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(Research Article)

Kinematic and optimal design of a three-wheeled holonomic omnidirectional robot platform for mobile manipulation tasks

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Abstract

Mobile manipulator robots are increasingly vital in industrial and service sectors, serving roles in assembly, inspection, and hazardous environments. The integration of a manipulator with a mobile robot base imposes unique demands on the vehicle's drive system. This paper introduces a three-wheel holonomic omnidirectional robot designed for mobile applications. It explores kinematic equations, electronic integration, and mechanical design for holonomic motion. This platform excels in mobility, capable of simultaneous translation and rotation, facilitating precise multidirectional motion. Its equilateral truncated triangular structure ensures stability, supporting up to 4 kg. With three omnidirectional wheels and DC motors, controlled by EMS 30A H-Bridge and Arduino Mega 2560, it offers an open platform for research and development. This robust platform aligns kinematic calculations with mathematical models, promising efficiency for diverse mobile manipulation robot applications.

Keywords: Mobile Manipulator robot; Holonomic; Omnidirectional wheels; Kinematic Equation; H-Bridge; Arduino Mega

1. Introduction

A mobile robot may choose its own path for mobility and is designed for movement around an environment [1-3]. According to their mode of movement, mobile robots can be classified into two categories: wheeled robots and legged robots [4].

Mobile robot solutions are now needed for an increasing number of industrial and service issues. Mobile robots are typically utilized in the industrial sector to move raw materials or assembly components between production sells or lines and the automated warehouse. Robots are typically utilized for cleaning, grass mowing, etc. in the service sector [5 - 7]. Rolling on wheels is another popular method of movement for interior industrial and service robots. It uses less energy, takes less time to create, and costs less than walking or flying. With the exception of the stairs and doorsteps, most homes, industrial buildings, and warehouses can be moved around on wheels. One robot typically works on a single floor, and the doorsteps are simple to modify. Rough terrain does not pose any movement issues in an indoor environment. The mechanical design of the drive system, design of the embedded system(s), design of the power electronics, execution of the odometry computations, interpolation, inverse kinematics, and power management are all parts of the long-term, labour-intensive development of a mobile robot that is, in most cases.

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The most popular kind of omnidirectional mobile robot is a three-wheeled model that can move in any direction [8]. Comparing an omnidirectional robot to a traditional two-wheeled robot and a four-wheel drive robot, omnidirectional robots have many advantages, including versatility in movement patterns and the freedom to travel in either direction [9–10]. The robot with omnidirectional wheels may travel in any direction with the same speed and acceleration. The three-wheel layout, with each wheel positioned 120 degrees differently, is the omnidirectional design that enables it to be used on robots. This technique calls for rotating the wheels either parallel or perpendicular to the direction of motion [11].

In this study, an omnidirectional mobile robot uses the holonomic technique. In order to increase the mobility of the mobile robot and allow it to travel in either direction and with any orientation, it offers an omnidirectional three-wheel design [12–13]. The robot can move in any direction thanks to its three wheels, eliminating the requirement for a traditional driving system. Even the kinematic model is shown with an Omni-wheel drive that has been adjusted for the proportions of the robot. The omni wheel is driven differentially by the DC motor, refer to Figure 1 for an illustration of the omni wheel.

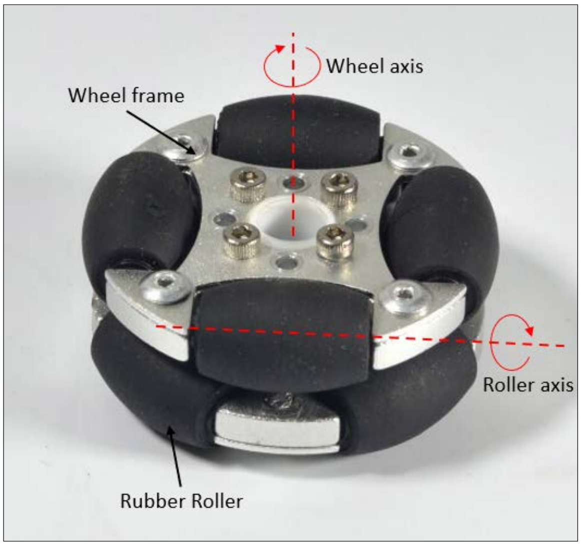

Figure 1 Omni wheel

An understanding of the design of a three-wheeled, holonomic, omnidirectional robot platform for mobile manipulation tasks is provided by the work given in this paper. A system is said to be holonomic if it has the same number of degrees of freedom as the coordinates required to specify the configuration of the system. In the realm of mobile robotics, the abstraction known as the robot, or base, is referred to as a holonomic mobile robot without consideration for the rigid bodies that actually make up the mechanism. As a result, holonomic mobile robots are any mobile robots with three degrees of freedom of motion in the plane.

2. Kinematic analysis of omnidirectional robot platform

Constrained and unconstrained motions can provide full omnidirectional motion, or arbitrary translation and rotation when three or more of these wheels are utilized on a platform. The wheels are positioned evenly spaced apart from the platform's centre, with a consistent separation angle between adjacent pairs of wheels and their driving direction vectors oriented tangentially to the circle that connects them. The three-wheeled design is easy to operate mechanically. The universal wheel's design makes it possible to achieve a velocity without using any external driving power. The other wheels' rotation provides the force. The induced velocity is the speed that is created, refer to Figure 2.

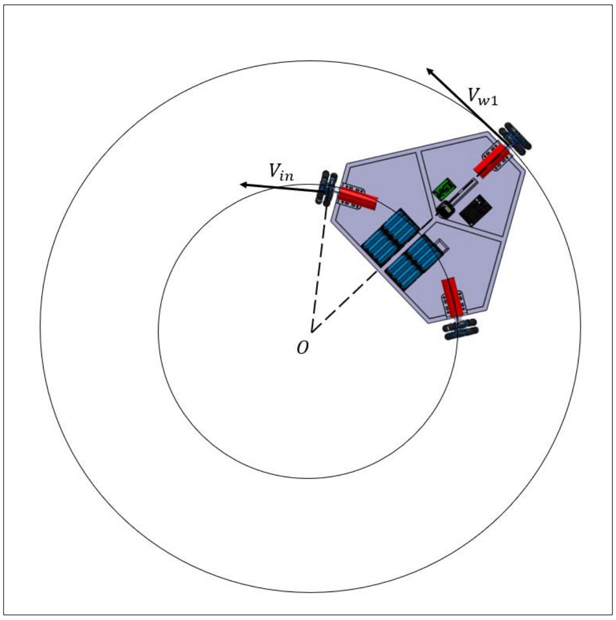

Figure 2 The left wheel has induced velocity, while the right wheel drives the system

The top-right wheel is shown to be moving, but the left wheel is locked and unable to turn around its axle. If there is no slippage, the only way that can roll is perpendicular to the left wheel's direction of travel. The left wheel, which is not being driven, has since reached velocity V_{in}. The induced velocity is as follows. The junction of the lines parallel to V_{w1} and V_{in} marks the location of the platform's rotational center.

Figure 3 depicts a three-wheeled omnidirectional robot with a schematic view. The angle between each wheel (W1, W2, and W3) is 120 degrees, and "L" represents the length of the robot's center mass to each wheel. The linear velocities of wheels 1, 2, and 3 are VW1, VW2, and VW3. "r" refers to each omnidirectional wheel's radius. All forces are split into two parts by the kinematics equation: a vertical component along the 'Y' axis called 'sin' and a horizontal component along the 'X' axis called 'cosine'.

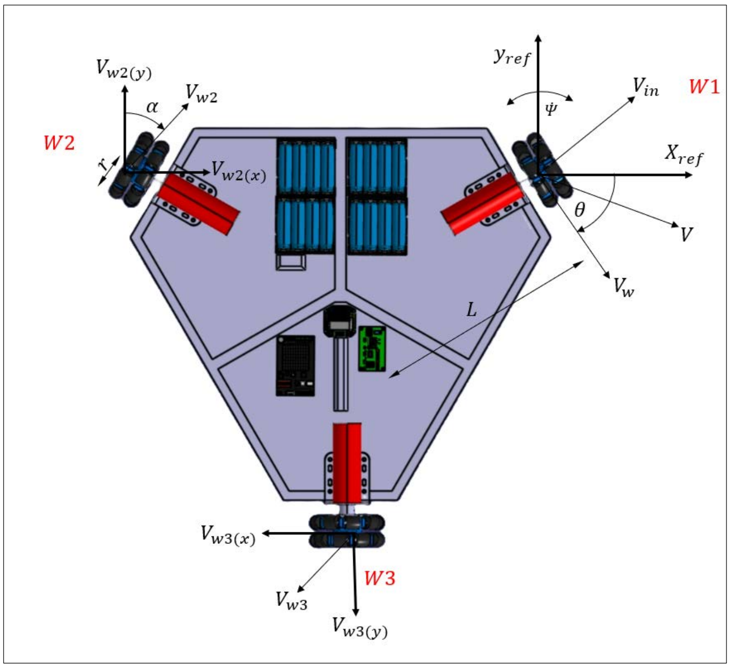

Figure 3 Three-wheeled omnidirectional robot schematic model

For wheel 1 (W1),

$$V_{w1(x)} = (-)\, V_{w1} \cdot \cos\alpha \ldots\ldots\ldots \tag{1}$$

$$V_{w1(y)} = (+)\, V_{w1} \cdot \sin\alpha \ldots\ldots\ldots \tag{2}$$

$$V_{w2(x)} = (-)\, V_{w2} \cdot \cos\alpha \ldots\ldots\ldots \tag{3}$$

$$V_{w2(y)} = (+)\, V_{w2} \cdot \sin\alpha \ldots\ldots \tag{4}$$

$$V_{w(x)} = V_{w3} - \{V_{w1} \cdot \cos\alpha\} - \{V_{w2} \cdot \cos\alpha\} \ldots\ldots\ldots \tag{5}$$

$$V_{w(y)} = \{V_{w1} \cdot \sin\alpha\} - \{V_{w2} \cdot \sin\alpha\} \ldots\ldots\ldots \tag{6}$$

$$V_{\theta} = \frac{V_{w1}}{L} + \frac{V_{w2}}{L} + \frac{V_{w3}}{L} \ldots\ldots\ldots \tag{7}$$

$$V_{wi(1,2,3)} = \omega \cdot r \ldots\ldots\ldots \tag{8}$$

$$\theta = \tan^{-1} \frac{V_{w(y)}}{V_{w(x)}} \ldots\ldots\ldots \tag{9}$$

Where, ω is the omnidirectional wheel's angular velocity in (rad/sec), r is the wheel's radius in (cm), V_{θ} is the robot's movement speed/ velocity and $\alpha = 60°$. Equations (5) and (6) can be solved by adding the value of alpha there.

$$V_{w(x)} = V_{w3} - \frac{V_{w1}}{2} + \frac{V_{w2}}{2} \ldots\ldots\ldots \tag{10}$$

$$V_{w(y)} = V_{w3} \cdot \left(\frac{\sqrt{3}}{2}\right) - V_{w2} \cdot \left(\frac{\sqrt{3}}{2}\right) \ldots\ldots\ldots \tag{11}$$

Equations (7), (10), and (11) rewritten in matrix form:

$$\begin{bmatrix} V_{w(x)} \\ V_{w(y)} \\ V_{\theta} \end{bmatrix} = \begin{bmatrix} -1/2 & -1/2 & 1 \\ \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 1/L & 1/L & 1/L \end{bmatrix} \cdot \begin{bmatrix} V_{w1} \\ V_{w2} \\ V_{w3} \end{bmatrix} \ldots\ldots\ldots \tag{12}$$

The following equation can be used to determine the robot's velocity and orientation at any given point:

$$V^{r} = \sqrt{V^{2}{}_{w(x)} + V^{2}{}_{w(y)}} \ldots\ldots\ldots \tag{13}$$

Where, $V_{w(x)}$ and $V_{w(y)}$vectors are acts along 'X' and 'Y' direction, V^{r} is resultant vector.

3. Electronic Control System

The control system comprises a multitude of electronic components collaboratively engaged in governing the Omni wheel holonomic robotic platform. This section delves into an exploration of the diverse electronic systems employed in the platform's design.

3.1. DC Motor

A DC motor is one that uses DC voltage as its input power source. A mobile robot is frequently designed using DC motors. In order to obtain an idea of how much power the motors of the robot platform must be able to deliver, the scenario shown in Figure 4 is used. For this case, it is assumed that there is no rotation of the platform, and then the front wheel does not have angular velocity. The robot moves through the hill straight forward. The forces operating on the vehicle base platform are clearly shown in the free-body diagram.

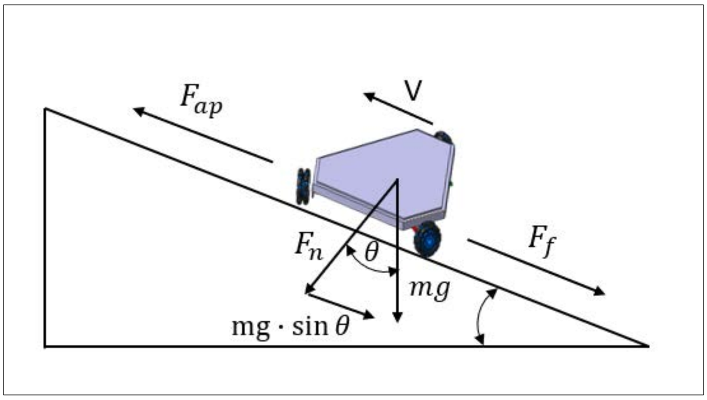

Figure 4 Free body diagram of robot

If the vehicle is going at a constant speed, there is no acceleration, hence there can be no net force. As a result, we discover from the free body diagram:

$$F_{ap} = F_f + F_w \ldots\ldots\ldots\ldots\ldots \quad (14)$$

Where F_{ap} denotes the applied force, (F_f) is the friction force, and (F_w) is the weight-related force operating in the direction of the robot's descent of the slope. F_f is calculated by multiplying the normal force F, by the rolling coefficient of friction (μ). Thus, we have:

$$F_{ap} = \mu mg \cos\theta + mg \sin\theta \ldots\ldots \quad (15)$$

The amount of power required by the motors is determined by multiplying the force that the wheels must exert by the robot's uphill travel velocity V is:

$$P_m = F_{ap} \cdot V \ldots\ldots \quad (16)$$

The power required equation can be written as using equations 15 and 16.

$$F_{ap} = mg \cdot (\mu\cos\theta + \sin\theta) \cdot V \ldots\ldots \quad (17)$$

Table 1 Assumed characteristics of Omni-wheel Robot

Parameters	**Assumptions Values**
Robot Weight (m)	4 Kg
Rolling Coefficient of friction (μ)	0.1
Ramp angle (θ)	10 degrees
Maximum velocity (V)	0.25 m/s

For our current application, we make a few assumptions, refer Table 1, and with these assumptions, the required power is 2.67 W. The motors utilized were a 12 V DC planetary motor with a 35 mm diameter gearbox in consideration of the power demand value. This motor's planetary gearbox has a 19.2:1 reduction ratio and generates 262 RPM with a torque of about 45 N-cm, see Figure 5 for an illustration of a motor.

Figure 5 Planetary gearbox motor

3.2. System Sensors and Communication Module

To ensure the availability of feedback data, several sensors are used. This section provides a thorough explanation of various sensors.

- Accelerometer: 3 Axis accelerometer that provide acceleration information for X, Y, Z movement.
- Wheel encoder: It is a Mechanical speed encoder with 24 pulse per rotation. This encoder is connected from outside to the rear wheel. A wheel encoder is a sensor or device attached to a robot's wheels to measure the rotation or displacement of the wheels. It provides information about how far the wheel has rotated or moved.
- Odometry Sensor: Odometry sensors are used to estimate a robot's position and movement by measuring changes in wheel rotation or motion. These sensors typically track how far and in what direction a robot has travelled based on the rotation of its wheels. It provides information about the robot's position relative to its starting point.
- Distance sensors: Obstacle detection is done using ultrasonic sensors, which have a range of 2–300 cm. The robotic platform is equipped with ultrasonic sensors on the front, back, left, and right sides.
- Communication: For development & monitoring USB wireless adapter that utilize the benefits of 802.11n technology. 802.11g support a maximum connection speed of 54 megabits per second (Mbps) and supports multi-channel utilization and dual band support for both 2.4 gigahertz (GHz) and 5 GHz frequencies with a maximum data rate of 600 Mbps. The use of the aforementioned sensors is illustrated in Figure 6.

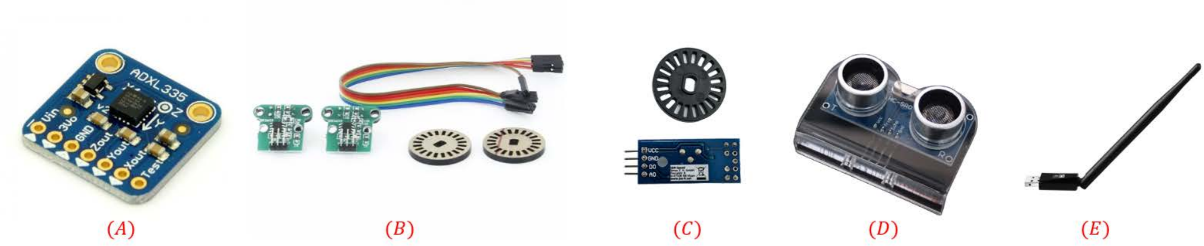

Figure 6 Types of sensors used for feedback and communication module (A) Accelerometer sensor (B)Wheel encoder (C) Odometry sensor (D) Ultrasonic distance sensor (E)Wireless USB Adapter

3.3. Motor Controller and Battery Management

A microcontroller board called Arduino Mega 2560 is based on the Atmega 2560 [14]. The Arduino Mega 2560, as depicted in Figure 7, features 54 digital input/output pins, including a 16-MHz crystal oscillator, a 4-pin UART (port serial hardware), 15 PWM output pins, 16 analog input pins, a reset button, a USB connection, a power socket, and an ICSP header, this module serves to support the control system. An Embedded Module Series (EMS) 30 A H-Bridge is integrated with the Arduino Mega 2560.

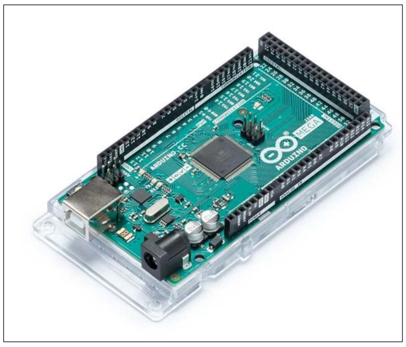

Figure 7 Arduino Mega 2560

Three planetary DC motors are driven by a 30 A H-Bridge, a H Bridge driver capable of producing a two-way drive at a voltage range of 4 to 16 volts and up to 30 A of continuous current. In order to provide input to the controller, this module is fitted with a load current sensor circuit; for a H bridge driver, see Figure 8**.** For Power management a 24 V Lithium Polymer (LiPo) battery is used in conjunction with a battery protection circuit, which tracks the battery's voltage and disconnects the load to prevent deep drain when a Li-Ion battery's voltage falls below the lockout threshold.

Figure 8 Embedded Module Series (EMS) 30 A H-Bridge driver

4. System for Motor Motion Control

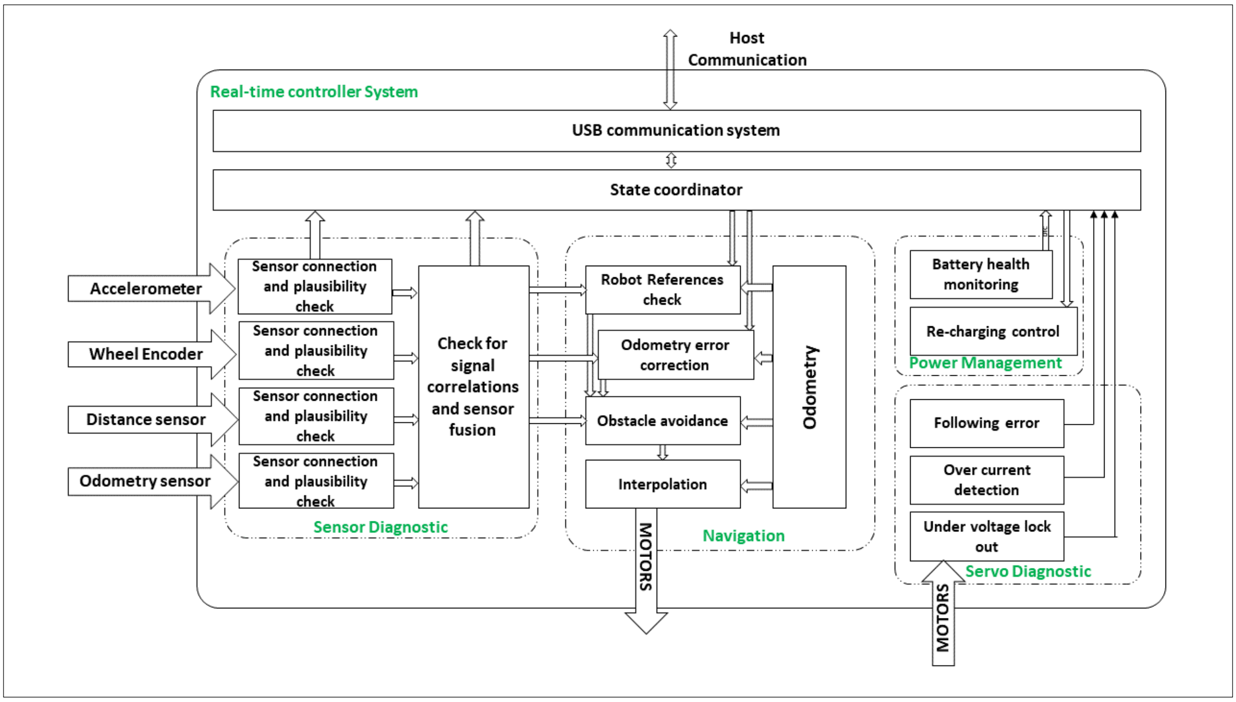

Figure 9 Motor motion controller system block diagram

Figure 9 depicts the real-time omni wheel motor motion control movement system's block diagram. All real-time tasks, such as robot kinematics, interpolations, battery management, odometry computations, sensor information handling, charging control, follow mistakes, etc., are handled by this embedded system. The control system includes USB connectivity and a CAN bus, a vehicle bus standard created to let microcontrollers and other devices communicate with each other's applications without the need for a host computer. The DC servo amplifiers are provided for the CAN, and the references between the robot and the controller as well as additional data transfer are handled by the other communications. The robot has ultrasonic distance sensors for obstacle avoidance. The follow error, over current, or under voltage lockout issues can be found and handled by the servo diagnostics. The navigation task, which deals with interpolation and servo driver references, is the controller's primary responsibility.

5. Mechanical Design of Omnidirectional three-wheeled robot platform

In the construction of an omnidirectional movable platform, there are numerous possibilities for where the wheel assemblies should be placed. The platform must remain stable regardless of how the assemblies are internally configured, or which wheel in each assembly is in contact with the ground. These are the only requirements for the layout: it must provide enough directions for constrained motions of the assemblies to allow for both omnidirectional translation and rotation of the platform. The platform load stability is quite simple to secure with the three assemblies placed at each of the triangle's three apexes, and great directional control is possible because of the 120° orientation relationship between the three limited motion directions.

For designing the structural platform three Omni wheels where selected. The unique feature of the omni wheel is its ability to move independently in each of the directions [15]. This wheel can move laterally across its outer circumference and typically revolves in a circle thanks to the screw. The robots can change from being non-holonomic robots to holonomic robots by using omnidirectional wheels. Only two degrees of freedom may be operated by a non-holonomic robot that uses standard wheels, such as moving forward, backward, and rotating. Since holonomic omni wheels have three degrees of freedom, this problem should be resolved. The holonomic omni directional robot may move in either direction without changing wheel alignment, in contrast to the non-holonomic robot. Wheels with holonomic omni-direction can spin, slide sideways, travel forward and backward, and slide.

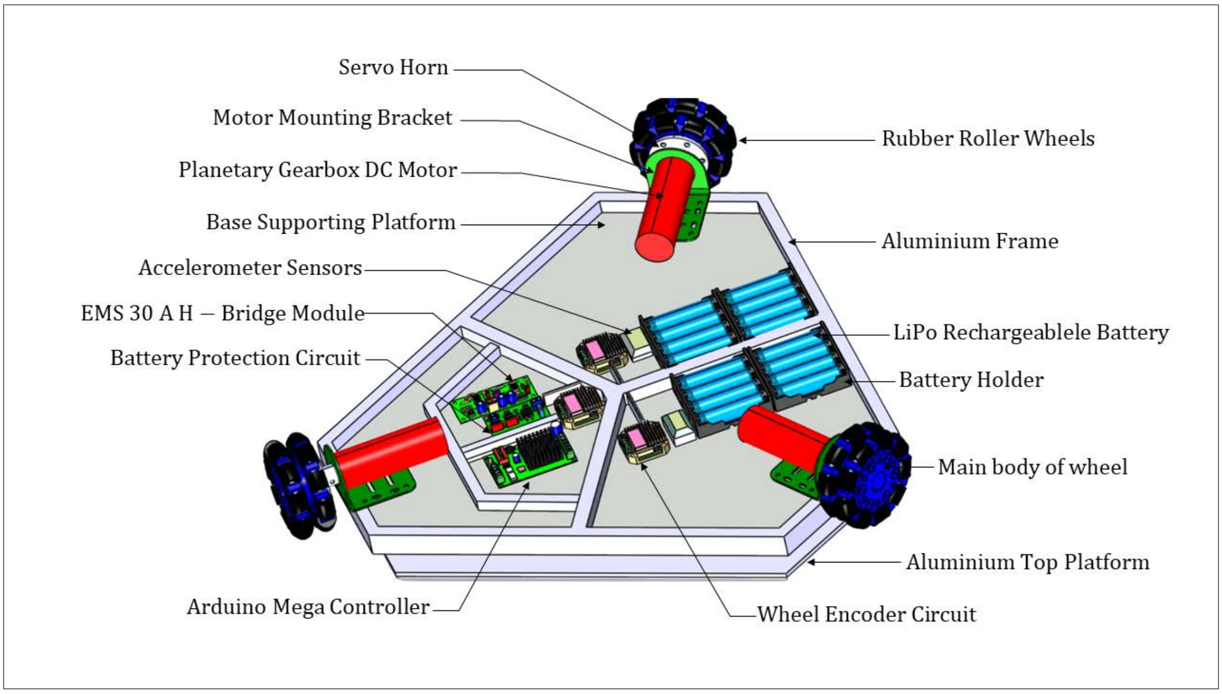

Figure 10 Three-wheeled holonomic omnidirectional robot platform bottom view

Three high torque motors were selected which were placed underneath the robot platform with the help of motor hub, the robot platform was designed in an equilateral truncated triangular shape having 60cm each side, providing a total platform surface area of 0.1020 m^2, where the platform was constructed from aluminium sheet of 0.5cm supporting total of around 4kg of weight handling capacity. The motors were placed at edges proving even weight distribution and supports holonomic drive. The elements of the structure are made from aluminium plates for structural support. The

24 Ah battery pack is attached beneath the robot platform additionally the bottom plate has windows to the ground for additional sensors, like a laser odometry sensor, a line following sensor, or even mechanical elements. The bottom plate houses the electronic control unit for driving the three motors of omni wheels. The top plate has several holes in a raster for cables, screws and peripheries, the platform is designed to allocate future extensions, such as additional sensors and a robotic arm. The platform can structurally support around 4kg of weight. Figure 10 and Figure 11 illustrates the whole platform bottom and top view concept.

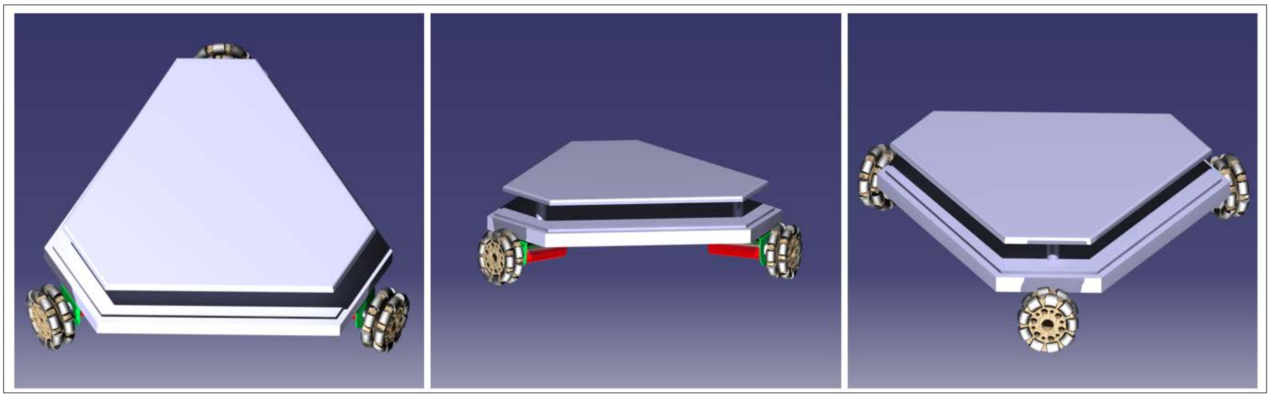

Figure 11 Three-wheeled holonomic omnidirectional robot platform top views

6. Discussion

The conceptual framework for the holonomic robot platform design holds applicability across a wide spectrum of prevalent mobile robot applications. Employing a consistent robot base across various service and industrial mobile robot applications can yield substantial reductions in both development time and associated costs. In congruence with these economies achieved during development, the mass production of identical robot bases for diverse applications results in cost efficiencies, thereby reducing expenses per unit manufactured.

7. Conclusion

This paper has presented the optimal mechanical design of a three-wheel holonomic omnidirectional robot platform intended for mobile robot applications. The paper has furnished a comprehensive design methodology for kinematic analysis of motion, alongside an exposition of the electronic control system and the mechanical CAD design underpinning the robotics platform. This platform possesses the capacity to support payloads of up to 4 kg and offers omnidirectional mobility, enabled by the omni drive system, which facilitates instantaneous changes in direction without necessitating wheel rotation.

This mobile robot serves as an open platform for researchers, fostering opportunities for the expansion and refinement of both mechanical and electronic systems. Future endeavours will focus on advancing the motion control system electronics, exploring dynamic motion characteristics, and refining path trajectory generation to enhance the performance of robots of this nature. It is necessary to build a robust and reliable platform for future enhancement. Such a reliable platform will ensure that the kinematic motion and generated trajectories closely approximate the kinematic equations elucidated in this research.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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