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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF METHODS FOR DESIGNING HYBRID CONTROL SYSTEMS OF QUADCOPTERS PERFORMING OVERLAND MONITORING

Specialty:	3338.01 – System analysis, control and information processing (information technology)
Field of science:	Technical sciences
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Baku – 2024

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GENERAL CHARACTERISTICS OF WORK

Relevance of work. Quadcopter is a four-propeller driven unmanned aerial vehicle (UAV). Currently, these aircrafts are in a very broad and diverse usage. However, this usage is limited by remote control modes manually operated by operators and flight along a simple path. The underlying reason for such limitations is complexity of automatic flight between different obstacles and low autonomy of the quadcopter due to autonomous navigation difficulty when no signal is available from the satellite navigation system (SNS). The matter under consideration is to create an autonomous flight control system enabling its flight along the planned path with autonomous navigation.

The operation setting of the quadcopters is growing in complexity in as much as their applications expand and it may have multiple and different obstacles (both mobile and stationary). It may not have SNS signals either. Most of the path planning algorithms and control systems described in the literature have been well developed for usage in the deterministically known static setting. Nevertheless, it does not ensure the ability to operate sufficiently well in the complex unknown setting against various obstacles and atmospheric influences.

The integrated navigation systems (INS) available for quadcopters may not ensure reliability of the navigation data when no SNS signals are available. Across the world, intensive research is carried out on quadcopter navigation technologies using visual navigation system (VNS), computer vision, terrain maps and etc., based on simultaneous localization and mapping (SLAM). VNS usage helps to make major achievements such as navigation precision for quadcopter, particularly in an unknown dynamic setting. However, this usage is very limited for quadcopters due to image processing and low performance of SLAM algorithms.

Many scientists from various countries have contributed to the development of this field of scientific novelty and their results have been largely referred to in this dissertation work: D.P. Inozemtsev, D.S. Michael, A. Sharma and A. Barve, A. Rodic and G. Mester, H. Khebbache and M. Tadjine, V. Lopez and F. Morata, S.A. Raza and

W. Gueaieb, B. Kadmiry, F. Jurado and B. Castillo-Toledo, C. Nicoli, C.J.B. Macnab and A. Ramirez-Serrano, A. Burka and S. Foster, J.F. Shepherd and K. Tumer, S. Suresha and N. Sundararajan, C.T. Lee and C.C. Tsai, M. Mohammadi and A.M. Shahri, P. Nirut, R. Masuda and H. Hirata, A. Kırlı, V.E. Omurlu, U. Buyukshahin and R. Artar, A.E. Kulchenko, A.V. Bozhenyuk and E.M. Gerasimenko, V.H. Pshihopov and V.A. Kruhmalev, M. Fatan, B.L. Sefidgari, A.V. Barenji, E. Ortak and etc.

Thus, solving and investigation of these problems is very pressing and namely therefore it is of practical importance in the context of development of the automated flight control system for quadcopters. Such solutions help to ensure autonomous flight along the planned path in the overland monitoring context under complex conditions and by its ability to fly around the obstacles with autonomous navigation.

The aim of the work. The aim of the dissertation work is to develop methods for designing hybrid control systems for the helicopter type unmanned aircrafts, specifically quadcopters on the basis of their applications during overland monitoring.

To achieve the goal, this dissertation work has outlined the following matters:

- Analysis of the practical usage peculiarities of the regulators of quadcopter’s automated control systems;
- Study dynamic tridimensional model of quadcopters taking into account the gyroscopic effects of both propellers and engines, the effects of wind and the gravity;
- Develop an incremental process for creating the prototype of the quadcopter using system modeling in MATLAB program package notation;
- Develop an algorithm to establish the quadcopter 3D flight trajectory in overland monitoring setting against the stationary obstructions;
- Using fuzzy inference system, develop an algorithm for quadcopters to avoid obstacles in a complex setting;
- Using the neural network modeling, develop an algorithm for path tracing in real time mode;

- Develop quadcopter control concept based on the application of adaptive hybrid controllers.

Research object and subject. The research object is the “X” configured UAV of quadcopter type (two propellers are guided along the flight path) with the ability to fly around obstacles in a complex overland monitoring setting, performing autonomous flight along the planned path. The subject of the research is to develop trajectory control algorithms for quadcopter prototype using intelligent hybrid adaptive controllers ensuring maneuvers to overcome various obstacles.

Research methods. Mathematical analysis, ways of system modeling, the mathematical apparatus of fuzzy logic, and neural network modeling, as well as the combination of linear PID – controller and velocity vector rotation control were used when addressing the matters outlined in the dissertation work. Computing systems were used in the mathematical modeling process such as: Excel spreadsheet, MATLAB modeling domain, including MATLAB\Simulink, MATLAB\FIS, MATLAB\Neural Network Toolbox and MATLAB\ANFIS tools.

The main provisions of the defense. The key outcomes of the dissertation research with scientific novelty personally obtained by the author are as follows:

1. Multiphase procedure concept to create a quadcopter prototype using object-oriented system modeling means in MATLAB program package notation.
2. Fast algorithm for processing a spatial path in overland monitoring setting by stationary obstacles based on fuzzy inference system
3. Quadcopter path tracing algorithm based on maneuver algorithm and three-layer feedforward neural network to overcome obstacles in a complex setting.
4. Quadcopter control system based on multimodal stabilization algorithm envisioning usage of connectionist hierarchical structured neural network consisting of “reasonable” and “instinctive” neural subnets.

5. Path tracing algorithm in overland monitoring setting based on maneuver algorithm and intelligent hybrid neuro-fuzzy controllers to overcome complex obstacles.

The scientific novelty of the work. Scientific novelty of the research is the algorithms obtained to form 3D trajectories of quadcopter autopilot flight in overland monitoring setting, including:

1. The concept for building quadcopter prototype has been developed using object-oriented system modeling tools in MATLAB program setting.

2. Algorithms were developed to control quadcopter trajectory using neuro-fuzzy modeling methods. They differ from the known algorithms by its performance, as long as they do not demand accurate space orientation maintenance and significantly simplify the control circuitry due to lack of solutions to interim problems.

3. An algorithm was developed for quadcopter adaptive control using hierarchical structured neural network model consisting of "reasonable" and "instinctive" neural subnets, which may serve to substantially minimize the timing and decision-making velocity when maneuvering around the obstacles in overland monitoring setting.

The practical significance of the work. The developed control algorithms are quite "simple" and may therefore be effectively used to monitor execution of infrastructure projects in the regions characterized by mountainous and wooded landscapes. The approaches suggested in the dissertation help to simulate tridimensional dynamics and optimal coefficients of PID controllers. Moreover, trajectory forming algorithms simplify creation of quadcopter prototype to perform full-scale testing of the control systems of rotationary winged apparatuses. The followings may be listed as the most important fields of application:

- As a load carrying vehicle for the personnel working in an inaccessible terrain, it is an ideal vehicle to supply long-term operation of the personnel equipped with portable solar energy panels or other small-size alternative power generators.
- It is a vehicle that may be operated to evacuate the injured persons from the dangerous area during natural disasters and other

emergency situations. Portable UAV is of major importance that may be easily transported when danger arises for pilots in cases when no helicopters or any other big-size aircrafts may be involved.

- It is a cheaper and effective alternative relative to other sprinkling methods in particularly post-rain periods to sprinkle agricultural chemicals.

Approbation of the work. Key provisions and outcomes of the dissertation work were presented and discussed at the seminars attended by qualified specialists and scientists.

Dissertation materials and key outcomes were presented through the reports presented during the international and national scientific conferences held on various levels, including:

- the 8th International Conference on Control and Optimization with Industrial Applications (COIA 2022) 24-26 August 2022, Baku, Azerbaijan.
- the 15th International Conference on Application of Fuzzy Systems, Soft Computing and Artificial Intelligence Tools (ICAFS-2022) August 26 – 27, 2022, Budva, Montenegro;
- Dokuz Eylül Üniversitesi ile Azerbaycan Milli İlimler Akademisi Arasındaki İkinci Uluslararası Temel Bilim İkili Çalıştayı, 18 November, 2022, Baku, Azerbaijan;
- the International Conference on Intelligent and Fuzzy Systems (INFUS 2023), August 22-24, 2023, Istanbul Technical University and Galatasaray University, Istanbul, Turkey;
- the Intelligent Systems Conference (IntelliSys 2023), September 7-8, 2023, Amsterdam, The Netherlands;
- the 5th International Conference on Problems of Cybernetics and Informatics (PCI 2023) August 28-30, 2023, Baku, Azerbaijan.

Institution where the dissertation work is performed. The dissertation work was performed at the Department No.1 (Information Society problems) of the Institute of Information Technology of the Ministry of Science and Education of the Republic of Azerbaijan.

Scientific publications. There have been 8 scientific works published based on the materials of the dissertation work, 3 of which in leading peer-reviewed journals and publications recommended by the Supreme Attestation Commission under the President of the Republic of Azerbaijan, and 4 works in the journals indexed by the Web of Science and Scopus databases.

The structure and volume of the work. The dissertation consists of an introduction, 4 chapters, a conclusion, and a list of references. The total volume of the work includes 118 pages of text and consists of 53 pictures, and 10 tables. Bibliography includes 80 references.

BRIEF OVERVIEW OF THE WORK

The introduction outlines relevance of the work, lists the tasks and approaches necessary to reach the research goal, and discusses the work structure and content, including the desirable outcomes put to defense.

The first chapter is devoted to analyzing the peculiarities of practical usage of automated control systems controllers for quadcopters. Due to the wide usage, the topic of this research is about the quadcopter with "X" configuration. Figure 1 presents the general functional layout of this quadcopter.

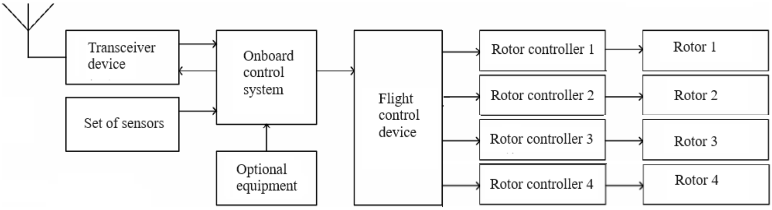

Figure 1. General layout of the quadcopter

Solving quadcopter control problem is interesting as a matter of science and practice and calls major interest for this topic. In this chapter, development of the methods of modern automated control theory and the outcomes obtained as P-, PI-, PD-, PID-controllers are analyzed.

To solve the main concerns of autonomous quadcopter flight using non-linear, neural and hybrid adaptive controllers, the existing methods have been considered, of which the most appropriate ones and the problems obstructing direct application of known methods and algorithms have been identified.

Application of fuzzy logic components to address the control problems is currently possible by applying two approaches. First is the situation classification outlining the goals of the object's performance. The second method is more traditional and is based upon direct regulation of the controlled object's variables. Despite the aforementioned differences, these methods resemble to each other.

Figure 2 presents the structures of controllers suggested by various authors in order to control the quadcopter flight process and the peculiarities of each are studied[1]. Figure 2 consists of four equivalent fuzzy regulators each producing general control (U) and the correction coefficients as angles (ΔU) under PID: Roll, Pitch, and Yaw. Computation of the final control movements for each of the quadcopter engines is performed in “Aggregation” block by summing up their outcome values.

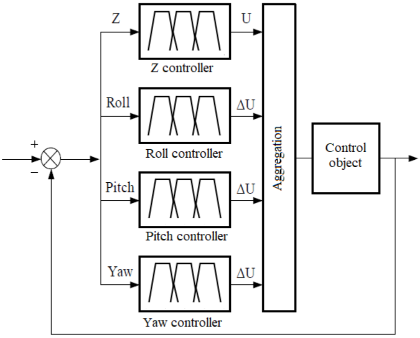

Figure 2. Sample fuzzy controller

Artificial neural networks represent some alternatives to building intelligent control systems. Interest in neural networks as a base for arranging control systems is due to their ability to work with non-linear, inaccurate data, which is typical for a number of technical control objects, including quadcopters. Features of neural networks enable to realize complex, fuzzy dependencies on their basis. This simplifies synthesis of control systems when designing the controllers, as long as implementation of the interconnected control systems based on artificial neural networks does not demand the designer having exact numeric knowledge about reciprocal influences of internal values. As a drawback, we may point to the need of a certain iteration of the controller synthesis, high dependence of the design process on

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[1] Lopez V., Morata F. Intelligent Fuzzy Controller of a Quadrotor // International Conference on Intelligent System and Knowledge Engineering – ISKE, 2010. – pp. 141-146.

designer intuition, the need for initial retrieval and development of training samples, which is not an easy task.

Figure 3 presents the structure of hybrid controller used to control quadcopters[2]. Its advantages and disadvantages, and working specifics are analyzed.

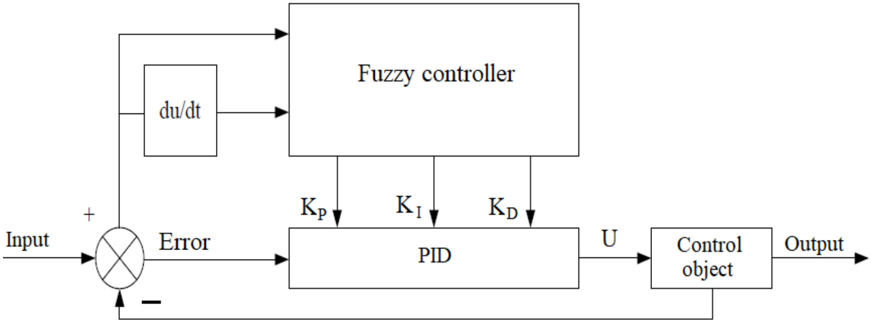

Figure 3. Fuzzy PID-controller

Analysis of the suggested approaches helps to reach conclusion on the advantages of using artificial intelligence methodologies in case if sufficient information is not available: fuzzy logic, artificial neural networks, neuro-fuzzy hybrid networks. Furthermore, it is clear that usage of any method, even if more effective compared to PI-, PD-, PID-controllers, is not conducive to addressing all the list of concerns faced by designers. Thus, we may talk about the need to build a "higher level", hybrid controllers integrating several control methods. Namely these presumptions have predefined the goals of the dissertation work expressed in the introductory part.

The second chapter discusses the methodology for designing dynamic tridimensional model[3] for quadcopters. As any physical object, quadcopters have 6 autonomy levels and it shows its ability to

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[2] Nirut P., Masuda R., Hirata H. Control System Design and Simulation for a Quadrotor Helicopter // International Conference on Simulation Technology. - Port Island, Kobe, Japan, 2013. – pp. 593-597.

[3] Гэн К., Чулин Н.А. Алгоритмы стабилизации для автоматического управления траекторным движением квадрокоптера. Наука и образование, 2015, № 5.

perform geometric movements in tridimensional space, i.e. forward / back, up / down, left / right (in tridimensional coordinate system), including Euler angles (yaw, pitch, roll) around each of the three-perpendicular axis (Figure 4).

Information is presented about each variable of the dynamic model of quadcopter:

1) x and y denote quadcopter position on the horizontal plane.
2) z determines height of the quadcopter on vertical plane.
3) φ, as a rotation angle around the axis 0_x indicates tilt of the quadcopter to one side.
4) θ, as a rotation angle around 0_y shows quadcopter's pitch.
5) ψ, as a rotation angle around 0_z shows quadcopter's yaw.

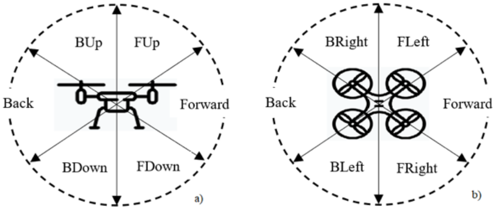

Figure 4. Quadcopter's geometric movements in tridimensional space

For a quadcopter with mass m, Newton's second law is applied and considering the autonomy level of quadcopter, this law is formulated as follows[4]:

$$m\vec{a} = -mg\vec{e}_y + R(\varphi,\theta,\psi)\vec{u}, \tag{1}$$

where $\vec{a} = (\ddot{x},\ddot{y},\ddot{z})^T$ aggregate quadcopter acceleration; $\vec{e}_y$ – a single vector guided along axis 0_y; $R(\varphi,\theta,\psi)$ – rotation matrix; $\vec{u}$ – aggregate of the non-conservative forces exerted upon the quadcopter. The design of quadcopter dynamic model should take into account the system of differential equations presented as below for each of 6 autonomy levels:

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[4] Гурьянов А.Е. Моделирование управления квадрокоптером. Инженерный вестник, 2014, № 8.

$$\begin{cases} \ddot{x} = [\cos(\varphi)\sin(\theta)\cos(\psi) + \sin(\varphi)\sin(\psi)]\dfrac{u_1}{m}, \\ \ddot{y} = [\cos(\varphi)\sin(\theta)\sin(\psi) - \sin(\varphi)\cos(\psi)]\dfrac{u_1}{m}, \\ \ddot{z} = -g + [\cos(\varphi)\cos(\theta)]\dfrac{u_1}{m}, \\ \ddot{\varphi} = \dot{\theta}\dot{\psi}\dfrac{I_y - I_z}{I_x} - \dot{\theta}\Omega\dfrac{J_r}{I_x} + \dfrac{1}{I_x}u_2, \\ \ddot{\theta} = \dot{\varphi}\dot{\psi}\dfrac{I_z - I_x}{I_y} - \dot{\varphi}\Omega\dfrac{J_r}{I_y} + \dfrac{1}{I_y}u_3, \\ \ddot{\psi} = \dot{\theta}\dot{\varphi}\dfrac{I_x - I_y}{I_z} + \dfrac{1}{I_z}u_4, \end{cases} \tag{2}$$

I_x − moment of inertia relative to axis 0_x; I_y – moment of inertia relative to axis 0_y; I_z –moment of inertia relative to axis 0_z; J_r − moment of inertia of the rotor; Ω – angle speed of rotors; u_i ($i = 1 \div 4$) – the forces exerted upon the dynamic system of the quadcopter as input data or translation vector coefficients.

Equation for the forces exerted upon the dynamic system of the quadcopter and propeller velocity equation Ω is presented below:

$$\begin{cases} u_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2), \\ u_2 = lb(\Omega_2^2 - \Omega_4^2), \\ u_3 = lb(\Omega_3^2 - \Omega_1^2), \\ u_4 = d(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2), \end{cases} \tag{3}$$

$$\Omega = (\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2), \tag{4}$$

where l – distance between the centers of propeller and quadcopter; b – parameter reflecting quadcopter height; d – resistance indicator; Ω_1, Ω_2, Ω_3 and Ω_4 – angle speeds of front, right, back, and left propellers respectively.

This chapter presents the design procedure of quadcopter prototype using the system modeling tools in MATLAB development environment. Mechanical model of the quadcopter in MATLAB\SimMechanics notation is presented in Figure 5.

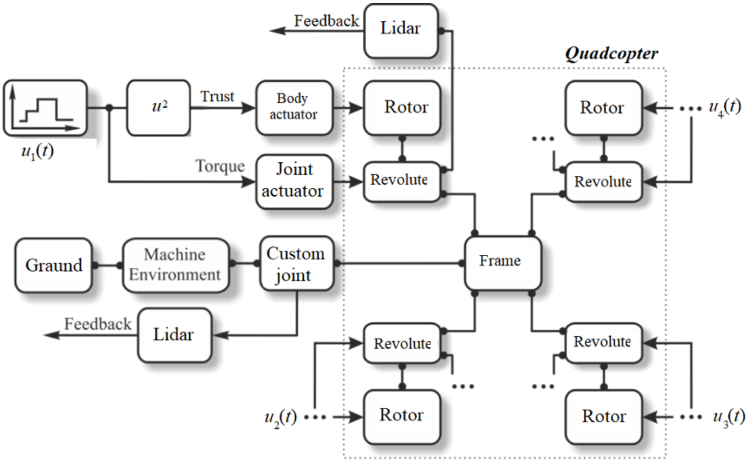

Figure 5. Mechanical model of quadcopter in MATLAB\SimMechanics

Designing quadcopter prototype via systemic modeling tools is executed across the following phases:

1) quadcopter design: choice of the main physical dimensions;
2) developing system model for quadcopter;
3) mechanics and electronics model for quadcopter;
4) comprehensive modeling of the navigation and control systems of the quadcopter;
5) developing the technical vision and communication system;
6) conducting 3D simulations (Simulink 3D Animation);
7) developing software and testing the quadcopter prototype;
8) assembling, calibrating, and testing the quadcopter prototype.

As a result, the number of prototypes may be reduced when developing quadcopters by using the system modeling approach.

Third chapter studies the information provision concerns for developing the infrastructure and agriculture in areas characterized with mountains and woods where the land is required to be monitored using unmanned technologies. This paradigm offers the algorithm creating 3D trajectory of quadcopter during the overland flight in mountainous and wooded landscapes[5].

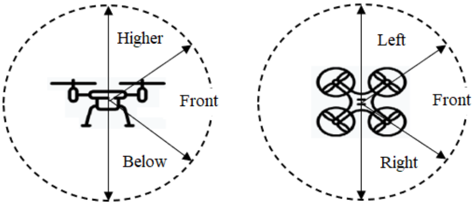

Figure 6. Obstacle view sectors: a) side view, b) view from above

Figure 6 shows visual sectors of the quadcopter and the obstacles found to be in the space. In reference to the data obtained from quadcopter sensors, the input signals vary in the following range (x_1=Front, x_2=Left, x_3=Right, x_4=Higher, x_5=Below) [0, 1]. Each input variable x_k (k=1÷5) corresponds to the horizontal and vertical spatial sector in the direction of quadcopter motion and the obstacles and distance up to them are analyzed within it. Effects on output variables change the velocity (y_1=Velocity), rotation angle (y_2 = Rotation) and flight altitude (y_3=Height), enabling the quadcopter to escape collision with the obstacle.

To determine the quadcopter's overland autopilot mode in five directions shown in the space, the bounded set of logically consistent rules have been considered as the following information fragments[6]:

d_1: "If any obstacle is not detected on the flight path of the quadcopter or it is too far away, then there is no need to change direction, height and to reduce speed";

d_2: "If the sensor detects an obstacle at a medium distance along the flight path of the quadcopter and the sector on the left is free, then it is necessary to lose velocity to an average value and to turn slightly to the left without changing the height";

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[5] Habibbayli T.H. Regulation of quadcopter autopiloting during overland monitoring using a fuzzy inference system. Proceedings of the 8th International Conference on Control and Optimization with Industrial Applications (COIA 2022) 24-26 August 2022, Baku, Azerbaijan. Vol. 1, pp. 207-209.

[6] Habibbayli T.H., Aliyev M.E. Fuzzy inference-based quadcopter flight regulation under overland monitoring. The Springer Series "Lecture Notes in Networks and Systems", Vol. 610, pp. 372-381, 2023.

d_3: “If the sensor detects an obstacle at a close distance along the flight path of the quadcopter and the sector on the left is free, then it is necessary to lose velocity to a minimum, and to turn sharply to the left without changing the height”;

d_4: “If the sensor detects an obstacle at a medium distance along the flight path of the quadcopter, there is also an obstacle in the left sector at a not remote distance and the sector on the right is free, then it is necessary to lose velocity to an average value, and to turn slightly to the right without changing the height”;

d_5: “If the sensor detects an obstacle at a close distance along the flight path of the quadcopter, there is also an obstacle in the left sector at a not remote distance and the sector on the right is free, then it is necessary to lose velocity to a minimum, and turn sharply to the right without changing the height”;

d_6: “If the sensor detects an obstacle at an average distance along the flight path of the quadcopter, there are also obstacles in the left and right sectors at a not remote distance, and the upper sector is free, then it is necessary to lose velocity to an average value, and slightly increase the flight altitude without yaw”;

d_7: “If the sensor detects an obstacle at a close distance along the flight path of the quadcopter, there are also obstacles in the left and right sectors at a not remote distance, and the upper sector is free, then it is necessary to lose velocity to a minimum, and sharply increase the flight altitude without yaw”;

d_8: “If the sensor detects an obstacle at an average distance along the flight path of the quadcopter, there are also obstacles in the left, right and upper sectors at a non-remote distance, and the lower sector is free, then it is necessary to lose velocity to an average value, and slightly reduce the flight altitude without yaw”;

d_9: “If the sensor detects an obstacle at a close distance along the flight path of the quadcopter, there are also obstacles in the left, right and upper sectors at a not remote distance, and the lower sector is free, then it is necessary to lose velocity to a minimum, and sharply reduce the flight altitude without yaw”;

d_{10}: “If the sensor detects an obstacle at an average distance along the flight path, and an obstacle is also detected at an average distance to the left, obstacles are detected at a not remote distance to the right, below and above, then it is necessary to lose velocity to an average value while maintaining the course and flight altitude”;

d_{11}: “If the sensor detects an obstacle at a close distance along the flight path of the quadcopter, and an obstacle is also detected at an average distance to the left, obstacles are detected at a not remote distance to the right, below and above, then it is necessary to lose velocity to a minimum and turn sharply to the left without changing the height”;

d_{12}: “If the sensor detects an obstacle at a medium distance along the flight path of the quadcopter, and an obstacle is detected at a close distance to the left, an obstacle is detected at an average distance to the right, and obstacles are detected at a not remote distance from below and above along the course, then it is necessary to lose velocity to an average value and turn sharply to the left without changing the course and height”;

d_{13}: “If the sensor detects an obstacle at a close distance along the flight path of the quadcopter, and an obstacle is also detected at a close distance to the left, an obstacle is detected at an average distance to the right, and obstacles are detected from below and above along the course at a not remote distance, then it is necessary to lose velocity to minimum and turn sharply to the right without changing the height”;

d_{14}: “If the sensor detects an obstacle at a medium distance along the flight path, an obstacle is detected at a close distance to the left, an obstacle is also detected at a close distance to the right, an obstacle is detected at an average distance from above, and an obstacle is detected at a not remote distance from below, then it is necessary to lose velocity to an average value and turn sharply to the right without changing the course and height”;

d_{15}: “If the sensor detects an obstacle at close distance along the flight path of the quadcopter, the obstacles are detected at an average distance to the left and to the right, as well as an obstacle is detected at a not remote distance from above, then it is necessary to lose velocity to a minimum and sharply increase flight altitude without yaw”;

d_{16}: “If the sensor detects an obstacle at a medium distance along the flight path, obstacles are detected at a close distance to the left, right and higher along the course, and an obstacle is detected at an average distance below the course, then it is necessary to lose velocity to an average value without changing the course and height”;

d_{17}: “If the sensor detects the obstacles at a close distance along the flight path of the quadcopter, as well as to the left, right and above, however, an obstacle is detected at an average distance below the course, then it is necessary to lose velocity to a minimum, sharply reduce the flight altitude without yaw”;

d_{18}: “If an obstacle is detected at a medium distance along the flight path, obstacles are detected at a close distance to the left, right, above and below the course, then it is necessary to lose velocity to an average value without changing the course and height”;

d_{19}: “If in all sectors of the view the detected obstacles are at a close distance, then it is necessary to lose velocity to a minimum and turn sharply to the left without changing the height”.

As a key model, fuzzy inference system is used as linguistic variables reflecting the fuzzy sectors of the space by their input features and availability of obstacles inside and the distance between them is expressed verbally as terms of input linguistic variables. It is proposed to overcome obstacles based on the fuzzy results of this system developed as terms of output linguistic variables reflecting the rotation angle on horizontal plane, flight altitude, and quadcopter velocity change. All linguistic variables, their corresponding terms, and the universes required for fuzzy sets are presented in Table 1.

Table 1

Variables of fuzzy inference system

Inputs	x_1	Variable name	*Front* – distance to the obstacle in the direction of flight
		Term set	{X_{11}=SIGNIFICANT, X_{12}=AVERAGE, X_{13} =UNSIGNIFICANT}
		Universe	[0, 1]
	x_2	Variable name	*Left* – distance to the obstacle on the left
		Term set	{X_{21}=SIGNIFICANT, X_{22}=AVERAGE, X_{23}=UNSIGNIFICANT}

		Universe	[0, 1]
	x_3	Variable name	*Right* – distance to the obstacle on the right
		Term set	$\{X_{31}$=SIGNIFICANT, X_{32}=AVERAGE, X_{33}=UNSIGNIFICANT$\}$
		Universe	[0, 1]
	x_4	Variable name	*Higher* – distance to the obstacle above
		Term set	$\{X_{41}$=SIGNIFICANT, X_{42}=AVERAGE, X_{43}=UNSIGNIFICANT$\}$
		Universe	[0, 1]
	x_5	Variable name	*Below* – distance to the obstacle below
		Term set	$\{X_{51}$=SIGNIFICANT, X_{52}=AVERAGE, X_{53}=UNSIGNIFICANT$\}$
		Universe	[0, 1]
Outputs	y_1	Variable name	*Velocity* – airspeed
		Term set	$\{Y_{11}$=FULL, Y_{12}=AVERAGE, Y_{13}=ZERO$\}$
		Universe	[0, 1]
	y_2	Variable name	*Rotation* – rotation on horizontal plane
		Term set	$\{Y_{21}$=SHARPLY TO THE LEFT, Y_{22}=SLIGHTLY TO THE LEFT, Y_{23}=IS ABSENT, Y_{24}=SLIGHTLY TO THE RIGHT, Y_{25}=SHARPLY TO THE RIGHT$\}$
		Universe	[-0.5, 0.5]
	y_3	Variable name	*Height* – change in the flight altitude
		Term set	$\{Y_{31}$= SHARPLY UP, Y_{32}=SLIGHTLY UP, Y_{33}=IS ABSENT, Y_{34}=SLIGHTLY DOWN, Y_{35}= SHARPLY DOWN$\}$
		Universe	[-0.5, 0.5]

The fuzzy inference system (FIS) based on given d_1–d_{19} rules, is described in symbolic form as below:

d_1: $(x_1 = X_{11}) \Rightarrow (y_1 = Y_{11})\ \&\ (y_2 = Y_{23})\ \&\ (y_3 = Y_{33})$;

d_2: $(x_1 = X_{12})\ \&\ (x_2 = X_{21}) \Rightarrow (y_1 = Y_{12})\ \&\ (y_2 = Y_{22})\ \&\ (y_3 = Y_{33})$;

d_3: $(x_1 = X_{13})\ \&\ (x_2 = X_{21}) \Rightarrow (y_1 = Y_{13})\ \&\ (y_2 = Y_{21})\ \&\ (y_3 = Y_{33})$;

……………………………………

d_{17}: $(x_1 = X_{13})\ \&\ (x_2 = X_{23})\ \&\ (x_3 = X_{33})\ \&\ (x_4 = X_{43})\ \&\ (x_5 = X_{52}) \Rightarrow$
$(y_1 = Y_{13})\ \&\ (y_2 = Y_{23})\ \&\ (y_3 = Y_{31})$;

d_{18}: $(x_1 = X_{12})\ \&\ (x_2 = X_{23})\ \&\ (x_3 = X_{33})\ \&\ (x_4 = X_{43})\ \&\ (x_5 = X_{53}) \Rightarrow$
$(y_1 = Y_{12})\ \&\ (y_2 = Y_{23})\ \&\ (y_3 = Y_{33})$;

d_{19}: $(x_1 = X_{13})\ \&\ (x_2 = X_{23})\ \&\ (x_3 = X_{33})\ \&\ (x_4 = X_{43})\ \&\ (x_5 = X_{53}) \Rightarrow$
$(y_1 = Y_{13})\ \&\ (y_2 = Y_{21})\ \&\ (y_3 = Y_{33})$.

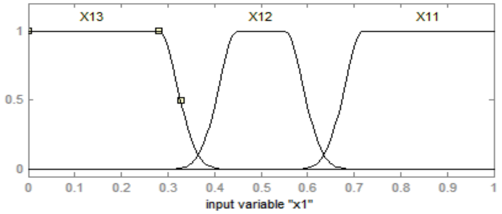

Figure 7. Terms of "distance to the obstacle in the direction of flight" x_1 input linguistic variable

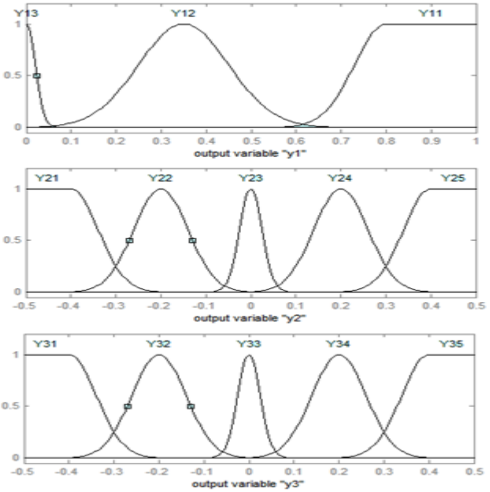

Figure 8. y_1 (Velocity), y_2 (Rotation) and y_3 (Height) output terms

To realize FIS, the membership functions "Bell-type" and Gauss were chosen and these functions were empirically identified in MATLAB\FIS editor (see Figure 7 and Figure 8). For this purpose, the fuzzy model with Mamdani type FIS with 5 inputs and 3 outputs is activated. In particular, the input and output features of the used fuzzy model, the terms of linguistic variables are presented on the level of relevant membership functions.

After identifying all variables, the membership functions, and building the rules of fuzzy knowledge base, various scenarios of quadcopter autopilot flight were obtained. The interactive window of graphical interface of MATLAB\FIS editor was used for this purpose.

Figure 9 presents the response to input vector (0.95, 0.5, 0.5, 0.5, 0.5) as FIS output (0.855, 0, 0).

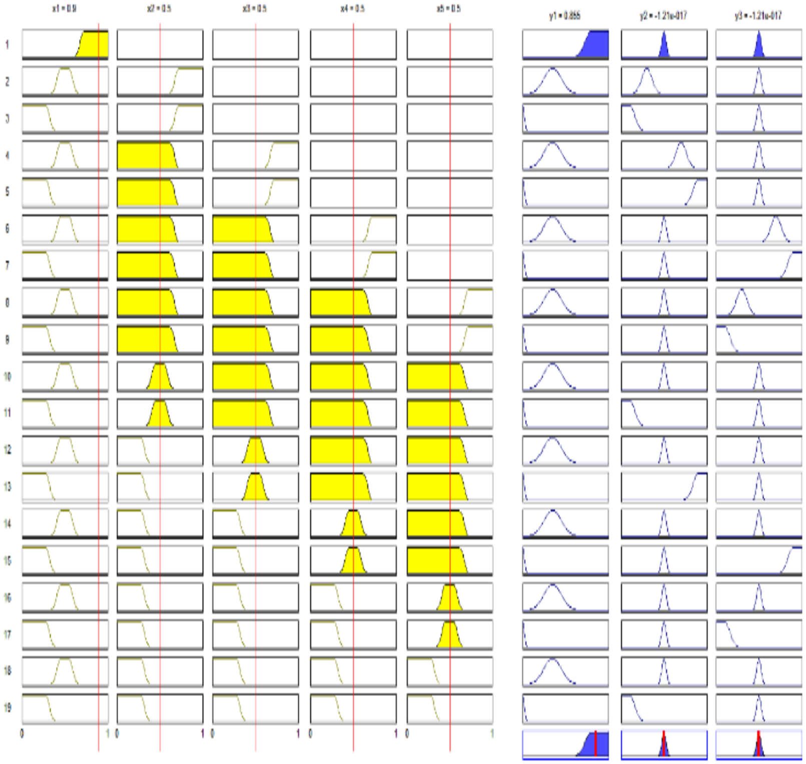

Figure 9. The graphical interface of MATLAB\FIS editor

The products of FIS were obtained as “input-output” based on realization of all linguistic rules via the graphic interface of MATLAB\FIS editor (see Table 2).

Table 2

Products of fuzzy inference system

Item No	Inputs					Outputs		
	x_1	x_2	x_3	x_4	x_5	y_1	y_2	y_3
1	0.95	0.50	0.50	0.50	0.50	0.855	0	0
2	0.50	0.95	0.50	0.50	0.50	0.350	-0.200	0
3	0.10	0.90	0.50	0.50	0.50	0.013	-0.411	0

4	0.50	0.50	0.90	0.50	0.50	0.350	0.200	0
5	0.10	0.50	0.90	0.50	0.50	0.013	0.411	0
6	0.50	0.50	0.50	0.90	0.50	0.350	0	0.200
7	0.10	0.50	0.50	0.90	0.50	0.013	0	0.411
8	0.50	0.50	0.50	0.50	0.90	0.350	0	-0.200
9	0.10	0.50	0.50	0.50	0.90	0.013	0	-0.411
10	0.50	0.50	0.40	0.40	0.40	0.350	0	0
11	0.10	0.50	0.50	0.50	0.50	0.013	-0.411	0
12	0.50	0.10	0.50	0.50	0.50	0.350	0	0
13	0.10	0.10	0.50	0.50	0.50	0.013	0.411	0
14	0.50	0.10	0.10	0.50	0.50	0.350	0	0
15	0.10	0.10	0.10	0.50	0.50	0.013	0	0.411
16	0.50	0.10	0.10	0.10	0.50	0.350	0	0
17	0.10	0.10	0.10	0.10	0.50	0.013	0	-0.411
18	0.50	0.10	0.10	0.10	0.10	0.350	0	0
19	0.10	0.10	0.10	0.10	0.10	0.013	-0.411	0

This chapter discusses results of quadcopter behavior in various flight scenarios chosen for operational trajectory development using neural network modeling[7]. Table 3 presents various scenarios via MATLAB\FIS editor for its behavior when obstacles are detected in five sectors of quadcopter's line of sight during the overland monitoring. Furthermore, the flight trajectory itself is formed based on operational five-dimensional assessment of the obstacles' presence (absence) in quadcopter's all visibility sectors acting as the quality assessment of the members of linguistic variables x_k (k=1÷5) including the flight trajectory. Following the below analytical approach, x_k enables to compare the alternative flight paths for each desirable vector (y_1, y_2, y_3) of the quadcopter reflecting the relative impact of factors. In the problem under consideration, "external knowledge" about 35 possible scenarios for the formation of the quadcopter's flight path is presented in the form of the following information model (see Table 3).

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[7] Аббасов А.М., Рзаев Р.Р., Ахмедов И.М., Алмасов А.Ш., Габиббейли Т.Г. Управление квадрокоптером в условиях наземного мониторинга с применением нейро-сетевых и нечётких методов моделирования. Нечеткие системы и мягкие вычисления, 2023, том 18, выпуск 1, 47-62.

Table 3

Scenarios for quadcopter maneuvering around obstacles

№	Inputs					Outputs		
	x_1	x_2	x_3	x_4	x_5	y_1	y_2	y_3
1	0.433	0.291	0.628	0.076	0.961	0.350	0.055	-0.190
2	0.611	0.824	0.460	0.862	0.855	0.380	-0.194	0.000
3	0.374	0.622	0.139	0.750	0.702	0.337	-0.154	0.215
4	0.712	0.738	0.568	0.438	0.469	0.854	0.000	0.000
5	0.922	0.535	0.320	0.107	0.102	0.855	0.000	0.000
6	0.396	0.283	0.318	0.925	0.001	0.349	0.000	0.204
7	0.026	0.563	0.311	0.177	0.959	0.013	-0.001	-0.410
……								
13	0.510	0.253	0.232	0.894	0.429	0.350	0.000	0.200
14	0.333	0.292	0.856	0.275	0.762	0.131	0.386	0.000
15	0.645	0.632	0.452	0.743	0.643	0.658	-0.103	0.103
16	0.524	0.833	0.781	0.985	0.546	0.350	-0.200	0.000
……								
30	0.605	0.961	0.766	0.756	0.306	0.367	-0.196	0.000
31	0.702	0.644	0.219	0.000	0.740	0.851	-0.001	-0.001
32	0.433	0.629	0.741	0.405	0.838	0.350	0.144	0.000
33	0.465	0.793	0.395	0.745	0.086	0.350	-0.200	0.000
34	0.065	0.004	0.789	0.553	0.318	0.013	0.411	0.000
35	0.026	0.245	0.480	0.651	0.787	0.014	0.000	-0.195

Neural network in MATLAB package has a “hidden” layer consisting of 5 non-linear neurons having log-sigmoid activation functions (see Figure 10). Their range enables to ensure rotations on both horizontal and vertical planes [-0.5, 0.5] and flight velocity [0, 1] interval along the quadcopter flight trajectory.

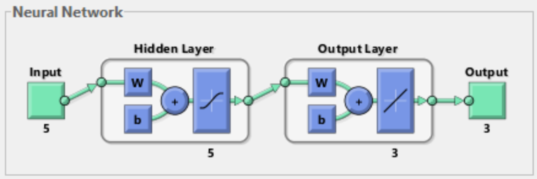

Figure 10. Three-layer feedforward neural network in MATLAB notation

Corresponding products (see Table 4) are created by neural network after training, testing, and validation (see Figure 11). The neural network generating heuristic knowledge about the quadcopter flight path processes the vectors entered with components according to the number of parameters in order to assess “proximity” of all sight obstacles numerically presented from the segment of [0, 1]. After adjusting the parameters, the neural network is able to approximate the $F: R^5 \rightarrow R^3$ multivariable function described in a tabulated format (see Table 3). For each individual case, the neural network forms the control command by quadcopter flight trajectory as a three-component vector (y_1, y_2, y_3) = (Velocity, Rotation, Height). Specifically, neural network responds with (0.510, 0.253, 0.232, 0.894, 0.429) to input vector (0.350, 0.000, 0.200) (see Table 3, scenario 13).

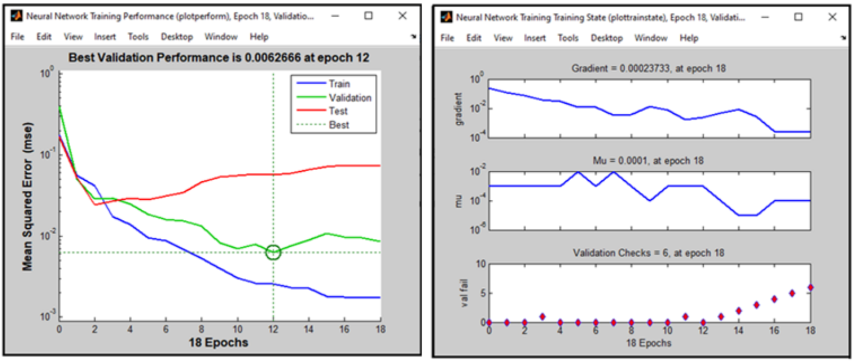

Figure 11. Training, testing, and validation of three-layer feedforward neural network in MATLAB package

Table 4

Signals generated by feedforward neural network

№	Inputs					Outputs					
						FIS			Feedforward Neural Network		
	x_1	x_2	x_3	x_4	x_5	y_1	y_2	y_3	z_1	z_2	z_3
1	0.433	0.291	0.628	0.076	0.961	0.350	0.055	-0.19	0.381	0.0638	-0.216
2	0.611	0.824	0.460	0.862	0.855	0.380	-0.19	0.000	0.372	-0.209	0.0435
3	0.374	0.622	0.139	0.750	0.702	0.337	-0.15	0.215	0.160	-0.101	0.1908
4	0.712	0.738	0.568	0.438	0.469	0.854	0.000	0.000	0.845	-0.033	0.0307
5	0.922	0.535	0.320	0.107	0.102	0.855	0.000	0.000	0.893	0.0019	-0.034
6	0.396	0.283	0.318	0.925	0.001	0.349	0.000	0.204	0.345	-0.013	0.1790

…………………………………………											
13	0.510	0.253	0.232	0.894	0.429	0.350	0.000	0.200	0.3598	-0.015	0.1699
14	0.333	0.292	0.856	0.275	0.762	0.131	0.386	0.000	0.1945	0.3646	-0.011
15	0.645	0.632	0.452	0.743	0.643	0.658	-0.10	0.103	0.6319	-0.092	0.2408
16	0.524	0.833	0.781	0.985	0.546	0.350	-0.20	0.000	0.3832	-0.090	0.1373
…………………………………………											
32	0.433	0.629	0.741	0.405	0.838	0.350	0.144	0.000	0.340	0.1108	-0.056
33	0.465	0.793	0.395	0.745	0.086	0.350	-0.20	0.000	0.183	-0.277	0.1751
34	0.065	0.004	0.789	0.553	0.318	0.013	0.411	0.000	0.005	0.4062	-0.085
35	0.026	0.245	0.480	0.651	0.787	0.014	0.000	-0.195	0.016	-0.008	-0.043

General structure of the fuzzy control system is shown at Figure 12 for the quadcopter flight process ensuring automatic maneuvers to overcome the obstacles in the sectors described at Figure 6. Fuzzy control system consists of four equivalent fuzzy controllers creating general control (u) and correction coefficients (Δu): front horizontal plane – Left/Right, along vertical plane – Up/Down and quadcopter velocity similar to PID. Estimation of final control actions per each quadcopter engine is performed in “Aggregation” block by summing the output signal values of the controllers[8].

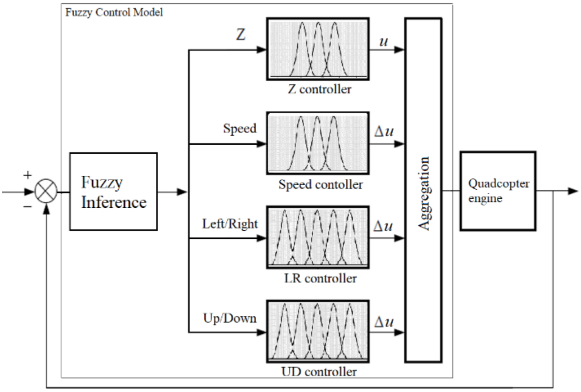

Figure 12. Fuzzy control system for quadcopter flight process

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[8] Rzayev R.R., Habibbayli T.H., Aliyev M.E. The use of fuzzy controllers in automatic control systems for quadcopters. Springer series “Lecture Notes in Networks and Systems”, Vol. 822, pp. 59-74.

Chapter four proposes control system using structured hierarchical neural network, including two subnets as “reasonable” and “instinctive”[9]. Figure 13 presents structured hierarchical neural network model integrating two types of multilayer neural networks: “reasonable” and “instinctive” neural networks. Quadcopter sensor signals are directly fed into the input layer of “reasonable” neural network, which verifies conformity of the input vector to a certain behavioral model and only after that it forms behavioral model for quadcopter: “*move without changing the direction, altitude, and velocity until an obstacle is detected by the sensor along flight path*”.

Instinctive neural network determines the conformity between sensor input and a number of behavioral models to be maintained by quadcopter during a certain maneuver. As a sample command given by instinctive neural network: “*Repeat the moves to left and right when sensor identifies obstacles”*. Quadcopter should perform stepwise movements sequentially and the function of instinctive network is vital when using the neural network in order to control the quadcopter in overland monitoring setting in complicated territories of mountainous and wooded landscapes.

This chapter discusses design methods of hybrid control systems for poorly formalized technical objects as quadcopters. Figure 14 outlines key configuration of the fuzzy logic control and it includes three main components: fuzzifier, fuzzy rule base and inference engine, defuzzifier.

To achieve the required adequacy level of fuzzy model, the main duty is to identify the input and output membership functions and opt for the optimal set of fuzzy logic rules. Incorporating learning skill into fuzzy model may be achieved by integrating its components and functions into multilayer structured connectionist neural network[10] with distributed learning capability.

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[9] Abbasov A.M., Rzayev R.R., Habibbayli T.H. Structured neural network based quadcopter control under overland monitoring. The Springer Series “Lecture Notes in Networks and Systems”, 758, Vol. 1, pp. 577-585, 2023.

[10] Lin C.T., George Lee C.S. Supervised and unsupervised learning with fuzzy similarity for neural network-based fuzzy logic control systems // Fuzzy sets,

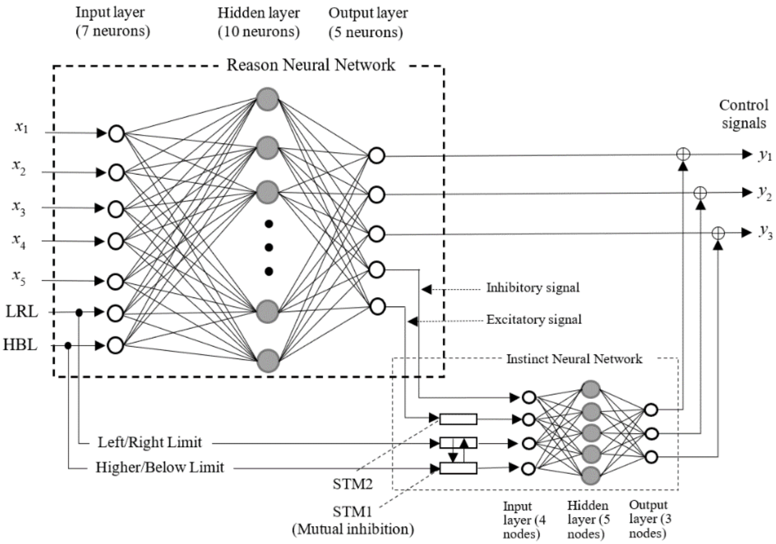

Figure 13. Quadcopter control model based on neural network

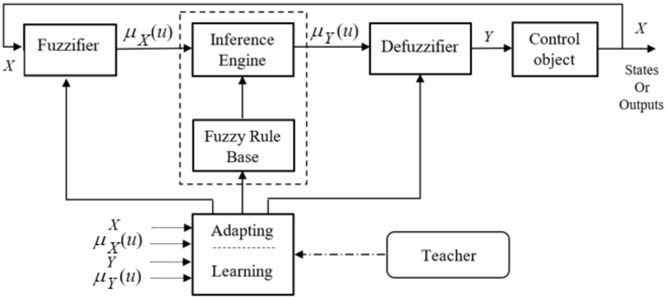

Figure 14. General model of fuzzy controller

The hierarchical structure of the connectionist neural network realizing multiple input and single output fuzzy model in reference to the linguistic rules or fuzzy inference system is presented in Figure 15.

Neural Networks, and Soft Computing. Edited by R.R. Yager and L.A. Zadeh. New York: Van Nostrand Reinhold, 1994, pp. 85-125.

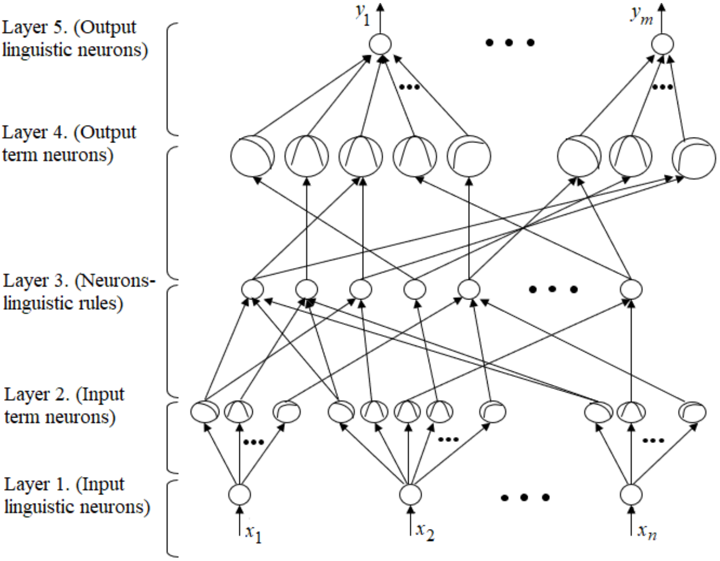

Figure 15. Fuzzy model on the basis of five-layer neural network

Analytical data have been obtained about understanding and practical usage of the existing structures of hybrid (neuro-fuzzy) controllers, their constructive properties using the simulation samples of the quadcopter trajectory control by use of MATLAB\ANFIS editor[11].

To generate the flight trajectory of the quadcopter in the matter under consideration, “external knowledge” information model is presented about 35 potential scenarios (see Table 3). Then F mapping may be approximated by the structured system integrating three ANFIS models (see Figure 16). In this case, a system with multiple outputs is replaced by a group of several independent systems with one output.

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[11] Abbasov A.M., Rzayev R.R., Habibbayli T.H. Formation of the flight path of a quadcopter under overland monitoring by the hybrid modeling system. Proceedings of the 5th International Conference on Problems of Cybernetics and Informatics (PCI), Baku, Azerbaijan, 2023, pp. 1-4.

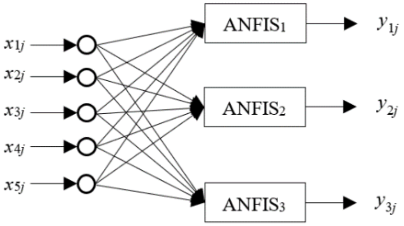


Figure 16. Structured modelling system on the basis of ANFIS

Each ANFIS$_k$ (k=1÷3) generates optimal number of linguistic rules and identifies Gauss “Bell-type” membership functions describing the terms of linguistic variables as a result of structural and parametric optimization based on the training set of 35 behavior models. For instance, ANFIS$_1$ model has identified 243 implication rules, and membership functions (see Figure 17, Figure 18, Figure 19, Figure 20 and Figure 21).

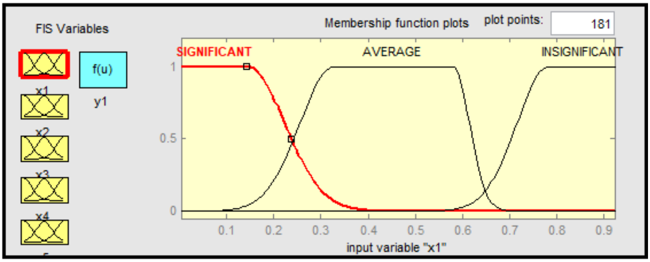

plot points: 181

Figure 17. Membership functions of fuzzy sets describing the terms of “Front” input linguistic variable

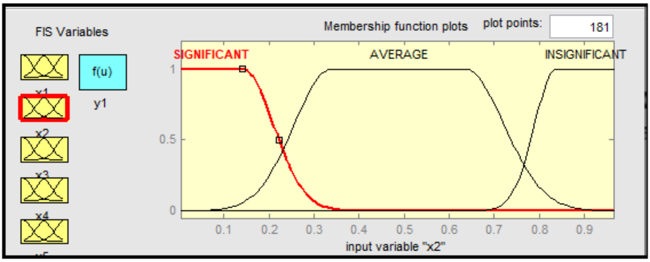
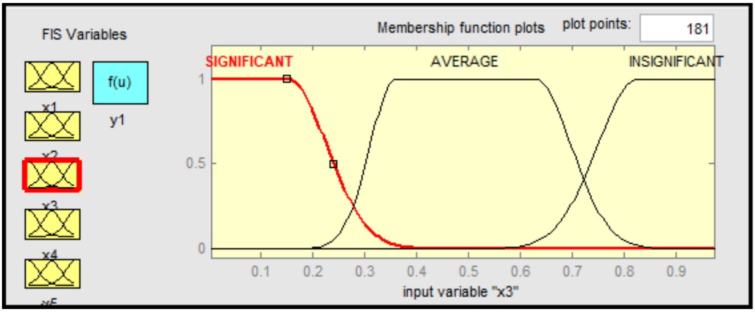
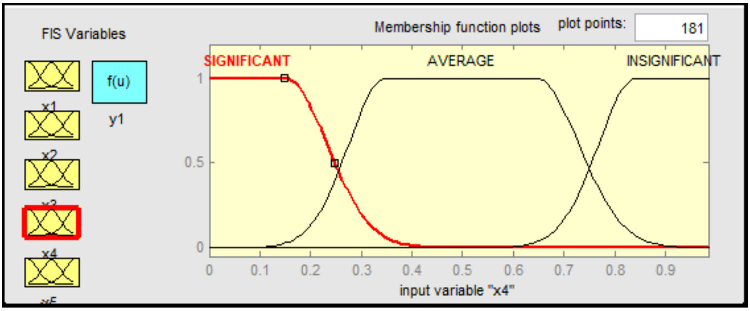

plot points: 181

Figure 18. Membership functions of fuzzy sets describing the terms of “Left” input linguistic variable



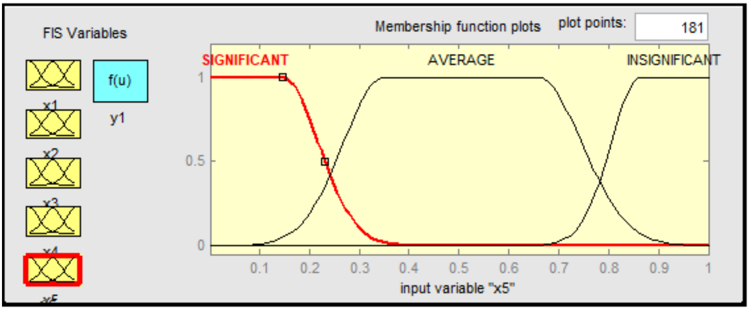
plot points: 181

Figure 19. Membership functions of fuzzy sets describing the terms of "Right" input linguistic variable



plot points: 181

Figure 20. Membership functions of fuzzy sets describing the terms of "Higher" input linguistic variable



plot points: 181

Figure 21. Membership functions of fuzzy sets describing the terms of "Below" input linguistic variable

Figure 22 presents the graphical functional interface to view the rules of fuzzy inference system generated by ANFIS$_1$. It becomes apparent from the figure that trained ANFIS$_1$ for input vector denoting existence of obstacles in five sectors of frontal view (0.524, 0.833, 0.781, 0.985, 0.546) generates output signal 0.35.

x1 = 0.524
x2 = 0.833
x3 = 0.781
x4 = 0.985
x5 = 0.546
y1 = 0.35

Input: [0.524 0.833 0.781 0.985 0.546]
Plot points: 101

Figure 22. Interactive functional window to view the results obtained using ANFIS$_1$

Similar outcomes of the program simulation were obtained using the interactive functional windows of ANFIS$_2$ and ANFIS$_3$. As a result, ANFIS based structured model generates the desirable output y^{16}= (0.350, -0.200, 0.000) for input signal x^{16} = (0.524, 0.833, 0.781, 0.985, 0.546). Similar outcomes have also been obtained for all other scenarios of quadcopter flight during the overland monitoring.

RESULTS

The main scientific results presented for defense based on studies carried out on the topic of dissertation are formulated as the following provisions:

- Multiphase procedural concept to create the quadcopter prototype using object-oriented system modeling means in MATLAB program environment.
- An algorithm to develop the spatial path in overland monitoring setting with stationary obstacles by using fuzzy inference system.
- A maneuver algorithm to overcome the obstacles in a complex setting and quadcopter path tracing algorithm based on three-layer feedforward neural network.
- Control system for quadcopter based on multimodal stabilization algorithm envisioning usage of the connectionist hierarchical structured neural network consisting of “reasonable” and “instinctive” neural subnets.
- A maneuver algorithm to overcome the obstacles in a complex setting and quadcopter path tracing algorithm based on intelligent hybrid (neuro-fuzzy) adaptive controllers in overland monitoring setting.

The following scientific works on Dissertation materials have been published:

1. Habibbayli T.H. Regulation of quadcopter autopiloting during overland monitoring using a fuzzy inference system. Proceedings of the 8th International Conference on Control and Optimization with Industrial Applications (COIA – 2022) 24-26 August 2022, Baku, Azerbaijan. Vol. 1, pp. 207-209.
2. Habibbayli T.H. Formation of the quadcopter flight path under overland monitoring using neuro-fuzzy modeling methods. Mathematical Machines and Systems, Institute of Mathematical Machines and Systems Problems of National Academy of Ukraine, Kyiv, 2022, №3, pp. 97-107.
3. Габиббейли Т.Г. Об одном подходе к вопросу регламентации поведения квадрокоптера при наземном мониторинге.

Доклады Национальной Академии Наук Азербайджана, Том LXXVIII, № 3-4, стр. 39-50, 2022.

4. Habibbayli T.H., Aliyev M.E. Fuzzy inference-based quadcopter flight regulation under overland monitoring. The Springer Series "Lecture Notes in Networks and Systems", Vol. 610, pp. 372-381, 2023. (Web of Science, Scopus)
5. Аббасов А.М., Рзаев Р.Р., Ахмедов И.М., Алмасов А.Ш., Габиббейли Т.Г. Управление квадрокоптером в условиях наземного мониторинга с применением нейро-сетевых и нечётких методов моделирования. Нечеткие системы и мягкие вычисления, 2023, том 18, выпуск 1, 47-62.
6. Abbasov A.M., Rzayev R.R., Habibbayli T.H. Structured neural network based quadcopter control under overland monitoring. The Springer Series "Lecture Notes in Networks and Systems", 758, Vol. 1, pp. 577-585, 2023. (Web of Science, Scopus)
7. Rzayev R.R., Habibbayli T.H., Aliyev M.E. The use of fuzzy controllers in automatic control systems for quadcopters. The Springer series "Lecture Notes in Networks and Systems", Vol. 822, pp. 59-74. (Web of Science, Scopus)
8. Abbasov A.M., Rzayev R.R., Habibbayli T.H. Formation of the flight path of a quadcopter under overland monitoring by the hybrid modeling system. Proceedings of the 5th International Conference on Problems of Cybernetics and Informatics (PCI), Baku, Azerbaijan, 2023, pp. 1-4. (Web of Science, Scopus)

The personal role of applicant in works published with co-authors:

[4] Adaptation and development of fuzzy inference system to build the algorithm for forming quadcopter flight path in overland monitoring setting.

[5] Development of neural network model to build the algorithm to form quadcopter flight path in overland monitoring setting.

[6] Development of hierarchical connectionist neural network consisting of two subnets to build the algorithm for forming quadcopter flight path in overland monitoring setting.

[7] Development of fuzzy controller for quadcopter flight in overland monitoring setting.
[8] Development of hybrid (neuro-fuzzy) controller for quadcopter flight in overland monitoring setting.

The defense will be held on 3 May 2024 at 14^{00} at the meeting of the Dissertation council ED 1.35 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the Institute of Information Technology of the Ministry of Science and Education of the Republic of Azerbaijan.

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Electronic versions of dissertation and its abstract are available on the official website (*www.ict.az*) of the Institute of Information Technology of the Ministry of Science and Education of the Republic of Azerbaijan.

Abstract was sent to the required addresses on 29 March 2024.

Signed for print: 28.03.2024

Paper format: 60x84 $^{1/16}$

Volume: 34561 characters

Number of hard copies: 20