

Design of force-driven online motion plans for door opening under uncertainties

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Abstract—The problem of door opening is fundamental for household robotic applications. Domestic environments are generally less structured than industrial environments and thus several types of uncertainties associated with the dynamics and kinematics of a door must be dealt with to achieve successful opening. This paper proposes a method to open doors without prior knowledge of the kinematics. The proposed method can be implemented on a velocity-controlled manipulator with force sensing capabilities at the end-effector. The velocity reference is designed by using feedback of force measurements while constraint and motion directions are updated online based on adaptive estimates of the position of the door hinge. The online estimator is designed to identify the unknown directions. The proposed scheme has theoretically guaranteed performance which is further demonstrated in experiments on a real robot. Experimental results also show the robustness of the proposed method under disturbances introduced by the motion of the mobile platform.

I. INTRODUCTION

Doors or drawers can be considered typical components in a domestic environment. Hence, a household robot should be able to open doors in a wide range of household applications. A typical example of domestic manipulation may be the task of retrieving a glass from a cupboard. In this case, the task also involves the prerequisite task of opening the door of the cupboard so that the primary task of picking up the glass can be performed. Moreover, in order to bring the glass to its final destination, the robot may have to negotiate doors between rooms or hallways. Furthermore, domestic environments include several types of uncertainty that disqualifies the use of motion control with preplanned trajectories typically used on stiff industrial robots, making the door opening task more challenging. Thus, the motion plans have to be recomputed online in reaction to encountered measurement errors.

Typical sources of uncertainty in the door-opening problem are the location of the hinge in terms of kinematics, and the force model of the dynamic motion of the door. If we also consider a mobile robot, then extra difficulties arise from the disturbances caused by motion of the platform.

Pioneering work on the door opening problem include [1] and [2]. In [1], experiments on door opening with an autonomous mobile manipulator were performed under the assumption of a known door model, using the combined motion of the manipulator and the mobile platform, while in [2], velocity-based estimation of the constraints describing the kinematics of the motion for the door opening problem

is proposed. Recent works of [3] and [4] has been inspired by [2]; however, they suffer from ill-defined normalization when the velocity is small and estimation lags. Furthermore, there exist several position-based estimation techniques [5]–[8]; optimization algorithms that uses the end-effector position are used in parallel with controllers that provide the system with the proper compliance in order to deal with inaccurate trajectory planning. On the other hand, off-line methods using prior phases have been also proposed: slowly pulling and pushing in a prior phase [9], probabilistic methods based on a set of motion observations of the objects [10] or based on the use of particle filters and extended Kalman filters for an a priori defined detailed model of the door [11]. Another part of the literature on the door opening problem exploits advanced hardware capabilities to accomplish the manipulation task: combination of tactile-sensor and force-torque sensor [12], clutches that disengage selected robot motors from the corresponding actuating joints for passive joint’s rotation [13], exploitation of the compliance of the DLR lightweight robot II [14] and use of the humanoid robot HRP-2 exerting impulsive force on a swinging door [15].

In this paper, we propose a controller which is proved to achieve stable force regulation as well as learning the constraint direction, and thus is able to continuously generate online motion plans for smooth door opening in case of uncertainty. The proposed method can be implemented on any velocity controlled manipulator — with force measurements at the end-effector or wrist — and differs from the existing work by simultaneously providing on-line performance while explicitly including the uncertain estimates in the controller.

II. SYSTEM AND PROBLEM DESCRIPTION

A. Notation and Preliminaries

Bold roman small letters denote vectors while bold roman capital letters denote matrices. The generalized position of a moving frame $\{i\}$ with respect to a inertial frame $\{B\}$ (typically located at the robots base) is described by a position vector $\mathbf{p}_i \in \mathbb{R}^m$ and a rotation matrix $\mathbf{R}_i \in SO(m)$ where $m = 2$ for the planar case. We also consider the

following normalization and orthogonalization operators:

$$\underline{\mathbf{z}} = \frac{\mathbf{z}}{\|\mathbf{z}\|} \quad (1)$$

$$\mathbf{s}(\mathbf{z}) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \underline{\mathbf{z}} \quad (2)$$

with \mathbf{z} being any non-trivial two-dimensional vector. Note that in case of $\mathbf{z} = \mathbf{z}(t)$ the derivative of $\underline{\mathbf{z}}$ is calculated as:

$$\dot{\underline{\mathbf{z}}} = \|\mathbf{z}\|^{-1} \mathbf{s}(\underline{\mathbf{z}}) \mathbf{s}(\underline{\mathbf{z}})^\top \dot{\mathbf{z}}. \quad (3)$$

Furthermore, we denote with $\mathcal{I}(z)$ the integral of some scalar function of time $z(t) \in \mathbb{R}$ over the time variable t , i.e:

$$\mathcal{I}(z) = \int_0^t z(\tau) d\tau \quad (4)$$

B. Kinematic model of robot door opening

We consider the case where the robot's end-effector has achieved a fixed grasp of the handle of a kinematic mechanism e.g. a door in a domestic environment. The term fixed grasp denotes that there is no relative translational velocity between the handle and the end-effector but we place no constraints on the relative rotation of the end-effector around the handle. We consider also that the motion of the handle is inherently planar which implies a planar problem definition.

Let $\{e\}$ and $\{o\}$ be the end-effector and the door frame respectively (Fig. 1); the door frame $\{o\}$ is attached at the hinge which in our case is the center of door-mechanism rotation. The radial direction vector \mathbf{r} is defined as the relative position of the aforementioned frames:

$$\mathbf{r} \triangleq \mathbf{p}_o - \mathbf{p}_e \quad (5)$$

By expressing \mathbf{r} with respect to the door frame and differentiating the resultant equation we get:

$$\dot{\mathbf{R}}_o {}^o \mathbf{r} + \mathbf{R}_o {}^o \dot{\mathbf{r}} = \dot{\mathbf{p}}_o - \dot{\mathbf{p}}_e \quad (6)$$

The substitutions ${}^o \dot{\mathbf{r}} = \dot{\mathbf{p}}_o = 0$ and $\dot{\mathbf{R}}_o = \omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \mathbf{R}_o$, with ω being the rotational velocity of the door, give us:

$$\dot{\mathbf{p}}_e = -\mathbf{s}(\mathbf{r})\omega \quad (7)$$

which describes the first-order differential kinematics of the door opening problem in case of a revolute hinge. Notice that the end-effector velocity along the radial direction of the motion is zero, i.e:

$$\mathbf{r}^\top \dot{\mathbf{p}}_e = 0 \quad (8)$$

The latter can be regarded as the constraint on the robot end-effector velocity.

C. Robot kinematic model

In case of velocity controlled manipulators, the robot joint velocity is controlled directly by the reference velocity \mathbf{v}_{ref} . In particular, the reference velocity \mathbf{v}_{ref} can be considered as a kinematic controller which is mapped to the joint space in order to be applied at the joint velocity level as follows:

$$\dot{\mathbf{q}} = \mathbf{J}^+(\mathbf{q})\mathbf{v}_{\text{ref}} \quad (9)$$

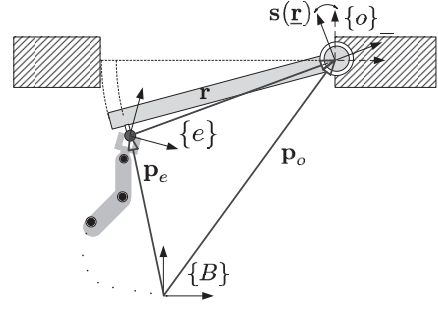


Fig. 1: Kinematics of the door opening

with $\mathbf{q}, \dot{\mathbf{q}} \in \mathbb{R}^n$ being the joint positions and velocities and $\mathbf{J}(\mathbf{q})^+ = \mathbf{J}(\mathbf{q})^\top [\mathbf{J}(\mathbf{q})\mathbf{J}(\mathbf{q})^\top]^{-1}$ being the pseudo-inverse of the manipulator Jacobian $\mathbf{J}(\mathbf{q}) \in \mathbb{R}^{2 \times n}$ which relates the joint velocities $\dot{\mathbf{q}}$ to the end-effector velocities $\dot{\mathbf{p}}_e$; without loss of generality we consider only the translational end-effector velocity $\dot{\mathbf{p}}_e \in \mathbb{R}^2$ and the associated Jacobian. If we consider the typical Euler-Lagrange robot dynamic model, the velocity error at the joint level drive the torque (current) controller $\mathbf{u}(t)$. If we assume a high frequency current control loop with external forces' compensators and weak inertial dynamics, the kinematic model is valid.

D. Control Objective

The objective is to control the motion of the robot to achieve a smooth interaction with an external kinematic mechanism such as a door. In applications which take place in a dynamic unstructured environments such as a domestic environment, it is difficult to accurately identify the position of the hinges and the associated dynamics. Hence, it is difficult to design a priori the desired velocity within the constraints imposed by the kinematic mechanism. The execution of a trajectory which is inconsistent with system constraints gives rise to high interaction forces along the constraint direction which may be harmful for both the manipulated mechanism and the robot.

Let f_{rd} and v_d be the desired radial force and desired tangent velocity magnitudes respectively. If we define the force along the radial direction as $f_r = \mathbf{r}^\top \mathbf{f}$ with $\mathbf{f} \in \mathbb{R}^2$ being the total interaction force, the control objective can be formulated as follows: $f_r \rightarrow f_{rd}$ and $\dot{\mathbf{p}}_e \rightarrow \mathbf{s}(\mathbf{r})v_d$. These objectives have to be achieved without knowing accurately the \mathbf{r} direction which subsequently implies that there are uncertainties in the control variables f_r and $\mathbf{s}(\mathbf{r})v_d$. From a high level perspective, we consider that the door opening task is accomplished when the observed end-effector trajectory, which coincides with the handle trajectory, enable the robot to perform the subsequent task which can be for example "get an object" or "pass through the door". Thus the command to halt the door opening procedure is given externally based on the observations of the rotation angle ϑ .

III. CONTROL DESIGN

A. Incorporating Force Feedback in the Velocity Reference

Let us first define an estimated radial direction $\hat{\mathbf{r}}(t)$ based on appropriately designed adaptive estimates of the center of rotation $\hat{\mathbf{p}}_o(t)$:

$$\hat{\mathbf{r}}(t) = \hat{\mathbf{p}}_o(t) - \mathbf{p}_e \quad (10)$$

For notation convenience we will drop out the argument of t from $\hat{\mathbf{r}}(t)$ and $\hat{\mathbf{p}}_o(t)$. We will use the estimated radial direction (10) considering that $\|\hat{\mathbf{r}}(t)\| \neq 0, \forall t$ in order to introduce a reference velocity vector \mathbf{v}_{ref} for controlling the end-effector velocity:

$$\mathbf{v}_{\text{ref}} = \mathbf{s}(\hat{\mathbf{r}})v_d - \alpha\hat{\mathbf{r}}v_f \quad (11)$$

with α being a positive control gain acting on the force feedback term v_f which has been incorporated in the reference velocity.

We can now introduce the velocity error:

$$\tilde{\mathbf{v}} \triangleq \mathbf{v} - \mathbf{v}_{\text{ref}} \quad (12)$$

where $\mathbf{v} \triangleq \dot{\mathbf{p}}_e$ can be decomposed along $\hat{\mathbf{r}}$ and $\mathbf{s}(\hat{\mathbf{r}})$ and subsequently expressed with respect to the parameter estimation error $\tilde{\mathbf{p}}_o = \tilde{\mathbf{r}} = \mathbf{p}_o - \hat{\mathbf{p}}_o$ by adding $-\|\hat{\mathbf{r}}\|^{-1}\hat{\mathbf{r}}\mathbf{r}^\top\mathbf{v}$ as follows:

$$\mathbf{v} = \mathbf{s}(\hat{\mathbf{r}})\mathbf{s}(\hat{\mathbf{r}})^\top\mathbf{v} - \|\hat{\mathbf{r}}\|^{-1}\hat{\mathbf{r}}\tilde{\mathbf{p}}_o^\top\mathbf{v} \quad (13)$$

Substituting (13) and (11) in (12) we can obtain the following decomposition of the velocity error along the estimated radial direction $\hat{\mathbf{r}}$ and the estimated direction of motion $\mathbf{s}(\hat{\mathbf{r}})$:

$$\tilde{\mathbf{v}} = \hat{\mathbf{R}}_o \begin{bmatrix} -\|\hat{\mathbf{r}}\|^{-1}\tilde{\mathbf{p}}_o^\top\mathbf{v} + \alpha v_f \\ \mathbf{s}(\hat{\mathbf{r}})^\top\mathbf{v} - v_d \end{bmatrix} \quad (14)$$

where $\hat{\mathbf{R}}_o \triangleq \begin{bmatrix} \hat{\mathbf{r}} & \mathbf{s}(\hat{\mathbf{r}}) \end{bmatrix}$.

In the next step, we are going to design the force feedback v_f employed in the reference velocity \mathbf{v}_{ref} . The force feedback term v_f is derived from the magnitude of the measured force components projected along the estimated radial direction:

$$\hat{f}_r = \hat{\mathbf{r}}^\top \mathbf{f} \quad (15)$$

the corresponding force error:

$$\Delta\hat{f}_r = \hat{f}_r - f_{rd} \quad (16)$$

as well as the corresponding force error integral $\mathcal{I}(\Delta\hat{f}_r)$. In particular, for velocity controlled robotic manipulators, we propose a PI control loop of the estimated radial force error $\Delta\hat{f}_r$:

$$v_f = \Delta\hat{f}_r + \beta\mathcal{I}(\Delta\hat{f}_r) \quad (17)$$

with β being a positive control gain. By projecting $\tilde{\mathbf{v}} = 0$ along $\hat{\mathbf{r}}$ we can calculate \hat{f}_r as a Lagrange multiplier associated with the constraint (6) for the system (9):

$$\hat{f}_r = f_{rd} - \beta\mathcal{I}(\Delta\hat{f}_r) + \frac{v_d\mathbf{r}^\top\mathbf{s}(\hat{\mathbf{r}})}{\alpha\mathbf{r}^\top\hat{\mathbf{r}}}. \quad (18)$$

Equation (18) is well defined for $\mathbf{r}^\top\hat{\mathbf{r}}(t) > 0$. Equation (18) is consistent to (15) in case of rigid contacts and fixed grasps.

Remark 1: For torque controlled robotic manipulators, the derivative of reference velocity also known as reference acceleration is required in the implementation. In order to avoid the differentiation of the force measurements in case of torque controlled manipulators, the force feedback part of the reference velocity should be designed using only the integral of the estimated radial force error.

B. Update Law Design

The update law for the vector $\hat{\mathbf{p}}_o$ is designed via a passivity-based approach, by defining the output of the system as follows:

$$y_f = \alpha_f\Delta\hat{f}_r + \alpha_I\mathcal{I}(\Delta\hat{f}_r) \quad (19)$$

with α_f and α_I being positive constants. Taking the inner product of $\tilde{\mathbf{v}}$ (14) with $\hat{\mathbf{r}}y_f$ (19) we obtain:

$$\begin{aligned} y_f\hat{\mathbf{r}}^\top\tilde{\mathbf{v}} &= y_f(-\|\hat{\mathbf{r}}\|^{-1}\tilde{\mathbf{p}}_o^\top\mathbf{v} + v_f) \\ &= -\|\hat{\mathbf{r}}\|^{-1}y_f\mathbf{v}^\top\tilde{\mathbf{p}}_o + c_1\Delta\hat{f}_r^2 \\ &\quad + c_2\mathcal{I}(\Delta\hat{f}_r)^2 + c_3\frac{d}{dt}\left[\mathcal{I}(\Delta\hat{f}_r)^2\right] \end{aligned} \quad (20)$$

where:

$$c_1 = \alpha\alpha_f, \quad c_2 = \alpha\alpha_I\beta, \quad c_3 = \frac{\alpha(\alpha_f\beta + \alpha_I)}{2} \quad (21)$$

Next, we design the update law $\dot{\hat{\mathbf{p}}}_o \triangleq -\dot{\tilde{\mathbf{p}}}_o$ as follows:

$$\dot{\hat{\mathbf{p}}}_o = \mathcal{P}\{\gamma\|\hat{\mathbf{r}}\|^{-1}y_f\mathbf{v}\} \quad (22)$$

Notice that \mathcal{P} is an appropriately designed projection operator [16] with respect to a convex set of the estimates $\hat{\mathbf{p}}_o$ around \mathbf{p}_o (Fig. 2) in which the following properties hold: i) $\|\hat{\mathbf{r}}\| \neq 0, \forall t$, in order to enable the implementation of the reference velocity and calculate estimated radial force and ii) $\mathbf{r}^\top\hat{\mathbf{r}} > 0$; which is required for the system's stability. It

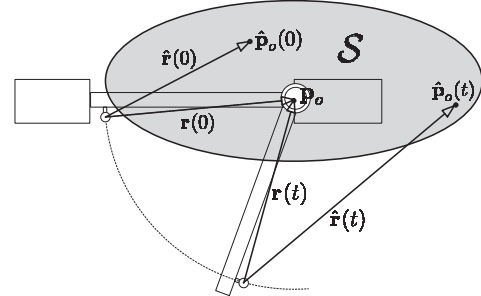


Fig. 2: Convex set \mathcal{S} for the projection operator \mathcal{P}

is clear that the update law (22) gives rise to the potential owing to estimation error i.e. $\frac{1}{2\gamma}\tilde{\mathbf{p}}_o^\top\tilde{\mathbf{p}}_o$ and allow us to use the following function $V(\mathcal{I}(\Delta\hat{f}_r), \tilde{\mathbf{p}}_o)$ in order to prove Theorem 1 for velocity controlled manipulators. In particular $V(\mathcal{I}(\Delta\hat{f}_r), \tilde{\mathbf{p}}_o)$ is given by:

$$V(\mathcal{I}(\Delta\hat{f}_r), \tilde{\mathbf{p}}_o) = c_3\mathcal{I}(\Delta\hat{f}_r)^2 + \frac{1}{2\gamma}\tilde{\mathbf{p}}_o^\top\tilde{\mathbf{p}}_o \quad (23)$$

and is positive-definite with respect to $\mathcal{I}(\Delta\hat{f}_r)$, $\tilde{\mathbf{p}}_o$ and Theorem 1 is stated below:

Theorem 1: The kinematic controller \mathbf{v}_{ref} (11) with the update law (22) applied to the system (9) achieves the following objectives: $\hat{\mathbf{r}} \rightarrow \mathbf{r}$, $\mathbf{v} \rightarrow \mathbf{s}(\hat{\mathbf{r}})v_d$, $\mathcal{I}(\Delta f_r) \rightarrow 0$ and $f_r \rightarrow f_{rd}$, which are equivalent with the control objective of smooth door opening stated in Section II-D.

Proof: Substituting (11) in (9) and multiplying by $\mathbf{J}(\mathbf{q})$, implies $\tilde{\mathbf{v}} = 0$. Differentiating $V(\mathcal{I}(\Delta \hat{f}_r), \tilde{\mathbf{p}}_o)$ with respect to time and substituting $\tilde{\mathbf{v}} = 0$ and (22) we get: $\dot{V} = -c_1 \Delta \hat{f}_r^2 - c_2 \mathcal{I}(\Delta \hat{f}_r)^2$; note that \dot{V} has extra negative terms when the estimates reach the bound of the convex set and the projection operator applies and thus the stability properties of the system are not affected. Hence, $\mathcal{I}(\Delta \hat{f}_r)$, $\tilde{\mathbf{p}}_o$ are bounded and we can prove the boundedness of the following variables: (a) \hat{f}_r is bounded, given the use of projection operator in (18), (b) \mathbf{v}_{ref} is bounded, (c) $\dot{\mathbf{q}}$ is bounded, given the assumption of a non-singular manipulator in (9), (d) $\dot{\tilde{\mathbf{p}}}_o$ is bounded, given (22) and the boundedness of \mathbf{v} .

The boundedness of the aforementioned variables implies that \hat{f}_r and subsequently $\ddot{V} = -2\Delta \hat{f}_r [c_1 \dot{\hat{f}}_r + c_2 \mathcal{I}(\Delta \hat{f}_r)]$ are bounded and thus Barbalat's Lemma implies $\dot{V} \rightarrow 0$ and in turn $\mathcal{I}(\Delta \hat{f}_r)$, $\Delta \hat{f}_r \rightarrow 0$. Substituting the convergence results in (9) and (18) we get $\mathbf{v} \rightarrow \mathbf{s}(\hat{\mathbf{r}})v_d$ and $\hat{\mathbf{r}}^\top \mathbf{s}(\hat{\mathbf{r}}) \rightarrow 0$ for $\lim_{t \rightarrow \infty} |v_d| \neq 0$ (or for a v_d satisfying the persistent excitation condition) respectively; the latter implies $\hat{\mathbf{r}} \rightarrow \mathbf{r}$. Since the estimated direction of the constraint is identified we get: $\mathbf{v} \rightarrow \mathbf{s}(\hat{\mathbf{r}})v_d$, $\mathcal{I}(\Delta f_r) \rightarrow 0$ and $f_r \rightarrow f_{rd}$. \square

C. Summary and Discussion

The proposed method is based on a reference velocity (11) which is decomposed to a feedforward velocity on the estimated direction of motion and a PI force control loop on the estimated constrained direction. The estimated direction is obtained on-line using the update law (22) and the definition of the radial estimate (10). The use of (22) and (10) within a typical velocity reference like (11) enables the proof of the overall scheme stability as well as the proof that the estimates converge to the true values, driving the velocity and radial force to their desired values. Note that the proposed control scheme can easily be implemented on a common robotic setup with a velocity-controlled robotic manipulator with a force/torque sensor in the end-effector frame.

It is also clear that the proposed method is inherently on-line and explicitly includes the uncertain estimates in the controller, as opposed to the state of the art for door opening (as described in Section I), which assumes that the estimate obtained in each step is approximately equal to the actual value. The proposed method can be also combined with off-line door kinematic estimation; in this case the off-line estimates can be used as the initial estimates of the estimator (22). However, our scheme is proven to work satisfactorily even in the case of large estimation errors, where off-line methods fail. Last but not least, the proposed method can be also be applied to other types of robot manipulation under kinematic uncertainties. We have chosen here the door opening problem since it is very challenging, but can be described in terms of concrete motion constraints.

IV. EXPERIMENTAL EVALUATION

The performance was evaluated on a real robot system. The arm used is constructed from Schunk rotary modules, that can be sent velocity commands over a CAN bus. The modules incorporate an internal PID controller that keeps the set velocity, and return angle measurements. In this setup, the modules are sent updated velocity commands at 400 Hz. Angle measurements are read at the same frequency. The arm has an ATI Mini45 6 DoF force/torque sensor mounted at the wrist. The forces are also read at 400 Hz in this experiment. The force readings display white measurement noise with a magnitude of approximately 0.2 N, apart from any process noise that may be present in the mechanical system. In the experiment, we actuate the second and fifth joints, and start the experiment with the end-effector firmly grasping the handle of a cupboard door. The cupboard door is a 60 cm width IKEA kitchen cupboard, with multiple-link hinges, so that the centre of rotation moves slightly (< 1 cm) as a function of door angle. The handle of the door has been extended an additional 5 cm to accommodate the width of the fingers on the parallel gripper.

We examine two scenarios. The first scenario assumes a large error in the initial estimate (initial error of 50°), but a stationary platform, while the second scenario assumes a smaller initial error (initial error of 5°) but with a moving base. The desired velocity value $v_d = 0.05$ m/s for both scenarios. The controller gains are set to $a_f = 0.1$, $a_I = 0.05$, $\alpha = 0.001$, $\beta = 0.1$, $\gamma = 0.5$. These gains have not been tuned specifically for the robot configuration or problem parameters, in order to show the generality of the approach. Fig. 3 shows the robot performing the task in the first case, and Fig. 4 shows the robot performing the task in the second case. Note that the base motion allows the cupboard to be opened to a wider angle. The base motion was 0.3 m along a straight line, driven by a human operator at approximately 0.04 m/s. The base motion was not modelled or included in the controller, but treated as an external disturbance.

The experimental results are shown in Figs. 5 and 6 for stationary and moving base respectively. In the stationary case, both force error and estimation error converge to zero in approximately 4 s. In the moving base scenario, we see larger force errors and slower convergence. This is to be expected, as the base motion continuously injects new errors into the system.

V. CONCLUSIONS

This paper proposes a method for manipulation with uncertain kinematic constraints. It is inherently on-line and real-time, and convergence and stability is analytically provable. The method can be used with any velocity controllable manipulator with force measurements in the end-effector frame. In this paper, the method has been applied to the task of opening a door with unknown location of the hinges, while limiting the interaction forces. In particular, a velocity reference is designed using force and position measurements to deal with the door opening problem in the presence of incomplete knowledge of the door model. In



Fig. 3: The robot performing the door opening experiment. $v_d = 0.05$ m/s. The images are taken at $t = 0$ s, $t = 1.5$ s, $t = 3.6$ s, and $t = 5.7$ s, respectively.

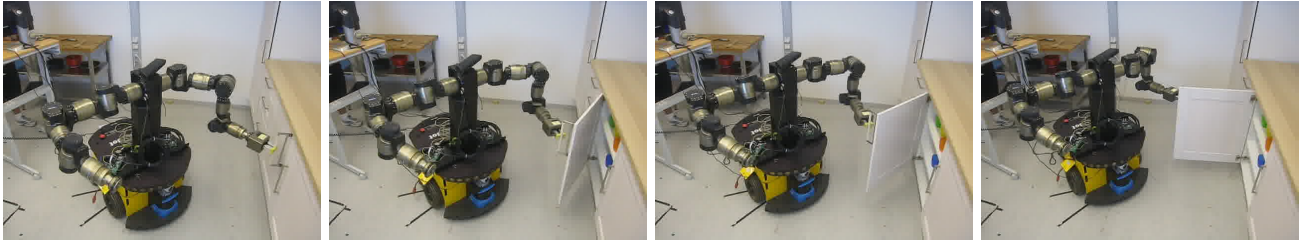


Fig. 4: The robot performing the door opening experiment, with moving base. $v_d = 0.05$ m/s. The images are taken at $t = 0$ s, $t = 2.2$ s, $t = 4.8$ s, and $t = 9.2$ s, respectively.

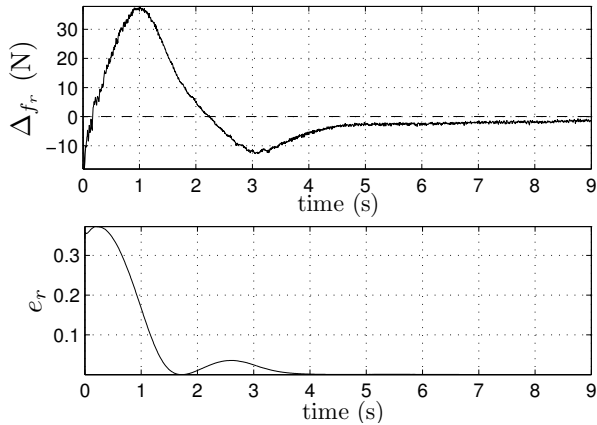


Fig. 5: Radial force (upper plot) and estimation error (lower plot) responses - robot experiment, stationary base, high error in initial estimate $\hat{\mathbf{p}}_{o1}(0)$

the velocity reference, the constraint direction is explicitly considered uncertain by including online estimates based on the adaptation of the hinge's location. Convergence results are theoretically proved. An experiment on a real robot show that the estimates converge to the actual values even for large initial errors in the estimates as well as that the method can achieve smooth door opening even in case of disturbances due to the motion of the robotic mobile platform. Future work includes applying the proposed method to a wider range of domestic manipulation tasks with uncertainties in the kinematic constraints.

ACKNOWLEDGMENT

This work has been supported by the Swedish Research Council (VR) and Swedish Foundation for Strategic

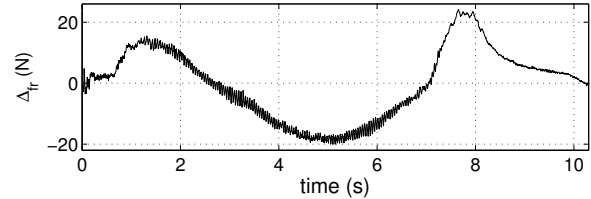


Fig. 6: Radial force error responses - robot experiment, moving base, smaller error in initial estimate $\hat{\mathbf{p}}_{o2}(0)$

Research (SSF), and the European Union FP7 project RoboHow.Cog (FP7-ICT-288533). The authors gratefully acknowledge the support.

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