UDC 621.865:004.896 https://doi.org/10.32515/2664-262X.2025.11(42).2.135-142

Bohdan Tsymbal[1,2], Assoc. Prof., D.P.A., **Nataliya Karyavkina**[2]
[1]*National University of Civil Protection of Ukraine, Cherkassy, Ukraine*
[2]*LLC "Technical University "Metinvest Polytechnic", Zaporizhzhia, Ukraine*
e-mail: tsembalbogdan@ukr.net

Modernisation of Foundry Production with Industrial Robots and Manipulators

The modernization of foundry production through industrial robots and manipulators represents a significant advancement in automation, efficiency, and occupational safety. The foundry industry plays a crucial role in the manufacturing sector, providing high-quality metal products for various applications. However, traditional foundry processes are often labor-intensive, hazardous, and prone to inefficiencies. In recent years, the integration of robotics and automated technologies has become an essential aspect of improving productivity, ensuring precision, and enhancing workplace safety. This study focuses on the application of industrial drones in foundry production, particularly for material transportation, coating application, and quality control. The research explores the feasibility of integrating the DJI Matrice 300 RTK drone into the casting process, analyzing its potential benefits in optimizing logistics, minimizing defects, and improving overall process efficiency. The use of drones in foundry operations offers several advantages, including the ability to operate in high-temperature environments, automate routine tasks, and reduce human exposure to hazardous conditions. To achieve these objectives, the study employs a combination of theoretical analysis, mathematical modeling, and experimental testing. A mathematical model of drone movement within the foundry environment is developed to optimize flight paths, minimize energy consumption, and ensure precise navigation. Additionally, simulations are conducted to assess the impact of high temperatures and airborne particles on drone performance. Experimental trials are carried out in real production conditions to validate the proposed approach and evaluate the efficiency of drone-assisted operations. The results of the study indicate that industrial drones can significantly improve foundry logistics by reducing material transportation time and ensuring the precise application of protective coatings. The implementation of automated aerial systems enhances quality control by enabling real-time monitoring of casting processes and early defect detection. Moreover, the reduction of human involvement in hazardous tasks contributes to workplace safety and minimizes occupational risks. Based on the findings, recommendations are proposed for optimizing the integration of drones into foundry production. These include refining navigation algorithms, enhancing thermal protection measures, and developing advanced sensor technologies for improved defect detection. The implementation of these recommendations can lead to higher efficiency, reduced waste, and increased competitiveness in the foundry industry. The study's outcomes have been applied in practical settings, including their adoption at PJSC "Kamet Stal" and incorporation into educational programs to enhance training in industrial automation. The research highlights the transformative potential of drone technology in modernizing foundry production and underscores the importance of continued innovation in automation and robotics. Future research directions include exploring alternative energy sources for drones, improving their adaptability to extreme environmental conditions, and expanding their functionality for broader industrial applications.
automation, foundry production, industrial drones, modernization, robotics, Industry 4.0, occupational safety

Statement of the problem. Foundry is one of the examples of efficient use of resources, as castings are almost completely recyclable. After completing their “life” cycle, they are subject to remelting. In addition, modern technologies make it possible to recover up to 95% of the sand mixture for the manufacture of various casting molds, which has a positive impact on the environment [1]. One of the important areas of automation and improving energy efficiency is the introduction of robotization [2].

The foundry industry is undergoing significant transformations due to the emergence of automation and robotics. This revolution not only increases efficiency and productivity, but also improves safety and quality in the sector. The integration of automation and robotics into foundry processes is changing the situation dramatically. Traditionally, foundry processes have been labor-intensive, involving a high level of manual labor. Workers have to perform tasks such as molding and casting, often in hazardous conditions. However, the introduction of automation and robotics is changing this process.

Analysis of recent research and publications. Foundries, historically labor-intensive and dangerous, have evolved in parallel with technological progress. In the early days, workers manually handled high-temperature molten metal and performed physically demanding tasks. This led to significant risk safety and potential inconsistency in casting quality. However, as the Industrial Revolution progressed, mechanization and automation.

Among the different types of robots, automated industrial robots are in the greatest demand. Robotic systems of the near future will allow replacing humans in most of the main and auxiliary production operations, contributing to the automation of technological processes in various industrial sectors. This is especially true for the foundry and metallurgical industry, where there are dangerous and harmful working conditions, in particular in hot shops [3-5].

The technology of casting by gasified patterns (LGM) with the use of robotic systems [4] includes the use of a thermal furnace with a rotating hearth manufactured by CAN-ENG Furnaces International Limited (USA). The robot loads the furnace with castings in three rows, which optimizes the heat treatment of aluminum products at a temperature of 500-550 °C. These furnaces are also suitable for isothermal holding of iron-carbon alloys in the range of 350-450 °C. Similar systems are used in foundry RCC schemes [6].

There is a robotic wafer transfer system, which is an innovative equipment for foundry production. This system includes a 4 DOF robotic arm to transfer wafers between the cassette and the processing chambers. It has intelligent automation for wafer manufacturing, in which multiple wafers and chambers need to be processed simultaneously. The robotic system integrates defect detection and wafer processing endpoint determination [7].

A robot is an automated machine designed to reproduce human motor and intellectual functions. Manipulator robots that perform universal tasks are equipped with executive manipulator devices (mechanical arms) [8].

Increasing the payload of robotic systems for foundry operations contributes to the optimization of production cycles compared to traditional casting methods, which is a major factor in the growth of the foundry robotics market. The introduction of technological innovations aimed at reducing the time of integration of robots into the casting process and expanding their functionality is also a key factor stimulating the demand for such solutions [8].

The development of the foundry robotics market is constrained by the difficulty of protecting exposed drives of robotic systems from dust and liquids. At the same time, optimizing production costs and classifying casting methods into four main categories - sand casting, injection molding, gravity casting and LGM - remain key aspects of the industry.

Let us consider examples of the latest technical solutions that demonstrate the interaction of people and cobots, as implemented in the case of Kuka and ABB robotic systems [9]. In foundry production, such an implementation is most appropriate for precision, large-scale and mass casting operations. The ideal option is to combine human advantages (flexibility, subjectivity of decisions, creativity, experience, intuition, wide overview) with the advantages of robotic systems (automation, high accuracy, power), which contributes to the effective distribution of tasks and an increase in overall productivity.

Sand casting is widely used to manufacture components such as engine mounts and differential housings. Once cast, these parts undergo precise cutting and grinding, performed by an industrial robot – specifically, the IRB 6660 ABB – within an automated production cell developed by Automations Robotic GmbH. In this process, an operator secures the raw workpiece in a specialized positioner, which then transfers it into the robotic cell for machining. After the robotic processing is completed, the component is moved to the next workstation for further operations [10].

By adjusting the robot's speed under high force conditions, force control technology minimizes the risk of part damage or machining errors while also preserving tool integrity. This approach extends the lifespan of cutting tools, enhances spindle durability, and improves the precision of the robot's axes. Furthermore, the implementation of this technology results in a 20% reduction in cycle time, increasing overall production efficiency [10].

The industrial robotic casting process consists of multiple stages, including molding, additional processing, and cold working. At the molding phase, robots precisely shape the sand core using intelligent automation. In the post-processing stage, automated systems refine the rough casting with high accuracy. Finally, the cold processing phase integrates robotic deburring, chamfering, cleaning, and air-blowing to enhance the overall quality and consistency of the final product [11].

TIE Industrial's selection of robots for foundry production includes models known for their durability and performance: The Fanuc M–2000 iA is known for its exceptional load capacity and reach, which making it ideal for handling large castings and complex tasks; ABB IRB 7600 provides robust design and versatile performance, suitable for a variety of foundry applications, from casting to finishing; KUKA KR QUANTEC F series are designed specifically for foundry production, these robots provide high resistance to heat and contamination; Motoman ES 165 D is characterized by high speed and precision, ideal for finishing and efficient work with small castings [1].

Despite significant achievements in the field of automation of foundry production, a number of scientific questions remain open that require further research, one of which is the integration of flying robots into the production cycle - studying the possibilities of using drones not only for monitoring, but also for active intervention in the production process, for example, transporting materials or applying coatings.

Setting the task. The purpose of the scientific work is to evaluate the effectiveness of integrating the DJI Matrice 300 RTK drone into the casting technological cycle to improve the productivity, quality, and safety of production processes. To achieve this goal, the following research tasks were defined: conducting an analysis of the possibilities of using industrial drones in foundry production, developing a mathematical model of drone movement in a production environment, studying the impact of high temperatures on the operational characteristics of the drone, assessing the efficiency of material transportation, coating application and quality control using a drone, performing experimental tests and summarizing the results to determine optimal operating modes and develop recommendations.

Presentation of the main material. The use of drones in foundry production opens up new opportunities for automation and efficiency of technological processes. The main scenarios of their application include material transportation, coating application and product quality control.

One key scenario involves transporting materials between different production sections. A drone can move small batches of sand mixtures, chemical reagents or auxiliary components, which allows to reduce delivery delays and optimize logistics operations. With autonomous control and precise positioning systems such as GPS, RTK and LiDAR, drones can quickly and safely deliver materials to specific points in the production process.

Another scenario involves applying coatings to metal workpieces before or after the casting process. A drone equipped with spraying systems can evenly apply anti-corrosion or heat-resistant coatings to parts. This improves product quality, reduces material waste, and minimizes human intervention in the process. Automation of coating also helps reduce defects, improving the final product.

Quality control is another promising area of drone use in foundry production. Drones equipped with high-precision cameras, thermal imagers and spectrometers can perform non-contact monitoring of the condition of molds and finished products. They are able to detect casting defects, assess the uniformity of metal cooling and transmit the collected data in real time to quality management systems. This allows for timely detection of problems and prompt correction of the production process, which helps to reduce the number of scrap and increase overall production efficiency.

Thus, the integration of drones into foundry production allows improving logistics processes, automating coating applications, and ensuring quality control of finished products. The use of such technologies contributes to increasing productivity, reducing production costs, and improving working conditions.

Mathematical modeling allows analyzing drone trajectories, their interaction with the foundry environment, and estimating energy consumption during production tasks. This study examines the use of the DJI Matrice 300 RTK unmanned aerial vehicle for material transportation, coating, and quality control in foundry production.

Kinematic analysis of the drone trajectory. The drone motion is described by the kinematic equations according to Newton's second law [12]:

$$x(t) = x_0 + v_x t + \frac{1}{2} a_x t^2 \tag{1}$$

$$(t) = y_0 + v_y t + \frac{1}{2} a_y t^2 \tag{2}$$

$$z(t) = z_0 + v_z t + \frac{1}{2} a_z t^2 \tag{3}$$

where x_0 = 2 m, y_0 = 1 m, z_0 = 5 m – initial coordinates of the drone; v_x = 3 m/s, v_y = 2 m/s, v_z = 1.5 m/s – initial velocities; a_x = 0.5 m/s ^{2} , a_y = 0.3 m/s ^{2} , a_z = 0.2 m /s ^{2} – acceleration.

The dynamics of the drone's motion is determined by the Lagrange equation of the second kind [13]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = Q \tag{4}$$

where L is the Lagrangian of the system, q is the generalized coordinates, and Q is the generalized forces.

The drone is used to transport small batches of sand mixtures, low-melting metals and auxiliary materials between working areas of the foundry. Thanks to precise navigation (RTK GPS), stable movement is ensured even in closed rooms. Taking into account the drone's payload capacity (up to 2.7 kg), the route is optimized to minimize energy consumption. The optimal flight trajectory is modeled using a dynamic programming algorithm [14], which allows determining the most economical route taking into account air flows and temperature differences.

The drone is equipped with spraying systems for applying anti-corrosion, heat-resistant or protective coatings to metal parts. The uniformity of the spray is taken into account, which is modeled by the flow equation:

$$Q_s = \frac{m}{t} = \rho V \tag{5}$$

where m is the mass of the coating, t is the application time, ρ is the density of the material, V is the spray volume.

To improve spray accuracy, the Navier-Stokes turbulent flow model [15] is used, which allows predicting the direction and uniformity of the coating under variable temperature conditions.

The drone is equipped with high-precision cameras and thermal imagers to monitor the condition of castings and detect defects. Spectral analysis is used to assess deviations from standard parameters. The optical analysis system is based on machine learning methods [16], which allows for automatic classification of defects by their nature and degree of criticality.

The foundry environment is characterized by high temperatures, strong electromagnetic interference, and the presence of metal obstacles that can affect the drone's navigation systems. The temperature effect is taken into account through the thermal radiation coefficient:

$$Q = \sigma\varepsilon A(T_s^4 - T_e^4) \quad (6)$$

where σ = 5.67 ×10 $^{-8}$ W/m² K□ – Stefan-Boltzmann constant; ε = 0.85 – emissivity of the drone surface; A = 0.2 m² – drone surface area; T_s =1200 K – foundry furnace temperature; T_s = 300 K is the ambient temperature.

A series of experimental studies were conducted to evaluate the effectiveness of using the DJI Matrice 300 RTK unmanned aerial vehicle in foundry production. The main areas of evaluation were material transportation, application of protective coatings, and product quality control in conditions of elevated temperatures and polluted environments.

Experimental tests were conducted in the production workshops of the foundry, where the drone's performance was evaluated according to several key criteria. First, the speed of material transportation was analyzed, that is, the time required to deliver the cargo to a given distance. Second, the accuracy of coating application was checked, where the uniformity of material spraying on metal surfaces was assessed. Casting quality control was also checked, which included the detection of defects using cameras and thermal imagers. In addition, energy consumption was measured to assess the battery life and overall energy consumption of the device. The last criterion was the drone's resistance to the influence of the foundry environment, including high temperature and increased concentration of metal dust.

During testing, the DJI Matrice 300 RTK drone was found to be capable of transporting loads such as sand mixtures and auxiliary materials over a distance of 50 meters in an average of 18 seconds. Using a load of up to 2.5 kg had little effect on flight speed, while increasing the weight to 2.7 kg resulted in a 15% decrease in efficiency. The results indicate that the drone can be effectively used for transportation operations within the foundry, however, the recommended load weight should not exceed 2.5 kg to maintain flight stability.

Experiments with coating application showed high accuracy of the spraying system. The uniformity of the coating deviated by no more than ±5% from the specified thickness at a flight speed of 1 m/s. At the same time, conditions of high humidity and high temperature up to 800°C did not affect the quality of the application. However, effective coating application in such conditions required the use of special heat-resistant paints and stabilization of the drone to minimize deviations in the spraying trajectory.

Quality control of foundry castings using a drone has shown high efficiency in detecting defects. The thermal imaging system allowed to identify 90% of surface cracks, the size of which exceeded 0.5 mm. However, for a deeper analysis of defects, it is recommended to use additional infrared sensors that can detect hidden internal damage to parts.

Energy consumption assessment showed that the maximum autonomous operation time of the drone without load was 45 minutes, while when carrying a load of 2.5 kg, it decreased to 35 minutes. In addition, when operating at elevated temperatures above 700°C, the drone's energy consumption increased by 25%, indicating the need to develop more efficient cooling systems for onboard electronic components.

To visually present the results obtained, dependence graphs were constructed. The first graph demonstrates the change in transportation time depending on the mass of the cargo (Fig. 1.a). It was found that with an increase in mass above 2.5 kg, the transportation time increases significantly, which confirms the efficiency of the drone in conditions of limited load capacity. The second and third graphs show the relationship between the mass of the cargo and the time of autonomous operation of the drone, as well as the influence of the ambient temperature on energy consumption (Fig. 1.b and Fig. 1.c). The optimal value of the mass of 2.5 kg turned out to be, at which an acceptable balance between energy consumption and flight time is maintained. In addition, it was determined that at a temperature of 700 K, the energy consumption of the drone increases to 125%, which indicates the need for additional measures to cool the electronic systems.

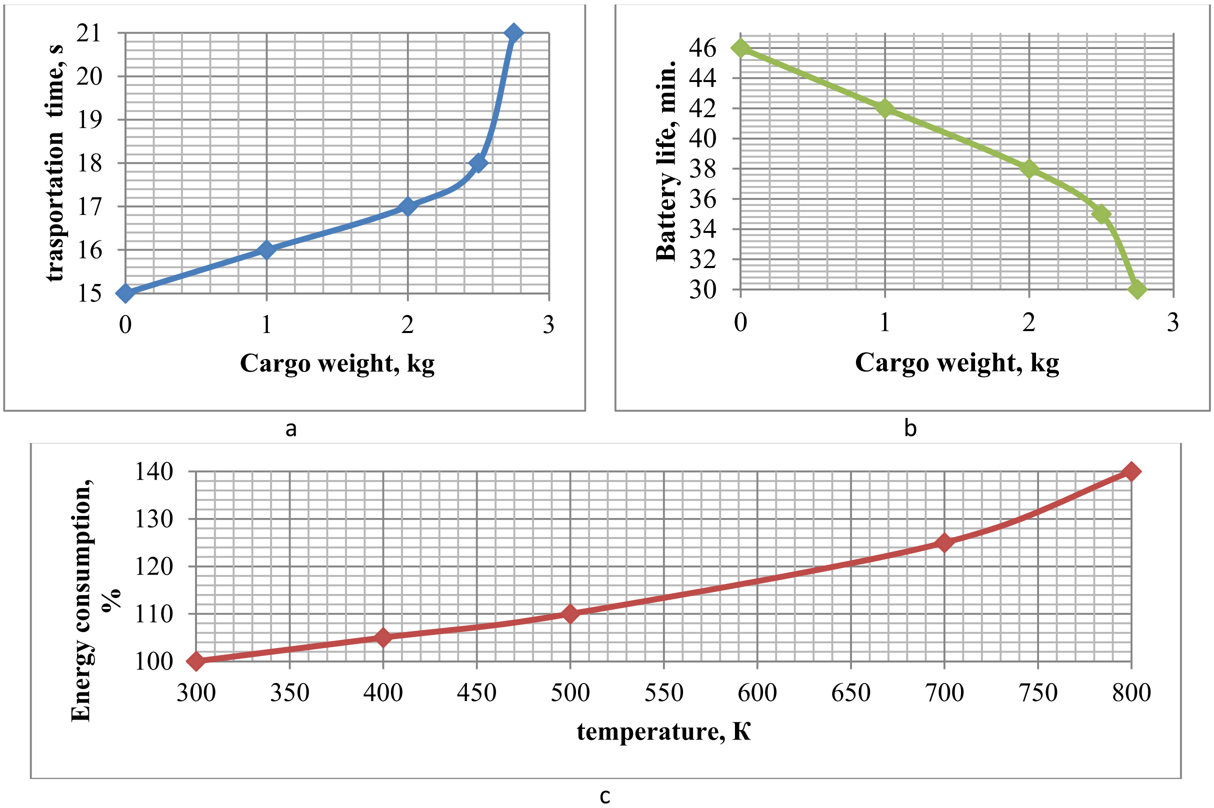

Figure 1 – Graphs of dependences: a - transportation time on cargo mass, b - autonomous operation time on cargo mass and c - energy consumption and temperature
Source: developed by the authors.

In general, experimental studies have confirmed the effectiveness of using the DJI Matrice 300 RTK drone in foundry production. The optimal payload should not exceed 2.5 kg, which ensures maximum stability and efficiency of work. The speed of transportation and accuracy of coating application meet production requirements, and the use of thermal imagers significantly improves the quality of casting control. The impact of high temperatures requires further research to develop additional cooling systems and increase the thermal resistance of electronic components. In the future, it is also advisable to optimize the aerodynamics of the drone to improve flight stability and expand its functionality in difficult industrial conditions.

Conclusions. The study achieved its goal – the effectiveness of integrating the DJI Matrice 300 RTK drone into the casting process cycle was assessed to improve productivity, quality, and safety of production processes. The analysis of the possibilities of using industrial drones in foundry production allowed us to identify their main advantages and limitations. The use of drones helps to increase the efficiency of material transportation, quality control, and coating.

The developed mathematical model allows predicting the trajectory of the drone, taking into account changes in the workshop. The impact of high temperatures on operational characteristics was studied, which allowed determining critical limits and measures to improve thermal resistance.

The effectiveness of drones in production processes was assessed. It was found that their use reduces logistics costs, minimizes the risk of injuries and increases the accuracy of operations. Technical challenges associated with the effects of temperatures, metal dust and electromagnetic interference were identified, which requires additional solutions for thermal protection, navigation and structural stability.

The results obtained have been implemented in production and in the educational process, which confirms their practical significance. Further research can be aimed at improving autonomous control, sensor systems, and integrating drones into automated production processes.

List of References

1. Doroshenko V., Yanchenko O. Improving the resource efficiency of foundry due to the assembly of conveyor and rotor-conveyor lines by robots. *Modern Technology, Materials and Design in Construction.* 2020. Vol. 27. № 2. P. 179–186. DOI: 10.31649/2311-1429-2019-2-179-186
2. Дорошенко В. С. Метод нейтралізації газів, що виділяються з ливарної форми при литві за газифікованими моделями. *Ливарне виробництво*. 2021. № 9. С. 8-14.
3. Дорошенко В.С. Комплектація роботами конвеєрних та роторно-конвеєрних ліній ливарного виробництва. *Лиття України*. 2019. № 6. С. 21-23.
4. Дорошенко, В.С. Лиття по газифікованих моделям з кристалізацією металу під тиском. *Ливарне виробництво.* 2016. № 1. С. 25-28.
5. Калюжний П. Б., Бродовий О. В., Дорошенко В. С., Нейма О. В. 3d-генерація пористих структур для друку ливарних моделей, що газифікуються в ливарній формі. *Нові матеріали і технології в машинобудуванні (Праці Міжнародної науково-технічної конференції).* 2024. № 5. DOI: 10.20535/2519-450x.5.2024.319032
6. Дорошенко В. С. Концепція роторно-конвейєрного комплексу для літа по газофікованим моделям і термообробки відливок. *Металл и литье Украины*. 2019. № 1-2. С. 31-40. URL: http://jnas.nbuv.gov.ua/article/UJRN-0001001769
7. Song K.-T., Ou S.-Q., Yang C.-A., Sun Y.-X., Kang L.-R., Wang Z.-Y., Wang Y.-S., Lu P.-C., Ko C.-L., Chen Y. H.. Scheduling and control of a wafer transfer robot for foundry equipment innovation competition. *IFAC-PapersOnLine*. 2019. Vol. 52. № 15. P. 627–632. DOI: 10.1016/j.ifacol.2019.11.654
8. Калюжний П.Б., Шинський О.Й., Дорошенко В.С. Удосконалення ступінчастої ливникової системи для лиття за моделями, що газифікуються. *Литво. Металургія. 2024* : Матеріали XX Ювіл. Міжнар. науково-практ. конф., м. Харків, 30 трав. 2024 р. Харків. 2024. С. 123–126. URL: https://repository.kpi.kharkov.ua/handle/KhPI-Press/79750
9. Kaliuzhnyi P., Doroshenko V., Neima O. Casting of combined polymer patterns that are gasified. Casting processes. 2023. Vol. 152. № 2. P. 49–55. DOI: 10.15407/plit2023.02.049
10. ABB Robotics magazine. *International customer magazine from ABB Robotics.* 2015. № 2. Publisher: ABB Robotics AB. URL: https://surl.li/wvzrjm
11. Yang, Y., Zheng, Y., Xu, Y., Yang, M., Boyang, B., & Liu, F. Robotic applications of foundry industry in china. У Proceedings of the 72nd world foundry congress. 21-25th May 2016. Nagoya. URL: https://www.senkyo.co.jp/shishido/wfc2016/pdf/O-153.pdf
12. Lynch K. M., Park F. C. Modern robotics: mechanics, planning and control. Cambridge University Press, 2017. 544 p. URL: http://modernrobotics.org
13. Goldstein H., Poole C., Safko J., Classical Mechanics, Addison-Wesley, 2002. URL: https://surl.li/mrdcyr
14. Bertsekas D., Dynamic Programming and Optimal Control, Athena Scientific, 2012. URL: https://surl.li/srkwtv
15. Batchelor G. K., An Introduction to Fluid Dynamics, Cambridge University Press. 2000. DOI: 10.1017/CBO978051180095
16. Heaton I., Goodfellow J. Ian, Bengio Y., Courville A.: Deep learning. *Genetic programming and evolvable machines.* 2017. Vol. 19, № 1-2. P. 305–307. URL: DOI: 10.1007/s10710-017-9314-z

References

1. Doroshenko, V., & Yanchenko, O. (2020). Improving the resource efficiency of foundry due to the assembly of conveyor and rotor-conveyor lines by robots. *Modern Technology, Materials and Design in Construction*, 27(2), 179–186. https://doi.org/10.31649/2311-1429-2019-2-179-186
2. Doroshenko, V.S. (2021). Metod neitralizatsii haziv, shcho vydiliaiutsia z lyvarnoi formy pry lytvi za hazifikovanymy modeliami. *Lyvarne vyrobnytstvo*, (9), 8–14 [in Ukrainian].
3. Doroshenko, V.S. (2019). Komplektatsiia robotamy konveiernykh ta rotorno-konveiernykh linii lyvarnoho vyrobnytstva. *Lyttia Ukrainy*, (6), 21–23 [in Ukrainian].
4. Doroshenko, V.S. (2016). Lyttia po hazifikovanykh modeliakh z krystalizatsiieiu metalu pid tyskom. *Lyvarne vyrobnytstvo*, (1), 25–28 [in Ukrainian].
5. Kaliuzhnyi, P.B., Brodovyi, O.V., Doroshenko, V.S., & Neima, O.V. (2024). 3D-heneratsiia porystykh struktur dlia drukuvannia lyvarnykh modeli, shcho hazifikuiutsia v lyvarnii formi. *Novi materialy i tekhnolohii v mashynobuduvanni*, (5). https://doi.org/10.20535/2519-450x.5.2024.319032 [in Ukrainian].

6. Doroshenko, V.S. (2019). Kontseptsiia rotorno-konveiiernoho kompleksu dlia lytia po hazifikovanym modeliakh i termoobrabotky viddlivok. *Metall i lytie Ukrainy*, (1–2), 31–40. http://jnas.nbuv.gov.ua/article/UJRN-0001001769 [in Ukrainian].
7. Song, K.-T., Ou, S.-Q., Yang, C.-A., Sun, Y.-X., Kang, L.-R., Wang, Z.-Y., Wang, Y.-S., Lu, P.-C., Ko, C.-L., & Chen, Y.H. (2019). Scheduling and control of a wafer transfer robot for foundry equipment innovation competition. *IFAC-PapersOnLine*, 52(15), 627–632. https://doi.org/10.1016/j.ifacol.2019.11.654
8. Kaliuzhnyi, P.B., Shynskyi, O.Yi., & Doroshenko, V.S. (2024). Udoskonalennia stupinchastoi lyvnykovoi systemy dlia lytia za modeliami, shcho hazifikuiutsia. In *Lytvo. Metalurhiia: Materialy XX Yuvileinoi Mizhnarodnoi naukovo-praktychnoi konferentsii*, Kharkiv, 30 travnia 2024 (pp. 123–126). https://repository.kpi.kharkov.ua/handle/KhPI-Press/79750 [in Ukrainian].
9. Kaliuzhnyi, P., Doroshenko, V., & Neima, O. (2023). Casting of combined polymer patterns that are gasified. *Casting Processes*, 152(2), 49–55. https://doi.org/10.15407/plit2023.02.049
10. ABB Robotics AB. (2015). *ABB Robotics Magazine. International customer magazine*, (2). https://surl.li/wvzrjm
11. Yang, Y., Zheng, Y., Xu, Y., Yang, M., Boyang, B., & Liu, F. (2016). Robotic applications of foundry industry in China. In *Proceedings of the 72nd World Foundry Congress*, May 21–25, 2016, Nagoya. https://www.senkyo.co.jp/shishido/wfc2016/pdf/O-153.pdf
12. Lynch, K.M., & Park, F.C. (2017). *Modern robotics: Mechanics, planning and control*. Cambridge: Cambridge University Press. http://modernrobotics.org
13. Goldstein, H., Poole, C., & Safko, J. (2002). *Classical mechanics*. Addison-Wesley. https://surl.li/mrdcyr
14. Bertsekas, D. (2012). *Dynamic programming and optimal control*. Athena Scientific. https://surl.li/srkwtv
15. Batchelor, G.K. (2000). *An introduction to fluid dynamics*. Cambridge University Press. https://doi.org/10.1017/CBO978051180095
16. Heaton, I., Goodfellow, J., Ian, Y., Bengio, Y., & Courville, A. (2017). Deep learning. *Genetic Programming and Evolvable Machines*, 19(1–2), 305–307. https://doi.org/10.1007/s10710-017-9314-z

В. М. Цимбал[1, 2], доц., д-р держ. упр., **Н. С. Карявкіна**[2]
[1]*Національний університет цивільного захисту України, м. Черкаси, Україна*
[2]*ТОВ «Технічний університет «Метінвест політехніка», м. Запоріжжя, Україна*

Модернізація ливарного виробництва промисловими роботами та маніпуляторами

Метою даного дослідження є оцінка ефективності інтеграції промислових дронів у ливарне виробництво для підвищення рівня автоматизації, продуктивності та безпеки праці. Робота зосереджена на використанні безпілотного літального апарата DJI Matrice 300 RTK для транспортування матеріалів, нанесення захисних покриттів та контролю якості в складних умовах ливарного виробництва. Основним завданням є визначення впливу дронів на оптимізацію виробничих процесів, зменшення рівня дефектності продукції та мінімізацію ручної праці в небезпечних умовах.

Методологія дослідження включає комплексний аналіз можливостей використання промислових дронів, математичне моделювання їхнього руху в умовах ливарного виробництва та експериментальну перевірку в реальних виробничих умовах. Розглянуто вплив високих температур, забруднення повітря металевим пилом та обмеженого простору на роботу дрона. Розроблена математична модель дозволяє оптимізувати траєкторії польоту для забезпечення точного позиціонування, мінімізації енергоспоживання та підвищення ефективності виконання завдань. Експериментальні дослідження підтвердили доцільність використання дронів для внутрішньоцехової логістики, автоматизованого нанесення покриттів і контролю якості виливків. Використання дронів дозволяє скоротити час транспортування матеріалів, покращити рівномірність нанесення покриттів та здійснювати ефективний моніторинг виробничих процесів, що позитивно впливає на якість продукції та знижує виробничі витрати.

Отримані результати свідчать про високу ефективність застосування промислових дронів у ливарному виробництві, що сприяє його модернізації та підвищенню рівня автоматизації. Запропоновані рекомендації щодо покращення роботи дронів, зокрема оптимізація алгоритмів навігації та вдосконалення термозахисту, були впроваджені на підприємстві та інтегровані у навчальний процес. Перспективними напрямами подальших досліджень є розробка вдосконалених сенсорних систем, підвищення стійкості дронів до екстремальних умов та розширення їхнього функціоналу для застосування в інших промислових галузях.

автоматизація, ливарне виробництво, промислові дрони, модернізація, роботизація, Industry 4.0, безпека праці

Одержано (Received) 23.03.2025 *Прорецензовано (Reviewed) 18.04.2025*
Прийнято до друку (Approved) 27.04.2025