Jurnal Mekanikal
Disember 2003, Bil. 16, 57- 78

INTELLIGENT ACTIVE FORCE CONTROL OF A THREE-LINK MANIPULATOR USING FUZZY LOGIC

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ABSTRACT

The paper presents a novel approach to estimate the inertia matrix of a robot arm using a fuzzy logic (FL) mechanism in order to trigger the active force control (AFC) strategy. A comprehensive study is performed on a rigid three-link manipulator subjected to a number of external disturbances. The robustness and effectiveness of the proposed control scheme are investigated considering the trajectory track performance of the robotic arm taking into account the application of external disturbances and that the arm is commanded to describe a reference trajectory given a number of initial and operating conditions. The results show that the FL mechanism used in the study successfully computes appropriate estimated inertia matrix value to execute the control action. The proposed scheme exhibits a high degree of robustness and accuracy as the track error is bounded within an acceptable range of value even under the influence of the introduced disturbances.

Keywords: *Active force control, fuzzy logic, estimated inertia matrix, robust, three-link manipulator.*

1.0 INTRODUCTION

The force control of a robot arm is concerned with the subject of how well the arm performs and responds under various loading conditions and changes in the robot parameters. The performance of the arm should not degrade with the presence of these 'disturbances'. Robot force control involves the physical interaction of the robot's end effector with the external environment in the forms of applied forces or torques, changes in the mass payloads and constrained elements. A number of control methods has been proposed to achieve stable and robust performance ranging from the classical proportional-derivative (PD) control [1] to the more recent intelligent control technique such as those employing neural network or fuzzy logic elements. The PD control is simple, efficient and provides stable performance when the operational speed is low and there are very little or no disturbances. The performance however is severely affected with the increase in speed and presence of disturbances. Adaptive control method [2,3] improves the stability and robustness of the system via its adaptive feature, which enables it to operate in a wider range of parametric uncertainties and disturbances. However, this technique is more commonly found in theoretical and simulation study as it involves rigorous mathematical manipulation and assumptions. Active force control (AFC) of a robot arm has been demonstrated to be superior compared to the conventional methods [4,5] in dealing with compensating a variety of disturbances. There is a growing trend in robotic control to include intelligent mechanism such as iterative learning algorithm, neural network, knowledge-based expert system, genetic algorithm and fuzzy logic.

In this paper, a fuzzy logic (FL) mechanism is used together with the AFC strategy to control a rigid three-link horizontal planar manipulator. The scheme known as AFCAFL (an acronym for Active Force Control And Fuzzy Logic), is an extension to the work described in a previous study [6] where the effectiveness and practicality of the scheme applied to a two-link planar manipulator has been clearly demonstrated. It is the objective of the proposed study to extend the application of the AFCAFL control scheme to the control of a three-link manipulator. The study also demonstrates that the FL mechanism is able to compute the estimated inertia matrix of the manipulator automatically, continuously and on-line while the manipulator performs its task under the influence of disturbances.

The paper is structured as follows. The first part presents a description of the problem statement and the fundamentals of both the AFC strategy and FL mechanism. The integration of the FL and the AFC applied to a rigid three-link horizontal planar manipulator is demonstrated in the form of a simulation study. Consequently, simulation results of the control scheme are analyzed and discussed with a particular attention given to the trajectory track performance of the manipulator and the computed estimated inertia matrix of the manipulator. Finally, a conclusion is derived and the direction for potential future work is outlined.

2.0 PROBLEM STATEMENT

AFC is a force control strategy originated by Hewit [4,7] and is primarily designed to ensure that a system remains stable and robust even in the presence of known or unknown disturbances. In AFC, the system mainly uses the estimated or measured values of a number of identified parameters to execute its compensation action. In this way, the mathematical complexity of the robotic system, which is known to be highly coupled and non-linear can be greatly reduced.

The main setback of AFC is the acquisition of the estimated inertia matrix required by the AFC feed-forward loop. Previous methods rely heavily on either perfect modeling of the inertia matrix, crude approximation or the reference of a look-up table, which obviously require prior knowledge of the estimated inertia matrix. Although the methods are quite effective to implement, they lack in systematic approach and flexibility to compute the inertia matrix. Thus, a search for better ways to generate efficiently suitable estimated inertia matrix is undertaken. If a suitable method of estimating the inertia matrix can be found, then the potential of implementing the practical AFC scheme is considerably enhanced. Obviously, intelligent methods are viable options and should be exploited to achieve the objective as already pointed out in [8,9], i.e. to approximate appropriately the estimated inertia matrix in the AFC loop.

In this study, a FL mechanism is employed in conjunction with the AFC strategy to control the manipulator. The basic idea of this scheme is to generate the estimated inertia matrix of the manipulator continuously, automatically and with the actual execution 'on-line' using a suitable FL controller as the manipulator is commanded to execute a prescribed task accurately even in the presence of disturbances. The FL controller uses manipulator's links rotational angle (θ) as its input to compute the appropriate estimated inertia matrix (output). Figure 1 is a block diagram showing the mechanism of the proposed scheme.

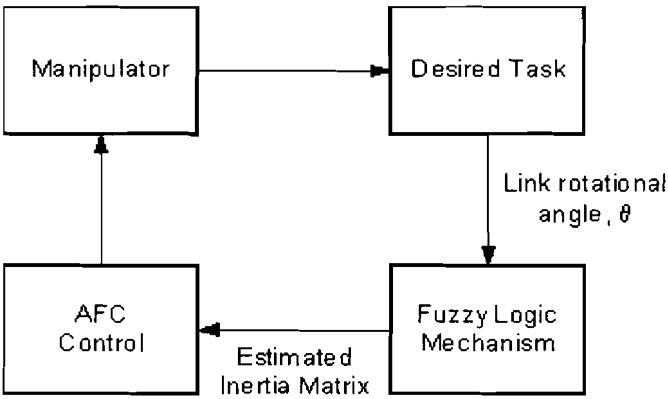


Figure 1 Mechanism of the proposed control scheme

In the following sections, the object of study, i.e. the three-link robotic manipulator mathematical model and the fundamentals of both AFC and FL mechanisms are adequately presented so that a better understanding of the overall proposed scheme can be derived.

3.0 MATHEMATICAL MODEL OF THE ROBOT ARM

The dynamic model or the general equation of motion of a robot manipulator [10] can be described as follows:

$$T_q = H(\theta)\ddot{\theta} + h(\theta,\dot{\theta}) + G(\theta) + T_d \tag{1}$$

where T_q : vector of actuated torque
H : $N \times N$ dimensional manipulator and actuator inertia matrix
h : vector of the coriolis and centrifugal torque
G : vector of gravitational torque
T_d : vector of the external disturbance torque

Figure 2 shows a representation of a rigid three-link horizontal planar manipulator under study. The gravitational term can be ommitted here since the arm is assumed to move in a horizontal plane. Thus, the dynamic model is reduced to:

$$T_q = H(\theta)\ddot{\theta} + h(\theta,\dot{\theta}) + T_d \tag{2}$$

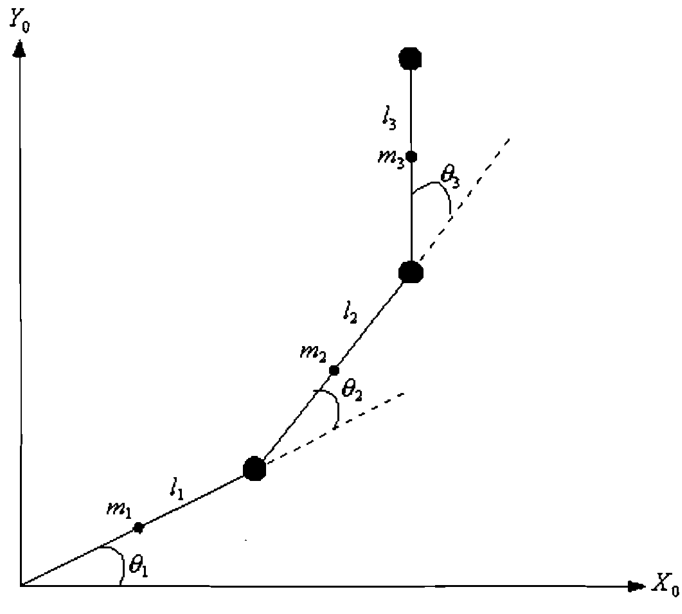


Figure 2 A representation of a rigid three-link horizontal planar manipulator

4.0 ACTIVE FORCE CONTROL

In AFC, it is shown that a robotic system subjected to disturbances remains stable and robust through the compensating action of the control strategy. The detailed mathematical analysis of the AFC scheme can be found in [4,11,12]. The main computational burden in AFC is the multiplication of the estimated inertia matrix with the angular acceleration of the manipulator before being fed into the AFC feed-forward loop. Apart from that, the output of the control system pertaining to the Cartesian position (x,y) at the free end of robotic arm needs to be computed from the joint angle space via forward kinematics. Also, the basic controller (typically, the classic PD type) prior to the AFC loop has to be determined. For a given robot arm configuration, the schematic of a basic AFC method applied to control a robot arm is shown in Figure 3. The principal advantage of AFC is the practical viability of the scheme to accomplish the control action. The torque and acceleration of the arm can be accurately measured by means of suitable state-of-the-art transducers while the estimated inertia matrix can be easily acquired by crude approximation, a reference of a look-up table or intelligent methods. It has been shown that the estimated inertia matrix needs not be accurately approximated; the only requirement is that it should be within a suitable range of values [4,10, 11,12,13].

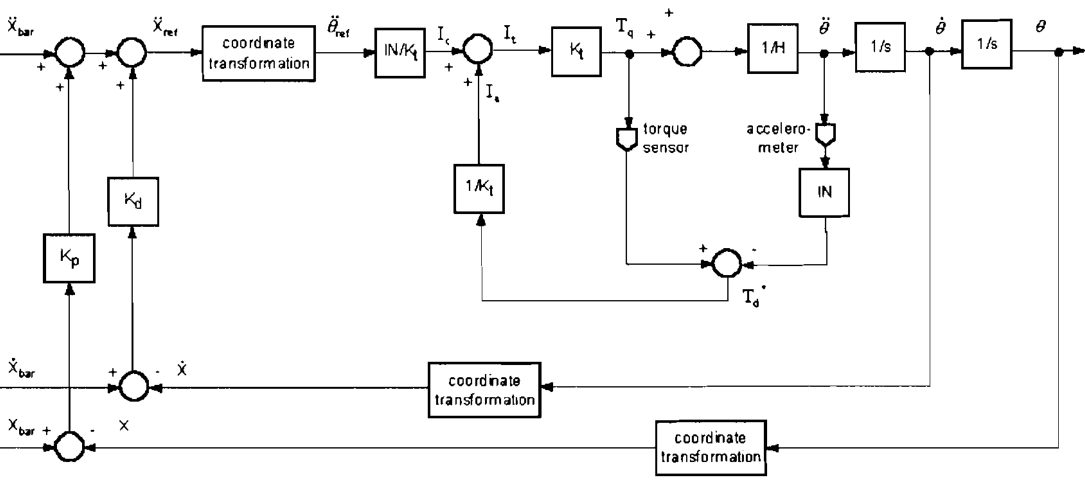


Figure 3 AFC scheme applied to a robot arm

The notation used in Figure 3 is as follows:

θ	:	vector of positions in joint space
K_p, K_d	:	PD controller gains
K_t	:	motor torque constant
I_c	:	current command vector
I_a	:	compensated current vector
I_t	:	armature current for the torque motor
IN	:	estimated inertia matrix
T_d *	:	estimated disturbance torque
T_q	:	applied torque (measured)

x, x_{bar} : vectors of actual and desired positions respectively in Cartesian space

$\ddot{\theta}_{ref}$, $\ddot{x}_{ref}$: reference acceleration vectors in joint and Cartesian spaces respectively

On the left-hand side of Figure 3, a resolved-motion-acceleration-control (RMAC) controller is employed with a PD element. It is governed by the following equation:

$$\ddot{x}_{ref} = \ddot{x}_{bar} + K_d(\dot{x}_{bar} - \dot{x}) + K_p(x_{bar} - x) \tag{3}$$

The RMAC produces the acceleration command vector signal $\ddot{\theta}_{ref}$ which when multiplied with a decoupling transfer function gives the required command vector to the main AFC loop. The equation describing the disturbances is given as:

$$T_d{}^* = T_q - IN\ddot{\theta} \tag{4}$$

In AFC, the disturbances can be effectively accommodated by obtaining the measurements of the acceleration and the torque using physical accelerometer and torque sensor respectively. Based on the torque-current relationship, Equation (4) can be conveniently rewritten in the following form:

$$T_d{}^* = K_t I_t - IN\ddot{\theta} \tag{5}$$

Thus, the controlled current I_t to the motor can be measured instead and similar outcome can be achieved. The AFC concept has been successfully implemented to robot arm via simulation and experimental works [4,8,11, 14,15,16]. The only additional and necessary requirement is the acquisition of an appropriate estimated inertia matrix of the arm to be multiplied with the 'measured' acceleration as in Equation (5). Previous cited works on AFC use conventional techniques that are rather crude, not systematic and mostly based on rough estimation. Thus, it is highly desirable that a method should be devised in such a manner that the inertial parameter can be identified intelligently without having to resort to the approaches described above. A number of intelligent methods have been proposed using neural network and iterative learning algorithms [8,9,17,18]. The proposed study described in the paper considers fuzzy logic (FL) as the estimator of the inertial parameters of the robot arm. The control scheme is known as AFCAFL. The scheme applied to control a robot arm can be seen in Figure 4.

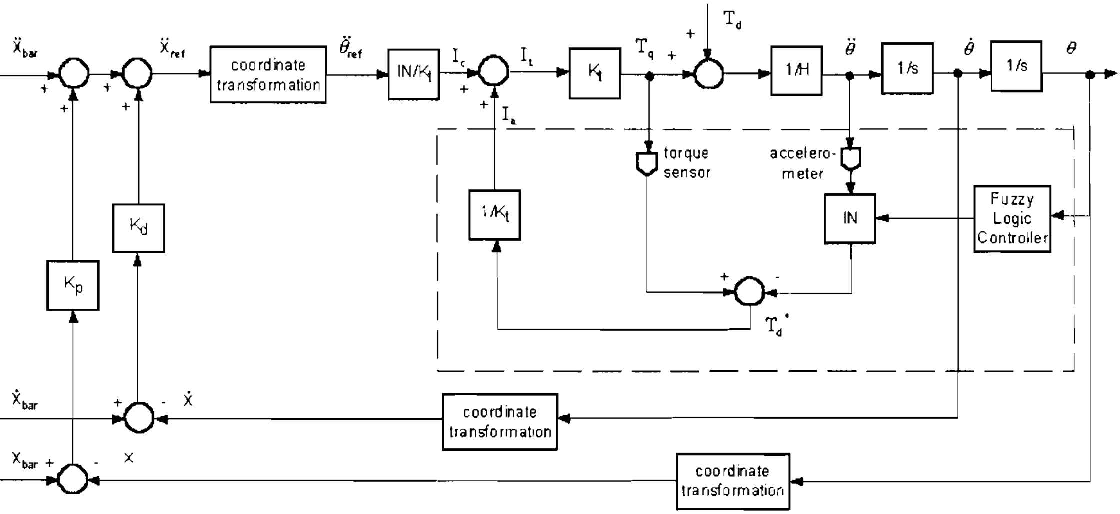


Figure 4 The proposed AFCAFL scheme

The FL component can be treated as a black box as shown in Figure 5 where the input is the vector of joint angles (θ) and the required estimated inertia matrix (**IN**) of the arm is the output to be fed into the AFC loop. The description of the FL mechanism is described in the following section.

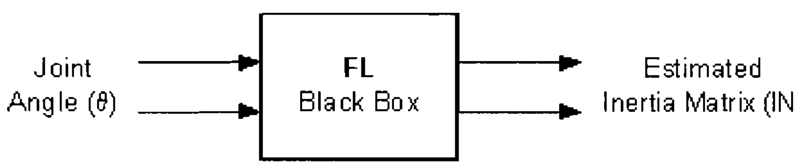


Figure 5 Fuzzy logic black box

5.0 FUZZY LOGIC CONTROL

5.1 Fuzzy Logic Concept

The concept of applied FL was pioneered by *Lotfi Zadeh* in the mid-60s. A fuzzy controller is an expert control system capable of performing smooth interpolation between hard boundary crisp rules [19]. The basic FL concept is as shown in Figure 6.

Figure 6 Fuzzy concept

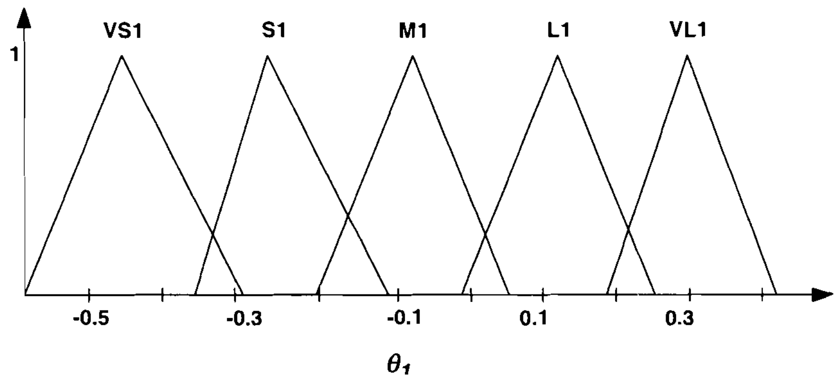
The first step of the FL process is fuzzification in which crisp input values are transformed into fuzzy input involving the construction of suitable membership functions representing the fuzzy sets. This is followed by the process of rules evaluation normally in the form of linguistic statements (e.g., *if-then* rules) to determine the dynamics of the controller as a response to the given fuzzy inputs. It is then passed through a defuzzification process using an averaging technique to produce crisp output values. The application of the FL concept to AFC strategy to control a three-link arm is described in the following section.

5.2 Application of FL in AFC Scheme

The main purpose of using the FL in the study is to compute the estimated inertia matrix of a robot arm intelligently so that it can be utilized by the AFC mechanism to execute its control strategy. The three-link manipulator in the study is assumed to operate horizontally, thereby ignoring the effect of the gravitational torque. Throughout the study, only the diagonal elements of the manipulator inertia matrix (**H**) are considered and that for convenience, the elements of the matrix are denoted as $H_{11} = IN_1$, $H_{22} = IN_2$ and $H_{33} = IN_3$. The off-diagonal terms are disregarded since it has been shown that the coupling terms can be safely ignored by the AFC strategy [4].

The design procedure of the fuzzy logic controller used in the study is described as follows:

1. Membership functions representing the input (joint angles of the arm) and output (estimated inertia matrix) of the FL component were determined as part of the fuzzification process. Approximate values within specific bounds were obtained based on crude approximation and also from the results previously acquired in [8,9,18]. The membership functions used in the study can be seen in Figures 7 and 8 (a) through (c).



(a)

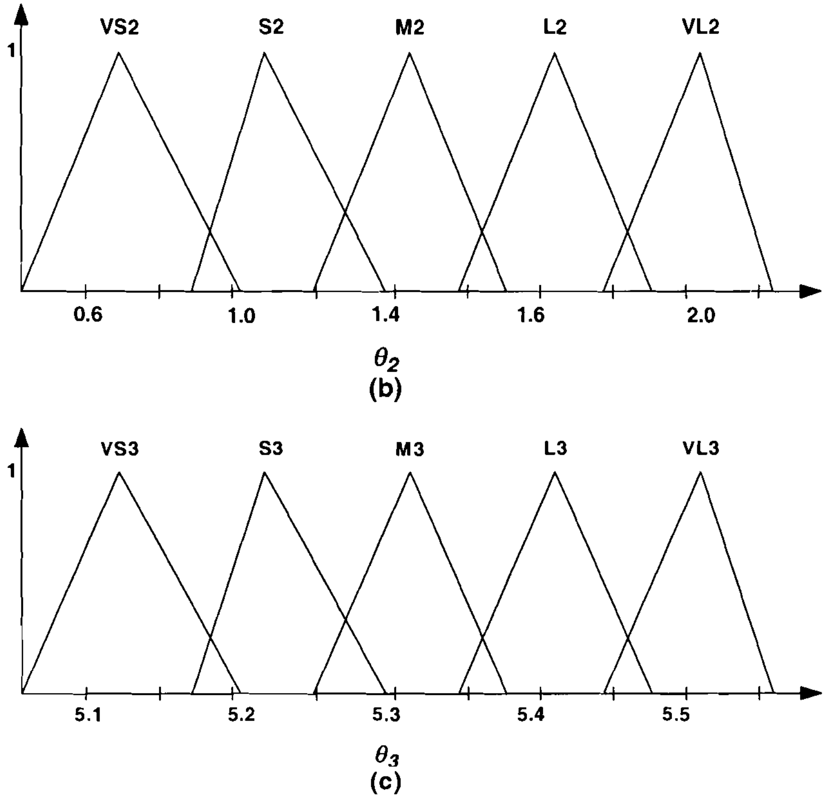
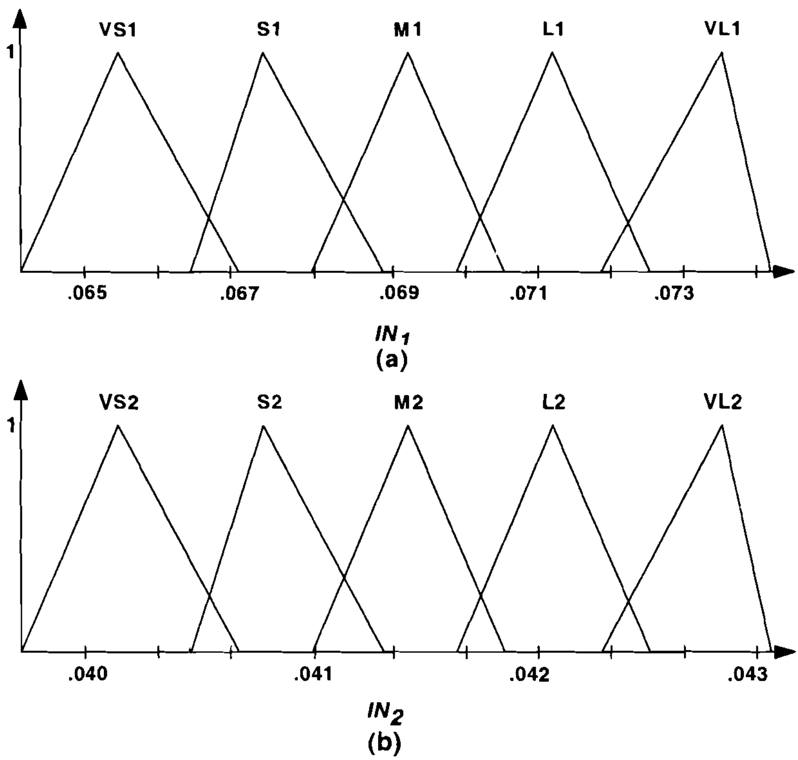
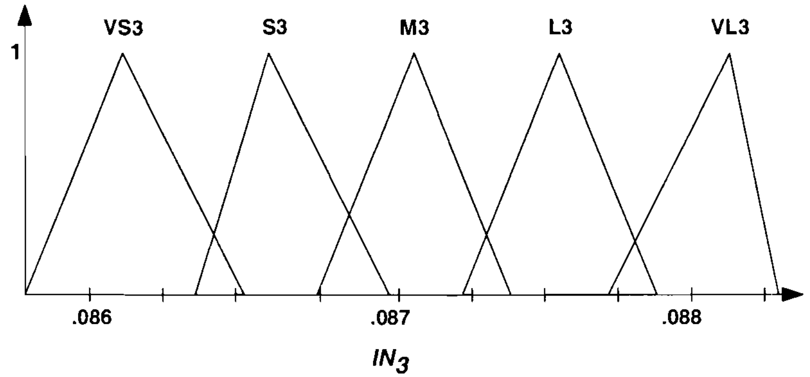


Figure 7 Input membership functions for (a) θ_1 (b) θ_2 and (c) θ_3





(c)

Figure 8 Output membership functions for (a) IN_1, (b) IN_2 and (c) IN_3

2. A set of rules was designed in the form of *if-then* structure. In the study, *Mamdani* fuzzy inference system was used [20]. *Mamdani* proposed to control the plant (or dynamic system) by realising some fuzzy rules or fuzzy conditional statements. In this manner, one can measure the outputs of a dynamic system and calculate a control action according to the devised rules. This can be illustrated in the following example that is directly related to the study. One of the rules can be written as

   If (theta1 is VS1) and (theta2 is VS2) and (theta3 is VS3)
   then (IN1 is VS1)(IN2 is VL2)(IN3 is VS3)

   The above statement implies that if the first joint angle of the manipulator is very small (VS1), the second joint angle is very small (VS2) and the third joint angle is very small (VS3), then the estimated inertia matrix (IN) of the first link is very small (VS1), the second link is very large (VL2) and the third link is very small (VS3).

3. A crisp output was obtained through a defuzzification process using an averaging technique called *centroidal* or *center of gravity* method and is described by the following equation:

$$\bar{x} = \frac{\int \mu_X(x) \cdot x dx}{\int \mu_X(x) dx} \tag{6}$$

   The method is depicted in Figure 9.

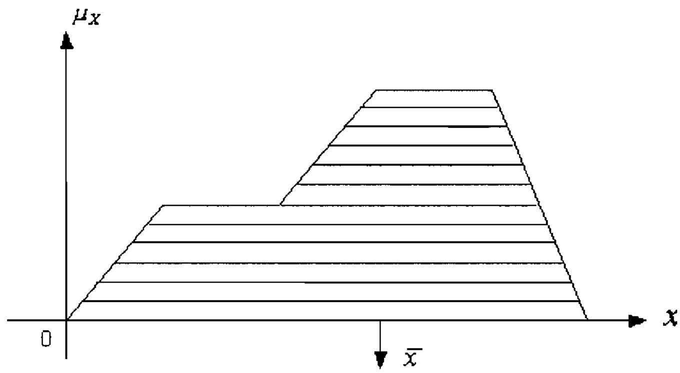


Figure 9 Centroidal method in defuzzification process

Once the FL black box was appropriately designed, it was embedded in the overall control strategy for the on-line implementation and computation of the estimated inertia matrix.

6.0 SIMULATION OF THE AFCAFL CONTROL SCHEME

Simulation work was performed using MATLAB and SIMULINK software packages. In addition, a complimentary toolbox known as Planar Manipulator Toolbox [21] was also utilized in the simulation. Figure 10 shows the SIMULINK block diagram of the proposed scheme.

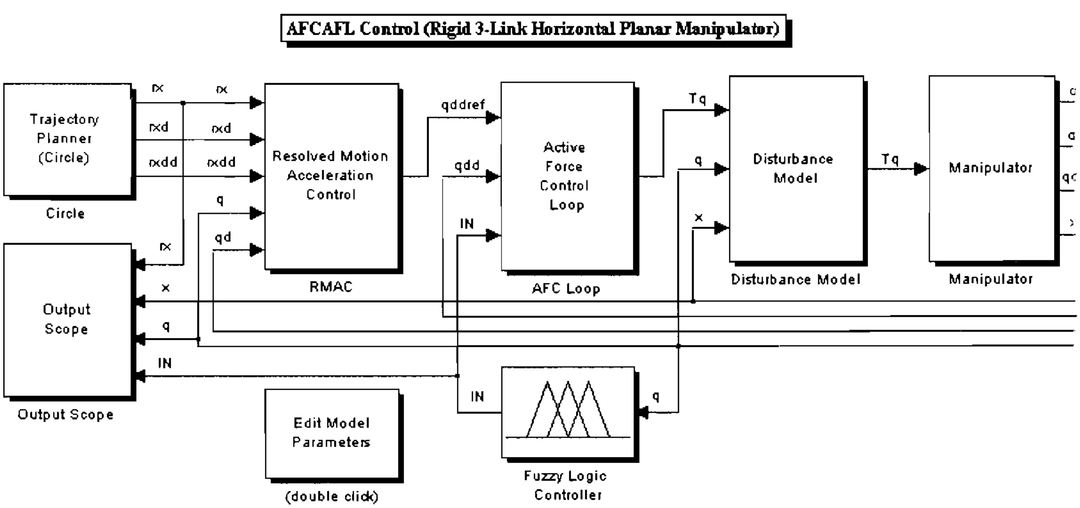


Figure 10 A SIMULINK block diagram representing the AFCAFL scheme

The system comprises the trajectory planner, RMAC section, main AFC loop, manipulator (robot dynamic model), fuzzy logic controller, disturbance model as well as the output scope. These models are linked by means of a series of connecting lines representing the flow of signals. The relevant blocks used in this model were obtained from SIMULINK library as well as the Planar Manipulator Toolbox [21]. A number of simulation parameters needs to be specified before simulation work is carried out and is described in the following section.

6.1 Simulation Parameters

The following parameters were used in the simulation study:

Robot parameters:

Link length	:	$l_1 = 0.25$ m	$l_2 = 0.2236$ m	$l_3 = 0.2$ m
Link mass	:	$m_1 = 0.25$ kg	$m_2 = 0.2236$ kg	$m_3 = 0.2$ kg
Payload mass	:	$m_{pl} = 0.01$ kg		

Controller parameters:

Controller gain: $K_p = 800$ $K_d = 600$

Motor torque constant: $K_t = 0.263$ Nm/A

Main simulation parameters:

Integration algorithm:	ode113 (Adams)
Simulation time start, *tstart*:	0.0 s
Simulation time stop, *tstop*:	πs (3.142 s)
Minimum step size:	0.001 s
Maximum step size:	0.01 s
Relative tolerance:	5×10^{-4}
Absolute tolerance:	1×10^{-3}

Fuzzy logic parameters:

Fuzzy inference engine:	*Mamdani* model
Defuzzification method:	Centroid

Other parameters:

Sampling time:	0.01 s
Endpoint tangential velocity:	$V_{cut} = 0.2$ m/s
Center of circle:	[0.5, 0.2]
Radius of circle:	0.1 m

K_p and K_d were assumed to be satisfactorily tuned heuristically prior to the simulation work while K_t was derived from the actual data sheet for a dc torque motor [22]. Simulation was first performed without considering any external disturbances acting on the system. Later, a number of applied disturbances was introduced to test the system's robustness and effectiveness.

6.2 The Prescribed Trajectory

Figure 11 shows the prescribed circular trajectory considered in the simulation study. It serves as the reference trajectory that the arm should accurately track via the control strategy. The trajectory is generated using the time (t) dependent functions given below:

$$x_{bar1} = C_x + R\cos[(V_{cut}/R)t] = 0.5 + 0.1\cos[(0.2/0.1)t] \quad (7a)$$

$$x_{bar2} = C_y + R\sin[(V_{cut}/R)t] = 0.5 + 0.1\sin[(0.2/0.1)t] \quad (7b)$$

where
x_{bar} : vector of end positions of link-3 in Cartesian space
C : position of the center of circle in Cartesian space
R : radius of the circle
V_{cut} : tangential velocity

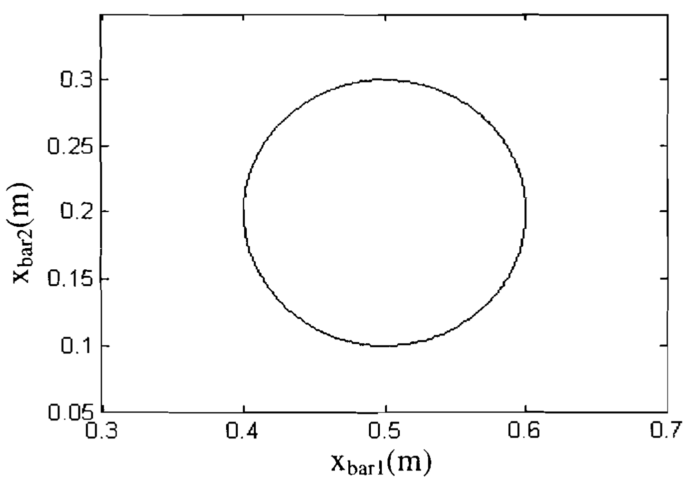


Figure 11 The desired circular trajectory of the arm

6.3 The Applied Disturbances

A number of disturbances was modelled and introduced to test the system's robustness in compensating the disturbances. The analysis starts by first considering no external disturbances acting on the system, i.e., F_0 = 0 N; this was done to facilitate comparison. Later, three types of external disturbances were modelled as follows:

i. A constant torque, T_q acting at the joint of each link, the magnitude of which is equal to 100 Nm.

ii. A sequence of pulsating force F_p applied at the free end of the third link parallel to the horizontal axis. F_p can be described as shown in Table 1.

Table 1 The pulsating force cycle

F_p (N)	Time interval
0	0.00 s < t < 0.40 s
P	0.40 s < t < 0.41 s
0	0.41 s < t < 0.90 s
P	0.90 s < t < 0.91 s

where the magnitude of the applied force P is equal to 100 N. The pulsating force is applied for 0.01 s for every 0.5 s until the simulation stops.

iii. A spring force F_s also applied at the free end of the third link parallel to the horizontal axis. The spring force F_s can be described as

$$F_s = k\Delta x \quad (8)$$

where Δx represents the linear extension of the spring and k is the spring constant. One end of the spring is attached to the free end of the third link of the manipulator while the other end is located at a fixed point corresponding to the coordinate [0.6, 0.1] in Cartesian space. The spring constant k used in the simulation is 400 N/m.

7.0 RESULTS AND DISCUSSION

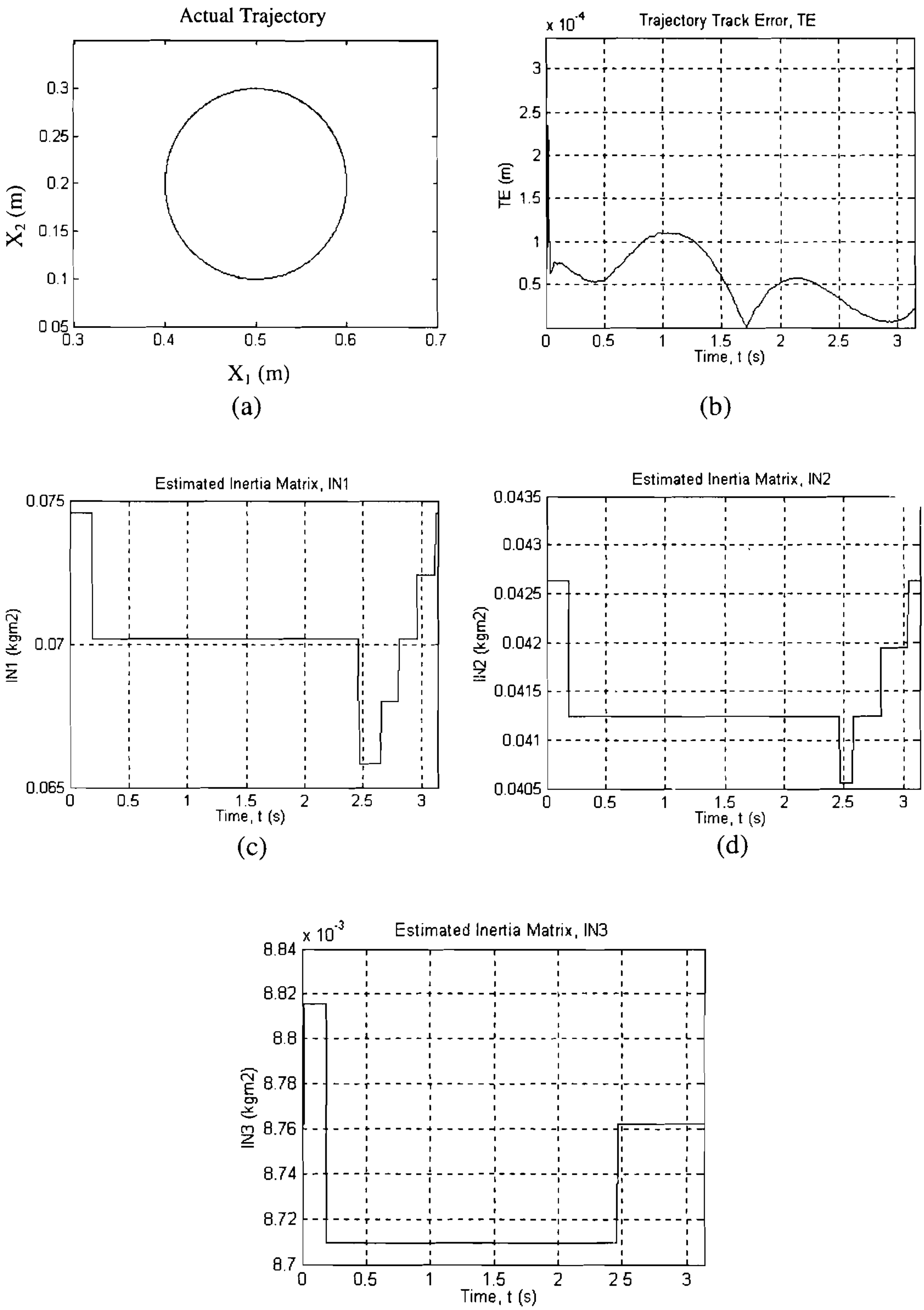
The results of the simulation work are shown in Figures 12 through 15 which respectively relate to the four types of disturbances (F_o, T_q, F_p and F_s) considered in the study. The graphical results show the actual trajectory generated, the trajectory track error obtained and the estimated inertia matrix computed.

7.1 Actual Trajectory and Trajectory Track Performance

The graphs (a) of Figures 12 through 15 show the actual trajectory generated by the manipulator. These four graphs show that the actual trajectory almost replicates the desired trajectory without implying the system's robustness against the disturbances introduced. A similar conclusion can be deduced from the trajectory track error graphs shown by graphs (b) of Figures 12 through 15. All the trajectory track error curves demonstrate very small differences between actual and desired trajectories, i.e., all the maximum errors are less than 1%. These results clearly imply that the AFCAFL scheme is very robust and effective due to the fact that it is able to track the reference trajectory very accurately even under the influence of applied disturbances. Table 2 summarizes the maximum trajectory track errors produced by the four types of disturbances.

Table 2 Maximum trajectory track errors produced by the applied disturbances

Type of Disturbances	**Maximum Trajectory Track Error**
No disturbances, $F_0 = 0$ N	0.24 mm (0.24%)
Constant Torque, $T_q = 100$ Nm	0.22 mm (0.22%)
Pulsating Force, $F_p = 100$ N	0.88 mm (0.88%)
Spring Force, $F_s = 400\ \Delta x$	0.98 mm (0.98%)



(e)

Figure 12 Results for the AFCAFL scheme, no disturbance, F_0 = 0N

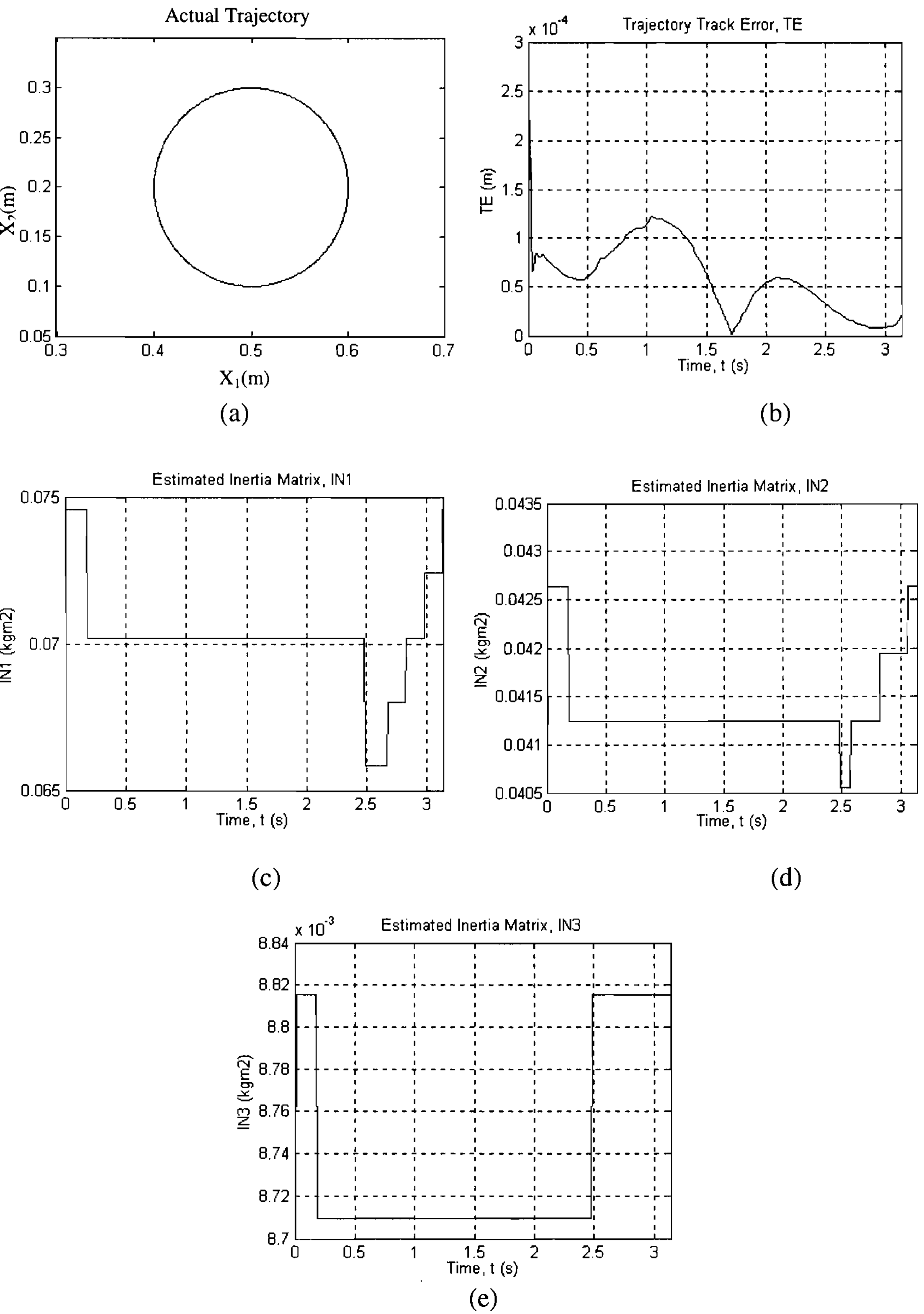


Figure 13 Results for the AFCAFL scheme, constant torque, $T_q = 100$ Nm

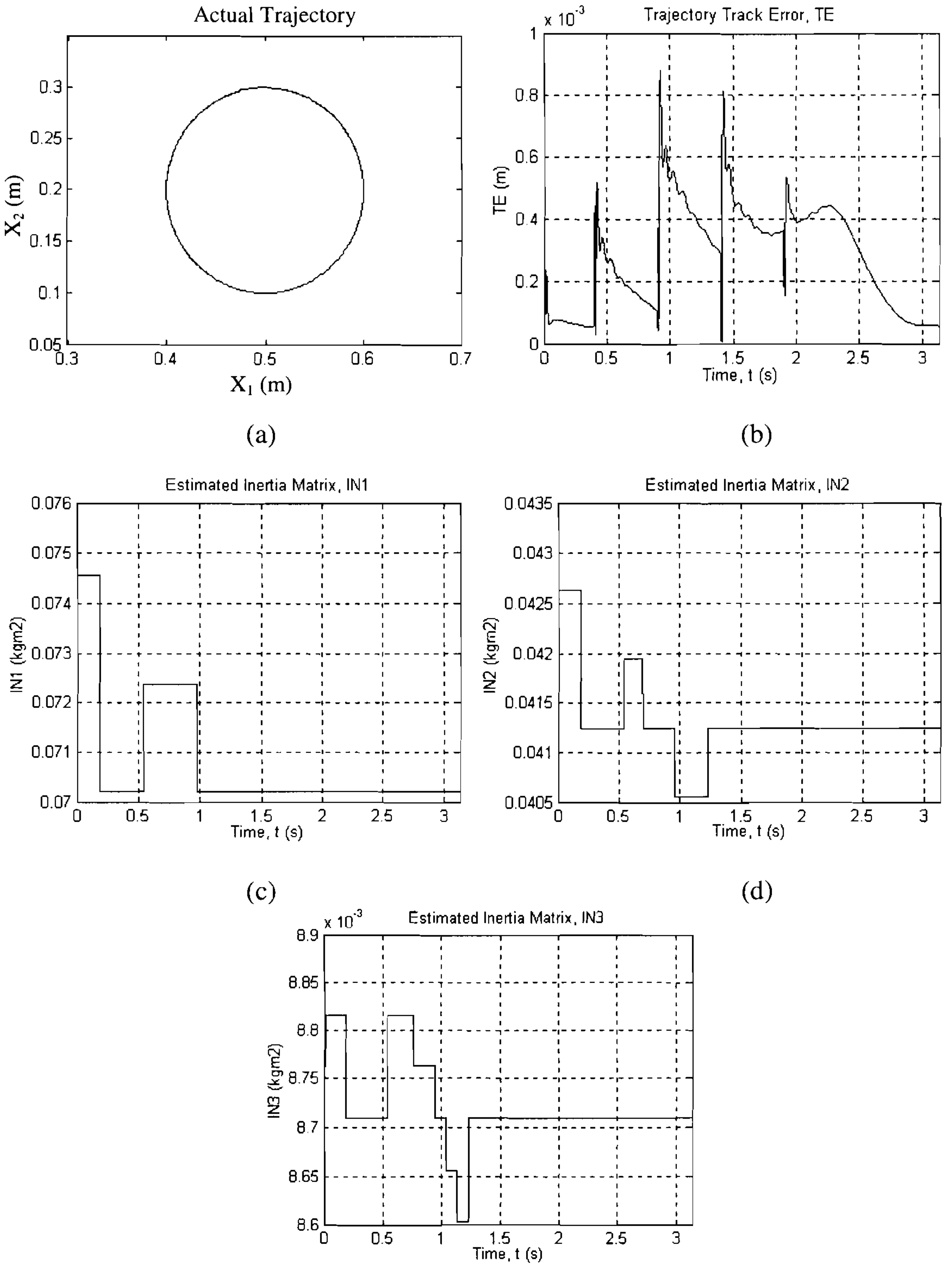


Figure 14 Results for the AFCAFL scheme, pulsating force, F_p = 100 N

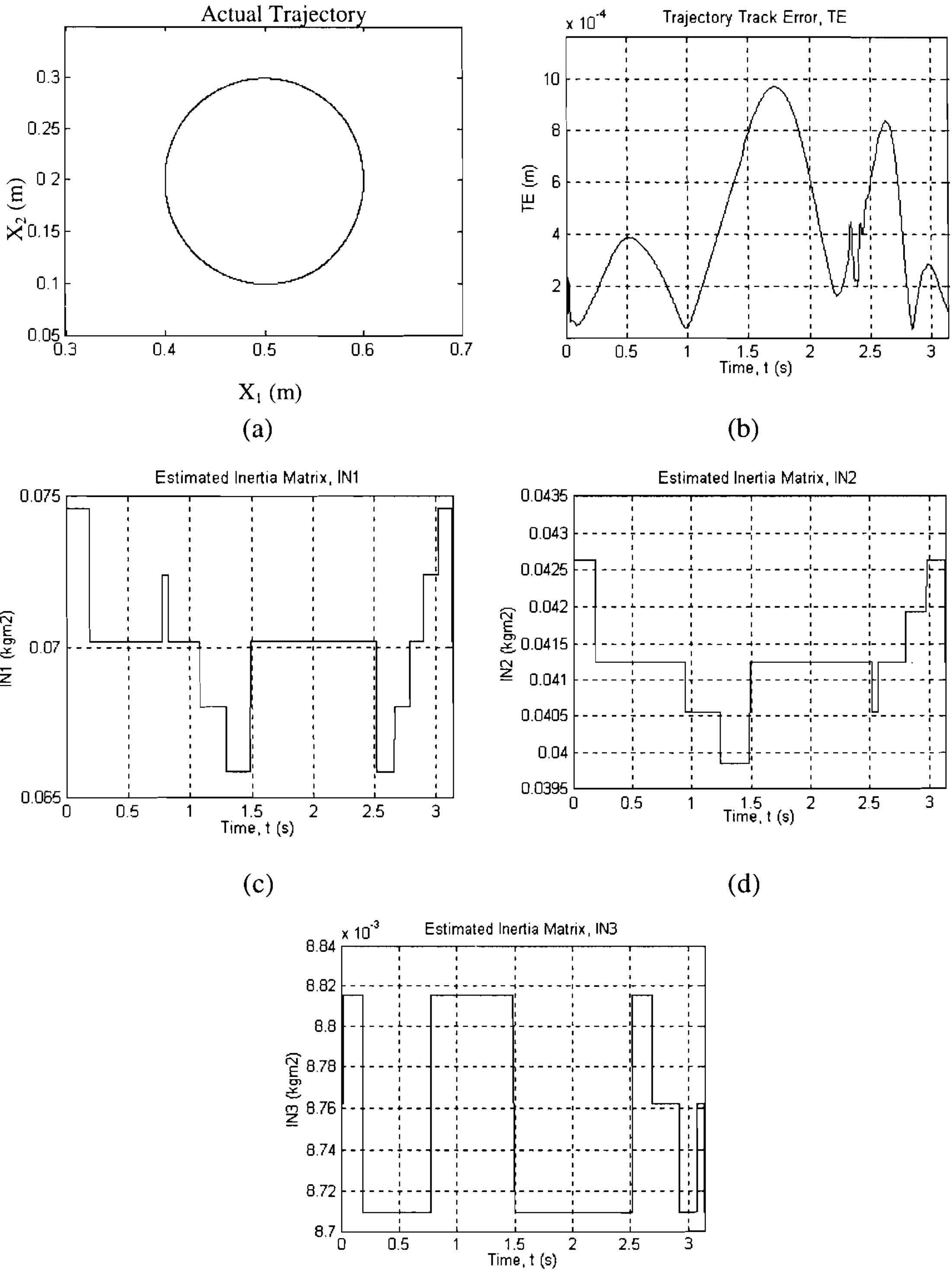


Figure 15 Results for the AFCAFL scheme, spring force with spring constant, k = 400 N/m

The system with applied torque disturbance T_q experiences the smallest maximum trajectory track error, which is 0.22 mm. On the other hand, the one with spring force F_s has the largest maximum trajectory track error, which is 0.98 mm. For the no disturbance and pulsating force conditions, the maximum trajectory track errors are 0.24 mm and 0.88 mm respectively. The trajectory track error curves for F_o, T_q and F_s systems exhibit sinusoidal curve patterns whereas the F_p system exhibits a series of spikes that indicates the direct effect of the pulsating and intermittent nature of the applied force.

7.2 Estimated Inertia Matrix

With reference to graphs (c), (d) and (e) of Figures 12 through 15, the estimated inertia matrix (**IN**) curves for all the figures exhibit discrete signal patterns in the form of a series of 'steps' with or without very little time lag and varies positively within certain limits. Moreover, it was found that the inertial value of link-1 (IN_1) always has the largest positive value followed by that of link-2 (IN_2) and finally of link-3 (IN_3) where IN_3 always has the smallest positive value. This is because at the joint of link-1, the forces and torques with respect to every link are accumulated here, whereas it can be easily seen that the joint of link-3 has to support only the force/torque in link-3. Table 3 summarizes the range of IN_1, IN_2 and IN_3 computed by the fuzzy logic controller under the influence of the four types of disturbances.

Table 3 Ranges of IN_1, IN_2 and IN_3 computed by the fuzzy logic controller

Type of Disturbances	**Estimated Inertia Matrix Range, IN (kgm^2)**		
	IN_1	IN_2	IN_3
No disturbance, $F_0 = 0$ N	0.06583-0.07457	0.04055-0.04263	0.008709-0.008816
Constant Torque, T_q = 100 Nm	0.06583-0.07457	0.04055-0.04263	0.008709-0.008816
Pulsating Force, F_p =100 N	0.07020-0.07457	0.04055-0.04263	0.008603-0.008816
Spring Force, $F_s = 400\,\Delta x$	0.06583-0.07457	0.03986-0.04263	0.008709-0.008816

8.0 CONCLUSION

The proposed AFCAFL performs excellently even under the influence of external disturbances. The FL controller embedded in the AFC scheme used in the study has been shown to be very effective in generating the required estimated inertia matrix automatically, continuously and on-line, which when implemented to the main control scheme with or without disturbances, produces favorable results. The estimated inertia matrix varies within a range of values as expected. Thus, the integration of the FL in the AFC strategy is shown to be feasible and practical. The trajectory track error obtained is reasonably small (less than 1%) showing the excellent capability of AFCAFL scheme to accommodate the disturbances very effectively. The finding further substantiates previous works in similar area, thereby verifying the robustness and effectiveness of the AFC scheme. For future development, this work can be extended to applications involving a more intricate design of the fuzzy logic controller and designing hybrid intelligent control with adaptive features applied to the system to enhance the system capability. Also, other form of complicated prescribed trajectories within the robot workspace and different disturbances should be considered to further investigate the dynamic performance of the system.

ACKNOWLEDGEMENT

The authors are grateful to Dr. Leon Zlajpah of Jozef Stefan Institute, Slovenia who personally provides the *Planar Manipulator Toolbox* used in the study.

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