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&
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TERM PAPER

FUZZY LOGIC CONTROL OF A FOUR ROTOR UNMANNED AIR VEHICLE, QUADROTOR

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I. INTRODUCTION

A quadrotor is an unmanned air vehicle which has four rotors located at the ends of a cross frame. A quadrotor UAV can be highly maneuverable, has the potential to hover and to take off, fly, and land in small areas, and can have simple control mechanisms. However, because of its low rate damping, electronic stability augmentation is required for stable flight.

Typical aircraft can fly with considerably less thrust than required by a rotorcraft in hover. As the scale decreases, however, the ratio of wing lift to drag decreases and so does the conventional aircraft's advantage. Small-area monitoring, building exploration and intervention in hostile environments, surveillance, search and rescue in hazardous cluttered environments are the most important applications. Thus, vertical, stationary and slow flight capabilities seem to be unavoidable making the rotorcraft dynamic behavior a significant pro. A quadrotor may also be able to fly closer to an obstacle than conventional helicopter configurations that have a large single rotor without fear of a rotor strike.

In the literature, nonlinear control techniques such as input-output linearization, backstepping and sliding mode control have been succesfully applied experimentally to a quadrotor UAV. There aren't any journals found about fuzzy logic application to a quadrotor. However there are some journals about the application of fuzzy logic control to a conventional helicopter. In this project fuzzy logic control of a quadrotor is done without the aid of any journals, but two of the journals about fuzzy logic control applications to a conventional helicopter are included with the paper which are similar in terms of human control strategies.

II. QUADROTOR CONCEPT

A quadrotor has four motors located at the front, rear, left, and right ends of a cross frame. The quadrotor is controlled by changing the speed of rotation of each motor. The front and rear rotors rotate in a counter-clockwise direction while the left and right rotors rotate in a clockwise direction to balance the torque created by the spinning rotors as shown in Figure 1.

Rotate Left   Rotate Right

Going Up   Move Right

Figure 1 – Quadrotor Concept

III. DYNAMIC MODEL

The quadrotor has six degrees of freedom which are translations and rotations. There will be two coordinate frames which are body fixed frame and earth frame as shown in Figure 2.

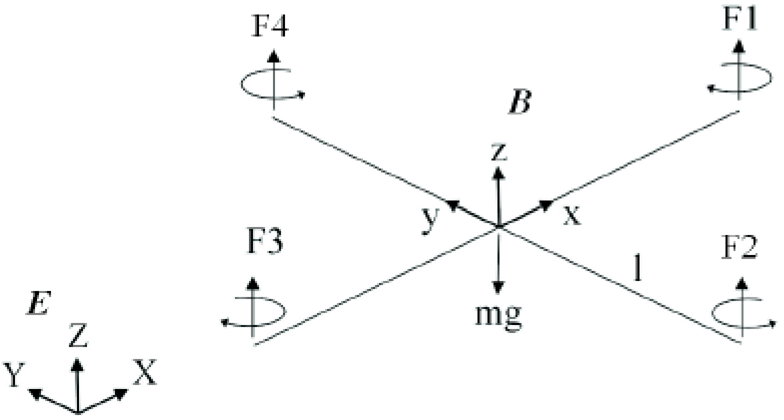

Figure 2 – Body fixed frame and earth frame

A simplified dynamic model of the quadrotor can be obtained from the literature where translations are expressed with respect to earth frame as shown below:

$$m\ddot{X} = \sum_{i=1}^{n} F_i(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)$$

$$m\ddot{Y} = \sum_{i=1}^{n} F_i(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi)$$

$$m\ddot{Z} = \sum_{i=1}^{n} F_i(\cos\theta\cos\psi) - mg$$

$$I_{xx}\ddot{\psi} = (F_3 - F_1)l$$

$$I_{yy}\ddot{\theta} = (F_4 - F_2)l$$

$$I_{zz}\ddot{\phi} = C(-F_1 + F_2 - F_3 + F_4)$$

Where;

ψ	: Rotation around x axis	X	: Translation along X axis of earth frame
θ	: Rotation around y axis	Y	: Translation along Y axis of earth frame
ϕ	: Rotation around z axis	Z	: Translation along Z axis of earth frame
I_{xx}	: Inertia around x axis	C	: Force to moment scaling factor
I_{yy}	: Inertia around y axis	l	: Distance between rotors and C.G.
I_{zz}	: Inertia around z axis	m	: Mass of quadrotor
$\sum_{i=1}^{4} F_i$	: Total thrust		

If we select the control inputs as;

$$
\begin{aligned}
u_1 &= (F_1 + F_2 + F_3 + F_4)/m \\
u_2 &= (F_4 - F_2)/I_{yy} \\
u_3 &= (F_3 - F_1)/I_{xx} \\
u_4 &= C(-F_1 + F_2 - F_3 + F_4)/I_{zz}
\end{aligned}
$$

Dynamic equations of the quadrotor will become:

$$
\begin{aligned}
\ddot{X} &= u_1(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) \\
\ddot{Y} &= u_1(\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi) \\
\ddot{Z} &= u_1(\cos\theta \cos\psi) - g \\
\ddot{\theta} &= u_2 l \\
\ddot{\psi} &= u_3 l \\
\ddot{\phi} &= u_4
\end{aligned}
$$

A. Physical Values & Constraints

Physical values of the quadrotor which can be obtained from the literature are shown below:

$I_{xx} = 0.0142\,kg.m^2$ $\quad l = 0.21m$ $\quad C = 1.3$

$I_{yy} = 0.0142\,kg.m^2$ $\quad m = 0.56\,kg$

$I_{zz} = 0.0071\,kg.m^2$ $\quad g = 9.81\,m/s^2$

Maximum thrust force which can be generated at one propeller is restricted to 10N. So the inputs to the system are limited to:

$F_{\max} = 10N \qquad F_{\min} = 0N$

$$
\begin{array}{rcr}
0 \le u_1 \le 4F_{\max}/m & & 0 \le u_1 \le 71.429 \\
-F_{\max}/I_{yy} \le u_2 \le F_{\max}/I_{yy} & \Rightarrow & -704.23 \le u_2 \le 704.23 \\
-F_{\max}/I_{xx} \le u_3 \le F_{\max}/I_{xx} & & -704.23 \le u_3 \le 704.23 \\
-2CF_{\max}/I_{zz} \le u_4 \le 2CF_{\max}/I_{zz} & & -3662 \le u_4 \le 3662
\end{array}
$$

B. Properties of Dynamic Model

From the dynamic model of the quadrotor we see some special properties as listed below:

- Rotations are not affected by translations
- Angular subsystem is linear
- System is underactuated
- System has coupling effects
- System is unstable

IV. CONTROL STRATEGY

While the rotations are not affected by translations we can split the system into two subsystems as shown in Figure 3.

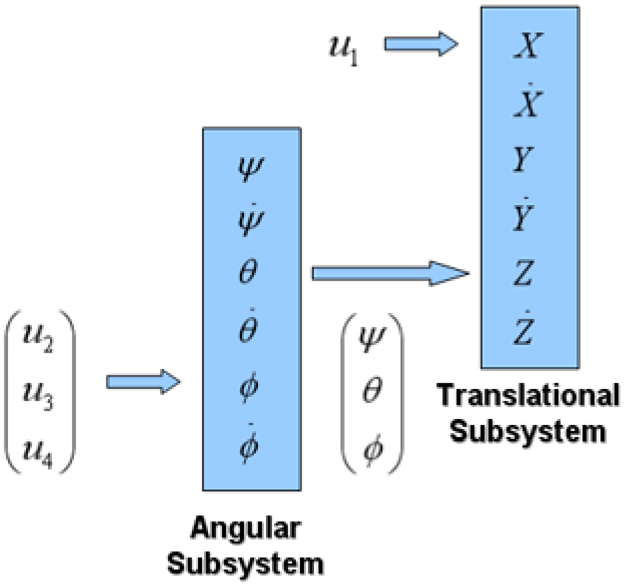

Figure 3 – Angular and translational subsystems

Angular subsystem can be controlled independent from the translational subsystem with the control inputs u_2, u_3, u_4. Outputs from angular subsystem will be the inputs to the translational subsystem together with the control input u_1. First stabilization of the angular subsystem will be realized using 3 independent fuzzy logic controllers. Altitude control will be realized with the control input u_1 using 1 fuzzy logic controller. X and Y motion of the quadrotor will be controlled with the angles θ and ψ respectively. Changing these angles will generate X and Y components from the total thrust force as shown in Figure 4.

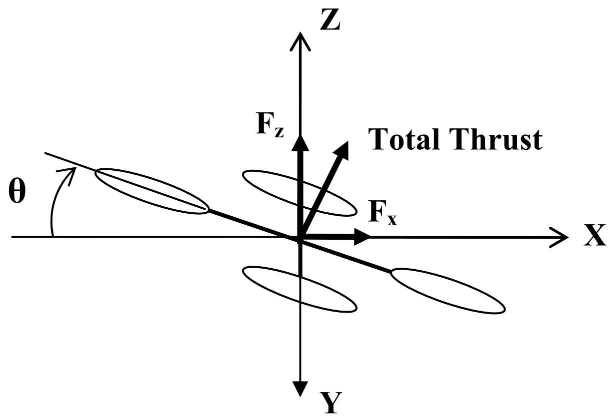

Figure 4 – Change of angle θ and components of the thrust vector

Changing angle θ or ψ will make the Z component of the thrust vector get smaller which is balancing the weight of the quadrotor in hover mode. This will make the altitude controller to increase the magnitude of the thrust vector.

V. FUZZY LOGIC CONTROL OF QUADROTOR

The block diagram of the controlled system with the fuzzy logic controllers will be as shown below:

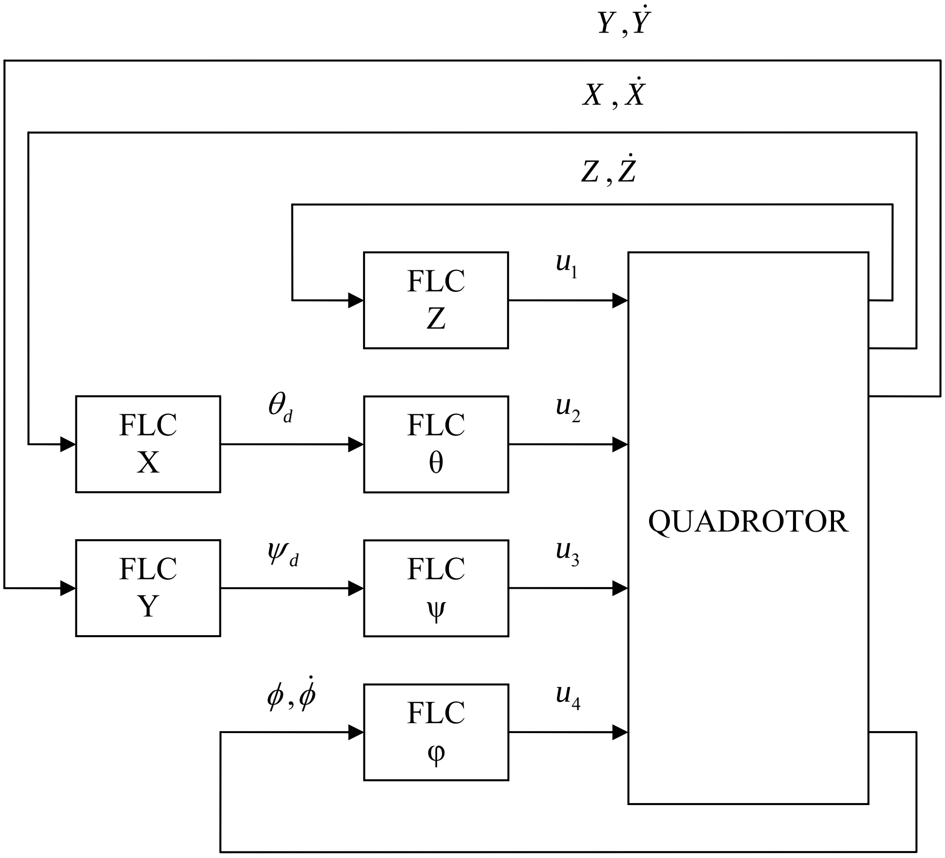

Figure 5 – Block diagram of the controlled system

Here controller FLC Z is controlling the altitude of the quadrotor. FLC θ , FLC ψ , FLC φ are the controllers which are controlling the desired angles. FLC X and FLC Y are controlling the X and Y motion through the states θ and ψ respectively.

All of the FLCs are setup with 9 rules. Increasing rules also increase the computation time while there are 6 FLCs as shown in Figure 5, so minimum number of rules is used. Also all of the controllers are designed as Fuzzy-PD controllers which have two inputs which are error and change in error and one output. All of the controllers are designed as mamdani type with max-min composition and with center of gravity deffuzification method. In addition to this all of the FLCs' rulebase are same and shown below:

Table 1. Rule Base

			e	
		P	**Z**	**N**
de	**P**	P	P	Z
	Z	P	Z	N
	N	Z	N	N

A. Z Motion Fuzzy Logic Controller Structure

This controllers input and MFs are shown below:

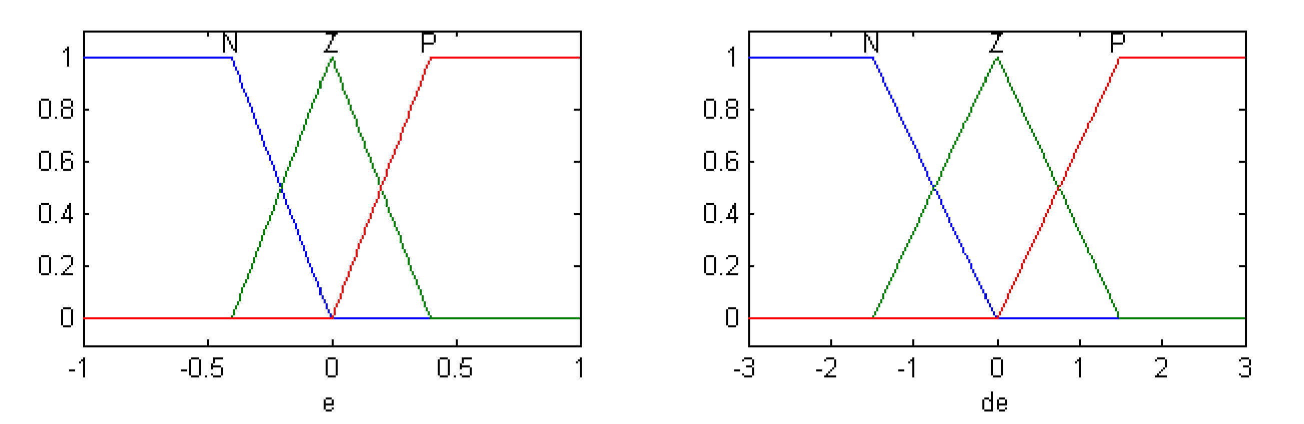

Figure 6 – Input MFs of Z motion FLC

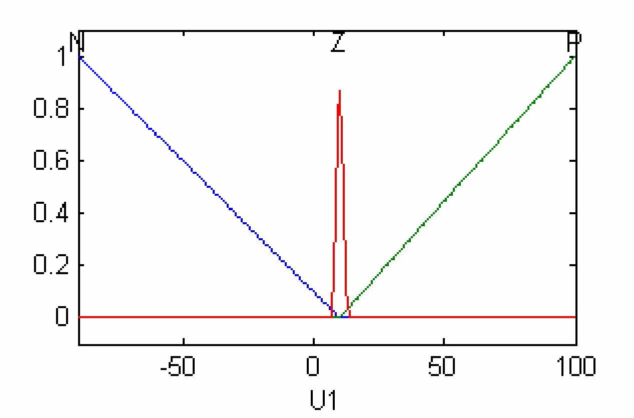

Figure 7 – Output MFs of Z motion FLC

This controllers zero output MF is in fact not zero and corresponds to 9.81 which is the gravity constant which must be balanced in steady state.

B. X and Y Motion Fuzzy Logic Controller Structure

These controllers both have the same structure as shown below:

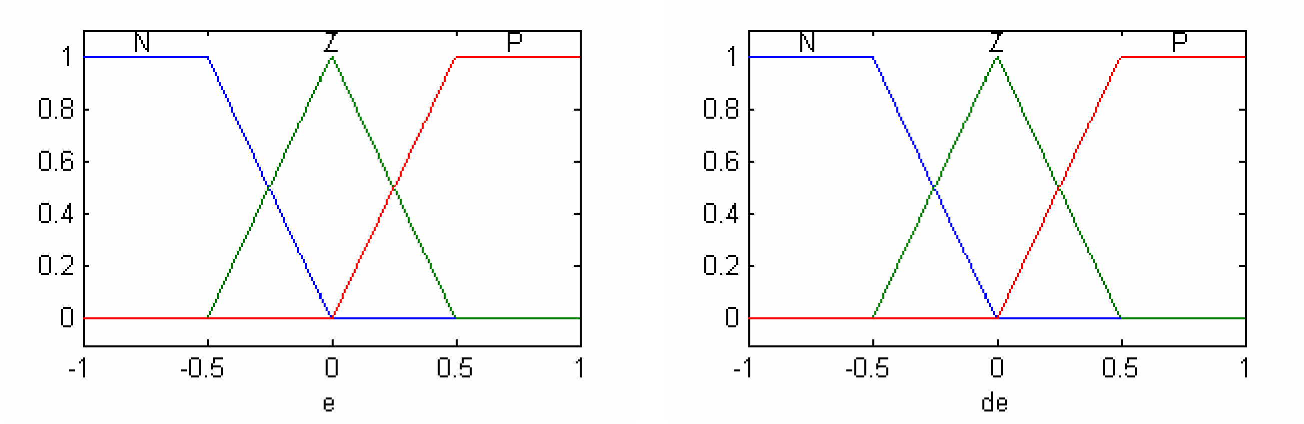

Figure 8 – Input MFs of X and Y motion FLC

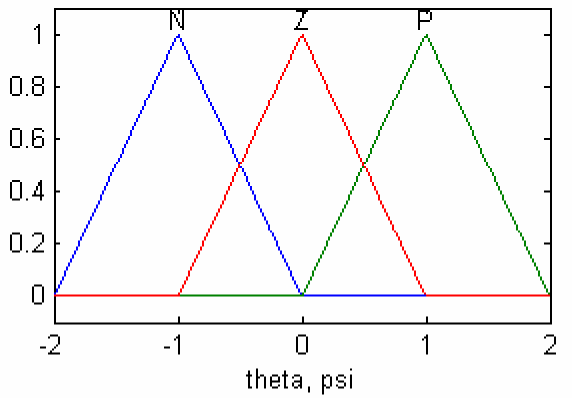

Figure 9 – Output MFs of X and Y motion FLC

C. θ and ψ Rotations Fuzzy Logic Controller Structure

These controllers also both have the same structure as it was for X and Y controllers as shown below:

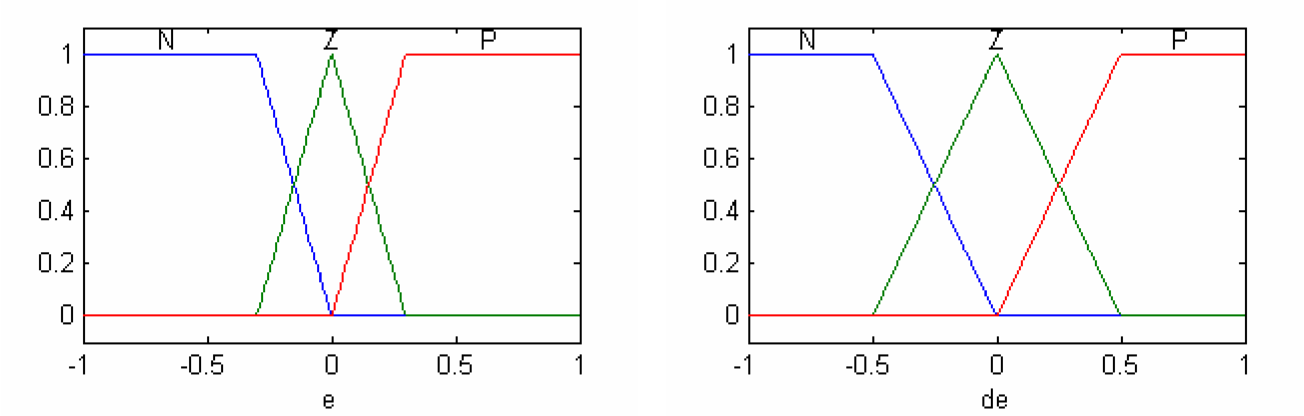

Figure 10 – Input MFs of θ and ψ Rotations FLC

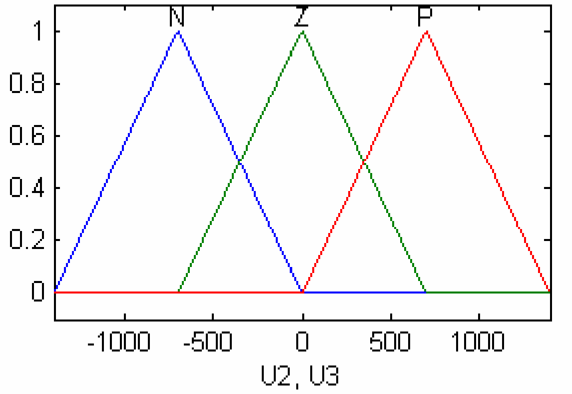

Figure 11 – Output MFs of θ and ψ Rotations FLC

D. φ Rotation Fuzzy Logic Controller Structure

This controller's structure is shown in Figure 12 and 13.

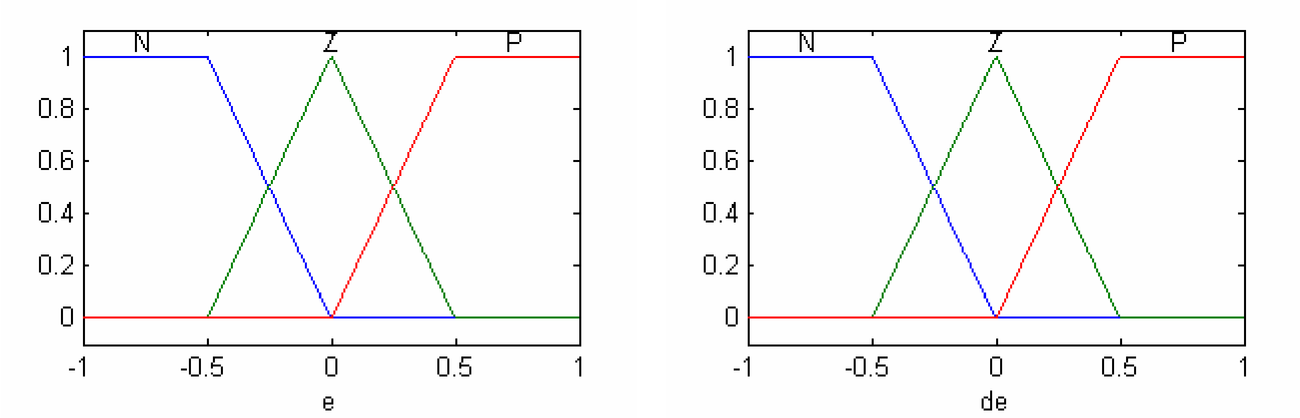

Figure 12 – Input MFs of φ Rotation FLC

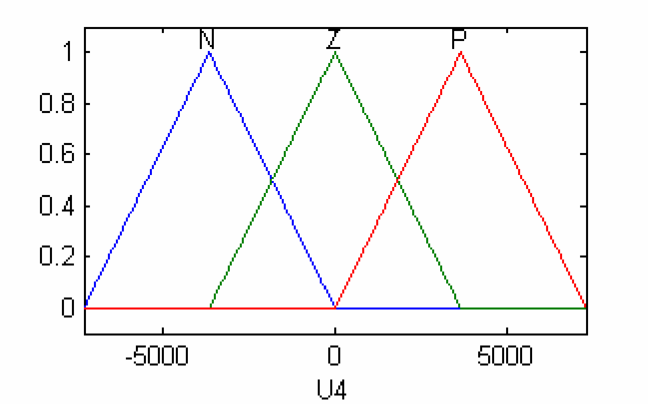

Figure 13 – Output MFs of φ Rotation FLC

VI. SIMULATION AND RESULTS

Simulink block diagram of the controlled system is shown below:

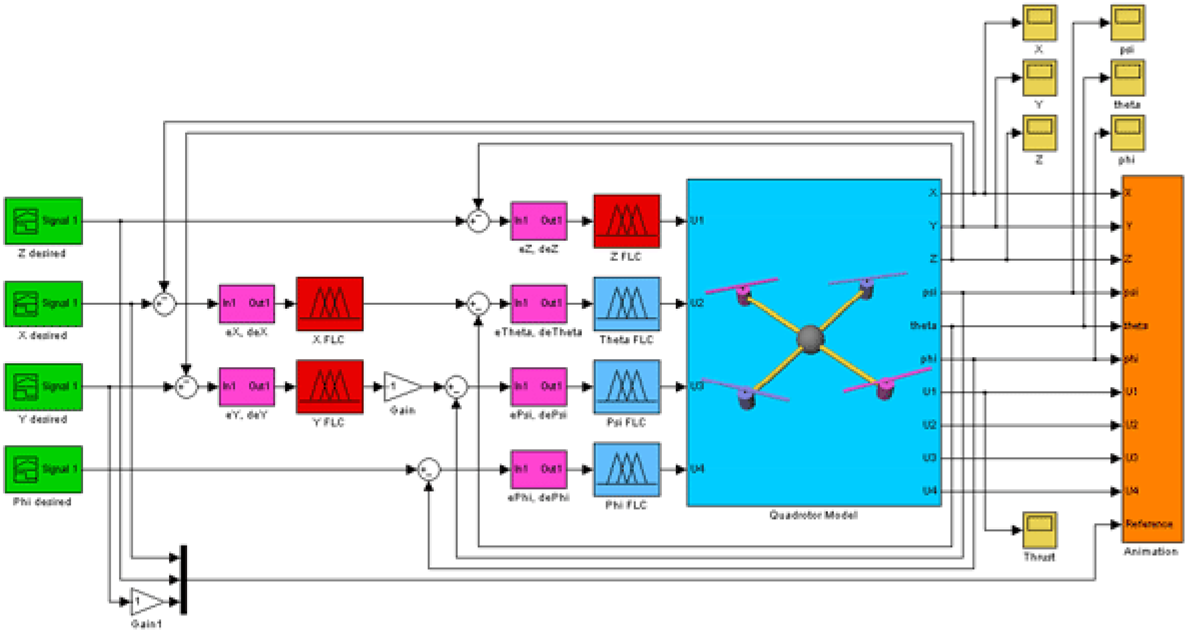

Figure 14- Simulink block diagram

Obtained results for the desired references $Z_d = 2m \quad X_d = 5m \quad Y_d = 3m \quad \psi_d = \pi/6$ are shown below:

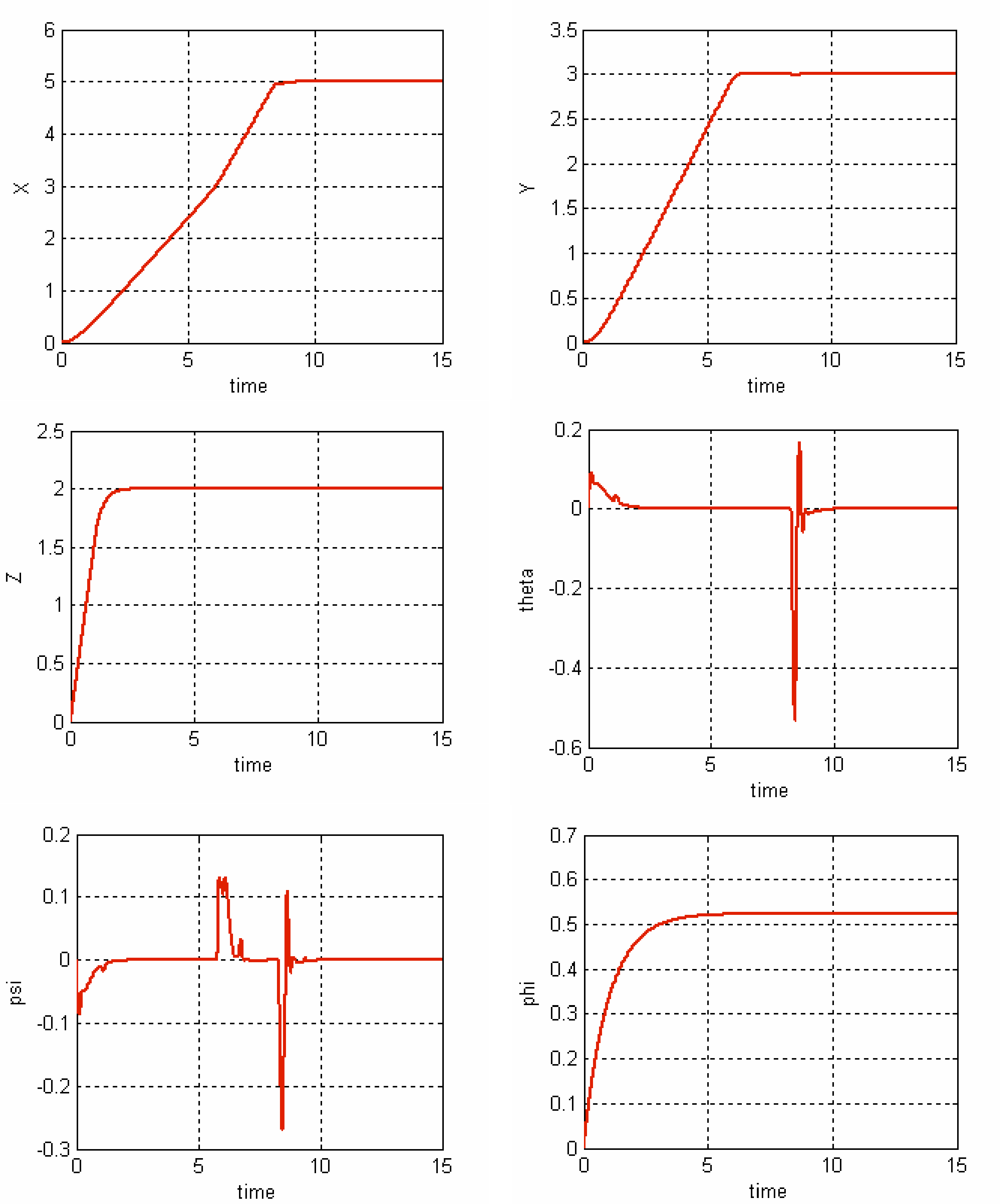

Figure 15 – System response to $Z_d = 2m \quad X_d = 5m \quad Y_d = 3m \quad \psi_d = \pi/6$

VII. CONCLUSION AND REMARKS

Being a highly unstable and nonlinear system, control of a quadrotor UAV is not so easy. There can be found applications where nonlinear control techniques applied succesfully in the literature. Although there are four inputs, it is shown that application of fuzzy logic control to a quadrotor is possible as well and from the results we see that control of the system is successful. However some disadvantages are noted.

While there are six FLCs which control the quadrotor, this increases the computation time which is quite noticeable. Using more than 9 rules with the FLCs will make this situation worse. Also it is noted that there is a bug in MATLAB's fuzzy logic toolbox which makes the output non-zero while the inputs to the controllers are zero. Although the ouput error is very small like 10^{-14} , this error gets bigger in the closed loop and not only violates the sensitivity of the controllers but also increases computation time.

To decrease computation time mamdani type inferencing can be changed to sugeno type with the usage of 'mam2sug' command. However this makes the response of the system a little different with the response where mamdani type controllers are used.

Translations are controlled succesfully if the angle φ is zero. If the angle φ is between $\pm \pi/6$ radians, controllers which control the X and Y motion can compensate eachother and achieving to the desired references is still possible. However, while the effect of angle φ is not considered when designing the FLCs, if the angle φ is outside this range system will become unstable.

Successful control applications in the literature are mostly indoor. To control a quadrotor UAV successfully outdoor one has to consider the disturbances which arise from the atmospheric conditions such as winds and gusts. Hence this makes the usage of fuzzy logic controllers a significant pro.