, the unknown parameter estimation procedure explained in section 3.A is used to estimate the door parameters as well as the mobile base initial position. Once these parameters are estimated, the mobile base trajectory is obtained using the path planning method explained in section 3.B. Fourth, the steps (3 to 5) of the door opening method proposed in section 3.C are executed. Finally, the mobile robot base moves along the predefined trajectory to pull the door open as shown in Fig. 5. The MRR inverse kinematics is not used in the proposed door opening method except for grasping the door knob (Step 1). However, it was

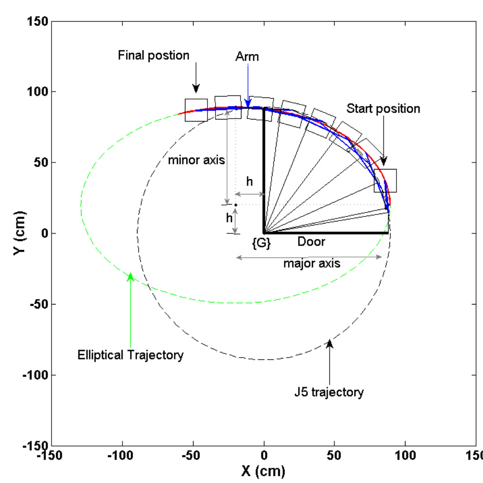

Fig. 5. Top-view of different mobile base positions and the MRR during door opening process

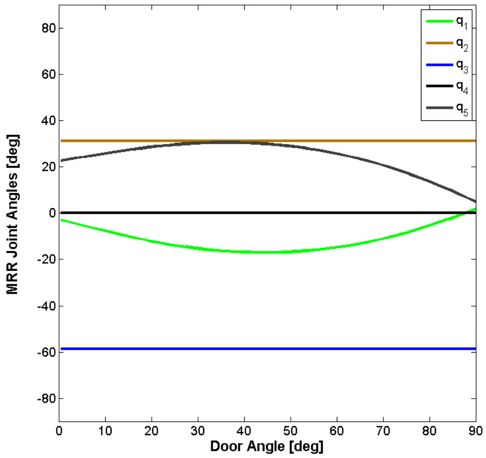

Fig. 6. MRR joint angles vs. the door opening angle

solved off-line for all points in the predefined trajectory to make sure that there are no mechanical or workspace constraints throughout the door opening process. The MRR joint angles are plotted vs. the door opening angle in Fig. 6. The simulation results show the efficiency of the proposed door opening method, the door was open to a 90 degrees angle.

V. CONCLUSIONS

A new method for opening a door with mobile robot manipulator was presented in this paper. The efficiency of the proposed method is demonstrated through the simulation results. The method presented in this paper has some advantages over the methods proposed in the literature of door opening as there is no need for expensive force/torque sensors and complicated compliance control algorithms. In addition, the heavy computation of the inverse kinematics during the door opening process has been avoided by taking advantage of the passive mode of the MRR joint modules.

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