Safe Strategy of Door Opening with Impedance Controlled Manipulator

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Tomasz Winiarski, Konrad Banachowicz, Maciej Stefańczyk

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Abstract:

Modern robotic systems are able to localize doors and its handle or knob, grasp the handle and open the door. Service robots need to open doors and drawers to autonomously operate in human environment. The mechanical properties of doors lead to incorporation of force and velocity constraints into the control law, to avoid the environment damage. In the article the impedance control law was expanded with these factors to achieve safe behavior of direct (explicit) position-force controller of KUKA LWR4+ robot that opens the door.

Keywords: *manipulation, impedance control, service robots*

1. Introduction

Recent years have resulted in a number of robotic manipulator structures [4, 9] mounted on mobile bases. The main scientific motivation for their creation was to build a hardware and software base for service robots operating in human environment. The research covers many issues related to human's everyday existence, such as working in the kitchen [11] or movement between rooms [7]. Both of these tasks require opening doors. Depending on the needs it can be a little door in the kitchen cabinet as well as a massive room door.

One of the first works in this matter considers door opening with a four degrees of freedom robotic manipulator [8]. The control law assumed that the manipulator exerts the desired general force set in its end–effector and system measures the position in the same coordinate system simultaneously. Taking into account the real trajectory of the end–effector, the control law parameters were chosen to generate the desired force that opens the door. Modern applications [4, 7, 9, 11] are much more comprehensive and take into account several aspects e.g.: location of the door, location of the handle or knob, grip generation and grip execution.

It is worth noting that the final outcome of the experiments presented so far related to door opening is comparable for various structures of the controllers. The work [4] presents robotic system that is controlled indirectly and general force readings came not from a six-axis sensor mounted in the manipulator wrist [15] but from sensors located in the gripper fingers phalanges. The control law applied in the direction of door opening was constructed by superposition of reference velocity and force error dependent correction velocity. Similarly, the robot described in [11] had indirect control structure, but in this case the force feeling was the fusion of measurements from a six-axis transducer placed in a manipulator wrist and force data from two finger gripper phalanges. PR2 Robot [7] control system does not measure the general force in manipulator wrist, but, on the basis of velocity command specified in the end–effector, computes the additional desired joints torque component for gravitationally balanced manipulator. System described in [9] utilized one of the first generations of directly controlled DLR-LWR robot, where the manipulator tip contact force computation is based on the torques measured in joints.

It is impossible to pass in silence over the fact that the opening of doors and drawers is also important in medical research. For example [13] studied opening a drawer by healthy people and patients with impaired cerebellum. It turns out that patients with dysfunction of the cerebellum have a different drawer opening strategy than healthy patients. Typically, fingers' clamping force on the handle is proportional to the pulling force to avoid handle slip. Similarly, healthy patients, shortly after the end of the movement is felt, more strongly tighten the handle so as not to lose their grip. Patients with cerebellar dysfunction also perform the whole tasks, but clench tighter in the first phase and sometimes lose the grip at the end of the motion, when the drawer reaches mechanical limitations. The forces exerted by the man and the speed of movement during similar operations are well known and tested. It results in the construction of doors and drawers, in particular, the durability of handles, hinges etc.

There are software drivers [10, 16] for robots performing service tasks, as well as methods of image acquisition and analysis [6] necessary to detect objects (e.g. handles or doors [3]). The latter task can also utilize fused information from depth sensors and color cameras [14], which can further improve detection results. So far, there was a lack of control law relating to some of the top-imposed limitations resulting from the door construction adapted for use by humans. The handle has a limited resistance, so it is important to limit the force with which the door is pulled. On the other hand, a rotational speed of the door can not be arbitrarily high, because the accumulated kinetic energy may be potentially dangerous in the case of encountering an obstacle (e.g., human being).

In this paper we present in a formal way a robotic system (sections 2, 3), where the control law allows both opening a door with previously unknown kinematic and dynamic models, taking into account the constraints derived from safety requirements. Moreover, the algorithm allows to open the door without prior knowledge of opening direction and without a known position of the hinge (the same algorithm opens both the „right" and „left" doors). In the experimental stage (section 4) the door and manipulator end–effector were rigidly connected to test the control law by exposing the system to the fast-growing strain. The paper finishes with conclusions in section 5.

2. Notation

The controller description is formal, hence it starts with the notation. Position of frame Q relative to U can be expressed as either homogeneous matrix ${}^U_Q\mathcal{T}$ or a column vector ${}^U_Q r$. In the latter case, the position in Cartesian coordinates is extended by a rotation angle around the axis represented by directional vector. The rotational angle and the directional vector (after multiplication) are aggregated into three coordinates. The operator $\mathcal{A}$ transforms this column vector into a homogeneous matrix, and $\mathcal{A}^{-1}$ defines an inverse transformation:

$$\mathcal{A}({}^U_Q r) = {}^U_Q\mathcal{T}, \ \ \mathcal{A}^{-1}({}^U_Q\mathcal{T}) = {}^U_Q r \tag{1}$$

Manipulator configuration can also be expressed with a joint position vector q.

The column vector ${}^U\dot{r} = \left[{}^U v^T, \ {}^U\omega^T\right]^T$ of size 6×1 represents generalized velocity of frame U moving relative to frame 0 expressed in U. It consists of linear velocity v and rotational velocity ω:

$${}^U({}^0_U\dot{r}) = {}^U\dot{r} \tag{2}$$

The column vector ${}^U\mathcal{F}$ of the same size 6×1 expresses generalized force and consists of a 3 element force vector and a torque vector of the same size. In this case, force is applied to the origin of the U coordinate frame, and is expressed in the same frame.

Some other useful transformations ${}^U_Q\xi_F$, ${}^U_Q\xi_V$ express generalized force or velocity in one coordinate frame relative to the other, fixed to it:

$${}^U\mathcal{F} = {}^U_Q\xi_F \ {}^Q\mathcal{F}, \ \ {}^U\dot{r} = {}^U_Q\xi_V \ {}^Q\dot{r} \tag{3}$$

In the case when free vectors are used (such as increments of position, orientation, velocity or force) there exists a need to express them relatively to the frame, with an orientation other than the one in which it was formerly expressed. In this case, one can use the ${}^C({}^U\dot{r})$ notation, in which generalized velocity of U frame in relation to 0 is expressed in frame C. For the transformation purpose the matrix ξ_*, [16] is used:

$${}^C({}^U\dot{r}) = {}^C_U\xi_* \ {}^U\dot{r} \tag{4}$$

In the notation below, d means desired value, and m is the measured value (if d or m are placed in the bottom right index). Similarly, the bottom right index with square brackets denotes a coordinate associated with a vector or a matrix. We employ the convention of using x, y and z to indicate the linear parts and ax, ay, az to indicate the rotational parts. In fig. 2 some selected coordinate frames are marked: 0 – base, W – wrist, E – end–effector (task frame).

3. Controller

Research has been done on the system based on KUKA LWR4+ robots. To present the system structure, the formal notation presented earlier in [6, 16] was used in a modified form. The graphical representation (fig. 1) was supplemented by a direct definition of the data exchanged within a single agent (between its control subsystem c, virtual effector e and real effector E).

The transition functions that generate outputs based on inputs and internal state are defined for particular components and indicate inputs and outputs for the described component: $[S]^t_x$ are inputs, $[S]^t_y$ are outputs, where S is the input/output value and t means discrete time index. Other variables (the internal state of the agent in particular) are written without the additional symbols.

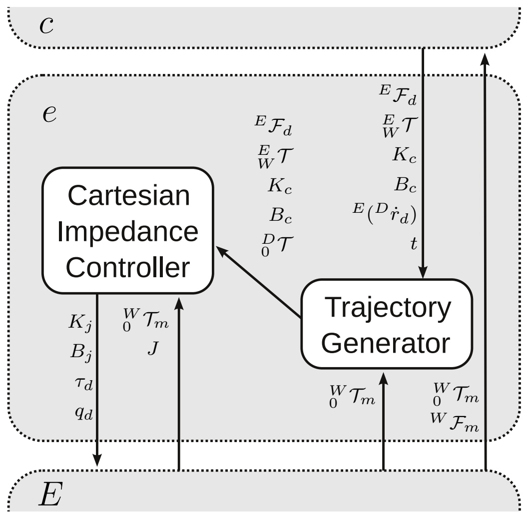

Fig. 1. The General structure of the designed single-agent controller: E ***- real effector,*** e ***- virtual effector,*** c ***- control subsystem. The two components presented are an impedance controller in task space and a trajectory generator for the impedance controller***

The detailed description of the system is presented in the following part of the article. In section 3.1 the real effector E (KUKA LWR4+ arm) is described with its industrial controller adapted to work with research systems. Later on, section 3.2 characterizes the developed research controller (virtual effector e) implemented in Orocos [2] system. This particular framework was chosen because of the availability of communication interface with KUKA and since its structure is universal (so it can be used in many works, going beyond the scope of this project). Further part of the paper (section 3.3) presents a strategy for opening a door, especially the developed control law embedded in control subsystem c. This is implemented in ROS [10] system, which was chosen due to the simplicity of the formulation of tasks using scripting

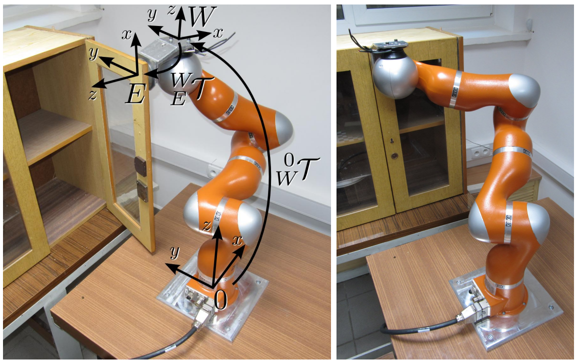

Fig. 2. KUKA LWR4+ arm with its coordinate frames and transformation between them, while executing the task of opening the door

languages and ready-to-use communication interface with Orocos system.

3.1. Industrial controller KUKA LWR4+

KUKA LWR4+ is a serial, lightweight (16kg), redundant robotic arm with seven degrees of freedom. Its construction (fig. 2) is similar to human arm in terms of size, lifting capacity and manipulation capabilities, which enables it to safely operate in human environment. Just like typical industrial robots, LWR4+ is equipped with motor encoders, but it also has sensors of joint position and torque. It can be controlled in joint space and external space, moreover the desired torques can be set in joints. KUKA provided the possibility to use LWR4+ with external controllers, particularly for research purposes. The controller is equipped with Fast Research Interface (FRI) [12] and uses Ethernet and UDP protocols, that allow to read robot's state and to send control commands.

In this work the impedance control law extended by desired torque is used for joints control (5), in the same way as parallel position-force controller in external space extends position regulators with the desired force [16].

$$\tau_c^{\kappa+1} = [K_j]_x^\iota([q_d]_x^\iota - q_m^\kappa) + [B_j]_x^\iota\,\dot{q}_m^\kappa + [\tau_d]_x^\iota + f(q_m^\iota, \dot{q}_m^\iota, \ddot{q}_m^\iota) \tag{5}$$

The control law above presents an external control loop of real effector ($\Delta\kappa \approx 0.3ms$), with desired torque τ_c^κ as output, which is then used as an input to the internal loop with torque controller running with the frequency of tens of kHz. Some variables are updated less frequently, typically with the period of $\Delta\iota = 1ms$. Input values for extended impedance controller are as follows: $[K_j]_x^\iota$ - stiffness, $[B_j]_x^\iota$ - damping, $[q_d]_x^\iota$ - desired position, $[\tau_d]_x^\iota$ - desired torque. The impedance controller needs the measured position q_m^κ and velocity $\dot{q}_m^\kappa$, and the dynamic model itself $f(q_m^\iota, \dot{q}_m^\iota, \ddot{q}_m^\iota)$. The structure of this regulator as well as its stability analysis were presented in [1].

3.2. KUKA LWR4+ research controller

The research controller (virtual effector e) consists of a number of Orocos components and an XML file that defines the connection between them. The individual components are responsible for communication within the entire system (including the use of FRI), internal diagnostics, as well as the implementation of the control law and trajectory generation. In this article, we focus on the latter two aspects.

Trajectory generator component Two key components used in the research controller are trajectory generator and impedance controller. Trajectory generator receives commands from the control subsystem c in discrete time instants t. On the other side, in each step ι of the real effector regulator E, trajectory generator has to prepare the command for impedance controller in external space (implemented in cartesian impedance controller component). For two consecutive time instants i, the interval is defined by $[t]_x^i$. In the initial phase, the desired position is copied from the measured position (6):

$$[{}^0_D\mathcal{T}]_y^{\iota_0} = {}^0_E\mathcal{T}_m^{\iota_0} \tag{6}$$

It is assumed that stiffness, damping, desired force and the geometric matrix of the tool are simply copied (7):

$$\begin{aligned} [K_c]_y^\iota = [K_c]_x^i, \qquad [B_c]_y^\iota = [B_c]_x^i, \\ [{}^E\mathcal{F}_d]_y^\iota = [{}^E\mathcal{F}_d]_x^i, \quad [{}^W_E\mathcal{T}]_y^\iota = [{}^W_E\mathcal{T}]_x^i \end{aligned} \tag{7}$$

Desired position $[{}^0_D\mathcal{T}]_y^\iota$ is computed based on desired velocity $[{}^E({}^D\dot{r}_d)]_x^i$ and previous control (8) according to the presented notation:

$$[{}^0_D\mathcal{T}]_y^\iota = {}^0_D\mathcal{T}^{(\iota-1)}\mathcal{A}\left(({}^D_E\xi_*^\iota\,[{}^E({}^D\dot{r}_d)]_x^i)\Delta\iota\right) \tag{8}$$

where matrix ${}^D_E\xi_*^\iota$ is computed in the way presented in [16] based on the matrix ${}^0_E\mathcal{T}_m^\iota$ from (9) and matrix ${}^0_D\mathcal{T}^{(\iota-1)}$.

$${}^0_E\mathcal{T}_m^\iota = [{}^0_W\mathcal{T}_m]_x^\iota\;[{}^W_E\mathcal{T}]_x^i \tag{9}$$

Impedance controller component Cartesian impedance controller component implements control law in task-related space. Column vector ${}^E_D r$ representing the length of the virtual spring (10) is computed taking into account the measured effector position ${}^0_E\mathcal{T}_m$ and the desired position ${}^0_D\mathcal{T}$.

$${}^E_D r^\iota = \mathcal{A}^{-1}({}^E_0\mathcal{T}_m^\iota\;[{}^0_D\mathcal{T}]_x^\iota) \tag{10}$$

Velocity ${}^E\dot{r}_m$ of the end–effector (11) is computed as:

$${}^E\dot{r}_m{}^\iota = \frac{\mathcal{A}^{-1}({}^E_0\mathcal{T}_m^{(\iota-1)}\;\;{}^0_E\mathcal{T}_m^\iota)}{\Delta\iota} \tag{11}$$

In the next step, the force ${}^E\mathcal{F}_c$ (12) is computed taking into account the spring length ${}^E_D r$, stiffness K_c, end-effector velocity ${}^E\dot{r}_m$, damping B_c and desired force ${}^E\mathcal{F}_d$. The force ${}^E\mathcal{F}_c$ is then transformed to the wrist frame (13).

$${}^E\mathcal{F}_c^\iota = [K_c]_x^\iota\;{}^E_D r^\iota + [B_c]_x^\iota\;{}^E\dot{r}_m^\iota + [{}^E\mathcal{F}_d]_x^\iota \tag{12}$$

$${}^W\mathcal{F}_c^\iota = {}^W_E\xi_F^\iota\;\;{}^E\mathcal{F}_c^\iota \tag{13}$$

where ${}^{W}_{E}\xi^{\iota}_{F}$ is based on $[{}^{W}_{E}\mathcal{T}]^{\iota}_{x}$. Finally, according to (14) joint torques vector τ_d is computed using Jacobian J.

$$[\tau_d]^{\iota}_{y} = [J^T]^{\iota}_{x} \quad {}^{W}\mathcal{F}^{\iota}_{c} \tag{14}$$

Stiffness and damping in the output of the component are set to zero $[K_j]^{\iota}_{y} = 0, \quad [B_j]^{\iota}_{y} = 0$, in order to command the joint level controller implemented in the real effector E (5) to work as a torque controller with compensation of both gravity and partially dynamics.

3.3. Door opening strategy

The control subsystem c includes outermost control loop running over the existing impedance controller implemented in the virtual effector e. This solution enables the incorporation of the door opening tasks in a larger application, consisting of multiple phases of motion, by adjusting the impedance characteristics for smooth transition from the movement without any contact with the environment to the contact phase, as it is possible in the pneumatic-powered robots [5].

The matrix $[{}^{W}_{E}\mathcal{T}]^{i}_{y}$ defines the pose of the manipulator tool. It depends on the mechanical construction of the end–effector and it is sent to the virtual effector. This matrix does not change during task execution. Similarly, the general set force $[{}^{E}\mathcal{F}_{d}]^{i}_{y}$ is always zero (i.e. all of the force and torque coordinates are zeros). In addition, the time $[t]^{i}_{y}$ of the single trajectory segment execution is sent. The other output parameters are defined in terms of the direction of motion in the task space. For directions x, y, ax, ay and az it is assumed that the manipulator should be compliant and move in order to eliminate tension, so the corresponding coordinates of the reference velocity, stiffness and damping (15) become zero.

$$\begin{aligned} [{}^{E}({}^{D}\dot{r}_{d[x,y,ax,ay,az]})]^{i}_{y} = 0, [K_{c[x,y,ax,ay,az]}]^{i}_{y} &= 0, \\ [B_{c[x,y,ax,ay,az]}]^{i}_{y} = 0 \end{aligned} \tag{15}$$

Towards the z axis control law is more elaborated, since it sets the velocity $[{}^{E}({}^{D}\dot{r}_{d[z]})]^{i}_{y}$ taking into account the measured position ${}^{0}_{E}\mathcal{T}^{i}_{m}$, the maximum speed $\dot{r}_{[z]}$, the measured force ${}^{E}\mathcal{F}^{i}_{m[z]}$ and two force thresholds: braking threshold $\mathcal{F}_0$ and motion termination threshold $\mathcal{F}_l$. The stiffness $[K_{c[z]}]^{i}_{y}$ and damping $[B_{c[z]}]^{i}_{y}$ are also defined. In each iteration, the controller first checks the completion of the predicate of the movement (16), (17). The predicate $P()$ returns $true$, if the force measured along the z axis of the task coordinate system exceeds the threshold value (door is blocked) or the dot product of the vector that is normal to the plane of the door at the beginning of the motion and the same vector at the current time instant is less than zero (the door turn angle exceeded 90 degrees).

$$N^{i} = [{}^{0}_{E}\mathcal{T}^{i}_{m[1][3]}, {}^{0}_{E}\mathcal{T}^{i}_{m[2][3]}, {}^{0}_{E}\mathcal{T}^{i}_{m[3][3]}] \tag{16}$$

$$P() = \begin{cases} true \text{ if } N^{i_0} \cdot N^{i} \leq 0 \ \vee \ [\mathcal{F}_{m[z]}]^{i}_{x} \geq \mathcal{F}_l \\ false \text{ otherwise} \end{cases} \tag{17}$$

If the predicate $P()$ is satisfied, the desired velocity $[{}^{E}({}^{D}\dot{r}_{d[z]})]^{i}_{y} = 0$. The robot motion is not commanded, but the manipulator end–effector is still impedance controlled in z axis. Otherwise, the velocity is determined according to the formula (18), so as to continuously slow down the robot, starting from the moment when the measured force values exceed the braking threshold $\mathcal{F}_0$.

$$[{}^{E}({}^{D}\dot{r}_{d[z]})]^{i}_{y} = \begin{cases} \dot{r}_{[z]} & \text{for } {}^{E}\mathcal{F}^{i}_{m[z]} \leq \mathcal{F}_0 \\ \dot{r}_{[z]}\left(1.0 - \frac{{}^{E}\mathcal{F}^{i}_{m[z]} - \mathcal{F}_0}{\mathcal{F}_l - \mathcal{F}_0}\right) & \text{for } \mathcal{F}_0 < {}^{E}\mathcal{F}^{i}_{m[z]} \leq \mathcal{F}_l \\ 0 & \text{for } {}^{E}\mathcal{F}^{i}_{m[z]} > \mathcal{F}_l \end{cases} \tag{18}$$

4. Experiments

The verification of the strategy of door opening consists of a series of experiments conducted on the test-bed presented in figure 2 and video[1]. The end–effector of the manipulator is rigidly fixed to the kitchen cabinet door. The experiments consisted of alternating closing and opening the door for different sets of controller parameters and limitations of the contact force. The control subsystem time period was constantly set to $[t]^{i}_{y} = 10ms$. In addition, door motion was disturbed by an obstacle in the form of heavy object standing in its way. Experiments have confirmed the correctness of the approach. For the further presentation the door opening case was chosen (fig. 3), where the following coefficients where chosen experimentally. The velocity limit was set as $\dot{r}_{[z]} = 0.04\frac{m}{s}$, the braking threshold $\mathcal{F}_0 = 10N$, the force limit $\mathcal{F}_l = 20N$, stiffness $[K_{c[z]}]^{i}_{y} = 4000\frac{N}{m}$ and damping $[B_{c[z]}]^{i}_{y} = 80\frac{Ns}{m}$.

Initially, the manipulator is slightly pushing the door along with the z axis of the current task coordinate system (it can be seen at the beginning of the forces graph), because the door opening was preceded by its closure, which ended up with a little stretch of impedance controller „spring" while the door was closed. Then, at the time instant a, the motion is ordered, the force along the z axis changes direction, and finally, after crossing the static friction of hinge, door begins to move as illustrated by the significant increase in speed along the z axis. The slight oscillation of the forces is visible while the manipulator is in motion. The force in the z direction, which moves the door, is clearly dominant over the values of the forces in the xy plane, where manipulator is compliant. The velocities in the xy plane are adequately

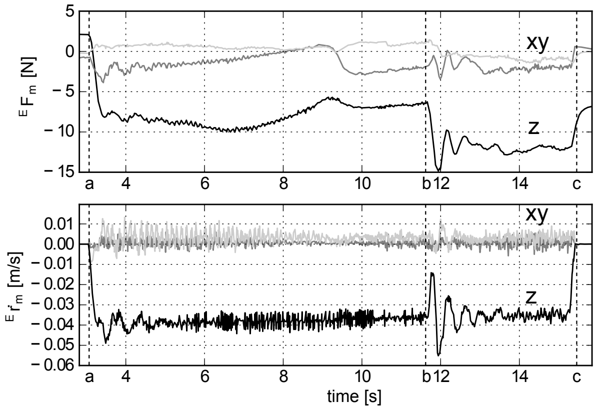

Fig. 3. The measured forces and velocities recorded during door opening

small. At the time instant b the door encounter an obstacle in the form of a box weighing about 3kg, which lies directly on the surface below the closet. The force along the z axis is growing rapidly, but in this case does not exceed the limit value. The speed drops dramatically and starts to oscillate, while the manipulator is pulling the doors with the obstacle. Later, after passing through the phase of the oscillation caused by the impedance controller behaviour, the measured velocity stabilizes slightly below the limit. At this stage, noticeable higher force is seen, with which the manipulator pushes the door against the resistance of the obstacle. Movement stops in time instant c, when the desired angle is reached. The force in the z direction is non-zero, as the impedance controller „spring" is stretched due to non-zero static friction inside the door hinge and static friction of the obstacle with the ground.

5. Conclusions

In the article a research oriented controller of KUKA LWR4+ robotic manipulator, that executes a safe door opening strategy, is presented in a formal way. This approach takes into account the limitations of both the speed of the door, from its handle point of view, and the contact force recorded in the end–effector of the manipulator. Experimental verification confirmed the correct behavior of the system. Future research will rely on the solution already worked out and will include the selection of the controller parameters (stiffness and damping) in the face of the experimentally identified constraints on the speed and strength of the contact. The work will begin with the study of the method of opening the door by a representative group of people, and then the implementation of a similar strategy for the robot.

Notes

[1] http://vimeo.com/rcprg/door-opening-stiff-contact

AUTHOR
Tomasz Winiarski, Konrad Banachowicz, Maciej Stefańczyk – Institute of Control and Computation Engineering, Warsaw University of Technology, e-mail: tmwiniarski@gmail.com, www: http://robotics.ia.pw.edu.pl.

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