# A New Approach to Control of Robot

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***Abstract*—In this paper, a new and simple method to design a robust controller for a robotic system is proposed. The presented work expands on previous research into the uses of robust control design methodology. Specifically, we combined quantitative feedback theory (QFT) with the fuzzy logic controller (FLC). This combination takes advantage of both methodologies. The hybrid controller could be utilized to control a class of nonlinear systems, where the plant is expressed as a linear model with time varying parameters. In order to illustrate the utility of our algorithm, we apply it to a robot arm having two degrees of freedom. A desired trajectory is specified. First, a robust QFT controller is designed for each link of the robot arm. QFT controller is used to follow the desired trajectory. Next, an appropriate fuzzy controller is designed to alleviate the complexities of the system dynamics. Lastly nonlinear simulation for tracking problem in an arbitrary path has been carried out which indicates successful design of QFT and Fuzzy controllers.**

***Keywords*—QFT, loop shaping, prefilter, fuzzy control, nonlinear system.**

## I. Introduction

The main difference between multiple-input multiple-output (MIMO) control systems and single-input single-output (SISO) control systems is in the means of assessing and compensating for the interaction between the degrees of freedom. MIMO systems usually include complicated dynamic coupling. Determining the accurate dynamic model and decoupling it for designing the controller is very difficult. Therefore the model established on SISO system control plan is hard to apply to complicated MIMO systems because the computational load is large. Moreover loop shaping [1] is a key step in the process of designing a controller. Even shaping a controller around a SISO plant may not be a simple task. For complicated applications it may be hard, even for one skilled in the art, it might take a long time and a close to optimal controller is not guaranteed [2-3]. Clearly, the difficulty in controlling MIMO systems is how to solve the coupling effects between the degrees of freedom [2-4]. Although QFT control has been successfully employed in many control engineering fields [5-7], its control strategies were mostly designed for SISO systems, in spite of the effect of dynamic coupling on a MIMO control system. So designing controller for SISO systems do not have sufficient accuracy.

Considering the complexities of a QFT controller design [8] and complexities of a system being controlled, a new and simple control system is proposed where QFT and Fuzzy logic are uses.

## II. Methode of Control

### A. QFT controller design

QFT is the main controller for controlling each degree of freedom of the system. QFT is a robust feedback control system design technique introduced by Horowitz [9], which allows direct design to closed-loop robust performance and stability specifications.

Consider the feedback system shown in Fig.1. This system has two-degrees of freedom structure. In this diagram p(s) is uncertain plant belongs to a set $p(s) \in \{p(s, \alpha);\ \alpha \in p\}$ where α is the vector of uncertain parameters for uncertainty structured of p(s), G(s) is the fixed structure feedback controller and F(s) is the prefilter [3].

### B. Fuzzy controller designs

Fuzzy control originally proposed by Lotfi Zadeh in 1965, fuzzy logic is a method of classifying a quantity by expressing that it is neither "Big" nor "Small" but to appoint a value to the "Smallness" or "Bigness" of the quantity. [10]

Fuzzy logic was later expanded into a decision making process which results to fuzzy control.

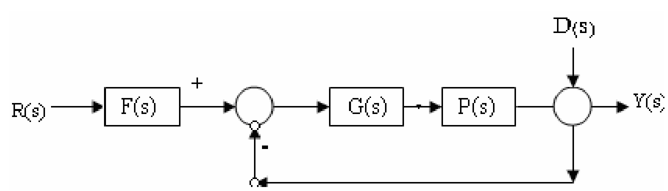


Figure 1. Structure of a Two Degrees of Freedom System

## III. Illustrative Example (Two link robotic manipulator)

A 2×2 MIMO problem (control of a two link robotic manipulator) is employed to illustrate the application of the method mentioned in Section. 2.

The purpose of a robot is to control the movement of its gripper to perform various industrial jobs such as assembly, material handling, painting, and welding [11]. Robot manipulators have complex nonlinear dynamics that might make accurate and robust control difficult. Fortunately, robots are in the class of Lagrangian dynamical systems, so that they have several extremely nice physical properties that make their control straight forward. There are several methods for controlling of a robot such as: classical joint control, digital control, adaptive control, robust control, learning control, and force control [12-14]. In this paper we consider the two arm manipulators as a two degree of freedom nonlinear system and as a controlling mentioned procedure will be used.

### A. Dynamic equations of the robotic manipulator

Fig.2 depicts a two degree of freedom robot, where $m_1, m_2$ are the masses of links 1, 2 and $l_1, l_2$ are the length of the links 1, 2 respectively. The dynamic equation of the robotic manipulator is [11].

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) = \tau \quad (1)$$

G (q) is a 2×1 gravity vector where g represents gravity acceleration constant.

$C(q,\dot{q})$ is a 2×2 matrix of coriolis and centrifugal forces.

The following numerical values are chosen for the robot manipulator (m1=2kg, m2=3kg, L1=0.4m and L2=0.6m) [14]. So, dynamic equations of the robot can be derived as follows:

$$\begin{aligned}\tau_1 &= (0.9467 + 0.72\cos(q_2))\ddot{q}_1 + (0.36 + 0.36\cos(q_2))\ddot{q}_2 - 0.72\dot{q}_1\dot{q}_2 \\ &\quad - 0.36\dot{q}_2^2\sin(q_2) + 15.68\cos(q_1) + 8.82\cos(q_1+q_2) \\ \tau_2 &= (0.36 + 0.36\cos(q_2))\ddot{q}_2 + 0.36\ddot{q}_2 + 0.36\dot{q}_1^2\sin(q_2) \\ &\quad + 8.82\cos(q_1+q_2)\end{aligned} \quad (2)$$

Block diagram representation of the above equations which simulates nonlinear multivariable dynamics of robot in MATLAB is show in Fig 3.

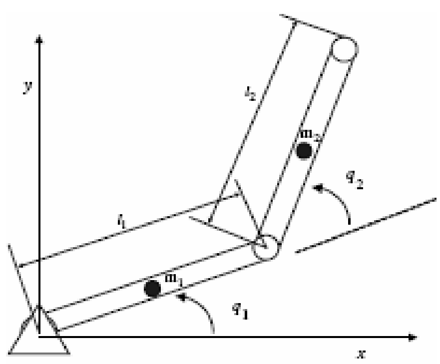


Figure 2. Two-link robotic manipulator

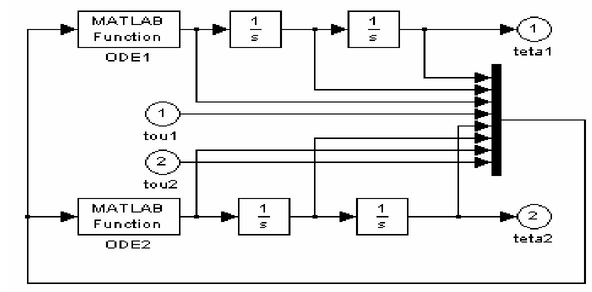


Figure 3. Simulation of Robot Dynamic in MATLAB

### B. Design of QFT controller for nonlinear systems

In QFT method, the nonlinear plant is converted to family of linear and uncertain processes. For this purpose, literature on QFT offers two different techniques [3], namely Linear Time Invariant Equivalent (LTIE) of nonlinear plant, and Non Linear Equivalent Disturbance Attenuation (NLEDA) techniques.

In both methods, limited accepted output is the main tool to translate nonlinearities of the plant into templates for the first technique, or disturbance bounds for the second technique.

In this paper the first method is used. For this conversion at the first acceptable out put set is introduced and then the input set produced. Dividing of output laplasian to input laplasian, introduces transfer function between each input and out put. This transfer function will be linear and uncertain. Response condition is provided with use of fixed-point theorem [3], [15].

In this paper the Golubev method [15] is applied for each input-output set, in order to reach directly to a linear time-invariant transfer function, relating acceptable plant input-output data set.

Next step involves linearization by using Golubev method. Application of this method involves producing acceptable out put set, and then based on nonlinear dynamic obtaining input set. Dividing of output laplasian to input laplasian, introduces transfer function between each input and out put. This transfer function will be linear and uncertain. By generating different trajectory for robot arm suitable output set will be produced then according to nonlinear dynamic of robot associated input set (required torque in joints) will be obtained. Robotic Toolbox was used for solving inverse kinematics of robot Fig 4.

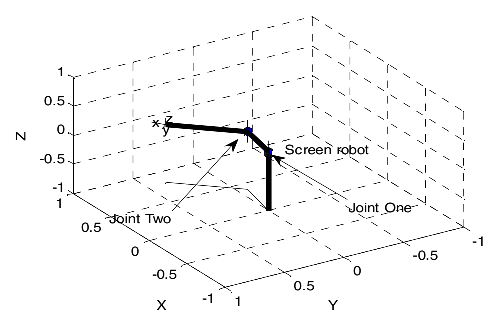


Figure 4. Application of Robotic Toolbox for solving inverse kinematics

In order to find the linear uncertain plant transfer function, numerical methods can be used. Therefore by means of numerical software which applies in frequency domain (with minimization of square error between input and output of nonlinear transfer function) the uncertain linear family of processes was achieved.

Figure 5 depicts nonlinear dynamic of robot which is modeled with an uncertain linear 2×2 by two matrix transfer function.

Seven different paths were used in order to achieve suitable linear model. Therefore the uncertain linear matrix transfer function is as below:

$$P(s,\alpha) = \begin{bmatrix} P_{11}(s,\alpha) & 0 \\ 0 & P_{22}(s,\alpha) \end{bmatrix} \quad (3)$$

Where:

$$P_{11} = \frac{q_1}{\tau_1} = \frac{a_{11}}{s(s+b_{11})}; \qquad a_{11} \in [0.135 \;\; 0.185] \quad \text{and}$$

$$b_{11} \in [3.76 \;\; 10.3] \quad (4)$$

$$P_{22} = \frac{q_2}{\tau_2} = \frac{a_{22}}{s(s+b_{22})}; \quad a_{22} \in [0.24 \;\; 0.32] \quad \text{and}$$

$$b_{22} \in [-0.082 \;\; 5.597] \quad (5)$$

## C. Template Generation

Figs.6, 7 show plant uncertainty in Nichols chart for each arm. The linear uncertain plant transfer functions of manipulator can be modeled as below:


Figure 5. Substitution of nonlinear system with its associated linear system

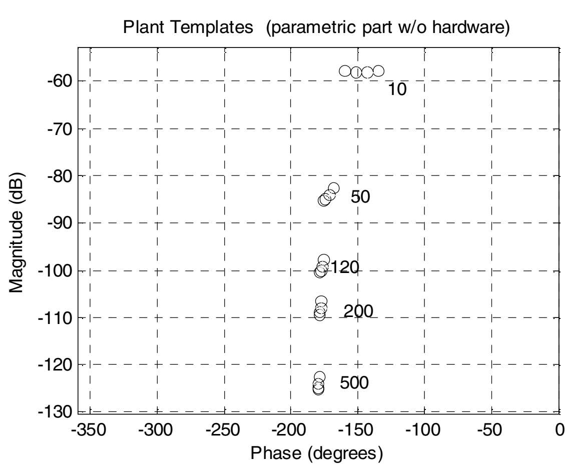


Figure 6. Uncertainty Templates for Arm 1

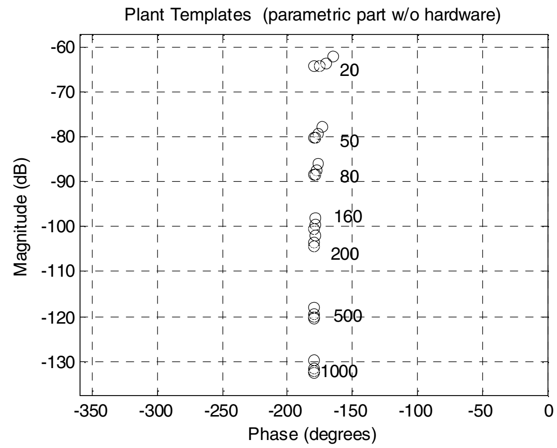


Figure 7. Uncertainty Templates for Arm 2

## D. Tracking Problem

The overshoot and the settling time specifications ($M_p$ =5%) and ($T_s$ =0.05 s) respectively are given in the form of upper and lower bounds in frequency domain, usually based on simple second-order models to represent the status of damped condition .Figs 8, 9.

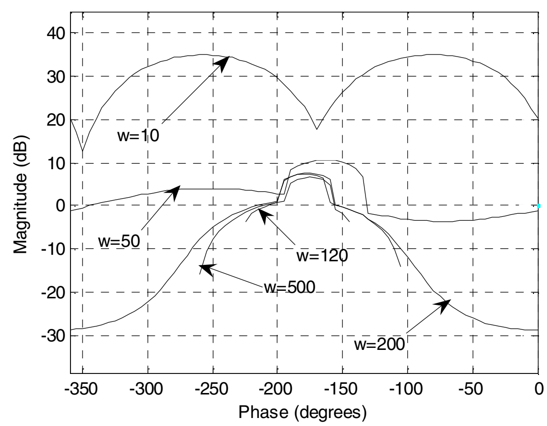


Figure 8. Robust Tracking Bounds for Arm 1

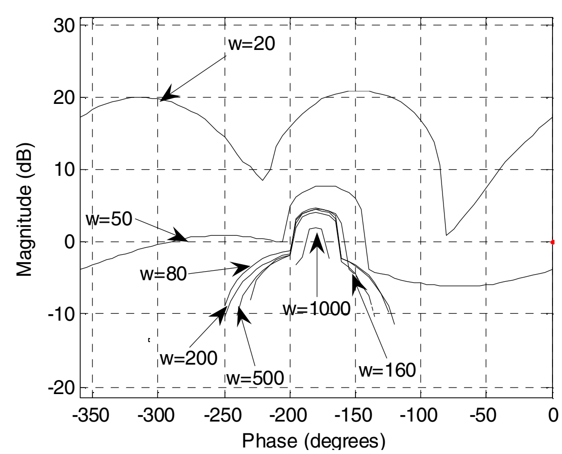


Figure 9. Robust Tracking Bounds for Arm 2

### E. Robust Margins

The following two conditions to achieve robust stability are:

First, stability of the nominal system which means: the Nichols chart envelope should not intersect the critical point *q* (-180°, 0 *dB*). [3]

Second, magnitude constraint condition which means: placing a magnitude constraint on the complementary sensitivity function. $\left|\frac{1}{1+1}(j\omega)\right|\langle 1.05$ for each arm (Figs. 10, 11).

### F. Robust Performance Bounds

Having obtained the robust-performance bounds tracking and robust stability bounds *(U*-contour) the overall bounds of the design can be calculated by combining appropriately the individual bounds for each point of the phase-grid. Figs. 12, 13

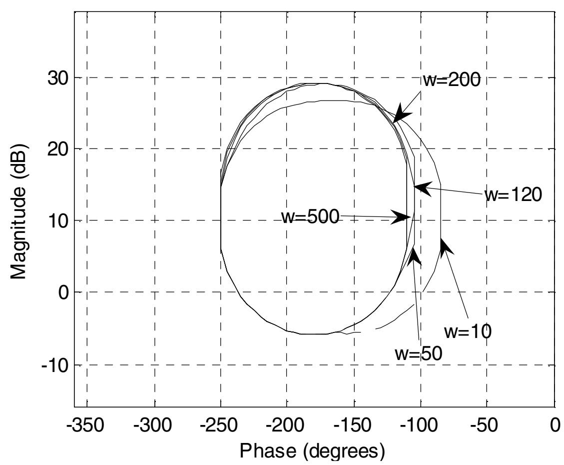

Figure 10. Robust Margins Bounds for Arm 1

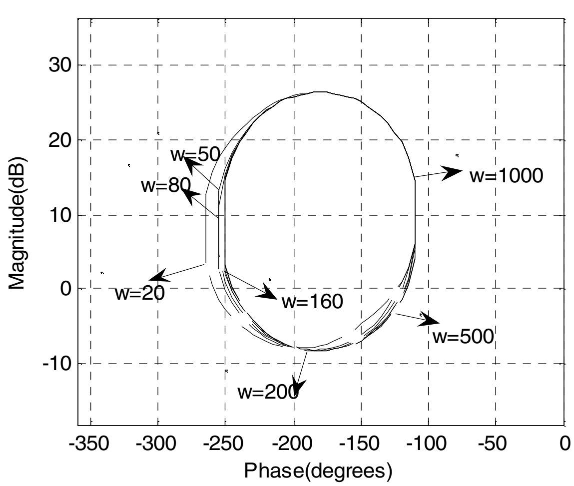

Figure 11. Robust Margins Bounds for Arm 2

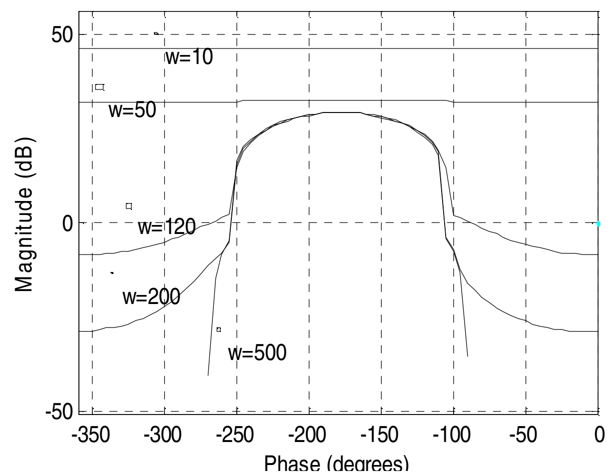

Figure 12. Robust Performance Bounds for Arm 1

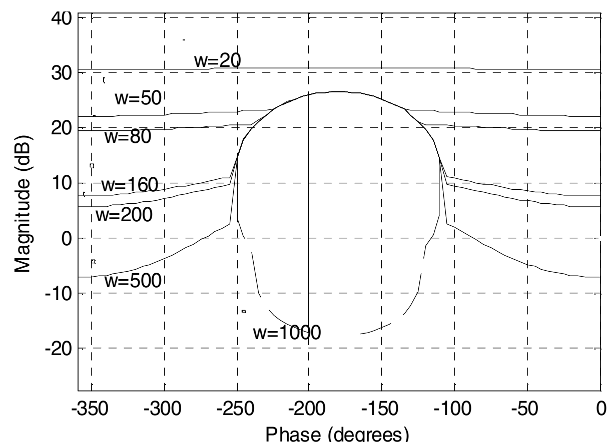

Figure 13. Robust Performance Bounds for Arm 2

### G. Loop and Pre-Filter Shaping

Among all possible controllers which meet the above requirements, the "best" design is considered to be the one in which the open-loop frequency response at the design frequencies lies as close as possible to the robust performance templates. This is in order to avoid "over-designing'' the system by using excessively large gains, which may lead to noise amplification, instability due to unmodelled dynamics, etc.

By using the elements of the QFT toolbox we design the controller so that the open loop transfer function exactly lies on its robust performance bounds and does not penetrate the U-contour at all frequency values ($\omega_i$).Fig. 14, 15. The design of pre-filter guarantees the satisfaction of tracking specification. In Figs. 16, 17 pre-filter shaping of open loop transfer function for each arm is shown. So the optimal controller and pre-filter are designed and given as follows.

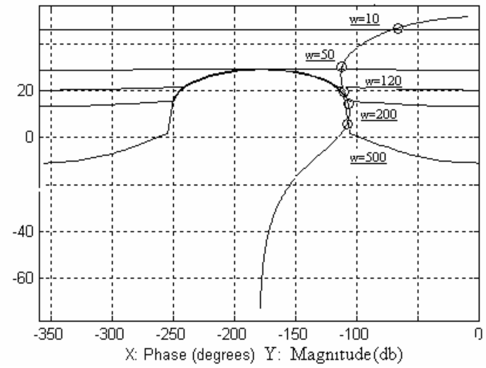


Figure 14. Loop-Shaping In Nichols Chart for Arm 1

$$G(s) = 238.33 \frac{s\,(s+77.58)}{\left(\frac{s}{26.76}+1\right)\left(\frac{s}{2213}+1\right)} \quad (6)$$

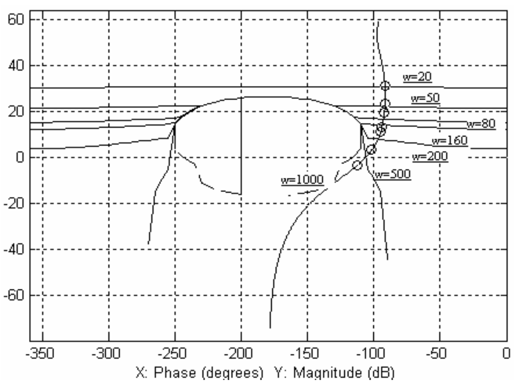


Figure 15. Loop-Shaping in Nichols Chart For Arm 2

$$G(s) = 3033.3 \frac{(s+2.012)}{\left(\frac{s}{2444}+1\right)} \quad (7)$$

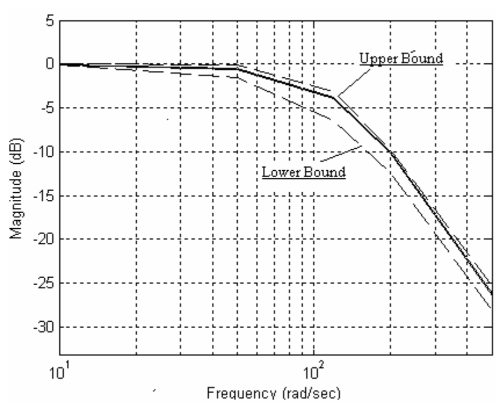


Figure 16. Pre-Filter Shaping in Nichols Chart for Arm 1

$$F(s) = \frac{138.1^2\left(\frac{s}{204.3}+1\right)}{\left(\frac{s}{122.1}+1\right)\left(s^2+207.15\,s+138.1^2\right)} \quad (8)$$

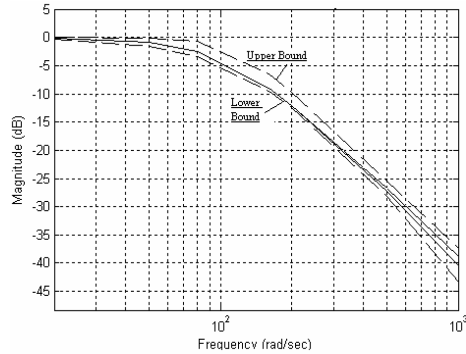


Figure 17. Pre-Filter Shaping in Nichols Chart for Arm 2

$$F(s) = \frac{107.5^2\left(\frac{s}{1542}+1\right)}{\left(s^2+181.1\,s+107.5^2\right)} \quad (9)$$

## IV. FUZZY CONTROLLER

Fig. 18 shows the membership function of the fuzzy controller. Fig 19 demonstrates the fuzzy control rules in controlling a robotic system [14].

$$\alpha_i^j = \begin{cases} \alpha_1^1 = \alpha_2^1 = 1.2 \\ \alpha_1^2 = \alpha_2^2 = 0.02 \\ \alpha_1^3 = \alpha_2^3 = 1.4 \end{cases} \quad (10)$$

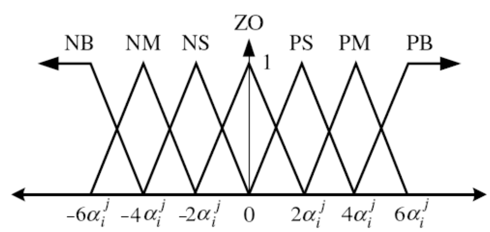


Figure 18. Membership functions of a coupling fuzzy controller [14]

| $\tilde{U}_i$ \ $\tilde{E}_i$ / $\tilde{\dot{E}}_i$ | NB | NM | NS | ZO | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | NB | NB | NB | NM | NS | NS | ZO |
| NM | NB | NB | NM | NM | NS | ZO | PS |
| NS | NM | NM | NS | NS | ZO | PS | PM |
| ZO | NM | NM | NS | ZO | PS | PM | PM |
| PS | NM | NS | ZO | PS | PM | PM | PB |
| PM | NS | ZO | PS | PM | PM | PM | PB |
| PB | ZO | PS | PM | PM | PM | PB | PB |

Figure 19. Fuzzy control rules [14].

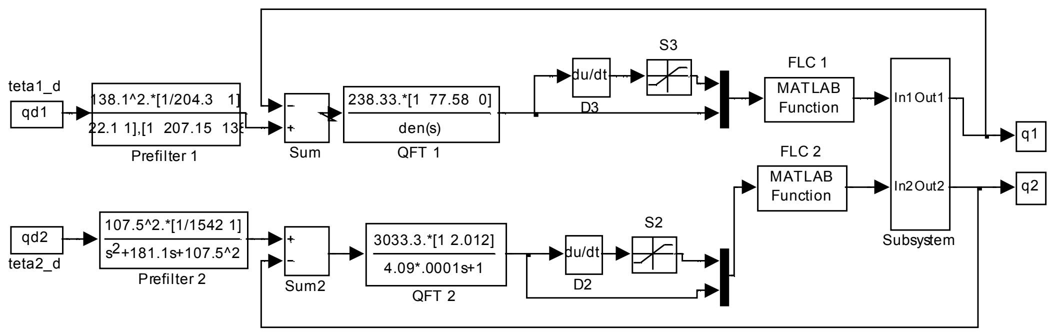


Figure 20. Block diagram of the control strategy

## V. NONLINEAR ANALYSIS OF ROBOT

Fig. 20 demonstrates the block diagram of the control strategy which including QFT and Fuzzy controllers.

The result of tracking problem for an elliptical path is shown in Fig .21.

## VI. CONCLUSIONS

This paper presents a new and simple algorithm for designing a robust controller for a system applying QFT and fuzzy techniques. The advantages of such a method can be demonstrated as following:

By combining QFT and FLC the advantages from both methodologies are achieved.

Successful implementation of robust controller design for a two arm manipulator.

We should notice that tracking accuracy by using tighter robust performance bounds could be increased which in turn leads to an increase in the controller gain, therefore based on the design limitation suitable solutions will be obtained.

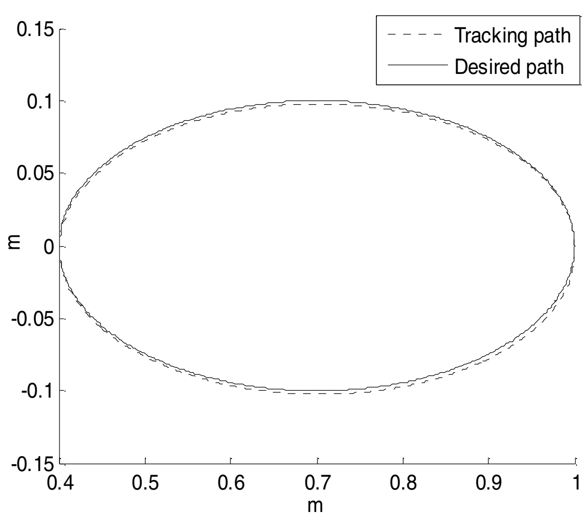


Figure 21. Tracking Problem for Elliptical Path

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