Hybrid Fuzzy-PID Closed Loop to Regulate Quadcopter System

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***Abstract*—In this paper, we proposed a hybrid intelligent algorithm to control the quadcopter which allows having the movement with six degrees of freedom. The mathematical approach is presented to build the structure of the attitude and positions controllers for this system. Hybrid fuzzy-PID controller is implemented to reach the stability for indoor or outdoor scenarios. The proposed approach imitates the heuristic knowledge design for the system's membership functions by tuning system uncertainties to new values which is bounded and rebuilt during the real time process. Thus, the initial memberships function will be tuned to create new membership functions based on the predefined uncertainty values. To optimize the structure for the rule knowledge base as well as the processing time, the bacterial evaluation criterion is implemented. The simulation results are analyzed and proved the desired flying behaviors during several scenarios. These results demonstrate the effectiveness of the presented control system and its good performance.**

***Index Terms*—fuzzy system, drone, quadcopter, attitude, fuzzy-PID**

I. Introduction

Recently, the Unmanned Air Vehicles (UAVs), that are usually referred to drones or quad-copter or multi-copters, have grown significantly and attract much interest from researchers in various research areas or commercial activities such as disaster response, infrastructure inspection and recently fight the coronavirus pandemic. They have gained their popularity in the scientific community due to several advantages such as high maneuverability, diversity of applications, and reliability [1-3]. Therefore, several governments have been used drones equipped with thermal sensors to find the infected people with COVID-19. Jordan started using the drone's technology to fight the corona virus pandemic.

The government deploys these drones as well as other robots to enforce curfews and even monitor people's temperatures [4]. However, Jordan is underdeveloped country and suffers from lacking resources which causes these projects and demonstrations are in their earliest phases. In [5], the authors presented drones to collect images and then analyze these images to achieve a significant improvement in safety during helping and removing human being from hazardous situations. Furthermore some UAVs, for example, should operate in disaster areas without harming any persons. Since they are much smaller comparing to manned helicopter, they might be deployed much more quickly to be used in constrained areas such as forest [6]. In addition, more recent studies have developed a smart drone for object tracking purposes. The control system is implemented for stability in hovering as well as image acquisition. Even though the behavior of system is stable, but due to higher degree of freedom it is very difficult to keep capturing the target in continuous manner [7]. Another strong application is the Forestry operations that is necessary to keep and growth forest especially in regions that is hard to receive the survey by human in the aging society [8]. The hot applicable topic that researchers are nowadays undertaking is based on reliable altitude controller such as autonomous and precision landing [9–14] and autonomous delivery tasks [15–17].

Therefore, designing a superior performance controller is important efforts. In [18], the author proposed adaptive dynamic controller to accomplish quadcopter tracking tasks by controlling the altitude through an adaptive dynamic controller which is able to reduce the tracking errors and deal with uncertainties parameters. Some researchers have used the second order SMC method to improve the altitude control performances [19-21]. Since the PID control is simple to design and delivers a satisfactory performance, it was presented in several researches to control stabilization, position as well as the altitude [22-24]. In most specific applications the PID architecture was implemented by using inner and outer loop [25–27]. However, the classical PID controller has several limitations [28] for example over a wide range of operation; the PID controlled system has limited performances due to steady coefficients. Much more widely is the range; the PID controller will become prone instability. In addition, PID controllers are based on a linear model, thus, the performance may suffer in a nonlinearity system [28]. Therefore, a drone self-tuning fuzzy-PID controller was presented to tune the PID gains by fuzzy logic in order to address this problem [29]. This paper will be presented a hybrid fuzzy-PD controller for the quadcopter. In addition, the detailed model of the quadcopter is presented in section 2. Section 3 contains the detailed of design the proposed control. Finally, the performances results of the proposed fuzzy-PD controller

Manuscript received January 21, 2021; revised April 7, 2021.

doi: 10.18178/ijmerr.10.9.469-477

are compared to classical PID and classical Fuzzy controllers.

II. Mathematical Model of the System

A. Reference Frames

It is very important to analyze the equations of motion of the flying platform in order to design an accurate control system. Therefore, the mathematical model of our platform is based on the Newton–Euler equations and it is described as a rigid body that flies through the global frame as it is illustrated in Fig. 1. Whilst the state velocity variables are in the quadcopter frame (FB), the state position variables are in the global frame (FG) [30, 31].

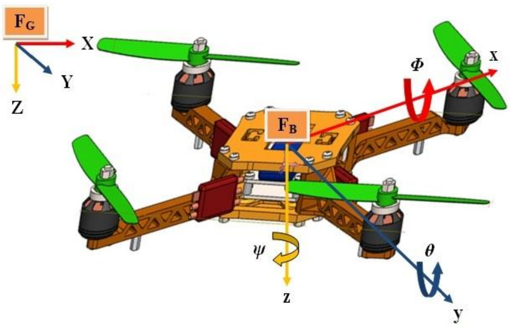

Figure 1. Coordinate system.

B. Kinematics

Whilst angular rates p, q, r are defined in quadcopter frame, the Euler angles are defined in intermediate coordinate frames given by equation 1 and The angular velocities on the vehicle frame is given by equation 2.

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin(\theta) \\ 0 & \cos(\phi) & \sin(\phi)\cos(\theta) \\ 0 & -\sin(\phi) & \cos(\phi)\cos(\theta) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)\sec(\theta) & \cos(\phi)\sec(\theta) \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{2}$$

C. Dynamics, Forces and Moments

The motors are used to generate the forces and moments that are needed to control the quadcopter. Each motor generates upward force F and torque τ. The thrust and torques on the quadcopter described on the Fig. 2. The motor configuration is devised to balance drag created by the spinning motors. Thus, four maneuvers that are accomplished by changing the speeds motors are illustrated in Fig.3.

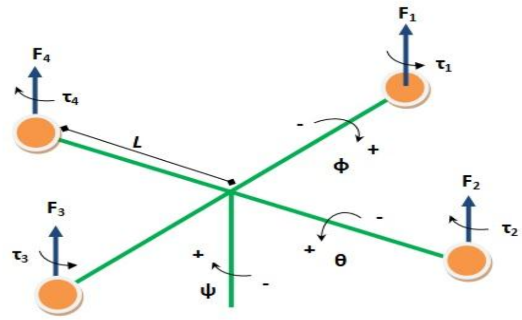

Figure 2. Forces and moment

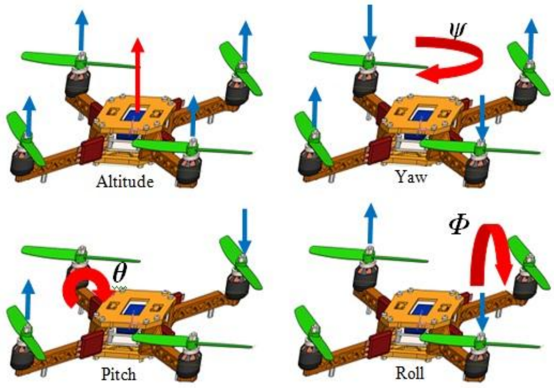

Figure 3. The quadcopter dynamic

The power of single motor and the quadcopter stability at hover to generate the thrust are given by:

$$P_m = \frac{K_e \tau \omega}{K_t} \tag{3}$$

$$T_H = K_T \omega^2 \tag{4}$$

Regarding to simplest model of fluid friction in the inertial frame, the total force and the body torques τ_m generated by motors in the quadcopter are described as

$$F_{total}^{G} = \begin{bmatrix} 0 \\ 0 \\ K_T \sum_{i=1}^{4} \omega_i^2 \end{bmatrix} \tag{5}$$

$$\tau_m = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} lK_T\left(\omega_4^2 - \omega_2^2\right) \\ lK_T\left(\omega_1^2 - \omega_3^2\right) \\ K_D\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \end{bmatrix} \tag{6}$$

Taking into consideration that the drone is completely symmetrical about all its axes; thus, $J_{xy} = J_{yz} = J_{xz} = 0$. The angular rates are approximately equal the time derivative of the Euler angles

$$\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{1}{J_x}[qr(J_x - J_z) - J_x qr(\omega_1 - \omega_2 + \omega_3 - \omega_4) + lK_T\left(\omega_4^2 - \omega_2^2\right)] \\ \frac{1}{J_y}[pr(J_z - J_x) - J_y pr(\omega_1 - \omega_2 + \omega_3 - \omega_4) + lK_T\left(\omega_1^2 - \omega_3^2\right)] \\ \frac{1}{J_z}[pq(J_x - J_y) + K_D\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right)] \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} F_{total} \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} K_T & K_T & K_T & K_T \\ 0 & -lK_T & 0 & lK_T \\ lK_T & 0 & -lK_T & 0 \\ K_D & -K_D & K_D & -K_D \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} F_{total} \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} F_1 + F_2 + F_3 + F_4 \\ l(F_4 - F_2) \\ l(F_1 - F_3) \\ (\tau_2 + \tau_4) - (\tau_1 + \tau_3) \end{bmatrix} \tag{9}$$

D. Simplified Model

In order to reduce the system complexity, some assumptions have been made without losing the motion behavior precision. In this paper, it was assumed that the system operates around a stable hover and the aerodynamic forces as well as the moments assumed to be zero. Therefore, Φ, θ and ψ are very small angles, thus; cos(Φ)=cos(θ)= cos(ψ)=1 and sin(Φ) =sin (θ)= sin(ψ) =0 and the angular velocity will be given by

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} \tag{10}$$

Moreover, the Coriolis Effect terms do not have an important influence, thus, the following equations describe the linear acceleration.

$$\begin{bmatrix} \ddot{X}^G \\ \ddot{Y}^G \\ \ddot{Z}^G \end{bmatrix} = \begin{bmatrix} \frac{-1}{M}\theta f_1 \\ \frac{1}{M}\phi f_1 \\ \frac{-1}{M} f_1 + g \end{bmatrix} \tag{11}$$

The angular acceleration is represented by the following.

$$\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{1}{J_x}\tau_\phi \\ \frac{1}{J_y}\tau_\theta \\ \frac{1}{J_z}\tau_\psi \end{bmatrix} \tag{12}$$

E. Motor System Modeling

Considering the experiment made by Selby [32] on Brushless DC motor AC2836-358, 880Kv, it was possible to obtain the motor behavior on different states of work as well as to measure the response and estimate the motor parameters. The PWM signal as well as the motor behavior and parameters are described on Table 1. These values were obtained through MATLAB software as well as the selected motor data sheet [33].

TABLE I. THE MOTOR BEHAVIOR AND PARAMETERS

Throttle	PWM (ms)	RPM	A	Watt	Thrust (N)
0%	1	-	-	-	-
25%	1.25	3514	1.5	17.5	2.26
50%	1.5	6175	6.1	70	6.37
75%	1.75	8214	14.2	160	12.65
100%	2	8999	20	210	13.5

As it was illustrated in Fig. 5 through Fig. 8, the model was validated since the simulated RPM values approximated matching the experimental values. In addition, the value of the propeller speed can be obtained from Fig. 5 and Fig. 6 and it was 368 rad/sec at hover point and from Fig. 8 it has been found 942 rad/sec at full power. Table II shows the parameters results of the system. In [34], the author presented and implemented of nonlinear regression using the Adaptive Neuro-Fuzzy Inference System (ANFIS) in MATLAB. ANFIS is highly convenient since it incorporates all the benefits of both neural networks and fuzzy logic. Thus, MATLAB software has been adapted and implemented to make the whole motor system more robust. The linearization relation between the propeller speed and the Thrust as it is shown in Fig.9.

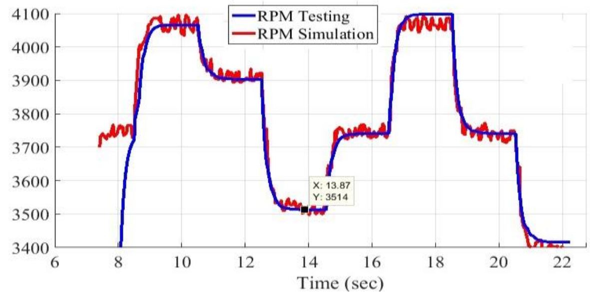

Figure 4. Verification model at 25% throttle

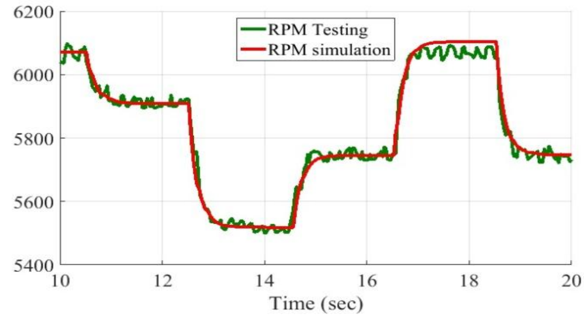

Figure 5. Verification model at 50% throttle

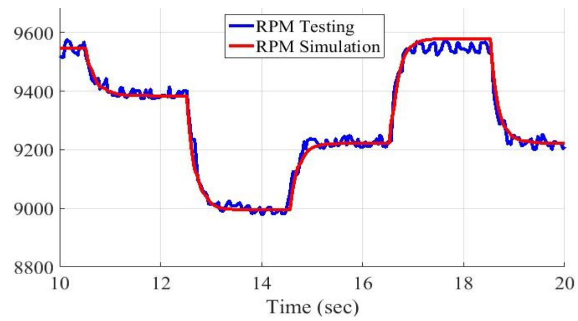

Figure 6. Verification model at 100% throttle

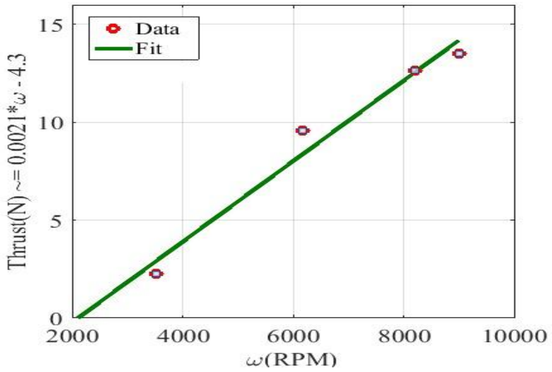

Figure 7. Linearization between speed and Thrust

TABLE II. THE PARAMETERS RESULTS OF THE SYSTEM

Cases	ωn rad/sec	RPM	PWM (msec)	Volt
Hover	368	3514	1.25	4.1
Full power	942	8999	2	10.5

III. CONTROLLER DESIGN

As it was mention previously that the PID controller is based on the linear model and the nonlinearity in the drone system will bring the uncertainty and degraded performance. Thus, it is very necessary to overcome nonlinearities and uncertainties in such system to increase the learning capability and adaptability in different scenarios. Thus, several studies have been done based on fuzzy technique which tunes the proportional, derivative and integral gains of the PID [35-38]. In [39], the authors proposed Fuzzy-PID controllers for analysis the dynamic attitude of quadcopter on a circular trajectory, and then comparing the modeling results (PID) and their proposed algorithm. Based on these researches and others, it has been pointed out that the traditional fuzzy system will provide better performance and more robust comparing with PID and (LQR) controllers [40, 41]. However, this kind of controller, fuzzy control, gives this performance ability only under particular circumstances, but it suffers from drawbacks and uncertainties under larger framework [42-44]. Therefore, in this research adaptive fuzzy-PID controllers have been designed and implemented to control the drone system as well as to overcome these uncertainties and drawbacks in the system. The overall control scheme is illustrated in Fig. 8. This adaptive control scheme contains several controllers for position, attitude, and altitude behaviors. First, the modify Fuzzy-PID controllers are used for horizontal position (x- and y-) control. Second, the modify Fuzzy-PID controller has been implemented for attitude control behavior. Finally, the adaptive Fuzzy-PID controller is proposed to control the altitude of the system.

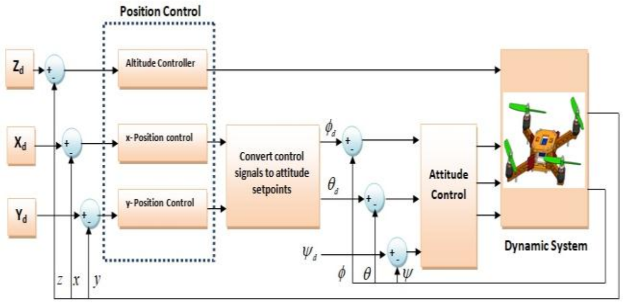

Figure 8. Full control scheme

A. Design the Membership Functions

Even though the fuzzy control system is able to map the relation between the input-output of the system, but it does not capable of handling the vagueness in real time applications [45, 46]. In the quadcopter system, the uncertainty might come into the control system from many resources such as changing conditions in the environment, arising in the data during collected time, and occurring due to design membership functions which is nontrivial task [47-50]. Thereby, introducing the degree of uncertainties in designing the membership functions $\mu(x)$ can be helpful to obtain the proper membership functions for the quadcopter control system. From mathematical perspective, the trapezoidal MSF is the best choice in practical applications [45, 49]. The trapezoidal membership functions and its four uncertainties cases are illustrated in Fig. 13. Two sides of uncertainties values are shown in Table III. Therefore, the old membership functions will be tuned and the final membership functions will be generated depend on the four possible uncertainties. In the meantime the system is presented to have two fuzzy inference systems {left and right}. It uses the max–min operator product to process the knowledge rules, perform the reasoning process as well as to minimize the computational time.

B. Design the Fuzzy Sets System

The general layout for the proposed adaptive fuzzy sets is illustrated in Fig.9. It is clear that this system includes the same operations and stages like any standard fuzzy logic. The initial memberships function will be tuned to create new membership functions based on the predefined uncertainty values. However, the adaptive new fuzzy system consists of two fuzzy inference systems for the left and the right values. This stage will implement the max–min product for operating fuzzy rules and performing the reasoning process with these rules. The second stage in the fuzzy engine process is the iterations method that is implemented for optimizing purposes such as to minimize the intervals values for both sides. These results obtained from the iterations method combined with reference function $\mathbf{F}_{\mathbf{ref}}$ will be defuzzified to derive accurate control outputs signal. As a result, this tuning process will improve the control performance and the new uncertainty will rebuilt online in real time.

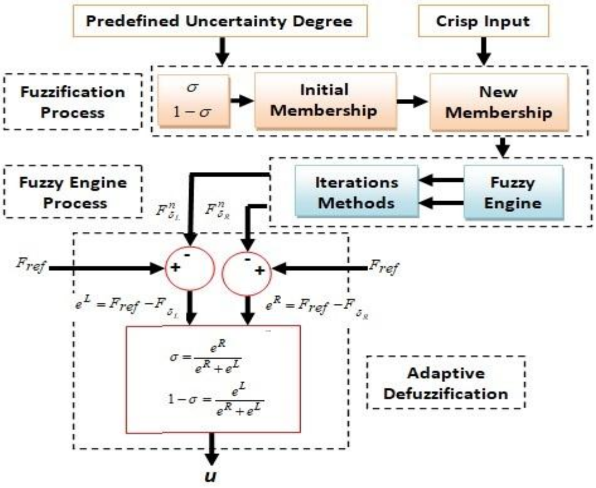

Figure 9. Adaptive Fuzzy control scheme

TABLE III. THE MEMBERSHIP FUNCTIONS

Definition	Uncertain Values	Old Break points	New Break points	$\mu(x)$
Core point	--	b_o	b_o	1
Core point	-	c_o	c_o	1
left uncertainty	δ_L^a	a_o	$a = a_o - \delta_L^a$	$\mu_{\delta_L^a}$
right uncertainty	δ_R^a	a_o	$a = a_o + \delta_R^a$	$\mu_{\delta_R^a}$
left uncertainty	δ_L^d	d_o	$d = d_o - \delta_L^d$	$\mu_{\delta_L^d}$
right uncertainty	δ_R^d	d_o	$d = d_o + \delta_R^d$	$\mu_{\delta_R^d}$

Regarding to the adapted max-min algorithm inside the inference engine, the two sides of membership functions will be acquired as sets. Actually, the multi antecedents will be connected by using the meet operation. Since inference system has two sides, the procedure determines the membership function weight by reposition the fired intervals rather than using center of gravity. For left and right sides as illustrated in Fig.10, the left and the right sides points are obtained by the center of gravity method as the following:

$$F_{\delta_L}^n = \min\left(F_1^n, F_2^n, \ldots, F_m^n\right) \tag{13}$$

$$F_{\delta_R}^n = \max\left(F_1^n, F_2^n, \ldots, F_m^n\right) \tag{14}$$

$$F = \left[F_{\delta_L}^n, F_{\delta_R}^n\right] \tag{15}$$

$$F_{\delta_L}^n = \frac{A+B+C}{\dfrac{A}{F^m} + \dfrac{2B}{\varepsilon - a} + \dfrac{C}{F^m}} \tag{16}$$

$$F_{\delta_R}^n = \frac{A-B-C}{\dfrac{A}{F^m} - \dfrac{2B}{\varepsilon - a} - \dfrac{C}{F^m}} \tag{17}$$

$$A = \delta\left(\sum_1^m \left(F_{\delta_L}^n\right) F^m\right) \tag{18}$$

$$B = (\varepsilon - a)\left(F_{\delta_L}^k - F_{\delta_R}^k\right)\left(\frac{\varepsilon - a}{2}\right) \tag{19}$$

$$C = \sum_1^m \left(F_{\delta_L}^n + F_{\delta_R}^n - F^m\right)\left(F_{\delta_L}^n - F_{\delta_R}^n\right) F^m \tag{20}$$

Where the point ϵ is a test point,ϵ >a→k=m and Fm is the mth output MSF’s centroid.

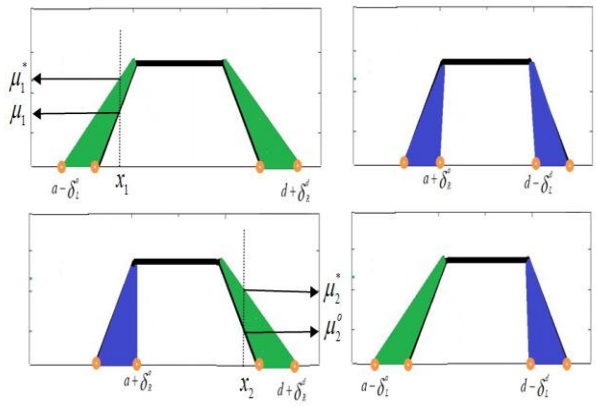

Figure 10. Uncertainty intervals in trapezoidal MSF.

C. Improved the Initial Membership Functions

In this research, the chosen interval domain for two input variables error and error rate is [-3, 3]. While the selected domains of control parameters output for the proportional and derivative are [-0.3, 0.3], the chosen domain for integral parameters is [-0.06, 0.06]. The initial rules were 49 rules for each output control parameters. However, to optimize the structure rule base and thus the number of rules and the processing time, the bacterial evaluation criterion has been implemented [53, 54]. The optimized rules were reduced to 27 rules and it has been found that the best fitness function value for 1000 generations = 0.0712 as it is shown in Fig. 11.

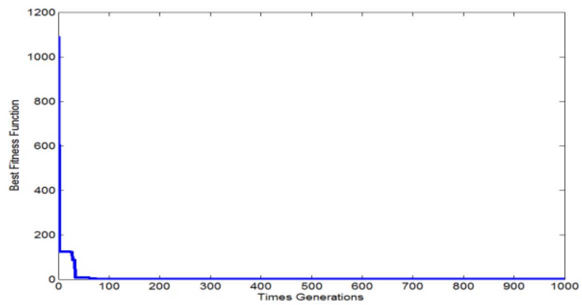

Figure 11. The Fitness function absolute value.

D. Design Fuzzy-PID Controller

The hybrid fuzzy and PID nonlinear controllers are used in order to achieve very good drone nonlinear system performance and stability. The core of such combination between the two controllers is to create a strong relationship between the PID parameters, the error and error rate. Thereby, the hybrid fuzzy controller will adjust and update the initial PID coefficients on-line, This adjusting is used in order to meet the requirements of controlling the drone system under different circumstances of the error and its rate. The control structure is shown in Fig. 12. However, the self-tuning of the parameters has to satisfy some criteria mentioned in [51, 52].

E. Angle Configuration Controller

It is well known that one important consideration for making the quadcopter is to consider the system robustly regarding to external disturbances and forces. Since the induced wind force might be either constant or variable, it is very important to take into consideration how the controller should react in short time. Therefore, the fuzzy-PID controller design is divided into two stages as it is illustrated in Fig.13. First one is the angle stabilization controller that reacts as fast as possible and has high stability. Considering the desired signal was already given from the autopilot system so the desired angle of movement based on the quadcopter coordinate system. The feedback input is given by the sensors; in this case, the input feedback value is the actual angle of the quadcopter. The output will be considered as the desired rotational rate, which will be the input for the next stage of the control system. The second configuration is the rate stabilization to consider any deviation of the angle and rate. The purpose behind this configuration is that when the first stage gives the desired angle, the input for rate control stage will be null and there will be no rotational movement. This stage is responsible for the stability against external forces. This controller receives the desired angular rates from the previous stage and then computes the error between desired rates and the gyroscope rates in order to compensate for any undesired changes and compute the three moment control inputs which are combined with the thrust to calculate the motor speeds.

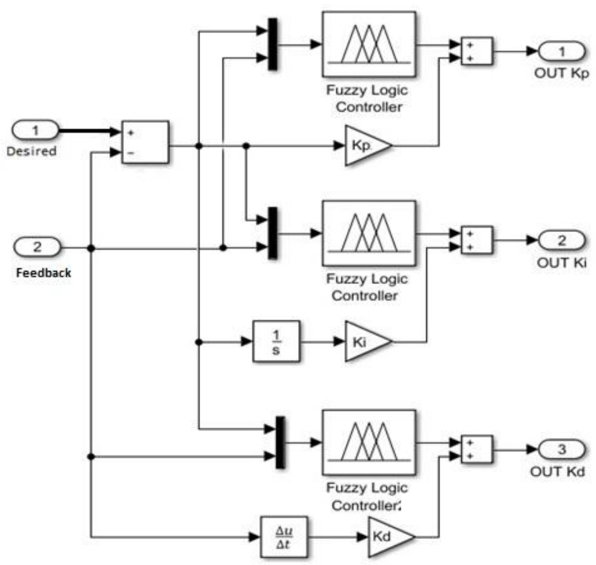

Figure 12. Fuzzy PID control design

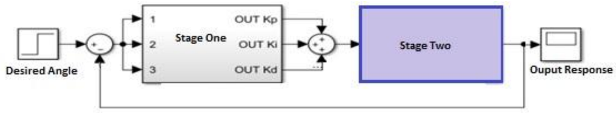

Figure 13. Yaw and rate controllers

IV. Simulation Results and Discussions

In this section, the demonstration of the effectiveness for the proposed adaptive fuzzy-PID control is presented. The quadcopter dynamics from previous sections are implemented in MATLAB simulation to verify the stability and advanced performance of proposed adaptive controller. By comparing the new method to either the conventional PID controller or classical fuzzy control, we highlight and discuss the effectiveness of the proposed controller. Through the MATLAB simulation adaptive fuzzy controllers are constructed in the software. In addition, to visually observe the effect of the simulation, the classical PID as well as the conventional fuzzy control are simulated, and in the simulation they are put together for comparison, thus, an intuitive conclusion can be obtained. For compare between the controlling of sub-systems corresponding to Roll, Pitch and Yaw angles of the system is illustrated in Fig.14, Fig. 15 and Fig. 16. The test consisted of analysis of the system's response to a unit step signal as the input parameter. It is possible to notice the behavior of the subsystems is better in the proposed hybrid Fuzzy-PID controller. First, Fig.17 and Fig.18 are the altitude responses of the fuzzy controller at 5m and 10m. It can be seen that the proposed fuzzy controller has a very good stable time. Since the quadcopter will possibly face variations in the environment, it must be tested and verified for variations altitude on same scenario to check if it has the optimal response performance. For Specified input altitude as it is illustrated in Fig.19, Fig. 20 and Fig. 22, the result demonstrates the ability of the proposed controller to deal with such scenario. In addition, for real time applications the proposed algorithm shows the system has very good behavior due to disturbances that occur at the beginning of flying. It can clearly be noticed that the adjustment effect of the proposed control on the overshoot that happens between {0, 2} seconds is better than either classical PID or classical Fuzzy controllers. Thus, the disturbances and the uncertainties of the system can be avoided and the system becomes more stable in real time applications.

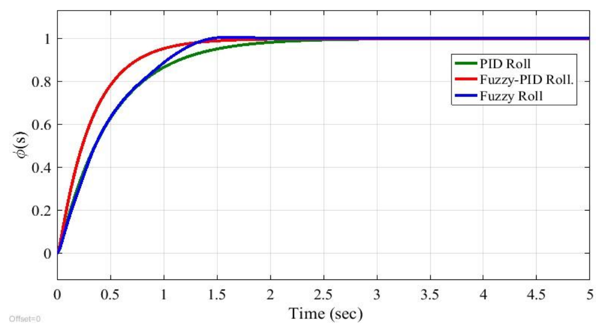

Figure 14. Comparison results for roll angle

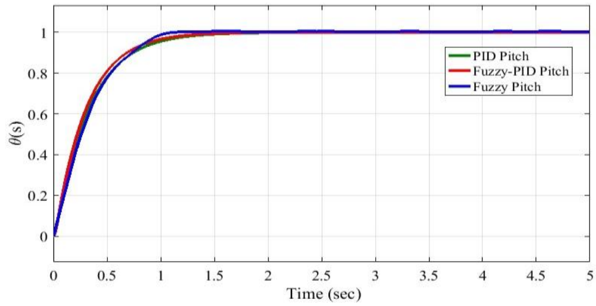

Figure 15. Comparison results for pitch angle

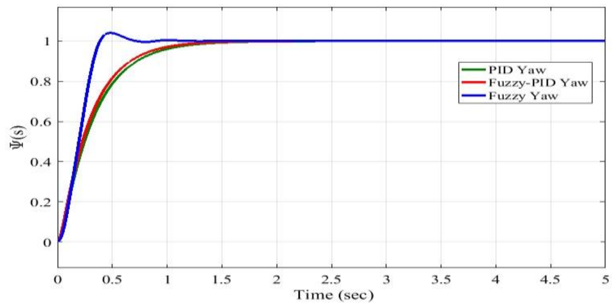

Figure 16. Comparison results for yaw angle

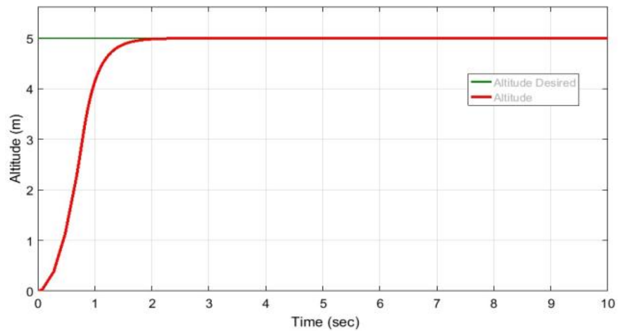

Figure 17. The altitude response of fuzzy control at 5m

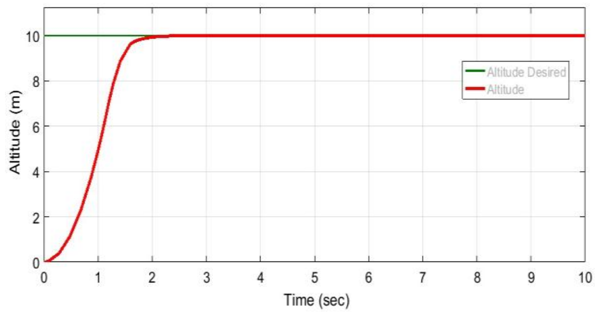

Figure 18. The altitude response of fuzzy control at 10m

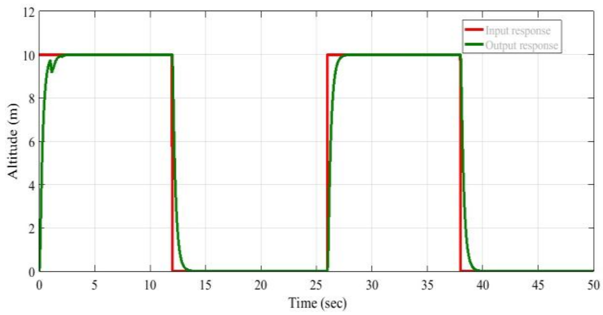

Figure 19. Control system response graph

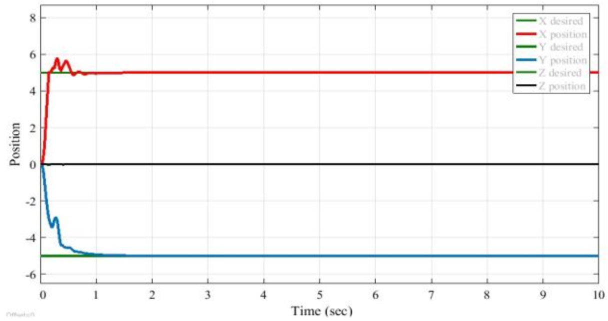

Figure 20. Position x & Y and Z (=0) responses of proposed control.

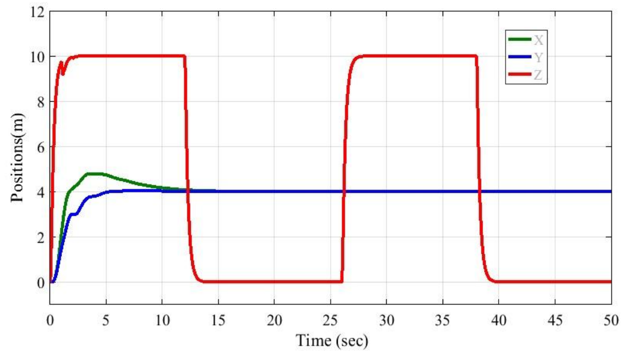

Figure 21. Position x & Y and Z (varies) responses of proposed control.

V. Conclusion

This paper presented theoretical model for a quadcopter with four-rotor as well as hybrid control system for indoor and outdoor flights. The initial memberships functions were tuned to create new membership functions based on the predefined uncertainty values. It has been clearly seen that the proposed adaptive fuzzy system that has been implemented in this paper has two fuzzy inference systems to reduce the uncertainty values in the system. The max–min product had been proposed for first stage for performing the reasoning process with fuzzy rules. The proposed fuzzy engine process has the iterations method that is implemented for optimizing purposes and to minimize the intervals values for both sides of the membership functions. These results obtained from the iterations method had been combined with reference function and defuzzified to derive accurate control outputs signal. The Matlab model has been designed and the numerical simulation results clearly demonstrated that the proposed algorithm performs significantly better compared to other controllers. The results show that the tuning process for the adaptive fuzzy controller has improved the control performance. The proposed approach has better control quality, stronger adaptability and good dynamic behavior when comparing and comprehensive analysis are carried out. For the future work, it is being directed towards building, designing and achieving a full autonomous quadcopter in controlled indoor and outdoor conditions. Also, the low cost vision SLAM system will be proposed for construction 2D map for localization purposes.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this article.

NOMENCLATURE

M	Mass of the quadcopter (Kg)
g	Acceleration of the gravity m/s2
F_i	Thrust of each motor (N)
K_T	Thrust coefficient.
K_D	Drag coefficient
τ_m	Motor torque (N-m)
τ	Torque along the body axes (N-m)
Jx	Quadcopter moment of inertia in x (kg-m2)
Jy	Quadcopter moment of inertia in y (kg-m2)
Jz	Quadcopter moment of inertia in z (kg-m2)
m	Mass of the motor (kg)
r	Radius of the motor (m)
h	Height of the motor (m)
R	Radius of the stack-up (m)
K_{DC}	Motor constant DC gain
τ:	Time constant.
Kt	Thrust coefficient (Kg.m)
Pm:	Motor power (watt)
Kv:	Back EMF coefficient
T_H:	Thrust to hover (N)
ω	Motor angular velocity (rad/sec)
Kt	Torque proportional constant
L	Length of arm (m)
f_1	Total thrust of all motors
f_2	The roll control input
f_3	The pitch control input
f_4	The yaw control input

REFERENCES

[1] N. Xuan-Mung and S. K Hong, "A Multicopter ground testbed for the evaluation of attitude and position controller," *Int. J. Eng. Technol*, vol. 7, pp. 65–73, 2018.

[2] N. P. Nguyen and S. K. Hong, "Sliding mode thau observer for actuator fault diagnosis of quadcopter UAVs," *Appl. Sci.*, vol. 8, pp. 80-93, 2018.

[3] H. Du, W. Zhu, G. Wen, and Z. Duan, "Distributed formation control of multiple quadrotor aircraft based on nonsmooth consensus algorithms," *IEEE Trans. Cybern*. vol. 49, pp. 342–353, 2017

[4] J. Jammot. (2020). Robots may become heroes in war on coronavirus. [Online]. Available:: https://www.thestar.com.my/tech/tech-news/2020/04/06/jordan-becomes-latest-mideast-country-to-deploy-drones-in-virus-response

[5] M. Owen, M. Jonathan, and M. V. Sandor, "A model based design framework for safety verification of a Semi-autonomous inspection drone," in *Proc. 11th International Conference on Control*, Belfast, UK, 2016.

[6] H. Maximilian, C. B. Robert, and V. Yuriy, "Design of a portable drone for educational purposes," in *Proc. 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED)*, Moscow, Russia, Jan 31 – Feb 02, 2018.

[7] Y. Woo-Seok, C. Myung-Hyun, J. Gun-Woo, B. Jong-Hwan, and K. Sang-Hoon, "A study on smart drone using quadcopter and object tracking techniques," in *Proc. 4th International Conference on Computer Applications and Information Processing Technology (CAIPT)*, 2017.

[8] S. Masaru and I. Masami, "Semi-autonomous flight control of forestry-use drone," in *Proc. 58th Annual Conference of Society of Instrument & Control Engineers of Japan,* September 10-13, Hiroshima, Japan, 2019.

[9] L. Wang and X. Bai, "Quadrotor autonomous approaching and landing on a vessel deck," *Journal of Intel. Robot. Syst*, pp. 125–143, 2018.

[10] A. Borowczyk, D. T. Nguyen, A. P. V. Nguyen, D. Q. Nguyen, D. Saussie, and J. L. Ny, "Autonomous landing of a multirotor micro air vehicle on a high velocity ground vehicle," IFAC Pap. Online, 50, pp. 10488–10494, 2017.

[11] J. Ghommam and M. Saad, "Autonomous landing of a quadrotor on a moving platform," *IEEE Trans. Aerosp. Electr. Syst.*, vol. 53, pp. 1504–1509, 2017.

[12] A. Junaid, A. Konoiko, and Y. Zweiri, "Autonomous wireless self-charging for multi-rotor unmanned aerial vehicles," *Energies*, vol. 10, pp. 803, 2017.

[13] B. Hu, L. Lu, and S. Mishra, "Safe and precise landing of a quadrotor on an oscillating platform," in *Proc. the American Control Conference*, Palmer House Hilton, Chicago, IL, USA, 2015.

[14] G. Croon, H. Ho, C. Wagter, E. Kampen, B. Remes, and Q. Chu, "Optic-flow based slope estimation for autonomous landing," *International. Journal of Micro Air Veh*., vol. 5, 2013.

[15] A. Faust, I. Palunko, P. Cruz, R. Fierro, and L. Tapia, "Automated aerial suspended cargo delivery through reinforcement learning," *Artif. Intell*, vol. 247, pp. 381–398, 2017.

[16] B. Arbanas, A. Ivanovic, M. Car, T. Haus, and M. Orsag, "Aerial-ground robotic system for autonomous delivery tasks," in *Proc. the IEEE International Conference on Robotics and Automation (ICRA)*, Stockholm, Sweden, 2016.

[17] N. Mathew, S. Smith, and S. Waslander, "Planning paths for package delivery in heterogeneous multirobot teams," *IEEE Trans. Autom. Sci. Eng*., vol. 12, pp. 1298–1308, 2015.

[18] M. Santos and J. Sarapura, "An adaptive dynamic controller for quadrotor to perform trajectory tracking tasks," *Journal of Intell. Robot. Syst.*, vol. 93, pp. 5–16, 2019.

[19] S. Nadda and A. Swarup, "Improved quadrotor altitude control design using second-order sliding mode," *Journal of Aerosp. Eng*., vol. 30, 2017.

[20] N. Moawad and A. M. Sarhan, "Adaptive PID sliding surface-based second order sliding mode controller for perturbed nonlinear systems," in *Proc. the 12th International Conference on Computer Engineering and Systems (ICCES)*, Cairo, Egypt, 2017.

[21] I. González, S. Salazar, and R. Lozano, "Chattering-free sliding mode altitude control for a quad-rotor aircraft: Real-time application," *Journal of Intell. Robot. Syst.*, vol. 73, pp. 137–155, 2014.

[22] M. Santos, V. Pereira, and E. J. Oliveira, "Simulation and comparison between a linear and nonlinear technique applied to altitude control in quadcopters," in *Proc. the 18th International Carpathian Control Conference (ICCC)*, Sinaia, Romania, pp. 234–239, 2017.

[23] A. H. Ahmed, A. N. Ouda, and Y. Z. Elhalwagy, "Attitude stabilization and altitude control of quadrotor," in *Proc. the 12th International Computer Engineering Conference*, Cairo, Egypt, 2016.

[24] H. S. Khan and M. Kadri, "Attitude and altitude control of quadrotor by discrete PID control and non-linear model Predictive control," *in* Proc. the International Conference on Information and Communication Technologies (ICICT), Karachi, Pakistan, 2015.

[25] N. P. Nguyen and S. K. Hong, "Fault-tolerant control of quadcopter UAVs using robust adaptive sliding mode approach," *Energies Journal*, vol. 12, no. 95, 2019.

[26] H. Thanh, S. Hong, "Quadcopter robust adaptive second order sliding mode control based on PID sliding surface," *IEEE Access*, vol. 6, pp. 66850–66860, 2018.

[27] H. Thanh, N. Nguyen, and S. Hong, "Simple nonlinear control of quadcopter for collision avoidance based on geometric approach in static environment," *Int. J. Adv. Robot. System*, 2018.

[28] X. M. Nguyen and H. Sung-Kyung, "Improved altitude control algorithm for quadcopter unmanned aerial vehicles," *Journal of Applied Science*, vol. 9, 2019.

[29] D. Gautam and C. Ha, "Control of a quadrotor using a smart self-tuning fuzzy PID controller," *International Journal of Adv.Robot. System*, vol. 10, 2013.

[30] CHRobotics (2013) AN-1005 Understanding Euler Angles. Article. Vol. Rev 1.1. Web: http://www.chrob otics .com/docs/AN-1005-Under stand ingEu lerAn gles.pdf Last access: 22 July 2020.

[31] S. A. Raza and G. Wail, "Intelligent flight control of an autonomous quadrotor," *In Tech. Journal*, 2010.

[32] W. Selby, Product Management team at the robotics startup Ouster, [Online]. Available: https://www.wilselby.com/research/arducopter/model-verification/. Last acces 28/4/2020.

[33] Jdrones. [Online]. Available: http://store.jdrones.com/AC2836_358_Motors_p/ac2836358.htm

[34] M. K. Heris.(2015). Nonlinear Regression using ANFIS. [Online]. Available: https://yarpiz.com/301/ypfz101-nonlinear-regression-using-anfis

[35] V. PT, S. Fendy, A. G. Matthew, and R. P. Ian, "Fuzzy self-tuning of strictly negative-imaginary controllers for trajectory tracking of a quadcopter unmanned aerial vehicle," *IEEE Transactions on Industrial Electronics*, 2020.

[36] J. Dong and B. He, "Novel fuzzy PID-type iterative learning control for quadrotor UAV," *Sensors Journal*, 2019.

[37] J. Shi, "Research on fuzzy closed loop control system for unmanned aerial vehicle," *Journal of Information Technology*, 2018.

[38] W. Si, H. She, and Z. Wang, "Fuzzy PID controller for UAV tracking moving target," *Control and Decision Conference IEEE*, pp. 3023-3027, 2017.

[39] E. K. Parameter, T. Vesselenyi, S. Dzitac, and R. Tarca, "PID and fuzzy-pid control model for quadcopter attitude with disturbance," *International Journal of Computers, Communications & Control (IJCCC)*, 2017.

[40] N. S. Bhangal and K. Amit Raj, "Fuzzy control of vehicle active suspension system," *International Journal of Mechanical Engineering and Robotics Research*, vol. 5, no. 2, pp. 144-148, 2016.

[41] R. AL-Jarrah and H. Tlilan, "Bounded interval fuzzy control for half vehicle's active suspension system," *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 8, no. 3, pp. 1625- 1637, 2019.

[42] Y. M. Chen, C. Hsueh, V. Wang, and T. Wu, "Decision fusion using fuzzy threshold scheme for target detection in sensor networks," *Journal of Computational Science*, vol. 25, pp. 327-338, 2018.

[43] R. Al-Jarrah and H. Roth, "Developed blimp robot based on ultrasonic sensors using possibilities distribution and fuzzy logic," *Journal of Automation and Control Engineering*, vol. 1, no. 2, pp. 1-7, 2013.

[44] R. Al-Jarrah, "Blimp based on embedded computer vision and fuzzy control for following ground vehicles," in *Proc. 3rd IFAC Symposium on Telematics Applications, The International Federation of Automatic Control*, pp. 7-13, 2013.

[45] O. R. Carvajal, O. Castillo, and J. Soria, "Optimization of membership function parameters for fuzzy controllers of an autonomous mobile robot using the flower pollination algorithm," *J. of Automation, Mobile Robotics & Intelligent Systems*, vol. 12, no. 1, pp. 44-49, 2018.

[46] P. Aimtongkham, T. Nguyen, and C. So-In, "Congestion control and prediction schemes using fuzzy logic system with adaptive membership function in wireless sensor networks," *Wireless Comm. and Mobile Computing J*., vol. 2018.

[47] P. Harliana and R. Rahim, "Comparative analysis of membership function on mamdani fuzzy inference system for decision making," *Int. Conf. on Info. and Comm. Tech.*, Series 930-012029, 2017.

[48] R. Al-Jarrah, and M. Al-Jarrah, "A novel edge detection algorithm for mobile robot path planning," *Journal of Robotics*, vol. 2018, 2018.

[49] R. Al-Jarrah, "Path planning and motion coordination for multi-robots system using probabilistic neuro-fuzzy," *Elsevier Conference Paper Archive*, IFAC-Papers On Line, pp. 046–051, 2015.

[50] R. Al-Jarrah and H. Roth, "Design blimp robot based on embedded system and software architecture with high level communication and fuzzy logic," in *Proc. the 9th International Symposium on Mechatronics and its Applications*, Jordan, 2013.

[51] S. Weiyong, S. Haoping, and W. Zhanglong," Fuzzy PID Controller for UAV Tracking Moving Target", in *Proc. 29th Chinese Control And Decision Conference (CCDC)*, 2017.

[52] Y. K. Qiao, F. W. Jian, and R. Wang, "Novel multicast congestion control mechanism based on Fuzzy-PID control," *Journal of Systems Engineering and Electronics*, vol. 33, no. 2, pp. 416-422, 2011.

[53] R. Al-Jarrah, "Development of cooperation between flying robot, ground robot and ground station with fuzzy logic and image processing," Ph.D. dissertation, Siegen University, Germany, 2015.

[54] J. Botzheim, C. Cabrita, L. T. Kóczy, and A. E. Runao, "Fuzzy rule extraction by bacterial memetic algorithms," *International Journal of Intelligent Systems*, vol. 24, no. 3, pp. 312-339, 2009.

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