

Forward Kinematic Analysis and Simulation of Reconfigurable Four-Wheeled Omni-Drive Mobile Robot

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Abstract. Robots that are flexible, reconfigurable and universally adaptable and capable of performing various tasks in constrained and dynamic workspaces are in high demand. In this research general forward kinematic model has been developed and analyzed for two different geometric structures of reconfigurable four wheeled omni drive mobile robot. These two structures named Rhombus and Swastik model can reconfigure their geometry by varying design parameters as per task need. Six predefined motion M1 to M6 named forward, rotation, forward left turn, forward right turn, left yaw and right yaw motion are considered for performance evaluation for eleven different configurations C1 to C11 of each model. A MATLAB based simulation is carried out using time step of 0.1 second for 10 seconds duration, to evaluate the robots' trajectories, velocities, and angular orientations. Simulation result demonstrates, rhombus model has high stability and uniform motion due to symmetric wheel placements. It shows a nearly constant resultant velocity of 50 mm/s almost for all configurations and motions. In contrast, Swastik model has higher resultant velocity of 111 mm/s for M3 and 86 mm/s for M2 due to wheel offset arrangements which enhances maneuverability. The results show a clear trade-off between stability versus maneuverability across two models. In addition, geometric reconfiguration has minimal effect on linear motion but significant impact on turning and angular motions. The proposed model comes up with validated forward kinematic modelling and simulation framework for reconfigurable four wheeled omni drive mobile robot. It enhances the performance of geometry-dependent robots.

1 Introduction

Due to the industrial revolution, customized products' demand has increased in large measures. It plays very important role in the need for flexible production systems. Adaptable robotic systems that can adjust to environmental needs and perform a wide range of operational tasks have become increasingly essential in modern applications. The requirements of current manufacturing systems are to increase production to meet the global

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consumption needs which highlights the importance of Industry 4.0[1]. The applications of mobile robots have remarkable growth in various fields like defense, agriculture, industry, healthcare, service sector etc.[2]. Different types of Mobile robots like humanoid, quadruped and wheeled robots have different types of locomotion method. Robots that can move in any direction precisely and accurately are essential for the narrow and dynamics environment. In addition, energy efficiency is also important parameter for better performance of robots. Legged robots have capability of maneuvering in multiple directions, uneven terrain as well as express adaptable posture control. Leg robots consume more energy while wheeled robots are more energy efficient. But, due to the limit movement, particularly, in case of normal wheels, maneuverability can reduce. As a result of continuous research omni directional wheels were developed which can deploy with robots. Omni directional wheels are best suited for multidirectional movement precisely and for better energy efficiency[3].

A wheeled mobile robot with holonomic constraints can maneuver in any direction and change its position and orientation quickly. It can also parallelly achieve any required orientation. This kind of ability called omni directional mobility and by using specially designed wheels, omni directional movement can be achieved[4]. The design and development of autonomous and flexible mobile robots that can work in dynamic environments, which is one of major focuses of current robotics research. The robots that reconfigure their geometry as per need of surrounding referred as self-reconfigurable robots. Reconfigurability has certain characteristics like sustainability, adaptability and multi-functionality, which enable robots to perform specific task and prepare them to handle uncertain circumstances[5]. Structural adaptation over time helps these types of robots to work in dynamic environment effectively. Reconfigurable robots improve safety precautions and reduce failure chances. In addition, if partial damage occurs, they can adjust their structure and maintain important operational functionality. This makes these robots more adaptable and responsive in complex situations[6].

Hamid Taheri et al. have carried out study on omni directional drive systems for mobile robotics. Different working mechanisms and applications have been discussed. The author explained difficulties and recent development in omnidirectional mobile robots (OMRs). Comparison of different wheel mechanisms and navigation methods used in OMRs have been analyzed. This helped designers to choose appropriate wheel and drive systems. The trends for the development of application and constructive research and importance of differences of wheel design have been highlighted in the proposed study[7]. Eyad Almasri et al. compared benefits and drawbacks of various omni directional wheels with focus on stability and maneuverability aspects. The author has created a compact mathematical model for a symmetrical annular shaped omnidirectional wheeled mobile robot (SAOWMR) and validated it experimentally. This fundamental mathematical model can be applied to omnidirectional mobile robots having two, three, four, six or even more omni directional wheels. Computationally efficient techniques have been used for the improvement of trajectory planning for a SAOWMR. Furthermore, for collision-free navigation and by adding the path limitations, the evaluation has been done for the suggested approach. For the verification of efficiency and efficacy of the suggested approach, numerical tests and simulations are provided[8]. Masaaki Hijikata et al. highlighted the importance of wheel configurations that reduce vibration and improve compactness. This study proposes a robot with wheels placed at its four corners, enabling smooth movement in all directions. Experiments using a DC motor and a lightweight linear–quadratic regulator shows that the proposed design exhibits different trajectory distortions compared to conventional robots, mainly due to motor instability at low speeds. The results show that wheel arrangements strongly affect motion control in proposed design. Along with it improves robot performance also which is suitable for industrial transport applications[9]. Masaaki Hijikata et al. explained different inverse kinematic frameworks for omni wheel robots. The study analyzed

how wheel configuration affects robot behavior and analyzed robot behavior by modeling propulsive forces based on wheel ground speed. Experimental results shows velocity moments affect straight line motion which suggested improvements in robot design[10]. Chengcheng Wang et al. discussed benefits of omni directional mobile robots (OMRs) when compared to conventional wheeled robots with focus on efficiency and adaptability. They reviewed different motion control algorithms and highlighted the use of model predictive control (MPC). This method is mostly used in industrial applications. The researchers developed a kinematic framework for omni directional mobile robots and validated it using simulation results. It confirmed the efficiency of the proposed MPC controller[11]. Lim Yi et al. developed omni-directional self-reconfigurable robot. This robot can change width to move in confined spaces and improve adaptability in narrow areas. They studied complete coverage path planning (CCPP) method. The method enhances area coverage efficiency in complex environments by balancing speed and navigation through tight spaces. The study employed a modified Glasius Bioinspired Neural Network (GBNN) algorithm that generates global path autonomously as per robot width configuration state. Simulations and experimental results demonstrated that the algorithm reduced path length, steps and energy consumption with higher area coverage compared to exiting methods[12]. Minglu Chi et al. discussed the significance of modular design in robotics, emphasizing reconfiguration and dynamic expansion and developing an omni-directional mobile reconfigurable robot (OMRR) using an Arduino control board. It analyzes two OMRR forms: I shape and C shape, establishing a dynamics model and deformation mechanism. Results confirm the OMRR's stable movement and ability to navigate narrow spaces, validating the design's feasibility[13]. Shuaiby Mohamed et al. introduced mobility enhancing a quad omni-wheeled mobile robot in which linear servo actuators combined with omni wheels. With utilization of one servo motor and four DC motors, robots are designed for flat terrains as well as stair climbing. For the validation of robot's reliability, capabilities, demonstrating stability in movement, a prototype has been developed. The study employs SolidWorks and MATLAB for simulation, confirming the robot's effectiveness in stair climbing[14]. Aghus Sofwan et al. developed an omni wheeled mobile robot which utilizes inverse kinematics for driving the robot to specific trajectory and heading angles for indoor navigation, focusing on automatic warehousing applications. The robot employs internal wheeled encoders and an IMU for precise odometry and position estimation. For maintaining the position of robot with respect to the required target, a PID control algorithm is implemented. Test results indicate the robot's capability to follow controlled trajectories with minimal error[15].

Many solutions for omni drive mobile robots are widely available but not able to reconfigure itself to navigate through narrow passages. Few solutions are available with geometric reconfigurability but of non-holonomic nature. Lim yi et al[12] presented reconfigurable geometry in which width can vary for path planning but not provide comparative kinematic framework for different geometry. Masaaki hijikata et al[9] [10] and Minglu chi et al [13] proposed fixed and limited geometric design but not discussed how parametric changes in wheel placement affect kinematic performance across different configurations and motions. This is clear research gap that no literature direct provides systematic evaluation of a holonomic omni drive robot with two different geometrical and reconfigurable structures across multiple configurations and motion types. This study fills the gap through proposed design which has holonomic mobility with geometric reconfigurability and comparative analysis of kinematic structure. This type of omni-drive mobile robot with adaptive reconfigurability can be useful in warehouses, cold storage, orchards, farms etc. where the path of navigation has varied width and direction.

In this research, a kinematic model of 4 wheeled omni drive robot with reconfigurability is developed and applied to two different designs. The effect of geometrical reconfigurability on kinematic motion of omni drive robots is studied for both designs. General kinematic

formulation of omni drive robots are available in many literatures but this study presents, systematic application of this framework to two geometrically different reconfigurable models – Rhombus and Swastik across eleven parametric configurations and six motion types which has not been clearly explained in existing literature.

2 Kinematic model

To understand the concept of robot, pose, which refers to the representation of the robot's location and orientation, is crucial for the development of kinematic model of a mobile robot. For instance, consider a robot positioned at a certain point P relative to an inertial frame X_I and Y_I . Additionally, the robot is aligned at an angle θ . The local coordinate frame of the robot, denoted as X_R and Y_R , is attached to the robot body with its origin at point P which is geometric center of the robot. It is worth noting that the X_R direction always corresponds to the forward motion or heading direction of the robot.

For a 4-wheel omni-drive mobile robot, the general forward kinematic model relates the robot's velocity vector in the inertial frame to its wheel velocities as,

$$\dot{\xi}_I = R(\theta) J^{-1} \omega \quad (1)$$

where, $\dot{\xi}_I = \begin{bmatrix} \dot{X}_I \\ \dot{Y}_I \\ \dot{\theta}_I \end{bmatrix}$ is robot velocity vector w.r.t inertial frame, $R(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is

the transformation matrix from robot frame to inertial frame, $\omega = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}$ is wheel velocity

vector, and J is wheel configuration matrix of dimension 4×3 , each row is given by,

$$J_n = \frac{1}{r_n \cos \gamma_n} [\sin(\alpha_n + \beta_n + \gamma_n) \quad -\cos(\alpha_n + \beta_n + \gamma_n) \quad -L_n \cos(\beta_n + \gamma_n)] \quad (2)$$

here, n stands for number of wheels, α_n is corresponding wheel position angle, β_n is wheel orientation angle, γ_n is roller axis angle, r_n is wheel radius and L_n is linear distance from wheel center to geometric center of the robot. The general kinematic model developed for 4-wheel omni-drive mobile robot has been applied to two distinct reconfigurable robot models, namely Rhombus model and Swastik model. Figure 1(a) shows the geometric representations of the Rhombus model. The axis of wheel center intersects at the geometric center of the robot, ensuring symmetry in their positioning in the Rhombus model. In contrast, the wheel center axes are offset by a distance Y as shown in figure 1 (b) in Swastik model. Here, X is the distance of wheel plane from the geometric center of the robot. For both models, the nomenclature for wheels 1, 2, 3 and 4 is W1, W2, W3, and W4 respectively. Additionally, parameter L represents the distance of center of each wheel to center of the robot in a horizontal plane, which is a key dimension influencing the kinematic behavior of robots.

The pictorial view of CAD model for Rhombus and Swastik model can be shown in figure 2 (a) & (b). These views offer a clear and detailed visualization of the four wheeled omni-drive mobile robots. It showcases the geometric differences between Rhombus and Swastik models. These visuals help to understand the spatial arrangements and design characteristics in terms of their functionality and reconfigurability.

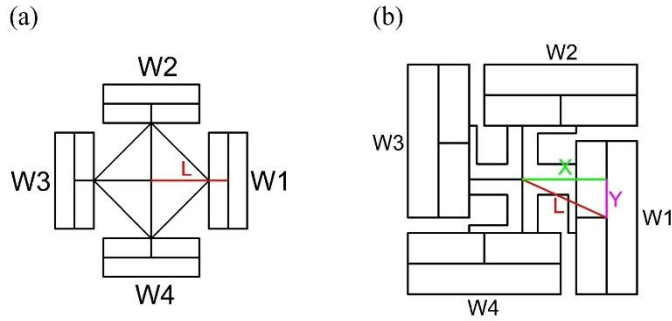


Fig. 1. Geometry of (a) Rhombus Model & (b) Swastik Model

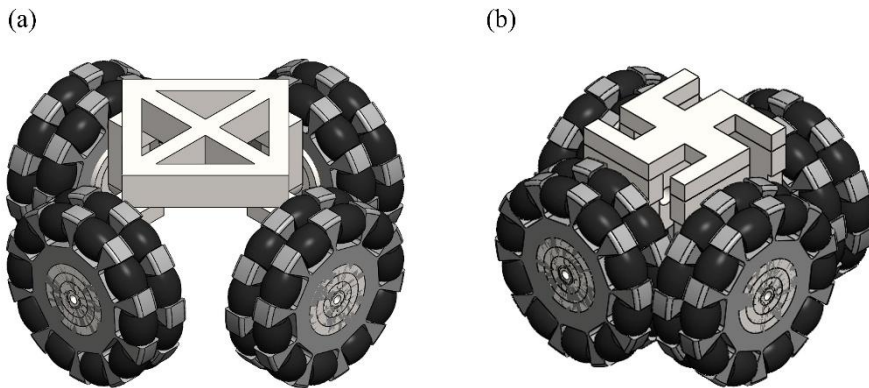


Fig. 2. Pictorial View of (a) Rhombus Model & (b) Swastik Model

From the geometry of the Rhombus model seen in figure 1 (a), geometrical parameter values, angles α , β , and γ are determined. These values for each wheel, which define the orientation and configuration of the robot's geometry, are presented in table 1.

Table 1. Geometric Parameter of Rhombus Model

| | W1 | W2 | W3 | W4 |
|----------|----|---------|-------|----------|
| α | 0 | $\pi/2$ | π | $-\pi/2$ |
| β | 0 | 0 | 0 | 0 |
| γ | 0 | 0 | 0 | 0 |
| L (mm) | L1 | L2 | L3 | L4 |
| r (mm) | 50 | 50 | 50 | 50 |

Table 2 represents the geometrical parameters values for Swastik model. These values can be calculated as per the geometric design of Swastik model which is shown in figure 1 (b). From the geometric design, $\beta = \tan^{-1}(Y/X)$ and $Y^2 + X^2 = L^2$ and $Y1=Y2=Y3=Y4=30$ mm, which is offset distance from robot center to wheel center. Mathematical equations are derived from the geometric design of Swastik model which describes the model structure and motion behavior. The study of mathematical models and relationships helps to understand kinematic behavior, and it is highly important for simulation accuracy as well as execution of real-world applications. All the geometric parameters and mathematic formulas of the Swastik model are highly responsible for the reconfiguration and functionality operation.

Table 2. Geometric Parameter of Swastik Model

| | W1 | W2 | W3 | W4 |
|----------|------------------------|------------------------|------------------------|------------------------|
| α | β_1 | $\pi/2 - \beta_2$ | $\pi - \beta_3$ | $\pi/2 + \beta_4$ |
| β | $\tan^{-1}(Y_1 / X_1)$ | $\tan^{-1}(Y_2 / X_2)$ | $\tan^{-1}(Y_3 / X_3)$ | $\tan^{-1}(Y_4 / X_4)$ |
| γ | 0 | 0 | 0 | 0 |
| X (mm) | X1 | X2 | X3 | X4 |
| r (mm) | 50 | 50 | 50 | 50 |

The wheel radius is 50 mm for both Rhombus and Swastik model. This ensures fair comparison in the analysis of the two different geometric configurations. Accurate geometric parameters are crucial for kinematic modeling and also necessary for the correct simulation results. Wheel dimensions directly affect the motion behavior and influence overall performance of the robot. The consistency of wheel dimensions simplifies the comparison between two models and maintains uniformity in the reconfigurable design study. The geometric parameters α_n , β_n , r_n and L_n decides kinematic output of proposed design as per equation 2. Due to symmetric wheels placement (responsible α angle) and distance variations of L, it affects all jacobian rows uniformly in Rhombus design which scale the robot velocities without changing direction. While asymmetric wheel placements (responsible β angle) can be seen due to offset parameter Y in Swastik design affects jacobina rows non-uniformly. The Swastik model ensures that it has stronger kinematic impact in form of geometric reconfiguration during mathematical modeling than Rhombus model.

3 Computer simulation

Rhombus and Swastik models can reconfigure their geometric design by changing the distance of robot center to wheel center. Due to this, eleven different configurations named configuration 1 (C1) to configuration 11 (C11) for each model are considered and used for simulation. The configuration details of parameter comparison for Rhombus and Swastik model are shown in table 3.

Table 3. Configurations Details of Rhombus & Swastik Model

| | Rhombus Model Configuration | | | | Swastik Model Configuration | | | |
|------------------------|-----------------------------|-------|-------|-------|-----------------------------|-------|-------|-------|
| | L1 | L2 | L3 | L4 | X1 | X2 | X3 | X4 |
| Configuration 1 (C1) | L | L | L | L | X | X | X | X |
| Configuration 2 (C2) | 1.5 L | L | L | L | 1.5 X | X | X | X |
| Configuration 3 (C3) | L | 1.5 L | L | L | X | 1.5 X | X | X |
| Configuration 4 (C4) | L | L | 1.5 L | L | X | X | 1.5 X | X |
| Configuration 5 (C5) | L | L | L | 1.5 L | X | X | X | 1.5 X |
| Configuration 6 (C6) | 1.5 L | L | 1.5 L | L | 1.5 X | X | 1.5 X | X |
| Configuration 7 (C7) | L | 1.5 L | L | 1.5 L | X | 1.5 X | X | 1.5 X |
| Configuration 8 (C8) | 1.5 L | 1.5 L | L | L | 1.5 X | 1.5 X | X | X |
| Configuration 9 (C9) | L | 1.5 L | 1.5 L | L | X | 1.5 X | 1.5 X | X |
| Configuration 10 (C10) | L | L | 1.5 L | 1.5 L | X | X | 1.5 X | 1.5 X |
| Configuration 11 (C11) | 1.5 L | L | L | 1.5 L | 1.5 X | X | X | 1.5 X |

Figure 3 (a) shows the geometric structure of configurations 1 to configurations 11 (C1 to C11) for Rhombus model while figure 3 (b) shows for Swastik model. These visuals images of all the configurations help in clear understating of the designs. They allow easy

comparison between configuration and design variations can be analyzed visually. Differences between configurations and all features are properly illustrated in tabular data and graphical visualization.

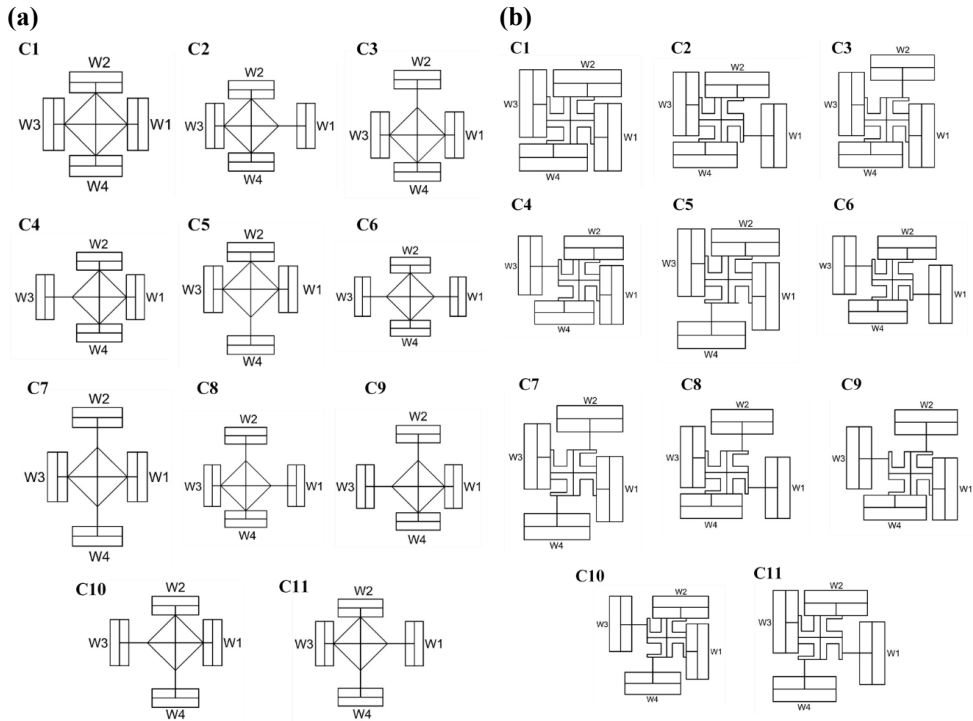


Fig. 3. Eleven Configurations (a) Rhombus Model (b) Swastik Model

Six predefined motions, forward motion (M1), rotation motion (M2), forward left turn motion (M3), forward right turn motion (M4), left yaw motion (M5) and right yaw motion (M6) are considered, and wheel velocities are ω_1 , ω_2 , ω_3 and ω_4 for wheel 1, 2, 3 and 4 respectively for both models. These velocities are considered as input to simulate the above six motion M1 to M6. These details are presented in Table 4 and used for the analysis of kinematic behavior and reconfigurability for all eleven configurations C1 to C11 for both models.

Kinematic constraints are responsible for robot motion and control movement capability of the robot. A four-wheeled omni-drive mobile robot is highly maneuverable and is most suited for tasks requiring flexible movement. A MATLAB based kinematic simulations framework is used to evaluate robot motion for both models for each configuration and used for computational efficiency. Chengcheng Wang et al [11] and Eyad Almasri et al [8] used MATLAB based kinematic simulation and results obtained from simulation were used for validation of kinematic model before making prototype. This validation methodology is broadly acceptable in research of omni drive mobile robots. The simulation employs a discrete time step ($dt=0.1$ s) and spans $t=1$ to 10s. Initial robot states, including position (X_0 , Y_0) and orientation (θ_0), are set to zero, forming the initial state vector, $\xi_1 = [X_0; Y_0; \theta_0]$. The values of wheel configurations of robot- wheel radius r , wheel center distance L , wheel velocities ω_1 , ω_2 , ω_3 , ω_4 and angular orientations α , β , γ for both models are mentioned in table 1 to 4. The MATLAB script systematically updates these parameters over six velocity sets and eleven configurations. The Jacobian matrix which is present in equation 3 connects

wheel velocities to robot velocities. It is computed based on wheel orientations and distances from the robot's center. The generalized velocity of the robot $\dot{\xi}_R$ is calculated using the pseudo-inverse of the Jacobian and the wheel velocity vector ω .

$$\dot{\xi}_R = J\omega, \tag{3}$$

Table 4. Robot Motion Types & Wheel velocity

| Robot Motion | Wheel Velocity (rad/s) | | | |
|--------------------------------|------------------------|------------|------------|------------|
| | ω_1 | ω_2 | ω_3 | ω_4 |
| Forward Motion (M1) | 0 | 1 | 0 | -1 |
| Rotation Motion (M2) | 1 | 1 | 1 | 1 |
| Forward Left Turn Motion (M3) | 0 | 0.5 | 0 | -1 |
| Forward Right Turn Motion (M4) | 0 | 1 | 0 | -0.5 |
| Left Yaw Motion (M5) | -1 | 0 | 1 | 0 |
| Right Yaw Motion (M6) | 1 | 0 | -1 | 0 |

where J = pseudo – inverse of the jacobian, Using Euler integration, the robot's position and orientation are updated iteratively over discrete time steps. The transformation matrix $R(\theta)$ accounts for the robot's rotation, converting velocities from the robot frame to the inertial frame, $\xi_I = R(\theta) \xi_R$. The state is updated as, $\xi_I(t + 1) = \xi_I(t) + dt R(\theta) \dot{\xi}_I$. So, here from the simulation data the robot velocities \dot{x}_I, \dot{y}_I and $\dot{\theta}_I$ are obtained with respect to inertial frame for C1 to C11 of M1 to M6 for Rhombus and Swastik model. From \dot{x}_I and \dot{y}_I the resultant velocity is calculated as,

$$\dot{v}_I = \sqrt{\dot{x}_I^2 + \dot{y}_I^2} \tag{4}$$

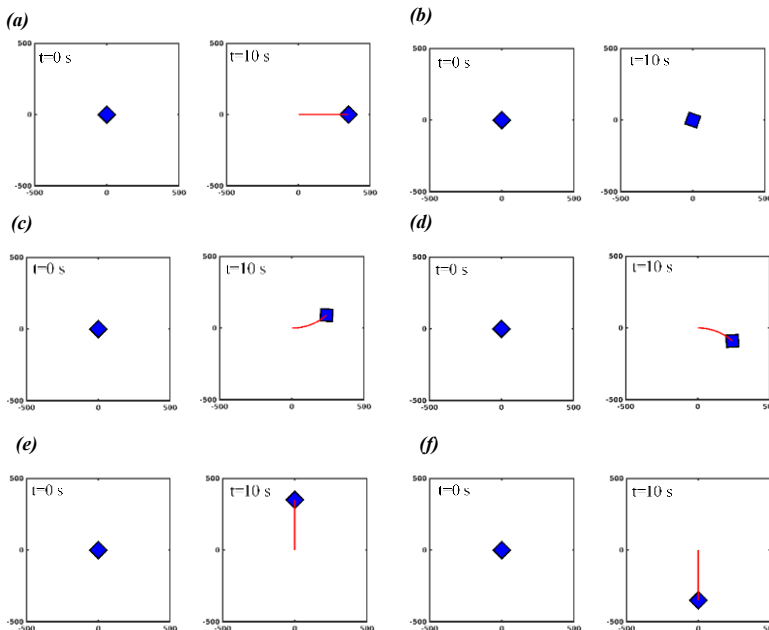


Fig. 4. Robot Motion for initial time & final time for Configuration 1 of Rhombus Model for (a) Forward Motion (b) Rotation Motion (c) Forward Left Turn Motion (d) Forward Right Turn Motion (e) Left Yaw Motion (f) Right Yaw Motion

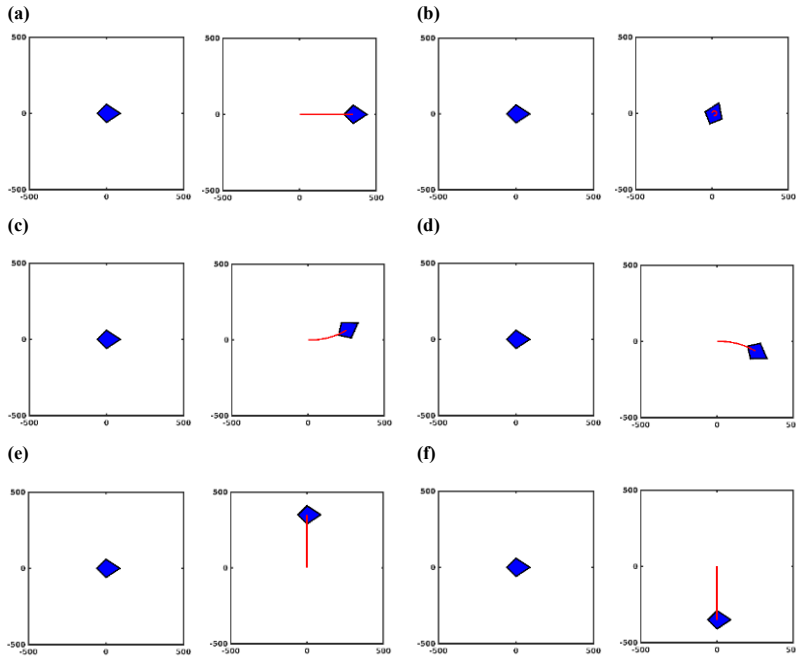


Fig. 5. Robot Motion for initial time & final time for Configuration 2 of Rhombus Model for (a) Forward Motion (b) Rotation Motion (c) Forward Left Turn Motion (d) Forward Right Turn Motion (e) Left Yaw Motion (f) Right Yaw Motion

Figure 4 & 5 shows the trajectory at initial time $t=0$ second and trajectory at final time $t=10$ seconds for M1 to M6 for configuration 1 and configuration 2 of Rhombus model. Generated using MATLAB, these trajectories provide insights into the model's motion capabilities and adaptability under varying velocity inputs.

4 Results and discussion

4.1 Comparative analysis of resultant velocities

Variations in geometric parameter L and X result in configurations C1 to C11 for Rhombus model and Swastik model respectively. These parameters and configurations represent parametric sensitivity analysis of forward kinematic model in terms of wheel placement distances. The resultant velocity is calculated as per equation (4) for M1 to M6 across C1 to C11 for Rhombus and Swastik model and presented in table 5. The calculation of resultant velocity for each configuration reveals detailed analysis of performance of the robot across various movement types, enabling a detailed comparison of the two models under different operating conditions. From the forward kinematic simulation framework, resultant velocity is calculated and it is considered as main performance criteria for this research. Other performance criteria like stability margin, energy efficiency and tracking error which require dynamic modeling and control system design, which is excluded in this present study, but it implies future work.

Figure 6 shows a comparative analysis of the resultant velocities of C1 to C11 for both Rhombus and Swastik models across, M1 to M6. Rhombus model indicates nearly constant resultant velocity of approximately 50 mm/s across all the configurations and motion types which reveals that it is more stable and has predictable motion characteristics. Geometric

symmetry of rhombus model improves the performance, and dimensional changes have very low effect on velocity. This model is suitable for precise trajectory tracking and useful for constant speed applications. This type of robot is used in medical service robots, for transportation of material in warehouses, industrial inspection etc.

Table 5. Resultant Velocity of Rhombus & Swastik Model Robot for 6 Different Motion

| | Rhombus Model | | | | | | Swastik Model | | | | | |
|-----|---------------|----|----|----|----|----|---------------|----|-----|----|----|----|
| | M1 | M2 | M3 | M4 | M5 | M6 | M1 | M2 | M3 | M4 | M5 | M6 |
| C1 | 50 | 0 | 38 | 38 | 50 | 50 | 22 | 0 | 33 | 33 | 45 | 45 |
| C2 | 50 | 11 | 38 | 38 | 50 | 50 | 33 | 17 | 17 | 41 | 42 | 42 |
| C3 | 50 | 11 | 39 | 36 | 50 | 50 | 98 | 7 | 102 | 45 | 68 | 68 |
| C4 | 50 | 11 | 38 | 38 | 50 | 50 | 29 | 21 | 40 | 20 | 44 | 44 |
| C5 | 50 | 11 | 36 | 39 | 50 | 50 | 71 | 13 | 25 | 82 | 67 | 67 |
| C6 | 50 | 0 | 38 | 38 | 50 | 50 | 24 | 24 | 18 | 31 | 43 | 43 |
| C7 | 50 | 0 | 38 | 38 | 50 | 50 | 92 | 86 | 111 | 28 | 50 | 50 |
| C8 | 50 | 14 | 39 | 36 | 50 | 50 | 21 | 13 | 23 | 30 | 45 | 45 |
| C9 | 50 | 14 | 39 | 36 | 50 | 50 | 65 | 18 | 71 | 28 | 52 | 52 |
| C10 | 50 | 14 | 36 | 39 | 50 | 50 | 19 | 13 | 21 | 36 | 56 | 56 |
| C11 | 50 | 14 | 36 | 39 | 50 | 50 | 38 | 10 | 15 | 46 | 48 | 48 |

Results for Swastik model shows exceptional variations in resultant velocity with reconfiguration, especially for angular and turning motions (M3–M6). The maximum resultant velocities are recorded as 86 mm/s in rotational motion (M2, C7), 111 mm/s during forward-left turn motion (M3, C7), and 82 mm/s for forward-right turn motion (M4, C5). These higher velocities are due to the offset wheel design that improves maneuverability. In addition, turning efficiency is also increased and directional control becomes better. Higher velocities are also responsible for non-uniform kinematic behavior because of asymmetric geometry of Swastik model. It is suitable for fast movement and performs effectively in quick directional changes. This model is useful for flexible navigation tasks as well as narrow and complex environments.

Table 6. Optimum Configuration Parameters for Each Motion Type for Both Models

| Motion Type | Optimum Model | Optimum Configuration | Resultant Velocity (mm/s) | Performance Remark |
|--------------------------------|---------------|------------------------|---------------------------|--|
| M1 – Forward Motion | Rhombus | C1–C11 (All identical) | 50 | linear stability, geometric balance, constant velocity |
| M2 – Rotation Motion | Swastik | C7 | 86 | enhances dynamic turning, higher rotational velocity |
| M3 – Forward Left Turn Motion | Swastik | C7 | 111 | highest left-turn agility, rapid response |
| M4 – Forward Right Turn Motion | Swastik | C5 | 82 | smooth right- turn control with balanced angular momentum with response |
| M5 – Left Yaw Motion | Rhombus | C1–C11 (All identical) | 50 | minimal trajectory deviation, uniform yaw control, superior stability |
| M6- Right Yaw Motion | Rhombus | C1–C11 (All identical) | 50 | Consistent angular velocity; precise control in rotational and directional maneuvers |

It is clear trade-off between maneuverability and stability. Swastik model offers better adaptability and agility as resultant velocities ranging from 0 to 111 mm/s which increases 122% compared to Rhombus model. On the other hand, Rhombus model focuses on stability and predictability as constant resultant velocity of 50 mm/s with almost zero variance across all configurations.

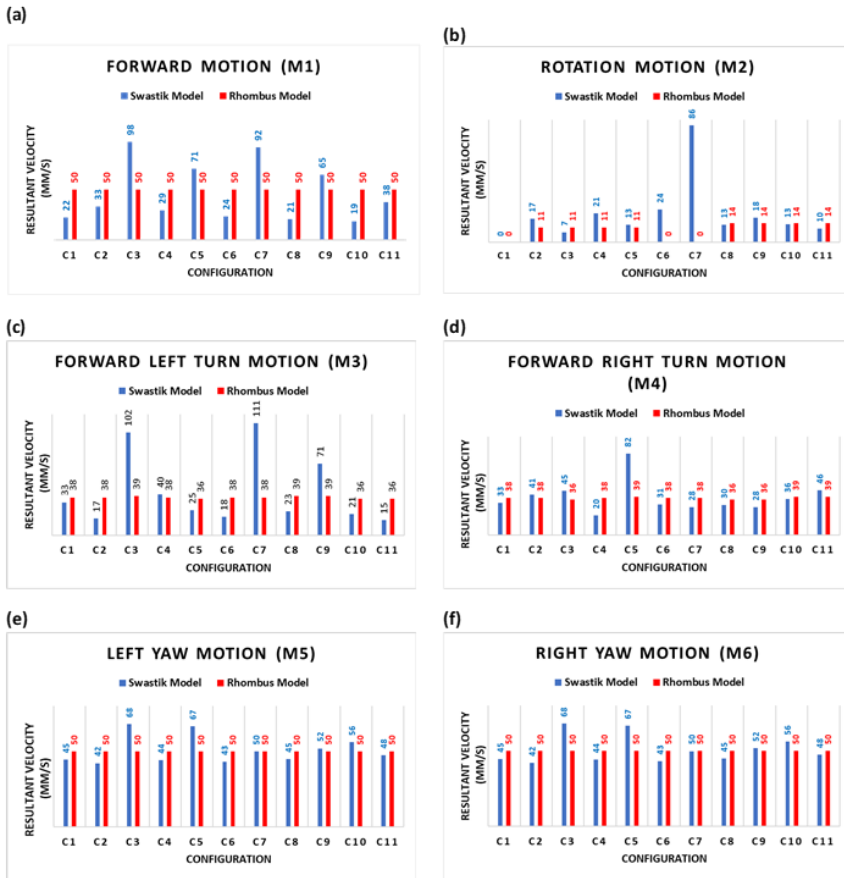


Fig. 6. Resultant Velocities Comparison of C1 to C11 for (a) Forward Motion M1 (b) Rotation Motion M2 (c) Forward Left Turn Motion M3 (d) Forward Right Turn Motion M4 (e) Left Yaw Motion M5 (f) Right Yaw Motion M6 of Rhombus Model & Swastik Model

4.2 Performance evaluation and model suitability for real-world applications

In the present work, wheel placement distances, wheel configuration geometry and input wheel velocities are key design variables that govern the robot’s resultant velocity which is the principal performance parameter for forward kinematic analysis. A comparative kinematic analysis is carried out for Rhombus and Swastik model which shows different characteristics that affect their practical applications. Rhombus model has symmetric geometry, provides higher stability, consistent trajectory repeatability and predictable motion behavior. Performance of the rhombus model is not much affected by geometric changes and most preferable for structured environments where path accuracy is important. Applications

of this robot in various fields like automated warehouse transport, hospital service robot, industrial inspection etc.

Swastik model shows higher agility and better dynamic adaptability. Offset wheel configuration is responsible for higher velocities because it creates higher torque differentials and higher angular acceleration. This allows quick direction changes and improves maneuvering in narrow spaces. Applications of this robot in various domains like cold storage, rescue operations, agricultural etc. Here, stability is reduced and control becomes more complex. So, accurate feedback control is required for path tracking. Both models undergo real world obstacles during physical deployment. Symmetric design and balanced wheel loading help to decrease wheel slip in Rhombus model. During configuration changes confined actuator torque impact repeatability and positional accuracy. In turning motions, offset wheel arrangement leads to higher resultant velocity, maximizing the possibility of wheel slip and uneven terrain interaction. To achieve the result, slip compensation algorithm and higher torque actuators should be required.

From design perspective, rhombus model is suitable for stable and accurate tasks as well as providing good energy efficiency. Swastik model offers better reconfigurability and is highly maneuverable. It is better for unstructured or time sensitive tasks. Both designs can be combined in single control system where the robot can switch between stable and agile modes. Configuration can change as per task requirements. Finally, this study shows that kinematic reconfigurability increases operational flexibility which expands application areas of omni drive mobile robots. It is useful in industry 4.0 where modularity, precision and adaptability are important.

5 Conclusion and future scope

This study shows forward kinematic analysis and MATLAB based simulation of reconfigurable four wheeled omni drive mobile robot for rhombus and Swastik model. Eleven different configurations C1 to C1 and six motions M1 to M6 considered for analysis. This research investigates the impact of geometric reconfigurations on resultant velocity, stability and maneuverability for both models and results indicate that geometric reconfigurations have significant impact on motion behavior and performance efficiency. Rhombus model has uniform resultant velocity of 50 mm/s for all configurations, because of that it is more stable and predictable motion behavior. It is suitable for applications where path precision, steady navigation and energy efficient motion requirements such as industrial inspection systems. Swastik model has higher velocities of 111 mm/s for M3 and 86 mm/s for M2 in turning and rotation motions because of that it is more maneuverable and capable of agile navigation in dynamic environments where fast orientation and obstacle avoidance are more critical.

Finally, this research shows a clear trade-off between stability and maneuverability. Rhombus model is responsible for steady locomotion as it has 50 mm/s constant velocity across all configurations while Swastik model has delivered up to 111 mm/s in turning motions which is suitable for dynamic motion control. Future work implies for further validation and strengthening the conclusion through dynamic modeling and closed loop control. It also reveals, reconfigurability has minimal effect on linear motion while significant effect on angular and turning motions which are important characteristics for adaptive mobile robots.

Future work focuses on closed loop control strategies like adaptive PID or Model Predictive Control (MPC) to allow trajectory tracking and evaluation of control performance. Sensor fusion method and AI based path planning can be used for better localization which enhances autonomy. To support robustness assessment under parameter uncertainties and trajectory error analysis dynamic modelling will be done. For real world operating conditions

disturbance modeling will be considered. Physical prototype of Rhombus and Swastik model will be made as part of immediate future work for experimental validation which includes testing of path trajectory across all configurations C1 to C11 and motion types M1 to M6. Future work also includes practical challenges like wheel slip and actuator limitations. Finally, performance should be tested on different terrains.

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