# APPLICATION REPORT
# ENGG7302

TOPIC: A fuzzy logic controller for the UAV together with optimized gains designed utilizing the genetic algorithm.

NAME: LIKITH SRINIVAS
STUDENT NO. 48237657

# CONTENTS

# A fuzzy logic controller for the UAV together with optimized gains designed utilizing the genetic algorithm.

## Introduction

Unmanned Aerial Vehicles (UAVs), also known as drones, have come to solve many problems, concerning the research of nature, health, security, industries, commerce, rescue, recreation, and services. These are inspection, supervision, monitoring, photographic purposes and transportation of goods and/or cargoes. The fact that it can be fully self-operated or can be operated through electronic control has created more ways on how individuals go through their immediate surrounding and perform several tasks. Several control strategies have been looked at to control UAVs and some of the one looked at include the nonlinear Proportional-Integral-Derivative (PID) control used to regulate the movements in translation and rotation of a 6 dofs UAVs.

For instance, in the case of controller optimization, the works established that it is possible to enhance the UAVs controllers. While metaheuristic algorithms have made some previous appearances in UAVs, as in the work discussed in . The study offers a solution where by on the basis of the ANFIS method to define the flight dynamics of the aircraft and subsequently GA to fine-tune the parameters of attitude control. This paper presents the design of an ideal direct, highly flexible adaptive fuzzy controller for the quadrotor system based on the BA. This approach is concentrated on increasing control by dividing the system into four single input and single output sub-systems. All the subsystems are controlled using Mamdani-type fuzzy adaptive controllers and a variable correcting term that is depending on the tracking error. BA method is applied in order to improve adjusting parameters of adaptation. Nevertheless, some authors contemplate on the issue of the variability of the knowledge base of the fuzzy logic controller. This option is an alternative in the optimization but requires more consciousness about the effect of the internal parameters in the controller. However, the work is carried out for a controller based on error and its derivative whereas; thus, it is understood that the proposed method can be extendable, more accurate or incorporate the knowledge based tuning methods in Fuzzy logic controllers.

The application of metaheuristic algorithm is frequently implemented and it is known as the Genetic Algorithm (GA). It is universally applied in numerous engineering difficulties with high efficiency. Optimization is acquired with the help of a steady-state genetic algorithm and dynamic fitness function.

# UAV modelling

In this section, the drone model used in subsequent tests is developed. A multirotor is an under-actuated system with six degrees of freedom. The drone model has been widely studied [ Mini-auv hydrodynamic parameters identification via cfd simulations and their application on control performance evaluation], which is why the model obtained for a multi-rotor UAV is summarized in Equation 1.

$$\left.\begin{aligned} \ddot{\phi} &= \frac{I_{yy}-I_{zz}}{I_{xx}}(\dot{\theta}\dot{\psi}) - \frac{lU_2}{I_{xx}} \\ \ddot{\theta} &= \frac{I_{zz}-I_{xx}}{I_{yy}}(\dot{\phi}\dot{\psi}) + \frac{lU_3}{I_{yy}} \\ \ddot{\psi} &= \frac{I_{xx}-I_{yy}}{I_{zz}}(\dot{\phi}\dot{\theta}) - \frac{U_4}{I_{zz}} \\ \ddot{z} &= (\cos\theta\cos\phi - g)\frac{U_1}{m_T} \\ \ddot{x} &= (\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)\frac{U_1}{m_T} \\ \ddot{y} &= (\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi)\frac{U_1}{m_T} \end{aligned}\right\} \tag{1}$$

In this kind of modelling, the system is divided into two sub-systems; rotation one and the translation one, with being the mass of the drone. The linear coordinates for the global frame are x, y, z and those of the orientation are $\phi$, $\theta$, $\psi$ Main Angles of rotation in 3-space. These are the inertia in the main axes. Last, U1, U2, U3 and U4 are the control signals due to motor speeds. The previous model follows the following approximations: div_ = 0, div_ = 0, the angle is slightly on, the gyroscopic torques are disregarded, as well as the ground effect. Depending on the translation of the x-y plane, two virtual control inputs, Ux and Uy are produced which are utilised to determine the pitch and bank angle through which UAV has to move to translate in the x-y plane. Thus, the dynamic model is not necessary to use a fuzzy controller.

Nevertheless, the process of design involves simulation tests that are not possible in the physical system. For the purpose of modelling the given system, there was used a tool called Simulink as well as S-function in order to utilize the calculation abilities of MATLAB and combination of generality of Simulink. For the UAV rotation (Fig. 1a) amid, an S-function was developed for the rotation subsystem and for the translation subsystem as well (Fig. 2b).

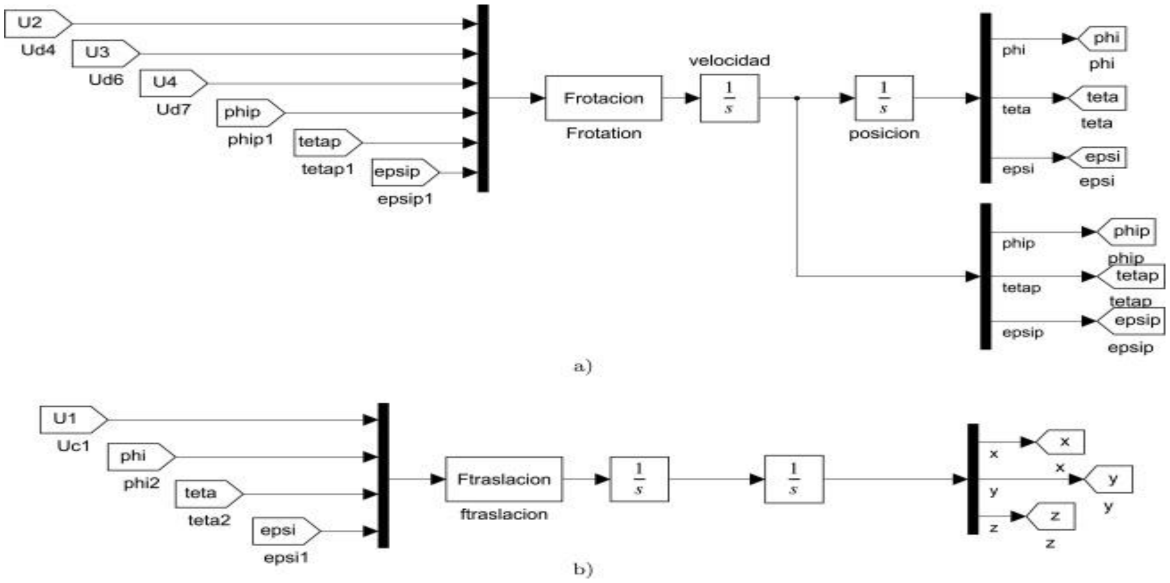



Figure 1. Simulink model used for simulated the UAV dynamic. (**a**) Model used for simulated the rotation subsystem; (**b**) Model used for simulated the translation subsystem.

# Fuzzy controller design

This section describes the design of a fuzzy controller that allows the system to follow a predetermined path. Therefore, the mathematical model defined by the set of (Equations 1) was used to simulate the dynamics of the UAV. Six fuzzy controllers were designed in the Simulink-MATLAB to control the complete system.

Four controllers generated the control signals, which the method used directly ($z$, $\phi$, $\theta$, $\psi$). On the other hand, the remaining torques and  allowed the calculation of the reference pitch and roll angles, which, together with the control signals, will enable the system to follow the desired trajectory.

# Optimization of the gains via genetic algorithm

For all types of fuzzy controllers, the gains can be set or adjusted by hand. Nevertheless, it is not possible to define a standard tuning method and the one explained is a manual approach that has low efficiency. Thus, the metaheuristics algorithms are one of the ways to determine the optimum value of these gains in tracking trajectory tasks. The metaheuristic algorithm widely used is the Genetic Algorithm. These algorithms are from a family of Evolutionary algorithms well known in the scientific community and used in different applications for instance Particle swarm optimization (PSO) Differential evolution(DE) and others Bio inspired search methods. In the following, the working of a Genetic Algorithm with elitism is described in the form of Algorithm 1.

```
Begin
Generate initial population P based on random gains with range [0 50]
while fitness evaluations consumed limit ≤ 1500 do
    Evaluate fitness of P members
    Selection of best P members based on their fitness
    Crossover of best parents from P based on a random single point
    Mutation in a part of the individuals based on a probability value
    Create new population P based on most-fit individuals and elitism
end while
Save the best solution (minimum fitness)
end
```

Algorithm 1. Genetic algorithm with elitism.

As for the details, the Genetic Algorithm has a set of particular parameters that depend on the type. In this case, the particular attributes of the employed GA were Elitism, the Mutation Rate, and the Cross Over Rate. Thus, the consideration depends on the number of individuals, the stopping condition, the fitness function, and the range of the general parameters as characteristic features of population-based algorithms. Further, the Execution of the Genetic Algorithm is easy, the most time taking and tiresome part is the calculation of the fitness. This characteristic is useful when dealing with expensive computational systems as the one in this work; an expensive algorithm would raise the difficulty level of the gains tuning. As a point of interest, it should be noted that the design of the fuzzy controller can be semi simple or complex, meaning that it variedly affects the processing time during the tuning stage of the Fuzzy Logic Controller. The only factor that will in any case have a higher cost in terms of computational when tuning the same controller with metaheuristic algorithms is the fitness evaluation of each individual..

For this work, the general parameters used in the metaheuristic algorithm are shown in Table 2. The lower limit was selected because the gains are defined as positive constants. On the other hand, the upper limit was chosen as 50 since, with higher values, a saturation effect is observed. The stop limit was chosen at 50 since the RMSE value drops drastically in early iterations. However, in some cases, the RMSE decreased even after 30 or 40 iterations, so it was decided to stop at 50 to obtain the optimum values without extending the simulations.

| Parameter | Value 2 | Description |
|---|---|---|
| Population | 30 | Numbers of individuals in the search |
| Range of the search | [0 50] | Values between which best gains were searched |
| Stop condition | 50 | Number of iterations in which the search was done |
| Fitness function | $\sqrt{(t_s - t_{sd})^2 + (M_p - M_{pd})^2}$ | Function for evaluate the performance of proposed gains |
| Elitism | 10% | Numbers of individuals in the search |
| Biological pressure | 50% | Percentage of individuals that reproduce |
| Mutation probability | 30% | Probability that individuals have a mutation |

Table 2. Parameter used in Genetic Algorithm.

The desired response in an energy-limited system such as a UAV must reach the reference quickly without causing an overshoot. This guarantees that energy is not lost at low speeds or, on the contrary, that energy is lost in unnecessary braking (drone orientation changes). That is why the desired response is proposed with the following response characteristics to the step, as shown in Fig. 4.

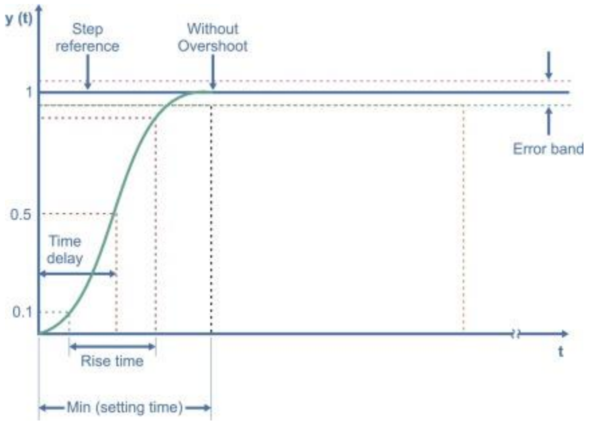



Figure 4. Ideal step response in UAV.

In the tuning process, the principal characteristics for optimization are 0% overshoot but with a faster settling time and minimal steady-state error. The proposed reference signal complies with these characteristics. The transfer function shown in Equation 2 described the reference.

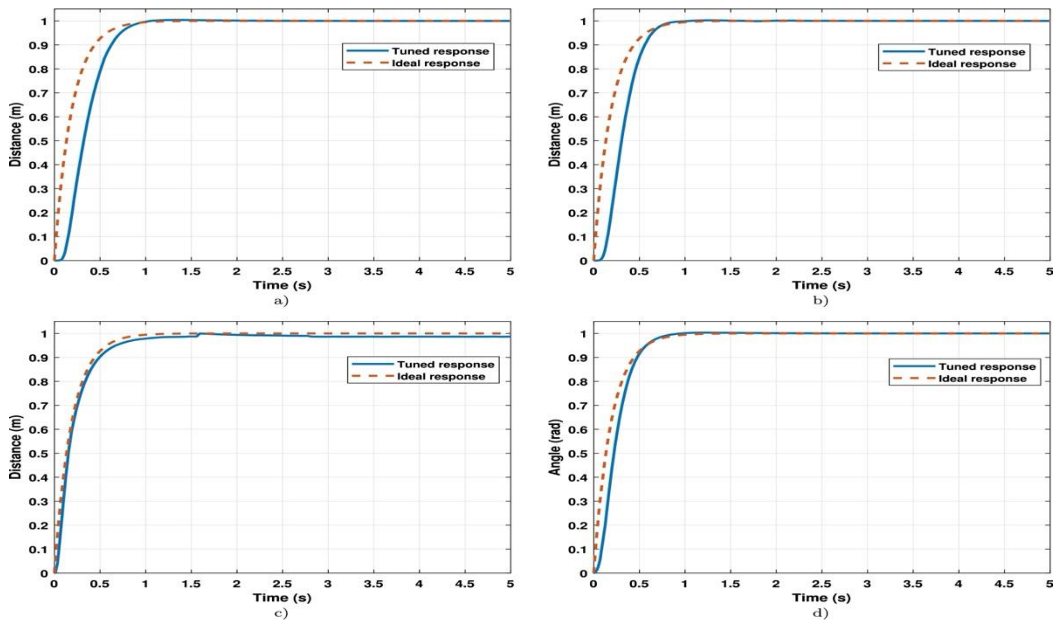
Reference = step($\frac{5.22}{s+5.22}$). $\quad eqn\ 2$

The Genetic Algorithm found the gains that minimize the Euclidean distance between the overshoot error and the establishing time error. The obtained gains and the features of the dynamic response are displayed in Table 3.

| Axis | Gains obtained | ts | Overshoot |
|---|---|---|---|
| $z-\psi$ | $k_1 = 3.401$, $k_2 = 44.803$, $k_3 = 0.421$, $k_4 = 3.874$ | 0.801 s | 0.15% |
| $x-\phi$ | $k_5 = 0.068$, $k_6 = 0.729$, $k_7 = 0.9178$, $k_8 = 0.490$ | 0.843 s | 0.4% |
| $y-\theta$ | $k_9 = 0.15$, $k_{10} = 0.81$, $k_{11} = 0.91$, $k_{12} = 0.46$ | 0.729 s | 0.31% |

Table 3. Gains and dynamic response parameters obtained by Genetic Algorithm.

On the other hand, the graphic results are shown in Figures.



# Results

This section shows the results of the adjustment of the gains. For this, the UAV is subjected to the monitoring of two trajectories. The first of these trajectories is described by set of Equations 3.

$$\begin{aligned} x &= step\left(\frac{1}{(s+1)^6}\right) \text{ (in second 40)} \\ y &= step\left(\frac{1}{(s+1)^6}\right) \text{ (in second 20)} \\ z &= step\left(\frac{1}{(s+1)^6}\right) \text{ (in second 2 to 70)} \\ \psi &= step\left(\frac{1}{(s+1)^6}\right) \text{ (in second 2)} \end{aligned} \quad \text{..Equation 3}$$

The set of Equations 4 describes the second trajectory:

$$\left.\begin{aligned} x &= 0.5cos(0.8t) \\ y &= 0.5sin(0.8t) \\ z &= \frac{t}{5} \\ \psi &= \frac{\pi}{3} \end{aligned}\right\} \quad \text{..Equation 4}$$

Both simulations were run for 90 seconds. The result of the tracking of the first trajectory is observed in Fig. 6, where the tracking is compared with the adjusted gains (Fig. 6a) without adjusting them (Fig. 6b).

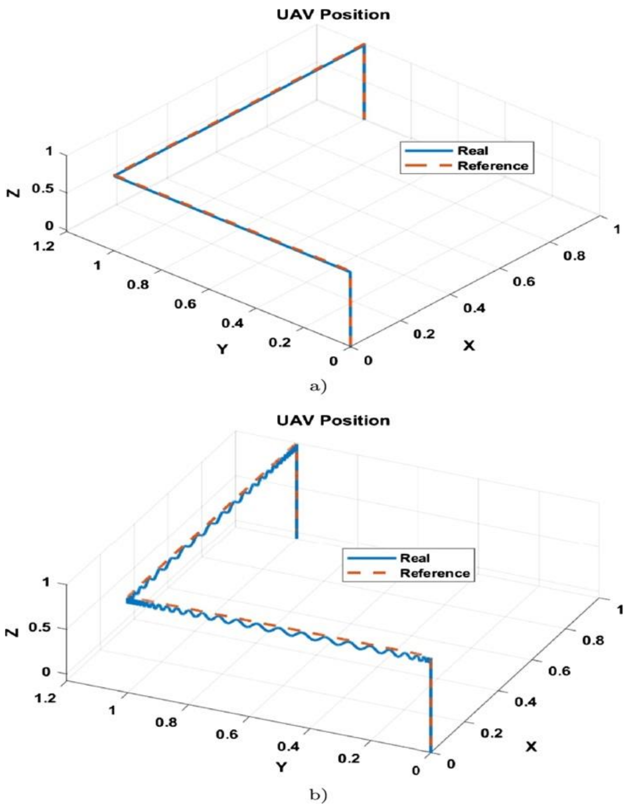
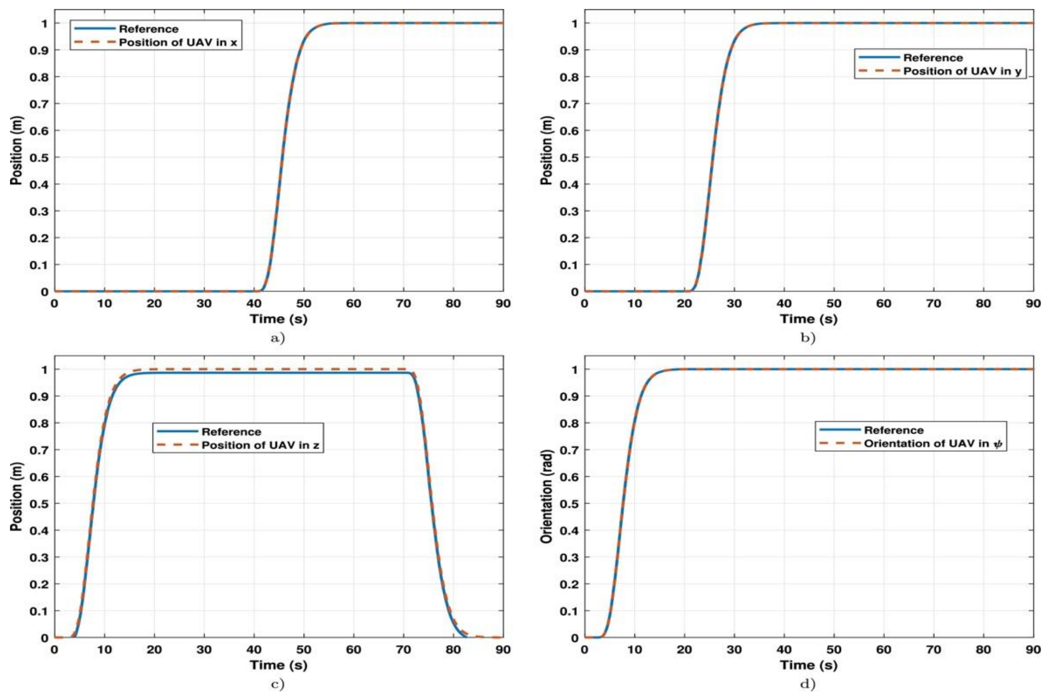



Figure 6. Position of the UAV in tracking the trajectory 1 (**a**) Tracking with tuned controller; (**b**) Tracking with untuned controller.




The results per axis in tracking path 1 with tuned gains are shown in Fig. 7, where Fig. 7a) is the axis x, Fig. 7b) is the axis y, Fig. 7c) is the axis z, and Fig. 7d) is the yaw angle.

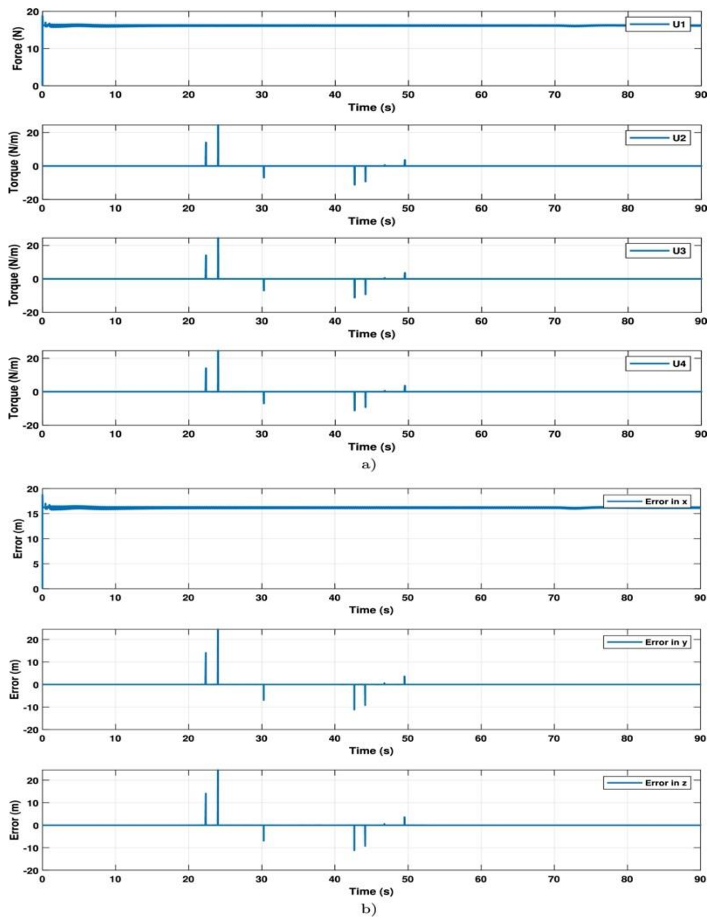



Figure 8. Signals control and errors in the trajectory 1 (a) Signals control; (b) errors in tracking.

Despite being a simple tracking trajectory, a clear improvement is observed in Fig. 6 when using the adjusted controller. For path 2, a helical type path was chosen, described by Equation (6).This trajectory has more difficulty than the first since it has constant motion changes in the x-y plane. The result of the second trajectory is exhibited in Fig. 9 with the tuned controller is show in Fig. 9a and the untuned controller is depicted in Fig. 9b.

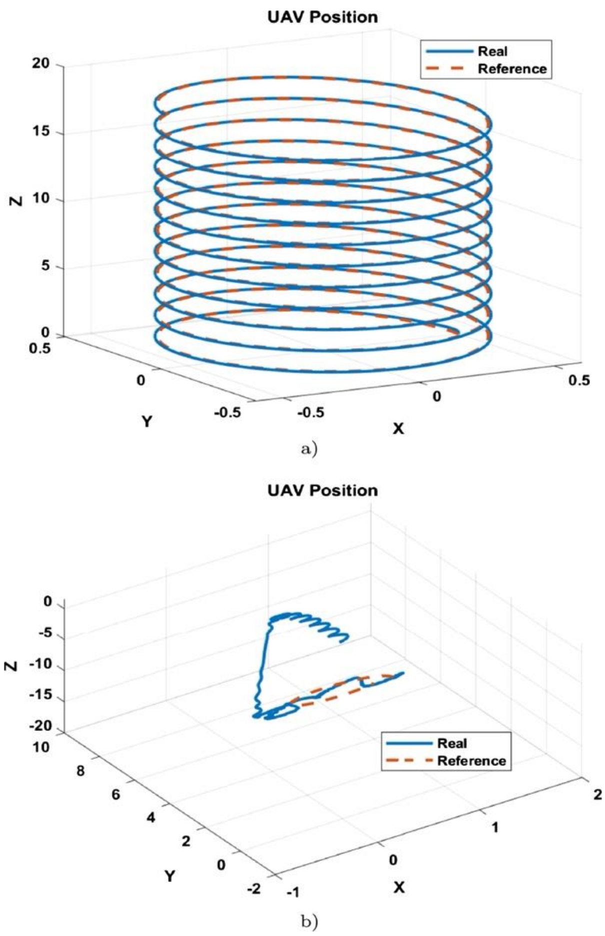



Figure 9. Position of the UAV in tracking the trajectory 2 (**a**) Tracking with tuned controller; (**b**) Tracking with untuned controller.

The results show that the untuned controller cannot follow the trajectory, and only the first 7 seconds of the trajectory were simulated. The effects of the second tracking trajectory with the tuned controller are observed in detail in Fig. 10, where Fig. 10a) is the axis x, Fig. 10b) is the axis y, Fig. 10c) is the axis z, and Fig. 10d) is the yaw angle.

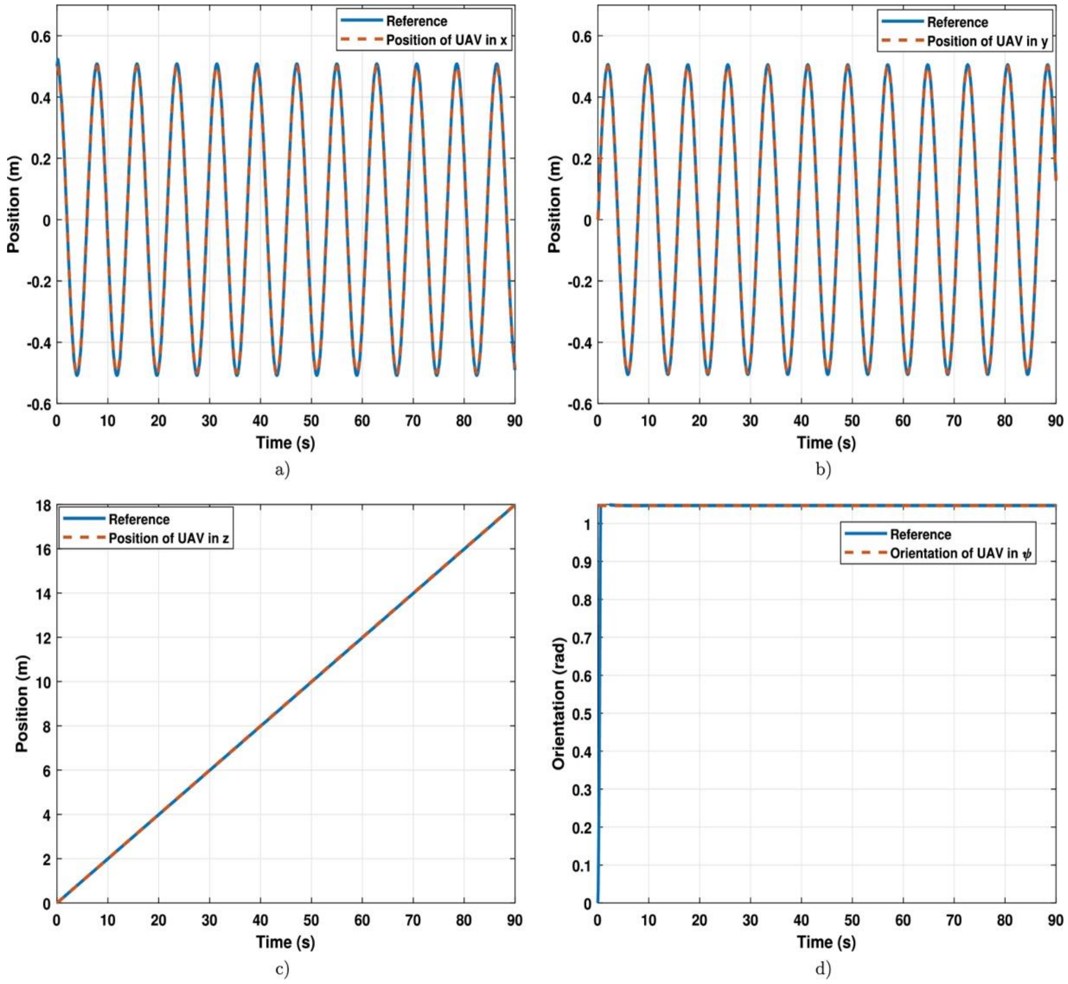
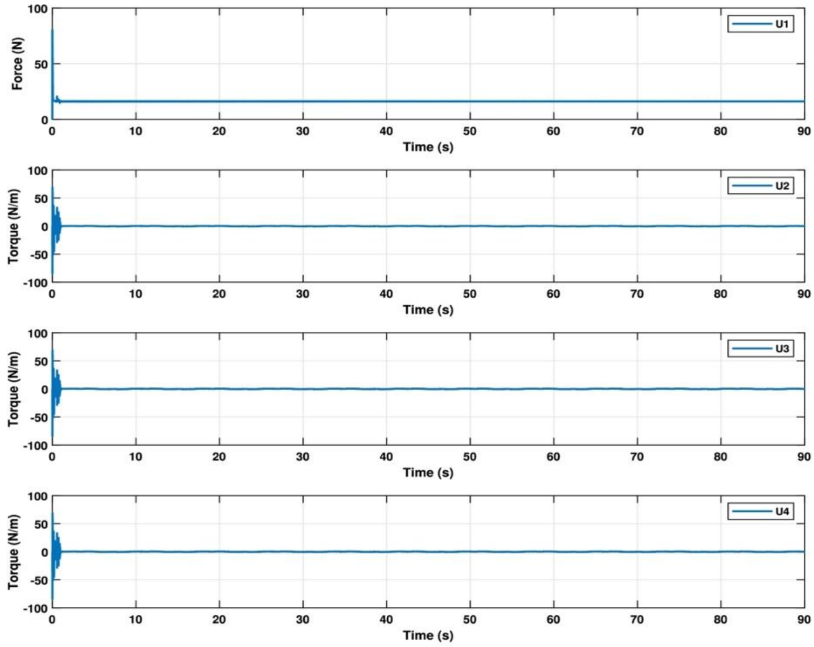
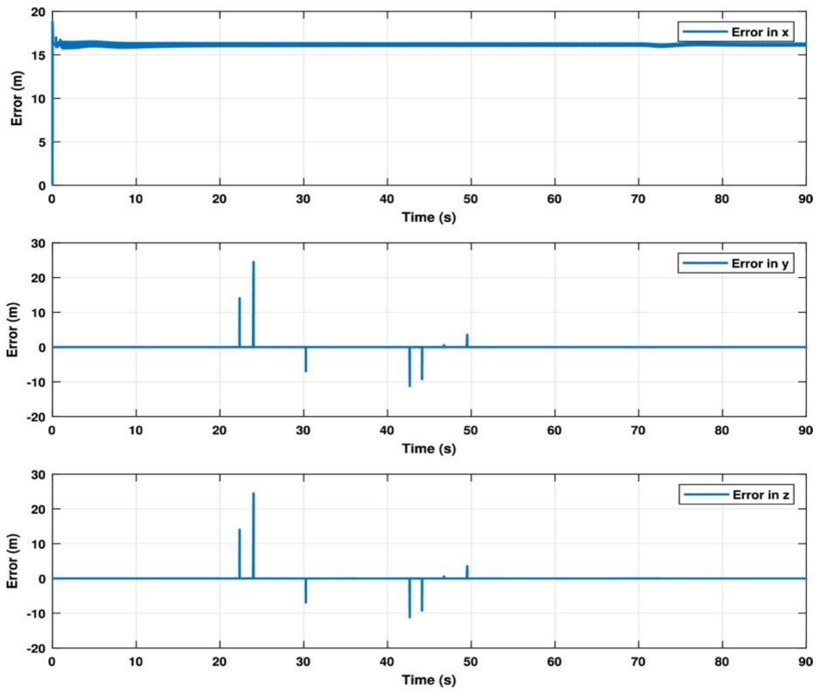



Figure 10. Position per axis of the UAV in tracking the trajectory 2 (a) x-axis vs reference; (b) y-axis vs reference; (c) z-axis vs reference; (d) ψ-axis vs reference.

Finally, the torques are displayed in Fig. 11a, and signals control are displayed in Fig. 11b.




a)




b)

Figure 11. Signals control and errors in the trajectory 2 (**a**) Signals control; (**b**) errors in tracking.

It can be seen that the tuned controller has better performance than the untuned controller, as displayed in Fig. 9. This is because the untuned controller could not track the trajectory, while the tuned one could achieve it smoothly.

Interferences with a UAV are relatively, in most cases, turbulence in the form of gusts of wind. In contrast to manipulators, UAVs also do not have load changes since they do not engage with the environment. Consequently, in addition to random magnitudes of wind gusts in the X, Y, and Z directions, a wind gust with the specific magnitude was added from 4. 5 seconds to 5. 5 seconds in simulation to trajectory 2 to also view how well the selected controller perform when interference that is anticipated manifests on the system. The result of tracking the trajectory of the tuned controller under disturbances is shown in Fig. 12, where Fig. 12a) shows the UAV movement in space, Fig. 12b) displays the trajectory in the x-axis, Fig. 12c) displays the trajectory in the y-axis and Fig. 12d) displays the trajectory in the z-axis.

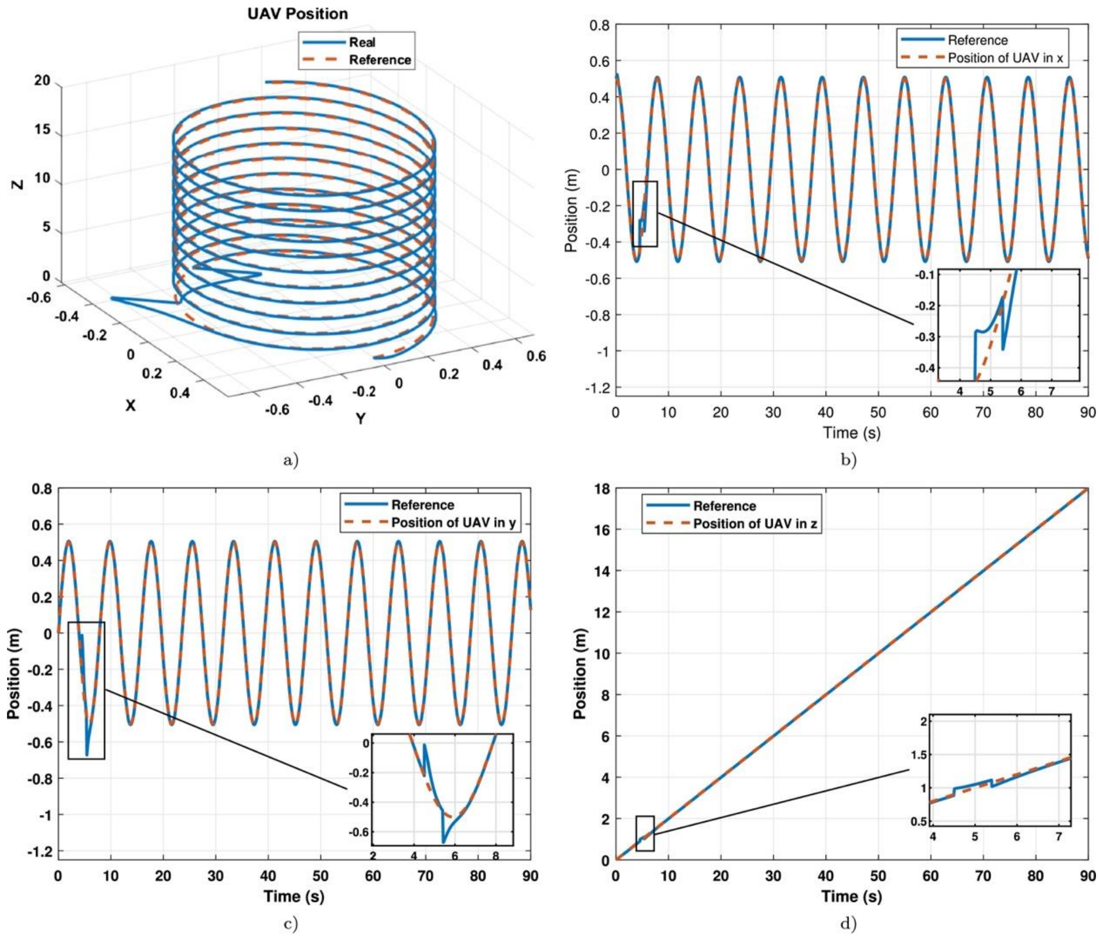



Figure 12. Position per axis of the UAV in tracking the trajectory 2 under disturbance (a) x-axis vs reference; (b) y-axis vs reference; (c) z-axis vs reference; (d) ψ-axis vs reference.

The Genetic Algorithm identified the gains that provides the design specifications of the controller. The design requirements being two factors of the dynamic response characteristic of the structure were fully shaped. The drawbacks of this method are as follows: While the metaheuristic algorithm is being used, the global optima cannot be reached because no metaheuristic algorithm adheres to the condition. As for the correct tuning the latter is required to have knowledge of the dynamic model of the plant and the parameters of this model. In as much as it is relatively easy, it can be quite complicated depending on the specific plant that pest wants to control. Also, the proposed method does not have any provision for identifying combinations or design specifications that would render the system marginally unstable or physically intractable. Hence, there is a necessity to select the design parameters taking into account the possibilities of the plant. Finally, Table 4 was created to bring out the contrast between investigations. There is a difference in the way they use the dynamic response to arrive at the value of gains mostly in this particular aspect.

| **Variables and methods used** | | | | | |
|---|---|---|---|---|---|
| **ts** | **Mp** | **Plant** | **Using of fuzzy logic** | **Tuning method** | **Additional variables** |
| x | x | UAV | Controller | Genetic algorithm | – |
| – | – | DC motor | Gain tuner | Fuzzy | – |
| – | – | Active Suspension | Gain tuner | Fuzzy | Unknown nonlinear dynamics |
| – | – | UAV | Gain tuner | Fuzzy | Output controller |
| – | – | UAV | Controller | Double exponential smoothing | Environment video |
| – | – | UAV | Controller | Bad algorithm | RMSE |

Table 4. Comparison of the proposed tuning system with similar works.

# Conclusion

In this work, a gains tuning fuzzy controller system was developed, and the gains were added to the fuzzy controller inputs along with a non-linearity of the saturation type to keep the inputs in the operating range. The gains were adjusted with the Genetic Algorithm. The results indicate improved path tracking as path two was completed if the tuned controller was used, and the task was incomplete if the untuned controller was used.

Although other parameters of the fuzzy controller can be adjusted, a greater knowledge of the inputs and outputs of the system is required. When the operating ranges are not precisely known, the method presented in this article can be used to optimize a controller. However, its use depends on knowing the system model and its precision. Finally, the computational cost depends on the parameters of the algorithm and the complexity of the differential equations that describe the dynamic model. Therefore, in some cases, tuning by this method is not feasible.

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