

Analysis of the Effectiveness of Using a Mobile Robot Digital Twin for Teaching School Students the Fundamentals of Robotics

Vladyslav Yevsieiv¹, Svitlana Starikova²

¹Department of Computer Integrated Technologies, Automation, Robotics and Safety Engineering (CITARSE),
Kharkiv National University of Radio Electronics, UKRAINE,
Kharkiv, Nauki Ave. 14., e-mail: vladyslav.yevsieiv@nure.ua

Abstract: This paper proposes a structure for using a mobile robot digital twin to teach school students the fundamentals of robotics, which integrates a virtual model of the robotic platform, a real mobile robot, data synchronization tools, learning scenarios, and learning outcome assessment. The proposed approach enables the safe and repeated performance of practical experiments and provides the possibility of quantitatively assessing acquired theoretical knowledge and practical skills based on task completion time, the number of errors, control accuracy, and the success rate of learning scenario completion, thereby contributing to the development of practice-oriented STEM education.

Keywords: EDGE Digital Twin, mobile robot, robotics, STEM education, virtual modeling, educational technologies, practical skills, digital learning environment.

I. INTRODUCTION

The rapid development of digital technologies, robotics, and STEM education necessitates the search for new approaches to the practical teaching of school students in the fundamentals of robotic system design, programming, and control. One promising approach is the use of Digital Twin technology, which makes it possible to create a virtual model of a mobile robot and investigate its behavior without the need for continuous use of a physical robotic platform. The application of a Digital Twin in the educational process enables school students to conduct virtual experiments, modify motion parameters and control algorithms, and analyze the obtained results in an interactive environment. At the same time, the quantitative assessment of the impact of this approach on learning effectiveness, practical task completion time, the number of errors, and the level of learning material acquisition remains an important scientific and applied task. Therefore, the analysis of the effectiveness of using a mobile robot Digital Twin for teaching school students the fundamentals of robotics is a relevant research direction aimed at improving the quality of practice-oriented STEM education and developing students' competencies in modern digital and robotic technologies..

II. DEVELOPMENT OF THE MOBILE ROBOT DIGITAL TWIN STRUCTURE FOR TEACHING SCHOOL STUDENTS THE FUNDAMENTALS OF ROBOTICS

A mobile robot Digital Twin can be defined as a software-based virtual model of a real robotic platform that reproduces its structural parameters, kinematics, actuator and sensor operation, control algorithms, and robot behavior within a simulated working environment. The use of a Digital Twin in the educational process enables school

students to investigate the operating principles of mobile robots without the need for continuous interaction with a physical platform and without the risk of damaging its components. In the virtual environment, a student can specify the robot's motion speed and direction, generate a trajectory, modify control system parameters, simulate obstacle locations, and analyze data obtained from virtual sensors. An important feature of this approach is the possibility of repeatedly performing the same educational experiment while modifying individual parameters, which makes it possible to establish cause-and-effect relationships between control actions and the behavior of the robotic system. The learning process is proposed to be organized as a sequence of practical tasks with gradually increasing complexity, starting with straight-line motion control and progressing to autonomous traversal of a specified trajectory and obstacle avoidance. For each task, the Digital Twin provides automatic recording of the educational experiment parameters, task performance results, and errors made by the student. The effectiveness of using the Digital Twin can be evaluated by comparing the initial and final levels of learning material acquisition, as well as the results of practical task performance. Quantitative analysis can be based on task completion time, the number of incorrect control actions, trajectory-following accuracy, the number of successfully completed tasks, and changes in test results. To assess mobile robot control accuracy, the deviation of the actual Digital Twin trajectory from the specified trajectory can be determined, thereby providing a quantitative characterization of the practical control skills acquired by the student. Comparing the results of several consecutive educational experiments makes it possible to investigate the dynamics of reducing the number of errors and task completion time while simultaneously improving the control accuracy of the robotic platform. Based on the obtained indicators, an integrated learning effectiveness indicator can be formed to characterize the overall changes in the student's theoretical knowledge and practical skills after working with the Digital Twin. This approach makes it possible to move from a qualitative description of the advantages of Digital Twin technology to a quantitative analysis of its effectiveness in teaching the fundamentals of robotics and provides a basis for further comparison of virtual experiment results with students' performance using a real mobile robotic platform..

Structure of Using a Mobile Robot Digital Twin for Teaching School Students the Fundamentals of Robotics представлена на рисунку 1.

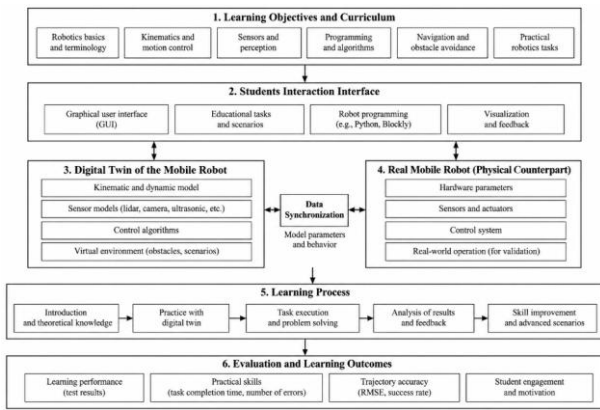


Figure 1 – Structure of Using a Mobile Robot Digital Twin for Teaching School Students the Fundamentals of Robotics

The structure presented in Figure 1 reflects the sequential organization of using a mobile robot Digital Twin in the process of teaching school students the fundamentals of robotics and integrates educational, virtual, and physical components within a unified learning environment. The Learning Objectives and Curriculum block defines the content and objectives of the learning process and covers the study of fundamental concepts of robotics, kinematics and motion control, sensor operating principles, programming and algorithms, navigation, obstacle avoidance, and the performance of practical robotics tasks. The Students Interaction Interface block serves as the primary means of interaction between the student and the system and provides access to the graphical user interface, learning tasks and scenarios, robot programming tools, as well as result visualization and feedback generation. The central technological element of the structure is the Digital Twin of the Mobile Robot, which represents a virtual model of the mobile robotic platform and includes its kinematic and dynamic models, sensor models, control algorithms, and a virtual working environment with obstacles and predefined scenarios. Its main purpose is to ensure the safe and repeated performance of educational experiments, during which the student can modify robot parameters, control algorithms, and environmental conditions and observe the results of these changes. The Real Mobile Robot (Physical Counterpart) block represents the physical robotic platform with its hardware parameters, sensors, actuators, and control system and is used to verify the results previously obtained in the virtual environment. The interconnection between the Digital Twin and the real mobile robot is provided by the Data Synchronization block, whose purpose is to coordinate the model parameters and behavior of the virtual and physical objects, thereby bringing the educational experiment closer to the real operating conditions of the robotic system. The Learning Process block defines the direct sequence of the student's learning activities, which includes acquiring initial theoretical knowledge, practical work with the Digital Twin, performing assigned tasks and solving problem situations, analyzing the obtained results, and using feedback to gradually improve practical skills. In this way, a closed-loop learning cycle is formed in which the results of previously completed tasks can be used to

adjust the student's subsequent actions and enable progression to more complex scenarios. The final element of the structure is Evaluation and Learning Outcomes, which is intended for the quantitative and qualitative assessment of the effectiveness of the proposed approach based on test results, acquired practical skills, task completion time, number of errors, trajectory-following accuracy, and the success rate of learning scenario completion. In addition, this block enables the assessment of students' engagement and motivation, which, together with indicators of theoretical and practical training, makes it possible to comprehensively analyze the effectiveness of using a mobile robot Digital Twin for teaching the fundamentals of robotics..

Under the current conditions in Ukraine, Digital Twin technology has significant prospects for education, as it enables part of the practical training in robotics, automation, and STEM disciplines to be transferred to a safe virtual environment while supporting face-to-face, blended, and distance learning formats. This approach is particularly important under wartime risks and unequal access to educational facilities and technical resources, as digital transformation is considered by the Ministry of Education and Science of Ukraine as one of the means of ensuring the resilience and accessibility of the educational process. The use of mobile robot Digital Twins can provide school students with the opportunity to repeatedly conduct virtual experiments, investigate the operation of sensors and actuators, develop control algorithms, and verify them before transferring them to a real robotic platform. The prospects of this direction are further strengthened by the development of STEM education in Ukraine: in 2026, UAH 700 million in state subvention funding was allocated for modern equipment for classrooms and STEM laboratories, while the piloting of updated educational programs already covers technological education and STEM courses. In the future, Digital Twins can become an integral component of a unified learning environment in which virtual modeling is combined with real robots, artificial intelligence technologies, computer vision, and automated tools for assessing learning outcomes. This will enable a gradual transition from conventional laboratory exercises to project-based learning, in which school students can develop, test, and improve their own control algorithms for complex cyber-physical systems. In the long term, the implementation of Digital Twins in Ukrainian school education can contribute to the development of practical competencies in robotics, programming, modeling, and automation required for the future training of specialists for the digital economy and the technological recovery of the country.

IV. CONCLUSION

As a result of the conducted research, a structure for using a mobile robot Digital Twin to teach school students the fundamentals of robotics was proposed, integrating learning objectives, a student interaction interface, a virtual model, a real robotic platform, data synchronization, and learning outcome assessment tools within a unified educational environment. The proposed approach enables the safe and repeated performance of practical experiments

with a gradual increase in task complexity, while its effectiveness can be evaluated based on changes in theoretical knowledge, task completion time, the number of errors, control accuracy, and the success rate of learning scenario completion. The use of a Digital Twin creates conditions for transitioning from the traditional study of robotics fundamentals to interactive, practice-oriented learning, with the possibility of subsequently validating the algorithms developed by students on a real mobile robot. Further development of the proposed approach should focus on integrating the Digital Twin with artificial intelligence, computer vision, and automated assessment technologies, thereby contributing to the development of students' practical competencies in robotics, programming, modeling, and automation..

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