"Open Sesame!"
Adaptive Force/Velocity Control for Opening Unknown Doors

Yiannis Karayiannidis, Christian Smith, Francisco E. Viña, Petter Ögren, and Danica Kragic
Computer Vision and Active Perception Lab., Centre for Autonomous Systems,
School of Computer Science and Communication, Royal Institute of Technology (KTH)
SE-100 44 Stockholm, Sweden.
{yiankar|ccs|fevb|petter|dani}@kth.se

***Abstract*— The problem of door opening is fundamental for robots operating in domestic environments. Since these environments are generally less structured than industrial environments, 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 that can open doors without prior knowledge of the door kinematics. The proposed method can be implemented on a velocity-controlled manipulator with force sensing capabilities at the end-effector. The method consists of a velocity controller which uses force measurements and estimates of the radial direction based on adaptive estimates of the position of the door hinge. The control action is decomposed into an estimated radial and tangential direction following the concept of hybrid force/motion control. A force controller acting within the velocity controller regulates the radial force to a desired small value while the velocity controller ensures that the end effector of the robot moves with a desired tangential velocity leading to task completion. This paper also provides a proof that the adaptive estimates of the radial direction converge to the actual radial vector. The performance of the control scheme is demonstrated in both simulation and on a real robot.**

I. Introduction

A robot should be able to open doors as simple as saying "Open Sesame!". However, the task of opening a door — or a cupboard — in a domestic environment includes several types of uncertainty that disqualifies the use of motion control and trajectory planning that is effective for stiff industrial robots. The uncertainties in the manipulation of these kinematic mechanisms, e.g. doors and drawers, can be divided into (a) *dynamic uncertainties*, related to the dynamic model of the door or the drawer: door's inertia, dynamics of the hinge mechanism etc., and (b) *kinematic uncertainties* related to the kinematic model of the door or the drawer: type of joint that models the kinematic mechanism, which may be prismatic or revolute, size of the door, location of the hinge etc. This categorization has been used in several problems in robot control, like motion control [1] and force/motion control [2]. From a control perspective, the door-opening problem can be regarded as a force/motion control problem in which the robot workspace can be divided into motion and force controlled subspaces according to the concept of hybrid force/motion control [3], [4].

In this work, we consider a general robotic setup with a velocity controlled manipulator equipped with a wrist force/torque sensor, and we propose an adaptive controller which can be easily implemented for dealing with the kinematic and dynamic uncertainties of doors. The proposed control scheme, which is inspired by the adaptive surface slope learning [5], does not require accurate identification of the motion constraint at each step of the door opening procedure, as opposed to existing solutions to the door opening problem (see Section II). It uses adaptive estimates of the radial direction which are constructed from estimates of the door's hinge position and converge during the procedure to the actual, dynamically changing, radial direction. It should be noted that the proposed method can also be applied to other types of manipulation under uncertain kinematic constraints. We have chosen the door opening problem as a concrete example, since it is well-studied and has well-defined constraints. The paper is organised as follows: In Section II we provide an overview of the related works for the door opening problem. Section III provides description of the kinematic and the dynamic model of the system and the problem formulation. The proposed solution and the corresponding stability analysis are given in Section IV followed by the simulation example of Section V. In Section VII the final outcome of this work is briefly discussed.

II. Related Work and our Contributions

Pioneering works on the door opening problem are the papers of [6] and [7]. In [6], 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 [7], the estimation of the constraints describing the kinematics of the motion for the door opening problem is proposed.

The estimation technique of [7] is based on the observation that ideally, the motive force should be applied along the direction of the end-effector velocity. To overcome the problems of chattering due to measurement noise and ill-definedness of the normalization for slow end-effector motion, the authors propose estimation by spatial filtering, which may, however, cause lag and affect the system stability. The idea of using velocity measurements for estimating the direction of motion has inspired the recent work of [8] that uses a moving average filter in the velocity domain. An estimator is used to provide a velocity reference for an admittance controller. Ill-defined normalizations and estimation lags are not dealt with. Estimation of the constraint using velocity measurements has also been used in [9], where velocity and impedance control have been used along the tangent and the radial axis of the door opening trajectory respectively.

Several position-based estimation techniques have also been proposed. In [10], the recorded motion of the end-effector is used in a least-squares approximation algorithm to estimate the center and the radius of the motion arc, and a compliant controller is used to cancel the effects of the high forces exerted due to inaccurate trajectory planning.

An optimization algorithm using the position of the end-effector was used in [11], [12]. The algorithm produces estimates of the radius and the center of the door and, subsequently of the control directions. The velocity reference is composed of a feedforward estimated tangential velocity and radial force feedback along. An equilibrium point control law enables a viscoelastic behavior of the system around an equilibrium position.

In [13], an inverse Jacobian velocity control law with feedback of the force error following the Task Space Formalism [14] is considered. In order to obtain the natural decomposition of the task, which is essential within this framework, the authors propose to combine several sensor modalities so that robust estimation is established. In [13], the estimation is based on the end-effector trajectory, to align the task frame with the tangent of the hand trajectory.

Other works estimate the geometry of the door off-line, prior to manipulation. In [15], a multi-fingered hand with tactile sensors grasping the handle is used, and the geometry of the door is estimated by observing the positions of the fingertips position while slightly and slowly pulling and pushing the door in position control. In a subsequent step, the desired trajectory is derived from the estimation procedure, and is used in a position controller. In [16], a probabilistic framework in order to learn the kinematic model of articulated objects in terms of object's parts connectivity, degrees of freedom of the objects and kinematic constraints is proposed. The learning procedure requires a set of motion observations of the objects, e.g. doors. The estimates are generated in an off-line manner and can feed force/position cartesian controllers [17]. Probabilistic methods — particle filters and extended Kalman filters — for mobile manipulation have also been applied for opening doors under uncertainty, in [18]. The authors use an a priori defined detailed model of the door, and simultaneously estimate position of the robot and the angle of the door.

Another part of the literature on the door opening problem exploits advanced hardware capabilities to accomplish the manipulation task. In [19], a combination of tactile-sensor and force-torque sensor is used to control the position and the orientation of the end-effector with respect to the handle. In [20], a specific hardware configuration with clutches that disengage selected robot motors from the corresponding actuating joints and hence enable passive rotation of these joints is used. Since no force sensing is present, a magnetic end-effector was used which cannot always provide the appropriate force for keeping the grasp of the handle fixed. In, [21] the authors exploited the extensive abilities of the hardware, and used joint torque measurements to realize Cartesian impedance control of the DLR lightweight robot II in order to open a door. In [22], the authors present experiments using a force/torque sensor on a custom lightweight robot to define the desired trajectory for a door opening task. In [23], a method for door opening is proposed that uses an impulsive force exerted by the robot to the door which is assumed to be a swinging door. A specific dynamic model for the door dynamics is used to calculate the initial angular velocity which is required for a specific change of the door angle, and implemented on the humanoid robot HRP-2.

In this paper, we propose a method that differs from the existing work by simultaneously providing the following benefits:

- **Provable performance under uncertainty**. The proposed method explicitly includes the uncertain estimates in the controller, and we provide proof of convergence of the estimates, and of the stability of the proposed method even with initially large errors in the estimates.
- **On-line performance**. Our method does not require preparatory measurements or detailed modelling, or an off-line estimation phase before the manipulation task. Instead, our method allows the manipulator to open a previously unknown door as smooth as a known one.
- **Moderate hardware requirements**. Our method can be implemented on any manipulator that can be velocity controlled in either joint space or Cartesian space, with force measurements at the end effector or wrist.

III. System and Problem Description

In this section we define the problem of door opening under uncertainty.

A. Notation and Preliminaries

We introduce the following notation:

- 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 $\{B\}$ (located usually 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 consider also the following normalization and orthogonalization operators:

$$\underline{\mathbf{z}} = \frac{\mathbf{z}}{\|\mathbf{z}\|} \tag{1}$$

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

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

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

- 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:

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

B. Kinematic model of robot door opening

We consider a setting of a robot manipulator in which its end-effector has achieved a fixed grasp of the handle of a kinematic mechanism e.g. a door in a domestic environment. We use the term fixed grasp to denote 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 consequently 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:

$$\mathbf{r} \triangleq \mathbf{p}_o - \mathbf{p}_e \tag{5}$$

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

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

By performing the following 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, we get:

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

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:

$$\mathbf{r}^\top \dot{\mathbf{p}}_e = 0 \tag{8}$$

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

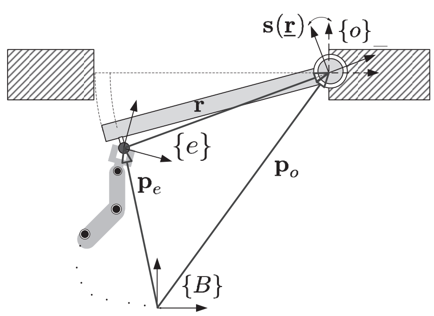

Fig. 1: Kinematics of the door opening

C. Robot kinematic model

In case of velocity controlled manipulators, the robot joint velocity is controlled directly by the reference velocity $\mathbf{v}_{\text{ref}}$. In particular, the reference velocity $\mathbf{v}_{\text{ref}}$ 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:

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

with $\mathbf{q}$, $\dot{\mathbf{q}} \in \mathbb{R}^n$ being the joint positions and velocities and $\mathbf{J}(\mathbf{q})^+ = \mathbf{J}(\mathbf{q})^\top \left[\mathbf{J}(\mathbf{q})\mathbf{J}(\mathbf{q})^\top\right]^{-1}$ 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 have here considered 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, then 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, and manipulate it in order to achieve a high level command such as "Open Sesame!". 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 $f_r = \underline{\mathbf{r}}^\top \mathbf{f}$ with $\mathbf{f} \in \mathbb{R}^2$ being the total interaction force, the control objective can be formulated as follows: $f_r \to f_{rd}$ and $\dot{\mathbf{p}}_e \to \mathbf{s}(\underline{\mathbf{r}})v_d$. These objectives have to be achieved without knowing accurately the $\underline{\mathbf{r}}$ direction which subsequently implies that there are uncertainties in the control variables f_r and $\mathbf{s}(\underline{\mathbf{r}})v_d$. 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.

IV. 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 $\hat{\mathbf{p}}_o(t)$:

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

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 $\mathbf{v}_{\text{ref}}$ for controlling the end-effector velocity:

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

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:

$$\tilde{\mathbf{v}} \triangleq \mathbf{v} - \mathbf{v}_{\text{ref}} \tag{12}$$

where $\mathbf{v} \triangleq \dot{\mathbf{p}}_e$ can be decomposed along $\underline{\hat{\mathbf{r}}}$ and $\mathbf{s}(\underline{\hat{\mathbf{r}}})$ 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 $-\|\hat{\mathbf{r}}\|^{-1}\underline{\hat{\mathbf{r}}}\mathbf{r}^\top\mathbf{v}$ as follows:

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

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

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

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

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

$$\hat{f}_r = \underline{\hat{\mathbf{r}}}^\top\mathbf{f} \tag{15}$$

the corresponding force error:

$$\Delta\hat{f}_r = \hat{f}_r - f_{rd} \tag{16}$$

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 $\Delta\hat{f}_r$:

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

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

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

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:

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

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

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

where:

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

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

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

Notice that $\mathcal{P}$ is an appropriately designed projection operator [24] 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) $\|\hat{\mathbf{r}}\| \neq 0, \quad \forall t$, 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 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 $V\left(\mathcal{I}(\Delta\hat{f}_r), \tilde{\mathbf{p}}_o\right)$ in order to prove Theorem 1 for velocity controlled manipulators. In particular $V\left(\mathcal{I}(\Delta\hat{f}_r), \tilde{\mathbf{p}}_o\right)$ is given by:

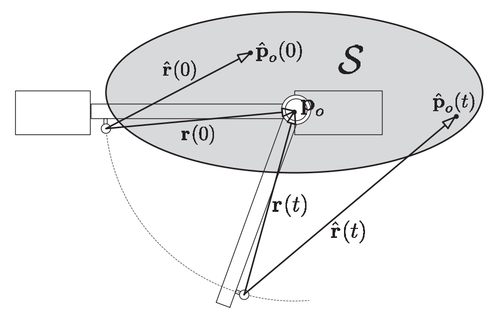

Fig. 2: Convex set $\mathcal{S}$ for the projection operator $\mathcal{P}$

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

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 $\mathbf{v}_{\text{ref}}$ (11) with the update law (22) applied to the system (9) achieves the following objectives: $\underline{\hat{\mathbf{r}}} \to \underline{\mathbf{r}}$, $\mathbf{v} \to \mathbf{s}(\underline{\mathbf{r}})v_d$, $\mathcal{I}(\Delta f_r) \to 0$ and

$f_r \to f_{rd}$, which are equivalent with the control objective of smooth door opening stated in Section III-D.

Proof: Substituting (11) in (9) and multiplying by $\mathbf{J}(\mathbf{q})$, implies $\tilde{\mathbf{v}} = 0$. Differentiating $V\left(\mathcal{I}(\Delta\hat{f}_r), \tilde{\mathbf{p}}_o\right)$ with respect to time and in turn substituting $\tilde{\mathbf{v}} = 0$ and (22) we get: $\dot{V} = -c_1\Delta\hat{f}_r^2 - c_2\mathcal{I}(\Delta\hat{f}_r)^2$; notice 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 consequently we can prove the boundedness of the following variables: (a) $\hat{f}_r$ is bounded, given the use of projection operator in (18), (b) $\mathbf{v}_{\text{ref}}$ is bounded, (c) $\dot{\mathbf{q}}$ is bounded, given the assumption of a non-singular manipulator in (9), (d) $\dot{\hat{\mathbf{p}}}_o$ is bounded, given (22) and the boundedness of $\mathbf{v}$.

The boundedness of the aforementioned variables implies that $\dot{\hat{f}}_r$ 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 $\dot{V} \to 0$ and in turn $\mathcal{I}(\Delta\hat{f}_r),\ \Delta\hat{f}_r \to 0$. Substituting the convergence results in (9) and (18) we get $\mathbf{v} \to \mathbf{s}(\hat{\underline{\mathbf{r}}})v_d$ and $\hat{\underline{\mathbf{r}}}^\top\mathbf{s}(\underline{\mathbf{r}}) \to 0$ for $\lim_{t\to\infty}|v_d| \neq 0$ (or for a v_d satisfying the persistent excitation condition) respectively; the latter implies $\hat{\underline{\mathbf{r}}} \to \underline{\mathbf{r}}$. Since the estimated direction of the constraint is identified we get: $\mathbf{v} \to \mathbf{s}(\underline{\mathbf{r}})v_d$, $\mathcal{I}(\Delta f_r) \to 0$ and $f_r \to f_{rd}$. □

C. Summary and Discussion

The proposed technique 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 will converge to the actual values, driving the velocity and the radial force to their desired values.

Note that the proposed control scheme can be easily implemented using a very 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 II), 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.

V. Evaluation Using Simulation

We consider a 2 DoF robot manipulator (Fig. 3) which is modeled after one of the two 7 DoF arms of a semi-anthropomorphic robot at CAS/KTH, with only 2 DoFs being actuated while the remaining DoFs are mechanically fixed. In particular, we consider that the second and fifth joints are actuated (red cylinders in Fig. 3) and simulate the case where this 2 DoFs planar manipulator can open a door through a fix-grasp of the cupboard handle. The DH parameters of the 7 DoF arm are shown in Table I. Regarding the kinematic parameters of the door, the center of rotation si $\mathbf{p}_o = [-0.85\ 0.37]^\top$ (m) in the robot world frame, while the length of the door (from hinge to handle) is approximately 0.51 m. In the simulation, the motion along the radial direction is governed by a stiff viscoelastic model while viscous friction is considered for the rotational motion.

Frame	α	**a**	θ	**d**
Base	$0°$	0.274	$90°$	0
Base	$90°$	0	$0°$	0
1	$0°$	0	θ_1	0
2	$-90°$	0	$\theta_2 + 180°$	0
3	$-90°$	0	$\theta_3 + 180°$	0.313
4	$-90°$	0	$\theta_4 + 180°$	0
5	$-90°$	0	$\theta_5 + 180°$	0.2665
6	$-90°$	0	$\theta_6 + 180°$	0
7	$-90°$	0	$\theta_7 + 180°$	0
Tool	$0°$	0	$0°$	0.42

TABLE I: DH parameters of the 7-DOF arm (using Craig's convention).

We set the initial estimate of the center of rotation $\hat{\mathbf{p}}_{o1}(0) = [-0.85\ \ 0.77]^\top$ (m) in the robot world frame which corresponds to the actual center of rotation misplaced for 40 cm along the x-axis; the initial uncertainty angle formed between the actual and the estimated radial direction is approximately 50 deg in this case which is extremely large. The controller objectives are set as follows: $v_d = 0.25$ m/s and $f_{rd} = 2$ N. The controller gains are chosen as follows: $a_f = 1$, $a_I = 0.8$, $\alpha = 0.6$, $\beta = 0.5$, $\gamma = 4$. Fig. 4 shows the top view of the manipulator while opening the door while Fig. 5 depicts the force error $\Delta f_r = f_r - f_{rd}$ response as well as the estimation error variable $e_r = 1 - \hat{\underline{\mathbf{r}}}^\top\underline{\mathbf{r}}$ response. Fig. 6 shows the velocity commands expressed in the joint space. Notice that very fast convergence in approximately 0.5 s is achieved (Fig. 5), but the demands of velocity (Fig. 6) is extremely high as compared to the maximum joint velocities in our experimental setup. (0.7 rad/s)

In the following simulations, we used the gains and considered the scenarios of Section VI (Experimental evaluation using Robot Platform). In the first scenario we consider the initial estimate of the center of rotation $\hat{\mathbf{p}}_{o1}(0)$ used before, by reducing the desired velocity to $v_d = 0.05$ m/s, while in the second scenario we consider that the center of rotation is misplaced for 5 cm along the x-axis of the robot world frame, i.e. $\hat{\mathbf{p}}_{o2}(0) = [-0.85\ 0.42]^\top$ (m) by setting the desired velocity to a higher value $v_d = 0.1$ m/s. The force control objective is set $f_{rd} = 2$ N and the controller gains are chosen as follows:

$a_f = 0.1$, $a_I = 0.05$, $\alpha = 0.001$, $\beta = 0.1$, $\gamma = 0.5$, for both cases of initial uncertainty. In the latter case, the initial uncertainty angle formed between the actual and the estimated radial direction is approximately 5 deg. Simulation results (force and estimation errors' responses) are shown in Fig. 7 and 8 for the case of higher and lower uncertainty respectively. Notice that the estimation error converges to zero in approximately 1 s while the convergence of the force error is slower. Notice also that the overshoot in the force error is much larger in the case of higher uncertainty (Fig. 7), but as the controller finally tracks the actual direction it slowly vanishes.

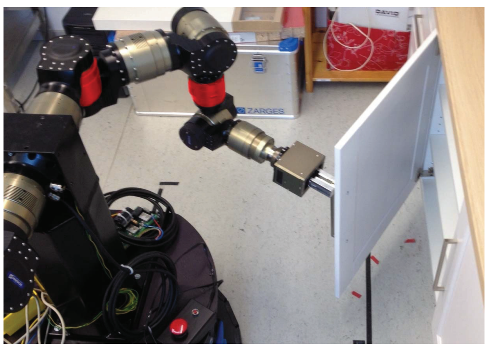

Fig. 3: 7 DoF arm of a semi-anthropomorphic robot at CAS/KTH; the figure has been digitally enhanced to mark the joints used for experimental evaluation with red hue

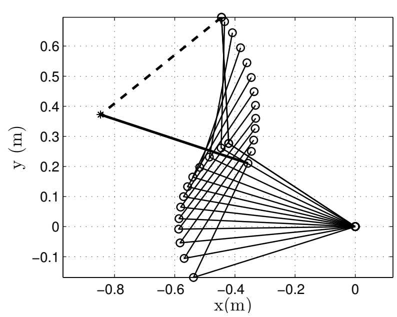

Fig. 4: Manipulator trace and door's initial (dashed bold line) and final(solid bold line) position

VI. Experimental Evaluation using Robot Platform

The performance was also evaluated on the real robot system. We consider the robot and door kinematic setup used in Section V. The arm 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

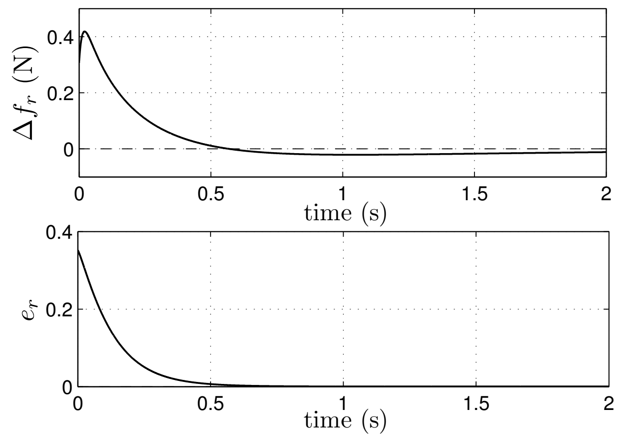

Fig. 5: Radial force error (Upper plot) and Estimation Error (Lower plot) responses - Simulation for $\hat{\mathbf{p}}_{o1}(0)$, $v_d = 0.25$ m/s

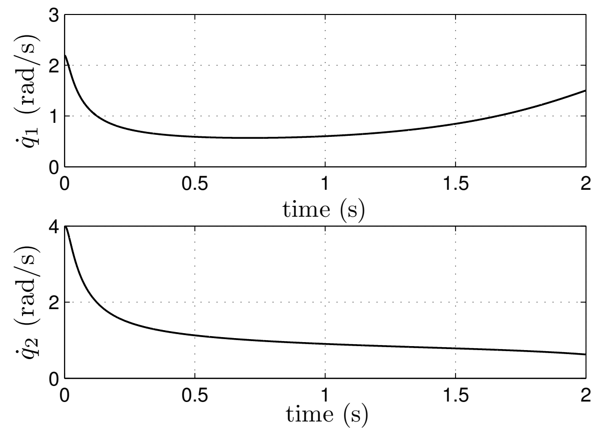

Fig. 6: Joint velocities' responses - simulation for $\hat{\mathbf{p}}_{o1}(0)$, $v_d =$ 0.25 m/s

from any process noise that may be present in the mechanical system. In the experiment, we actuate the second and fifth joints (red cylinders in Fig. 3), 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 accomodate the width of the fingers on the parallel gripper. The DH parameters of the 7 DoF arm are the same as in simulation, see Table I. The two different scenarios based on different initial estimates of the radial direction (with errors of 50^o and 5^o, respectively) as well as different desired force/velocity values (v_d=0.05 m/s and v_d=0.1 m/s respectively) are given in Section V along the controller gains. The same gains as in simulation were used, and these have not been tuned specifically for the robot configuration or problem parameters, in order to show the generality of the approach. Figure 9 shows the robot performing the motion in the second case, with v_d=0.1 m/s.

The experimental results are shown in Figs. 10 and 11 for

Fig. 9: The robot performing the door opening experiment. v_d = 0.1 m/s. The images are taken at $t = 0\ s$, $t = 1.5\ s$, $t = 3.6\ s$, and $t = 5.7\ s$, respectively.

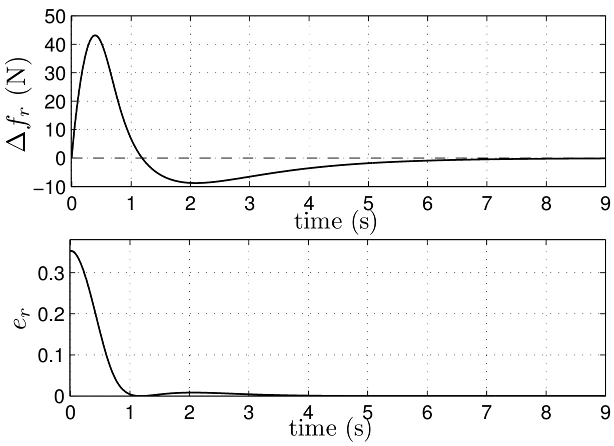

Fig. 7: Radial force error (upper plot) and estimation error (lower plot) responses - simulation with higher error in initial estimate $\hat{\mathbf{p}}_{o1}(0)$

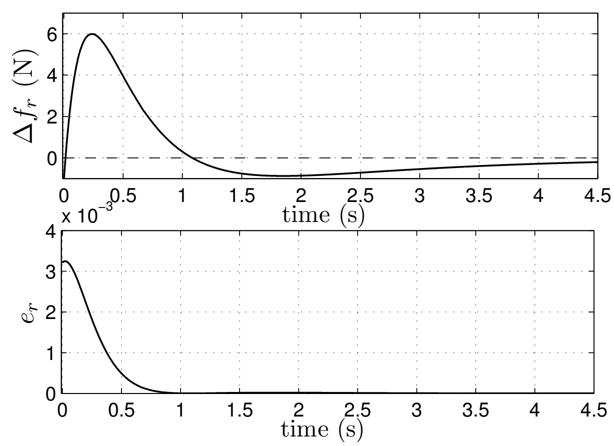

Fig. 8: Radial force error (upper plot) and estimation error (lower plot) responses - simulation with smaller error in initial estimate $\hat{\mathbf{p}}_{o2}(0)$

higher and lower uncertainty respectively; both force error and estimation error converge to zero in approximately 2 s. In the real experiment, we see larger initial force errors and slower convergence than in simulation. This is to be expected, as the real experiment differs from the simulation in several aspects. The real experiment includes measurement noise and process noise, as well as communication delays. Also, since feed-forward position control — not force control — was used when moving the manipulator into the initial position, the initial state contained force errors caused by small position offsets.

VII. 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.

The method consists of an adaptive controller which uses force and position/velocity measurements to deal with the door opening problem in the presence of incomplete knowledge of the door model. The controller uses an adaptive estimator of the door hinge's position to obtain adaptive estimates of the radial direction and to decompose the force and velocity control actions. The adaptive estimates of the radial direction are proven to converge to the actual radial vector, and the convergence of the radial force and the tangential velocity to the desired values has also been analytically proven. Simulation results along with an experiment on a real robot show that the estimates converge to the actual values even for large initial errors in the estimates, and the usefulness of the method has been demonstrated. Future work includes applying the proposed method to a wider range of domestic manipulation tasks with uncertainties in the kinematic constraints. Also, including humans in the loop and addressing human-robot collaborative manipulation will require extending the treatment to include dynamic uncertainties, and poses a challenging future problem.

Acknowledgment

This work has been supported by the Swedish Research Council (VR) and Swedish Foundation for Strategic Research (SSF), and the European Union FP7 project RoboHow.Cog (FP7-ICT-288533). The authors gratefully acknowledge the support.

References

[1] C. Cheah, C. Li, and J. Slotine, "Adaptive tracking control for robots with unknown kinematic and dynamic properties," *The International Journal of Robotics Research*, vol. 25, no. 3, pp. 283–296, 2006.

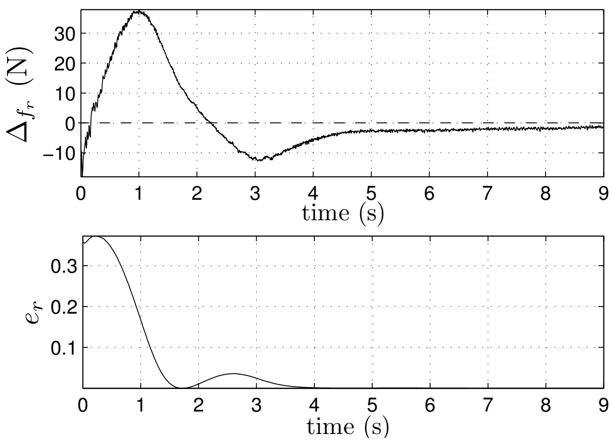

Fig. 10: Radial force (upper plot) and estimation error (lower plot) responses - robot experiment, higher error in initial estimate $\hat{\mathbf{p}}_{o1}(0)$

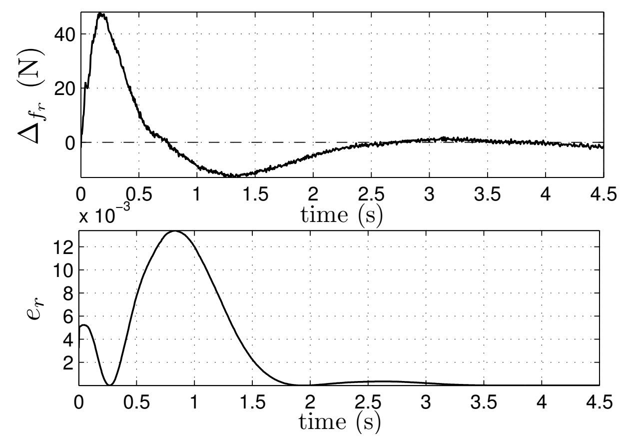

Fig. 11: Radial Force (Upper plot) and Estimation Error (Lower plot) Responses - robot experiment, smaller error in initial estimate $\hat{\mathbf{p}}_{o2}(0)$

[2] C. C. Cheah, S. Kawamura, and S. Arimoto, "Stability of hybrid position and force control for robotic kinematics and dynamics uncertainties," *Automatica*, vol. 39, pp. 847–855, 2003.

[3] T. Yoshikawa, *Foundations of Robotics*. Cambridge, MA:MIT Press, 1990.

[4] M. H. Raibert and J. J. Craig, "Hybrid position/force control of manipulators." *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, vol. 103, no. 2, pp. 126–133, 1981.

[5] Y. Karayiannidis and Z. Doulgeri, "Adaptive control of robot contact tasks with on-line learning of planar surfaces," *Automatica*, vol. 45, no. 10, pp. 2374–2382, 2009.

[6] K. Nagatani and S. Yuta, "An experiment on opening-door-behavior by an autonomous mobile robot with a manipulator," in *1995 IEEE/RSJ International Conference on Intelligent Robots and Systems 95*, vol. 2, aug 1995, pp. 45 –50.

[7] G. Niemeyer and J.-J. Slotine, "A simple strategy for opening an unknown door," in *1997 IEEE International Conference on Robotics and Automation*, vol. 2, apr 1997, pp. 1448 –1453 vol.2.

[8] E. Lutscher, M. Lawitzky, G. Cheng, and S. Hirche, "A control strategy for operating unknown constrained mechanisms," in *IEEE International Conference on Robotics and Automation*, may 2010, pp. 819 –824.

[9] D. Ma, H. Wang, and W. Chen, "Unknown constrained mechanisms operation based on dynamic hybrid compliance control," in *IEEE International Conference on Robotics and Biomimetics*, dec. 2011, pp. 2366 – 2371.

[10] L. Peterson, D. Austin, and D. Kragic, "High-level control of a mobile manipulator for door opening," in *2000 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, 2000, pp. 2333 –2338.

[11] A. Jain and C. Kemp, "Pulling open novel doors and drawers with equilibrium point control," in *9th IEEE-RAS International Conference on Humanoid Robots, Humanoids 2009*, dec. 2009, pp. 498 –505.

[12] ——, "Pulling open doors and drawers: Coordinating an omni-directional base and a compliant arm with equilibrium point control," in *Proceedings - IEEE International Conference on Robotics and Automation*, 2010, pp. 1807–1814.

[13] M. Prats, S. Wieland, T. Asfour, A. del Pobil, and R. Dillmann, "Compliant interaction in household environments by the Armar-III humanoid robot," in *8th IEEE-RAS International Conference on Humanoid Robots, Humanoids 2008*, dec. 2008, pp. 475 –480.

[14] H. Bruyninckx and J. De Schutter, "Specification of force-controlled actions in the "task frame formalism"-a synthesis," *IEEE Transactions on Robotics and Automation*, vol. 12, no. 4, pp. 581–589, Aug 1996.

[15] W. Chung, C. Rhee, Y. Shim, H. Lee, and S. Park, "Door-opening control of a service robot using the multifingered robot hand," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 3975–3984, oct. 2009.

[16] J. Sturm, C. Stachniss, and W. Burgard, "A probabilistic framework for learning kinematic models of articulated objects," *Journal of Artificial Intelligence Research*, vol. 41, pp. 477–526, 2011.

[17] J. Sturm, A. Jain, C. Stachniss, C. Kemp, and W. Burgard, "Operating articulated objects based on experience," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, oct. 2010, pp. 2739 –2744.

[18] A. Petrovskaya and A. Y. Ng, "Probabilistic mobile manipulation in dynamic environments with application to opening doors," in *Proc. of the 20th International Joint Conference on Artifical Intelligence*, Hydrabad, India, January 2007, pp. 2178–2184.

[19] A. Schmid, N. Gorges, D. Goger, and H. Worn, "Opening a door with a humanoid robot using multi-sensory tactile feedback," in *IEEE International Conference on Robotics and Automation (ICRA)*, may 2008, pp. 285 –291.

[20] C. Kessens, J. Rice, D. Smith, S. Biggs, and R. Garcia, "Utilizing compliance to manipulate doors with unmodeled constraints," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, oct. 2010, pp. 483 –489.

[21] C. Ott, B. Bäuml, C. Borst, and G. Hirzinger, "Employing cartesian impedance control for the opening of a door: A case study in mobile manipulation," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop on mobile manipulators: Basic techniques, new trends & applications*, 2005.

[22] D. Kim and G.-T. Kang, J.-H.and Park, "Door-opening behaviour by home service robot in a house," *International Journal of Robotics and Automation*, vol. 25, no. 4, pp. 271–284, 2010.

[23] H. Arisumi, J.-R. Chardonnet, and K. Yokoi, "Whole-body motion of a humanoid robot for passing through a door - opening a door by impulsive force -," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, oct. 2009, pp. 428 –434.

[24] P. A. Ioannou and J. Sun, *Robust Adaptive Control*. Upper Saddle River, NJ:Prentice Hall, 1996.