ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ

UDC 004.4

Dr. Tech. Sci., prof. Lienkov S.V. (VIKNU)
Ph.D. Haisha O.O. (ICM CSIC, Barcelona)
Ph.D. Lenkov Y.S. (Ministry of Energy, Kyiv)
Haisha O.O. (MKU, Mykolaiv)

DOI: http://doi.org/10.17721/2519-481X/2025/88-05

APPLICATION OF FUZZY LOGIC METHODS TO DEVELOP A QUADCOPTER LANDING CONTROL SYSTEM

The article addresses a pressing scientific and applied problem related to the automation of the landing process of unmanned aerial vehicles, in particular quadcopters, which today occupy a leading position among the various types of drones and are widely employed in both military and civilian domains. The landing stage constitutes an obligatory phase in the operation of such aircraft, yet at the same time it is one of the most complex, since in its final stage the vehicle must ensure safe contact with a solid surface. Consequently, the development of an effective algorithm and system for automatic quadcopter landing becomes the central objective of the conducted research.

Existing landing control solutions based on ultrasonic, infrared, thermal, or radio signals require the use of additional equipment, which complicates their integration into small and medium-sized aerial platforms. In this context, the most rational approach is considered to be the use of the quadcopter's onboard camera in combination with a specially designed landing marker placed on the platform, constructed from simple geometric figures that are easily recognizable from altitude.

To achieve the stated objective, a mathematical model of quadcopter motion was created in the Matlab Simulink environment. This model takes into account the thrust of each of the four propellers, thereby enabling the reproduction of the aircraft's displacement along the coordinate axes and the simulation of landing scenarios. The automatic control system was implemented using a fuzzy controller, which operates on the basis of three input variables representing the deviations of the current coordinates from the target landing point along the x, y, and z axes. The outputs are expressed as thrust forces for each motor. A total of thirty fuzzy inference rules were constructed, ensuring adequate responsiveness to deviations from the designated trajectory and altitude.

Experimental investigations conducted in the modeling environment confirmed the effectiveness of the proposed solution. All tests demonstrated stable guidance of the quadcopter toward the designated marker and successful completion of the landing process. The average value of the static error after landing corresponds to the requirements of the technical specification and is regarded as acceptable for automated landing systems designed for platforms with limited surface area. The dynamics of the process were characterized by the absence of significant oscillations and overshoot, a smooth reduction of speed in the final phase, and reliable attainment of the designated point.

The obtained results indicate that the proposed approach possesses substantial practical value and may be effectively employed for the creation of real-world quadcopter landing control systems.

Keywords: UAV, quadcopter, automatic landing, AI control, fuzzy logic.

Introduction. At present, unmanned aerial vehicles are increasingly penetrating various sectors of modern society. In addition to their obvious military applications, they are also employed to address a wide range of civilian tasks, including those requiring a high degree of automation throughout the entire process of UAV operation. Landing constitutes one of the mandatory stages in the exploitation of aerial vehicles, while at the same time being a rather complex procedure, since at its final stage the aircraft must ensure safe and reliable contact with a solid surface [1]. It should also be emphasized that quadcopters represent one of the most extensive categories of UAVs. Consequently, the issue of providing fully automated landing of quadcopters is of considerable relevance, and it is precisely this problem that is addressed in the present study.

The objective of this work is to reduce the amount of time required from the human operator of an unmanned aerial vehicle to complete a flight mission, which can be achieved through the automation of the landing process. Moreover, provided that this process is implemented with sufficient quality, the prospect of creating fully autonomous aerial systems becomes feasible, since landing is one of the most complex operations such systems must perform.

Literature review and problem statement. A significant number of scientific and technical publications are devoted to the study of UAV motion control systems and, in particular, landing procedures. For instance, in [2], the onboard equipment of unmanned aerial vehicles intended for solving a wide spectrum of tasks is examined in detail. This includes the determination of navigational parameters such as angular velocities and accelerations, as well as the execution of navigation and control functions during flight along a predetermined trajectory. Additionally, the issues of stabilizing the angular orientation of the vehicle in flight and transmitting telemetry data on navigational parameters through the appropriate communication channel are considered.

In the majority of publications, UAVs are analyzed in the context of their application within specific sectors. Thus, [3] investigates the use of unmanned aerial vehicles in industry as a whole, as well as in particular branches, with a more detailed focus on their role in the marine sector. The text provides an extensive overview of current challenges and presents methods that may be employed for their resolution through unmanned technologies. The article also emphasizes the importance of integrating automatic control systems into UAVs and discusses both the technical aspects of drones and the interrelation between their components. An example of software used to operate unmanned aerial vehicles is also provided.

The issues of UAV control designed for specialized fields are also addressed in [4-6]. In these studies, the structure and features of control systems for UAVs designed for landing on moving platforms are proposed and described.

Although the studies mentioned above devote limited attention to the landing problem itself, they may nevertheless prove useful for the objectives of the present research. This is because, as has already been stated, during landing on a designated small-area platform, it is necessary to ensure the movement of the aircraft, which essentially corresponds to the regular flight regime. Therefore, the aforementioned works are considered valuable for addressing landing control as well.

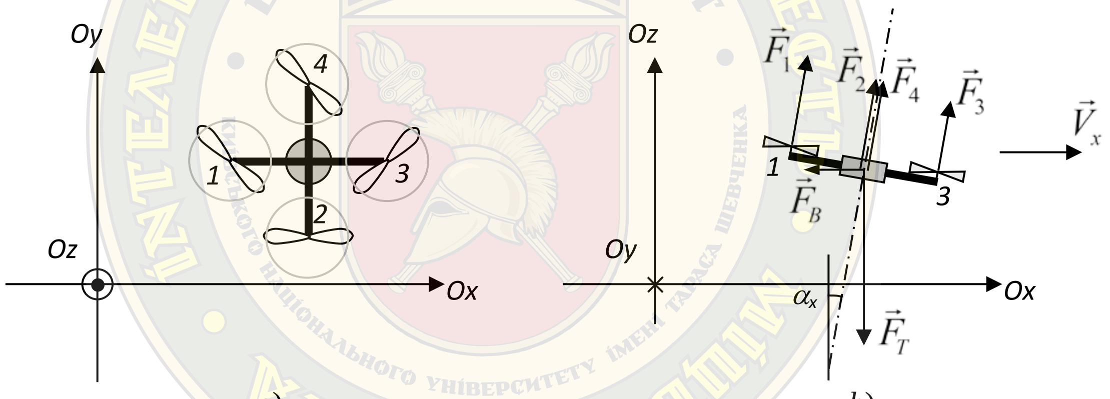
A more comprehensive consideration of UAV landing control is found in [7]. This work describes multirotor UAVs, which, at the most basic level, include quadcopters equipped with four rotors. The article examines the possibilities of implementing an automatic takeoff and landing system for small autonomous unmanned aerial vehicles. It substantiates the use of systems based on computer vision technology, employing optical capture of marker tags. It is emphasized that, for effective localization of key points of the UAV or the landing strip in computer vision systems during automatic takeoff and landing, the use of markers is necessary. The article further provides an analysis of different marker arrangements and variations in marker tag implementations. However, it should be noted that the work is largely conceptual in nature and does not offer a ready-made solution for the development of a UAV landing control system.

An important feature of this work lies in the fact that all algorithms related to image recognition (or computer vision, as termed by the authors) are proposed to be executed on ground-based computing systems, with data from the UAV’s cameras transmitted via a radio channel. Such an approach has both significant advantages and considerable drawbacks [8]. The evident advantage is the reduction of the overall weight of the aerial system due to the use of ground-based computational modules. However, a critical disadvantage is that, should communication be disrupted or lost, it would become impossible to land the vehicle in automatic mode, and in the absence of the option for manual landing, this would inevitably lead to a crash. Consequently, this study proposes not to transfer the recognition module for landing markers to ground systems but rather to simplify the corresponding algorithm by designing the marker itself in a special, maximally simplified form. This approach will form the basis for further development in the present research.

Thus, after analyzing the problem of unmanned aerial vehicle landing as well as the existing solutions, several conclusions can be drawn. First, the issue of UAV landing is of exceptional relevance due to their increasingly widespread implementation across diverse areas of modern society. Second, landing methods based on the use of ultrasonic, infrared, thermal, and radio signals require additional equipment, which makes them unsuitable for small and medium-sized vehicles. Third, from both an economic and weight–dimensional perspective, the most efficient approach is to employ the onboard camera of a quadcopter for performing landings on a prearranged platform [9]. Finally, as reference signals for such a platform, it is advisable to use an image that is clearly distinguishable from altitude and based on simple geometric primitives such as rectangles, circles, and line segments.

Consequently, there arises the necessity to develop a control system for the automatic landing of quadcopters that relies on the recognition of a specifically designed pattern indicating the designated landing site and based on AI-principles [10].

Materials and methods. During flight, the orientation of UAV propulsion units may be arbitrary with respect to the coordinate axes, taking into account the need for maneuvering and performing various turns. However, during the landing process, it is possible, without loss of generality, to impose a specific orientation of the vehicle, for example, as illustrated in Fig. 1, a. In this case, the thrust of propellers 1 and 3 determines movement along the Ox axis, while propellers 2 and 4 govern displacement along the Oy axis. It is evident that under such an arrangement, the action of the pairs of forces generated by the propellers located diagonally opposite each other does not interfere with one another: the difference in forces $F_1 - F_3$ defines movement along the Ox axis, whereas the difference $F_2 - F_4$ defines motion along the Oy axis.



a) b)

Figure 1 - Example of quadcopter orientation during landing: propellers 1–3 are responsible for displacement along the Ox axis, and propellers 2–4 are responsible for motion along the Oy axis (a top view is shown, with the Oz axis directed out of the plane of the figure): *a* – xOy plane, *b* – xOz plane

Let us now consider a case involving the difference $F_1 - F_3$, which is illustrated in the zOx plane in Fig. 1, b. Fig. 1, b shows the arrangement of forces that influence movement along the Ox axis. The complete system of equations describing the motion of the quadcopter is as follows:

$$\ddot{\alpha}_x = \frac{(F_1 - F_3)r}{I}$$

$$\ddot{\alpha}_y = \frac{(F_2 - F_4)r}{I}$$

$$\sum_{i=1}^{4} F_i \cdot \sin \alpha_x - C\dot{x} = m\ddot{x}$$

$$\sum_{i=1}^{4} F_i \cdot \sin\alpha_y - C\,\dot{y} = m\,\ddot{y}$$

$$\sum_{i=1}^{4} F_i \cdot \cos\alpha - F_T = m\,\ddot{z}$$

$$\cos\alpha = \frac{1}{\sqrt{tg^2\,\alpha_x + tg^2\,\alpha_y + 1}}$$

Let us now examine the software implementation of the presented mathematical model describing the motion of the drone. In the idealized case of this model (in the absence of external disturbances, which sufficiently corresponds to reality under conditions without sharp wind gusts), there are four inputs representing the thrust forces of the UAV engines. These are implemented using inport blocks in the Simulink system. The outputs of the model are the three coordinates of the vehicle – *x*, *y*, and *z* – for which three outport blocks are used. The general view of the already implemented mathematical model is presented in Fig. 2.

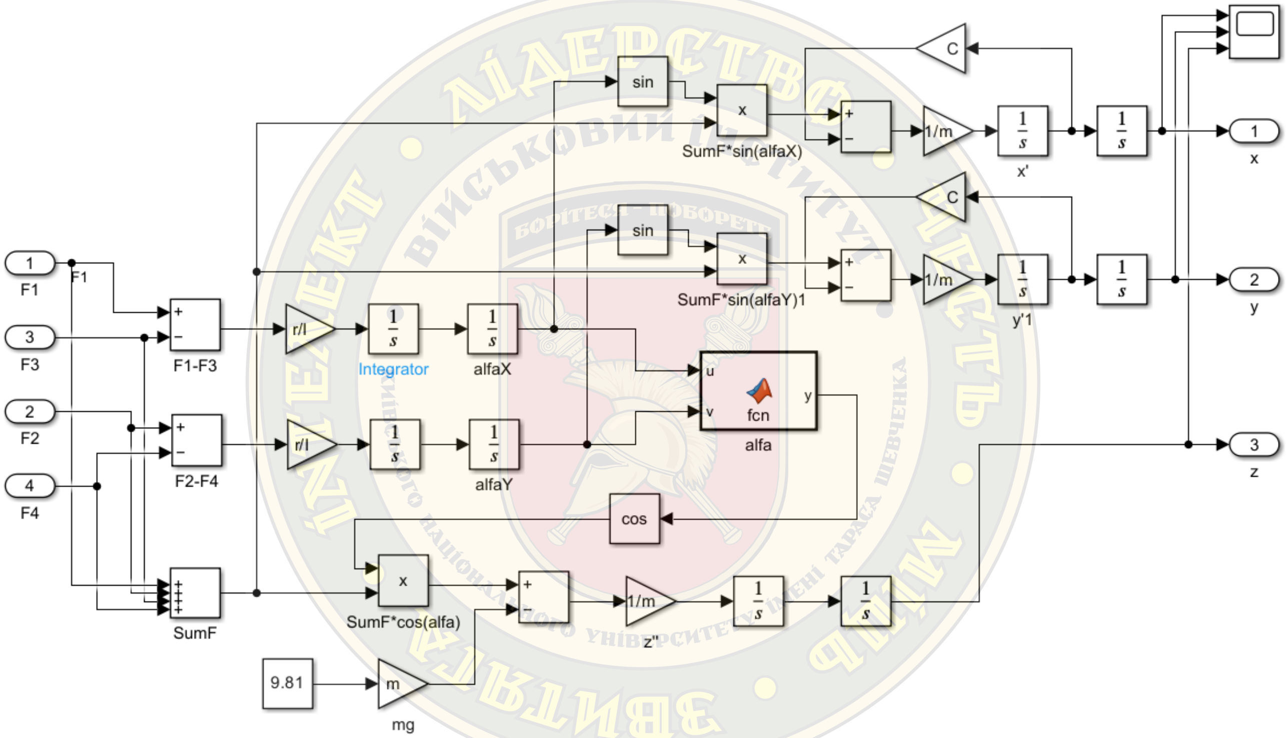


Figure 2 - Schematic representation of the mathematical model of the motion of a quadcopter-type UAV body, implemented in Matlab Simulink.

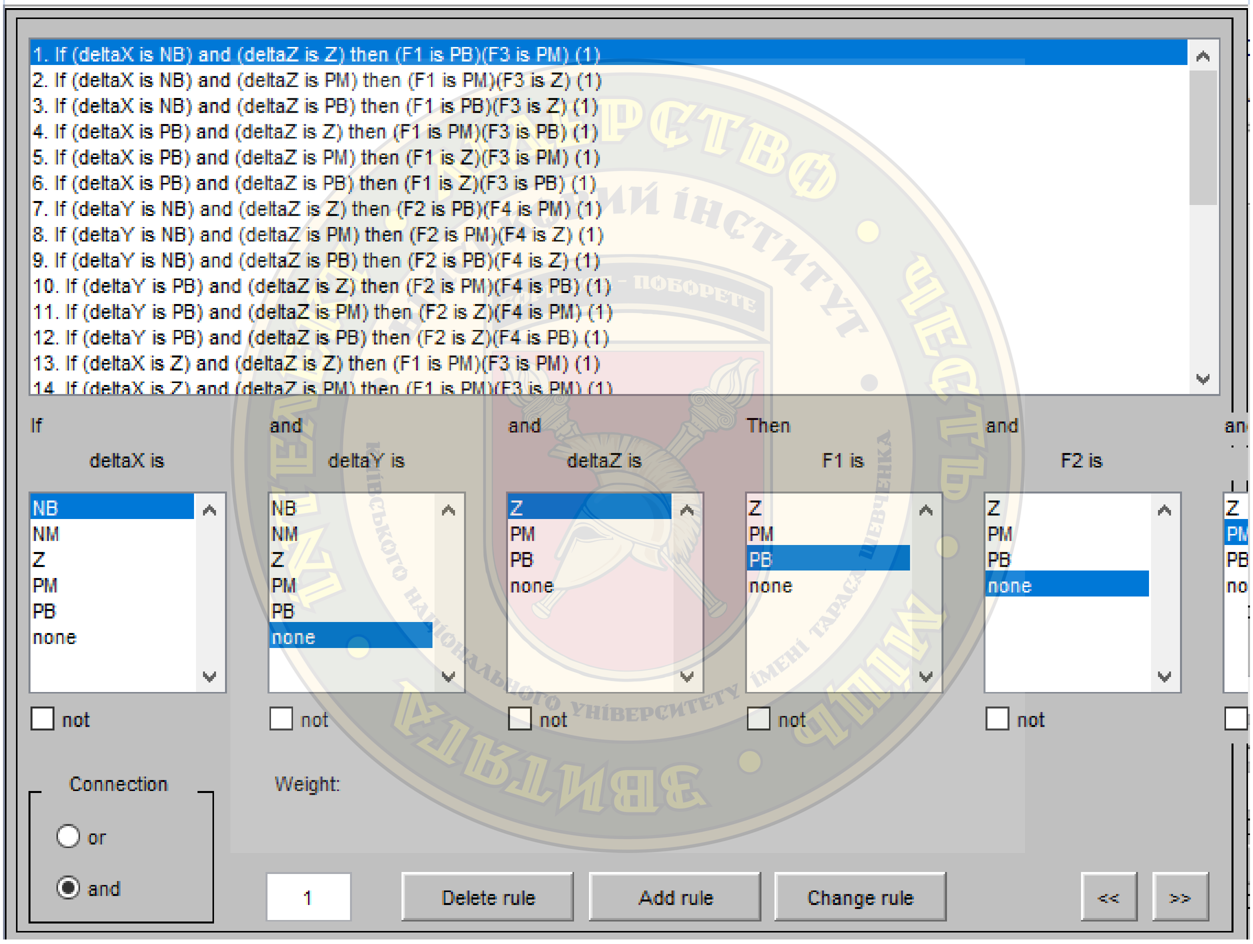
This implementation in the Simulink environment can serve as a mathematical model of the motion of a quadcopter-type unmanned aerial vehicle. This model makes it possible to test the adequacy and performance of the corresponding control system.

The automatic control system itself is implemented using a fuzzy controller [11]. In the developed control system, three input variables are defined. The first input corresponds to the difference between the current *x* coordinate and the coordinate x_0 of the intended landing point, denoted as deltaX. For this parameter, a range from -100 to 100 meters is applied. The second input is the difference between the current *y* coordinate and the coordinate y_0 of the intended landing point, denoted as deltaY, with the same range of -100 to 100 meters. The third input corresponds to the difference between the current *z* coordinate and the coordinate z_0 of the intended landing point, denoted as deltaZ, and for this characteristic the range from 0 to 100 meters is used.

As output variables, four thrust forces F_1, F_2, F_3, and F_4 are defined, which correspond to the propellers of the quadcopter (the distribution of force numbers along the respective axes was specified earlier and illustrated in Fig. 1). The variation range of these forces is set from 0 to 10 N. Since the modeling is performed on a small vehicle with a mass of about 2 kg, a total thrust capacity of 40 N is considered sufficient to execute rather sharp maneuvers, including rapid altitude changes.

For the input variables deltaX and deltaY, five linguistic terms are assigned: NB (Negative Big), NM (Negative Medium), Z (Zero), PM (Positive Medium), and PB (Positive Big). For the variable deltaZ, three terms are used: Z, PM, and PB. Each output linguistic variable is characterized by three terms corresponding to the values "small," "medium," and "large".

For the fuzzy control system, fuzzy inference rules were designed, amounting to a total of 30 rules, which are displayed in Fig. 3. The rules are structured in such a way that control of motion along the Ox axis and motion along the Oy axis are implemented independently, with 15 rules assigned to each axis. The number of 15 rules per axis results from the fact that the linguistic variables deltaX and deltaY are described by five terms each, while deltaZ contains three terms, leading to a total of 3×5 = 15 possible combinations for each axis.



```
1. If (deltaX is NB) and (deltaZ is Z) then (F1 is PB)(F3 is PM) (1)
2. If (deltaX is NB) and (deltaZ is PM) then (F1 is PM)(F3 is Z) (1)
3. If (deltaX is NB) and (deltaZ is PB) then (F1 is PB)(F3 is Z) (1)
4. If (deltaX is PB) and (deltaZ is Z) then (F1 is PM)(F3 is PB) (1)
5. If (deltaX is PB) and (deltaZ is PM) then (F1 is Z)(F3 is PM) (1)
6. If (deltaX is PB) and (deltaZ is PB) then (F1 is Z)(F3 is PB) (1)
7. If (deltaY is NB) and (deltaZ is Z) then (F2 is PB)(F4 is PM) (1)
8. If (deltaY is NB) and (deltaZ is PM) then (F2 is PM)(F4 is Z) (1)
9. If (deltaY is NB) and (deltaZ is PB) then (F2 is PB)(F4 is Z) (1)
10. If (deltaY is PB) and (deltaZ is Z) then (F2 is PM)(F4 is PB) (1)
11. If (deltaY is PB) and (deltaZ is PM) then (F2 is Z)(F4 is PM) (1)
12. If (deltaY is PB) and (deltaZ is PB) then (F2 is Z)(F4 is PB) (1)
13. If (deltaX is Z) and (deltaZ is Z) then (F1 is PM)(F3 is PM) (1)
14. If (deltaX is Z) and (deltaZ is PM) then (F1 is PM)(F3 is PM) (1)
```

Figure 3 - Rule base of fuzzy productions designed for the automatic landing system of UAV.

The rules were formulated in accordance with a general logic. The greater the deviation along the *x* or *y* coordinate, the larger the difference must be between the two thrust forces responsible for movement along that axis, thereby enabling the vehicle to shift rapidly in the desired direction. At the same time, another important factor is taken into account: if the altitude is relatively high, the total value of the two forces acting along the Ox or Oy axis must not be too large, which allows for accelerated descent. Conversely, as the altitude decreases, the total thrust of each pair of propellers is reduced, ensuring a gradual and smooth descent of the quadcopter [12].

All the rules implement the previously described logic, according to which a high altitude corresponds to its rapid decrease, a large deviation along the *x*-axis corresponds to a significant difference in thrust between F_1 and F_3, and a large deviation along the *y*-axis corresponds to a significant difference in thrust between F_2 and F_4.

The rule base was analyzed for consistency both manually and by means of examining the fuzzy inference surfaces provided by the Matlab Fuzzy Logic Toolbox. The developed fuzzy control system was imported into the fuzzy controller, which was subsequently integrated into the overall system combining the previously constructed quadcopter body dynamics model and the control subsystem, as shown in Fig. 4. This integrated system was employed to evaluate the quality of the obtained solution, with the evaluation process described in the following subsection.

Thus, based on the individual models obtained, a comprehensive system was constructed for investigating the performance characteristics of the proposed solution, with these models incorporated as subsystems (subsystems in Simulink terminology). The results of this investigation are presented in the next subsection.

Results. For the developed system, it is essential to conduct procedures aimed at assessing the quality of its operation, and such an evaluation can be effectively carried out using the model previously implemented in Matlab Simulink. After integrating the proposed solutions into a single framework, a series of tests was performed to examine the behavior of the aerial vehicle under different input conditions.

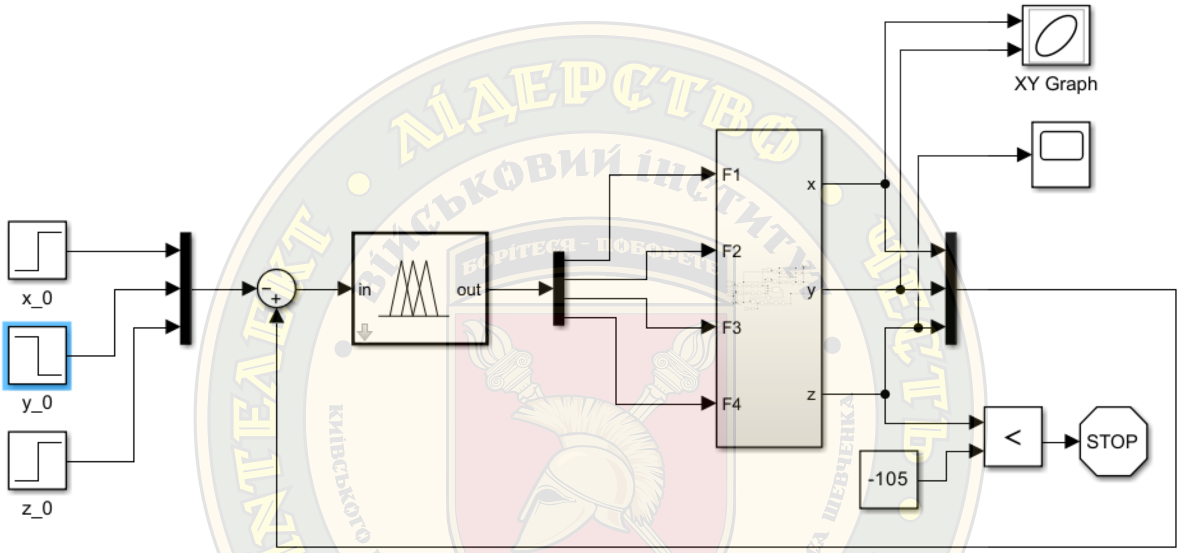


Figure 4 - System designed for testing the operation of the developed control solution.

The results of the conducted experiments revealed the following features of system behavior. The quadcopter consistently directed its motion toward the detected point of the intended landing site. The static error at the completion of the landing process did not exceed approximately 1.3 meters, which can be considered a satisfactory value for fully automated landings within a landing area of several meters in size. Overshoot was practically absent, and the landing process was predominantly aperiodic in character, ensuring stable descent dynamics. These observations are clearly illustrated in Fig. 5.

The final segment of the trajectory is shown in enlarged form in Fig. 6.

The descent in altitude corresponding to the trajectory shown in Fig. 5 is presented in Fig. 7. It is evident that the process initially occurs with a steep decline, but as the vehicle approaches the supporting surface, its motion becomes increasingly smooth and gradual.

Conclusion. Analysis of the data presented in Fig. 5, as well as in other graphs (not presented due to the limited article size), makes it possible to specify the value of the static error along the coordinates. In Fig. 5, this error amounts to approximately 1.27 meters, while the average over four experiments equals 1.2 meters. This value can be regarded as fully acceptable and corresponds to the requirements set by the technical specification for the development. On the curves shown in Fig. 3.9 (and similar), it is possible to identify distinct segments reflecting the transition from rapid motion, generated by the fuzzy control system at a considerable distance from the landing point, to medium-speed movement (in the region of x = 80–100), and finally to low-speed motion with precise positioning on the designated marker (approximately after x = 100).

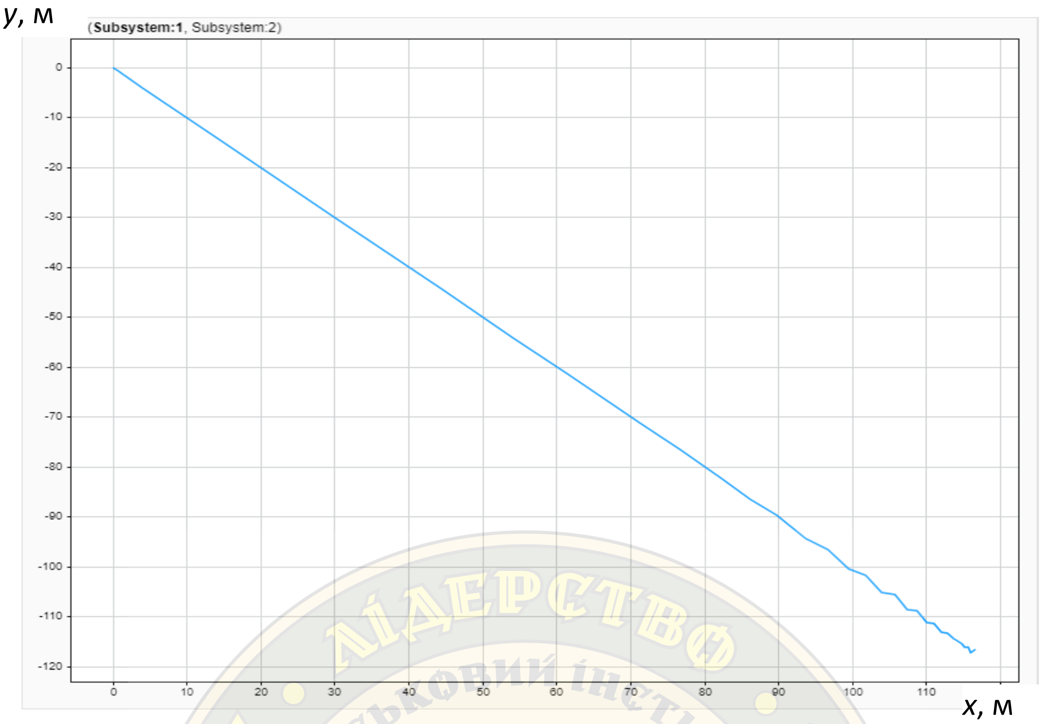


Figure 5 - Example of the quadcopter’s motion from the initial point (0;0), where the landing marker was first identified, to the designated landing point, which was initially detected at coordinates (115; -115).

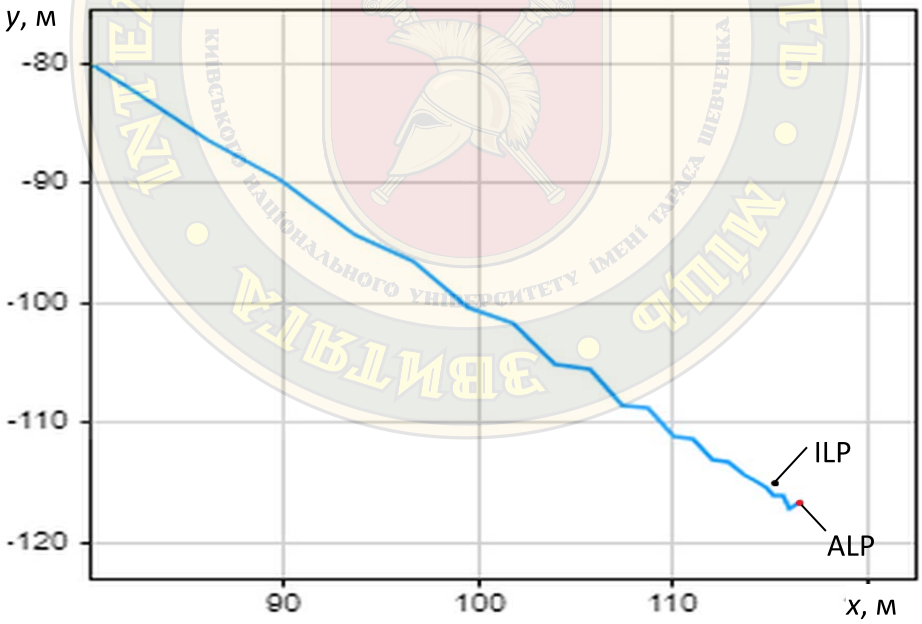


Figure 6 - Concluding part of the trajectory, displaying both the intended landing point (ILP) and the actual landing point (ALP).

ЛІДЕРСТВО ІНТЕЛЕКТ ЧЕСТЬ МІЦЬ ЗВИТЯГА
ВІЙСЬКОВИЙ ІНСТИТУТ КИЇВСЬКОГО НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ ІМЕНІ ТАРАСА ШЕВЧЕНКА

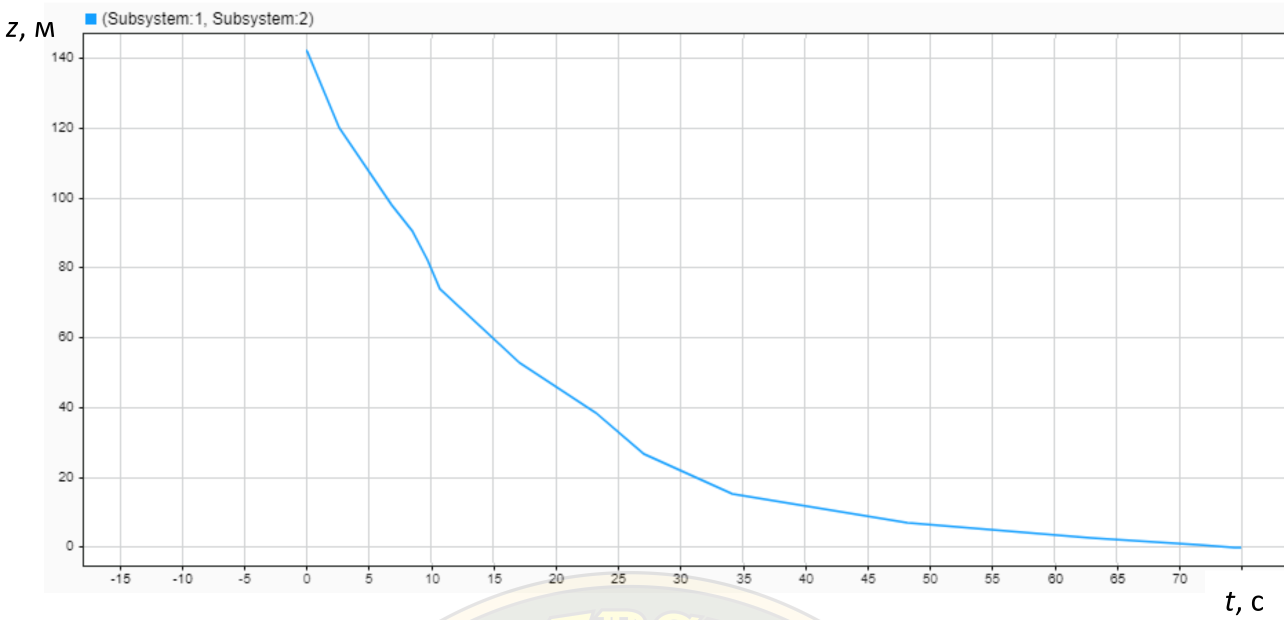


Figure 7 - Decrease in altitude over time corresponding to the motion in the xOy plane shown in Fig. 5.

Therefore, based on the analysis of the obtained results, it can be concluded that the developed solution demonstrates satisfactory performance characteristics and may be recommended for implementation in an actual aerial vehicle for the purpose of controlling automatic landing processes.

REFERENCES:

1. Long, X., Zimu, T., Weiqi, G. and Haobo, L. (2022) ‘Vision-Based Autonomous Landing for the UAV: A Review’, Aerospace, 9, p. 634.
2. Baidya, R. and Jeong, H. (2024) ‘Simulation and real-life implementation of UAV autonomous landing system based on object recognition and tracking for safe landing in uncertain environments’, Frontiers in Robotics and AI, 11, p. 1450266. doi:10.3389/frobt.2024.1450266.
3. Cho, G., Choi, J., Bae, G. and Oh, H. (2022) ‘Autonomous ship deck landing of a quadrotor UAV using feed-forward image-based visual servoing’, Aerospace Science and Technology, 130, p. 107869. doi:10.1016/j.ast.2022.107869.
4. Aikins, G., Jagtap, S. and Nguyen, K.-D. (2024) ‘A robust strategy for UAV autonomous landing on a moving platform under partial observability’, Drones, 8, p. 232. doi:10.3390/drones8060232.
5. Araar, O., Aouf, N. and Vitanov, I. (2017) ‘Vision based autonomous landing of multirotor UAV on moving platform’, Journal of Intelligent and Robotic Systems, 85, pp. 369–384. doi:10.1007/s10846-016-0399-z.
6. Kim, J., Jung, Y., Lee, D. and Shim, D.H. (2014) ‘Outdoor autonomous landing on a moving platform for quadrotors using an omnidirectional camera’, 2014 International Conference on Unmanned Aircraft Systems (ICUAS), IEEE, pp. 1243–1252.
7. Lv, M., Fan, B., Fang, J. and Wang, J. (2024) ‘Autonomous Landing of Quadrotor Unmanned Aerial Vehicles Based on Multi-Level Marker and Linear Active Disturbance Reject Control’, Sensors, 24(5), p. 1645. doi:10.3390/s24051645.
8. Chen, J., Miao, X., Jiang, H., Chen, J. and Liu, X. (2017) ‘Identification of autonomous landing sign for unmanned aerial vehicle based on faster regions with convolutional neural network’, 2017 Chinese Automation Congress (CAC), IEEE, pp. 2109–2114.
9. Ding, J., Xue, N., Xia, G.-S., Bai, X., Yang, W., Yang, M.Y. et al. (2021) ‘Object detection in aerial images: a large-scale benchmark and challenges’, IEEE Transactions on Pattern Analysis and Machine Intelligence, 44, pp. 7778–7796. doi:10.1109/tpami.2021.3117983.

10. Wang, Y., Liu, W., Liu, J. and Sun, C. (2023) ‘Cooperative USV-UAV marine search and rescue with visual navigation and reinforcement learning-based control’, ISA Transactions, 137, pp. 222–235. doi:10.1016/j.isatra.2023.04.025.

11. Rabah, M., Haghbayan, H., Immonen, E. and Plosila, J. (2022) ‘An AI-in-Loop Fuzzy-Control Technique for UAV’s Stabilization and Landing’, IEEE Access, 10, pp. 101119–101123. doi:10.1109/ACCESS.2022.3145186.

12. Bouaiss, O., Mechgoug, R. and Taleb-Ahmed, A. (2023) ‘Visual soft landing of an autonomous quadrotor on a moving pad using a combined fuzzy velocity control with model predictive control’, Signal, Image and Video Processing, 17, pp. 21–30. doi:10.1007/s11760-021-02065-0.

д.т.н., проф. **Лєнков С.В.**, к.т.н., доц. **Гайша О.О.**,
к.т.н., ст. досл. **Лєнков Є.С.**, **Гайша О.О.**

ЗАСТОСУВАННЯ МЕТОДІВ НЕЧІТКОЇ ЛОГІКИ ДЛЯ РОЗРОБКИ СИСТЕМИ КЕРУВАННЯ ПОСАДКОЮ КВАДРОКОПТЕРА

У статті розглянуто актуальну науково-прикладну проблему автоматизації процесу посадки безпілотних літальних апаратів, зокрема квадрокоптерів, які сьогодні посідають провідне місце серед різновидів дронів та знаходять широке застосування як у військовій, так і у цивільній сферах. Етап посадки є обов’язковою фазою експлуатації апарату, але водночас однією з найбільш складних, адже в її завершальній частині апарат має забезпечити безпечний контакт з твердою поверхнею. Саме тому розробка ефективного алгоритму та системи автоматичної посадки квадрокоптерів виступає ключовою метою проведеного дослідження.

Існуючі рішення по управлінню посадкою, засновані на ультразвукових, інфрачервоних, теплових чи радіосигналах, потребують додаткового обладнання, що ускладнює застосування їх на малих і середніх літальних апаратах. У цьому контексті найбільш раціональним підходом визнається використання штатної камери квадрокоптера та спеціально розробленого маркера на посадковій платформі, що складається з простих геометричних фігур, легко розпізнаваних з висоти.

Для досягнення мети створена математична модель руху квадрокоптера у середовищі Matlab Simulink. У моделі враховано тягу кожного з чотирьох пропелерів, що дозволяє відтворити переміщення апарату вздовж координатних осей та відпрацювати сценарії посадки. Система автоматичного керування реалізована на основі нечіткого регулятора, для якого визначено три вхідні змінні – відхилення поточних координат від цільової точки посадки за осями x, y та z. На виході формуються керуючі впливи у вигляді сил тяги для кожного двигуна. Всього побудовано 30 правил нечіткого виведення, які забезпечують адекватне реагування на відхилення від цільової траєкторії та висоти.

Проведені експериментальні дослідження у середовищі моделювання засвідчили ефективність запропонованого рішення. Усі тести показали стабільне спрямування квадрокоптера до позначеного маркера та успішне завершення процесу посадки. Середнє значення статичної похибки після посадки відповідає вимогам технічного завдання і вважається прийнятним для автоматизованих систем посадки на обмежені за площею платформи. Динаміка процесу характеризувалася відсутністю значних коливань і перевищень, плавним зниженням швидкості у фінальній фазі та впевненим досягненням позначеної точки.

Отримані результати свідчать, що запропонований підхід має достатню практичну цінність та може бути використаний для створення реальних систем керування посадкою квадрокоптерів.

Ключові слова: БПЛА, квадрокопотер, автоматична посадка, ШІ управління, нечітка логіка.