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*Research Article*

# Robust fuzzy-logic flight control for unmanned aerial vehicles (UAVs)

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ABSTRACT

Researches on Unmanned Aerial Vehicles (UAVs) have been recently attracting considerable interest in the field of control theory applications. They are used in a wide range of areas thanks to having the potential of high manoeuvrability, hovering and flying, taking off and landing capabilities. However, to maintain robust control action towards changing conditions of the system is not an easy matter since quadrotor UAVs are highly unstable systems with high precision. Therefore, the main purpose of this study is to control a quadrotor UAV by using a proposed multi-input single-output (MISO) fuzzy-logic controller that ensures robustness if model parameters and trajectory change. For that reason, a 2-dimensional 3 degree-of-freedom quadrotor was used in this study to better evaluate the performance of proposed controller on UAVs. Afterwards, numerical analysis was performed and the findings were analysed. Consequently, the single most striking observation to emerge from the study is that the satisfactory results have been obtained demonstrating that the proposed fuzzy logic controller has remarkable advantage on the robustness of quadrotor UAVs.



## 1. Introduction

Most recent attentions have focused on the quadrotor UAVs (also known as drones) since they have significant potential applications such as load transportation [1], military applications and safety operations [2]. It is a well-known fact that the quadrotor UAVs are highly unstable systems. Therefore, in recent years, there has been a growing number of publications focusing on control of quadrotor UAVs so as to obtain better tracking performance of a desired trajectory [3], [4] and [5]. Given the fact that, conventional PID controllers plays a key role in industrial applications thanks to its simplicity, preliminary studies have been carried out by using PID controllers [6]. However, determination of the controller parameters of PID controllers is technically challenging. There is a growing body of literature that recognizes this phenomenon. A major problem with this kind of controllers is having constant controller parameters that are not preferable in the changing conditions of the system. Despite its shortcomings, this method has been widely applied to quadrotor UAVs. For one instance, if the mass of payload changes, then the constant-gain PID controllers will inevitably not maintain the control action. Additionally, the external disturbances on quadrotor UAVs such as wind disturbances [7], may adversely affect the tracking performance of a given trajectory. For that reason, making constant controller parameters of PID controller adaptive is necessary for an appropriate control application in case of changing conditions of the system. This implies that if the controller encounters any changes on the system, then it will create new controller parameters to deal with the challenges. In an attempt to make these parameters adaptive, fuzzy logic tuning method [8] is widely used and is attracting considerable interest. In addition to this, pure fuzzy logic control method that is one of the most commonly used methods in commercial applications, represents valuable alternative to fuzzy PID controllers for above-mentioned concerns [9], [10] and [11]. Besides, this method ensures the robustness of the system towards all kind of uncertainties.

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With this in mind, this paper calls into question that how fuzzy logic controller will react for a better tracking performance if model parameters and trajectory change. Within the framework of this criteria, this paper is organized as follows. The introduction section gives a brief overview on the main motivation of this study. The dynamic modelling of a 2-D quadrotor UAV and the structure of the proposed fuzzy logic controller are described in the second section. Additionally, the input and output membership functions (MFs), FAM (Fuzzy Associative Memory) table, fuzzy logic rules of the proposed Mamdani-type multi-input single-output (MISO) fuzzy logic controller are given. In the third section, the results obtained through numerical analysis are presented. Finally, the conclusions are drawn in the final section of the study.

## 2. Materials and Methods

### *2.1. Mathematical Modelling of a 2-D Quadrotor UAV*

In this section of the study, dynamic modelling of a 2D 3 d-o-f quadrotor UAV is introduced. Physical model of this quadrotor UAV is illustrated in Figure 1.

Then, the equations of motion for above-given system is obtained as follows by using Newton's second law,

$$m\ddot{y} = -mg + u_1.cos\emptyset \tag{1}$$

$$m\ddot{x} = u_1.sin\emptyset \tag{2}$$

$$I_{xx}\ddot{\emptyset} = u_2 \tag{3}$$

where $m$ stands for mass and $I_{xx}$ stands for mass moment of inertia of the quadrotor UAV, respectively. Herein, $g$ denotes gravitational acceleration, $\emptyset$ denotes roll angle, $\ddot{x}$ denotes acceleration along horizontal axis, $\ddot{y}$ denotes acceleration along vertical axis, $u_1$ denotes thrust force input and $u_2$ denotes torque input. It is obvious from the equations of motion that the system has nonlinearities.

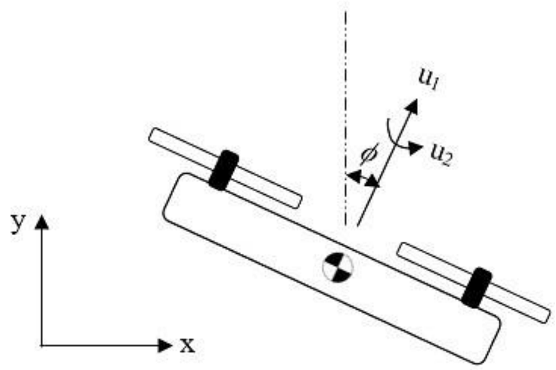



**Figure 1.** 2-D 3 d-o-f quadrotor UAV

Afterwards, this system is linearized at around quadrotor UAV's hovering point [6], where $u_1 = mg$, $\emptyset=0$ ( that is, $cos\emptyset = 1$ and $sin\emptyset = \emptyset$) and $u_2 = 0$, and then, Equations (1), (2) and (3) are written as,

$$m\ddot{y} = -mg + u_1 \tag{4}$$

$$m\ddot{x} = u_1.\emptyset \tag{5}$$

$$I_{xx}\ddot{\emptyset} = u_2 \tag{6}$$

For the sake of simplicity, after some arrangements, the equations of motion for the system can be written in below-given matrix form,

$$\begin{bmatrix} \ddot{y} \\ \ddot{x} \\ \ddot{\emptyset} \end{bmatrix} = \begin{bmatrix} -g \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{1}{m} & 0 \\ \frac{\emptyset}{m} & 0 \\ 0 & \frac{1}{I_{xx}} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{7}$$

Note that physical parameters of the quadrotor UAV are taken to be $m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$ [12] and $m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$ [6].

### *2.2. Design of Robust Fuzzy Logic Controller*

In this section of the research, the structure of proposed Mamdani-type multi-input single-output (MISO) fuzzy logic controller is briefly introduced. Then, the error dynamics is presented as follows:

$$\tilde{q}(t) = q_d - q \tag{9}$$

where $q_d = [x_d \; y_d \; \emptyset_d]^T$ is the desired trajectory, $q = [x \; y \; \emptyset]^T$ is actual measurement. Herein, the error $\tilde{q}(t) = [\tilde{x} \; \tilde{y} \; \tilde{\emptyset}]^T$ and the error rate $\dot{\tilde{q}}(t) = [\dot{\tilde{x}} \; \dot{\tilde{y}} \; \dot{\tilde{\emptyset}}]^T$ are used for fuzzy input variables while controller force *u(t)* is used for fuzzy output variable. In line with these criteria, the general structure of fuzzy logic controller is depicted in Figure 2.

Afterwards, the proposed FAM (Fuzzy Associative Memory) table that highlights linguistic fuzzy inference rules is given in Table 1.

**Table 1.** Fuzzy Associative Memory (FAM) table

| *u(t)* | $\dot{\tilde{q}}(t)$ | | | | | |
|---|---|---|---|---|---|---|
| | | **NB** | **NS** | **Z** | **PS** | **PB** |
| $\tilde{q}(t)$ | **NB** | *NB* | *NB* | *NS* | *NS* | *Z* |
| | **NS** | *NB* | *NS* | *NS* | *Z* | *PS* |
| | **Z** | *NS* | *NS* | *Z* | *PS* | *PS* |
| | **PS** | *NS* | *Z* | *PS* | *PS* | *PB* |
| | **PB** | *Z* | *PS* | *PS* | *PB* | *PB* |

Herein, *NB* stands for Negative Big, *NS* stands for Negative Small, *Z* stands for Zero, *PS* stands for Positive Small and *PB* stands for Positive Big. Therefore, for one instance, one can read the rules from the table as follow:

If $\tilde{q}(t)$ is *Z* and $\dot{\tilde{q}}(t)$ is *PB*, then *u(t)* is *PS*.

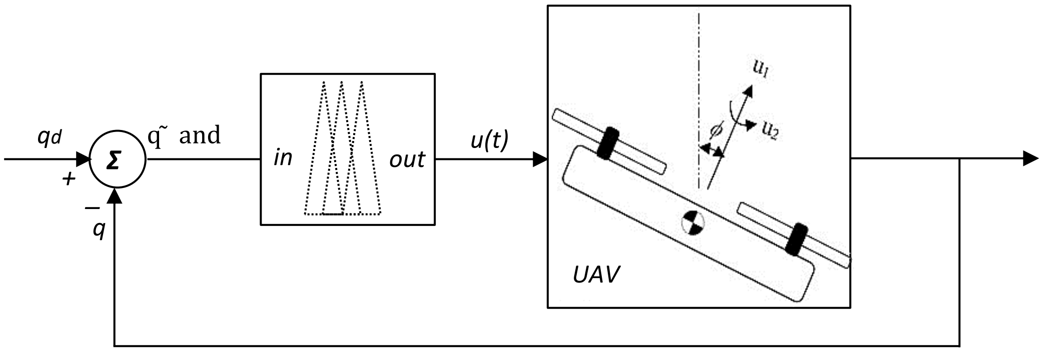



**Figure 2.** Fuzzy logic control application on quadrotor UAV

Correspondingly, the designed membership functions of proposed fuzzy logic controller with two inputs and one output for elevation, lateral and roll motions are given in Figures 3, 4 and 5, respectively. It should be noted that three controllers are used within one control action. One controller is used for elevation control, one for lateral control and another for roll motion control. It is worth to note that creating a FAM table, that is, determining minimum number of fuzzy rules is so crucial because it is one of the most feasible and rapid ways to control of a highly unstable UAV due to practical reasons since it has direct effect on computation time.

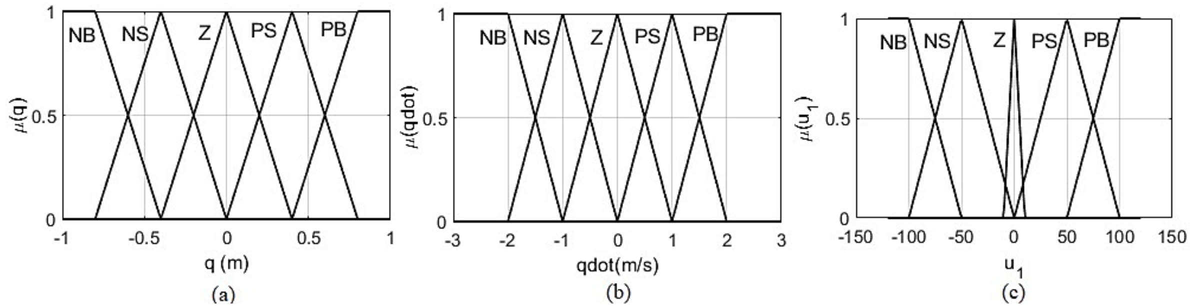



**Figure 3.** Membership functions of elevation: (a) input $\tilde{q}(t)$, (b) input $\dot{\tilde{q}}(t)$ and (c) output $u_1$

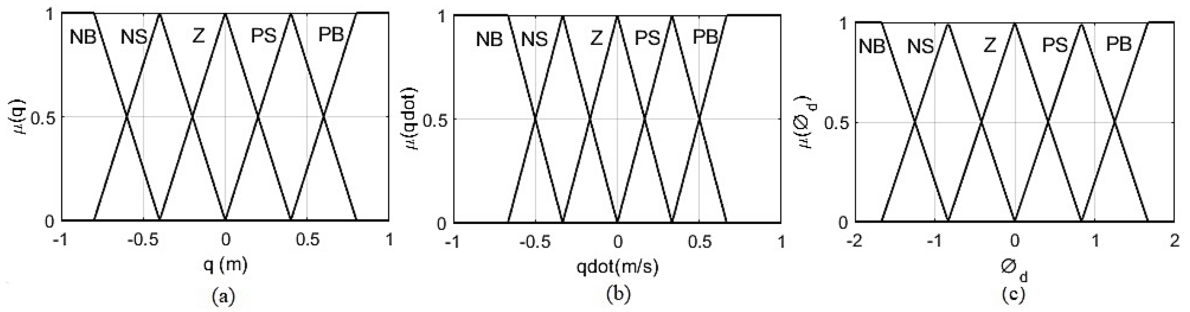



**Figure 4.** Membership functions of lateral motion: (a) input $\tilde{q}(t)$, (b) input $\dot{\tilde{q}}(t)$ and (c) output $\emptyset_d$

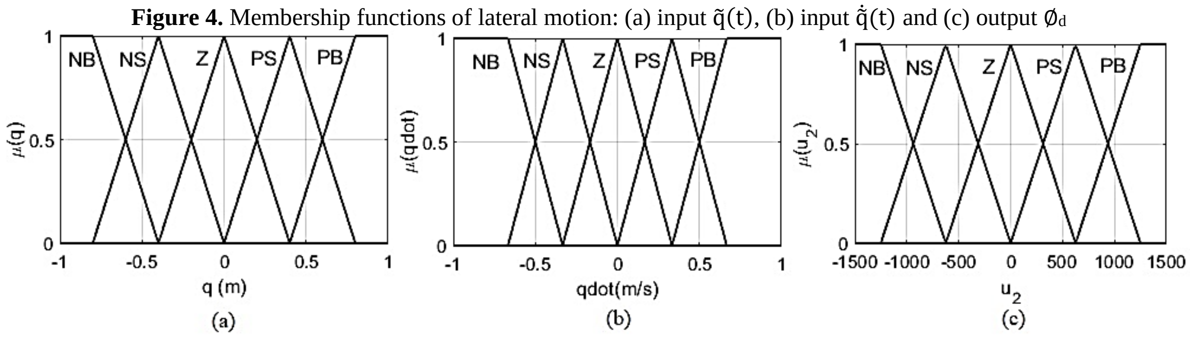



**Figure 5.** Membership functions of roll motion: (a) input $\tilde{q}(t)$, (b) input $\dot{\tilde{q}}(t)$ and (c) output $u_2$

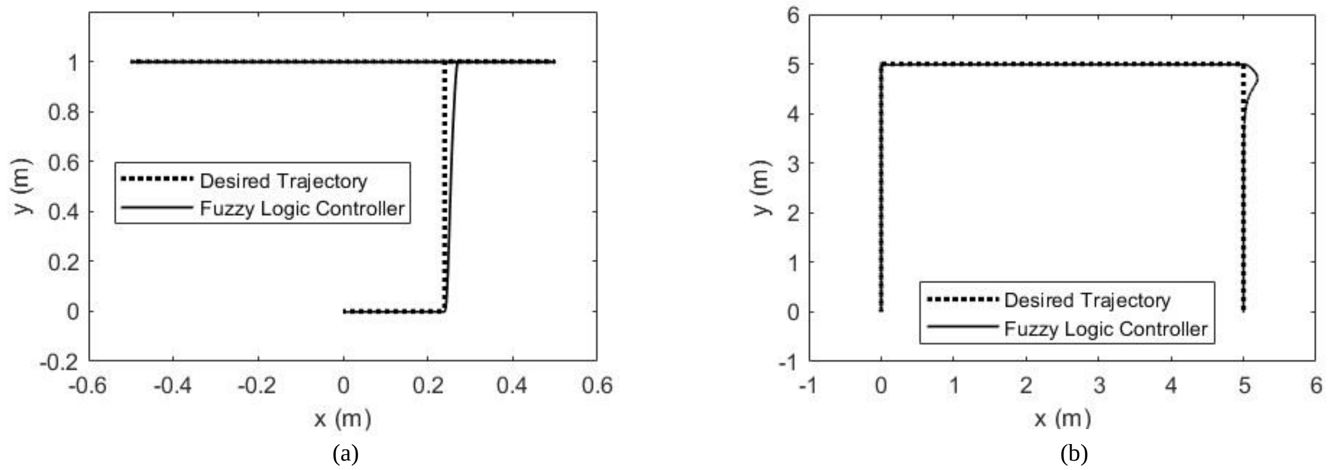



**Figure 6.** Overall tracking performance of fuzzy-logic controlled UAV; (a) 1st trajectory ($m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$), (b) 2nd trajectory ($m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$)

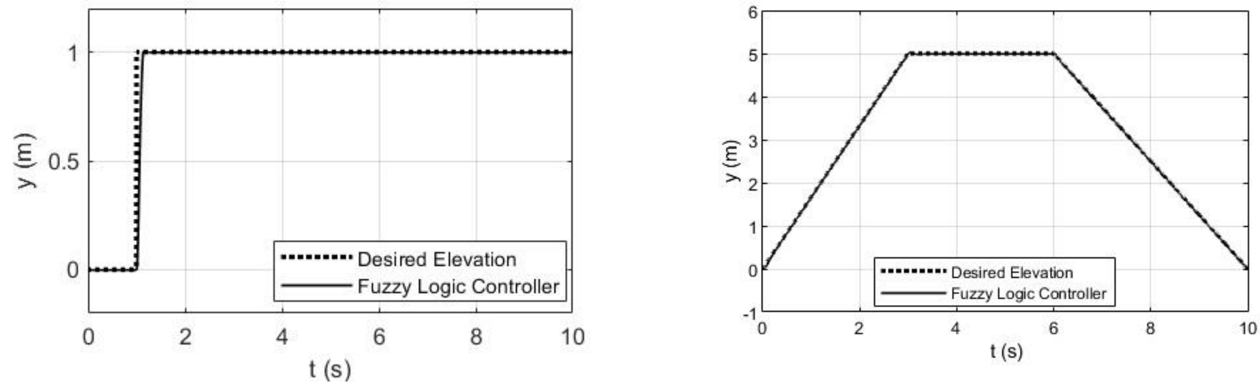
## 3. Results

In this section, the dynamic model of a 2-dimensional 3 degree-of-freedom quadrotor UAV along with above-presented multi-input single-output (MISO) robust fuzzy logic controller is used to verify the trajectory tracking performance. Therefore, to evaluate the performance of proposed fuzzy logic controller on a quadrotor UAV having different system parameters, numerical analysis was performed by utilizing two different trajectories and the results were presented in Figures 6-11. That is, first numerical analysis has been performed by using 1st trajectory with the system parameters of $m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$ and second numerical analysis has been performed by using 2nd trajectory with the system parameters of $m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$. It is crucial to note that the proposed fuzzy logic controller is applied on the system for both cases with the same fuzzy inference rules, same membership functions and same controller gains in order to verify the success and robustness of applied fuzzy logic controller.

The elevation of quadrotor UAV for different trajectories with respect to time is presented in Figure 7 (a) and (b). As can be clearly seen from the figures that proposed fuzzy logic controller has significant tracking performance and there is a rapid response during control action. It is worthwhile noting that the considerable enhancement has been achieved.

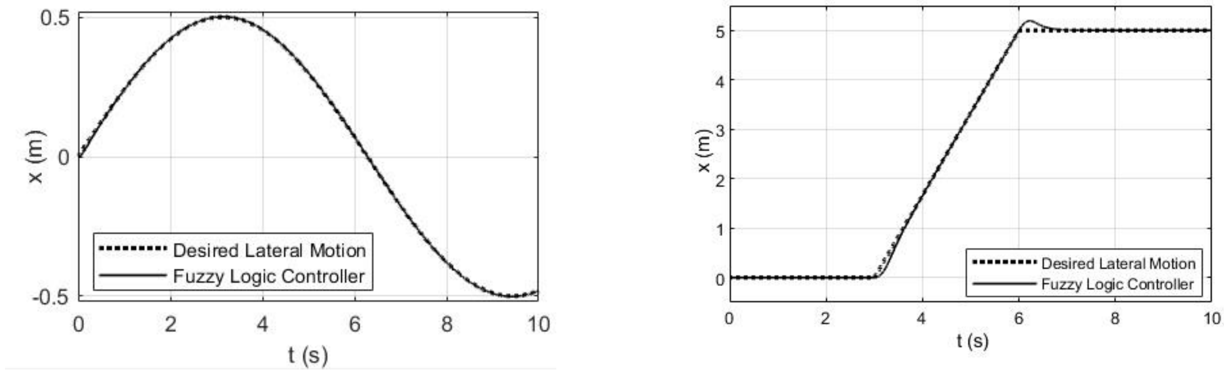
The time history of lateral motion of the quadrotor UAV is given in Figure 8 (a) and (b). The above-given interpretations of the results can similarly be given for lateral motion, as well. Additionally, the most remarkable result to emerge from the figures is that proposed fuzzy logic controller tracks the trajectory successfully. Consequently, this underlines just how important the application of fuzzy logic controller on quadrotor UAVs is. The roll motion of the quadrotor UAV with respect to time is illustrated in Figure 9 (a) and (b). It is crucial to note that roll motion of a quadrotor UAV should be in a reasonable range since there is always a potential of overturning phenomenon. With this in mind, as demonstrated in the figures, the roll angle of quadrotor UAV reaches 20 degrees for 1st trajectory and 45 degrees for 2nd trajectory. Thus, one can easily say that the proposed fuzzy logic controller has remarkable performance on the control of roll motion since it tends to avoid bigger values of roll angles. Taken together, these findings suggest that proposed fuzzy logic controller provides a powerful methodology for ensuring that it will better avoid quadrotor UAV from overturning.

Finally, so as to make final decision on whether proposed controller needs thrust force in reasonable ranges or not, the thrust force values (Figure 10 (a) and (b)) and torque input values (Figure 11 (a) and (b)) with respect to time figures come into focus. For a quadrotor UAV, a motor produces thrust forces within the reasonable values due to physical capabilities. As can be obviously seen from the Figure 10 that the proposed fuzzy logic controller needs reasonable thrust force values. It clearly has an advantage in terms of controller force needed that is critical for both practical application and economic viability. The maximum values of thrust force and torque input produced by proposed fuzzy logic controller are up to 60 N and 1000 Nm, respectively. As a result, it can be said that the control of a quadrotor UAV via proposed fuzzy logic controller is viable for practical reasons. Besides, one can easily come to the conclusion that proposed fuzzy logic controller needs reasonable energy consumption values. This study has revealed that satisfactory results are obtained by proposed fuzzy logic controller in terms of thrust force and torque input needed.



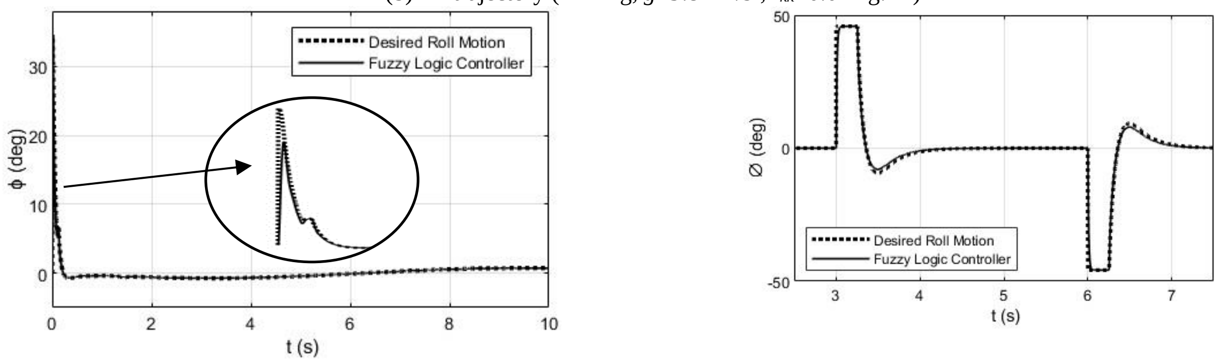

(a) (b)

**Figure 7.** Tracking performance for elevation; (a) 1st trajectory ($m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$), (b) 2nd trajectory ($m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$)



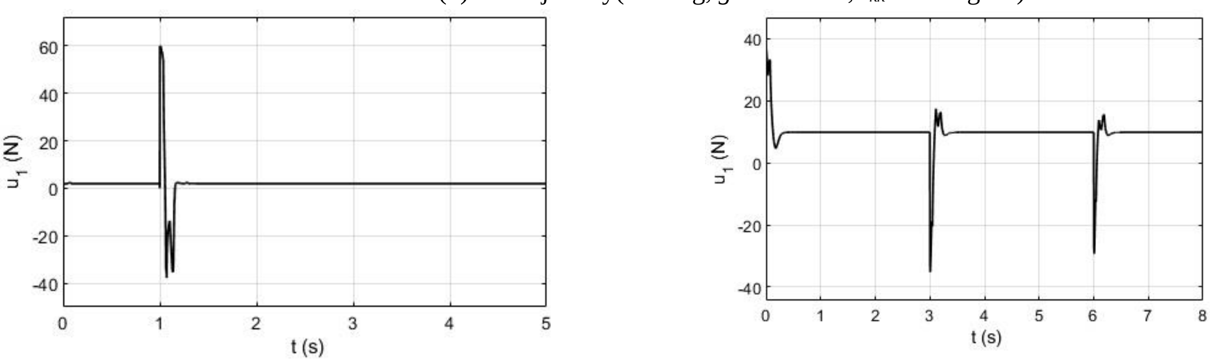

(a) (b)

**Figure 8.** Tracking performance for lateral motion; (a) 1st trajectory ($m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$), (b) 2nd trajectory ($m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$)



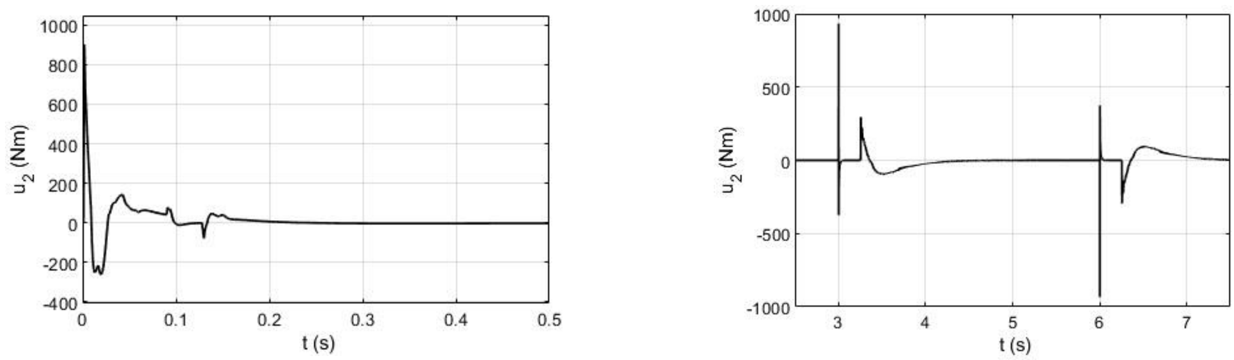

(a) (b)

**Figure 9.** Tracking performance for roll motion; (a) 1st trajectory ($m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$), (b) 2nd trajectory($m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$)




(a) (b)

**Figure 10.** Thrust force; (a) 1st trajectory ($m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$), (b) 2nd trajectory ($m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$).




(a) (b)

**Figure 11**. Torque input; (a) 1st trajectory ($m$=0.2 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.1 kg.m$^2$), (b) 2nd trajectory ($m$=1 kg, $g$=9.81 m/s$^2$, $I_{xx}$=0.01 kg.m$^2$).

## 4. Conclusions

The main goal of the current study was to verify a significant trajectory tracking performance of a quadrotor UAV to ensure robustness of the system if model parameters and trajectory change. The findings clearly indicate that both reference trajectories have been significantly tracked by proposed fuzzy logic controller even if mass and moment of inertia parameters of the system change. The results are in good agreement with the literature. Another key strength of the present study was to determine a controller for UAVs which provides reasonable controller force/torque needed during control action. The research has also shown that the proposed controller has a remarkable performance on this regard. Returning to the question posed at the beginning of this study, it is now possible to state that the maintaining a control action with reasonable controller force/torque values that has direct relevance to energy consumption is ensured in terms of economic viability. The results have also suggest that choosing a fuzzy logic-controlled DC motor that is producing reasonable controller force is said to be enough for real quadrotor UAV applications.

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