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# Employing Cartesian Impedance Control for the Opening of a Door: A Case Study in Mobile Manipulation

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**Abstract**—In this work a Cartesian impedance controller for flexible joint robots is applied in a mobile manipulation setup for opening a door. The considered mobile manipulation system is a combination of the DLR-Lightweight-Robot-II and the DLR-Hand-II with a mobile platform. The presentation focuses on the Cartesian impedance control of the arm with special emphasis on the treatment of the joint elasticities and on the robustness of the controller. The application of opening a door is described in detail. After grasping and turning the door handle a simple strategy for opening the door is applied. The arm uses a particular Cartesian impedance controller which basically keeps the door at a distance while the mobile platform moves through the door hinge. This works without knowledge of the door size and without planning an explicit door opening trajectory.

**Index Terms**—Mobile Manipulation, Door Opening, Cartesian Impedance Control, Flexible Joint Robot.

## I. INTRODUCTION

Robotic systems in which a mobile platform is combined with one or more robot manipulators are commonly known under the term *mobile manipulators*. A large amount of work has been devoted to the coordination of locomotion and manipulation for these kind of systems, both for planning and for control. In case that the mobile platform is holonomic in particular the Operational Space Formulation can be applied in a straightforward way [7].

Robot manipulators designed for the use in a mobile manipulation setup typically should be built very light and highly integrated in order to allow for an efficient combination with the locomotion part. Moreover, for reasons of security the use of lightweight manipulators is particularly important when the robot is supposed to work in human environments or even has to interact with humans. Consequently, these systems usually have considerable elasticity and the need for control strategies arises which take account not only of the rigid body dynamics but also of the joint flexibility. Most works in the context of mobile manipulation whereas consider only a rigid body system for the manipulator dynamics and concentrate on the coordination of the vehicle motion and the arm motion.

For the fulfillment of advanced manipulation tasks Cartesian impedance and compliance control methods are crucial techniques. These methods complement position and force control schemes and allow to limit contact forces during manipulation tasks also when the environment model is uncertain [16].

In this work the task of opening a door is considered as a

benchmark application for an impedance controlled mobile manipulator system consisting of the DLR-Lightweight-Robot-II, the DLR-Hand-II, and a mobile platform (see Fig. 1). The focus of the presentation is put on the Cartesian impedance control of the manipulator. The underlying control method is described with special emphasis on its robustness properties and on the treatment of the joint elasticity of the arm. It is shown in detail how the resulting impedance controller was employed for the task of opening the door.

In the literature several approaches for the opening of a door were proposed. Niemeyer and Slotine [10] presented a method which is based on an online estimation of the door kinematics. During movement, the actual velocity of the system is observed and the robot basically pushes into the direction of least resistance in order to open the door. For a good estimation of the trajectory of the door handle a firm grasp is required.

Petersson et al. [14] use off-the-shelf force/torque control algorithms in a mobile manipulation setup for opening a door using a hybrid dynamic system model. For coping with unknown environments they estimate the door radius and the center of rotation online.

Rhee et al. [15] considered the opening of a door with a compliance controlled mobile manipulator. In a first stage they explored the shape of the door knob by using the force sensor data from a multi-fingered hand. Then, they estimate the door parameters by shaking the door knob with the manipulator. Finally, they plan a door opening trajectory which is executed with a compliance control scheme.

Nagatani and Yuta [8] discuss the use of action primitives for the opening of a door with a mobile manipulator system.

In our approach the door opening will be performed by a simple strategy which does not rely on a knowledge of the door size or on a planned door opening trajectory. The complete procedure will be split up into three steps. First, contact of the DLR-Hand-II with the door handle must be established. Then, the door handle is turned and opened via a sequence of impedance controlled movements of the arm. Finally, the robot system moves through the door hinge while the arm keeps the door at a distance. This is realized by an appropriate impedance controller of the arm, in which the set of virtual equilibrium positions for the end-effector is given by a circular path fixed to the mobile platform.

The paper is organized as follows. Section II gives a short

overview of our mobile manipulator system. Section III presents the method used for the Cartesian impedance control of the arm. In Section IV the door opening application is described in detail. Finally, Section V gives a short summary and presents an outlook on further improvements.

## II. SYSTEM OVERVIEW

In this section a short overview of the used mobile manipulator system (Fig. 1) is given. The system consists of the seven joint DLR-Lightweight-Robot-II, the DLR-Hand-II, and an omni-directional mobile platform originally designed at the Technical University of Munich. The DLR-



Fig. 1. The used mobile manipulator system.

Lightweight-Robot-II is equipped with joint torque sensors additionally to the common motor angle sensors [6]. This allows for the implementation of highly sensitive torque and impedance controllers which take account of the joint flexibility. Its low weight of about 18 kg and the integration of all the power electronics make this robot ideally suited for the use in a mobile manipulation setup.

The four-fingered DLR-Hand-II is equipped with joint torque sensors and a six degrees-of-freedom (DOF) force-torque sensor in each of the finger tips. This hand has three DOF per finger and a reconfigurable palm offering two configurations for power grasps and precision grasps. Further details on this system can be found in [3].

The mobile platform has four steerable wheels, for which (in contrary to the often used castor wheels) the steering axis and the rotation axis of each wheel intersect. Therefore, this mobile platform is omni-directional but non-holonomic.

The system is furthermore equipped with a SICK laser range scanner, a vision system consisting of three onboard cameras (DIGICLOPS), and a collection of distance sensors included in some parts of the covering for measuring external forces exerted on the platform.

The robot system previously has been used for vision-based object manipulation in a table-top scenario [5], [13].

## III. CARTESIAN IMPEDANCE CONTROL

In this section the Cartesian impedance control method used for the DLR-Lightweight-Robot-II is described. The Harmonic drive gears of the  $n = 7$  joints present the main amount of elasticity. The stiffness of the joint torque sensors, which are attached at the output end after the gears, is about an order of magnitude higher than the stiffness of the gears. Therefore, the reduced flexible joint robot model from [17] is considered for the controller design

$$\begin{aligned} M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) &= K(\theta - q) + \tau_{ext}, (1) \\ B\ddot{\theta} + K(\theta - q) &= \tau_m. \end{aligned} \quad (2)$$

Herein,  $\theta \in \mathbb{R}^n$  and  $q \in \mathbb{R}^n$  are the motor angles and link angles, respectively. According to the flexible joint robot model, the difference between the motor and the link angles correspond via the diagonal joint stiffness matrix  $K \in \mathbb{R}^{n \times n}$  to the joint torques  $\tau = K(\theta - q)$ . The matrix  $B \in \mathbb{R}^{n \times n}$  is a diagonal matrix consisting of the motor inertia values. The components  $M(q) \in \mathbb{R}^{n \times n}$ ,  $C(q, \dot{q})\dot{q}$ , and  $g(q)$  of the link side rigid body dynamics (1) represent the inertia matrix, the Coriolis and centrifugal terms, and the gravity terms. Finally,  $\tau_m \in \mathbb{R}^n$  is the vector of motor torques which is the control input and  $\tau_{ext} \in \mathbb{R}^n$  is a vector of external torques which are exerted on the robot by the environment.

For the considered application of opening a door the Cartesian impedance controller developed in [11], [2], [12] will be used. In the design of this controller a passivity based approach was followed which endows the controller with advantageous robustness properties. The controller basically consists of two cascaded loops (see Fig. 2). In an inner loop a torque feedback controller of the form

$$\tau_m = \tau_d - K_\tau(\tau - \tau_d) - K_s\dot{\tau} \quad (3)$$

with positive definite gain matrices  $K_\tau \in \mathbb{R}^{n \times n}$  and  $K_s \in \mathbb{R}^{n \times n}$  is used. Herein, the vector  $\tau_d \in \mathbb{R}^n$  is an intermediate control input corresponding to the desired torque from an outer loop impedance control law. In [11], [2] a detailed analysis of this type of impedance controllers is given. Therein a physical interpretation of the inner torque feedback loop was given in the sense that it scales the effective motor inertia from  $B$  to  $(I - K_\tau)^{-1}B$ . This physical interpretation of torque feedback can be seized for the stability analysis.

The purpose of the inner torque feedback loop is twofold.

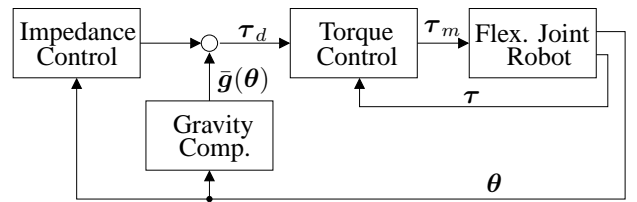


Fig. 2. Impedance controller structure for the arm.

On the one hand, the torque feedback causes a decrease of the effective motor inertia for forces acting on the link side [11]. Thereby it enhances the vibration damping effects of an additional outer control loop. On the other hand it also diminishes the effects of motor side friction since the joint torque sensors are placed on the link side.

In addition to the torque controller, an outer impedance control loop

$$\tau_d = \bar{g}(\theta) - \frac{\partial V(\theta)}{\partial \theta} - D(\theta)\dot{\theta} \quad (4)$$

is used, which is based on the measurement of the motor position  $\theta$  and does not rely on the measurement of the link side position  $q$ .

The first part of the control law (4), i.e.  $\bar{g}(\theta)$ , corresponds to the online gravity compensation term introduced in [11]. This particular online gravity compensation term  $\bar{g}(\theta)$  allows to compensate for the static effects of the link side gravity torques  $g(q)$  based solely on the measurement of the motor side position  $\theta$  and without feedback of the link side position  $q$  (see also [11]). The design of this gravity compensation term is based on the observation that for the case of free motion in steady state the condition

$$\tau = K(\theta - q) = g(q) \quad (5)$$

must hold. Equation (5) can be seen as a relation between the steady state motor angles and the steady state link side angles. One can show that, under (extremely) mild conditions on the joint stiffness matrix, this relation represents a one-to-one mapping. For every motor angle  $\theta$  the equation (5) can thus be solved (at least numerically) for  $q$  and the resulting mapping shall be denoted by  $\bar{q}(\theta)$ . Clearly, a gravity compensation term of the form  $\bar{g}(\theta) = g(\bar{q}(\theta))$  exactly compensates for the link side gravity terms in steady state for the case of free motion. In [11] it was shown that this gravity compensation term can be seen as the differential of a potential function, and this potential function can furthermore be used for a passivity and stability analysis.

In addition to the gravity compensation term a *stiffness term* and a *damping term* are implemented in (4) via the potential function  $V(\theta)$  and a positive definite damping matrix  $D(\theta)$ . Notice that also these terms are computed based on the motor position  $\theta$  instead of the link side position  $q$ . The potential function  $V(\theta)$  is used in Section IV for the implementation of different impedance behaviors. The particular design of the damping matrix  $D(\theta)$  is not crucial for the presented application and will thereby be omitted herein. More details on an appropriate design method can be found in [2].

Some additional remarks on the used controller structure are in order. While the vibration damping effects of the inner torque control loop diminishes the dynamic effects of the joint elasticity, the static effects still are present. Since the joint stiffness values usually are quite high<sup>1</sup> the *static*

<sup>1</sup>These values lie in the range 10.000 – 15.000 Nm/rad for the DLR lightweight robot.

error of the desired stiffness relationship caused by the joint elasticity is not critical for the presented application. However, in [1] an extension of the controller is presented, which allows to take account for the joint elasticity more accurately.

Concerning the robustness of the closed loop system it is useful to investigate the passivity<sup>2</sup> properties [19] of the controller. Therefore, the system can be seen as a feedback interconnection of several subsystems as shown in Fig. 3. In [11] it was proven that for  $K_s = 0$  all the subsystems as partitioned in Fig. 3 are passive with respect to the indicated input and output signals. This is a result of using only the motor angle  $\theta$  in (4). If also the environment is a passive system (for the input  $\dot{q}$  and corresponding output  $-\tau_{ext}$ ) then the closed loop system is passive. For  $K_s \neq 0$  the situation is more involved and the passivity properties depend on both  $K_s$  and  $D(\theta)$ . Furthermore the matrix  $K_s$  allows to take account of additional joint damping which for simplicity was not included in the model (1)-(2) [2].

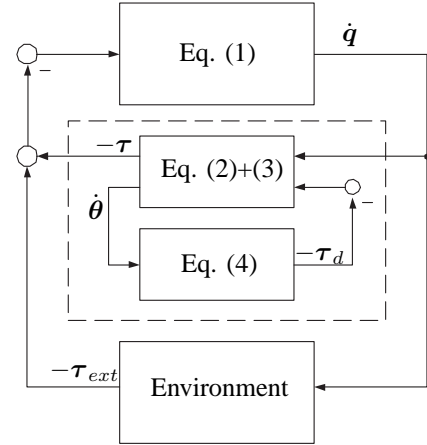


Fig. 3. System representation as a subsystem interconnection.

#### IV. THE DOOR OPENING APPLICATION

In the following it is shown how the Cartesian impedance control can be utilized in a *real world application*, namely the opening of a door. The whole application is divided into three subtasks.

- The localization of the door handle.
- The turning and opening of the door handle.
- The movement through the door hinge until the door is sufficiently wide open.

##### A. Localization of the door handle

It is assumed that the robot initially stands in front of the door. The exact localization of the door handle with

<sup>2</sup>A system  $\dot{x} = f(x, u), y = y(x, u)$  with state  $x \in \mathbb{R}^n$ , input  $u \in \mathbb{R}^m$  and output  $y \in \mathbb{R}^m$  is said to be *passive*, if for any admissible input  $u(t)$  the *energy* that can be extracted from the system in an arbitrary time interval  $[t_0, t_1]$  is bounded from below [19]:  $\exists c \in \mathbb{R} : \int_{t_0}^{t_1} u(t)^T y(t) dt \geq c$ . A sufficient condition therefore is given by the existence of a continuous function  $S(x)$  which is bounded from below and for which the derivative with respect to time along the solutions of the system satisfies the inequality  $\dot{S}(x) = \frac{\partial S(x)}{\partial x} f(x, u) \leq u^T y$ .

respect to the mobile platform can be done by using the onboard laser range scanner and the vision system. Notice that the distance and the orientation to the door can easily be measured by using the laser range scanner. The mobile platform can then align its orientation perpendicular to the door surface. What remains is to get a reliable estimate of the height and the translational distance between the robot and the door handle to the left.

For this a template matching algorithm for each of the three camera images is applied. Figure 4 shows the three camera images, the template of the door handle in the upper left corner, an intermediary resulting image in the upper left, and the estimated image locations of the template marked with a cross. In the algorithm first the template  $T$  of the door handle with width  $w$  and height  $h$  is matched to the image  $I$  at every pixel location. We use a normalized matching to be more invariant to image noise and changes in lighting conditions, where for the result image  $R$  holds

$$R(x, y) = \frac{\langle (I_{x,y} - \langle I_{x,y} \rangle)(T - \langle T \rangle) \rangle}{\sqrt{\langle (I_{x,y} - \langle I_{x,y} \rangle)^2 \rangle \langle (T - \langle T \rangle)^2 \rangle}}. \quad (6)$$

Here  $\langle A \rangle = \sum_{i=0}^{w-1, h-1} A(i, j)$  is the summation over a window of the size of the template and  $I_{x,y}(i, j) = I(i + x, j + y)$  is the image, shifted by  $(-x, -y)$ .

The estimated image location of the door handle is determined in a second step by searching for the maximum in the resulting image  $(x^*, y^*) = \arg \max_{x,y} R(x, y)$ .

The position of the handle with respect to the robot is then calculated by determining the disparity between the handle locations in two images and then using the common stereo equation (the camera parameters are calibrated from factory). Doing this for all three pairs of cameras one can average the results to get a more precise estimation of the handle position.

In the experiments this simple template matching worked quite robust. Notice that the scene (the door covered most of the image) did not include much clutter which typically is the primary problem (besides changing lighting conditions) for template matching.

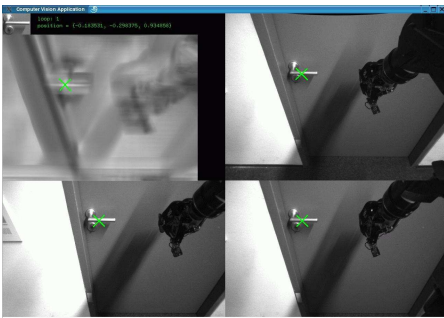


Fig. 4. Pattern Matching.

After localization of the door handle, the robot arm is brought into a configuration as depicted in Fig. 5. Clearly, the localization must be sufficiently accurate such that contact between the fingers of the hand and the door handle can be established by moving the arm to the left.

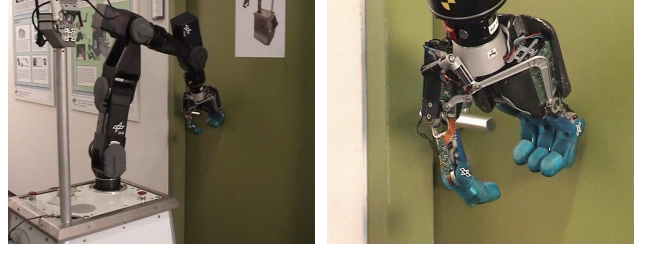


Fig. 5. Initial configuration after localizing the door handle.

### B. Turning the Door Handle

For the turning of the door handle the impedance controller from Sec. III is applied. First, in Section IV-B.1 it is described how the potential function  $V(\theta)$  in (4) was chosen. Section IV-B.2 then explains how the contact force was estimated. This estimation was used for the implementation of simple stopping and state transition conditions. Finally, the used sequence of impedance controller motions for turning the door handle is described in Section IV-B.3.

1) *Design of the Potential Function:* The potential function is designed according to a Cartesian stiffness behavior for the end-effector motion. Therefore, a simplified version of the spatial stiffness from [18] and [20] is used. Let the difference between the end-effector fixed tool frame and a *virtual*<sup>3</sup> equilibrium frame  $H_d \in SE(3)$  be given by the rotation matrix  $R(q) \in SO(3)$  and the position difference  $p(q) \in \mathbb{R}^3$  between the tool frame and the desired frame, which is expressed with respect to the tool frame. Notice that these signals depend on the link side position  $q$  of the joints, while the potential function will be computed based on the motor side positions  $\theta$  (see Sec. III).

For the rotational part of the stiffness a quaternion representation<sup>4</sup> of the end-effector orientation is used (see [4]). The vector part of the unit quaternion representation from  $R(q)$  shall be denoted by  $\epsilon(q)$ . The used potential function is then composed of a port-symmetric translational part (see [20]) and a quaternion-based rotational part (see [4])

$$V(\theta) = \frac{1}{4} p(\theta)^T K_t p(\theta) + \frac{1}{4} p(\theta)^T R(\theta)^T K_r R(\theta) p(\theta) + 2\epsilon(\theta)^T K_r \epsilon(\theta), \quad (7)$$

wherein  $K_t \in \mathbb{R}^{3 \times 3}$  and  $K_r \in \mathbb{R}^{3 \times 3}$  are the positive definite translational and rotational stiffness matrices respectively.

<sup>3</sup>In impedance control the desired configuration for the case that no external forces act on the system usually is called a *virtual* configuration.

<sup>4</sup>A unit quaternion  $(\eta, \epsilon)$  consists of a scalar part  $\eta \in \mathbb{R}$  and a vector part  $\epsilon \in \mathbb{R}^3$ , which fulfill the condition  $\eta^2 + \epsilon^T \epsilon = 1$ . The relation between a rotation matrix and unit quaternions is given as follows. Suppose that a rotation matrix is specified by a rotation of an angle  $\alpha$  about an axis  $r$ , then the corresponding unit quaternion is given by  $\eta = \cos(\alpha/2)$ ,  $\epsilon = r \sin(\alpha/2)$ . More details on the use of unit quaternions in the context of impedance control can be found for instance in [4], [9].



2) *Estimation of the contact force:* During the whole operation the contact force shall be observed. Since the robot does not have a force-torque sensor attached to the end-effector in this setup, the contact force must be estimated from other measurements. Therefore, a quasi-static estimation is done as follows. In a static equilibrium the external torques  $\tau_{ext}$ , which act on the robot, can be computed from the measurement of the joint torques  $\tau$  via  $\tau_{ext} = \tau - g(q)$ , where  $g(q)$  are the gravity torques which depend on the link side position  $q$ . If the external torques are assumed to be exerted via the generalized force  $F_{ext}$  acting at the tip of the robot, then the relationship  $J(q)^T F_{ext} = \tau - g(q)$  holds, where  $J(q)$  is the body Jacobian of the manipulator. This equation can then be used for a *rough*, i.e. a quasi-static, estimation of  $F_{ext}$ . This estimation of the generalized contact force allows the realization of simple stopping conditions. Within the presented application the Euclidean norm of the translational components from  $F_{ext}$  was used for the realization of state transition conditions.

In the experiments it turned out that such a rough estimation indeed works sufficiently reliable for the considered application. However, in future versions of this application it is planned to take advantage of the sensors of the DLR-Hand-II in order to get a more accurate estimation of the contact force.

3) *Motion Sequence for the Handle Turning:* The turning and opening of the door handle is split up into several steps as depicted in Fig. 6. For the state transition between these steps the above mentioned estimation of the contact force is used. By the first two steps the contact of the hand with the handle is established. Each of these two steps finishes when a predefined threshold value of 10 N for the estimated contact force is exceeded. For these motions a translational stiffness matrix of  $K_t = \text{diag}(2000, 2000, 2000)$  N/m was used. The rotational stiffness was set to  $K_r = \text{diag}(100, 100, 100)$  Nm/rad. Then the actual handle turning motion follows, which ends when the contact force exceeds another threshold value of 30 N indicating that the handle is turned to its maximum angle. From now on the translational stiffness is set to  $K_t = \text{diag}(2000, 1000, 2000)$  N/m, where the value of 1000 N/m corresponds to the direction along the main axis of the handle. In the implementation of the state transition this stiffness value is interpolated from its previous value of 2000 N/m to its new value in order to produce a smooth stiffness variation. After this, the door is opened by a horizontal movement of 30 mm into the normal direction of the door surface and the handle is turned back to its released configuration. This ends the second part of the door opening application.

### C. Movement Through the Door Hinge

Next, the door shall be moved until it is fully open. The main idea how to open the door is simply to control the arm such that the door is kept at a distance, while the mobile platform drives through the door hinge. This is realized by the Cartesian impedance behavior (4) with a

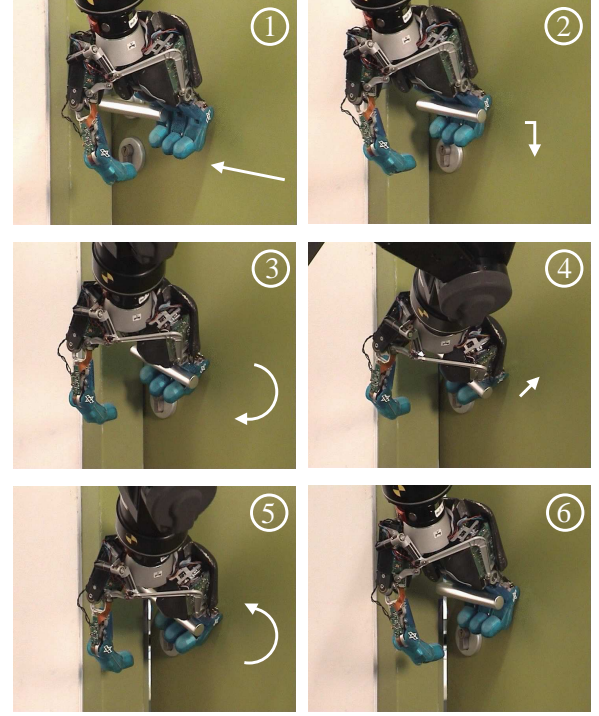


Fig. 6. Impedance controlled movements for the handle opening. The white arrows indicate the direction of motion. All these steps were performed with the Cartesian impedance controller using the potential function (7) by shifting the virtual equilibrium frame  $H_d$ .

potential function  $V(\theta)$  defined as follows. Let  $r(q) = (r_x(q), r_y(q), r_z(q))^T \in \mathbb{R}^3$  denote the position of the end-effector with respect to a platform fixed coordinate system centered at  $r_c \in \mathbb{R}^3$  (see also Fig. 7). The point  $r_c$  should be chosen somewhere in the front part of the mobile platform, its particular position, however, is not critical. The desired impedance shall be designed such that the end-effector holds its initial height and is free to move along a circular path centered at the point  $r_c$ . The diameter  $d_0$  of this circular path of virtual equilibrium points is determined by the starting configuration via  $d_0 = \sqrt{r_x(\theta_0)^2 + r_y(\theta_0)^2}$ . By choosing positive translational stiffness factors  $k_r \in \mathbb{R}$  and  $k_z \in \mathbb{R}$  the desired stiffness behavior can be formulated via the potential function

$$\begin{aligned} V(\theta) &= V_r(\theta) + V_z(\theta), \\ V_r(\theta) &= \frac{1}{2} k_r \left( \sqrt{r_x(\theta)^2 + r_y(\theta)^2} - d_0 \right)^2, \\ V_z(\theta) &= \frac{1}{2} k_z (r_z(\theta) - r_z(\theta_0))^2, \end{aligned}$$

which is used in (4). The stiffness values were chosen as  $k_r = k_z = 1000$  N/m. Notice that this potential function does not have an isolated minimum, but is at its minimum value all along a circular path, as shown in Fig. 7 and Fig. 8. While moving through the door hinge no orientational stiffness is used. The reason for this is that the orientation of the end-effector will then adjust automatically to the handle orientation when the handle is grasped by the artificial hand. By using the above potential function for

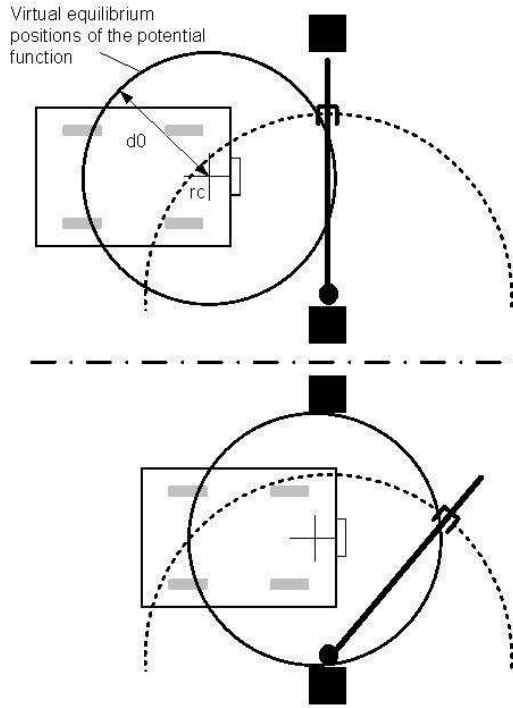


Fig. 7. Concept for the door opening.

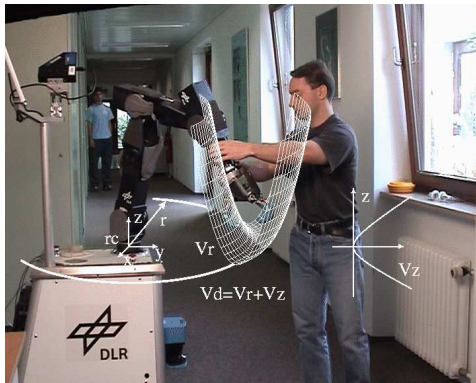


Fig. 8. Potential function used in the door opening.

the implementation of the desired impedance behavior the end-effector will be kept at the starting distance  $d_0$  from the platform fixed point  $r_c$ . When the mobile robot moves through the door hinge, the arm therefore will automatically move the door aside (see Figure 7). Notice that this works without any knowledge of the size of the door. Figure 9 shows a sequence of shots from the evaluation of the door opening application.

## V. SUMMARY AND OUTLOOK

In this work the opening of a door with a mobile manipulator system was considered. The treatment focused on the used control approaches and their employment in the application.

In the experimental evaluation a mobile manipulator system was used in which the DLR-lightweight-Robot-II and the

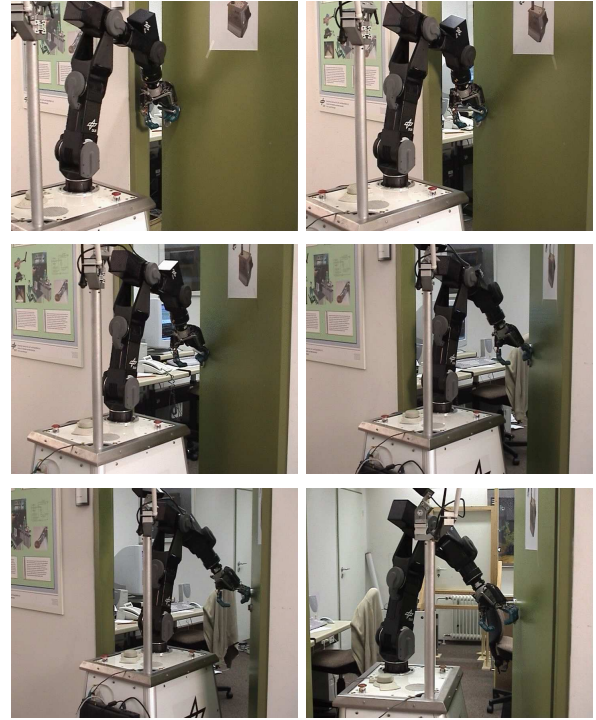


Fig. 9. Opening of the door.

DLR-Hand-II are combined with a mobile platform.

For the arm a Cartesian impedance controller is used which takes account of the joint flexibility. The controller and its robustness properties were shortly discussed.

A simple strategy for opening the door was described in detail. By implementing a particular impedance behavior with the arm the door is kept at a distance while the mobile platform moves through the door hinge.

Further work with this system shall focus on a closer coordination and cooperation between the robot arm, the hand, and the mobile platform.

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