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Improved Trajectory Tracking Control for a Three Axis SCARA Robot Using Fuzzy Logic

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***Abstract* –** This paper presents a fuzzy based adaptive controller for a three-axis SCARA robot (Selective Compliance Articulated Robot Arm) in the presence of non- linearities, uncertainties and external perturbations. The nonlinear system is treated as a partially known system. The known dynamic is used to design a nominal feedback controller based on the well-known feedback linearization method and Proportional Derivative (PD) controller. A fuzzy Proportional Integral (fuzzy-PI) based adaptive tracking controller is applied to further improves the control action. Compensation for the effects of the system uncertainties have been achieved and noticeable improvement of the tracking performance has been obtained. The improvements are based on simplified controller design and improved performance characteristics in terms of highly reduced maximum absolute error.

Keywords –Feedback linearization; Fuzzy PI; adaptive tracking controller; three-axis SCARA robot; uncertainties.

1. Introduction

SCARA robot is one of the mostly used robots in today's industry. Due to its characteristics this robot is mainly used for precision, high-speed and light assembly. Common applications are: inserting components on printed circuit board, assembling small electromechanical devices and assembling computer disk drives.

When exact knowledge of the nonlinearities is available, the techniques of feedback linearization are well understood. When system's nonlinearities are given as linear combination of known functions, adaptive control methods may be used to achieve asymptotic tracking [1].

To overcome the effects of specific types of uncertainties, many research works on robust control techniques have been proposed, as can be briefly summarized as follows:

Sanchez, et al. 2002 [2], applied a new PI + PD fuzzy controller, which includes a Dynamic Switching Fuzzy System (DFSFS). Takagi et al. 2005 [3] had proposed a simple decoupling method of robot dynamics, which allowed them to derive a robust stable pole-placement controller with respect to the estimation error of the mass. Sumathi 2005[4] used a fuzzy position control scheme. Voglewede et al. [5] showed an application of polynomial chaos theory (PCT) to analyze the dynamic response of an open-loop mechanism. Gokhan, et al. [6] proposed an adaptive fuzzy Sliding Mode Control (SMC) based on Radial Basis Function Neural Network (RBFNN) for trajectory tracking problem of three link robot manipulator. A Lyapunov function was selected for the design of the SMC and an adaptive algorithm was used for weight adaptation of the RBFNN. Raafat, et al 2009 [7] proposed a neural-network (NN) based robust adaptive controller for an industrial three-axis SCARA robot considering non-linearities, uncertainties and external perturbations. Lin et al. 2010 [8] developed an approach to design a continuous nonlinear control law with a linear state-feedback control for the uncertain nonlinearity of the two-link planar SCARA robot. The robust control for the uncertain nonlinear robotic system guaranteed the required robust stability and performance in face of parameter errors and other uncertainties. Aloui, et al 2010 [9] presented a hybrid robust tracking control scheme which based upon a combination of sliding mode technique, Proportional Integral (PI) controller and fuzzy control design. Davoodikeykani, et al 2014 [10] implement a PID controller to monitor and control the robot arm in real-time. Also, G.U.V.R. Kumar, et al. 2014 [11], presented a Fuzzy Supervisory Controller (FSC) with PID controller.

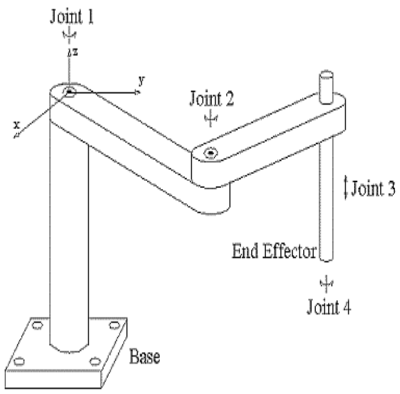
Due to the interesting capabilities of fuzzy logic in efficiently dealing with nonlinearities and uncertainties in a high nonlinear multivariable system, it will be implemented in this paper to improve the performance of the three-axis SCARA robot. The design steps are simply based on improving the control of a Feed Forward (FF) –PD control by using fuzzy PI. The outputs of the fuzzy PI will be adaptively adjusted to compensate the effects of system uncertainties. As a result, the output tracking error between the plant output and the desired reference signal can asymptotically converge to zero. Moreover, the proposed intelligent control guarantees precise accurate performance with less complicated control structure as compared to some previous works as in [6] – [9].

The paper is organized as follows: Section 2 describes the dynamics of the robotic system. Section 3 describes the proposed controller design. In Section 4, illustration of simulation results are given. Finally, some Conclusions are presented in Section 5.

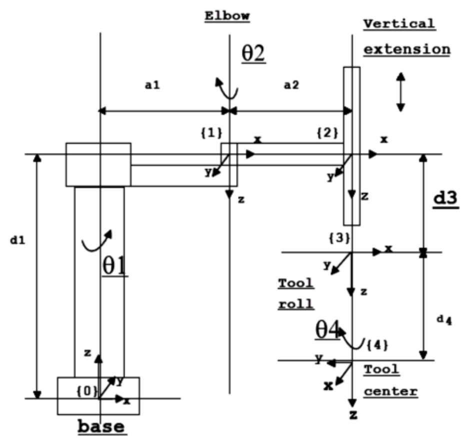
2. Three Axis SCARA Robot; Description and D Modelling

A robot manipulator is basically a positioning device. To control the position , the dynamic properties of the manipulator must be known in order to specify the required force for movement: too little force and the manipulator is slow to react; too much force and the arm may crash into objects or oscillate about its desired position [12].
Robots, in general, use the first three axis for gross manipulation (position control) while the remaining axis orient the tool during the fine manipulation (force or tactile control). [8]. A typical three-axis SCARA robot structure is shown in Fig.1 also table 1 shows the D-H coordinate frame assignment for the SCARA manipulator. It is compact and the working envelopes are relatively limited (ranges<1000mm). The range of payloads that can be supported by this robot is 10-100 kg. A three-axis SCARA manipulator which has three Degree of Freedom (DOF) can move up to 10 times faster than articulated robots. These robots are best used for planar type tasks such as pick and place or assembly line sorting [12].

Equation of motion can be described by a set of differential or difference equations. The equation set consists of two parts, the kinematics equations and the dynamic equation. Robot arm kinematics deals with the geometry of robot arm motion as a function of time (position, velocity, and acceleration) without regards to the forces and moments that cause it.



a)



b)

Figure 1. Three axis SCARA robot:
a) manipulator, b) configuration [7,12].

Table 1. D-H coordinate frame a assignment for the SCARA manipulator [12].

Link	a_i	α_i	d_i	ϑ_i
1	a_1	0	0	*
2	a_2	180	0	*
3	0	0	*	0
4	0	0	d_4	*

where:
a_i = distance between z_{i-1} and z_i along x_{i-1}.
d_i = distance between x_{i-1} and x_i along z_i.
α_i = angle between z_{i-1} and z_i along x_{i-1}.
ϑ_i = angle between x_{i-1} and x_i along z_i.

The dynamic model of the three axis SCARA robot is formulated using the Lagrange-Euler [12]:

1st joint:

$$\dot{v}_1 = \frac{1}{\Delta(q)}[D_{22}(q)\{\tau_1 + a_1 a_2 s_2[(m_2 + 2m_3)v_1 v_2 - (\frac{m_2}{2} + m_3)v_2^2 - b_1(\dot{q}_1)\} - D_{12}(q)[\tau_2 - (\frac{m_2}{2} + m_3) a_1 a_2 s_2 v_1^2] - b_2(\dot{q}_2)] \quad (1)$$

Note that there is no gravitational loading on joint one.

2nd joint:

$$\dot{v}_2 = \frac{1}{\Delta(q)}[-D_{12}(q)\{\tau_1 + a_1 a_2 s_2[(m_2 + 2m_3)v_1 v_2 - (\frac{m_2}{2} + m_3)v_2^2 - b_1(\dot{q}_1)\} - D_{11}(q)[\tau_2 - (\frac{m_2}{2} + m_3) a_1 a_2 s_2 v_1^2] - b_2(\dot{q}_2)] \quad (2)$$

, there is no gravitational loading on joint two.

3rd joint:

$$\dot{v}_3 = \frac{\tau_3 + g_0 m_3 - b_3(\dot{q}_3)}{m_3} \quad (3)$$

where,

$$\Delta(q) = D_{11}D_{22} - D_{12}D_{21} \quad (4)$$

$$D_{11}(q) = (\frac{m_1}{3} + m_2 + m_3)a_1^2 + (m_2 + 2m_3)a_1 a_2 c_2 + (\frac{m_2}{3} + m_3)a_2^2 \quad (5)$$

$$D_{12}(q) = D_{21}(q) = -[(\frac{m_2}{2} + m_3)a_1 a_2 c_2 + (\frac{m_2}{3} + m_3)a_2^2 \quad (6)$$

$$D_{22}(q) = (\frac{m_2}{3} + m_3)a_2^2 \quad (7)$$

where $\dot{v}_1$, $\dot{v}_2$ and $\dot{v}_3$ is the control torque for the first, second and third joints respectively, m_2 and m_3 are mass of first link and second link respectively, a_1, a_2 is the length of first link and second link respectively, b_1 b_2 and b_3 is friction coefficient for the first, second and third joints respectively, C is the centrifugal and Coriolis torque,q_1, q_2 and $q_3$are actual joint motion trajectory for the first, second and third joints respectively and $\dot{q}_1$, $\dot{q}_2$ and $\dot{q}_3$ are actual joint velocity for the first, second and third joints respectively.

3. Controller Design

The form of the dynamic equation of an n-degree of freedom manipulator is [7]:

$$D(q)\ddot{q} + d(q, \dot{q}) = \tau \quad (8)$$

The robot dynamic (8) is a highly nonlinear and coupled multi- input-multi-output (MIMO) system, where D(q) is symmetric and positive definite for each q. The control objective is to elaborate a required control law τ that forces the output q to follow their reference q_d.

The purpose of using controller is to make the robot joints motion trajectory q moving according to a desired trajectory qd, the output tracking error in this case can be defined as:

$$e = q_d - q \quad (9)$$

First a PD controller is designed to obtain the nominal system for three axis SCARA robot. Then the Feed forward acceleration controller in addition to the PD controller is used to improve the system response. In order to reach the optimal response an intelligent fuzzy PI along with the FF plus PD controller has been proposed.

A. Feed forward (FF) and PD controller

Given a joint space trajectory,q_d, a good choice for the outer loop termu_{PD} is as a FF plus PD acceleration control [13]:

$$u_{PD} = K_{p1} * e + K_d * \dot{e} \tag{10}$$

$$u = \ddot{q}_d + u_{PD} \tag{11}$$

Where u_{PD} is the control unit for the PD controller, K_{p1} and K_d are the proportional gain and derivative gain respectively, u is the control unit and $\ddot{q}_d$ is the desired joint acceleration. A nominal PD feedback is used to stabilize the error dynamics of the linearized system with the controller gains.

B. PI controller

Fuzzy logic control has a great potential since it is able to compensate for the uncertain nonlinear dynamics [4]. It is also particularly suitable for complex and ill-defined process in which analytical modeling is difficult due to the fact that the process is instantaneous changing with time.

The fuzzy controller is composed of the following elements [14]: Fuzzification interface, Rule Base, Inference mechanism and Defuzzification interface. In this work, center of gravity defuzzification method has been used:

$$u_{crisp} = \frac{\sum_{k=1}^{N} \mu_k . \beta_k}{\sum_{k=1}^{N} \mu_k} \tag{12}$$

where N is the number of the rules, μ_k is the center of area of the membership function in the kth rule and β_k is the defuzzification value of the output membership function of the kth rule. For Mamdani output fuzzy sets in the rule, the centroid defuzzification method can be used but with these fuzzy sets that are nonzero only at $u_{crisp} = \beta_1 ... \beta_N$.

In this paper, fuzzy logic control is implemented to provide an adaptive PI controller. The usual proportional plus integral control equation is [15]:

$$u_{fuzzy} = K_{p2} .e + K_i \int e.dt \tag{13}$$

Where u_{fuzzy} is the fuzzy action of the controller, K_{p2} is the proportional gain and Ki is the integral gain.

The fuzzy PI controller has two inputs; error and change of error (e and Δe) and one output (u_{fuzzy}). The membership function of each input and output will be selected to be triangular type with a normalized domain [-1, 1] as shown in Fig. 2.

According to the number of memberships in each input, the PI fuzzy controller will have a 7 * 7=49 rules. After several trials, the rules are selected to be as shown in Table 2 the fuzzy rules between the error e, change – of – error Δe and the controller output Δ u_{fuzzy}.

The proposed adaptive Fuzzy controller is illustrated in Fig. 3. Accordingly, (10) will be:

$$u_{PD} = \ddot{q}_d + K_{p1} * u_{fuzzy} + K_d * \frac{du_{fuzzy}}{dt} \tag{14}$$

The suggested fuzzy position control scheme performs the precise tracking for the desired trajectory.

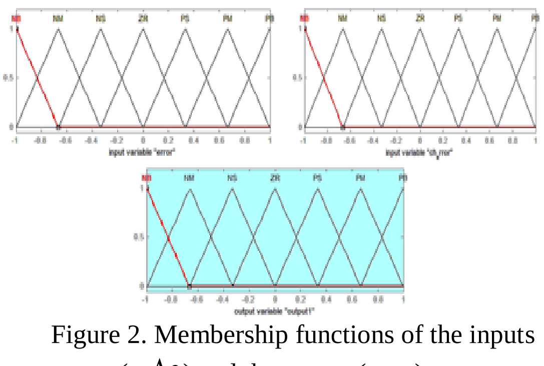


Figure 2. Membership functions of the inputs (e, Δe) and the output (u_{fuzzy}).

Table 2. Rule base of fuzzy PI controller.

Δe \ e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	Z	NB	NB
NM	NB	NS	NB	Z	NB	PM	NB
NS	NB	NB	NB	NB	PM	PB	PB
Z	PB	PB	PM	PS	PB	NM	NB
PS	PM	PM	PM	PB	PB	Z	PB
PM	PB	PM	PB	PB	PB	PM	NB
PB	NB	PB	PM	PM	PB	PM	Z

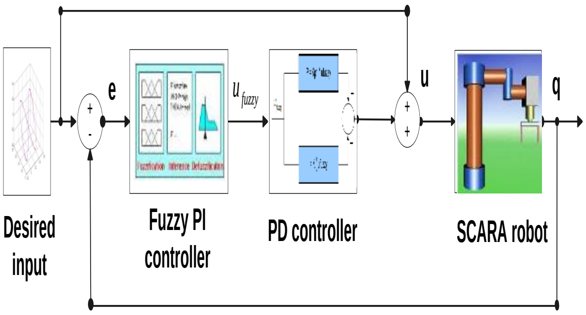


Figure 3. Bock diagram of the adaptive fuzzy controller with SCARA robot

C. Algorithm

The following algorithm summarizes the applied steps to design the proposed robust controller:

- Build the Simulink model of the robot dynamic using (1-7).
- Select the desired trajectory.
- Design the FF+PD controller using (10-11).
- Add the fuzzy PI control of (13) to FF+PD controller, as given in (14).
- Calculate and test the errors in the joints of the robot.
- If the results are not satisfied then tune the controller gains and return to previous stage.
- If the errors are minimized and the trajectory error is eliminated as required then the proposed controller can successfully be applied to the robot system.

4. Simulation and Results

The simulation of the three axis SCARA robot of (1-7) was carried out using MATLAB/Simulink. Fourth-order Runge-Kutta technique [16] and sampling time equal to 0.001s were selected to simulate the controlled system. The used parameters for the three-axis manipulator are listed in Table 3.

First, the FF -PD controller is applied to the three joints of the three axis SCARA model with K_{p11}, K_{p12},and $K_{p13}$are set to be 10 and K_{d1}, K_{d2} and K_{d3} are set to be 0.5. The actual and the desired trajectories for the FF - PD controller are shown in Fig. 4, where an improvement of tracking performance to the desired trajectory is achieved. Fig. 5 shows the control unit signal for each joint. The numerical values of tracking errors are illustrated in Table 4.

Then, by using the FF-PD and fuzzy PI controller for the simulated robot system as shown in Fig. 6, a considerable reduction in the in the steady state error from that of the open loop response by 99.9 % for the first joint, 99.8 % for the second joint, and 98.5 % for the third joint. Comparison results between the previously described experiments are given in Table 4.

Using the FF-PD and fuzzy PI results in the best reduction of the maximum absolute value of error, where it becomes 0.4 for the first joint, 0.308 for the second joint and 0.011 for the third joint as given in Table 5. Moreover, the tracking errors have been considerably reduced from that of the open loop responses by 99.5% for the first joint, 90.4 % for the second joint and 46.2% for the third joint.

Figure 7 shows fuzzy PI controller for the first joint. Similarly, fuzzy PI controller for joint 2 and joint 3 are simulated. The gains of the fuzzy PI are selected as: for the first joint K_{p21}= 1.3

and K_{i1}=70, for the second joint K_{p22}=2.5 and K_{i2}= 150 and for the third joint K_{p23}= 0.1, and K_{i3} = 70. The resulting trajectory and control signals are shown in Fig. 8 and Fig. 9 respectively. It is clear that using the fuzzy based adaptive controller has the best tracking performance.

Also using the adaptive fuzzy controller shows great improvements in the control action and robot performance compared with that of using FF plus PD controller only, where the error ratio improved by 95.3 % for the first joint, 97.5 % for the second joint and 97.3 % for the third joint.

Table 3. Parameter values of three-axis planar robot [7,12]

Parameter \ Joint No.	1	2	3
mass (kg)	8	5	3
link length (m)	0.8	0.3	0.3
coefficient of viscous friction (Nm s/rad)	1	1	1
coefficient of dynamic friction (Nm)	0	0	0
coefficient of static friction (Nm)	15	15	15
ε(rad/s)	0.1	0.1	0.1

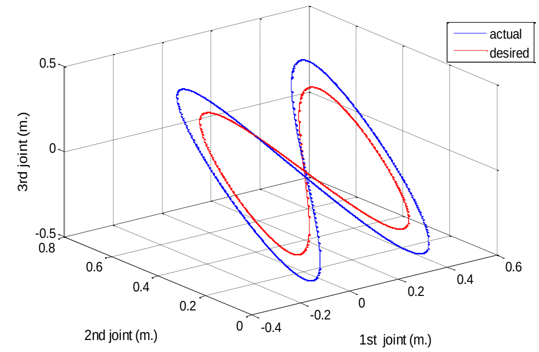


Figure 4. The actual and the desired trajectory for the FF plus PD controlled system.

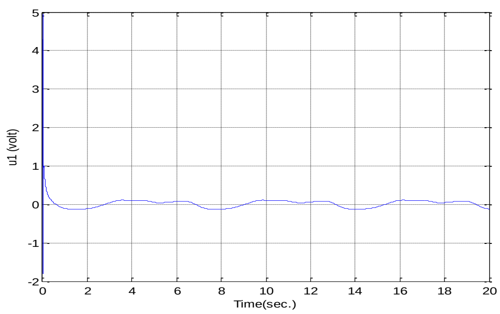


Figure 5. a)

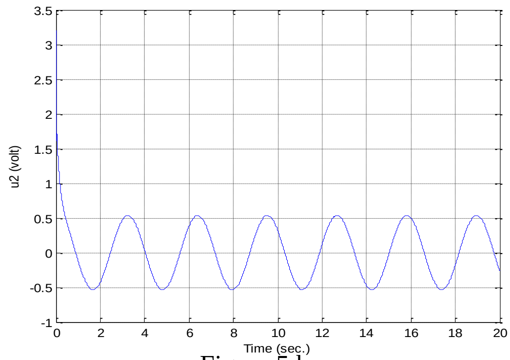


Figure 5 b

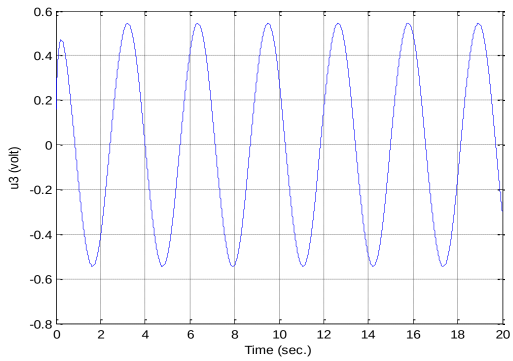


Figure 5c

Figure 5. The control signal of the FF plus PD controller for: a) the first, b) second and c) third joints.

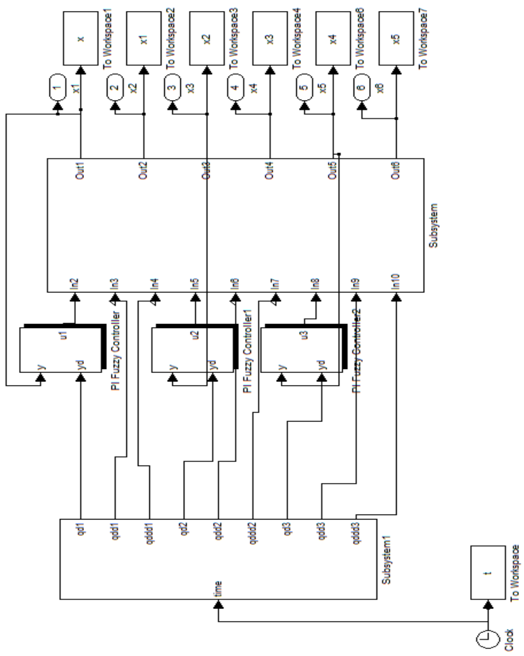


Figure 6. Modeling ofadaptive fuzzy controlled three axis SCARA robot using FF plus PD plus fuzzy PI

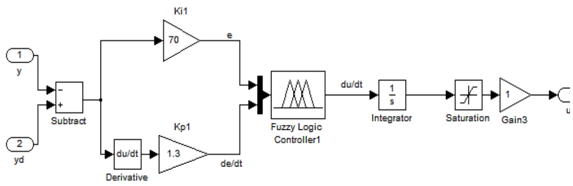


Figure 7. Modeling of fuzzy PI controller for the first joint.

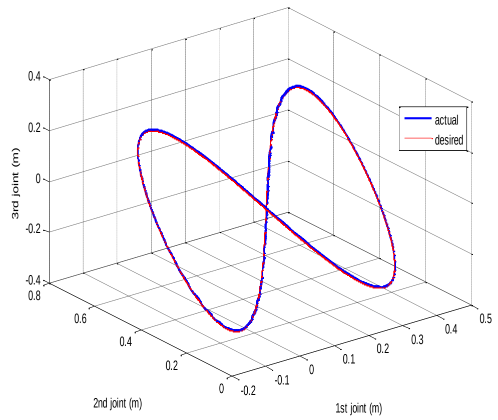


Figure 8.The actual and the desired trajectory using the FF plus PD plus fuzzy PI controller.

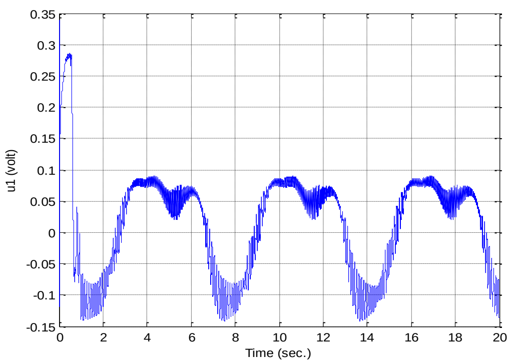


Figure 9. a

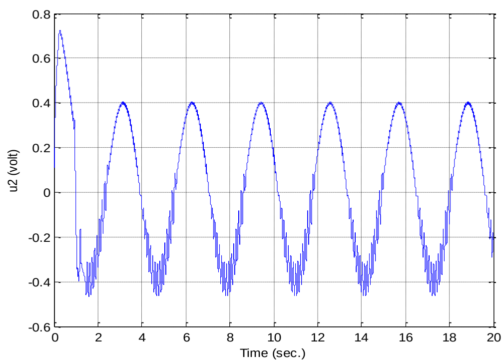


Figure 9. b

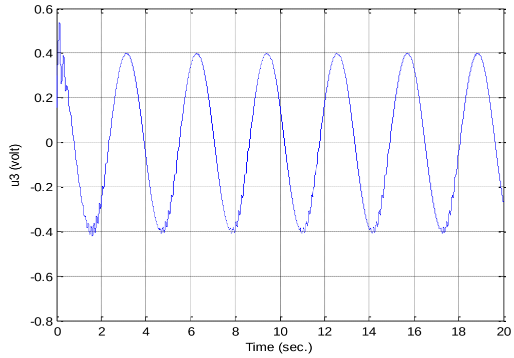


Figure 9-c

Figure 9. The control signal of the FF plus PD plus fuzzy PI controller for the first, second and third joints.

Table 4. The resulted steady state errors (m)

Joint No. / Controller type	1	2	3
Without controller	22	1.15	0.223
FF+PD	0.091	0.11	0.12
FF+PD+ Fuzzy PI	4.28 e-3	2.65e-3	3.3e-3

Table 5. The resulted maximum errors (m)

Joint No. / Controller type	1	2	3
Without controller	0.751	1.415	0.376
FF+PD	0.4	0.3004	0.123
FF+PD+ Fuzzy PI	0.4	0.3008	0.011

5. Conclusion

In this paper, the modeling of three axis SCARA robot system is studied and developed. Simulink / MATLAB tool is implemented to simulate the robot. The performance of the robot system in open loop control mode shows a great error in resulted trajectory. In order to eliminate this error a control strategy based on the FF plus PD plus fuzzy PI controller is evaluated for robust and accurate trajectory tracking. Through the trajectory tracking simulation it shows that the proposed FF plus PD plus fuzzy PI controller reduces the tracking error and enables to have sustainable improvements in the performance of the three joints of the three axis SCARA robot in the steady state error by 99 % for most of the robot joints and maximum value of error 46.74 % respectively as compared to FF+ PD controller. It should be mentioned that the versatile environment of Simulink provides an efficient tool for building a user friendly efficient program that can be easily used to test other types of control methods. Current work is carried on to develop an educational package on robots design, analysis and control. Future work will consider the inclusion of other intelligent techniques in the adaptive controller design like Neuro-Fuzzy control, T-S Fuzzy control and genetic algorithms.

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