Adaptive Force/Velocity control for opening unknown doors [1]

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Abstract: The problem of door opening is fundamental for robots operating in domestic environments. Since these environments are generally unstructured, a robot must deal with several types of uncertainties associated with the dynamics and kinematics of a door to achieve successful opening. The present paper proposes a dynamic force/velocity controller which uses adaptive estimation of the radial direction based on adaptive estimates of the door hinge's position. The control action is decomposed into estimated radial and tangential directions, which are proved to converge to the corresponding actual values. The force controller uses reactive compensation of the tangential forces and regulates the radial force to a desired small value, while the velocity controller ensures that the robot's end-effector moves with a desired tangential velocity. The performance of the control scheme is demonstrated in simulation with a 2 DoF planar manipulator opening a door.

Keywords: door opening, force/velocity control, adaptive estimation

1. INTRODUCTION

Recent years have seen increased efforts to design robots able to perform tasks in domestic environments which are less structured as compared to industrial environments. A very common robotic manipulation task in domestic environments is door-opening. The task of opening a door — or a drawer — in a domestic environment includes several uncertainties 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 two main categories: (a) *dynamic uncertainties* which are related to the dynamic model of the door or the drawer: door's inertia, dynamics of the hinge mechanism etc., and (b) *kinematic uncertainties* which are 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 (Cheah et al., 2006) and force/motion control (Cheah et al., 2003). 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 (Raibert and Craig, 1981; Yoshikawa, 1990).

In this work, we consider a general robotic setup with a manipulator equipped with a wrist force/torque sensor, and we proposed 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 (Karayiannidis and Doulgeri, 2009) does not require accurate identification of the motion constraint at each step of the door opening procedure as opposed to the majority of the solutions to the door opening problem (Section 2). It uses adaptive estimates of the radial direction which are constructed by estimates of the door's hinge position and converge during the procedure to the actual dynamically changing radial direction. The paper is organised as follows: In Section 2 we make an overview of the related works to the door opening problem. Section 3 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 4 followed by the simulation example of Section 5. In Section 6 the final outcome of this work is briefly discussed.

2. RELATED WORKS

Pioneering works on the door opening problem are the papers of Nagatani and Yuta (1995) and Niemeyer and Slotine (1997). In Nagatani and Yuta (1995), experiments on door opening with an autonomous mobile manipulator were performed under the assumption of a known door model, using the synergistic motion of the manipulator and the mobile platform, while in Niemeyer and Slotine (1997), the estimation of the constraints describing the

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kinematics of the motion for the door opening problem is proposed. The aforementioned estimation technique is based on the observation that the ideal motive force is applied along the direction of the end-effector velocity. The authors have proposed estimation by spatial filtering to overcome chattering due to the noisy nature of velocity measurements, and the ill-defined normalization for slow motion of the end-effector. Such estimates, however, cause lag which may affect the stability of the system by giving rise to prohibitively high internal forces.The idea of using velocity measurements for estimating the direction of motion has inspired the recent work of Lutscher et al. (2010). The estimates are obtained by a simple moving average filter in the velocity domain, based on the integration of the tip velocity over a time window, and are used in an admittance controller; possibly ill-defined normalization and estimation lags are not dealt with. The estimation of the constraint using velocity measurements has also been used in Ma et al. (2011) where velocity and impedance control have been used along the tangent and the radial axis of the door opening trajectory respectively.

Apart from the velocity-based estimation of the constraint, several position-based estimation techniques have been proposed. In Peterson et al. (2000), the recorded motion of the end-effector is used in a least-squares approximation algorithm in order to estimate the center and the radius of the motion arc while lowest level compliant control annihilates the effects of the high forces exerted due to inaccurate trajectory planning. An optimization algorithm using position of the end-effector has also been used in Jain and Kemp (2009, 2010); the algorithm obtains estimates of the radius and the center of the door trajectory and subsequently estimates of the control directions. The velocity reference is composed by the estimated tangential velocity and force feedback (bang-bang control in Jain and Kemp (2009) and proportional control in Jain and Kemp (2010)) along the radial direction and feeds a low level control law to enable a viscoelastic behavior of the system around an equilibrium position. Prats et al. (2008) consider an inverse Jacobian velocity control law with feedback of the force error following the Task Space Formalism (Bruyninckx and De Schutter, 1996).The estimation is based on the end-effector trajectory to align the task frame with the vector which is tangent on the hand's trajectory. The algorithm has been tested on the Armar-III Humanoid Robot.

In some cases the estimation of the geometric configuration of the door is determined in a prior phase (off-line estimation). Chung et al. (2009) consider a multi-fingered hand equipped with tactile sensors grasping the handle and an estimation procedure which is based on observations of the fingertips position while slightly and slowly pulling and pushing the door by using position control. In a subsequent step, the desired trajectory obtained from the estimation procedure is used in a position controller. Sturm et al. (2011) proposes 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. The learning procedure requires a set of motion observations of the articulated object based on marker-based perception for high-dimensional complex articulated objects and marker-less pose estimation or end-effector position for simple articulated objects e.g. doors in a domestic setting. The estimates are generated in an off line-manner and can feed force/position cartesian controllers (Sturm et al., 2010). Probabilistic methods for mobile manipulation have been applied for opening doors with an a priori defined model for the door (Petrovskaya and Ng, 2007).

Another part of the literature on the door opening problem exploits advanced hardware capabilities to accomplish the manipulation task. Schmid et al. (2008) use combination of a tactile and a force-torque sensor in order to control the position and the orientation of the end-effector with respect to the handle and enable a backward pulling of the door to result successful door opening. Kessens et al. (2010) use a magnetic end-effector and a specific hardware configuration with clutches that disengage selected robot motors from the corresponding actuating joints and hence enable passive rotation of these joints. Ott et al. (2005) exploit the extensive abilities of the hardware, and used Cartesian impedance control of the DLR lightweight robot II in order to open a door with a two phase procedure (turn the handle/open the door and pass through door). Joint torques and their derivatives are used in order to implement the impedance controller; the joint torques are additionally used in order to estimate the contact force between the hand and the handle. Kim and Kang (2010) have designed a small, compact and inexpensive mobile manipulator HomBot; experiments using a force/torque sensor in order to define the desired trajectory have shown the robot's efficiency in a door opening task. Arisumi et al. (2009) propose door opening with an impulsive force exerted by the robot to a swinging door. A specific dynamic model for the door dynamics is considered in order to calculate the initial angular velocity which is required for a specific change of the door angle. The proposed technique is implemented using the humanoid robot HRP-2 developed by Kawada Industries Inc.

3. SYSTEM AND PROBLEM DESCRIPTION

3.1 Notation and Preliminaries

Let the generalized position of a moving frame $\{i\}$ with respect to a inertial frame $\{B\}$ (located usually at the robots base) be described by a position vector $\mathbf{p}_i \in \mathbb{R}^m$ and a rotation matrix $\mathbf{R}_i \in SO(m)$ where $m = 2$ or 3 for the planar and spatial case respectively. We consider also the following operators:

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

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

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 $z(t)$ over the time variable t i.e:

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

3.2 Kinematic model of robot door opening

We consider a setting of a robot manipulator with its end-effector has achieved a translationally fixed-grasp with the handle of a kinematic mechanism e.g. a door in a domestic environment. We use the term translationally fixed-grasp to denote that there is no relative translational velocity between the handle and the end-effector. Let $\{e\}$, $\{h\}$, $\{o\}$ denote the frames attached at the end-effector, the handle, and the hinge which in our case is the center of door-mechanism rotation. Notice that in case of a fixed grasp, the end-effector position and the position of the hinge obeys the following constraint:

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

By expressing $\mathbf{r}$ with respect to the hinge's 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 substituting ${}^o\dot{\mathbf{r}} = \dot{\mathbf{p}}_o = 0$ as well as $\dot{\mathbf{R}}_o = \omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \mathbf{R}_o$, with ω being the rotational velocity of the door, we get:

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

describing 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. Notice that the description of kinematics implies a planar problem definition.

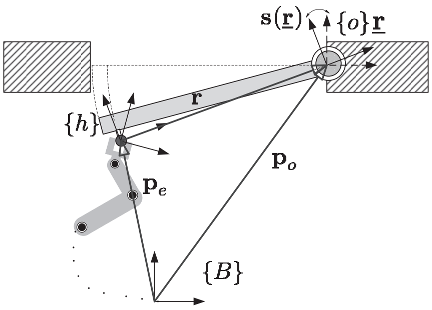

Fig. 1. Kinematics of the door opening

3.3 Robot dynamic and kinematic model

We consider a robotic manipulator with n revolute joints. Without loss of generality we consider a planar robotic manipulator which is adequate for performing the planar door opening (Subsection 3.2). Let $\mathbf{q}$, $\dot{\mathbf{q}}$, $\ddot{\mathbf{q}} \in \mathbb{R}^n$ be the joint position, velocity and acceleration vectors respectively. According to the first-order differential kinematics the joints velocities are related to the end effector velocities as follows:

$$\dot{\mathbf{q}} = \mathbf{J}^+ \dot{\mathbf{p}}_e \tag{9}$$

with $\mathbf{J}(\mathbf{q})^+ = \mathbf{J}(\mathbf{q})^\top \left[\mathbf{J}(\mathbf{q})\mathbf{J}(\mathbf{q})^\top\right]^{-1}$ being the pseudo-inverse of the manipulator Jacobian $\mathbf{J}(\mathbf{q}) \in \mathbb{R}^{2\times n}$; 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.

The dynamic model of the robot is described by a set of Euler-Lagrange equations as follows:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) + \mathbf{J}^\top\mathbf{F} = \mathbf{u} \tag{10}$$

where, $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{n\times n}$ is the positive definite inertia matrix i.e. $\mathbf{M}(\mathbf{q}) = \mathbf{M}^\top(\mathbf{q}) > 0, \quad \forall \mathbf{q} \in \mathbb{R}^n$, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} \in \mathbb{R}^n$ denotes the centripetal and Coriolis force vector, $\mathbf{g}(\mathbf{q}) \in \mathbb{R}^n$ is the gravity force vector, $\mathbf{F}$ is the total force between the manipulator and the kinematic mechanism, and $\mathbf{u}$ is the joint input torque vector.

3.4 Control Objective

The objective is to control the motion of the robot in order 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 the door". In applications which take place in a dynamic unstructured environments such as a domestic environment, it is very difficult to identify the position of the hinge as well as the associated dynamics. Hence, it is difficult to design a priori the desired velocity which obeys 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 $f_r = \underline{\mathbf{r}}^\top \mathbf{F}$ the control objective can be formulated as follows: $f_r \to f_{rd}$ and $\dot{\mathbf{p}}_e \to \mathbf{s}(\underline{\mathbf{r}})v_d$, without knowing 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". In case of a door rotating around a hinge a quadrocyclic orbit is adequate in order to halt the door opening procedure.

4. CONTROL DESIGN

In this section we introduce a control law to solve the problem defined in Section 3. In particular, we design force and velocity reference signals which in turn are used in the design of a dynamic controller which uses adaptive estimates of the door kinematics.

4.1 Force reference

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

$$\hat{\mathbf{r}}(t) = \hat{\mathbf{p}}_o(t) - \mathbf{p}_e \tag{11}$$

For notational convenience we will drop the argument of t from $\hat{\mathbf{r}}(t)$ and $\hat{\mathbf{p}}_o(t)$. We will use the estimated radial direction (11) considering that $\|\hat{\mathbf{r}}\| \neq 0, \ \forall t$ in order to define the estimated radial force which can be calculated using force measurements:

$$\hat{f}_r = \underline{\hat{\mathbf{r}}}^\top \mathbf{F} \tag{12}$$

Now we consider the following force reference for the force control part:

$$\mathbf{F}_{\text{ref}} = \mathbf{s}(\underline{\hat{\mathbf{r}}})\mathbf{s}(\underline{\hat{\mathbf{r}}})^\top \mathbf{F} + \underline{\hat{\mathbf{r}}} f_{rd} - \underline{\hat{\mathbf{r}}}(k_f \tilde{\hat{f}}_r + k_I \mathcal{I}(\tilde{\hat{f}}_r)) \tag{13}$$

Notice that the first term compensates for the forces acting on the estimated tangential direction, the second is the feedforward of the desired force along the estimated radial direction while the last one is a PI force control loop along the estimated radial direction with $\tilde{\hat{f}}_r = \hat{f}_r - f_{rd}$. The first term objective is to restrict the effect of the forces along the estimated tangent control direction in order to enable the velocity control loop to act along it and achieve the velocity control objective. Notice that the error between the current force $\mathbf{F}$ and the reference force $\mathbf{F}_{\text{ref}}$ denoted by $\tilde{\mathbf{F}} \triangleq \mathbf{F} - \mathbf{F}_{\text{ref}}$ lies entirely on the estimated radial direction:

$$\tilde{\mathbf{F}} = \underline{\hat{\mathbf{r}}}[(k_f+1)\tilde{\hat{f}}_r + k_I \mathcal{I}(\tilde{\hat{f}}_r)] \tag{14}$$

4.2 Reference Velocity and Acceleration

In the second step using again the estimated radial direction $\hat{\mathbf{r}}$ (11) we introduce a reference velocity vector $\mathbf{v}_{\text{ref}}$ for controlling the end-effector velocity:

$$\mathbf{v}_{\text{ref}} = \mathbf{s}(\underline{\hat{\mathbf{r}}})v_d - \alpha \underline{\hat{\mathbf{r}}} \mathcal{I}(\tilde{\hat{f}}_r) \tag{15}$$

with α being a positive control gain acting on the integral force feedback term $\mathcal{I}(\tilde{\hat{f}}_r)$. We design the force feedback part of the reference velocity using the integral of the estimated radial force error to avoid the differentiation of the force measurements when we calculate the reference acceleration. We can now introduce the velocity error:

$$\tilde{\mathbf{v}} \triangleq \mathbf{v} - \mathbf{v}_{\text{ref}} \tag{16}$$

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:

$$\mathbf{v} = \mathbf{s}(\underline{\hat{\mathbf{r}}})\mathbf{s}(\underline{\hat{\mathbf{r}}})^\top\mathbf{v} - \|\hat{\mathbf{r}}\|^{-1}\underline{\hat{\mathbf{r}}}\tilde{\mathbf{p}}_o^\top\mathbf{v} \tag{17}$$

Substituting (17) and (15) in (16) 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 $\mathbf{s}(\underline{\hat{\mathbf{r}}})$:

$$\tilde{\mathbf{v}} = \hat{\mathbf{R}}_o \begin{bmatrix} -\|\hat{\mathbf{r}}\|^{-1}\tilde{\mathbf{p}}_o^\top\mathbf{v} + \alpha\mathcal{I}(\tilde{\hat{f}}_r) \\ \mathbf{s}(\underline{\hat{\mathbf{r}}})^\top\tilde{\mathbf{v}} \end{bmatrix} \tag{18}$$

where $\hat{\mathbf{R}}_o \triangleq \begin{bmatrix}\underline{\hat{\mathbf{r}}} & \mathbf{s}(\underline{\hat{\mathbf{r}}})\end{bmatrix}$. By differentiating (15) with respect to time we get the reference acceleration $\mathbf{a}_{\text{ref}} \triangleq \dot{\mathbf{v}}_{\text{ref}}$:

$$\mathbf{a}_{\text{ref}} = \hat{\mathbf{R}}_o \begin{bmatrix} -\alpha\tilde{\hat{f}}_r - v_d\|\hat{\mathbf{r}}\|^{-1}\mathbf{s}(\underline{\hat{\mathbf{r}}})^\top(\dot{\hat{\mathbf{p}}}_o - \dot{\mathbf{p}}_e) \\ a_d - \alpha\mathcal{I}(\tilde{\hat{f}}_r)\|\hat{\mathbf{r}}\|^{-1}\mathbf{s}(\underline{\hat{\mathbf{r}}})^\top(\dot{\hat{\mathbf{p}}}_o - \dot{\mathbf{p}}_e) \end{bmatrix} \tag{19}$$

which is free of force derivatives.

4.3 Dynamic Controller Design

The force, velocity and acceleration reference which have been designed previously can be used in the following torque control law:

$$\mathbf{u} = \mathbf{J}^\top\mathbf{F}_{\text{ref}} - \mathbf{D}\left(\dot{\mathbf{q}} - \mathbf{v}^q_{\text{ref}}\right) + \mathbf{Y}(\mathbf{q}, \dot{\mathbf{q}}, \mathbf{v}^q_{\text{ref}}, \mathbf{a}^q_{\text{ref}}) \tag{20}$$

where $\mathbf{v}^q_{\text{ref}} = \mathbf{J}^+\mathbf{v}_{\text{ref}}$ is the reference velocity mapped in the joint space and $\mathbf{a}^q_{\text{ref}}$ is the derivative of $\mathbf{v}^q_{\text{ref}}$ with respect to time. The first part of the controller is the torque dedicated to force control, the second part is the velocity controller with $\mathbf{D}$ being a diagonal matrix with positive entries while the third part is the dynamic compensator which in case of known dynamic model and parameters is given by:

$$\mathbf{Y}(\mathbf{q}, \dot{\mathbf{q}}, \mathbf{v}^q_{\text{ref}}, \mathbf{a}^q_{\text{ref}}) = \mathbf{M}(\mathbf{q})\mathbf{a}^q_{\text{ref}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\mathbf{v}^q_{\text{ref}} + \mathbf{g}(\mathbf{q}) \tag{21}$$

In case of dynamic uncertainties the update law of Slotine and Li (1993) can be easily proved applicable.

Substituting the dynamic controller into the robot dynamic model (10) we get:

$$\mathbf{M}(\mathbf{q})\dot{\tilde{\mathbf{v}}}_q + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\tilde{\mathbf{v}}_q + \mathbf{D}\tilde{\mathbf{v}}_q = -\mathbf{J}^\top\tilde{\mathbf{F}} \tag{22}$$

with $\tilde{\mathbf{v}}_q = \dot{\mathbf{q}} - \mathbf{J}^+\mathbf{v}_{\text{ref}}$.
In turn, we calculate the rate of the system kinetic energy $E(\tilde{\mathbf{v}}_q) \triangleq \frac{1}{2}\tilde{\mathbf{v}}_q^\top\mathbf{M}(\mathbf{q})\tilde{\mathbf{v}}_q$:

$$\frac{d}{dt}E(\tilde{\mathbf{v}}_q) = -\tilde{\mathbf{v}}_q^\top\mathbf{D}\tilde{\mathbf{v}}_q - \tilde{\mathbf{v}}^\top\tilde{\mathbf{F}} \tag{23}$$

while the inner product $\tilde{\mathbf{v}}^\top\tilde{\mathbf{F}}$ is calculated as follows:

$$\begin{aligned}\tilde{\mathbf{v}}^\top\tilde{\mathbf{F}} = {} & \frac{d}{dt}\left[\frac{(k_f+1)\alpha}{2}\mathcal{I}(\tilde{\hat{f}}_r)^2\right] + k_I\alpha\mathcal{I}(\tilde{\hat{f}}_r)^2 \\ & - \|\hat{\mathbf{r}}\|^{-1}\left(\underline{\hat{\mathbf{r}}}^\top\tilde{\mathbf{F}}\right)\mathbf{v}^\top\tilde{\mathbf{p}}_o\end{aligned} \tag{24}$$

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

$$\dot{\hat{\mathbf{p}}}_o = \mathcal{P}\{\gamma\|\hat{\mathbf{r}}\|^{-1}[(k_f+1)\tilde{\hat{f}}_r + k_I\mathcal{I}(\tilde{\hat{f}}_r)]\mathbf{v}\} \tag{25}$$

Notice that $\mathcal{P}$ is an appropriately designed projection operator (Ioannou and Sun, 1996) with respect to a convex set of the estimates $\hat{\mathbf{p}}_o$ around $\mathbf{p}_o$ in which the following properties hold: i) $\|\hat{\mathbf{r}}\| \neq 0, \quad \forall t$, in order to enable the implementation of the reference force, velocity and acceleration and ii) $\mathbf{r}^\top\hat{\mathbf{r}} > 0$; which is required for the system's stability. It is clear that the update law (25) 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 Lyapunov-like function in order to prove the Theorem 1 of the Subsection 4.4:

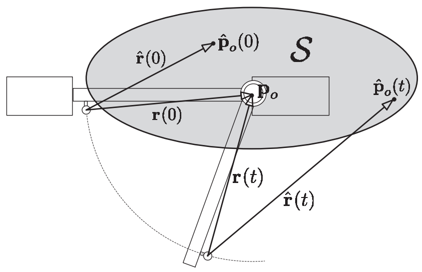

Fig. 2. Convex set $\mathcal{S}$ for the projection operator $\mathcal{P}$

$$\mathcal{V}\left(\mathcal{I}(\tilde{\hat{f}}_r), \tilde{\mathbf{p}}_o, \tilde{\mathbf{v}}_q\right) = E(\tilde{\mathbf{v}}_q) + \frac{(k_f+1)\alpha}{2}\mathcal{I}(\tilde{\hat{f}}_r)^2 + \frac{1}{2\gamma}\tilde{\mathbf{p}}_o^\top\tilde{\mathbf{p}}_o \tag{26}$$

which consists of the system kinetic energy owing to velocity error and the potential energy owing to estimation error and force integral action.

4.4 Stability Analysis

In this subsection we will prove the following theorem which implies that the proposed controller and the update law achieve the objectives defined in Section 3.4.

Theorem 1. If the input torque control $\mathbf{u}$ (20) with reference velocity (15), acceleration (19) and force (14), and the update law (25) applied to the system (10) the following objectives are achieved: $\underline{\hat{\mathbf{r}}} \to \underline{\mathbf{r}}$, $\mathbf{v} \to \mathbf{s}(\underline{\mathbf{r}})v_d$, $\mathcal{I}(f_r - f_{rd}) \to 0$ and $f_r \to f_{rd}$.

Proof. Differentiating $\mathcal{V}\left(\tilde{\mathbf{v}}_q, \mathcal{I}(\tilde{\hat{f}}_r), \tilde{\mathbf{p}}_o\right)$ we get (23) with (24) which in turn implies: $\dot{\mathcal{V}} = -\tilde{\mathbf{v}}_q^\top \mathbf{D}\tilde{\mathbf{v}}_q - k_I \alpha \mathcal{I}(\tilde{\hat{f}}_r)^2$. Notice that $\dot{\mathcal{V}}$ has extra negative terms when the estimates reach the bound of the convex set and the projection operator is applied and thus the stability properties of the system are not affected. Hence, $\mathcal{I}(\tilde{\hat{f}}_r)$, $\tilde{\mathbf{p}}_o$ and $\tilde{\mathbf{v}}_q$ are bounded, and given the assumption of non singular manipulator we conclude that $\mathbf{v}_{\text{ref}}^q$ and $\tilde{\mathbf{v}}_q$ are bounded. In Euler-Lagrange constrained systems the constraint forces, modeled by Lagrange multipliers, are functions of the system's state i.e. $\mathbf{q}$, $\dot{\mathbf{q}}$, $\mathcal{I}(\tilde{\hat{f}}_r)$, $\tilde{\mathbf{p}}_o$ and it can be proved that they are bounded for bounded arguments when the projection operator ensures that $\mathbf{r}^\top \hat{\mathbf{r}} > 0$. The boundedness of the aforementioned variables implies that $\ddot{\mathcal{V}}$ is bounded and thus Barbalat's Lemma implies $\dot{\mathcal{V}} \to 0$ and subsequently $\mathcal{I}(\tilde{\hat{f}}_r)$, $\tilde{\mathbf{v}}_q \to 0$. Given the boundedness of $\hat{f}_r$ and the convergence of $\mathcal{I}(\tilde{\hat{f}}_r)$ to zero we get $\hat{f}_r \to f_{rd}$. Substituting the convergence results in (9) 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); the latter implies $\hat{\underline{\mathbf{r}}} \to \underline{\mathbf{r}}$. Since the estimated direction of the constraint is identified we get: $\mathbf{v} \to \mathbf{s}(\underline{\mathbf{r}})v_d$, $\mathcal{I}(f_r - f_{rd}) \to 0$ and $f_r \to f_{rd}$. □

5. SIMULATION

We consider a 2 DoF robot manipulator (Fig. 3) which is 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 braked. In particular, we consider that the second and fourth joints (shoulder and elbow) are actuated (white cylinders in Fig. 3) and simulate the case of where this 2 DoF planar manipulator can open a door. The wrist of the manipulator is equipped with a 6 DoF force/torque sensor. Based on the dynamic and kinematic parameters of the 7 DoF arm we simulate the 2 DoF case by using the following parameters: masses $m_1 = 4$ kg, $m_2 = 7$ kg, link lengths $l_1 = 0.32$, $l_2 = 0.5746$ m and inertias $I_{z1} = 0.039$ kgm^2, $I_{z2} = 0.2012$ kgm^2. The initial angles of the robot arm are $q_1(0) = \pi/3$ rad, $q_2(0) = \pi/6$ rad. Regarding the kinematic parameters of the door, the center of rotation is $(0.91, 0.8517)$ m while the length of the door is 0.75 m. We consider that the door rotation is modeled by a rotational spring and damper with constants 20 Nm/rad and 2 Nms/rad. The motion along the radial direction is governed by a stiff viscoelastic model.

The controller objectives are $v_d = 0.5(1 - \exp(-8t))$ m/s (the exponential term removes unwanted initial transients) and $f_{rd} = 0.5$ N, and the controller gains are chosen as follows: $k_f = 20$, $k_I = 15$, $\mathbf{D} = \text{diag}[30 \;\; 30]$, $\alpha = 5$, $\gamma = 10$. The initial values of the rotation center is $\hat{\mathbf{p}}_o(0) = 0.75\mathbf{p}_o$. Simulation results are shown in Figs. 4–6. The initial, final and intermediate position of the robot are shown in Fig. 4. The force error $e_{f_r} = f_r - f_d$ as well as the estimation error variable $e_r = 1 - \hat{\underline{\mathbf{r}}}^\top \underline{\mathbf{r}}$ converge towards zero in less than 0.5 sec, as shown in Fig 5. Fig. 6 shows the joint torques which are required. Clearly, these torques can be provided by our experimental setup. The velocity errors during the whole procedure are of the order of 10^{-3}.

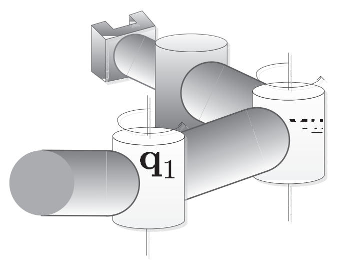

Fig. 3. Manipulator used in the simulation example

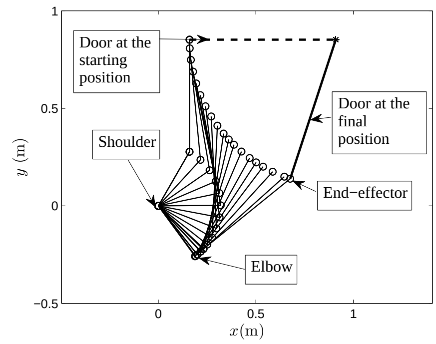

Fig. 4. Manipulator trace and door's initial(dashed bold line) and final(solid bold line) position

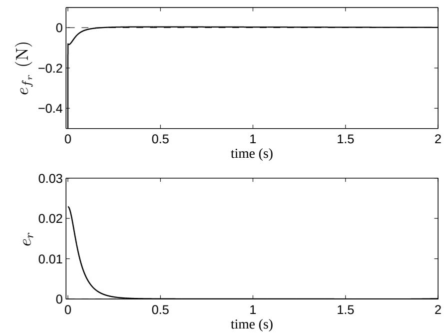

Fig. 5. Radial Force (Upper case) and Estimation Error (Lower case) Responses

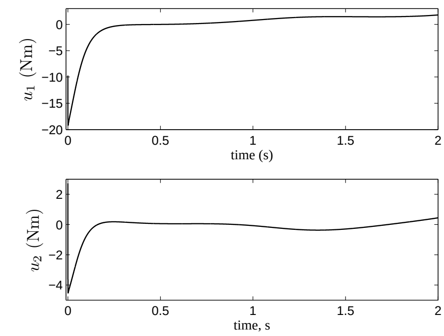

Fig. 6. Input torques responses before reduction

6. CONCLUSIONS

The door opening task is fundamental for robots made for household applications and its accomplishment is affected by the uncertainties usually arising when operating in unstructured domestic environments. This paper presents an adaptive dynamic force/velocity controller which uses force and position/velocity measurements in order to deal with the door opening problem in case of inaccurate knowledge of the door model. The dynamic controller uses an adaptive estimator of the door hinge's position in order to obtain adaptive estimates of the radial direction and to decompose the force and velocity control actions. The convergence of 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 been analytically proven. Simulation results are encouraging for the experimental validation of the proposed control scheme. Future work will additionally consider the demonstration of the door opening task in a domestic environment using the proposed technique.

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