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DESIGN OF MECHATRONIC MODULES THAT CAN FORM MULTIPLE CONFIGURATIONS OF MOBILE ROBOTS

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Abstract: *The ever-changing industrial environment has become very competitive these days, and industries such as the automotive industry are trying to find increasingly complex automation solutions that can lead to an increase in targeted productivity in several stages, from the supply of semi-finished products to the delivery of the final product. Solutions for automating the logistics system exist but can be greatly improved to increase productivity and reduce production costs. This paper presents the design of mechatronic modules that can form multiple configurations of modular mobile robots with multiple wheel types. In addition, the paper discusses the configuration of a mobile robot with four omnidirectional wheels having rollers arranged at 90 degrees. For this configuration, the constructive variants, the functionality of the subassemblies and the mathematical modelling of the kinematic and dynamic model are presented.*

Key words: *Mobile robots, Modular robots, Reconfigurable, Omnidirectional, Kinematics, Robot dynamics, mechatronic system.*

1. INTRODUCTION

Currently, mechatronics and robotics are the fastest growing fields of scientific research. The increased research interest in the field of mobile robots has led to their possibility to replace the human operator in many fields [1]. Mobile robots are defined in research studies as those robots that can move from one place to another to achieve desired results and perform complex, time-consuming, repetitive, or dangerous tasks. Currently, robots are replacing humans performing indoor or outdoor tasks in many fields such as industry, military, hospital operations, sports, agriculture, and others. Based on the field of application, mobile robots can have different locomotion systems and can be found in a multitude of configurations. Mobile robots are equipped with a multitude of sensors that work with different technologies (infrared, ultrasound, video cameras, GPS, etc.). They are controlled and commanded with different algorithms and are monitored locally or remotely [2]. The works [3, 4, 5] present mobile robots on wheels controlled in real time via the Internet through a protected web page or Internet of Things (IoT) technology. All these platforms are based on a Raspberry Pi computer that allows online viewing of the work environment through a web camera. In various industries (food, automotive, chemical, pharmaceutical, etc. [7]) robotic mobile platforms are used for different activities, such as the transport or handling of materials, parts, subassemblies, products, etc. inside the technological flow [6] or inside logistics centers [2]. Mobile robots can move autonomously, i.e. without assistance from external human operators. A mobile robot can be called autonomous when the robot itself can determine the actions to be taken to complete a task, using a perception system to help it detect obstacles and a control system to coordinate all the subsystems that make up the robot [1].

Mobile robotic platforms are also known as automated guided vehicles (AGV). Their sizes vary from centimeters to tens of meters. In production systems, in which handling and palletizing operations are major activities, the flexibility and productivity are increased by using robotic mobile platforms. Their use leads to production cost reduction and improved efficiency.

Mobile platforms can be equipped with various towing or transport systems. Among them, we can mention the systems of containers or tippers that handle the materials on the production line, but also stacking systems by moving objects vertically in storage systems.

Usually, with AGV systems, guidance or navigation is done by markings placed below the floor level, or attached or painted on the floor. Thus, although they are simple systems, there are also a number of disadvantages such as reduced possibilities of changing the route, high wear and high maintenance costs. Also, the transport areas used by AVGs cannot be shared with those for the movement of human personnel or human-operated vehicles. Moreover, the transport space cannot be used for other activities, such as storage. A modern idea of industrial automation within Industry 4.0 allows small

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autonomous entities to exchange data and cooperate with other equipment. These transport systems are similar to holonic ones in which the components are autonomous and collaborative. In such a system, autonomous vehicles can share their location to distribute tasks in the system to achieve an overall goal. The navigation system must be flexible and easy to reconfigure and, in addition, it must be separated from the fixed paths. Such a solution with a certain degree of vehicle autonomy is different from the concept of production line type systems. In such a system, the autonomous vehicle is equipped with specific systems for making decisions and planning routes adapted to changes in the common space in which it operates (avoiding obstacles or potholes) [8].

Modular robots are r structures robotics composed of individual devices with simple shapes and hardware configurations. The modules are designed so that they can be mounted in different arrangements through special connection systems. Thus, robots with high complexity and high performance specific to various applications are formed [9]. If a mobile platform is damaged during the execution of an application, there is a very important advantage in that the defective module can be replaced in a very short time and the robot can operate again without for example the line it powers being shut down. The defective modules can be replaced with new identical modules very quickly without the need for any hardware or software adjustments or modifications. In practice this makes the production costs of a modular robot as low as possible by making similar parts in mass production. Some modular robots can self-repair or self-assemble, these features make the performance even higher compared to robotic robots made for a specific application [10, 11, 12].

2. DESIGN OF THE MODULAR PLATFORM

Following the study of several articles, it was decided to build a mobile robot from several hexagonal modules, illustrated in Fig. 1,*b*. The robot consists of several types of independent modules with different roles. To design a modular mobile robot, it is necessary to consider several aspects such as:

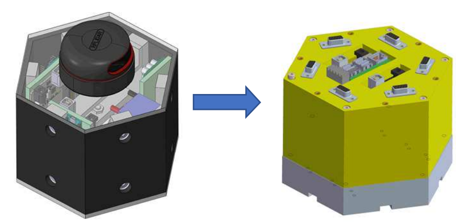
- Each module should be an independent and autonomous unit. Each module should be able to be connected to any other module regardless of type and size;
- Each module should be designed to have as little mass as possible, and to induce as little moment of inertia as possible;
- Each module should have the lowest possible impact on the environment;
- Considering all these aspects and the objectives of this research project, a series of modules have been

developed, which will be presented below, and with the help of which a series of mobile robots with different types of wheels can be made.

2.1. Description of the main module

The main robot unit or main module is a hexagonal shaped structure shown in Fig. 1, which has two important roles: as a control unit for all the other secondary modules, and as a mechanical connection, which together with the other modules forms different configurations of wheeled mobile robots. The main characteristics of this module are defined primarily by the hexagonal shape of the structure, which allows a quick configuration with 6 other modules of similar shape and the possibility to form different structures, Fig. 1 shows two designed variants of the main module.

This variant has been designed to be more compact, to ensure a high rigidity of the structures to be formed, simpler practical realization, and as few mechanical components to be made by machining, thus greatly reducing production costs. Another objective was that the base plate of this module could be used for the other types of modules, both in terms of increasing the degree of modularity and from an economic point of view. Compared to the previous version, the upper part of the module has been fitted with plugs for electrical connections to other modules, which are attached directly to the cover, which is a single piece made by 3D printing, and is attached with metric screws to the aluminum base plate. This provides quick access to the electronic components by removing the printed housing as shown in Fig. 2. The connection system with other modules has been modified and a simpler, more efficient, and cheaper system has been realized, having fewer components and



a b

Fig. 1. The main module of the robot isometric view: *a* – main module variant 1; *b* – main module variant 2.

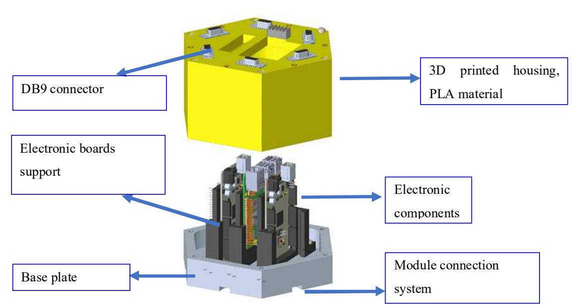


Fig. 2. Components of main module variant 2.

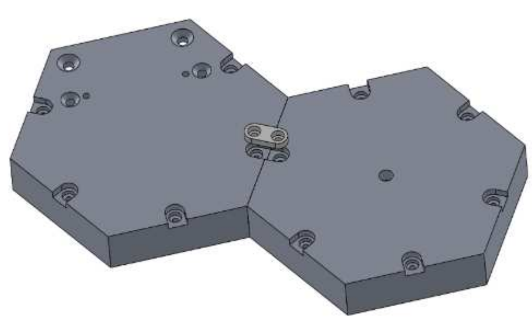


Fig. 3. Module connection system.

Table 1

Main module components

No.	Name	Quan-tity	Description
1	Raspberry Pi 4 Model B	1	This is the main master component of the robot's control system and communicates with the other Arduino control boards
2	Arduino Mega 2560	2	This component is used in the control system of the robot having the role of controlling the motors and the master board
3	Arduino Micro	3	This component is used in the robot control system having the role of interface for the sensory system and the communication between the modules
4	D24v150f3.5	1	3.3 V voltage regulator for power supply sensors
5	D24v150f5	1	5 V voltage regulator for powering Arduino and LiDAR boards
6	D24v150f12	1	12 V voltage regulator for Raspberry Pi power supply
7	DB9 connectors	6	Ensure bi-directional communication of up to 6-wheel modules with the main module

in this way a direct connection between the base plates of each module has been realized, needing only a simple connecting piece and screws, as shown in Fig. 3.

Table 1 shows the main components that make up the main module.

2.2. Drive wheel module

Figure 4 shows the driving wheel module, which will provide the locomotion system of the mobile platform, having the possibility to be configured with three types of wheels and to form together with the main module different robotic structures. This is a mechanical assembly consisting of a suspension system with springs and a hydraulic damper. It increases the robot's performance considerably, as it can run on surfaces that are not perfectly flat without any problems in terms of control and positioning accuracy. The main components of this module are:

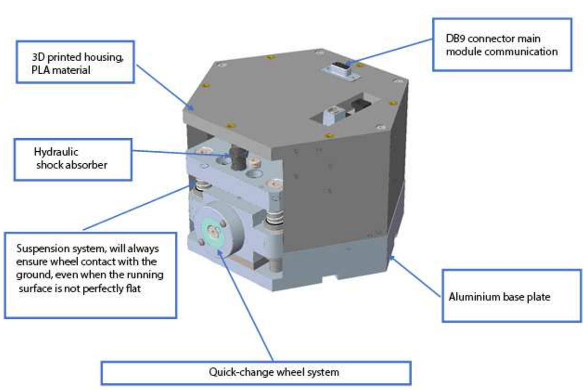


Fig. 4. Drive wheel module.

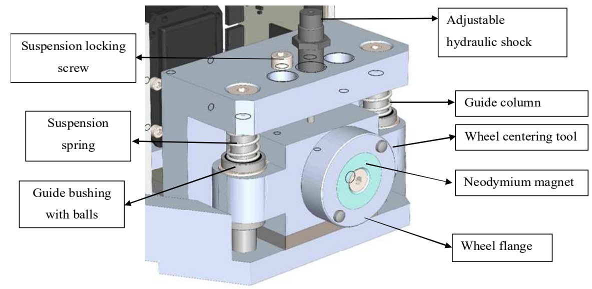


Fig. 5. Suspension system.

- Dynamixel Mx64 AT motor – DC motor, used to drive the wheel.
- Dual driver vnh5019- DC motor driver.
- Arduino Mega- driver control board.
- Current sensor – ACS712.
- DB9 connector-main module communication.

The suspension system is made of two ground guide columns, on which run two ball bearing guide bushes that are embedded in the wheel axle support piece.

Between the upper plate and the guide bushing, there is a spring that has been pre-dimensioned. There is also a hydraulic shock absorber that takes up the vibrations. In Fig. 5, one can also see the quick-change wheel system which consists of two flanges, one made of aluminum which is connected to the motor shaft and inside which there is a neodymium magnet with an adhesion force of approx. 10.5 kg, and the other flange is attached to the wheel and is made of steel. The flanges will be centered by two pins and will remain in contact due to the magnetic force. The base plate of the module is like that of the main module and there is the same connection system, the housing is also made by 3 D printing from PLA material, and at the top of the module there is a DB9 serial connection plug that provides bi-directional communication with the main module. The suspension system has another important advantage in achieving a main objective of this research project, namely measuring the current consumed by each wheel module for various types of wheels and robotic structures, achieving a permanent contact of the wheel with the ground and eliminating vibrations.

3. MODULAR MOBILE ROBOT WITH 4 OMNI-DIRECTIONAL WHEELS WITH ROLLERS ARRANGED AT 90°.

Figure 7 shows the angles between the wheel axes and a reference point at the center of the robot – $\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, $\boldsymbol{\alpha}_3$, $\boldsymbol{\alpha}_4$, angular velocity for each wheel – $\boldsymbol{\omega}_w = [\boldsymbol{\omega}_1\ \boldsymbol{\omega}_2\ \boldsymbol{\omega}_3\ \boldsymbol{\omega}_4]\ \boldsymbol{T}$, and linear velocities for each wheel – $\boldsymbol{v}_w = [\boldsymbol{v}_1\ \boldsymbol{v}_2\ \boldsymbol{v}_2\ \boldsymbol{v}_3\ \boldsymbol{v}_4]\ \boldsymbol{T}$. These two types of targets are illustrated in Fig. 6. According to Fig. 7, the linear velocities are positive when the wheel rotates clockwise (CW) and negative when the wheel will rotate trigonometrically (CCW). The relationship between the linear and angular velocity with respect to the global coordinate system of the XOY robot structure is given by $\boldsymbol{V}_{(g)} = [\dot{X}\ \dot{Y}\ \boldsymbol{\omega}]$, where R represents the distance from the center of the robot to the wheel, and r – radius of the omnidirectional wheel [13].

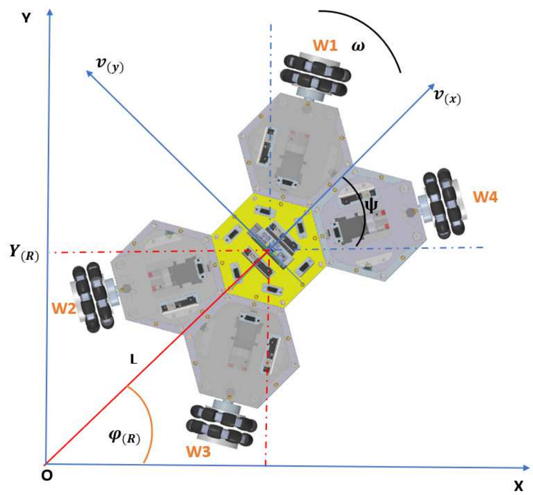


Fig. 6. Wheel layout for a modular mobile robot with 4 omnidirectional wheels.

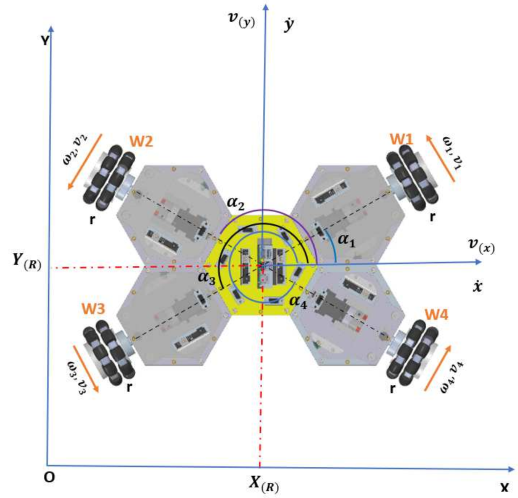


Fig. 7. Wheel layout for a modular mobile robot with 4 omnidirectional wheels.

4. KINEMATIC MODEL – MODULAR MOBILE ROBOT WITH FOUR OMNIDIRECTIONAL WHEELS

Kinematic modeling represents the study of robot movement based on the structure of a stationary or moving reference system from a geometrical point of view, without considering torque, force or certain moments that define the movement [14]. The position of the omnidirectional wheel has a major influence on the kinematic model of the mobile modular robot. In this case, 4 omnidirectional wheels are used, where the axes of the four wheels are joined to the center of the robot, and an angle of 90° will be formed between the wheels [13]. To obtain the kinematic model of the robots, two models must be defined, namely inverse kinematics (IK) and forward kinematics (FK), according to the robotic structure illustrated in Figs. 6 and 7. Thus, inverse kinematics will be used to determine the linear velocity of the four omnidirectional wheels and direct kinematics to determine the position of the robot, i.e. the linear velocity of the robot in relation to the global coordinates [13].

According to the notations in Fig. 7, the following equations can be determined:

$$\varphi_{(R)} = \tan^{-1}\frac{Y_{(R)}}{X_{(R)}}, \tag{1}$$

$$\mathrm{L} = \sqrt{{X_{(R)}}^2 + Y_R^2}, \tag{2}$$

$$\begin{matrix} v_{(x)} \\ v_{(y)} \\ \omega \end{matrix} = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \omega \end{bmatrix}. \tag{3}$$

According to Figs. 6 and 7, based on the notations and the presented robotic structure, the mathematical equation for inverse kinematics and direct kinematics can be determined. In the equation that defines the inverse kinematics, we will have as an input parameter, the linear speed of the robot $\boldsymbol{V(g)}$ and the linear speed for each wheel will be determined. The inverse kinematics equation for this case can be seen in Eq. (4).

$$v_w = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = T(\theta) \cdot V_{(g)} \tag{4}$$

$$V_{(g)} = [\dot{X} \quad \dot{Y} \quad \omega]^T \tag{5}$$

$$T(\theta) = \begin{bmatrix} -\sin(\psi+\alpha_1) & \cos(\psi+\alpha_1) & R \\ -\sin(\psi+\alpha_2) & \cos(\psi+\alpha_2) & R \\ -\sin(\psi+\alpha_3) & \cos(\psi+\alpha_3) & R \\ -\sin(\psi+\alpha_4) & \cos(\psi+\alpha_4) & R \end{bmatrix} \tag{6}$$

By reference to inverse kinematics, one can obtain the value of $\boldsymbol{V(g)}$ by multiplying $\boldsymbol{V(g)} = \boldsymbol{Vw}\cdot\boldsymbol{T(\theta)^{-1}}$, Equation (6) presents a new equation to avoid calculation errors.

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \omega \end{bmatrix} = D \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}, \tag{7}$$

$$D = \frac{1}{2}\begin{bmatrix} -\sin(\psi+\alpha_1) & \cos(\psi+\alpha_1) & 2R^{-1} \\ -\sin(\psi+\alpha_2) & \cos(\psi+\alpha_2) & 2R^{-1} \\ -\sin(\psi+\alpha_3) & \cos(\psi+\alpha_3) & 2R^{-1} \\ -\sin(\psi+\alpha_4) & \cos(\psi+\alpha_4) & 2R^{-1} \end{bmatrix}^T. \tag{8}$$

5. DYNAMIC MODEL - MODULAR MOBILE ROBOT WITH 4 OMNIDIRECTIONAL WHEELS

The modular mobile robot with omnidirectional wheels used for the development of dynamic equations is shown in Fig. 8. The robot has four omnidirectional wheels with rollers arranged at 90°, OXY represents the global reference system in which the robot is located, d-represents the distance between the wheels and the center of the robot, the linear speed of the robot in the two directions is defined as vx, vy and the angular speed ω, $\boldsymbol{v_1}, \boldsymbol{v_2}, \boldsymbol{v_3}, \boldsymbol{v_4}$ – rotation speeds for each individual wheel [15].

To determine the movement of the robot, the vector defining the coordinates of the robot is defined as $q = (x\ y\ \theta)^T$, and the velocity vector is the derivative of q. By means of the following equation, the above velocity vector can be transformed into the reference frame of the robot.

$$\dot{q} = H\underline{v} \tag{9}$$

where $\underline{v} = \left(v_x v_y \omega\right)^T$ and is the velocity along the robot axis, and H shows the relationship between $\dot{\underline{q}}$ and v, in the next equation:

$$H = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{10}$$

The dynamic model for the configuration shown in Fig. 8 can be expressed by the following mathematical relationship:

$$M\left(\underline{q}\right) = \begin{pmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & J \end{pmatrix}, \tag{11}$$

$$\underline{V} = [\mathrm{V_x} \quad \mathrm{V_y} \quad \omega]^{\mathrm{T}}, \tag{12}$$

$$C(\underline{q}, \dot{\underline{q}}) = \mathrm{diag}\left(B_x, B_y, B_\omega\right), \tag{13}$$

$$G(\underline{q}) = \mathrm{diag}\left(C_x, C_y, C_\omega\right), \tag{14}$$

$$B = \begin{pmatrix} -\frac{\sqrt{2}}{2r} & -\frac{\sqrt{2}}{2r} & \frac{\sqrt{2}}{2r} & \frac{\sqrt{2}}{2r} \\ \frac{\sqrt{2}}{2r} & -\frac{\sqrt{2}}{2r} & -\frac{\sqrt{2}}{2r} & \frac{\sqrt{2}}{2r} \\ \frac{d}{r} & \frac{d}{r} & \frac{d}{r} & \frac{d}{r} \end{pmatrix}. \tag{15}$$

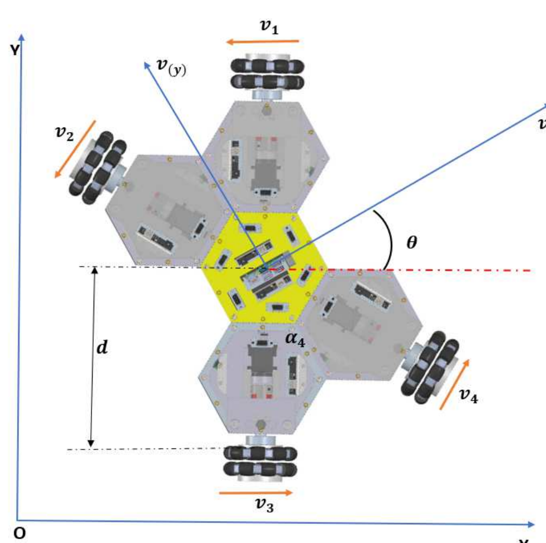


Fig. 8. Modular mobile robot with four omnidirectional wheels.

6. CONTROL-MODULAR MOBILE ROBOT WITH FOUR OMNIDIRECTIONAL WHEELS

This configuration of the robot has several four omni-directional wheels, positioned, and orientated in relation to the gravity center (GC) of the vehicle. Configurations with three or more independently driven wheels have full control of motion in all degrees of freedom.

Direct kinematics can be expressed using the following equation according to the notations shown in Fig. 9:

$$\begin{bmatrix} v_X \\ v_Y \\ \omega \end{bmatrix} = \frac{R}{N} \begin{bmatrix} \cos(\alpha_1) & \cos(\alpha_2) & \dots & \cos(\alpha_N) \\ \sin(\alpha_1) & \sin(\alpha_2) & \dots & \sin(\alpha_N) \\ \frac{1}{D_1} & \frac{1}{D_2} & \dots & \frac{1}{D_N} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_N \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_N \end{bmatrix}, \tag{16}$$

where: D_i- the perpendicular distance from the axis of rotation of the wheel to the centre of gravity of the robot. Inverse kinematics can be calculated by inverting the matrix M of the direct kinematics. However, since the matrix M is of order 3 it can only be inverted for $N = 3$. Therefore, this model uses the pseudo-inverse matrix M^+.

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_N \end{bmatrix} = \boldsymbol{M}^+ \begin{bmatrix} v_X \\ v_Y \\ \omega \end{bmatrix}. \tag{17}$$

Based on these equations, Fig. 10 describes the motion possibilities for the mobile robot configuration given in Fig. 9, the control being achieved by varying the speeds for each of the four wheels.

7. CONCLUSIONS

This paper also presents the implementation of mechatronic modules, which can form a modular mobile platform with different types of wheels. The mathematical models presented are only for a configuration with four omnidirectional wheels arranged at 90 degrees, being only one of the possible configurations of mobile wheels that can be realized with these mechatronic modules. Modularity offers advantages and increased performance of the robotic stocks made compared to a robot made only for a single application. With the help of these modules, a series of robots can also be made for various research projects, which can further increase the performance of mobile robots. Future research directions related to this work will focus on modular robot control and positioning accuracy verification by integrating a LiDAR sensor or encoders into the control system.

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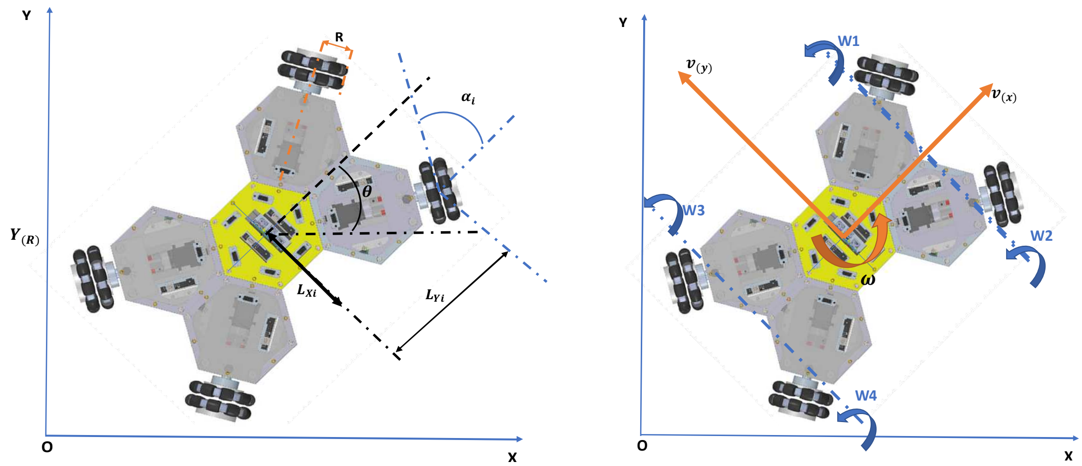

Fig. 9. Parameters of the modular mobile robot control with 4 omnidirectional wheels.

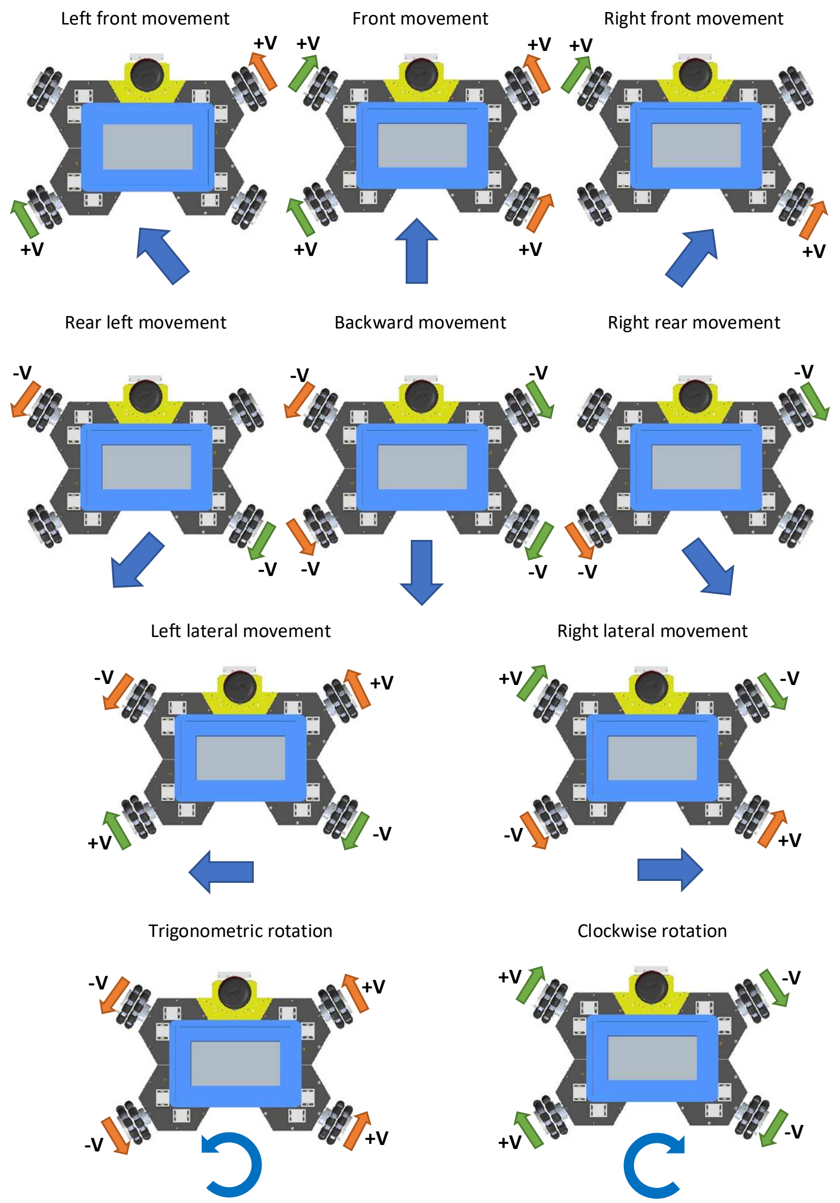

Fig. 10. Movement possibilities of the mobile modular robot with four omnidirectional wheels.

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