

A Study on Kinematic Analysis and Position Tracking Control of a Differential-Driven Four-Wheel Mobile Robot with a Rotary Axis for Steering Characteristic Improvement

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ABSTRACT

The wheel layout of a wheeled mobile robot has a crucial role in the steering characteristics of a mobile robot. In this paper, a differential-driven structure with a rotary axis is proposed to improve the steering characteristics of a differential-driven four-wheeled mobile robot, and its kinematic analysis and position tracking control performance are analyzed. To verify the effectiveness of the proposed structure, a comparative analysis of the position tracking performance with a generalized differential-driven mobile robot is carried out. Simulation and experimental results show that the proposed structure mobile robot has superior position tracking performance and smaller turning radius compared to the generalized differential-driven wheeled mobile robot.

Keyword: differential driven mobile robot, steering characteristics, kinematic analysis, position tracking control

INTRODUCTION

A mobile robot is an intelligent robot that performs its work by moving in a certain area on itself using a mobile mechanism such as legs, wheels, tracks, etc.[1, 3]

Research on mobile robots has been started decades ago and today, with the enhancement of intelligence and efficiency, it is widely used in the defense, industrial, space, and service sectors, and its application is expanding with each passing day. [2]

Currently, the mobile robots can be classified according to the moving mode, such as wheeled mobile robots, legged mobile robots, tracked mobile robots, etc. There are also mobile robots that perform navigation in air and underwater without touching the ground. [1, 5]

The focus of mobile robots is on improving the reliability of robotic mechanisms and further improving the level of robotic intelligence. In particular, the rational design of the robotic mechanism can positively affect the performance of the control system while ensuring the reliability of the mobile robot's work.

The mobile robot needs a mobile mechanism that can move in its work area without limitations and with ease and reliability, and the movement mechanism of this robot has been studied.[6]

The mobile mechanism of a mobile robot can be classified into different categories according to the criteria. According to the steering mode, it can be classified as the ackerman steering mode and the differential driving mode. [4]

The ackerman steering mode is a steering mode that actively changes the direction of movement of the robot, mimicking the steering structure of the vehicle, which has the advantage of relatively complex device design but easy control. The differential driving mode is a steering mode in which the direction of movement is passively

changed by the difference in speed of the moving mechanisms, and the design of the device is relatively easy, but the control is very sophisticated. Initially, the steering mode of the mobile robot was dominated by the ackerman steering mode, but with the performance of the mobile mechanisms and the higher work requirements of the mobile robot, the differential driving mode that can be rotated instantaneously in any direction is now becoming more popular.

The differential drive mode is the one in which the magnitude and direction of the moving speed are determined by the difference in the speed of the actuators that support the motion, and the kinematic and dynamic models are determined by the type and numbers of actuators and their configuration, and the motion performance of the robot is determined.

The stability, mobility, maneuverability and load capacity of wheeled mobile robots vary greatly depending on the type of wheel and the type of wheel layout. Wheeled mobile robots are divided into one-, two-, three-, four- and more wheeled mobile robots according to the numbers of wheels, and the type of wheel layout varies with the numbers of wheels.[4]

Francesco Galasso et al. [7] proposed a four-wheeled AGV structure with the ackerman structure and dual-drive kinematics and proposed a new method for external and internal auto-calibration. Leonardo Marn et al. [8] used a sensor fusion technique with event-based global position correction to improve the localization of mobile robots with limited computational resources. The proposed algorithm uses a new position dynamics model of the modified Kalman filter and the ackerman steering mobile robot, which has similar performance compared to more complex fusion schemes but faster execution speed and enables its implementation inside the robot. Haojie Chen et al. [9] proposed a new type of vehicle-shaped robot that can drive and steer the front wheel to solve the jammed front wheel problem due to the passive trajectory tracking of a vehicle-like robot popular in the roadway-follower formation control, and then built its kinematic model, analyzed its controllability through the method of a chain-like system, and designed the trajectory tracking controller using the backstepping method. Chih-Lyang [10] Hwang et al. proposed a trajectory tracking and (dynamic) obstacle avoidance method for a mobile robot with the ackerman steering mechanism in sensor distribution-network space using fuzzy distributed sliding mode control (FDSMC). Jin Xin et al. [11] proposed a kinematic model of a welding mobile robot with ackerman steering mode and a real-time trajectory tracking algorithm based on fuzzy neural network, and a special learning structure that can adjust the membership function in real time by applying back propagation algorithm of FGNN. A.A.A. Razak et al. [12] proposed a mobile robot structure that can be instantaneous and steep turning by introducing a four-wheel sliding steering mechanism and analyzed the structure. Mircea Niulescu et al. [13] performed a mathematical model and control solution of a two-wheel differential-driven mobile robot. Chih-Lyang Hwang et al. [14] developed trajectory tracking of an ackerman Steering Mobile Robot (CLMR) using Network-based Fuzzy Distributed Sliding Mode Control (NBFDSMC). Joaquín Gutiérrez et al. [15] describe an analytical method for localization error modeling of a differential driven mobile robot with joint structure, and the measurement of this error is compared with the geometries of various steering profiles. Diana Diaz et al. [16] analyzed the mathematical model of a generalized differential-driven wheeled mobile robot and based on it, the position tracking control was carried out. ZHANG Feng et al. [17] studied the modeling and path estimation of a wheeled mobile robot with the ackerman steering mode. Genya Ishigami et al. [18] developed a model that takes into account the dynamics of the slip and slip behaviour of each wheel in the four-wheel car-like configuration of the ackerman steering mode to analyze the steering characteristics of the vehicle in natural soil. Imad Matraji et al. [19] designed an adaptive second order sliding mode controller of a four-wheel steering-sliding mobile robot (SSMR) and implemented a robust control with neglected oscillations in steady state using an adaptive supertwist (AST) algorithm. Martin Velasco-Villa et al. [20] implemented a measurement-based partial state feedback strategy from an indoor vision-based absolute positioning system to solve the tracking problem of a wheeled mobile robot with differential drive.

The analysis of the above structural studies and the research context of control system design and implementation of wheeled mobile robots reveals that most of the research on wheeled mobile robots with already determined structure, such as the ackerman steering and differential driving, has been mostly carried out. The differential driven wheeled mobile robot consists of a driving wheel and a freewheels, which can be mounted either in the front or rear. While this configuration is simple to manufacture and relatively easy to analyze, it is also possible that the dynamic inertia is large compared to the ackerman steering mode and the sliding characteristics of the

wheels may have a detrimental effect on the steering and position tracking of the robot.

In this paper, to avoid the drawbacks of this differential driven mode, a structure of a front differential driven wheeled mobile robot connected with a rotary axis is proposed, kinematic analysis is carried out, and position tracking performance is analyzed to compare the simulation with a generalized differential driven wheeled mobile robot.

The simulation results showed that the proposed front differential wheeled mobile robot with the rotary axis has better position tracking performance and load-bearing performance and smaller working turning radius of the robot compared to the conventional ackerman steering wheeled mobile robot or the generalized differential-driven wheeled mobile robot.

Kinematic analysis of a differential driven four-wheeled mobile robot with a rotary axis

To perform the kinematic analysis of the proposed differential-driven four-wheeled mobile robot with a rotary axis, we set the mobile robot coordinate system xRy to the reference coordinate XOY and the rotary point R of the driving wheel platform of the mobile robot as shown in Fig. 1. Also, point P , which is situated at a distance a from the point R in the direction perpendicular to the prolongation of the actuated wheels' rotation axes, is the considered point.

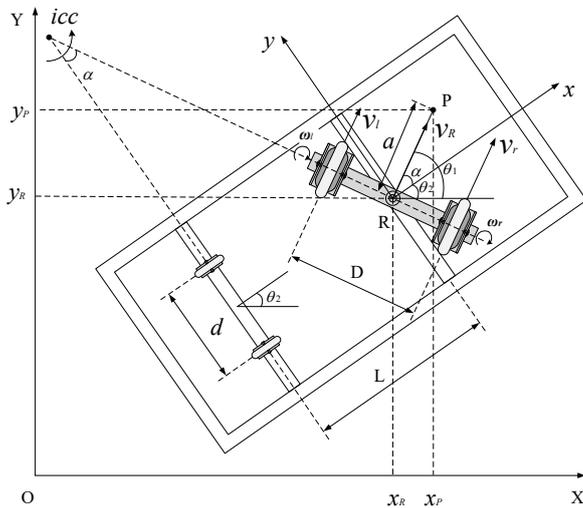


Fig. 1. Motion analysis of a differential-driven four-wheeled mobile robot

In the figure, θ_1 is the orientation angle of the driving wheel turntable, θ_2 is the orientation angle of a robot, α is the angle between the line perpendicular to the driving wheel axis and the x -axis of the mobile robot coordinate system.

And v_l, v_r, ω_l and ω_r are the linear and angular velocities of the left and right driving wheels, respectively, and v_R is the translational velocity of point R .

The coordinate vector that completely describes the motion of the mobile robot is expressed as

$$\xi_P = [x_P, y_P, \theta_1, \theta_2]^T \tag{1}$$

In this paper, the kinematic analysis model of a mobile robot is constructed into two models, model 1, which takes as input the translational and angular velocities of the mobile robot, and model 2, which takes as input the angular velocities of the driving wheels of the mobile robot.

First, model 1 is written as follows.

The relationship between the coordinates of the point $P (x_P, y_P)$ and the coordinates of the point $R (x_R, y_R)$ is as follows:

$$\begin{cases} x_P = x_R + a \cos \theta_1 \\ y_P = y_R + a \sin \theta_1 \end{cases} \quad (2)$$

Taking the time derivate

$$\begin{cases} \dot{x}_P = \dot{x}_R - a\dot{\theta}_1 \sin \theta_1 \\ \dot{y}_P = \dot{y}_R + a\dot{\theta}_1 \cos \theta_1 \end{cases} \quad (3)$$

On the other hand, if the x- and y-directions of the driving wheel bracket rotation point R are given by \dot{x}_R and \dot{y}_R , respectively, the following equation holds :

$$\begin{cases} \dot{x}_R = v_R \cos \theta_1 \\ \dot{y}_R = v_R \sin \theta_1 \end{cases} \quad (4)$$

Substituting Eq. 4 into Eq. 3, we have

$$\begin{cases} \dot{x}_P = v_R \cos \theta_1 - a\dot{\theta}_1 \sin \theta_1 \\ \dot{y}_P = v_R \sin \theta_1 + a\dot{\theta}_1 \cos \theta_1 \end{cases} \quad (5)$$

In Fig. 1, $\theta_1 = \theta_2 + \alpha$, and the angular velocity of point P ω_1 is given by

$$\dot{\theta}_1 = \omega_1 = \frac{v_R - v_l}{D} \quad (6)$$

Moreover, the pose change of the mobile robot $\dot{\theta}_2$, i.e., ω_2 , depends on $v_R \cdot \sin \alpha$, which is the y-component of v_R , and we have

$$\dot{\theta}_2 = \omega_2 = \frac{v_R \sin \alpha}{L} = \frac{(v_R + v_l) \sin \alpha}{2L} \quad (7)$$

Therefore, the kinematic model of the mobile robot is expressed as.

$$\xi_P = \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} v_R \cos \theta_1 - a\dot{\theta}_1 \sin \theta_1 \\ v_R \sin \theta_1 + a\dot{\theta}_1 \cos \theta_1 \\ \omega_1 \\ \omega_2 \end{bmatrix} \quad (8)$$

Expressing Eq. 8 in terms of v_R , ω_1 and ω_2 , we have

$$\xi_P = \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & -a \sin \theta_1 & 0 \\ \sin \theta_1 & a \cos \theta_1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_R \\ \omega_1 \\ \omega_2 \end{bmatrix} \quad (9)$$

Equation 9 is the kinematic model for v_R , ω_1, ω_2 . of a differential-driven four-wheeled mobile robot with the rotational axis.

From the above equations, the magnitude of the velocity of point P, $\|v_P\|$, is

$$\|v_P\| = \sqrt{v_R^2 + a^2 \omega_1^2} \quad (10)$$

Thus, in the case of $a = 0$, $\|v_P\| = v_R$ is the case, and then Eq. 9 is

$$\dot{\xi}_P = \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & 0 & 0 \\ \sin \theta_1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_R \\ \omega_1 \\ \omega_2 \end{bmatrix} \quad (11)$$

Next, model 2 is constructed as follows.

The translational velocity v_R of the mobile robot is expressed in terms of the linear velocity v_l and v_r of the driving wheels as follows :

$$v_R = \frac{v_l + v_r}{2} \quad (12)$$

Let the radius of the driving wheels be r

$$\begin{cases} v_l = r\omega_l \\ v_r = r\omega_r \end{cases} \quad (13)$$

From Eqs. 6 and 7, Eqs. 12 and 13, v_R , ω_1 and ω_2 are expressed in terms of the angular velocity ω_l and ω_r of the driving wheels as follows :

$$\begin{bmatrix} v_R \\ \omega_1 \\ \omega_2 \end{bmatrix} = \begin{bmatrix} \frac{r}{2}(\omega_l + \omega_r) \\ \frac{r}{D}(\omega_r - \omega_l) \\ \frac{\sin \alpha}{L} \cdot \frac{r}{2}(\omega_l + \omega_r) \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{D} & -\frac{r}{D} \\ \frac{\sin \alpha}{L} \cdot \frac{r}{2} & \frac{\sin \alpha}{L} \cdot \frac{r}{2} \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \quad (14)$$

Thus, expressing Eq. 9 with respect to the angular velocities of the driving wheels ω_l and ω_r , we have.

$$\dot{\xi}_P = \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & -a \sin \theta_1 & 0 \\ \sin \theta_1 & a \cos \theta_1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{D} & -\frac{r}{D} \\ \frac{\sin \alpha}{L} \cdot \frac{r}{2} & \frac{\sin \alpha}{L} \cdot \frac{r}{2} \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \quad (15)$$

Ordering Eq. 15, we have

$$\dot{\xi}_P = \begin{bmatrix} \dot{x}_P \\ \dot{y}_P \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \frac{r}{2} \begin{bmatrix} \cos \theta_1 - \frac{2a}{D} \sin \theta_1 & \cos \theta_1 + \frac{2a}{D} \sin \theta_1 \\ \sin \theta_1 + \frac{2a}{D} \cos \theta_1 & \sin \theta_1 - \frac{2a}{D} \cos \theta_1 \\ -\frac{2}{D} & \frac{2}{D} \\ \frac{\sin \alpha}{L} & \frac{\sin \alpha}{L} \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \quad (16)$$

Equation 16 is the kinematic model of a differential-driven four-wheeled mobile robot with a rotary axis, with respect to angular velocities ω_r and ω_l .

Position tracking controller design

From Eq. 16, the input variable of the control plant is the angular velocity of the driving wheels.

Thus, we can write.

$$u = \begin{bmatrix} \omega_l \\ \omega_r \end{bmatrix} \quad (17)$$

And partitioning the state variables as

$$\xi = \begin{bmatrix} x \\ y \\ \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} q \\ \theta_1 \\ \theta_2 \end{bmatrix} \quad (18)$$

Then, the model of the control plant can be written as.

$$\dot{\xi} = \begin{bmatrix} [D(\theta_1)] \\ \varphi^T \\ F^T \end{bmatrix} \quad (19)$$

Here

$$D(\theta_1) = \begin{bmatrix} \frac{r}{2} \cos \theta_1 - \frac{ar}{D} \sin \theta_1 & \frac{r}{2} \cos \theta_1 + \frac{ar}{D} \sin \theta_1 \\ \frac{r}{2} \sin \theta_1 + \frac{ar}{D} \cos \theta_1 & \frac{r}{2} \sin \theta_1 - \frac{ar}{D} \cos \theta_1 \end{bmatrix} \quad (20)$$

$$\varphi^T = \begin{bmatrix} \frac{r}{D} & -\frac{r}{D} \end{bmatrix} \quad (21)$$

$$F^T = \begin{bmatrix} \frac{r \sin \alpha}{2L} & \frac{r \sin \alpha}{2L} \end{bmatrix} \quad (22)$$

Given that the value of a is nonzero, the position tracking controller can be designed as follows

$$u = D^{-1}(\theta)[\dot{q}_d + K_P \tilde{q}] \quad (23)$$

Here

$$D^{-1}(\theta_1) = \begin{bmatrix} -\frac{D}{2ar} \sin \theta_1 + \frac{1}{r} \cos \theta_1 & \frac{D}{2ar} \cos \theta_1 + \frac{1}{r} \sin \theta_1 \\ \frac{D}{2ar} \sin \theta_1 + \frac{1}{r} \cos \theta_1 & -\frac{D}{2ar} \cos \theta_1 + \frac{1}{r} \sin \theta_1 \end{bmatrix} \quad (24)$$

And hen, the position error can be given by

$$\tilde{q} = q_d - q \quad (25)$$

$q_d(t)$: desired trajectory, $q(t)$: Trajectory of the considered point P, K_P : proportional matrix

The goal of the control system is $\lim_{t \rightarrow \infty} [q_d(t) - q(t)] = 0$, which allows the desired trajectory to be tracked without deviation.

Here $q_d(t)$ is differentiable and $q(t)$ is given. It is shown that the control objective is independent of the orientation angle of the mobile robot.

The analysis of the feedback system is as follows.

$$\dot{q} = D(\theta)D^{-1}(\theta)[\dot{q}_d + K_P \tilde{q}] \quad (26)$$

$$\dot{\theta}_1 = \varphi^T D^{-1}(\theta)[\dot{q}_d + K_P \tilde{q}] \quad (27)$$

$$\dot{\theta}_2 = F^T D^{-1}(\theta)[\dot{q}_d + K_P \tilde{q}] \quad (28)$$

So, equation 26 becomes as follows.

$$\dot{q} = \dot{q}_d + K_P \tilde{q} \tag{29}$$

Thus, $\dot{\tilde{q}} = -K_P \tilde{q}$.

Solving this, we have $\tilde{q}(t) = be^{-t}$ (b is a nonzero constant) and hence $\lim_{t \rightarrow \infty} \tilde{q} = 0$.

Thus, the mobile robot moves along the desired trajectory with the error approaching zero as time increases.

On the other hand, for the control purpose of mobile robot, the orientation angle of mobile robot and steering angle of driving wheel bracket were not defined.

To achieve a higher tracking accuracy of the mobile robot, the tracking error should be close to zero as soon as possible.

The proportional gain matrix in Eq. 23 is assumed as

$$K_P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{30}$$

From Equations 27 and 28,

$$\dot{\theta}_1 = -\frac{\sin \theta_1}{a}, \tag{31}$$

$$\dot{\theta}_2 = \frac{\sin \alpha}{4L} \cos \theta_1 \tag{32}$$

Simulation and verification

To verify the steering characteristics and position tracking performance of a proposed mobile robot, we simulated for a mobile robot with design parameters such as the table below.

Table 1. design parameter of a proposed mobile robot

design parameter	value	design parameter	value
L(mm)	500.7	D(mm)	400
a(mm)	250.3	R(mm)	125

It can be seen that the error of the rotation angle of the driving wheel turntable depends on the distance from the driving wheel turntable to the sensor, and the error of the rotation angle of the robot depends on the distance D between two driving wheels and the distance L from the driving wheels frame to the driven wheels.

Thus, the error convergence speed of the robot should be $\min t_1 = f(a)$, $\min t_2 = f(D, L)$ as fast as possible.

Assuming that the initial position of the mobile robot is $(x_0, y_0) = (0,0)$, the initial orientation angle is $\theta_0 = \frac{\pi}{2}$, and the mobile robot is moving along the x-axis.

The target trajectory of the mobile robot is

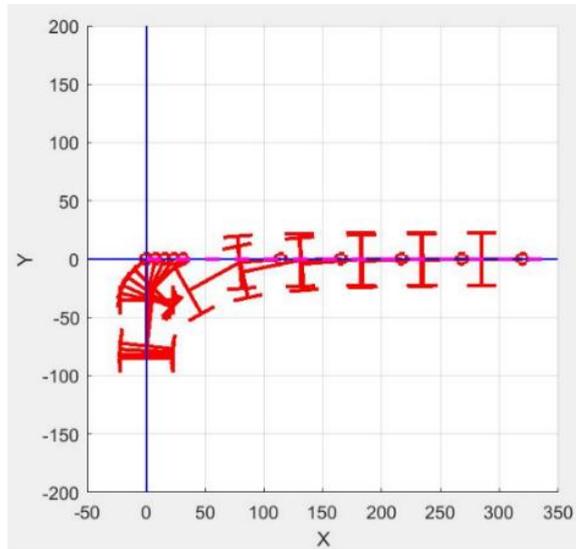
$$q_d(t) = \begin{bmatrix} v_x t + x_0 \\ v_y t + y_0 \end{bmatrix} \tag{33}$$

Here, $v_x = 1$, $v_y = 0$.

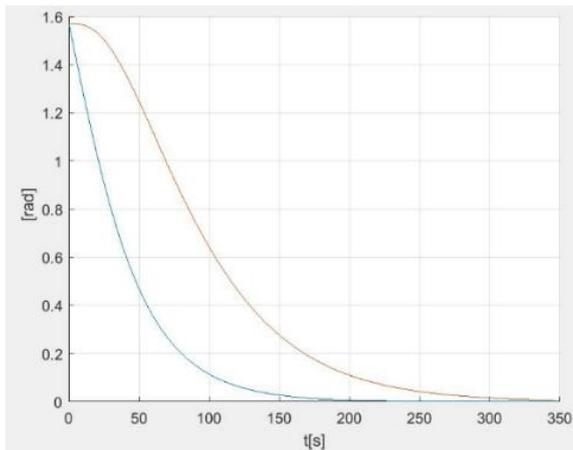
In the following figures, the robot's motion trajectory analysis model and the error of each case and the change

of the drive and driven wheel angles are presented.

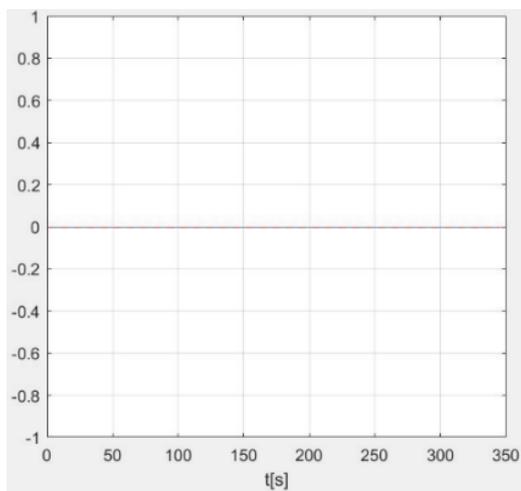
The following figures show the robot's motion trajectory analysis model and the error of the change of the drive and driven wheels angles in each cases.



a)



b)

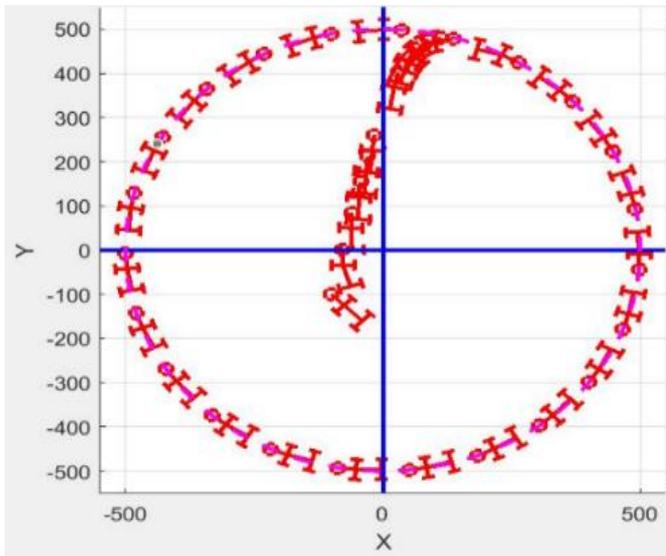


c)

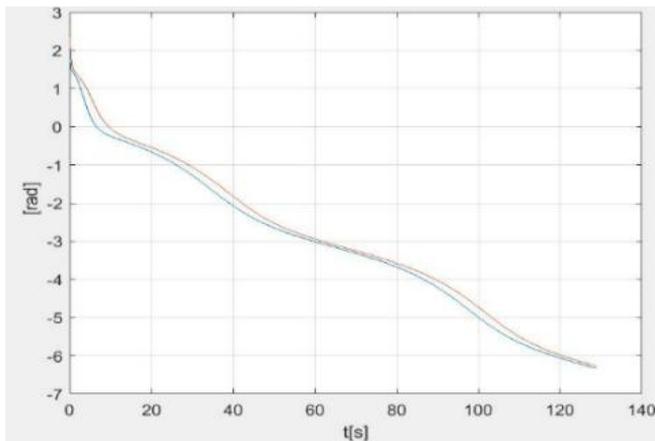
Figure 2. Kinematics simulation analysis (1)

(a- Stroboscopic Graph for the first scenario, b-simulation results for driving wheel's orientation θ_1 and the robot's orientation θ_2 , c-position error)

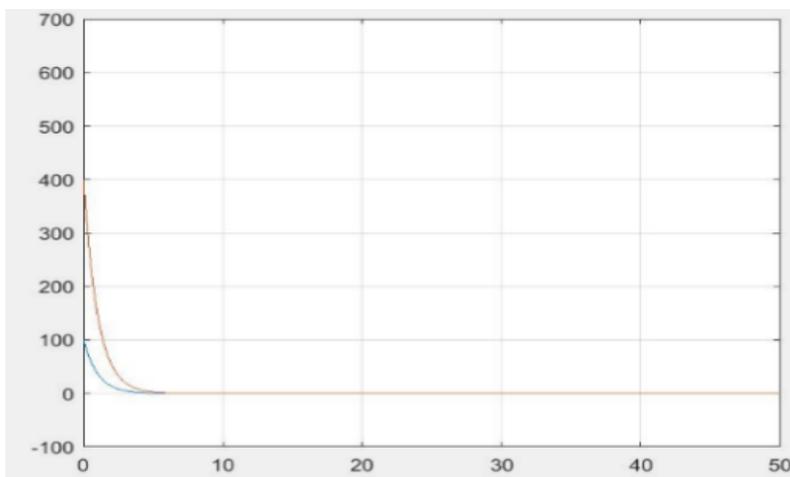
(b- Figure 3 shows that the robot smoothly get into the track and then the errors, and the orientations.



a)



b)



c)

Figure 3. Kinematics simulation analysis (2)

(a-Stroboscopic Graph for the first scenario, b-simulation results for driving wheel's orientation θ_1 and the robot's orientation θ_2 , c-position error, d-detailed view of the position error)

To perform the final experiments on the proposed mobile robot, experiments were carried out on a mobile robot for carrying the workpiece.

The final experiment of a proposed mobile robot is shown in Figure 4.



Figure 4. The position tracking control experiment of the proposed mobile robot

CONCLUSION

In this paper, to improve the steering characteristics of a mobile robot, we proposed a structure of a differential-driven wheeled mobile robot with two driving wheels connected by a rotary axis, and analyzed its kinematics analysis and position tracking performance.

Simulation and verification results showed that the proposed mobile robot has a better position tracking performance and a smaller turning radius compared to the generalized differential-driven mobile robot.

The proposed mobile robot can be effectively used to carry the heavier weight product in a narrow working area.

In using the proposed mobile robot, it is necessary to consider that the mobile robot is easily derailed from the trajectory during the first maneuver.

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Conflict of interests

The author declares no conflict of interest.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data Availability

The data that support the findings of this study are available within the article.

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