

# Design and Development of Educational Modular Mobile Robot Platform

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**Abstract:** This paper presents the design and experimental validation of a modular educational robot platform. The development of a novel modular unmanned ground vehicle (UGV) platform is based on open-source system architecture featuring carefully considered modules and is specifically tailored for application in STEM education. The proposed platform is comprehensive in terms of motion planning and modelling. Mathematical description of the non-holonomic and holonomic configuration of the robot is given, and a derived model is implemented in a software package in order to perform simulations and experiments. The design process resulted in a 3D printed novel brick-based robot chassis, offering advantages such as low manufacturing costs, easy repair and maintenance, and seamless expandability with additional modules. The proposed modular platform underwent validation across three robot configurations and three different control ecosystems.

**Keywords:** 3D printing; modular robot platform; STEM education; unmanned ground vehicle

## 1 INTRODUCTION

Nowadays, the field of robotics represents a very important, we could even say crucial, segment of industrial development and society as a whole. It can be said that robotics is a multidisciplinary field that includes various disciplines including mechanical engineering, electrical and electronic engineering, and computer science (software engineering). There is a need and great potential for integrating robotics into the education system through classes and extracurricular activities for primary and secondary school pupils with the goal of training technical experts. Robots are already used to some extent in introducing Science, Technology, Engineering, and Mathematics (STEM), as motivating and interesting tools for teaching engineering concepts and developing algorithmic thinking. Through practical exercises, laboratory classes and experiments, and work on projects, pupils and students develop creativity, critical thinking, teamwork, and other valuable skills. With the aim of the wider integration and increased accessibility, the goal of STEM education robotic platforms is to be open, cheap, and, among other things, multipurpose, like the modular robot presented in research [1].

By searching the literature with the keywords: modular educational robot, numerous works on this topic were found. In the vast majority of papers, mobile robots are discussed, which represent a unique challenge in STEM education, considering that they attract pupils and students in various disciplines. If we are talking about education, but also in general, from the aspect of control, numerous ecosystems are inherently modular, expandable, and most importantly open-source. The most widespread ecosystem is based on the Arduino open-source electronic prototyping platform, which is used in a wide range of education, from elementary school to engineering education. The paper [2] presents the design of an educational cheap mobile robot that is suitable as an educational tool in classrooms and laboratories and e-learning through Massive Open Online Courses (MOOC). Furthermore, [3] presents an open-source extensible robot platform whose control system is based on the widespread

Raspberry Pi single-board computer, and whose software infrastructure is based on the Robot Operating System (ROS). In the aforementioned research, an overview of frequently used robotic platforms in education is presented, from which it is evident that mobile robots with differential drive configurations are mostly used.

In earlier research, educational mobile robots were considered for use in research and engineering education, such as the low-cost robotic vehicle described in the [4]. Considering the high price and limited functionality of the platforms used in the former phase of STEM education, [5] presents a cheap and very affordable robotic platform consisting of commercial components to facilitate robotic projects and further development of robotics. Commercial chassis that make up the robot systems were used in the mentioned works. In contrast to such an approach, [6] presents the hardware part of an educational mobile robot platform that enables the development of interesting and special applications using various expansion modules. Furthermore, [7] shows the creation of a robot chassis controlled by a mobile application that serves as a tool for teaching coding. In the above works, the mobile robot is based on a differential drive configuration. In addition to this most commonly used drive configuration, [8] presents a prototype of a mobile robot that represents an omnidirectional configuration. A robot rapid prototyping approach is proposed to implement different architectures and modules for robotic systems integrating hardware and software. Although the keywords in the listed references include modularity, this can be said mainly from the aspect of the software, i.e., the control part of the robot system.

In the full sense of the word modular, i.e., both from the software and hardware aspects, robotic structures that can be integrated for research and mostly engineering education at the graduate level have been researched and presented. Paper [9] describes a low-cost modular multipurpose robot intended for engineering students for research and education in the field of mechatronics and robotics. Such a platform is suitable because it encourages creativity and imagination and ensures the practice of fundamental control laws. Furthermore, [10] presents the development and integration

of the moreBots modular robotic system in education, which can be used as a tool in learning through play. The modular robotic system intended for creative learning, presented in [11], is considered for different user groups in the form of integration into everyday teaching. The system consists of independent modules that are equipped with actuators and sensors, and by assembling those users get a wide range of robotic designs. In paper [12], a new design of an inexpensive mobile reconfigurable modular robot is presented, which is intended for rapid development and testing of algorithms. Among other rapid prototyping technologies, mostly Additive Manufacturing (AM) was used in the development of the aforementioned modular robots. AM technologies have contributed to greater momentum in the field of educational robotics, as a new approach to the development of various robotic platforms and low-cost modules, such as the proposed 3D printed modules in [13]. The paper [14] presents the iterative process of developing a robotic educational platform for the Internet of Things (IoT) applications using 3D printing.

This paper discusses an educational modular robotic platform that can be used in a wide range of education, from elementary, and secondary school to engineering education. The open-source architecture of the system based on modules with selected take-off-the-shelf and low-cost components is presented. Experimental measurement of the drive components was carried out to identify the parameters of the modular robot drive configurations. Then a mathematical model of the robot, the so-called Unmanned Ground Vehicle (UGV), was developed, suitable for implementation in a software package with the aim of performing simulations and experiments. The main focus of the work is on the design and development of a novel modular brick-based robot chassis that can be manufactured cheaply, can be easily repaired and maintained, and is highly expandable with other modules. Chassis parts are constructed in the design phase using a CAD software package and then manufactured using AM technologies in the prototyping phase. After assembly, in order to validate the proposed modular robot platform, three versions of the robot with three different control ecosystems were tested.

## 2 EDUCATIONAL MODULAR ROBOT SYSTEM ARCHITECTURE

Given that mobile ground robots or UGVs are used in a wide range of applications, it is important to prepare users of STEM education for future jobs and challenges in the field of mechatronics and robotics. The most common configuration of such a robot is the mentioned differential drive, which is also widespread in education. One of the frequently used commercial platforms is the mBot robot [15], suitable for increasing the basic knowledge in programming and robotics at the elementary school level. But there are also real needs for the implementation of other configurations, such as so-called omnidirectional robots, given that their applications are widespread in the industry, such as KUKA omniMove robots used to assemble trains [16]. A fundamental requirement in the robot design phase is an open-source

system architecture based on low-cost and take-off-the-shelf components that make up individual robot modules. The robot can be divided into a control module, a drive module, an energy module, a sensor module, and additional equipment that integrates with other robot modules. The chassis of the robot connects the components, where the main goal is to enable the easy and quick connection of modules into the functional assembly of the modular robot.

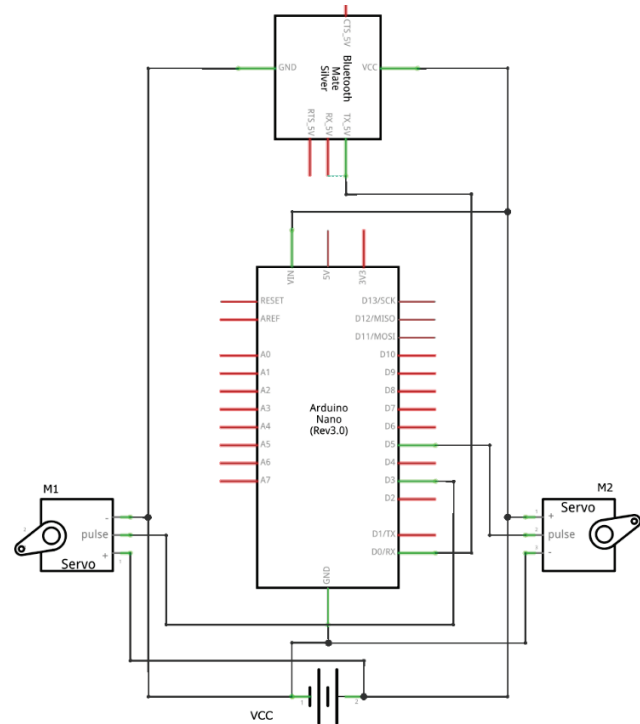


Figure 1 Diagram of differential configuration with remote control

The main component of the control module is the control unit, which essentially interprets the data from the sensors and, based on the control algorithm executed on it, sends control signals to the actuators of the drive module. This completes the basic control cycle sense-plan-act. Numerous open-source ecosystems are used in STEM education, and in this paper, in the testing phase of the modular platform, three types of control units that are suitable for integration into different levels of education are used, starting with BBC micro:bit, Arduino, and Pixhawk control unit, furthermore, ESP32 is considered for future application. Regardless, the control module encompasses remote control components, which communication methods rely on Bluetooth, radio control (across various frequencies), WiFi modules. More advanced control modules are further equipped with a telemetry link. There are also so-called shields that enable simple connection of different elements of the control module, sensor and drive components, and power supply with integrated different voltage levels. The sensor module should be compatible with the control module and power supply. Simpler versions of the sensor module, which are used mainly at the elementary school level of education, consist of distance sensors and IR sensors for line following. More advanced sensor modules suitable for use at a higher

level of education can consist of vision systems that enable Simultaneous Localization And Mapping (SLAM). The system diagram of the robot differential configuration, whose control module consists of an Arduino Nano board and a Bluetooth HC05 for remote control of the robot is shown in Fig. 1.

The locomotion mechanism affects the path planning, and the choice of mechanism often depends on the type of terrain for which the robot is intended. For the robot differential configuration, these are usually wheels or tracks for specific tasks. In this paper, the main focus is on the design of the modular chassis of the drive module, which, in addition to the standard differential configuration, enables the integration of an omnidirectional drive. The main component is the actuator, which has the task of converting the input electrical energy coming from the energy module (power supply) into mechanical outputs, i.e., angular velocity. In the proposed design, continuous servo motors were considered as they are available at a relatively low price and have a wide range of performances. Furthermore, they come in a very compact form, containing an electric motor, driver, and gearbox. Also, this type of actuator is used in other types of robots, such as educational robotic arms or Unmanned Aerial Vehicles (UAVs). The energy module essentially consists of batteries and additional elements for the distribution of electricity. For measurement purposes and in the validation phase of the proposed robot, two types of batteries are used, Nickel Metal Hydride (NiMH) and Lithium Polymer (LiPo) batteries. In order to identify the parameters of drive configurations, experimental measurements of the considered servo motors were carried out, the basic characteristics of which are shown in Tab. 1. Measurement results in the form of the characteristics of the Revolutions Per Minute (RPM) in relation to the Pulse Width Modulation (PWM) are shown in Fig. 2.

Table 1 Considered continuous servo motors

Continuous servo	Size (mm)	Weight (grams)	Operating voltage (V)
S1 HITEC HSR-1425CR	40.6 × 19.8 × 36.6	41.7	4.8 – 6.0
S2 FEETECH FS5103R	40.8 × 20.1 × 38.0	36.0	4.8 – 6.0
S3 PARALLAX High Speed	40.6 × 19.0 × 41.0	42.0	6.0 – 8.4
S4 PARALLAX Feedback 360	40.0 × 20.0 × 37.2	40.0	5.0 – 8.4

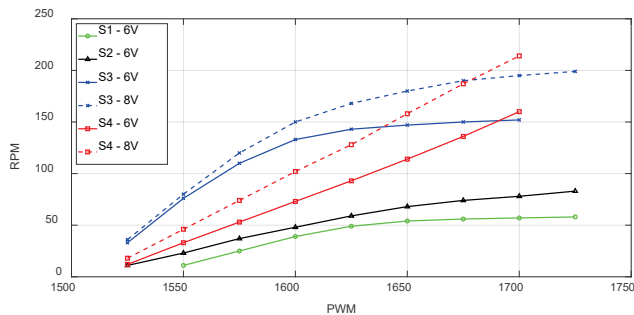


Figure 2 Characteristics of the four considered servo motors - revolutions per minute as a function of the input PWM signal

### 3 MATHEMATICAL DESCRIPTION OF THE UGV ROBOT

The modular UGV robot can be applied in a wide range of education, which is important from the aspect of preparing pupils, but also students for future technicians, engineers, and researchers. This type of robot exists in two-dimensional space and has three Degrees Of Freedom (DOF), position ( $x$ ,  $y$ ), and orientation ( $\psi$ ) since the assumption is that it moves on a flat surface. For the purpose of mathematical representation, it is necessary to define two Cartesian reference coordinate systems. The base coordinate system (Earth frame)  $\mathcal{F}^E$ ,  $\{O_E, X_E, Y_E\}$ , is attached to a stationary point on the Earth's surface where the position and orientation of the UGV robot are defined. Next, it is necessary to define the coordinate system of the robot, the so-called body frame  $\mathcal{F}^B$ ,  $\{O_B, X_B, Y_B\}$ , which is attached to the robot chassis.

#### 3.1 Kinematics of the Differential Drive Configuration

A mobile robot with a differential drive configuration due to the simple principle of operation is applied in a wide range of STEM education from the earliest age. Such a configuration most often consists of two actuators (electrical drives) whose arrangement enables rotation in place without changing position. The rotation of the robot, i.e., the heading angle, is determined by the differences in the angular velocities of the left and right actuators, on which, e.g., a wheel or a caterpillar drive element is mounted. A robot with a differential configuration belongs to non-holonomic robots [17] that do not have independent control of each of the variables (DOF), therefore, they perform complex manoeuvres to reach the desired state. Differential configuration robot parameters and variables, alongside reference coordinate systems, are shown in Fig. 3.

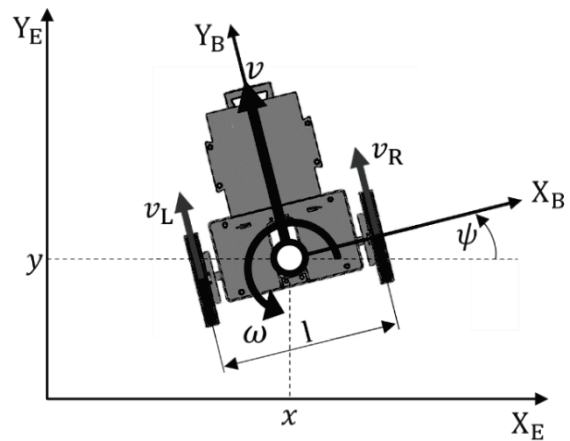


Figure 3 Differential drive configuration kinematic model

The kinematics of the differential configuration mobile robot is often described using the Unicycle-Type Wheeled robot model [18]. The robot velocities with respect to the earth frame are given with equations:

$$\dot{x} = v \cdot \cos \psi, \quad \dot{y} = v \cdot \sin \psi, \quad \dot{\psi} = \omega, \quad (1)$$

where  $v$  is the translational and  $\omega$  is the rotational velocity of the robot with respect to the body frame,  $v^B = [v \ \omega]^T$ . The problem of direct kinematics describes the mapping of the velocities of the left and right wheels  $\Omega = [\omega_L \ \omega_R]^T$ , which represent the input of the model, to the translational and rotational velocities of the robot, which represent the output of the model, and is given by the following expression:

$$v^B = \Gamma_R \Omega = \begin{bmatrix} \frac{d}{4} & \frac{d}{4} \\ -\frac{d}{2l} & \frac{d}{2l} \end{bmatrix} \begin{bmatrix} \omega_L \\ \omega_R \end{bmatrix}. \quad (2)$$

The mapping is described through the drive allocation matrix  $\Gamma_R$ , which is defined by the configuration arrangement, in this case by the distance between the drive wheels  $l$ , and by the actuator parameters, in this case, wheel diameter  $d$ .

From the aspect of implementing robot control, it is necessary to map the translational and rotational velocities of the robot to the angular velocities of the left and right wheels, which represents the problem of inverse kinematics and is given by the following expression:

$$\Omega = \Gamma_R^{-1} v^B = \begin{bmatrix} \frac{2}{d} & \frac{l}{d} \\ -\frac{2}{d} & -\frac{l}{d} \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}. \quad (3)$$

Among different types of electric motor drives, in this proposed design, servo motors with continuous rotation were considered. When implementing system control, it is necessary to adjust the control variables to the signal sent to the actuator. The model presented in this way can be easily implemented in a software package for performing simulations and implementing experiments on robot control.

### 3.2 Kinematics of the Omnidirectional Drive Configuration with Mecanum Wheels

Holonomic robots have the ability to independently control each DOF variable. Unlike the conventional differential configuration, so-called omnidirectional robot configurations allow the performing of more complex movements in 2D space (on the surface). Such UGV configurations consist of a minimum of three actuators. Wheels that enable omnidirectional motion are the key assembly of the holonomic drive configuration. The geometric arrangement and wheel type depend on the number of actuators. The most common are configurations with three actuators consisting of so-called omnidirectional wheels [8], and configurations with four actuators consisting of mecanum wheels [19]. Due to the considered modular approach, the configuration with four actuators is further discussed in this paper. The velocities of the omnidirectional robot with respect to the earth frame,  $\dot{\epsilon} = [\dot{x} \ \dot{y} \ \dot{\psi}]^T$  are defined by the following expression:

$$\dot{\epsilon} = R_\psi v^B = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix}, \quad (4)$$

where  $v_x$  is the translational robot velocity in the  $X_B$  axis,  $v_y$  is the translational velocity in the  $Y_B$  axis and  $\omega$  is the rotational velocity of the robot with respect to the body frame as shown in Fig. 4.

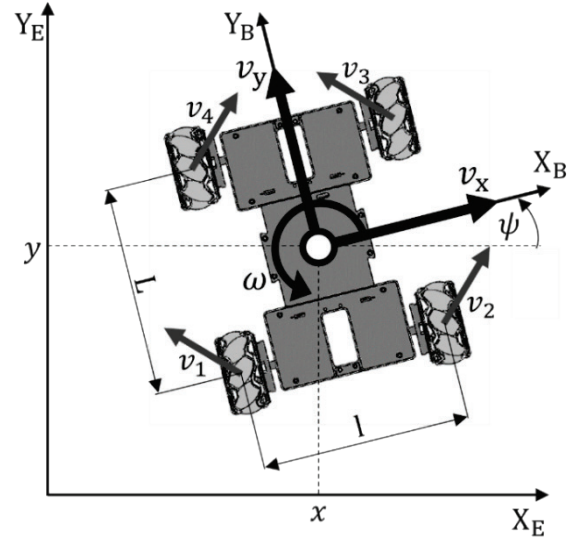


Figure 4 Omnidirectional drive configuration kinematic model

The translational and rotational velocities form the vector  $v^B = [v_x \ v_y \ \omega]^T$ , and they depend on the geometric arrangement of the actuators, the parameters of the mecanum wheel, and the angular velocities of each wheel,  $\Omega = [\omega_1 \ \omega_2 \ \omega_3 \ \omega_4]^T$ , which represents the input of the model. More detailed descriptions of kinematics have been presented in numerous works, such as [20, 21]. The problem of direct kinematics of an omnidirectional configuration can be defined by the following expression:

$$v^B = \Gamma_R \Omega = \begin{bmatrix} -\frac{d}{8} & \frac{d}{8} & -\frac{d}{8} & \frac{d}{8} \\ \frac{d}{8} & \frac{d}{8} & \frac{d}{8} & \frac{d}{8} \\ d & d & d & -d \\ \frac{d}{4(L+l)} & \frac{d}{4(L+l)} & \frac{d}{4(L+l)} & -\frac{d}{4(L+l)} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}, \quad (5)$$

where the distance between the drive wheels is  $l$ , the distance between axes is  $L$ , and by the actuator parameters, in this case, wheel diameter  $d$ , where the angle of the rollers is 45 degrees. For the inverse kinematics problem of the considered omnidirectional configuration, it is necessary to make a pseudoinverse since the allocation matrix is not square. Inverse kinematics can be defined by the following expression:

$$\Omega = \begin{bmatrix} \frac{2}{d} & \frac{2}{d} & -\frac{L+l}{d} \\ \frac{2}{d} & \frac{2}{d} & \frac{L+l}{d} \\ \frac{2}{d} & \frac{2}{d} & -\frac{L+l}{d} \\ \frac{2}{d} & \frac{2}{d} & \frac{L+l}{d} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \quad (6)$$

#### 4 DESIGN PROCESS AND DEVELOPMENT OF PRINTABLE MODULAR ROBOTIC PLATFORM

In the design phase of the educational robotic platform, it is necessary to select the components and technologies for prototyping affordable low-cost robotic platforms. By choosing a control subsystem based on open-source ecosystems that can be programmed, the educational character of the platform is enabled. Groups of components form control, sensor, drive, and energy modules. The system itself is scalable, which enables the realization of various learning outcomes at different levels of STEM education and enables integrated education of engineering systems.

##### 4.1 Design Considerations for a Modular Robotic Platform

The main focus of this work is on the design and development of a modular brick-based robot chassis, where each module combines 3D-printed parts with available standard electronic and mechanical components. The proposed approach enables the development of a highly expandable and versatile robotic platform. In order to realize the idea, it is necessary to carry out several phases, basically using software packages for 3D modelling and model preparation and a 3D printer for prototyping parts of the system. SolidWorks software package was used in the 3D modelling design phase. For the prototyping of parts, Fused Deposition Modelling (FDM) technology was considered since it is much cheaper compared to other AM technologies. Regardless of the AM technology, the process of designing and developing a mechatronic system is essentially the same as presented in [22]. The Prusa Slicer software was used for the preparation of parts and the Prusa i3 MK3S 3D printer for the parts prototyping. Key steps in the design phase of the robot chassis are shown in Fig. 5.

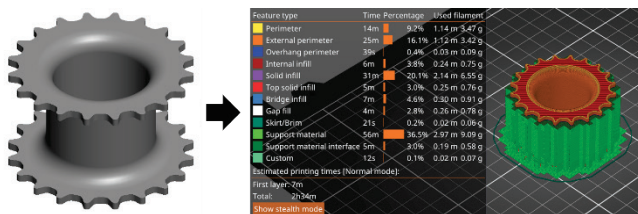


Figure 5 Robot part design phase

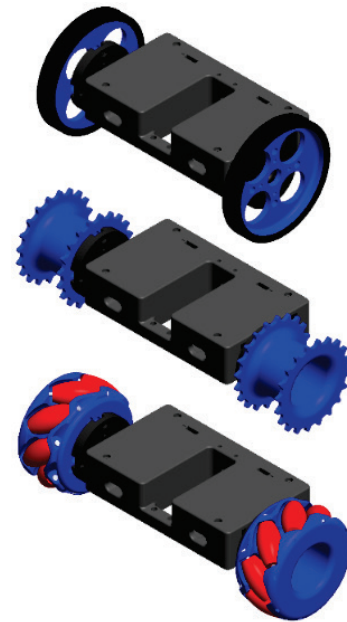
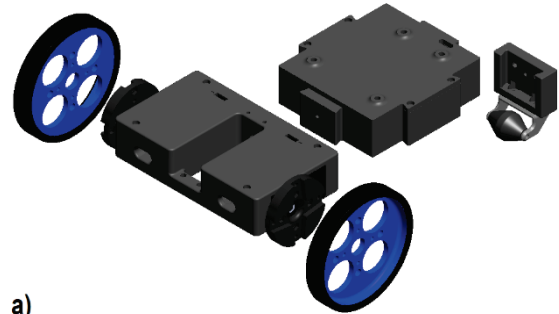
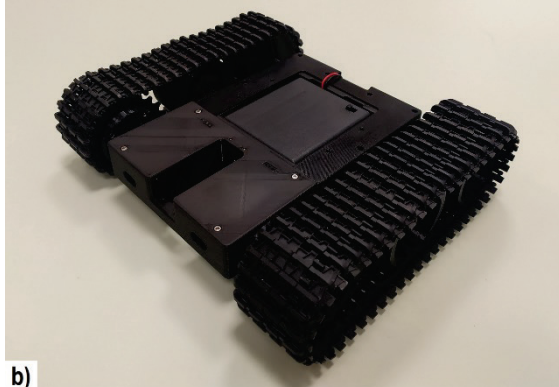


Figure 6 Drive module brick configurations



a)



b)

Figure 7 Differential configuration: (a) Drive and energy module exploded CAD model, (b) Assembled caterpillar platform

An approach to modular design in an educational sense can be presented through two production paradigms: mass customization and mass individualization. Paradigms refer to both, software and hardware, i.e., the structural parts of the assembly. In the field of STEM education, the second paradigm of mass individualization/personalization is of interest, which is enhanced by the use of 3D printing. Therefore, pupils/students will be able to participate in improving the design and creating their own constructions according to their needs, perfecting their knowledge. In order

to obtain complete open architecture products, not only product modularization is needed, but also interface compatibility. The platform and the module must have certain constraints and relationships, for the system to be valid. By replacing or adding a module the functionality of the robot changes, e.g., the different types of drive configurations can be used to adapt to different types of terrain (Fig. 6). Furthermore, different sensors can be used that can communicate with different control ecosystems, which changes the functionality of the overall system.

The development of the platform is actually an iterative process because the stages of construction, prototyping, and testing are repeated in order to eliminate design flaws and make further improvements. The basic assembly of the platform consists of a drive module with associated actuators, an energy module that basically consists of a battery, and a control and sensor module, depending on the level of education. The proposed design of the robot platform enables the rapid assembly of the functional robot. Exploded CAD model of the conventional differential configuration drive and energy module is shown in Fig. 7a. The differential configuration with the wheels consists of a freewheel that can be purchased, or it can also be prototyped using FDM technology. Such a basic platform can be further expanded with caterpillar elements. To assemble such a platform, it is necessary to replace the wheels with the caterpillar drive element, which is shown in Fig. 5, and it is necessary to expand the assembly with additional wheels that rotate freely and carry the tracks. Caterpillar tracks are affordable, a pair costs less than 10 euros, but they can also be prototyped. Assembled caterpillar platform ready for testing is shown in Fig. 7b.

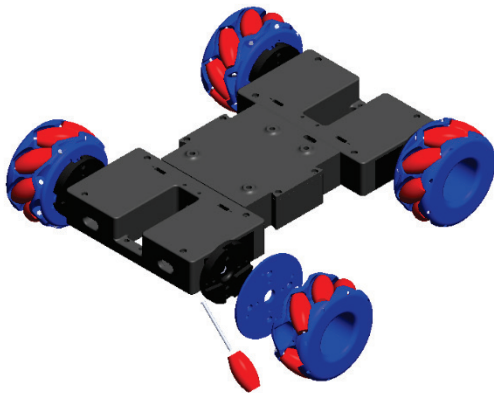


Figure 8 Omnidirectional configuration drive and energy module CAD model

The omnidirectional configuration of the robotic platform consists of two drive modules equipped with mecanum wheels. For this configuration, a mecanum wheel assembly is presented, consisting of printed parts and metal pins around which the wheel rollers rotate freely. The rollers are placed at an angle of 45 degrees, and the prototyped wheel consists of a total of eight rollers. The presented design significantly lowers the price of the robot, considering that such wheels are relatively expensive, and additional adaptation is required to fit the existing elements of the drive module. It is important to note that the layout of the

connections of the drive module is considered, which in further work will enable the connection with the control and energy module through an element that represents a shield. The omnidirectional robot CAD model of the drive and energy module is shown in Fig. 8.

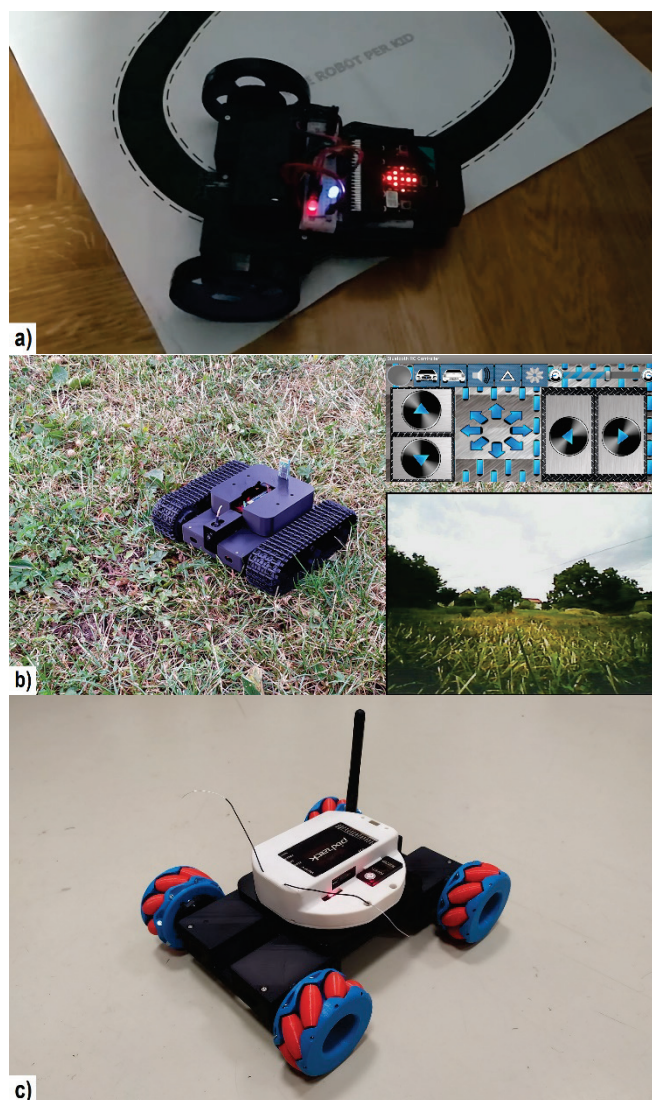
The price of the platform depends on the selected components. For instance, the servo brick can include two continuous servo motors (S2 – Tab. 1), priced at around 10 euros each, or two S4 motors, around 30 euros each. The materials for printing parts of the drive module brick, as seen in the Fig. 6, vary from three to six euros per assembly. The overall platform cost, for instance based on the ESP32 development ecosystem with the accompanying basic sensor package, the drive module brick module featuring two S2 motors and drive wheels, and the associated battery module, is below 50 euros per unit. Control modules utilizing Arduino and BBC micro:bit ecosystems are two to three times more expensive. Nevertheless, the material cost for proposed robotic module parts represents only a fraction of the total price.

## 4.2 Experimental Validation of Modular Robotic Platform Prototype

After assembly, in order to validate the proposed modular robot platform, tests of three versions of the robot with three different control ecosystems were carried out, as shown in Fig. 9. First, the basic configuration of the differential wheel drive in combination with the BBC micro:bit ecosystem was tested. A sensor module was used to track the line (Fig. 9a), which is one of the characteristic tasks at the elementary school level of education. This ecosystem can be programmed by block-based visual programming language (SCRATCH) or using Python, so it is suitable for a wider spectrum of integration into education. Furthermore, the caterpillar platform was tested in combination with the Arduino ecosystem, as shown in Fig. 9b, where remote control of the robot using a Bluetooth module and an Android application is utilized.

Finally, an omnidirectional robot was tested in combination with the PX4 module, which was used in previous work as a control module for UAV [23]. In the MATLAB software package, an experimental firmware was created in which the allocation for the omnidirectional configuration was implemented and the remote control (radio control) was tested, as shown in Fig. 9c.

It is planned to hold a workshop for pupils of the 7<sup>th</sup> and 8<sup>th</sup> grades of elementary school, where the differential configuration based on the BBC micro:bit ecosystem will be used. The preliminary demonstration workshop was successfully held. To conduct workshops for pupils of technical secondary schools, a platform based on the Arduino ecosystem with associated sensors and modules will be used. Regarding engineering education, the plan is to implement a modular robot platform through the mobile robots course, where the control module of the robot will be based on the ESP32 ecosystem with a companion Raspberry Pi on-board computer.



**Figure 9** Experimental validation: (a) Differential configuration with wheels in combination with BBC micro:bit ecosystem, (b) Differential configuration with a caterpillar in combination with Arduino ecosystem, (c) Omnidirectional configuration in combination with PX4 ecosystem

## 5 CONCLUSION

In this paper, the design process of a modular UGV robotic platform intended for STEM education is proposed. Besides modularity, the convenience of the proposed educational robotic platform is the usage of commercial off-the-shelf and open-source components. A prerequisite for the implementation of simulations and real tasks is knowledge of system parameters, which is particularly important for the proper platform control and selection of drive actuators. The characteristics of considered servo motors were presented based on conducted experimental measurements. A novel modular UGV robot platform was mathematically described, and the model implemented into the software package enabled the execution of simulations and experiments. The parts of the chassis that make up the robot assembly were made using FDM technology, and experimental testing was carried out. The presented novel modular platform is validated for three drive module assemblies in combination

with three control ecosystems. In future work, it is planned to implement workshops at three levels of education: elementary school, secondary school, and undergraduate degree.

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