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DESIGN OF THE MAIN UNIT FOR A MODULAR MOBILE ROBOT

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Abstract: *This paper presents the design of the main unit of a modular and re-configurable mobile platform, made of several hexagonal modules with reconfigurable locomotion systems, with conventional wheels, omnidirectional and Mecanum wheels. The main unit is the basic module that will contain the control system and the sensory system that will allow the robot to navigate and avoid obstacles with different configurations. It will also present the configuration possibilities of the platform, the interconnection system between modules with magnetic connection, which allows the realization of fast configurations, this configuration capability offers many interesting opportunities for the industrial field and for research in the field of robotics.*

Key words: *Mobile robots, Modular, Reconfigurable, Omnidirectional wheel, Mecanum wheel.*

1. INTRODUCTION

Mobile robots can be characterized as complex mechatronic systems equipped with various types of sensors and depending on their destination can have different types of locomotion and navigation systems [1]. Recently, research in the field of mobile robotics has grown exponentially. This is due to the many advantages of various industrial sectors, such as logistics in large companies [2]. The advantages of the presence of mobile robots in the industry include better control and new productivity management tools that will lead to a major increase and product quality, because robots can workday and night without getting tired, and their performance will not be affected. Through the rapid development of industry and information technology, we can observe the evolution of robots to intelligent generations that offer the possibility for mobile robots to "understand" the environment in which they work. The structure of robots depends very much on their usefulness and the purpose for which they are built. In general, robots have a structure like that of human beings, so they have an anthropomorphic structure designed to reproduce the behavior of humans or animals, and here are examples of bipedal, quadrupedal or hexapods mobile robots [3, 4]. Modular mobile robots are a new and challenging field of research that combines various fields such as robotics, mechatronics, navigation systems to avoid obstacles and artificial intelligence. These robots are composed of various autonomous cellular modules attached to one or more central units to form new geometric shapes. Communication between modules and inter-module computing lead to new principles of functionality, new forms of locomotion and the ability of the robot to self-configure / self-repair, which will lead to a very high flexibility and a very wide field of use of mobile robots [5]. Modularity offers advantages both functionally and economically and with a major impact far above traditional robots based on fixed structure. The ability to reconfigure and interconnect modules allows modular robots to adapt to changes in the environment quickly with high flexibility. For example, a modular robot may be able to change its configuration from a mobile robot with legs, to a snake-type robot or a rolling robot depending on the type of surface on which it moves and space. Modularity and configurability also allow mobile robots to perform tasks that a single module or fixed structure the robot cannot perform. This is done by assembling additional specialized units to perform an assigned task. These specialized units can be grippers, batteries, or sensor units, such as Lidar sensors. Modular robots also offer an economic advantage that results from the high flexibility and possibilities of expansion and development of robots by adding new specialized modules [6]. This paper presents the design of a module that acts as a main unit and to which various modules can relate to reconfigurable locomotion systems. It presents the main characteristics of the main unit and the possible configurations of mobile robots that can be obtained and their kinematics, the system of sensors for odometry and the system of interconnection and switching of modules.

2. DESIGN OF THE MAIN UNIT

The main unit of the robot or the main module is a structure with hexagonal shape shown in Fig. 1, which has the role of controller that will control all the other secondary modules together with which it forms different configurations of mobile robots with wheels. The main features 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 ability to form various structures. The main module is

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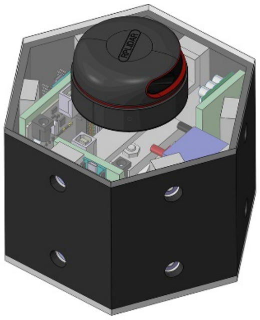


Fig. 1. The main module of the robot isometric view.

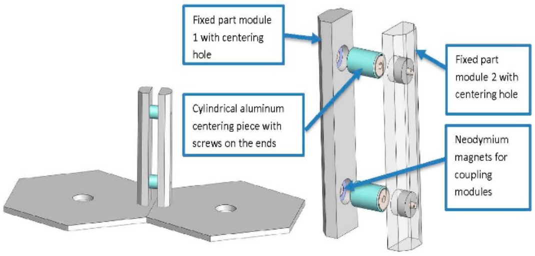


Fig. 2. Mechanical system for connecting modules and fixing with magnets.

Table 1

Master module components

No	Name	Quantity	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	LiDAR A2m4	1	This component is the LiDAR sensor that helps the modular robot to navigate and have an avoid obstacle system.
5	Sensor ADNS3080	1	It is an optical sensor like that of the optical mouse that will be positioned in the basic mode to provide coordinates on the X and Y axes, and with the help of this sensor will perform the odometry of the robot.
6	GYROSCOPEMPU 6050	1	The MPU6050 gyroscope sensor is used to know the rotation angle and together with ASNS3080 performs the odometry of the robot
7	NRF24L01	2	Module making possible wireless communication between robot modules
8	D24v150f3.5	1	3.3 V voltage regulator for power supply sensors
9	D24v150f5	1	5V voltage regulator for powering Arduino and LiDAR boards
10	D24v150f12	1	12v voltage regulator for Raspberry Pi power supply
11	Battery LiPo	1	Accumulator LiPo 14.8 V 2200 mA

powered by a large capacity LiPo battery that will ensure a high autonomy. The control system of the module is made of a Raspberry Pi 4 minicomputer. Which is the main unit, 2 Arduino Mega 2560 development boards, and 3 Arduino Micro development boards, the whole configuration can communicate wirelessly with other 6 modules and can control up to 6 engine modules.

2.1. Components of the main unit

Table 1 shows the main components that make up the main module. In addition, it shows the components that make up the control system, the sensory system that helps to orient and achieve odometry, the wireless communication module with secondary modules, as well as the mechanical system of fast interconnection with the other modules to achieve several configurations of mobile platforms.

2.2. Mechanical module connection system

Figure 2 shows a mechanical quick connection system between two hexagonal modules, the system was built to make a manual configuration by a human operator, but the effort required by the operator to be minimal, without the need for special tools or modifications hardware, at the same time there should be a rigid connection from a mechanical point of view to ensure adequate functionality and rigidity to the robot. From this consideration, this quick-connect magnetic system was also represented in Fig. 2, where in the bores in the modules we have 2 fixed magnets, and between it we will have an aluminum cylinder with two steel screws on the ends. The aluminum piece enters between the two modules and a centering on two such pieces will be made, and the magnets will attract the piece and the two modules will remain rigidly connected.

2.3. The communication system between the main unit and the secondary modules

For communication between modules and sending signals from the main module to the secondary modules, a wireless communication is used that will eliminate any electrical connection between the modules. This communication can be done with the NRF24L01 module which uses a 2.4 GHz band and works with a transmission rate between 250 kbps and 2 Mbs. The maximum transmission distance is about 100 m, this module is a cheap option for other module times such as Bluetooth and XBee transmitter. For this modular mobile platform, the use of this type of module fits perfectly with the hexagonal shape because, as shown in Fig. 3, the module can have 125 different channels. Each channel in turn can have up to 6 addresses, more precisely each module of the robot can communicate with 6 other different modules at the same time [13].

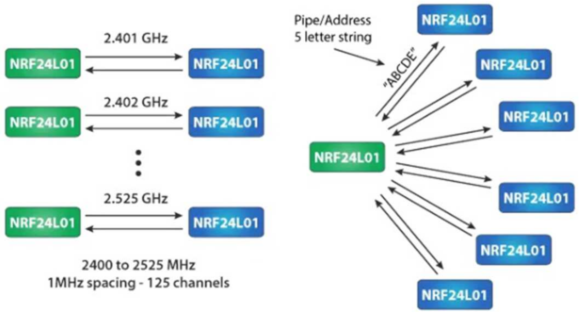


Fig. 3. Wireless communication network with NRF24L01 module [13].

3. POSSIBILITIES FOR CONFIGURING THE MOBILE ROBOT

Starting from the base unit (main module), due to the hexagonal shape, allows to obtain several configurations of mobile robots that can have different locomotion systems and can be used with high flexibility for various applications in industry and for the development of new research studies in the field of modular mobile robotics. The design of the locomotive system is a very important factor that gives the mobile robot the ability to move freely in narrow areas, as well as to avoid obstacles. This design specifies the degree of mobility and maneuverability of the mobile robot [11]. Due to the modular system and the rapid change of the locomotion system, a series of configurations can be obtained, which are further presented in this paper.

4. CONVENTIONAL 2-WHEEL MOBILE ROBOTIC PLATFORM

One of the most common examples of a non-holonomic system is a robot with two conventional differential drive wheels. The conventional wheel is widely used and is found in almost all engineering applications due to its simplicity and functionality, but which is limited to ensure the rotation of a wheel back and forth. For a robot with differential drive, conventional wheels allow the robot to move at different speeds and barely maneuverable by changing the rotational speed and direction of each wheel. Another type of wheel is the caster wheel or the directional wheel which has wide applicability not only in robotics, but also in medical equipment, production, etc. The use of caster wheels (directional) helps to achieve an almost omnidirectional mobility of a mobile robot or any other mechanical vehicle. In the case of a rigid wheel, the wheel can only rotate back and forth. A swivel wheel can passively rotate 360 degrees around the vertical axis as well as rotate back and forth, providing free movement of the wheel. Another special type of wheel is a ball-type wheel, which offers free movement in all directions due to the use of a passive ball wheel. Ball type wheels are widely used as additional passive wheels with other active (drive) wheels, for example, could be used to provide an additional point of contact with the ground (running) in a differential transmission system, a robotic mobile platform like the one shown in Fig. 4 [12].

Figure 4 shows a configuration consisting of 5 modules of which two secondary module s with conventional wheels and two secondary modules with directional wheels or ball caster. The 5th module is the master module which is arranged centrally to the other modules. This configuration gives the robot a simple control and increased travel speeds.

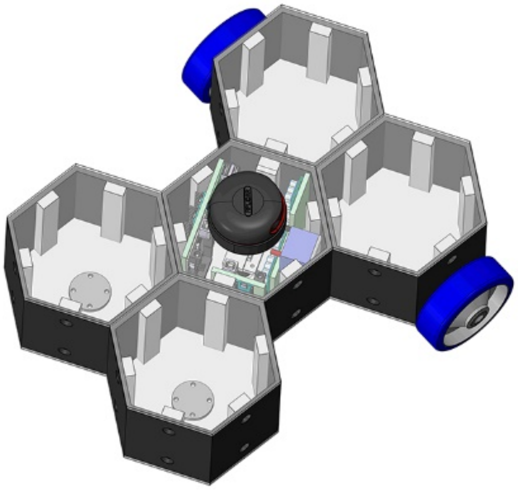


Fig. 4. Mobile robot with 2 conventional wheels and 2 directional wheels.

4.1. Kinematic model for mobile platform with differential configuration

Most mobile robots use a drive mechanism known as differential drive. It consists of 2 drive wheels mounted on a common axle, and each wheel can be driven independently either forward or backward at different speeds. While we can vary the speed of each wheel for the robot to perform rolling motion, the robot must rotate around a point along the common axis of the left and right wheels. The point that the robot rotates is known as the ICC – Center of Instantaneous Curvature shown in Fig. 5 [12].

By changing the speeds of the two wheels, we can vary the trajectories that the robot travels. If the ICC is the same for both wheels, we can write the following equations:

$$\omega(R + l/2) = V_r, \tag{1}$$

$$\omega(R - l/2) = V_l, \tag{2}$$

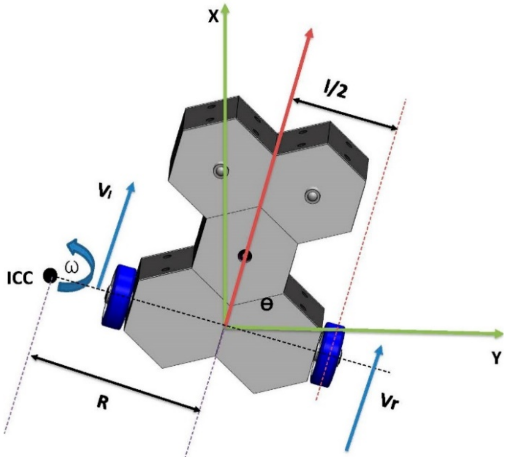


Fig. 5. Differential Drive kinematics.

where: l is the distance between the centers of rotation of the two wheels, V_r and V_l are the speeds of the right and left wheels, and R is the distance from the ICC and the point at half the distance between the two wheels denoted by R, and ω is the angular velocity.

$$R = \frac{l}{2}\frac{V_l + V_r}{V_r - V_l};\ \omega = \frac{V_r - V_l}{l}. \tag{3}$$

There are three possible situations for driving a robot:

If $V_l = V_r$ then we have linear motion in a straight line, R becomes infinite, ω is equal to zero and we will not have rotation.

If $V_l = -V_r$, then $R = 0$, then we have rotation about the axis of the center of the wheel.

If $V_l = 0$, then we had the left wheel rotation, and in this case $R = \frac{l}{2}$, the same is true if $V_r = 0$.

Knowing the velocities V_l and V_r and using equation 3, one can determine the position for ICC as:

$$ICC = [x - R\sin(\theta), y + R\cos(\theta)]. \tag{4}$$

For time $t + \delta t$ the position of the robot can be determined by the equation:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\omega\delta t) & -\sin(\omega\delta t) & 0 \\ \sin(\omega\delta t) & \cos(\omega\delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - ICC_x \\ y - ICC_y \\ \theta \end{bmatrix} + \begin{bmatrix} ICC_x \\ ICC_y \\ \omega\delta t \end{bmatrix}. \tag{5}$$

Equation (5) describes the motion of a robot rotating a distance R around the ICC point having angular velocity ω [12].

5. PLATFORMA ROBOTICA MOBILA CU 4 ROTI OMNIDIRECȚIONALE DISPUSE LA 45 GRADES (MECANUM)

These wheels have the rollers mounted with their axis at an angle of 45 degrees relative to an axis of active wheelbase. It was first developed by Mecanum AB in 1973 by Bengt Ilon. Because the design of a mechanical wheel is complex, the manufacturing cost is higher compared to universal wheels. These wheels can rotate around the axis and also the rollers rotate around their own axis arranged at an angle of 45 degrees. Applying different speeds for each wheel a robot can move in any direction; Classic Ilon wheels have 3 degrees of freedom: wheel rotation, roller rotation and sliding rotation around the vertical axis passing through a point of contact with the locomotive surface. Thus, the Mecanum wheels can move in the desired direction, allowing a diagonal movement, front-rear movement, and rotation without room for maneuver [12].

The configuration presented in Fig. 6 is also made of 5 modules of which 1 module is the main one and the other 4 modules are secondary, each with an omnidirectional mechanism type wheel. This type of robot configuration allows high mobility without the need for a maneuvering space as in the conventional two-wheel configuration. The behavior of such a modular robot with Mecanum wheels, and how it moves through space, is described by the following expression which defines the relationship between the speed of translation of the wheels $(v_{1w}, v_{2w}, v_{3w}, v_{4w},)^T$ and the speed of the robot (u, v, ω) represented in Fig. 7, using Eq. (6):

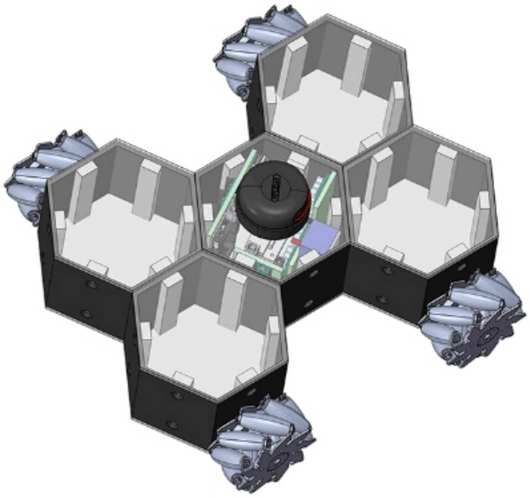


Fig. 6. Omnidirectional mobile robot with 4 Swedish wheels arranged at 45 °(Mecanum).

$$\begin{bmatrix} v_{1w} \\ v_{2w} \\ v_{3w} \\ v_{4w} \end{bmatrix} = \begin{bmatrix} 1 & 1 & l_a + l_b \\ 1 & 1 & l_a \quad l_b \\ 1 & 1 & -l_a - l_b \\ 1 & -1 & l_a + l_b \end{bmatrix} \begin{bmatrix} u \\ v \\ \omega \end{bmatrix} \tag{6}$$

where: l_a si l_b are the distances from the axis of rotation of the wheel to the center of the x, y coordinate system of the robot.

Some of the possibilities of the robot's movement and its angular velocity are presented in Fig. 8. These four-wheel drive combinations allow the modular mobile platform to move and rotate in any direction [11].

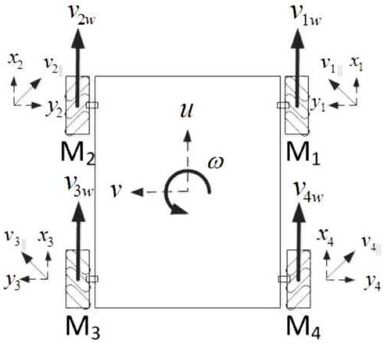


Fig. 7. Speed vectors resulting from motors connected to Mecanum Wheels [11].

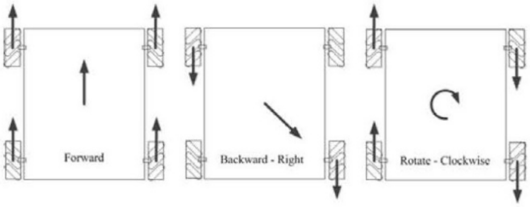


Fig. 8. The movement of the robot according to the direction and the angular speed of the wheels [11].

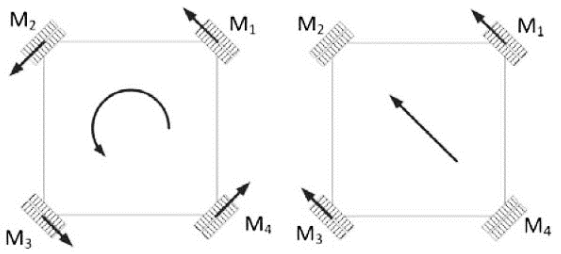
6. MOBILE ROBOTIC PLATFORM WITH FOUR OMNIDIRECTIONAL WHEELS ARRANGED AT 90 DEGREES

The basic idea of an omni wheel is a combination of the main active wheel and the passive wheels that rotate freely. The active wheel and the rollers have their own axes of rotation. As with universal wheels, the axles of the passive rollers are orthogonal to the main wheel axle. While an active wheel rotates clockwise or counterclockwise from its axis of rotation, passively rotating rollers allow the locomotive system to move in almost any direction. The rollers are usually cylindrical in shape and may vary in number. Even though omnidirectional wheels offer free locomotion, they have a few disadvantages (eg, inefficiency on a dirty surface), etc. [12].

Figure 9 shows the configuration for a robot consisting of 5 modules, with 4 secondary modules with welded omnidirectional wheels arranged at an angle of 90 degrees, this configuration gives the robot increased mobility, making rotations easily, there is less friction between rollers and ground as in the version with the rollers arranged at 45 degrees.

Some movement possibilities for this configuration are described in Fig. 10. Translational movement along any direction can be achieved by the composition of the translational movement along the *x* and *y* axis. The rotational motion around the z-axis is driven by all four wheels rotating in the same direction. However, robots have a high degree of freedom, which can cause control problems [12].

Fig. 9. Omnidirectional mobile robot with 4 Swedish wheels with rollers arranged at 90 °.



a b

Fig. 10. Examples of four-wheel robot movement: *a* – reverse rotation; *b* – forward-left movement [11].

7. MOBILE ROBOTIC PLATFORM WITH 3 OMNIDIRECTIONAL WHEELS ARRANGED AT 90 DEGREES

For the variant presented in Fig. 11, there is a smaller number of modules, having only 3 wheels with Swedish rollers arranged at 90 degrees, the friction will be reduced more, and the robot will have a higher mobility but also a smaller mass that will lead to an autonomy. higher due to lower energy consumption, the positioning accuracy will also increase compared to the 4-wheel version. As the omnidirectional wheels rotate, the alternating forces on the rollers create cyclic shock. The shock causes a periodic change in the positive pressure between each wheel of the robot and the wall. Therefore, when the robot is in a critical state of slip, this shock eventually leads to unstable friction between the robot wheels and the wall, hence oscillations occur [8].

7.1. Kinematic model for the configuration with 3 Swedish wheels with rollers arranged at 90 °

The kinematic model shown in Fig. 12 for a mobile robot with three wheels with welding rollers arranged at 90 degrees is described by the following mathematical equations:

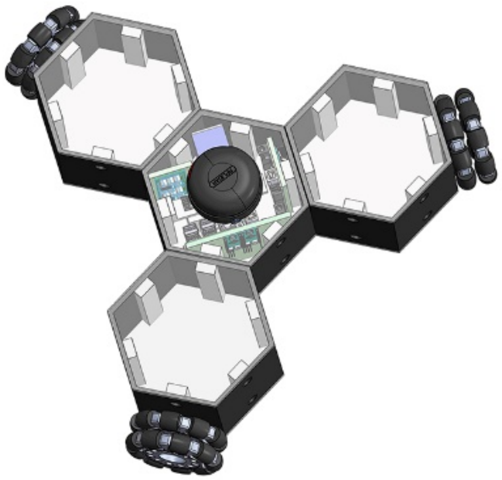


Fig. 11. Omnidirectional mobile robot with 3 Swedish wheels with rollers arranged at 90 °.

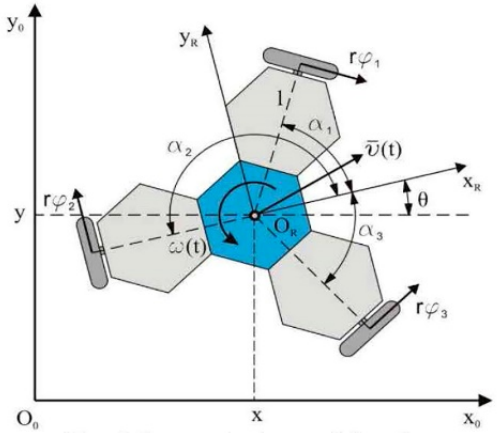


Fig. 12. Kinematic model for the configuration with 3 Swedish wheels with rollers arranged at 90 degrees [7].

Rolling contact constraint (orthogonal rollers with wheel plane) [7]:

$$[\sin(\alpha+\beta+\gamma) \quad -\cos(\alpha+\beta+\gamma) \quad -l\cos(\beta+\gamma)] \cdot R(\theta)\dot{\xi}_0 - r\dot{\phi}\cos\gamma = 0 \tag{7}$$

Sliding contact constraint (wheel direction in wheel plane) [7]:

$$[\cos(\alpha+\beta+\gamma) \quad \sin(\alpha+\beta+\gamma) \quad l\cos(\beta+\gamma)] \cdot R(\theta)\dot{\xi}_0 - r\dot{\phi}\sin\gamma - r_w\dot{\phi}_w = 0. \tag{8}$$

Equation (6) shows rolling contractions for each wheel [7]:

$$\begin{cases} \left[\frac{\sqrt{3}}{2} - \frac{1}{2} - l\right] R(\theta)\dot{\xi}_0 - r\dot{\phi}_1 = 0 \ \text{(Wheel 1)} \\ [0 \ 1 - l] R(\theta)\dot{\xi}_0 - r\dot{\phi}_2 = 0 \ \text{(Wheel 2)} \\ \left[-\frac{\sqrt{3}}{2} - \frac{1}{2} - l\right] R(\theta)\dot{\xi}_0 - r\dot{\phi}_3 = 0 \ \text{(Wheel 3)} \end{cases} . \tag{9}$$

In this case in Eq. (6) one uses:

$$\begin{cases} \alpha_1 = \frac{\pi}{3}, \alpha_2 = \pi, \alpha_1 = \frac{\pi}{3} \\ \beta_1 = \beta_2 = \beta_3 = 0 \\ \gamma_1 - \gamma_2 - \gamma_3 - 0 \end{cases} . \tag{10}$$

From Eq. (9) it will result the direct kinematics described by equation:

$$\xi = r\dot{R}(\theta)^{-1} \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} \\ -\frac{1}{2} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3l} & -\frac{1}{3l} & -\frac{1}{3l} \end{bmatrix} \begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \\ \dot{\phi}_3 \end{bmatrix}. \tag{11}$$

The inverse kinematics will be represented by the equation:

$$\begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \\ \dot{\phi}_3 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} \\ -\frac{1}{2} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3l} & -\frac{1}{3l} & -\frac{1}{3l} \end{bmatrix} R(\theta)\dot{\xi}_0, \tag{12}$$

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{13}$$

$$\dot{\xi}_0 = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} \tag{14}$$

where $R(\theta)$ represents the coordinates of the transformed matrix, r the radius of the wheel and $\dot{\xi}_0$ the speed of the robot expressed in $\{X_0, Y_0\}$.

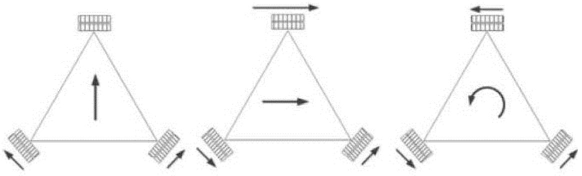


Fig. 13. Examples of robot movement with three omnidirectional wheels [11].

Several possibilities for this configuration are described in Fig. 13, which depends on the direction and speed of each wheel.

8. CONCLUSIONS

Starting from the main module with the proposed hexagonal shape, together with the other secondary modules, a series of configurations of mobile wheeled robots can be obtained that can be used in different industrial sectors as well as in research to develop modular mobile wheeled robots. The next stage would be the development of mathematical relationships that define the kinematics for all the proposed configurations and the realization of algorithms for positioning and orienting the robot. Future research aims at positioning accuracy for each proposed configuration, the robot running on different surfaces and the implementation of an obstacle bypass system.

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