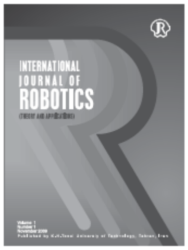

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Workspace Boundary Avoidance in Robot Teaching by Demonstration Using Fuzzy Impedance Control

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ABSTRACT

The present paper investigates an intuitive way of robot path planning, called robot teaching by demonstration. In this method, an operator holds the robot end-effector and moves it through a number of positions and orientations in order to teach it a desired task. The presented control architecture applies impedance control in such a way that the end-effector follows the operator's hand with desired dynamic properties. The operator often teaches the robot in the middle of the robot workspace. Then, this leads to lose a lot of accessible space. Workspace boundary is specified where a joint meets its end or a singularity happens. In this paper, a method is proposed to warn the operator before the end-effector faces the boundary of the workspace which results in using the robot workspace efficiently. It is achieved by means of two fuzzy controllers which smoothly increase the damping parameter of the impedance controller when the robot is closing on to a joint limit or a singularity. The increase of damping parameter dissipates the kinetic energy that is imposed by the operator to move the end-effector toward workspace boundary. The proposed method is applied on an industrial grade SCARA type robot. Experimental results show the effectiveness of the proposed method in a clear way

1. Introduction

Generally speaking, path planning for a robot is a complicated and tedious task. Offline robot path planning methods are more difficult in comparison with online ones. The offline methods including conventional and CAD-based methods need an accurate industrial robot. Therefore, the applied robot has to be calibrated carefully [1]. Also offline robot path planning methods need high level of robotics knowledge. This level of knowledge may not be accessible in small industries due to engineering resources limits [2, 3]. On the other hand, offline robot path planning methods often have to be set by a lot of trial and error. But these kinds of robot path planning methods are less expensive in comparison with online ones. In last two decades, using a teach pendant is going to be a common solution so as to program an industrial robot. It is more intuitive and needs less robotic expertise compared to offline robot path planning methods [4]. In addition, online demonstration is another important feature of teach pendants.

Recently, an online teaching method, called robot teaching by demonstration is presented. In this kind of robot path planning, applying operator's experience is achieved more than other methods. Herein, experience is the ability of a skilled operator to do a job such as welding or spray painting. Different kinds of control approaches can be applied to achieve the robot teaching by demonstration. Marcelo et al. [5] presented a robot teaching by demonstration method by applying impedance control. Pires et al. [2] utilized force control for robot path planning as a way of robot teaching by demonstration. Bascetta et al. [6] used admittance control for robot teaching by demonstration. Schraft and Meyer [3] applied teaching by demonstration method to program a gluing task. Virtual reality is added to the teaching by demonstration method in [7]. The state of the art of different types of easy robot path planning methods are presented in [8]. Robot teaching by demonstration methods must be very safe due to physical human-robot interaction. Safety standards are illustrated by international organization for standardization - ISO [9, 10]. A detailed review of the robot teaching by demonstration methods and relevant ISO standards are presented by Massa et al. [11]. Brunete et al. [12] added a tablet to the teaching by demonstration process in order to create a user-friendly visual software and reducing the required time to program tasks. Two types of the online path planning methods i.e. teach pendant and teaching by demonstration are compared by Rodamilans et al. [13]. They investigated these methods by evaluating analysis of variance in terms of three features: agility, accuracy, and learning. A joint space approach is presented by Winkler and Suchý [14] for manual guidance of industrial robots applying impedance control scheme. Teaching the position of the robot end-effector in constrained tasks are discussed in the literature [15-17]. Mohammadi and Akbarzadeh [18-20] defined and presented singularity avoidance methods during online manual guidance in order to prevent robot singularities. Operator feels a force resisting against end-effector movement towards robot singularities which originates from virtual force [18] or stiffness [19, 20] whereas in the proposed method, Cartesian damping parameter dissipates kinetic energy by slowing down the robot movement. As a result, operator finds out that the end-effector is close to singularity and tries to avoid it. In addition, the proposed method avoids robot joint-limits by increasing joints damping parameter. It must be highlighted that in the case of industrial robots, only the controller is responsible of avoiding robot singularities [21].

In this paper, an online method is presented in order to warn the operator about workspace boundary. The proposed method is applied on a SCARA robot in real-time. Section 2 describes robot teaching by demonstration method and the experimental equipment. Section 3 reviews fuzzy switching logic besides proposed singularity and joint limit methods. Experimental results including three experiments are presented in section 4 to evaluate the proposed singularity and joint limit methods. Finally, section 5 concludes the paper.

2. Robot Teaching by Demonstration

Robot teaching by demonstration method is an intuitive way of robot programing that can use operator's experience easily. Operator goes to robot workspace and holds the end-effector. Then operator moves the end-effector and robot follows his hand. This path is saved by controller and can be used to do a task alone. Teaching by demonstration already is applied in different industrial applications. It is utilized to program a 6-axis welding robot in shipyard industries [5, 22]. Deburring process of an aluminum wheel is done by this method in [6], considering some extra safety issues by applying admittance control. A piston insertion task is taught to the robot in [23] using impedance control concept. Spray painting is considered as a teaching task in [24] utilizing admittance control. A combination of a teaching by demonstration and force control is simulated in [25] to grind workpieces. In the present paper, experiments are carried out on a robot, called FUM SCARA in order to study the proposed workspace boundary avoidance method. This robot is shown in

Figure 1 during teaching by demonstration process. The FUM SCARA robot is a 4-axis SCARA type robot, designed, constructed, and controlled by a team of students in the Ferdowsi University of Mashhad. Detailed information of the FUM SCARA robot including design procedure and main features are described in [26-28].

Figure 1. The FUM SCARA robot during teaching by demonstration

In this paper, contact force is measured in 2 axes by a force sensor, installed in the robot end-effector. So the operator interacts with the robot in xy plane because contact force can be measured along x and y axes. It obliges us to use the FUM SCARA robot as a 2 degrees of freedom (DOF) serial planar robot. Schematic view of the FUM SCARA robot hardware configuration is depicted in

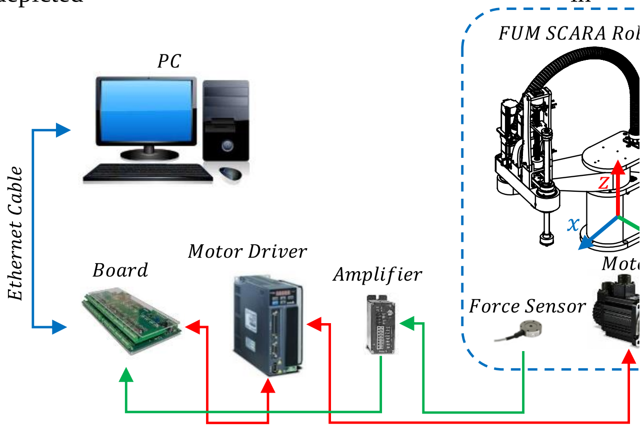


Figure 2. PC is communicating with robot through a custom board. Motor signal command and feedback besides force sensor feedback are shown in the figure by red and green arrows. The operator interacts with equivalent system instead of the robot. Since impedance control concept is applied to model the physical human-robot interaction. The impedance control equation for teaching by demonstration is defined by Marcelo et al. [5] as follows.

$$M_d\ddot{\vec{X}}_d + B_d\dot{\vec{X}}_d = \vec{F}_e \qquad (1)$$

M_d, B_d, $\ddot{\vec{X}}_d$, $\dot{\vec{X}}_d$ are desired mass, damping, acceleration, and velocity, respectively. $\vec{F}_e$ includes external forces and moments exerted by the operator. M_d and B_d are diagonal matrices that set by trial and error. In fact, operator is interacting with a system that has only mass and damping as depicted in

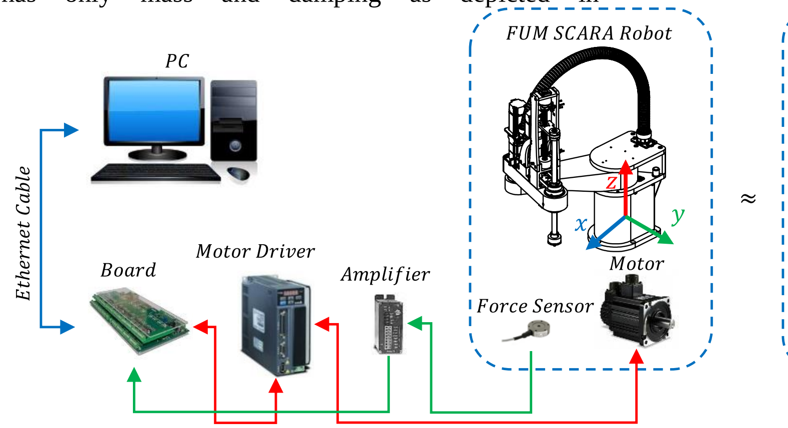


Figure 2. $\vec{F}_e$ is input of the equation and $\vec{X}_d$ is concluded as output. Equation (1) is rearranged as (2) so that the desired position can be calculated simply.

$$\vec{X}_d = \iint \frac{\vec{F}_e - B_d\dot{\vec{X}}_d}{M_d} \qquad (2)$$

$\vec{X}_d$ is assumed to be the desired trajectory. In fact, desired trajectory is generated online and the end-effector follows operator's hand. Impedance control equation acts like a filter to convert $\vec{F}_e$ to $\vec{X}_d$ by using M_d and B_d. Therefore, M_d and B_d determine the dynamic properties of the end-effector in the presence of $\vec{F}_e$.

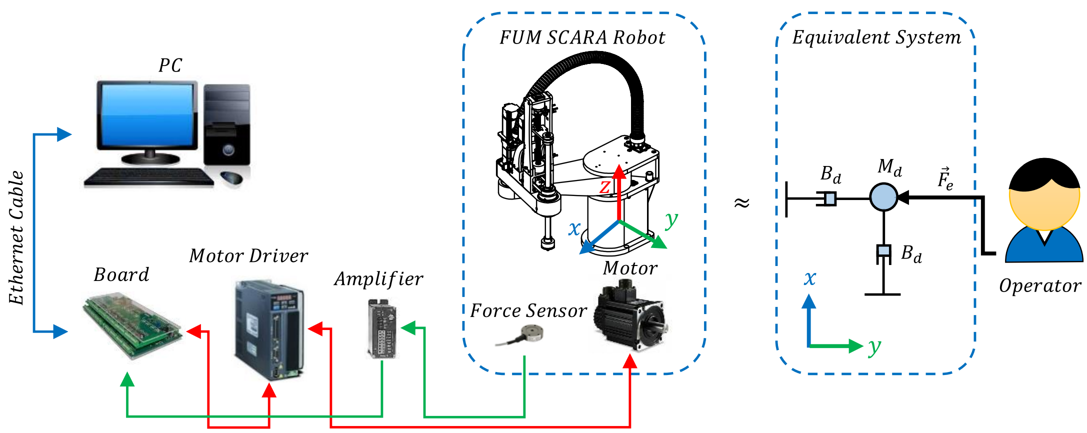


Figure 2. The FUM SCARA robot architecture and robot equivalent system using impedance control concept

3. Proposed Workspace Boundary Avoidance

This section illustrates the proposed method. First, fuzzy switching method is briefly described in section 3.1. Then, singularity and joint limits are expressed as two main parts of the workspace boundary avoidance method in sections 3.2 and 3.3, respectively. By considering singularity and joints ends of a robot, workspace boundary can be easily determined. Thus, avoiding the workspace boundary is possible by finding a proper strategy. Herein, damping parameter of the impedance control is increased by the proposed method. Indeed, as the end-effector is getting close to a singularity or a joint limit, the damping is increased. It leads to moving the end-effector more difficult than before.

The damping parameter varies near workspace boundary, called critical zone. In fact, the increase of the damping parameter is similar to the increase of the robot workspace density. From this point of view, effects of the proposed method are further understandable. Authors believe using this viewpoint, the performance of the method can be described for an operator with even no robotics knowledge straightforwardly.

Singularity and joints ends of the FUM SCARA robot are depicted in Figure 3. As shown in the figure, the workspace boundary can be specified by singularity and joints ends. From this perspective, the proposed method can be developed for robots with more combined DOFs e.g. 6-axis serial robots.

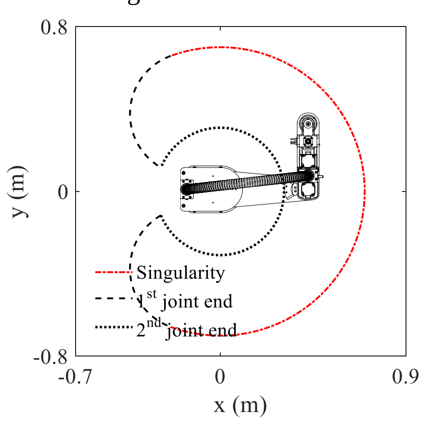


Figure 3. The FUM SCARA robot workspace boundary is defined by singularity and joints ends

3.1. Fuzzy Switching Logic

Since its introduction by Zadeh in 1965 [29], fuzzy logic has been the most powerful method to deal with ill-defined, imprecise and uncertain models. Fuzzy controllers for such models can be designed on the basis of expert knowledge, learning from a number of examples or both [30]. The expert knowledge, in the framework of fuzzy logic, is expressed in terms of fuzzy rules [31]. Each fuzzy rule is composed of an antecedent part, which addresses a particular situation or system state, and a consequent part which determines the appropriate action to be taken in that situation. The fuzzy logic controller (FLC) then continuously computes the matching degree of the current systems states with the existing rules and infers a fuzzy recommended action. In this interpretation, an FLC can be seen as a soft switch which smoothly alternates between different system states. In this paper, two single input-single output Takagi-Sugeno (T-S) fuzzy systems are used for singularity and joint limit avoidance control, separately. The ith rule in a T-S fuzzy system is in the form of (3).

$$\text{If } x \text{ is } A_i \text{ then } y \text{ is } b_i. \tag{3}$$

where x is the input variable taking values from a universe of discourse X, A_i is the ith fuzzy subset of X and $b_i \in R$ is the crisp consequent parameter of the ith rule. The output of the system, y, is then produced by (4).

$$y = \frac{\sum_{i=1}^{N} \mu_{A_i}(x) b_i}{\sum_{i=1}^{N} \mu_{A_i}(x)} \tag{4}$$

where N is the number of rules and $\mu_{A_i}(x)$ is the membership function corresponding to A_i. The first FLC produces the required Cartesian damping to avoid singularities and the second one produces the joint damping in order to avoid joint limits. The applied membership functions are completely illustrated in appendix. The proposed method is investigated in the following two sections in detail.

3.2. Singularity Limit

Fuzzy switching system for singularity limit method causes an increase in damping parameter of the impedance control in order to prevent singularity. The input and output of the presented fuzzy system is dexterity and Cartesian damping shown by κ and B_c, respectively. The dexterity index is a non-dimensional number that can be applied as a singularity detection criterion. It is calculated as follows,

$$\kappa = \sqrt{\frac{\lambda_{min}}{\lambda_{max}}} \tag{5}$$

where λ is the Eigen value of the robot Jacobian matrix. The dexterity index of the FUM SCARA robot is depicted in Figure 4. Singularity happens while the κ vanishes. Therefore, singularity of the FUM SCARA robot is located where the Figure 4 is darker.

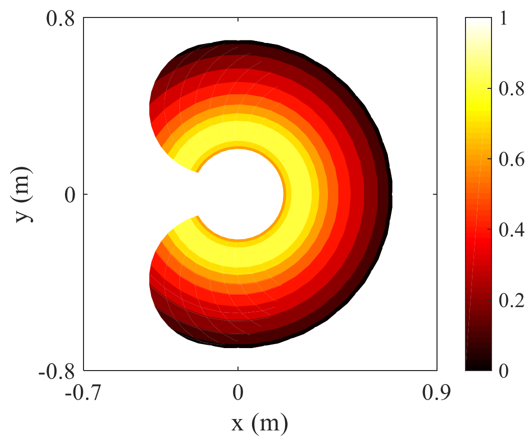


Figure 4. Dexterity index in the FUM SCARA robot workspace

Rules and number of membership functions are selected arbitrarily. Herein, two rules are assumed for each axis as follows.

- If "dexterity is low" then "damping is high".
- If "dexterity is high" then "damping is low".

The membership function is shown in Figure 5. The output of the proposed membership function is between zero and one and is multiplied by a gain.

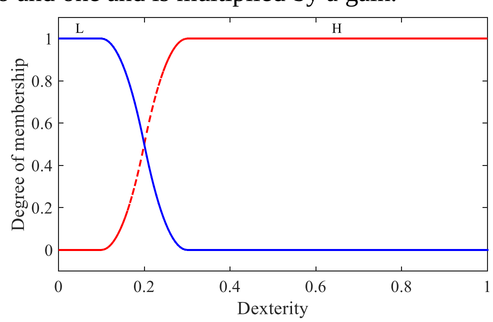


Figure 5. Input membership function of the singularity limit method (L: low – H: high)

Block-diagram of the proposed singularity limit method is shown in Figure 6. The fuzzy system output is multiplied by a factor of 250, set by trial and error. B_c is a diagonal matrix that is added to the B_d. Diagonal arrays of B_c are generated along all coordinate axes while dexterity is in critical zone defined by fuzzy upper and lower bands.

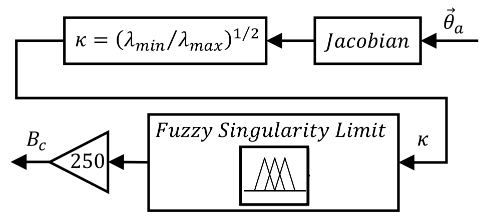


Figure 6. Block-diagram of the proposed fuzzy singularity limit method

3.3. Joint Limit

The second fuzzy switching system generates extra damping while a joint exceeds its limit. The damping is increased according to each joint angular position. Joints angular range are shown in Table 1 for the FUM SCARA robot [28].

Table 1. Joints range of the FUM SCARA robot

Axis	Joints range
1	$\pm 110°$
2	$\pm 130°$
3	∞
4	$0\ to\ 19\ cm$

The output of the presented fuzzy system is joint damping, shown by B_j. Rules and number of membership functions are selected arbitrarily same as the last section. Herein, three rules are assumed for each joint as follows.

- If "θ is negative low" then "damping is high".
- If "θ is positive high" then "damping is high".
- If "θ is medium" then "damping is low".

Membership functions are shown for the 1st and 2nd joints of the FUM SCARA robot in Figure 7 and Figure 8, respectively. Extra damping is generated while 1st and 2nd joints exceed $\pm 90°$ and $\pm 105°$, called critical zone.

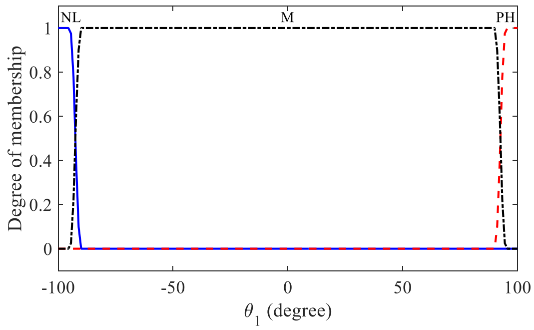


Figure 7. Input membership function of the 1st joint limit method (NL: negative low - M: medium - PH: positive high)

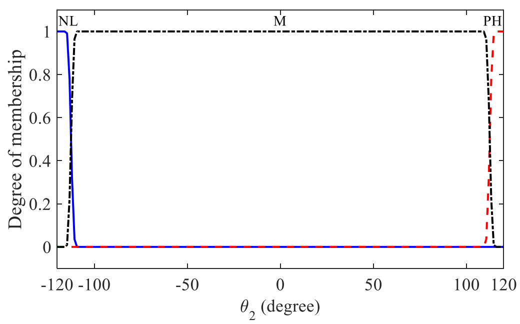


Figure 8. Input membership function of the 2nd joint limit method (NL: negative low - M: medium - PH: positive high)

Block-diagram of the proposed fuzzy joint limit method is simple and is depicted in Figure 9. The output of the fuzzy system is multiplied by a factor of 25, arbitrarily set to amplify the signal. B_j is a diagonal matrix that shows joint damping values.

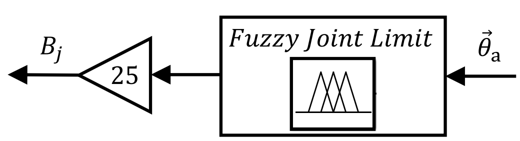


Figure 9. Block-diagram of the proposed fuzzy joint limit method

B_j must be mapped from joint space to Cartesian space using jacobian as following transformation, $J^{-t}B_jJ^{-1}$ [32, 33]. Therefore, by considering B_c and B_j, (2) has to be arranged again as shown by (6).

$$\vec{X}_d = \iint \frac{\vec{F}_e - \left(B_d + J^{-t}B_jJ^{-1} + B_c\right)\dot{\vec{X}}_d}{M_d} \qquad (6)$$

The proposed method is shown in Figure 10 including singularity and joint limits. Desired position, $\vec{X}_d$, is constant while there is not external forces and moments. It means the robot desired positions are constant values until $\vec{F}_e$ is exerted to the robot end-effector. On the other hand, joint and Cartesian damping, B_j and B_c, are generated while joint range and dexterity enters their critical zones, respectively. Then, fuzzy controller switches based on its input value and damping parameter of the impedance control equation is increased appropriately. Two fuzzy part including fuzzy joint limit and fuzzy singularity limit are highlighted by blue and red colors in Figure 10, respectively. As the figure shows, added blocks act as a supervisory controller to generate $\vec{X}_d$. Herein, it is assumed that stability of the industrial controller is guaranteed by the producer.

Adding extra damping to the impedance control equation because of the singularity and joint limit methods are shown schematically in Figure 11. Using this method, operator is dealing with higher damping before facing a joint end or singularity. So it leads to robot workspace boundary avoidance.

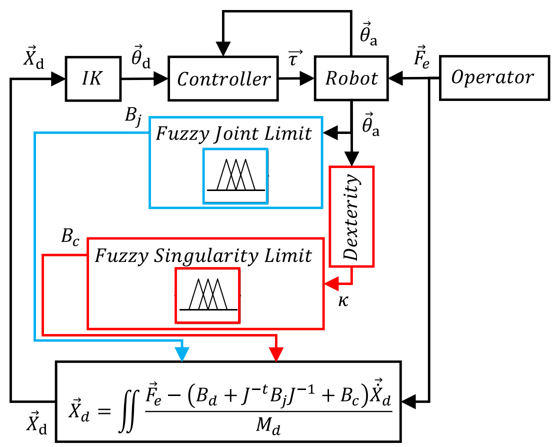


Figure 10. Block-diagram of the proposed method

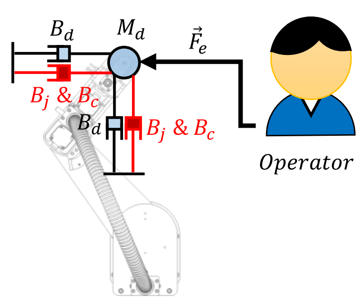


Figure 11. Schematic human- robot physical interaction known as PHRI

4. Experimental Results

Desired impedance parameters are selected as shown in Table 2. These values are arbitrarily chosen considering operator's convenience. The operator interacts with the robot in xy plane and consequently impedance control is defined along x and y axes.

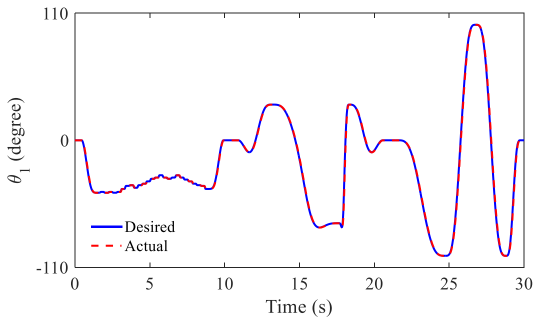
Desired impedance parameters are fixed throughout the experiments.

Table 2. Impedance control parameters

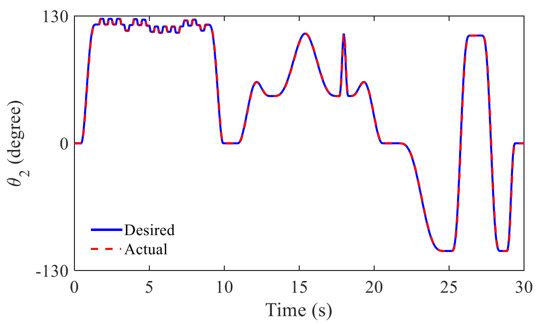
Axis	Mass (kg)	Damping (N.s/m)	Stiffness (N/m)
x	25	125	0
y	25	125	0

4.1. Position Control

As can be seen in Figure 10, controller has an inevitable role in the quality of the generated path. Because tracking of the desired trajectory with low error leads to better operator's hand following by the end-effector. In this section, position controller is examined by testing a desired trajectory generated in offline. This trajectory includes slow and fast motions in whole workspace. The desired trajectory is properly tracked by the controller as vividly shown in Figure 12-a and b. Therefore, it is expected that good tracking is achieved in online applications, regarding the controller results.



(a)



(b)

Figure 12. Desired and actual joints angular position of the FUM SCARA robot, (a) 1st joint (b) 2nd joint

4.2. Proposed Singularity Limit Method

This method tries to avoid robot singular configurations in online. The operator exerts force to the robot end-effector, measured by the sensor and shown in Figure 13. Generated position by the impedance control in joint and Cartesian space is depicted in Figure 14 and Figure 15, respectively. Joints angular position are far from their own critical zones. Therefore, no joint damping is generated during the experiment. Dexterity and Cartesian damping are depicted in Figure 16 and Figure 17, successively. As can be clearly seen, dexterity enters the critical zone, defined by fuzzy upper and lower bands, 4 times and as a result Cartesian damping is generated 4 times.

Singularity location and generated desired path are depicted in the workspace of the FUM SCARA robot in Figure 18. The proposed singularity limit is examined in different directions as shown in the Figure 18. Where the proposed method generates Cartesian damping are shown by numbers in Figure 16 to Figure 18. Operator has to change or stop the path while he feels the increase of the Cartesian damping. Decision on changing or stopping the process completely depends on the operator's experience and the task.

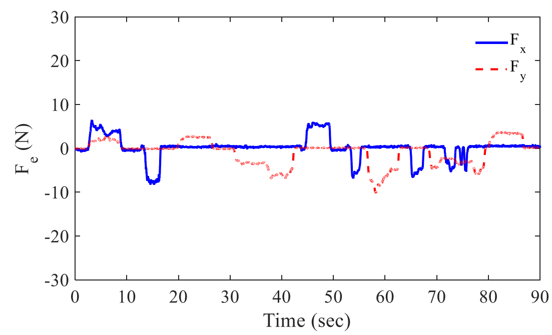


Figure 13. External force exerted by the operator

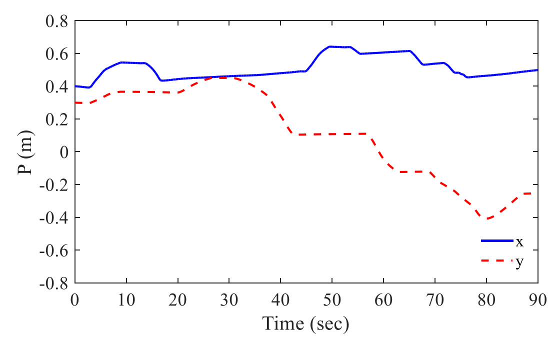
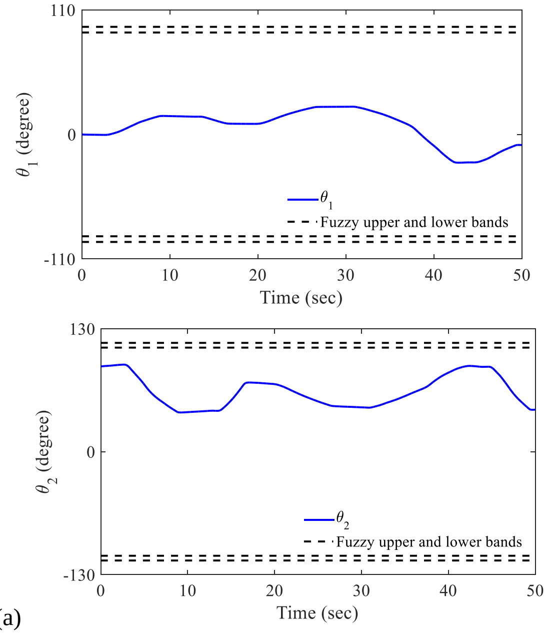


Figure 14. End-effector position of the robot



(a)

(b)

Figure 15. Joints angular position of the FUM SCARA robot, (a) 1st joint (b) 2nd joint

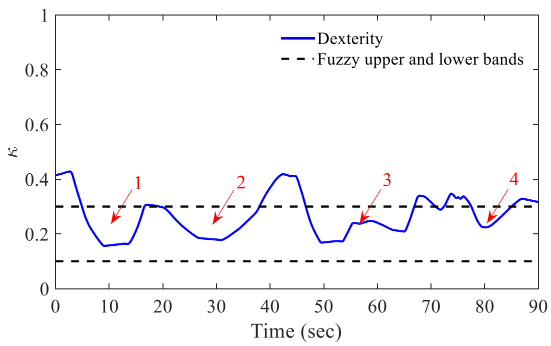


Figure 16. Dexterity of the FUM SCARA robot calculated in online

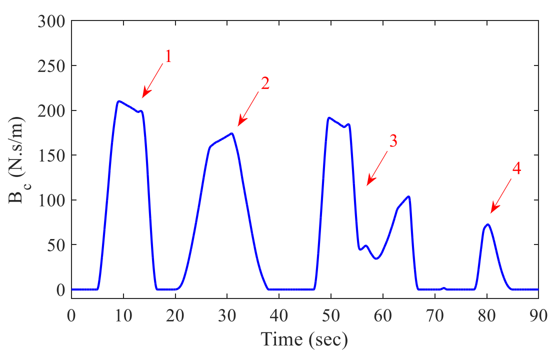


Figure 17. Cartesian damping generated by the proposed singularity limit method

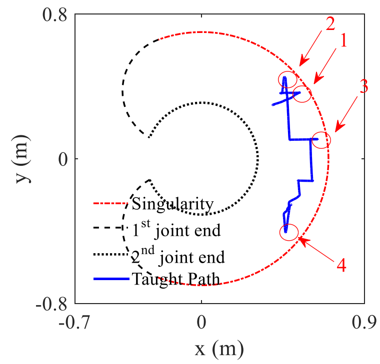


Figure 18. Taught path in the FUM SCARA robot workspace

4.3. Proposed Joint Limit Method

This method is responsible of avoiding joints ends. The end-effector is moved by the operator towards joints ends in order to test the proposed joint limit method. External force, end-effector position, joints angular position, dexterity, and joint damping are shown in Figure 19 to Figure 23, respectively. Dexterity is far from critical zone and as a result there is no Cartesian damping during this experiment. The proposed method generates joint damping for each joint 1 time (Figure 23) because first and second joints enter their critical zones only 1 time as shown by Figure 21-a and b. Both increases of the joint damping are shown by numbers in Figure 23. The first and second joints angular positions while entering the critical zone are highlighted by numbers.

Generated desired path is shown in the FUM SCARA robot workspace in Figure 24. Obviously, first and second joints limits happen near first and second joints ends, respectively. They are shown by numbers in the robot workspace. Increase of the joint damping causes a physical warning to the operator to stop or change the path. Then, operator decides what to do based on his experience and the task.

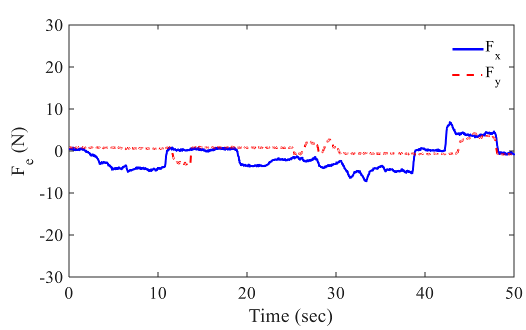


Figure 19. External force exerted by the operator

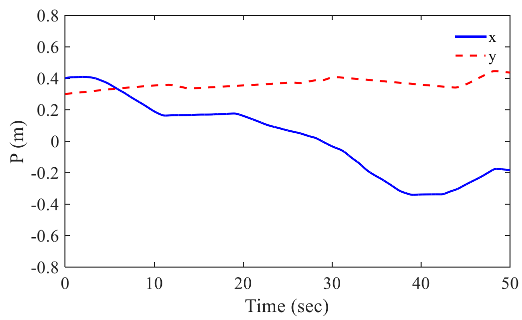
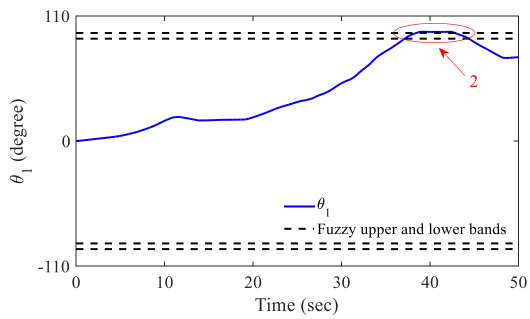
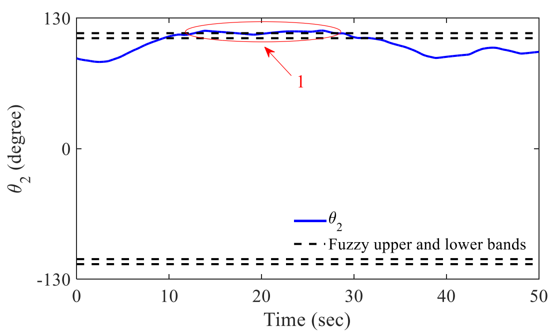


Figure 20. Position of the FUM SCARA robot end-effector



(a)



(b)

Figure 21. Joints angular position of the FUM SCARA robot, (a) 1st joint (b) 2nd joint

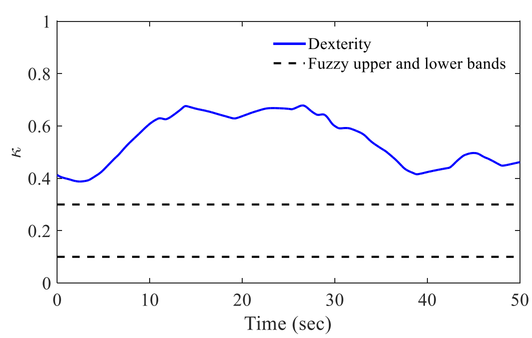


Figure 22. Dexterity of the FUM SCARA robot calculated in online

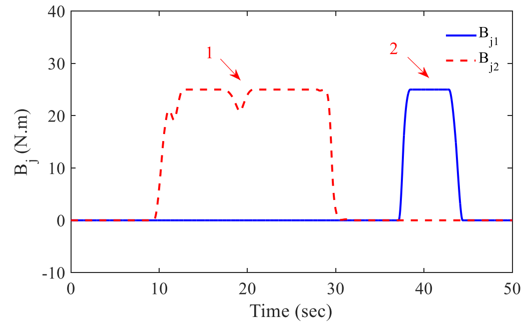


Figure 23. Joint damping generated by the proposed joint limit method

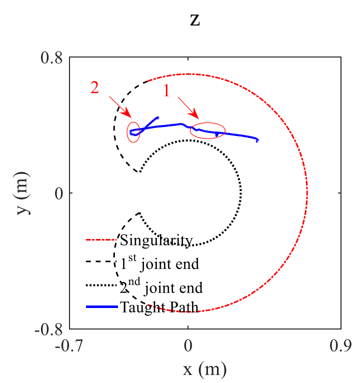


Figure 24. Taught path in the FUM SCARA robot workspace

5. Conclusions

Robot teaching by demonstration method as a fast, intuitive, and efficient way of robot path planning is investigated in this paper. In the proposed method, impedance control concept is considered as a tool to model the interaction between the operator and robot. In order to use the maximum volume of the robot workspace, the proposed method can be applied since it warns the operator about workspace boundary. Therefore, it significantly increases the usable space compared to conventional methods. This viable capability, additionally, minimizes the required knowledge of the robot workspace and its singularities hence simplifies the path planning process for the operator. To this end, damping parameter of the impedance control is increased by fuzzy switching control strategy. This causes reducing the velocity of the end-effector and prevents the robot motion in prohibited directions. Three experiments are applied on the FUM SCARA robot as an industrial grade robot. The proposed method is evaluated by practical experiments and the obtained results clarify its effectiveness.

6. References

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Appendix

In this section, the applied membership functions are discussed. They are named Z-shape, S-shape, and π-shape in the literature and are presented by (7) to (9), respectively. The π-shape one is a combination of S-shape and Z-shape membership functions. The parameters a, b, c, and d determine the extremes of the sloped span of the curve.

$$f(x,a,b) = \begin{cases} 1 & x \le a \\ 1-2\left(\frac{x-a}{b-a}\right)^2 & a \le x \le \frac{a+b}{2} \\ 2\left(\frac{x-b}{b-a}\right)^2 & \frac{a+b}{2} \le x \le b \\ 0 & x \ge b \end{cases} \quad \text{(A1)}$$

$$f(x,a,b) = \begin{cases} 0 & x \le a \\ 2\left(\frac{x-a}{b-a}\right)^2 & a \le x \le \frac{a+b}{2} \\ 1-2\left(\frac{x-b}{b-a}\right)^2 & \frac{a+b}{2} \le x \le b \\ 1 & x \ge b \end{cases} \quad \text{(A2)}$$

$$f(x,a,b,c,d) = \begin{cases} 0 & x \le a \\ 2\left(\frac{x-a}{b-a}\right)^2 & a \le x \le \frac{a+b}{2} \\ 1-2\left(\frac{x-b}{b-a}\right)^2 & \frac{a+b}{2} \le x \le b \\ 1 & b \le x \le c \\ 1-2\left(\frac{x-c}{d-c}\right)^2 & c \le x \le \frac{c+d}{2} \\ 2\left(\frac{x-d}{d-c}\right)^2 & \frac{c+d}{2} \le x \le d \\ 0 & x \ge d \end{cases} \quad \text{(A3)}$$

Biography

Ali Mousavi Mohammadi is currently a graduated M.Sc. of Mechanical Engineering. He received his BSc. and MSc. degrees in mechanical engineering from Ferdowsi University of Mashhad in 2013 and 2016, respectively. Since 2011, he has been an active researcher in FUM Robotics Lab. His main research interests include robotics, automation, and control.

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