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Sembolik Ayrık Kontrol Sentezi ve Optimal PID Kontrolörün Dört Rotorlu İHA'nın Durum Kontrolündeki Performanslarının Karşılaştırılması

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Balina optimizasyon algoritması
Genetik algoritmalar

ÖZ

İnsansız hava araçları (İHA) son yıllarda birçok mühendislik uygulamasında kullanılmaktadır. Dört rotorlu tipi İHA'lar basit yapıları nedeniyle en çok tercih edilen hava platformlarından biridir. Dört rotorlular 6 serbestlik dereceli hareket kabiliyetine sahiptir. Dört rotorlu kontrolü birçok araştırmacı tarafından üzerinde çalışılan önemli ve zor bir problem olarak bilinmektedir. Bu çalışmada, dört rotorlu İHA'nın durum kontrolü, sembolik sınırlı optimal ayrık denetleyici sentezleme (S-DCS) yöntemi ve optimal Oransal İntegral Türev (PID) denetleyici kullanılarak gerçekleştirilmiştir. PID kontrolör parametreleri, son yıllarda geliştirilen meta-sezgisel bir algoritma olan Balina optimizasyon algoritması (BOA) ve Genetik Algoritmalar (GA) kullanılarak tahmin edilmiştir. S-DCS, istenen sistem çıktısını elde etmek için tanımlanmış bir maliyet fonksiyonunu en aza indirmeyi amaçlayan yeni bir yöntemdir. Geliştirilen kontrolörlerin dört rotorlunun dinamik modelinin durum kontrolündeki başarısı karşılaştırılmış ve sonuçlar tartışılmıştır.

Comparison of The Performances of Symbolic Discrete Control Synthesis and Optimal PID Controller in Attitude Control of Quadcopter UAV

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ABSTRACT

Unmanned aerial vehicles (UAVs) have been utilized in numerous engineering applications in recent years. Quadcopter-type UAVs are among the most preferred air platforms due to their simple structure. Quadcopters have 6 degrees of freedom movement capability. Quadcopter control is known as a significant and challenging problem studied by many researchers. In this study, attitude control of the quadcopter UAV was realized using the symbolic discrete controller synthesis (S-DCS) method and an optimal Proportional Integral Derivative (PID) controller. PID controller parameters were estimated using the Whale Optimization Algorithm (WOA) and Genetic Algorithms (GA). S-DCS is a new method that aims to minimize a defined cost function to obtain a desired system output. The success of the developed controllers in attitude control of the quadcopter dynamic model was compared, and the results were discussed.

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1. Introduction

In recent years, the usage of unmanned aerial vehicles (UAVs) has increased rapidly in many civil and military application fields, such as real-time monitoring in surveillance missions and cargo delivery (Shakhatreh et al., 2019; Uçar et al., 2019). Among the UAV family, quadcopters have been preferred for all recent research and engineering applications due to their mechanical simplicity and vertical takeoff and landing capability. A quadcopter involves two pairs of counter-rotating rotors and propellers mounted on a frame (Sivakumar et al., 2021). A quadcopter uses its high-speed rotors to produce a push force, keeping the vehicle in the air.

The full dynamic model of the quadcopter is nonlinear; therefore, linearization is used to simplify it (Wang et al., 2016). Considering the linearized and simplified model, many different control techniques have been designed and applied for the control of the quadcopter (Thu et al., 2017). In the literature, one of the simple structured, commonly known, and preferred control methods is proportional, derivative, and integral (PID) control (Leva, 2018). However, in many cases, traditional PID alone is not the best solution, and researchers must apply optimal and adaptive controllers to guarantee optimal system output (Leal et al., 2021).

Metaheuristic (MH) methods are a type of stochastic optimization method. In the literature, there are different types of MH algorithms, such as nature-based, human-based, evolutionary, and physics-based; however, most MH methods are swarm-based. In recent years, there has been a growth in the number of these algorithms (Braik et al., 2022). MH algorithms developed in recent years are listed in Table 1.

Table 1. MH algorithms proposed in recent years

Algorithm	Type	Year published
Social Engineering Optimizer	Human-based	2018
Emperor Penguins Colony	Swarm-based	2019
Political Optimizer	Human-based	2020
African Vultures Optimization Algorithm	Nature-based	2021
Mountain Gazelle Optimizer	Nature-based	2022
Flying Fox Optimization Algorithm	Nature-based	2023

The P, I, and D coefficients of the PID controller were determined via WOA and GA. WOA draws inspiration from the logic of bubble-net hunting and is based on imitating the social behavior of humpback whales (Mirjalili et al., 2016). Optimal controllers aim to minimize the error between the reference signal and the plant's measured output in both the transient and steady-state regions. Performance indices are used to obtain optimal controllers. According to (Wang et al., 2014), four basic error performance indices were defined: integral of time-weighted absolute error (ITAE), integral of absolute error (IAE), integral of time squared error (ITSE), and integral of squared error (ISE).

MH algorithms have shown promising results in many optimization studies. It is well suited for problems involving multiple variables and constraints, such as setting the parameters of PID controllers in complex systems such as quadcopter attitude control. We aim to efficiently fine-tune the PID controller parameters to increase the performance of the quadcopter UAV in attitude control tasks by using WOA that was not used in attitude control of the quadcopters.

The review (Radosław and Giernacki, 2021) covers fault detection in UAVs from January 2016 to August 2022, emphasizing the need for heightened reliability due to their growing complexity and proximity to humans. Utilizing Web of Science and Google Scholar, relevant articles were summarized, underlining the ongoing necessity for research to enhance UAV safety amidst expanding applications. The study (Sophie et al., 2021) discusses the potential of UAVs for infrastructure inspections, aiming to alleviate challenges associated with current manual methods such as cost, labor intensiveness, and subjectivity. It reviews technologies addressing obstacles to UAV integration into existing practices while outlining current challenges and future research directions in UAV inspections of power facilities and structures. The article (Konrad et al., 2021) addresses the challenge of relying on uncertain information from fault detection algorithms in active fault-tolerant control (FTC), aiming to design a robust FTC controller that can handle missed "small" faults and fault detection delays. The study integrates adapted μ analysis into a DK-iteration approach to synthesize a controller within a robust control framework with $H\infty$-design objectives, demonstrated through real flight experiments on a fixed-wing UAV with aileron and flap faults.

In this paper, we consider the attitude control of quadcopters as a discrete controller synthesis problem. S-DCS is a new method that proposes to minimize a defined cost function to provide a desired system output. The control theory of discrete event systems has been proposed as a language theory; the theory usually targets synthesizing a controller for a given system and control objectives (Özbaltan and Berthier, 2018). Symbolic modeling is the modeling of a labeled input/output automaton. Controllability is based on the principle that outputs are provided through transitions of symbolic states as a function of inputs, rather than events. Thus, symbolic modeling and control of problems encountered in real life (such as controlling a system with a controllable input signal) offer a more effective solution instead of standard control algorithms.

In this study, attitude control of a quadcopter-type UAV was achieved via optimal PID and Symbolic Limited Optimal Discrete Controllers. Parameters of PID controllers were obtained using WOA and GA methods. IAE was used as the performance index for PID controllers. The success of the tested controllers in attitude control of the quadcopter dynamic model was compared and discussed in terms of transient and steady-state performances.

2. Materials and Methods

2.1. Materials

The quadcopter is a member of the multirotor-based UAV family. A quadcopter has 3 rotational and 3 translational movements which are provided by its four rotors. These movements are realized by changing the direction and the angular velocities of the rotors. Quadcopters are composed using BLDC motors that are placed at the tips of the arms integrated into a chassis. The structure of a quadcopter is shown in Figure 1.

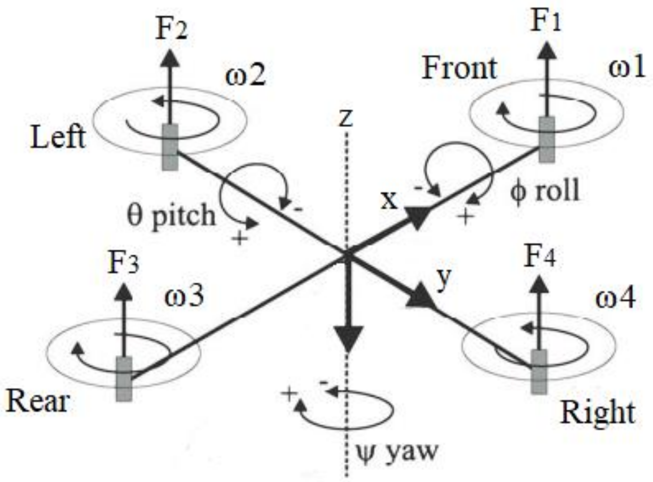

Figure 1. The structure of a quadcopter (Bolandi et al., 2013)

The full dynamic model of the quadcopter includes nonlinear dynamic equations. The quadcopter's simplified and linearized model has been utilized in many research studies. The linear model of the quadcopter is given between Equation 1 and Equation 6.

$$\ddot{x} = g * \theta \tag{1}$$

$$\ddot{y} = -g * \varphi \tag{2}$$

$$\ddot{z} = -g + \frac{u1}{m} \tag{3}$$

$$\ddot{\varphi} = \frac{u2}{I_x} \tag{4}$$

$$\ddot{\theta} = \frac{u3}{I_y} \tag{5}$$

$$\ddot{\psi} = \frac{u4}{I_z} \tag{6}$$

where u1 represents the thrust force produced by the quadcopter's rotors, u2 is the force that produces roll movement, u3 is the force that produces pitch movement, and u4 is the force that produces yaw movement. The x-axis moment of inertia is denoted by Ix, the y-axis by Iy, the z-axis by Iz, and the gravitational field by g. The rotors' angular velocities (ωi) represent the quadcopter's actual inputs. On the other hand, Equations 7-10 use virtual inputs to express the actual inputs.

$$u_1 = ({\omega_1}^2 + {\omega_2}^2 + {\omega_3}^2 + {\omega_4}^2) \tag{7}$$

$$u_2 = ({\omega_1}^2 - {\omega_3}^2) \tag{8}$$

$$u_3 = ({\omega_2}^2 - {\omega_4}^2) \tag{9}$$

$$u_4 = ({\omega_1}^2 - {\omega_2}^2 + {\omega_3}^2 - {\omega_4}^2) \tag{10}$$

There are studies that include obtaining dynamic parameters of quadcopters in the literature. Parameters obtained in an experimental study were used to specify the parameters of the quadcopter dynamic model used in this study (Bresciani, 2008). The dynamic parameters of the quadcopter model are as given in Table 2.

Table 2. Parameters of quadcopter

Name	Parameter	Value	Unit
quadcopter mass	m	1	Kg
gravity	g	9.81	m s^{-2}
moment of inertia of X-axis	Ixx	8.1E-3	N m s^2
moment of inertia of Y-axis	Iyy	8.1E-3	N m s^2
moment of inertia of Z-axis	Izz	14.2E-3	N m s^2

2.2. Methods

WOA was utilized in this study to compute the P, I, and D PID controller parameters. One of the more recent optimization techniques, WOA was put forth in 2016. It can be applied to several study disciplines to tackle optimization challenges. WOA demonstrated its efficacy in comparison to other widely used MH methods proposed in the literature. WOA was utilized to compute the P, I, and D parameters of the optimal PID controllers. Figure 2 displays the WOA flowchart (Rana et al., 2020). The genetic algorithm method was inspired by the theory of natural evolution. To produce the next generation, GA includes the natural selection process where the most proper individuals are used. In the GA procedure, there are main phases such as generation of initial population, calculation of the fitness function, selection, crossover and mutation. Figure 3 displays the GA flowchart (Çaşka et al., 2022). WOA and GA procedures were applied to the dynamic model using the R2021a version of The MATLAB software.

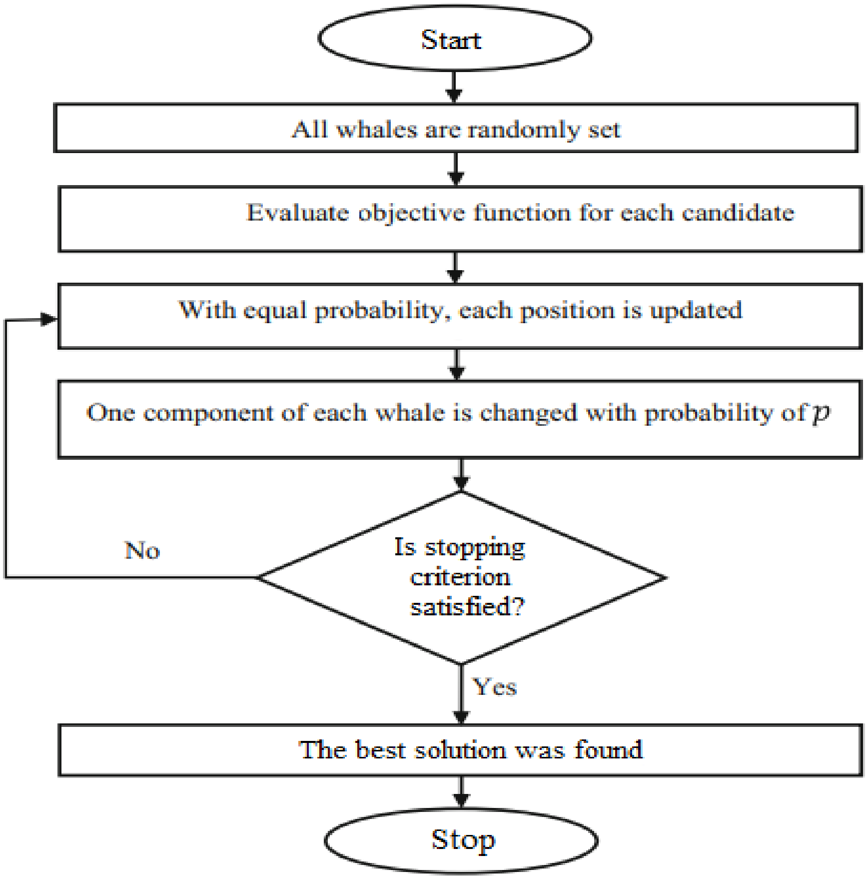

Figure 2. Flowchart of WOA

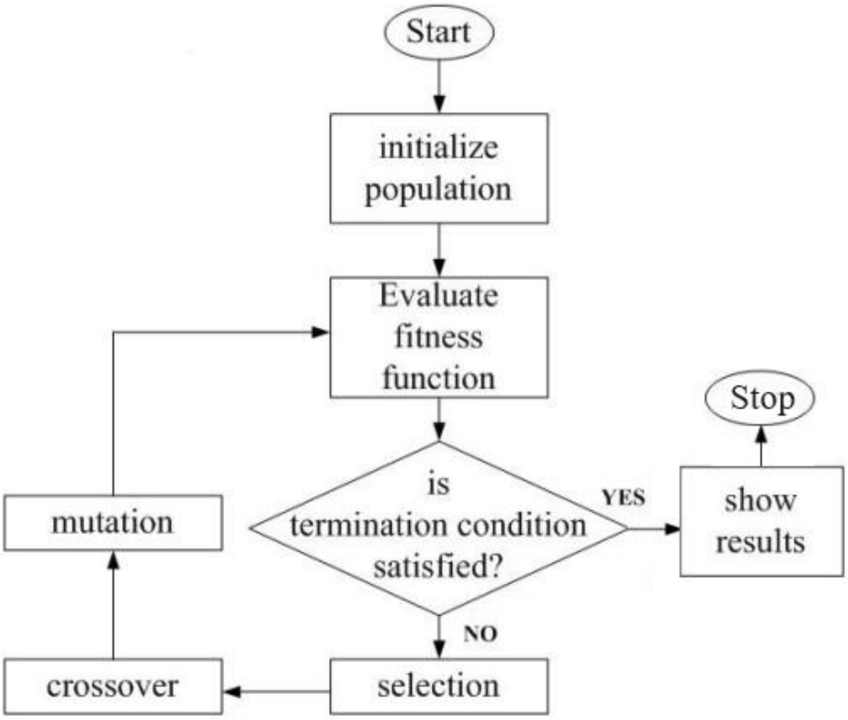

Figure 3. Flowchart of GA (Çaşka et al., 2022).

The PID block of Simulink includes a filter coefficient in the derivative branch. In this study, the filter coefficient was defined as 100. Structure of the PID controller used in this study is illustrated in Figure 4.

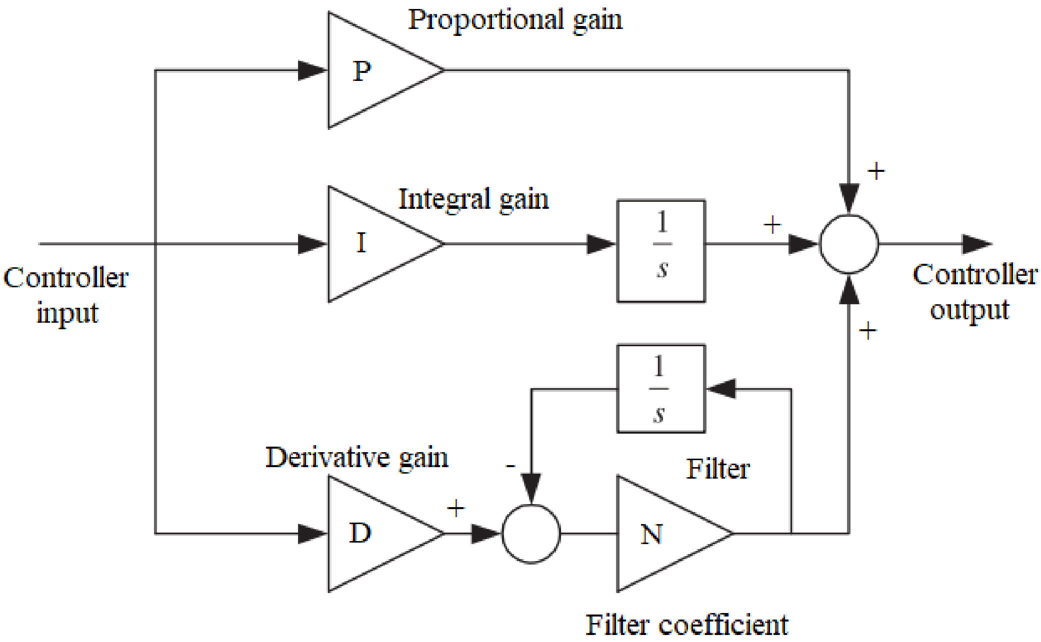

Figure 4. The structure of PID controller

The principle of discrete control synthesis we employ hinges upon ensuring the desired properties of two distinct Mealy machines. As illustrated in Figure 5, it is required that both Mealy machines A and B simultaneously exhibit state values of either 0 or 1. To achieve these desired system characteristics, a third Mealy machine, denoted as controller C, is employed to encapsulate the control signal b with the synchronized parallel composition of the three Mealy machines.

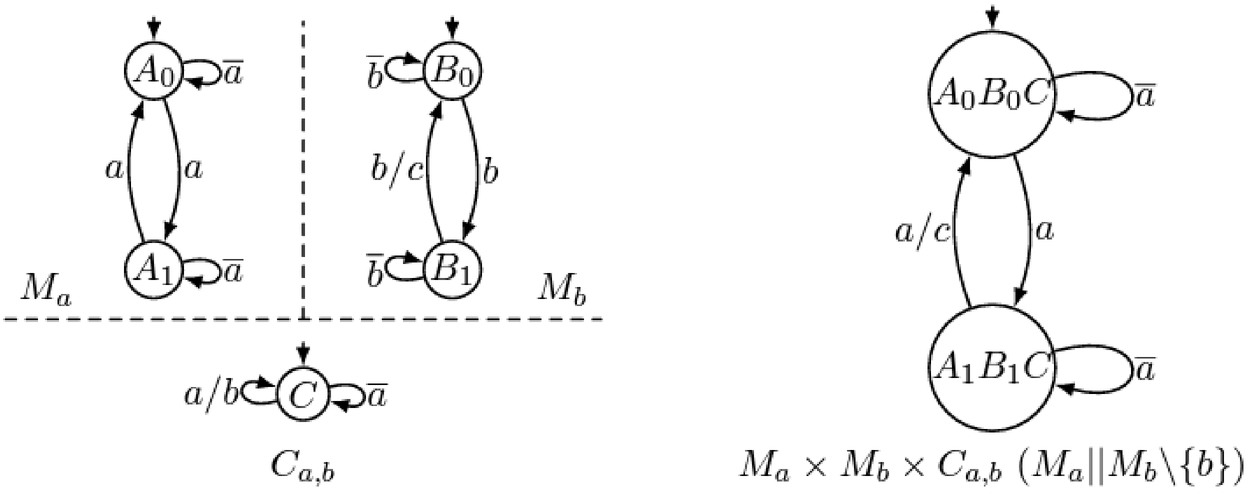

Figure 5. Representation of the Control Theory of Discrete Event Systems (DCS)

However, discrete control synthesis is generally focused on generating this controller given a specified plant and desired system objectives. The calculation steps are illustrated in Figure 6. The opposite of the specified objective yields a subset of the state space termed Bad states. This includes the possibility of Bad states for any uncontrollable input values, extending to a space termed as I_{Bad}, representing the illegal state space. Finally, identifying the remaining region in the state space allows us to produce our controller exhibiting controllable variables, enabling the desired system behaviors.

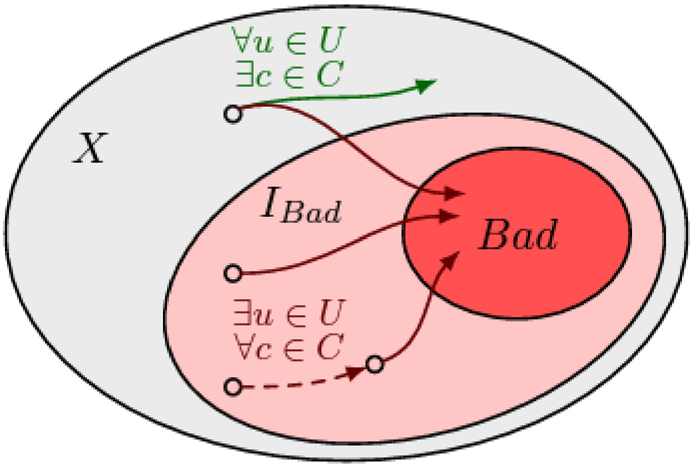

Figure 6. Computational steps on the state space X

The quadcopter plant was firstly modeled as data-flow equations. The thrust forces acting on a quadcopter are controllable variables of the model. Then, we synthesize a controller by applying our control algorithm with the given control targets. Our symbolic data-flow models of the velocity of quadcopters, both in the x and y axes, are given in Equations 11-14.

$$Vx' :\triangleq \frac{u3*g}{2*Iy}t^2 + Vx \tag{11}$$

$$Vx \coloneqq Vx' \tag{12}$$

$$Vy' :\triangleq \frac{u2*g}{2*Iy}t^2 + Vy \tag{13}$$

$$Vy \coloneqq Vy' \tag{14}$$

V′ represents the present velocity value, while V denotes the previous value; where t is the uncontrollable input variable, u2 and u3 is our controllable input variable, g, Ix, and Iy are fixed coefficients. The equations for the position of the quadcopter derived from the velocity equations above are as in Equation 15-18.

$$\Delta x :\triangleq (Vx + Vx') * 0.5t \tag{15}$$

$$X \coloneqq X + \Delta x \tag{16}$$

$$\Delta y :\triangleq (Vy + Vy') * 0.5t \tag{17}$$

$$Y \coloneqq Y + \Delta y \tag{18}$$

is encoded as in Equation 19:

$$\sigma :\triangleq \; Vx \leq Vx^{L} \wedge Vy \leq Vy^{L} \wedge \mathrm{u2} \leq u2^{L} \wedge \mathrm{u3} \leq u3^{L} \wedge Zx \leq Zx^{T} \wedge Zy \leq Zy^{T} \tag{19}$$

Our optimal control objective tries to minimize the positions by adhering to the safety objective by means of our limited optimization control algorithm. Then with the application of the algorithm, the suitable controller is automatically generated in C and HDL programming languages.

3. Results and Discussion

In this study, the coefficients of the optimal PID controllers were obtained for the attitude control of the quadcopter using WOA and GA. The optimization processes of WOA and GA were carried out while 1 rad was defined as the set point for roll, pitch, and yaw movements. Speed limits on roll, pitch, and yaw movements were defined as [-2 2] rad/sec. Table 2 shows the value of the objective function calculated by WOA and GA.

Table 2. Value of the objective function calculated by WOA and GA

Algorithm	Trial	Objective function(Roll,Pitch)	Objective function(Yaw)
WOA	1	0,566	0,567
WOA	2	0,587	0,544
WOA	3	0,612	0,635
WOA	**4**	0,557	**0,518**
WOA	5	0,549	0,654
WOA	6	0,635	0,588
WOA	**7**	**0,529**	0,675
WOA	8	0,576	0,554
WOA	9	0,604	0,562
WOA	10	0,679	0,577
GA	1	0,550	0,541
GA	2	0,651	0,614
GA	3	0,561	0,553
GA	4	0,665	0,541
GA	5	0,569	0,539
GA	6	0,547	0,554
GA	7	0,586	0,607
GA	8	0,623	0,640
GA	9	0,539	0,537
GA	10	0,603	0,569

Table 2 proves that WOA is more proper than GA in obtaining PID controller parameters. Thus WOA was selected to compare with the SDCS method. Performances obtained with different WOA parameters are as shown in Table 3.

Table 3. Performances obtained with different WOA parameters

Population size	Max. iteration number	Objective function(Roll,Pitch)	Objective function(Yaw)
20	10	0,564	0,543
20	20	**0,529**	**0,518**
20	30	0,553	0,540
40	10	0,561	0,539
40	20	0,567	0,541
40	30	0,546	0,544
60	10	0,545	0,555
60	20	0,538	0,529
60	30	0,548	0,534

The best case was obtained while both population size and maximum iteration number are 20. The calculated PID coefficients by WOA are as given in Table 4.

Table 4. Calculated controller coefficients for Roll, Pitch and Yaw movements

PID coefficients	Roll	Pitch	Yaw
P	6,238	6,238	9,415
I	0	0	0
D	0,291	0.291	0,472

Graphs illustrating the success of the roll and pitch controllers, as well as the yaw controller, are provided in Fig. 7 and Fig. 8, respectively.

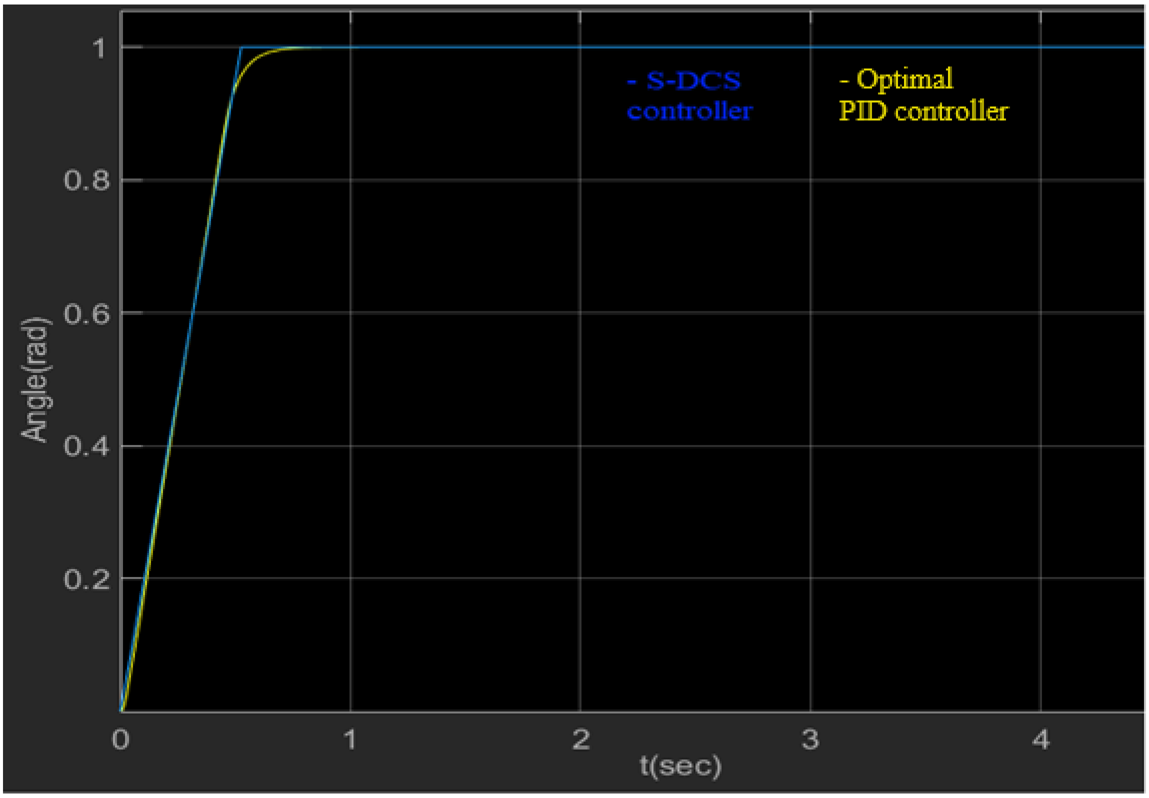

Fig. 5. Performance graphs of roll and pitch controllers for set value of 1 rad

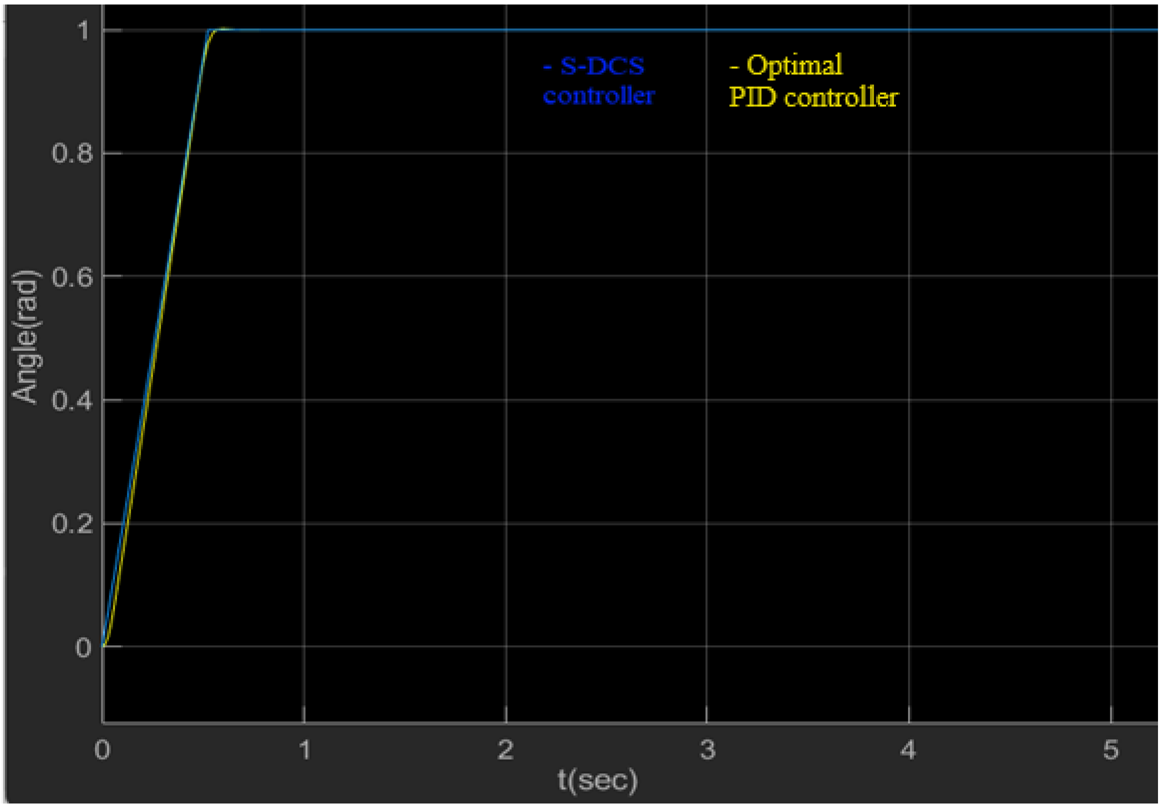

Fig. 6. Performance graphs of yaw controllers for set value of 1 rad

The success of the developed controllers for roll and pitch movements and yaw movement are provided in Table 5 and Table 6, respectively. In Table 5, parameters of steady-state error (Ess) representing steady-state performance, rising time (Tr), peak time (Tp), maximum overshoot measured at the peak time (Mp), and steady-state time (Ts) representing transient state performance were used to evaluate the success of the optimal controllers. Tr was considered the elapsed time until the output reached 90% of the input.

Table 5. Performance of the controllers in control of Roll(Φ) and Pitch(Θ) angles

Angle (rad)	S-DCS					Optimal PID				
	Tr(s)	Tp(s)	Mp(%)	Ts(s)	Ess(%)	Tr(s)	Tp(s)	Mp(%)	Ts(s)	Ess(%)
0,2	0,095	0,105	0	0,105	0	0,095	0,124	0	0,124	0
0,4	0,190	0,210	0	0,210	0	0,195	0,225	0	0,225	0
0,6	0,284	0,315	0	0,315	0	0,290	0,335	0	0,335	0
0,8	0,335	0,421	0	0,421	0	0,336	0,429	0	0,429	0
1,0	0,474	0,526	0	0,526	0	0,471	0,817	0	0,817	0
1,2	0,569	0,631	0	0,631	0	0,577	0,650	0	0,649	0

Table 6. Performance of the controllers in control of Yaw(Ψ) angle

Angle (rad)	S-DCS					Optimal PID				
	Tr(s)	Tp(s)	Mp(%)	Ts(s)	Ess(%)	Tr(s)	Tp(s)	Mp(%)	Ts(s)	Ess(%)
0,2	0,094	0,105	0	0,105	0	0,097	0,115	0,203	0,125	0
0,4	0,188	0,209	0	0,209	0	0,198	0,219	0,236	0,244	0
0,6	0,283	0,314	0	0,314	0	0,283	0,314	0,203	0,345	0
0,8	0,335	0,419	0	0,419	0	0,335	0,419	0,213	0,456	0
1,0	0,471	0,524	0	0,524	0	0,477	0,601	0,202	0,680	0
1,2	0,565	0,628	0	0,628	0	0,565	0,628	0,206	0,682	0

DCS acts as a model-checking tool, ensuring that a system meets specified properties crucial. Model-checking aids in detecting design errors and verifying system intricacies by confirming adherence to defined specifications, and utilizing symbolic representations like Binary Decision Diagrams for efficient verification. Thus, DCS guarantees the desired system properties for each model. However, accurate modeling of environmental conditions and real-world situations is essential for DCS to effectively guarantee desired system properties.

4. Conclusion

Table 4 shows that the Tr and Tp values are very similar for S-DCS and PID controllers. There is no oscillation in the roll and pitch output provided by S-DCS and PID controllers. The Ts value of the S-DCS controller is smaller than the Ts value of the PID controller. This proves that the S-DCS controller provides a faster transient response than the PID controller. In Table 5, there is no oscillation in the yaw output of the S-DCS controlled system. The Mp value is zero because there is no overshoot for the S-DCS controller, while there are Mp values for the PID controller. The Ess value of the yaw output provided by the S-DCS controller and the PID controller are both zero. Considering the results in Table 4 and Table 5, the S-DCS controller showed better performance than the WOA-based optimal controller in the attitude control of the quadcopter.

In this study, attitude control of the quadcopter was realized using S-DCS and PID controllers. The originality of this paper lies in being the first in the literature to compare S-DCS and PID methods in quadcopter control. Possible future research can include the integration of recently developed and commonly known MH algorithms (Nalbantoğlu et al., 2023). To further validate the success of S-DCS, a nonlinear model of the quadcopter should also be employed (Abdollahi et al., 2015). In this study, disturbances and noise were not considered, and future research should be conducted under these conditions. Additionally, besides PID, other common control methods should be used for comparison with the success of the S-DCS controller. In the GA procedures, both the population size and maximum iteration number were defined as 20. Future studies can explore variations in these parameters and the effect of the parameters such as crossover and mutation rates. In the literature, numerous studies include quadcopter control in simulation and real environments. Unlike the results of this study, transient and steady-state errors are not ideal in many of the studies in the literature (Sivakumar et al., 2021). Therefore, to validate the success of the S-DCS controller, tests should be conducted using a real quadcopter.

Table 3 was obtained as a result of the sensitivity analysis for parameter changes for WOA. Considering Table 3, it is seen that WOA gives different results if the population size and maximum number of iterations change. In this regard, it has been observed that changes in the considered parameters affect the optimization result and therefore the controller performance.

Environmental factors such as wind and modeling the limitations of yet unidentified scenarios for future work represent a highly complex process. While it is possible to identify primary factors in future studies and model them extensively, this process is intricate and susceptible to errors and deficiencies in modeling parameters. Hence, we believe that providing external world dynamics as an input to the system, termed as an oracle, results in much more accurate and reliable outcomes in synthesizing the controller. Here, the oracle is merely an input in our system model, but before being provided to the system, this input undergoes a series of computations, as mentioned in the studies by (Özbaltan and Berthier, 2020) and (Özbaltan and Berthier, 2021).

It is known that the full dynamic model of the quadcopter is non-linear. In this study, the linear model of the quadcopter was used. Working on linear or linearized models is an approach frequently used by researchers to solve problems in engineering systems. However, no linearized model can fully represent the nonlinear model. Considering that most engineering systems consist of nonlinear systems, it is certain that the methods applied in this study should also be tested on a nonlinear model. In addition, academic and industrial studies on multibody models or digital twin models have become widespread today. The authors plan to use the methods tested in this study to control a quadcopter modeled in an environment such as Simscape. In tests to be carried out in a simulation environment containing the solid model of the quadcopter, it will reflect the system response to the disturbance much better than the mathematical model. In future studies, the performance of the model reference adaptive controller, which has been used in quadcopter control in recent years, can be compared with the performance of the S-DCS method.

This study was conducted under ideal conditions without considering environmental factors such as wind. In future research, more precise modeling can be achieved by taking into account such environmental conditions. Furthermore, unmanned aerial vehicles can be applied to a variety of different plants. Lastly, our approach could contribute to cost and performance improvements when applied in industrial fields such as CNC robotics applications.

Statement of Conflict of Interest

The authors declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author's Contributions

The contribution of the authors is equal.

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