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Prototyping and Integration of Educational Low-Cost Mobile Robot Platform

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Abstract: This paper describes the process of designing and prototyping a low-cost robotic platform based on existing equipment and projects that enable extracurricular STEM activities in Croatia and beyond. A robotic platform with a differential drive configuration was chosen for education from an early age due to its simplicity and a wide range of cheap and compatible components from which it can be made. From the aspect of integration into extracurricular or curricular activities, the BBC micro:bit ecosystem was considered, enabling block-based visual programming. Components with printable parts make up the assembly of the educational robot. The main steps in designing and creating a robot prototype are presented, which consist of the modelling, 3D printing of robot parts, and assembly into a functional system. After several stages of testing, an interactive workshop was held with 7th-grade primary school pupils. Further work is planned to create educational material for extracurricular STEM workshops.

Keywords: 3D printing; BBC micro:bit; differential drive; Scratch; STEM education

1 INTRODUCTION

Education in the STEM field is quite diverse, which is made possible by the availability of a variety of components, technologies, and ultimately curricula that include practical work. 3D printers are very popular and are found in a wide range of applications, which is possible by creating a wide range of parts that can be further used in assemblies. The title of the paper [1] asks the question: What to build next, given in mind that the era of affordable 3D printing is underway. An interesting area is robotics which can be integrated into different levels of education with different outcomes. In paper [2], a study on learning and the problem-solving process among junior high school pupils through participation in robotics projects using Lego Mindstorm is presented.

The use of robotics education in Croatia in primary school is carried out mainly through extracurricular activities. The IRIM Association has launched various programs through the Croatian Makers League and other projects [3], which have further popularized the STEM area. One of the projects involved equipping libraries with BBC micro:bit sets of educational boards and 3D printers. This allows the integration of 3D printing with the BBC micro:bit unit, which is especially interesting from the aspect of robotics. In addition to the existing infrastructure, it is possible to further expand it with smaller investments, given that a low-cost system is being considered. Compared to existing robots available on the market such as mBot, keeping in mind a set of robots, for the same price range, it is possible to purchase a 3D printer and create your own robotic platforms. BBC micro:bit boards are versatile and can be used for various purposes such as mobile robots or robotic arms. Paper [4] presents a study that explores pupils' experience when designing programmed technological solutions using a BBC micro:bit board and identifies the technological knowledge in order to successfully solve a real-world task. Furthermore, in [5] study investigates ways of experiencing the process of solving a real-world task with programming material for pupils aged 10 and 14.

Differential drive robot configuration is very interesting from the aspect of education at primary school levels. The principle of operation is intuitive because the movement depends on the angular velocities of the drive motors. An example of a task can be to define the functions that allow for different movements, such as forward, backwards or turning in place. The Croatian Makers League used mBot robots, and the effectiveness of their usage to increase the basic knowledge in programming and robotics for pupils of age 13 is shown in [6]. Such robots can be made as low-cost platforms and can be integrated with existing BBC micro:bit sets. In addition, this type of robot is used at higher levels of education such as fuzzy control of a mobile robot in case of obstacle avoidance [7], using the Arduino eco-system. Arduino-based control is widespread and is particularly interesting in the field of education given its versatility [8], low component cost, and compatibility with various software packages such as MATLAB [9]. As mentioned, interesting platforms are also robotic arms, which in low-cost versions mainly consist of drive components in the form of servo motors [10].

Educational robots can usually be purchased in kits that need to be assembled, or they can be designed and developed mainly by rapid prototyping technologies, including 3D printing. The process of 3D printing (additive manufacturing) is preceded by the process of designing parts. Various tools can be used for 3D modelling, depending on the level of education, from primary school level to engineering education, some of which are presented in [11]. 3D tools used in teaching and extracurricular activities in the field of STEM education are mostly free. Preparation for manufacturing is carried out in so-called slicers and further production is realized by open-source printers [12]. The paper [13] presents a study on approaches to design and 3D printing in teacher education.

In this paper, potentials in the field of STEM education based on the existing infrastructure in Croatia are discussed. The concept of the educational platform has the following goals: do it yourself, take off the shelve components, low cost, and easy to repair and maintain. The components, their possibilities within such a system, and their advantages in the wider integration of education in the field of robotics are presented. In the robot design phase, it is necessary to construct the parts of the system that, together with the components, form a functional system. For constructed parts, the process of prototyping parts with fused deposition modelling (FDM) technology is presented. Then, the parts and components of the educational mobile robot with differential drive were assembled. A workshop was conducted with pupils up to 7th grade, using a presented platform. Through the workshop, the basic movements of robots were tested, and pupils were introduced to the principles of operation. Also, the reactions of pupils gave the impression that, as expected, there is an increased interest in the STEM area.

2 EDUCATIONAL ROBOTICS IN CROATIA – CURRENT STATE AND POTENTIALS

The education process in the Republic of Croatia consists of an eight-year elementary school level, then secondary school level whose length varies by qualifications, and higher education which is divided into university level and professional studies. Regarding engineering education in the field of mechatronics and robotics, there are a large number of institutions in Croatia that provide such education, such as universities with related technical faculties and universities of applied sciences. At such institutions, some studies consist of theoretical and practical knowledge in the field of robotics through a series of courses, many of which are interdisciplinary. This includes knowledge of mechanical engineering, electrical engineering, computer science, and other branches. It should be noted that engineering education has been established in Croatia. Robotics has been studied more intensively in secondary school level education since the early 2000s, when a new profession, mechatronics technicians were introduced. In gymnasium programs, programming is more common and can be applied to robots. As for extracurricular activities, they are provided through centres for technical culture and various workshops. Commonly, robots are available as kits or didactic sets, which have become more and more advanced and diverse over the years. The emergence of robotics at the elementary school level has so far been mainly carried out through extracurricular activities. There were various workshops, summer schools, and leagues such as the "Liga kumpanija" which took place from the beginning of 2010 and the most widespread Croatian Makers League, which continues today.

In general, as far as STEM in Croatia is concerned, it can be freely said that the IRIM Association launched the STEM revolution in Croatia, but also in the surrounding countries. Various projects made extracurricular activities for various levels of education and lifelong learning possible. The Junior Engineer Academy project distributed equipment such as 3D printers and electronics kits and organized mentor training in the involved secondary schools. The goal is to enable the development of project ideas and to establish and maintain close contacts with companies and universities that provide students with an early insight into the world of engineers and qualified professionals in various fields of technology and science. In addition to secondary schools, the libraries involved in projects "Digital libraries for local development - DL4LD" and "STEM Revolution continues - Libraries" were equipped with 3D printers, and training for librarians was also organized. This project was preceded by the crowdfunding campaign "STEM revolution", which enabled the financing of the mass introduction of BBC micro:bit technology in Croatian schools, libraries, associations, and other institutions that work with children. From the aspect of robotics, since 2014, IRIM has launched the Croatian Makers League as the most massive extracurricular activity in elementary schools in the field of robotics and programming.

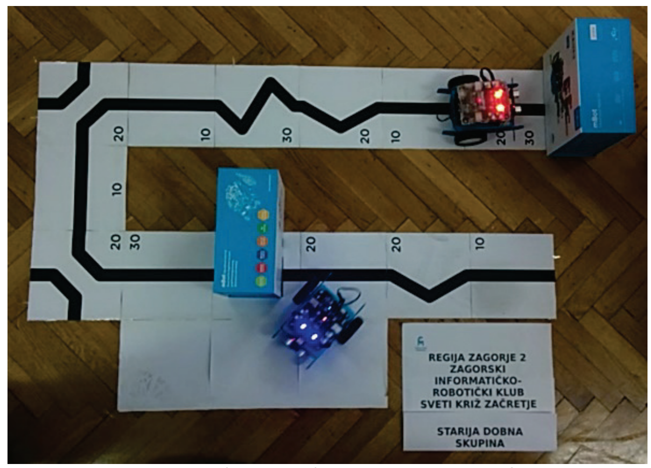

Figure 1 Demonstration of robots performing a task within the Croatian Makers League

The Croatian Makers League is part of the Croatian Makers project, the main goal of which is to enable the broad inclusion of robotics, automation, and programming in education at elementary school age. It is the largest competition of its kind in the EU with more than 12 000 children included per school year in more than 600 schools. The IRIM association donated more than 3000 robots, therefore Croatian Makers League represents IRIM's flagship project in robotics. The competition is divided into two categories: 1st-5th and 6th-8th grade of elementary school and takes place approximately four times a year. Institutions can be involved in the project by purchasing their equipment or by applying for a donation tender. The league was using the mBot platform until 2021 when they switched to another platform based on BBC micro:bit which offers an even easier entry into the world of robotics but also allows for more advanced usage. Fig. 1 shows the task to be performed by two mBot robots within the Croatian Makers League for the 2016/2017 school year. A common mission consists of a line-tracking task which is a typical problem that needs to be solved at that level of education.

From the aspect of understanding the principle of operation of the differential drive and understanding the operation of individual sensors, it is common to program robots to perform missions, such as those involved in education through the Croatian Makers League. Basic mission tasks are line tracking and obstacle avoidance. At the level of elementary school, in the first phase of education, the basic functions required for the movement of robots are defined, namely forward, backward, turn right and turn left. After the initial phase of education which includes testing the robot's differential drive, various types of sensors are implemented in the system. For the basic functions of the robot required for education at the elementary school level, infrared line-tracking sensors and an ultrasonic distance sensor were considered. Such sensors come in low-cost variants and are used in many educational kits. In the preliminary design phase of a low-cost system, drive and sensor components and their compatibility with control ecosystems were considered. Fig. 2 shows the testing of components that include line tracking sensors and distance sensors.

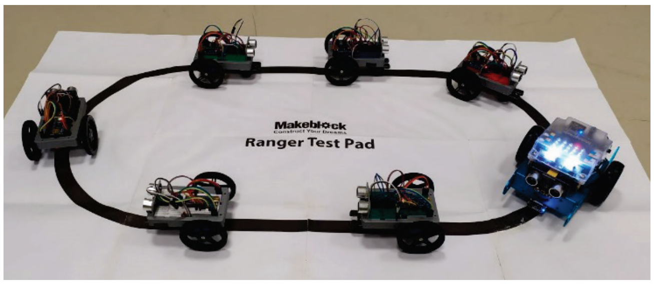

Figure 2 Preliminary testing of the low-cost platform considered components

3 LOW-COST MOBILE ROBOT PLATFORM

The mobile robot with a differential drive configuration is applied in a wide range of missions, which is especially interesting from the aspect of preparing pupils in the STEM field for future technicians, engineers, and scientists. The differential drive configuration of an unmanned ground vehicle (UGV) consists of two actuators (electric motor drives). Such a mobile robot has a simple principle of operation, therefore it can be applied from the earliest age to teach technical skills.

3.1 The Principle of Operation of the Differential Drive

Differential drive allows rotation in place (without translation), and the angle of rotation of the robot (heading angle) is determined by the differences in rotational speeds of the left and right wheels. This type of robot exists in two-dimensional space and has three degrees of freedom (DOF). The operating principle is defined with respect to the assumed two Cartesian coordinate systems (Fig. 3), the base coordinate system ($\mathcal{F}^{\mathrm{E}}$) and the mobile robot coordinate system ($\mathcal{F}^{\mathrm{B}}$). This type of drive configuration represents a non-holonomic mobile robot [15], given that the number of control variables is smaller than the number of robot DOFs, which are represented by the position (x, y) and orientation (ψ) of the robot. The translational v and rotational ω velocities of the robot are defined in $\mathcal{F}^{\mathrm{B}}$ and represent the motion of the robot in 2D space.

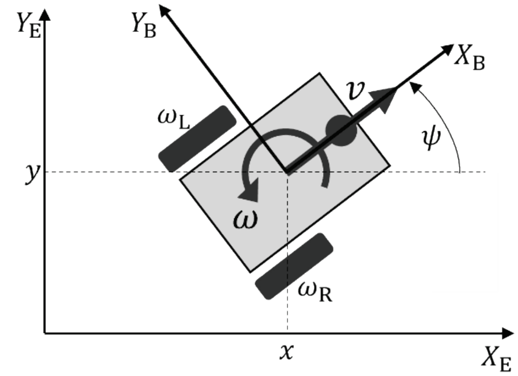

Figure 3 Schematic representation of a robot with a differential drive configuration

From the aspect of engineering education, robot kinematics is defined, where the robot speeds with respect to the base coordinate system are defined by the following expressions

$$\dot{x} = v\ \cos\psi,\ \ \dot{y} = v\ \sin\psi,\ \ \dot{\psi} = \omega. \tag{1}$$

The translational and rotational speeds of the robot depend on the angular velocities of the left and right wheels, i.e., the drive motor velocity $\boldsymbol{\Omega} = [\omega_{\mathrm{L}} \quad \omega_{\mathrm{R}}]^{\mathrm{T}}$, and the configuration parameters defined by the wheel diameter d and the distance between the drive wheels l. The robot velocity vector $\boldsymbol{v}^{\mathrm{B}} = [v \quad \omega]^{\mathrm{T}}$ is defined by the robot drive allocation matrix $\boldsymbol{\Gamma}_{\mathrm{R}}$ which maps the angular velocities of the motor to the robot velocity vector.

$$\boldsymbol{v}^{\mathrm{B}} = \boldsymbol{\Gamma}_{\mathrm{R}}\boldsymbol{\Omega} = \begin{bmatrix} \frac{d}{4} & \frac{d}{4} \\ -\frac{d}{2l} & \frac{d}{2l} \end{bmatrix} \begin{bmatrix} \omega_{\mathrm{L}} \\ \omega_{\mathrm{R}} \end{bmatrix} \tag{2}$$

The above Eq. (2) is a problem of direct kinematics which determines the translational and rotational speeds of robots based on the angular velocities of the wheels that represent the input variables of the model. The characteristic of a differential drive is that it has a smaller number of actuators than the number of DOFs, so a robot with this type of drive is a non-holonomic robot. The problem of inverse kinematics is the determination of the angular velocities of the left and right wheels based on the desired state of the robot, or the desired translational and rotational speed of the robot. From the aspect of motor control, there are different types of electric motor drives. Servo motors with continuous rotation were considered for the low-cost prototype.

3.2 System Components

From the aspect of education, the basic component of the educational robot is the control unit that is in charge of the system functioning. Practically speaking, it receives data from the sensor, interprets it and, based on the program, sends commands to the drive module. Since part of the infrastructure in Croatia has been secured through IRIM projects, and considering that since 2021 the most massive robot competition has been used by robots based on BBC micro:bit boards, it is logical to consider this board as a key robot component. The great advantage of the BBC micro:bit board is the versatility from the aspect of programming where it can be used from elementary school levels to engineering education. It can be programmed in a block-based visual programming language (Scratch) and using Python or JavaScript programming language. One of the advantages is that it is cheap, it is very widespread, and there is a very large community. Furthermore, no software is required, it can be programmed in a browser. Besides, no large computing resources are required, just a PC or tablet with an installed compatible browser. On the hardware side, there are a lot of input/output pins, also, there are numerous additions and compatibility with other components. Fig. 4 shows a BBC micro:bit board with marked parts.

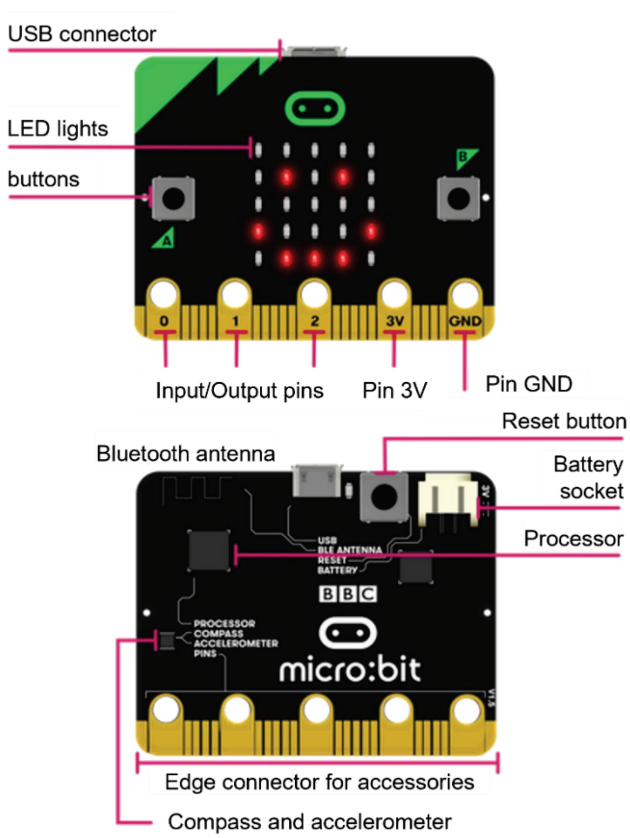

Figure 4 BBC micro:bit control unit

The success of the integration of BBC micro:bit boards as a robotic system has been presented to several commercial robots used primarily in education. An example of such a robot is cyber:bot [15]. If there is a need to involve a large number of pupils, for this price it is possible to provide a device for 3D printing and the necessary components for making robots, including BBC micro:bit boards. With a little time and imagination, robots can be made relatively easily. The advantages of such an approach are multiple. Through different phases, pupils get acquainted with electronics, 3D modelling, and 3D printing. In addition to being easy and cheap to build and repair, it is also easy to do system upgrades with new options. Such robots can also be combined with other control components like an Arduino board. The choice of components depends primarily on the level at which it is intended to be programmed, i.e., the programming language.

Two servo motors were used to drive the mobile robot. The advantage of this type of motor is compactness since the servo motor consists of a gearbox and feedback electronics. Such motors are controlled by a PWM signal, which is interesting because this signal modulation is used in a broader sense of robotics, from UGV robots to unmanned aerial vehicles (UAVs). Also, servo motors are often used in educational robotic arms. The servo motors with a price range of up to 10 $ were used in the different phases of system testing and they are shown in Tab. 1.

Table 1 Considered low-cost servo motors

Continuous servo	Size (mm)	Weight (grams)	Operating voltage (V)	RPM @ 6V
FEETECH FS90R	22,5×12,1×23,4	9	3-6	130
FEETECH FT90MR	23,2×12×25,5	12,5	3-6	100
FEETECH FS5103R	40,8×20,1×38	36	4,8-6	62

A basic sensor package was tested that includes IR sensors used in tasks involving line tracking and an ultrasonic distance sensor for obstacle avoidance tasks. The sensor package can be further expanded. The power supply of the mobile robot depends on the selected control, drive, and sensor components. These components do not necessarily operate at the same voltage levels. Different voltage levels can be achieved with buck/boost converters or with multiple batteries with required voltage levels. Fig. 5 shows the wiring diagram of a possible mobile robot, which was later tested.

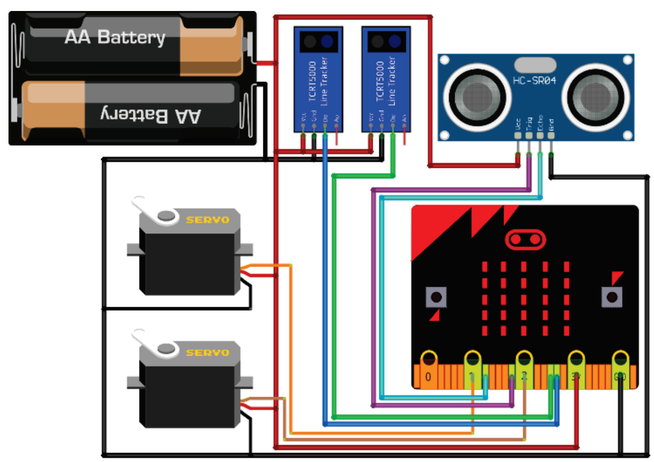

Figure 5 Schematic representation of the mobile robot electronic components connection

4 ROBOT PROTOTYPING AND INTEGRATION

4.1 Prototyping Procedure

The process of prototyping parts consists of the design and production phases, as shown in [16]. Although the same procedure is used at different levels of education, there are differences in approach, tools and learning outcomes. Additive manufacturing technologies enable an ever-widening range of research and applications in education, as shown in the case of designing a modular educational multirotor UAV that can be used in engineering education [17]. The process of prototyping a low-cost educational mobile robot that can be used at different levels of education, primarily at the primary school, but also at the secondary school level, is considered and presented. The Prusa i3 MK3S 3D printer, which enables FDM printing, was used for parts manufacturing.

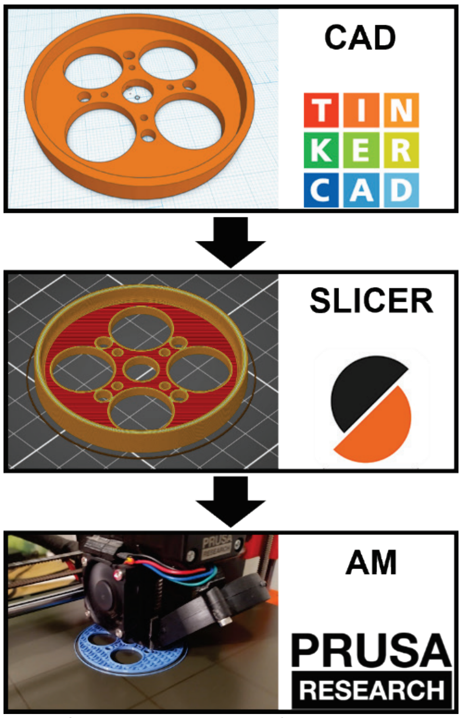

Figure 6 Schematic representation of the prototyping process

From idea to realization, it is necessary to take several steps that include 3D modelling, preparation of models for printing in the so-called slicer software, and part printing, as shown in Fig. 6. TinkerCAD software package for parts 3D modelling and assemblies was considered. Since the Prusa 3D printer was used to make the parts, the parts were prepared in the compatible Prusa Slicer software. Different print parameters can be set in the slicer, depending on the requirements of a particular part. Fig. 7 shows the robot wheel with different print parameters. The advantage of the FDM process is the low cost of materials compared to other technologies. Furthermore, in addition to the considered 3D printer, there are many different printer kits on the market, so the implementation of education can be even less expensive.

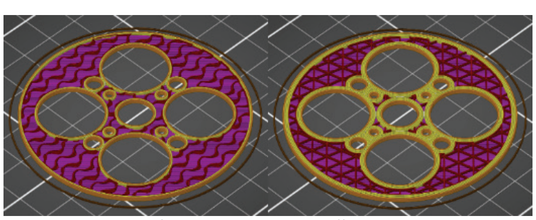

Figure 7 A slice of a wheel model with different print parameters

4.2 Experimental Testing and Integration of Robot Platform

After obtaining all the necessary components and making the final versions of the robot parts, the assembly of the robot can be started. The line tracking task at the primary school level of education can be achieved using several approaches, but in essence, it comes down to reading the left and right IR sensors which can have two output states, logic unit (white) or logic zero (black). By combining these two inputs, the movement of the robot is controlled. The basic set of robot movements consists of forward, backward, left turn, and right turn functions. Fig. 8 shows one of the possible implementations of the line tracking program.

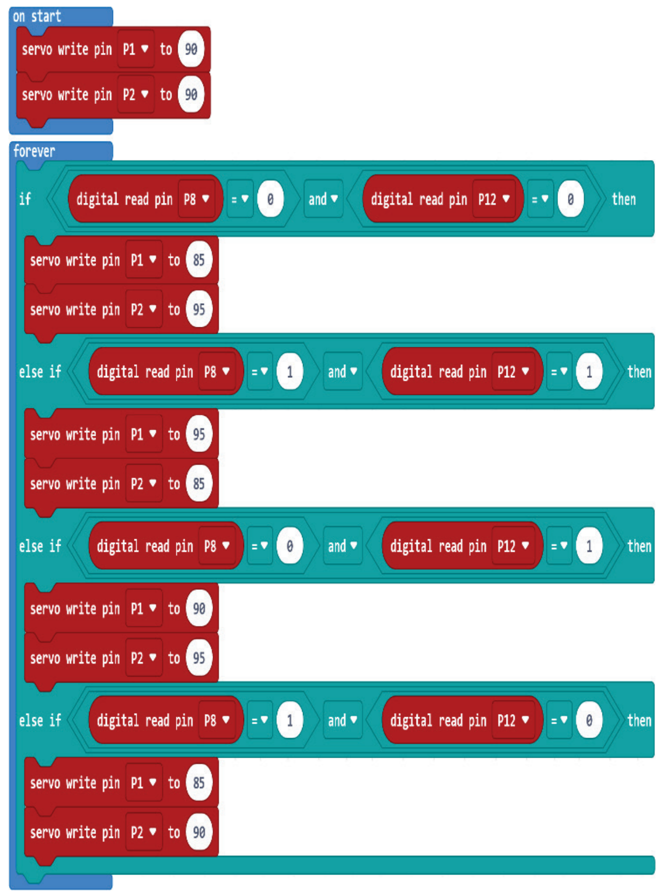

Figure 8 Scratch line tracking program

Figure 9 Experimental testing during a workshop

After successfully testing the robotic platform, a workshop was held as part of extracurricular activities at Mače Elementary School in collaboration with the Trivium STEM Edu association (Fig. 9). The participants of the workshop were 7th-grade pupils. Through the workshop, pupils were shown various tasks that can be implemented on the proposed low-cost platform. The integration of Bluetooth wireless control with another BBC micro:bit or with a phone was also tested.

5 CONCLUSION

In this paper procedure of educational low-cost robot platform design is presented. A mobile robot with a differential drive configuration was described in order to show the working principle and to define system components. In addition to the low cost of such a robot, it is important to emphasize several advantages of this design approach. Such a system can be used at different levels of education because it is easily upgradeable. Low-cost components can be used, but also more professional components can significantly expand the range of education. Furthermore, the considered drive components are also applied in a wide range, from mobile robots, and robotic arms to unmanned aerial vehicles. By conducting a series of experiments and workshops, it has been shown that such a system can be easily integrated into existing institutions and schools that have a 3D printer or plan to purchase it.

6 REFERENCES

[1] Eisenberg, M. (2013). 3D printing for children: What to build next, regarding the 3D printing?. *International Journal of Child-Computer Interaction, 1*(1), 7-13. https://doi.org/10.1016/j.ijcci.2012.08.004

[2] Barak, M. & Zadok, Y. (2009). Robotics projects and learning concepts in science, technology and problem solving. *International Journal of Technology and Design Education, 19,* 289-307. https://doi.org/10.1007/s10798-007-9043-3

[3] See https://croatianmakers.hr/hr/naslovnica/

[4] Cederqvist, AM. (2022). An exploratory study of technological knowledge when pupils are designing a programmed technological solution using BBC Micro:bit. *International Journal of Technology and Design Education, 32*, 355-381. https://doi.org/10.1007/s10798-020-09618-6

[5] Cederqvist, AM. (2021). Designing and coding with BBC micro:bit to solve a real-world task – a challenging movement between contexts. *Education and Information Technologies*. https://doi.org/10.1007/s10639-021-10865-w

[6] Lee, B. Y., Liew, L. H., Khan, M. Y. B. M. A., & Narawi, A. (2020). The Effectiveness of Using mBot to Increase the Interest and Basic Knowledge in Programming and Robotic among Children of Age 13. *Proceedings of the 2020 The 6th International Conference on E-Business and Applications*, 105-110. https://doi.org/10.1145/3387263.3387275

[7] Piljek, P. & Kotarski, D. (2020). Neizrazito upravljanje mobilnim robotom za slučaj izbjegavanja prepreka. *7th International Conference "Vallis Aurea", Focus on: Research & Innovation*, 509-518.

[8] Oltean, S. E. (2019). Mobile Robot Platform with Arduino Uno and Raspberry Pi for Autonomous Navigation. *Procedia Manufacturing, 32*, 572-577. https://doi.org/10.1016/j.promfg.2019.02.254

[9] Tejado, I., Serrano, J., Pérez, E., Torres, D., & Vinagre, B. M. (2016). Low-cost Hardware-in-the-loop Testbed of a Mobile Robot to Support Learning in Automatic Control and Robotics. *IFAC-PapersOnLine, 49*(6), 242-247. https://doi.org/10.1016/j.ifacol.2016.07.184

[10] Bhargava, A. & Kumar, A. (2017). Arduino controlled robotic arm. *International conference of Electronics, Communication and Aerospace Technology (ICECA)*, 376-380, https://doi.org/10.1109/ICECA.2017.8212837

[11] Nemec, R. (2017). Using and Citation of 3D Modeling Software for 3D Printers. *International Journal of Education and Information Technologies, 11*, 160-170.

[12] Kostakis, V., Niaros, V., & Giotitsas, C. (2015). Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece. *Telematics and Informatics, 32*(1), 118-128. https://doi.org/10.1016/j.tele.2014.05.001

[13] Verner, I. & Merksamer, A. (2015). Digital design and 3D printing in technology teacher education. *Procedia CIRP, 36*, 182-186. https://doi.org/10.1016/j.procir.2015.08.041

[14] See https://stemfinity.com/collections/micro-bit/products/cyber-bot-robot-kit-with-micro-bit

[15] Hassan Zarabadipour, H. & Yaghoubi, Z. (2019). Control of a non-holonomic mobile robot system with parametric uncertainty. *Technical Journal, 13*(1), 43-50. https://doi.org/10.31803/tg-20190116100550

[16] Piljek, P., Krznar, N., Krznar, M., & Kotarski, D. (2022). Framework for Design and Additive Manufacturing of Specialised Multirotor UAV Parts. In Răzvan Păcurar (Ed.), Trends and Opportunities of Rapid Prototyping Technologies [Working Title]. IntechOpen. https://doi.org/10.5772/intechopen.102781

[17] Kotarski, D., Piljek, P., Pranjic, M., Grlj, C. G., & Kasac, J. (2021). A Modular Multirotor Unmanned Aerial Vehicle Design Approach for Development of an Engineering Education Platform, *Sensors, 21*(8). https://doi.org/10.3390/s21082737

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