Intelligent Active Force Control of a Robot Arm Using Fuzzy Logic

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Abstract: The paper describes a novel and intelligent method of estimating the inertial parameter of a rigid robot arm employing an active force control (**AFC**) strategy with a fuzzy logic (**FL**) mechanism embedded in its control loop. The robustness and effectiveness of the proposed control scheme are investigated considering the trajectory track performance of the arm taking into account the application of some forms of external disturbances as the robot describes a reference trajectory given a number of initial and operating conditions. The track performance of the proposed scheme is also compared with an equivalent system employing classical proportional-derivative (**PD**) control.

Keywords: active force control, fuzzy logic, estimated inertia matrix.

I. INTRODUCTION

Force control of a robot arm is important because it deals with the interaction of the end effector with the environment (free or constrained) and various forms of external disturbances. Conventional control such as the classical **PD** control [1] is excellent when the robot operates either at low speed or in the absence of disturbances. The performance however degrades significantly with the presence of the two aforementioned factors. It is obvious that the method lacks the ability to compensate the disturbing elements. Adaptive force control methods [2,3] are proposed in view of its ability to adapt to changes in the parameters and uncertainties within appropriate range of values. However, more often than not it involves complex mathematical manipulation plus the need to impose bounds and assumptions in the analysis. Explicit force control method provides a specific means of tackling the applied forces/disturbances on the robot arm with the intention to compensate the effect via suitable control technique. A number of force control strategies has been proposed such as the hybrid force/position control [4], impedance control [5] and active force control [6]. Active force control (**AFC**) strategy unlike the former force control methods is a novel and more practical method in which the mathematical complexity is greatly minimized due to the fact that it operates on either the physical measurements of relevant parameters or simply their estimates.

In this paper, we propose an **AFC** strategy based on the works described in [3] but with the incorporation of an intelligent mechanism to estimate the inertial parameter of the robotic manipulator. We use **FL** for the purpose of updating this parameter continuously, automatically and on-line while the robot performs its task under the influence of disturbances. The paper is structured as follows; the first part describes the **AFC** strategy and the **FL** mechanism followed by a simulation study on the application of the method applied to a rigid two-link planar manipulator. Simulation results of the control schemes 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 arm. Finally, suitable conclusion is derived pointing out potential future works that can be carried out.

II. ACTIVE FORCE CONTROL

In **AFC**, it is shown that a robotic system subjecting to disturbances remains stable and robust through the compensating action of the control strategy. The full mathematical analysis of the **AFC** scheme can be found in [6-8]. The main computational burden in **AFC** is the multiplication of the estimated inertia matrix with the angular acceleration of the arm before being fed into the **AFC** feed-forward loop. Apart from that, the output of the system, e.g., *Cartesian* position needs to be computed from the joint angle space via forward kinematics and also the controller prior to the **AFC** loop be determined. For a given robot arm configuration, the schematic of a basic **AFC** method applied to control a robot arm is shown in **Fig. 1**. The principal advantage of **AFC** is the practical viability of the scheme to effect 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 need not be accurately approximated; the only requirement is that it should be within suitable range of values [6-8].

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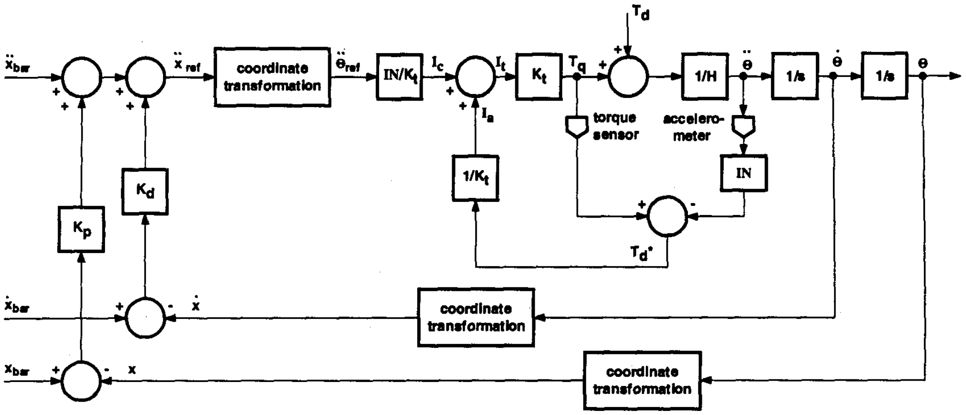


Fig. 1: The **AFC** scheme applied to a robot arm

The notation used in **Fig. 1** is as follows:

K_t : motor torque constant
K_p, K_d: controller gains
x : vector of positions in *Cartesian* space
θ : vector of positions in joint space
I_c : current command vector
I_a : compensated current vector
I_t : armature current for the motor
IN : estimated inertia matrix
$T_d{*}$: estimated disturbance torque
T_q : applied control torque
x, x_{bar}: vectors of the actual and desired positions respectively in *Cartesian* space

On the left-hand side of the figure, we have a resolved-motion-acceleration-control (**RMAC**) controller employing a proportional-derivative (**PD**) component. It is governed by the following equation:

$$\ddot{x}_{ref} = \ddot{x}_{bar} + K_d(\dot{x}_{bar} - \dot{x}) + K_p(x_{bar} - x) \qquad (1)$$

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 follows:

$$T_d{*} = T_q - IN\,\ddot{\theta} \qquad (2)$$

In **AFC**, we can effectively accommodate the disturbances by obtaining the measurements of the acceleration and the torque using physical accelerometer and torque sensor respectively. More conveniently, we can rewrite **Eqn. (2)** (based on the torque-current relationship) in the following form:

$$T_d{*} = K_t I_t - IN\,\ddot{\theta} \qquad (3)$$

In this way, we can instead measure the controlled current I_t to the motor and obtain exactly the same result. The **AFC** concept has been successfully implemented to robot arm via simulation and experimental works [6,7,9-13]. 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 **Eqn. (3)**. Previous cited works on **AFC** use traditional 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 conventional approaches described above. A number of intelligent methods has been proposed using neural network and iterative learning algorithms [13-15]. The proposed study described in the paper is in fact an extension to the previous methods; this time using fuzzy logic. The control scheme is to be known as **AFCAFL** (short for Active Force Control And Fuzzy Logic). The scheme applied to control a robot arm can be seen in **Fig. 2**.

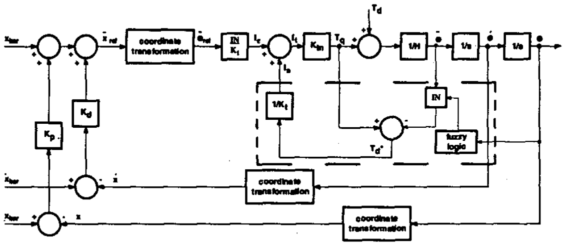


Fig.2: The proposed **AFCAFL** scheme

The **FL** component can be treated as a black box as shown in **Fig. 3** in which the input is the vector of joint angles (θ) while the required estimated inertia matrix (*IN*) of the arm is treated as the output to be fed into the **AFC** loop. The description of the **FL** mechanism is described in the following section.

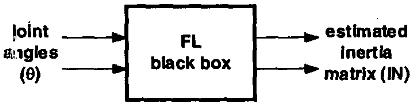


Fig.3: Fuzzy logic black box

III. FUZZY LOGIC CONTROL

A. 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 [16]. The basic **FL** concept is as shown in **Fig. 4**.

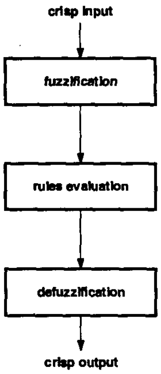


Fig. 4: Fuzzy concept

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 two-link arm is described in the following section.

B. Application of FL in AFC and Robot Control

The main aim of using the **FL** in the study is to compute the estimated inertia matrix (*IN*) of a robot arm intelligently so that it can be utilized by the **AFC** mechanism to effect its control strategy. Consider a representation of the arm as shown in **Fig.5**.

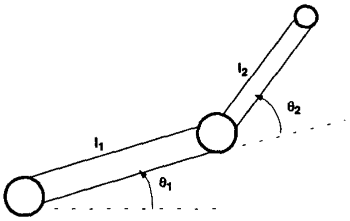


Fig. 5: A representation of the two-link robot arm

The mathematical model of the above arm is given as follows:

$$T_q = H(\theta)\,\ddot{\theta} + h(\theta, \dot{\theta}) + T_d \qquad (3)$$

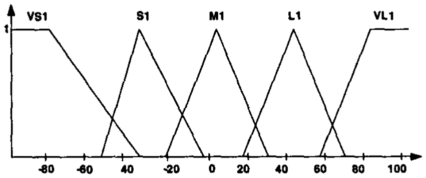
where

T_q: vector of actuated torque
H : $N\times N$ dimensional manipulator and actuator inertia matrix
h : vector of the *Coriolis* and centrifugal torque
T_d : vector of the external disturbance torque

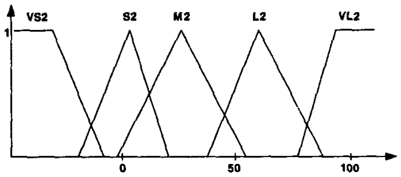
Note that the arm is assumed to operate horizontally; hence the gravitational torque is not considered. Also, throughout the study, we consider only the diagonal elements of the estimated inertia matrix *IN* and that for convenience we denote these as $IN_{11}=IN_1$ and $IN_{22}=IN_2$. The off-diagonal terms IN_{12} and IN_{21} are disregarded, i.e., $IN_{12}=IN_{21}=0$, since it has been shown that this coupling term can be safely ignored by the **AFC** strategy [6].

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

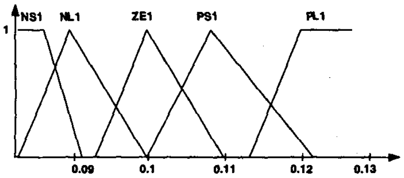
1. Membership functions representing the input (joint angles of the arm) and output (estimated inertia matrix of the arm) of the **FL** component are determined as part of the fuzzification process. Approximate values within specific bound are obtained based on crude approximation and also from the results previously acquired in [13-15]. The functions used in the study can be seen in **Fig. 6(a)** and **(d)**.



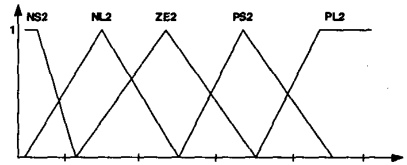
(a) Membership function for θ_1



(b) Membership function for θ_2



(c) Membership function for IN_1



(d) Membership function for IN_2

Fig. 6: Membership functions of the input and output

2. A set of rules is designed in the form of *if-then* structure. In the study, we use *Mamdani* fuzzy inference system [17]. Example is given as follows:

   IF th1 S AND th2 L THEN IN1 PS AND IN2 NS

   The above statement implies that if the first joint angle is small (S) and the second joint angle is large (L), then the estimated inertial parameter of the first link is positively small (PS) and that of the second link negatively small (NS).

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

$$\bar{x} = \frac{\int \mu_X(x).xdx}{\int \mu_X(x)dx} \qquad (4)$$

The method is depicted in **Fig. 7**.

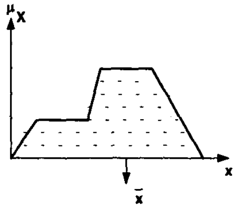


Fig. 7: Centroidal method

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

IV. SIMULATION OF THE PROPOSED AFCAFL CONTROL SCHEME

Simulation work is performed using the **MATLAB** and **SIMULINK** software packages[f]. In addition to that, we also use the *Fuzzy Logic Toolbox* for use with **MATLAB**. The **SIMULINK** block diagram for the proposed scheme is shown in **Fig. 8**.

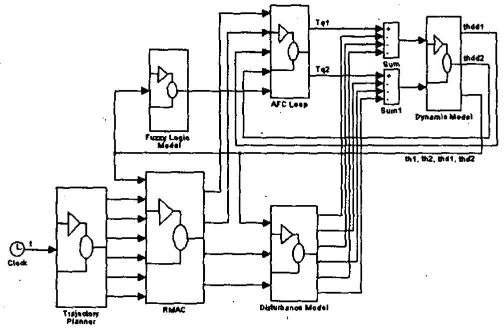


Fig. 8: A **SIMULINK** representation of the **AFCAFL** scheme

It comprises the trajectory planner, **RMAC** section, main **AFC** loop, robot dynamic model, fuzzy logic model and the disturbance model. These are interlinked by means of connecting lines representing the flow of signals and the relevant building blocks acquired from the **SIMULINK** library. In the simulation program, a number of disturbance torques can be described and introduced. In the study, we choose a combination of a spring force with stiffness k=300N/m and a pulsating force of magnitude 20N applied at the end of the second link. The reference trajectory is a circular path in which the arm has to track and the arm is assumed to be at rest at time t=0s. The fuzzy inference system used in the study is based on *Mamdani* model [17]. Other parameters related to the robot arm and controller is given below:

Robot parameters :

Link lengths,	$l_1 = 0.25$ m,	$l_2 = 0.2236$ m
Link masses,	$m_1 = 0.3$kg,	$m_2 = 0.25$ kg
Motor masses,	$mot_{11} = 1.3$ kg,	$mot_{21} = 0.8$ kg
Payload mass,	$mot_{22} = 0.1$ kg	

Controller parameters :

Controller gains,	$K_p = 750$ /s,	$K_d = 500$ /s^2
Torque constants,	$K_t = 0.263$ Nm/A	

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[f] **MATLAB** and **SIMULINK** are registered trademarks of The Math Works Inc.

V. RESULTS AND DISCUSSION

Fig. 9 through **12** show the results obtained from the simulation study.

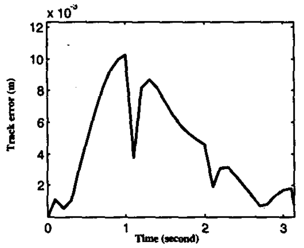

Fig. 9: Trajectory track error of the arm (**PD** scheme)

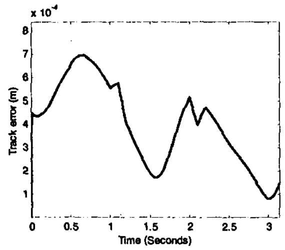

Fig. 10: Trajectory track error of the arm (**AFCAFL** scheme)

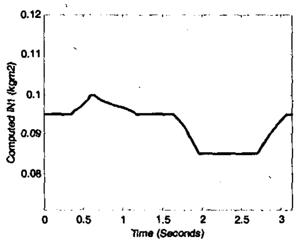

Fig. 11: Computed inertial parameter of the first link

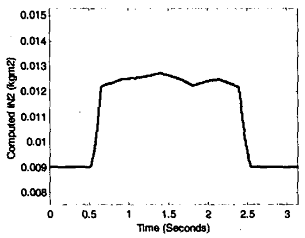

Fig. 12: Computed inertial parameter of the second link

For the classical **PD** control scheme, it can be seen from **Fig. 9** that the track error is very large, the maximum of which is about 10 mm. This is in contrast with that obtained for the **AFCAFL** scheme in which the maximum error is only 0.7 mm as shown in **Fig. 10**. This clearly implies that the proposed **AFCAFL** scheme is able to track the reference trajectory very accurately even when the spring and pulsating forces are applied. The track error curves for both schemes exhibits sinusoidal curve pattern with a series of '*spikes*' - an indication of the effect of the applied forces acting on the arm particularly the intermittent pulsating force.

The computed *IN* shows the non-linear feature of the parameter and that it varies within certain limits (**Fig. 11** and **12**). Based on the track performance of the proposed method, the inertial parameter of the arm is said to be appropriately identified. The approximate range of *IN* value for the first link is 0.085 kgm^2 to 0.1 kgm^2 while for the second link it is found to be 0.009 kgm^2 to 0.0128 kgm^2.

VI. CONCLUSION

The proposed **AFCAFL** performs excellently even under the influence of external disturbances. The **FL** mechanism computes *IN* automatically and continuously while the robot arm is in operation. Also, the inertial parameter varies non-linearly within a range of values as expected. The finding further substantiates previous works in similar area; thereby verifying the robustness of the **AFC** scheme. Future study should investigate the more intricate design of the fuzzy controller mechanism. The possibility of designing hybrid intelligent control with adaptive features should also be considered.

VII. ACKNOWLEDGEMENT

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