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Kinematics Modeling and Motions Analysis of Non-holonomic Mobile Robot

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***Abstract*—A study on kinematics modeling of non-holonomic mobile robot and the motion analysis is presented. The robot is a four-wheeled robot with two active wheels and two passive wheels. Each active wheel is driven by an independent DC motor. The robot has two degrees of freedom (2-DOF) of motions including translation and rotation. Kinematics modeling is carried out to obtain a mathematics model representing the robot motions. The resulted model is verified through analyzing the robot motion using calculus of parametric equations. A computer program is built based on the model for numeric simulation and visualization of the robot motions. Executing the program resulted in numerical data of the robot motion that was confirmed by an animation of the robot movement. The numerical data includes the position, orientation, linear and angular velocities of the robot, and the corresponding DC motors speed.**

***Index Terms*—Non-holonomic robot, kinematics modeling, motion analysis, simulation.**

I. Introduction

Mobile robots are a type of robots that can move the whole body from one location to another location. The mobile robots are also known as the unmanned vehicles. Based on the operating area, mobile robots can be classified into four types: aerial mobile robot [1]–[3], water-surface mobile robot [4]–[6], underwater mobile robot [7]–[9], and ground mobile robot [10]–[12]. The mobile robots have been one of the hot research topics since the last three decades [13]. However, the mobile robots are still remaining many research challenges [14]–[16]. The challenges are driven by a high demand of applying mobile robots in many different fields, such as military, industries, logistic, medical, and transportation. The demand needs to be met by developing more advanced robots. Several aspects have been considered in the robot development, such as frame design, kinematics and dynamics modeling, motion analysis, control, navigation, implementation, and applications.

Recently, the developments of mobile robots have a trend toward autonomous mobile robots or autonomous vehicles. The autonomous vehicle is an intelligent vehicle that is able to control and navigate itself for moving automatically from a departure point to a desired destination point safely. Basically, the autonomous vehicle is built to have three basic capabilities [17]: 1) sensing and perception, 2) planning, and 3) control. The sensing and perceptron are to recognize the current location and environment around the robot. This recognition is done by collecting data through measurement using navigation sensors. The planning is to determine a path that the robot should follow to reach the destination. This path is usually obtained through optimization to produce the optimal path among the available path choices. The control is to obtain the best strategy for steering the vehicle such that move precisely on the determined path and arrive at the destination safely. The strategy is obtained through applying the available control theories.

Basically, the ground mobile robots are able to move on the ground due to locomotion tools such as wheels or legs. The ground mobile robots using leg locomotion are usually developed for humanoid robots or imitating-animal robots. Meanwhile, the ground mobile robots using wheel locomotion or shortly called as the wheeled robots are similar to the common ground vehicles, such as cars, military tanks, trains, motorcycles, and others. Based on the number of wheels, there are several types of wheeled robots, such as: one-wheeled robot [18]–[20], two-wheeled robot [21]–[23], three-wheeled robot [24]–[26], four-wheeled robot [27]–[29], and other robots with more wheels. The four-wheeled robot (FWR) is a type of ground mobile robot that is quite popular robotic studies [30]–[32]. The FWR has four wheels, where the wheels have two functions: support the robot's body and/or drive the robot movements. The wheel that only supports the robot's body is known as a passive wheel, while the wheel that also drives the robot's movement is known as an active wheel. The active wheel is able to drive the movement as it is connected to a force generator component, such as an electric motor. The FWR can have either two active wheels or four active wheels. An FWR with two active wheels is known as the two wheel drive FWR, and if each active wheel moves independently then the robot is known as a two wheel differential drive FWR, the same mention applies for the FWR with four active wheels.

Let us assume a FWR is on a flat ground surface. This flat surface is a two dimensional space and also known as the planar space. Ideally, an object in planar space can move with three degrees of freedom (3-DoF) of motion that include: 1) forward and backward motions, 2) left and right side motions, and 3) right and left turns. We can find this while playing

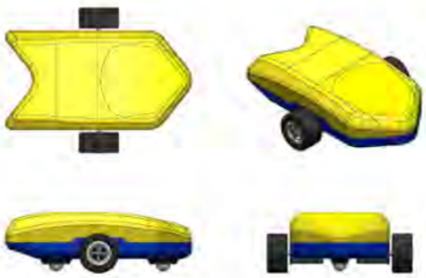

Fig. 1: A design of four-wheeled robot.

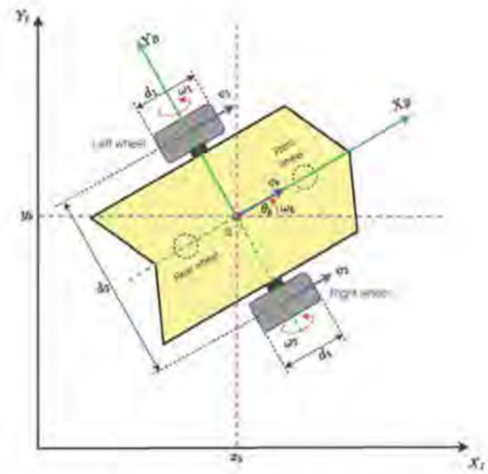

Fig. 2: A four-wheeled robot on the planar space.

football, but not while driving a car. A car that is not able to perform a side movement such that it has only 2-DoF of motion. The reason is that the car's wheels rotate at one axis only. Similar to the car, the FWR using conventional wheels with a single rotational axis has 2-DoF of motion. The FWR is being a system that has controllable DoF less then the total DoF. Such kind of this system is known as a non-holonomic system, where controlling the system is quite challenge [33]–[35]. The FWR can have 3-DoF if the robot utilizes unconventional wheels such as Swedish wheels. The Swedish wheel is an ideal wheel, but it is not practical in real applications. Most of the robots using the Swedish wheels are developed for a small scale application or academic research purpose [36]–[38] .

This study has a long-term goal to develop an autonomous mobile robot for real life application. A two wheel differential drive FWR with conventional wheels is of interest to be the platform. Since FWR is a non-holonomic system and controlling the robot's movement is a challenge. Prior to work in the control development, this study presents kinematics modeling and motion analysis of the robot. Kinematics modeling is to obtain mathematics model representing the robot motions. After the model was obtained, it is the verified through analysing the robot motion by applying the calculus of parametric function method. Based on the verified model, a computer program is built to demonstrate the robot motion in computer simulation. Presentation of the paper is organized as follows. Section I provide an introduction of the work. Section II presents a design of FWR, kinematics modelling, and motion analysis. Numerical simulations and the results are presented in Section III and followed by discussion. Finally, conclusion of the work is presented in Section IV.

II. Kinematics Modelling and Motion Analysis

Figure 1 shows a design of FWR that is being a platform for developing an autonomous mobile robot. The robot has two active wheels and two passive wheels. Both active wheels are located on the left and right sides of the center robot body. These active wheels are conventional wheels driven by two independent DC motors. Therefore, the designed FWR is a two-wheel differential drive FWR type. Rotational axis of both active wheels are inline and passing through the center point of the robot body. This center point is also the location of the robot's center of gravity. On another hand, both passive wheels are located at the front and rear of the robot body. Both passive wheels are located at the longitudinal-symmetric axis of the robot body and passing through the robot's center of gravity. The passive wheels are using the ball-caster wheel type, that has 3 DoF of motions. However, since the active wheels are using the conventional wheel, the designed FWR has only 3 DoF of motion and it is therefore a non-holonomic system.

A. Kinematic Model

Kinematics is a branch of mechanics that studies the motion of a body without considering the inertial force, inertia, and energy of the body. Kinematics of an object is represented by a kinematics model that consists of mathematics equations describing position, velocity, and acceleration of the object [39]. In robotics studies, a kinematics model of the robot is required to obtain a mathematics model representing the robot motions. This model can be used in many different purpose, such as motion analysis and control design of the robot.

The FWR can be represented are a two dimensional system on planar space as shown in Figure 2. It is assumed that the center of the robot body is also located at the robot's center of mass which is shown by the point B in the Figure 2. Each active wheel is driven by a DC motor. Rotations of the active wheels push the robot to move linearly and/or rotate. While both active wheels rotate at the same speed and direction, the robot moves linearly forward or backward. This linear movement is represented by a linear velocity defined as follows:

$$v_b = \frac{d_1(\omega_2 + \omega_1)}{4}, \tag{1}$$

where v_b is the robot's linear velocity, ω_1 is the angular velocity if the left active wheel, ω_2 is the angular velocities of the right rear-wheels, d_1 is the active wheel diameter, and d_2 is the distance between center points of the active wheels. However, if both active wheels rotations are not equal in the rotational speed and direction, the robot makes angular movement with the angular velocity defined as follows:

$$\omega_b = \frac{d_1(\omega_2 - \omega_1)}{d_2}, \tag{2}$$

where ω_b is the robot's angular velocity. The equations (1) and (2) can be expressed in a matrix equation as follows:

$$\begin{bmatrix} v_b \\ \omega_b \end{bmatrix} = \begin{bmatrix} \frac{d_1}{4} & \frac{d_1}{4} \\ \frac{-d_1}{d_2} & \frac{d_1}{d_2} \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} \tag{3}$$

or simply expressed by:

$$u_b = S_b u_\omega \tag{4}$$

where

$$u_b = \begin{bmatrix} v_b \\ \omega_b \end{bmatrix}, S_b = \begin{bmatrix} \frac{d_1}{4} & \frac{d_1}{4} \\ \frac{-d_1}{d_2} & \frac{d_1}{d_2} \end{bmatrix}, u_\omega = \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}.$$

In order to show the robot's velocities, define a coordinate system $O_B X_B Y_B$ as the body coordinate system, where the origin O_B is located at the robot's center of mass, the point B. The X_B axis is inline to the robot forward moving direction, and a Y_B axis inline to the robot side moving direction to the left as shown in the Figure 2. This body coordinate system sticks on the robot body and moves along the robot movements. Since the body coordinate system is moving, another coordinate system that is fixed and independent of the robot's motion is required to determine the robot's position and orientation. Therefore, a fixed coordinate system $O_I X_I Y_I$ is introduced as shown in the Figure 2. The $O_I X_I Y_I$ is known as the inertial coordinate system.

The position and orientation of FWR can be calculated based on both coordinate systems. The robot position is defined as the position of the robot's center of mass with respect to the inertial coordinate $O_I X_I Y_I$ and denoted by (x_b, y_b). The robot orientation is defined as the deviation angle of the $O_B X_B Y_B$ with respect to the $O_I X_I Y_I$ and denoted by θ_b, which is also known as the heading angle. The position and orientation of the robot is called as the robot posture which can be defined by the following vector:

$$p_b = \begin{bmatrix} x_b \\ y_b \\ \theta_b \end{bmatrix} \tag{5}$$

where p_b is the robot posture. Changes in the robot posture indicate the movement of the robot. Therefore, the robot motions can be represented by the time derivative of the robot posture and given as follows:

$$\dot{x}_b = v_b \cos\theta_b \tag{6}$$
$$\dot{y}_b = v_b \sin\theta_b \tag{7}$$
$$\dot{\theta}_b = \omega_b, \tag{8}$$

where $\dot{x}_b$ and $\dot{y}_b$ are the robot's linear velocity along X_I and Y_I axis, respectively, and $\dot{\theta}_b$ is the angular velocity of the robot.

B. Motions Analysis Based on Calculus of Parametric Function

The mobile robot moves on paths on the ground surface. In this study, it is assumed that the robot moves on a path with the same elevation such that the path can be represented in a two dimensional space. In this space, an inertial coordinate system $OX_I Y_I$ is defined as the reference for determining the robot posture. The position of robot is expressed by coordinate (x_b, y_b) in the inertial coordinate system. For a moving robot, the position is a function of time such that it can be represented as follows:

$$x_b = g(t) \tag{9}$$
$$y_b = h(t), \tag{10}$$

where $g(t)$ and $h(t)$ represents the robot position along X_I and Y_I, respectively, with respect to time. The equations (9) (10) are known as the parametric equation. The parametric equation is one of the interesting topics in Calculus that is very useful for analyzing motion of a moving object [40].

By using the concept of Calculus, the linear velocity of the robot along X_I and Y_I axis are defined as follows, respectively:

$$\dot{x}_b = \frac{dg(t)}{dt} \tag{11}$$
$$\dot{y}_b = \frac{dh(t)}{dt}, \tag{12}$$

where the $\dot{x}_b$ and $\dot{y}_b$ are the projection of the robot's linear velocity along the X_I and Y_I axis. The robot's linear velocity can be expressed in vector form with respect to the inertial coordinate system as follows:

$$\vec{v}_b = \dot{x}_b \hat{\imath}_0 + \dot{y}_b \hat{\jmath}_0 \tag{13}$$

where the $\hat{\imath}_0$ and $\hat{\jmath}_0$ are the unit vectors along the X_I and Y_I axis, respectively. The linear velocity value and orientation of the robot can be obtained by calculating the magnitude and direction of the velocity (13) as follows:

$$v_b = \sqrt{(\dot{x}_b)^2 + (\dot{y}_b)^2} \tag{14}$$
$$\theta_b = \tan^{-1}\left(\frac{\dot{y}_b}{\dot{x}_b}\right). \tag{15}$$

The angular velocity of the robot can be obtained by differentiating (15) with respect to the time as defined in (8). The travel distance of the robot at time t is obtained by integrating the velocity and given as follows:

$$L(t) = \int_0^t \sqrt{(\dot{x}_b)^2 + (\dot{y}_b)^2}\, dt \tag{16}$$

where L is the travel distance.

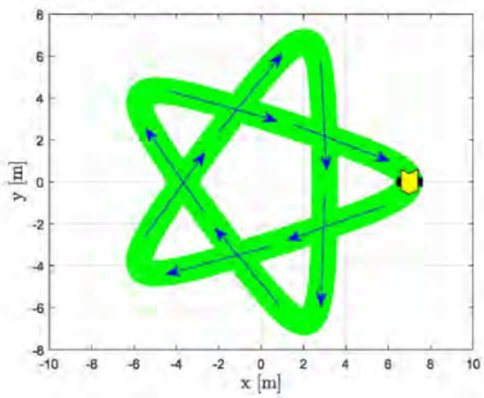

Fig. 3: Route for the mobile robot where the arrows show the moving direction.

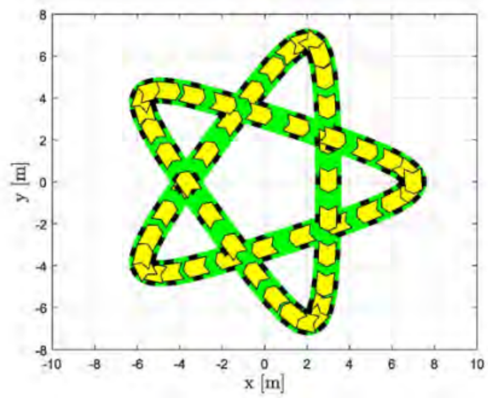

Fig. 4: Simulation of the robot to move for one cycle of the route takes 108 seconds.

III. SIMULATION AND RESULT

Numerical simulation are carried out to demonstrate the robot motions. The simulation scenario is given as follows. The robot is initially at idle position and located at the coordinate $(7, 0)$ with orientation $270°$. The initial posture of the robot can be defined as follows:

$$p_b(0) = \begin{bmatrix} x_b(0) \\ y_b(0) \\ \theta_b(0) \end{bmatrix} = \begin{bmatrix} 7 \\ 0 \\ 270° \end{bmatrix}, \tag{17}$$

where $p_b(0)$ is the initial posture. The robot is going to move on a path represented by the following parametric functions:

$$x(\alpha) = 2\cos\alpha + 5\cos\left(\frac{2}{3}\alpha\right) \tag{18}$$

$$y(\alpha) = 2\sin\alpha - 5\sin\left(\frac{2}{3}\alpha\right), \tag{19}$$

where x and y represent the path location in the inertia coordinate system. Both x and y are functions of parameter α, which is an independent parameter. The α has a range of $\alpha = [0, 6\pi]$ in this simulation. Plotting the values of x versus y for the whole values of α results in a green closed-curve shown in Figure 3. This curve is representing the path that will be passed by the robot.

The Figure 3 also shows the initial posture of the robot and moving direction on the path. The robot is represented by a robot icon which is the yellow object with a back wheel on the right and left sides. The blue arrows in the figure show the moving directions in the path. The robot is simulated to move on a cycle path. Simulation for a longer time will result in moving on the same path. Therefore, the robot-movement is demonstrated by simulating for one cycle. Define the variable t as the simulation time and assuming that it has linear relation to the parameter α as follows:

$$\alpha = kt, \tag{20}$$

where k is a constant. Substituting (20) into (18) and (19) results in the following equations:

$$x(t) = 2\cos(kt) + 5\cos\left(\frac{2}{3}kt\right) \tag{21}$$

$$y(t) = 2\sin(kt) - 5\sin\left(\frac{2}{3}kt\right). \tag{22}$$

Assuming that the robot has an ideal controller such that the robot is able to move and reach the position which is exactly at the same as the position on the path according to the simulation time,

$$x_b(t) = x(t) \tag{23}$$

$$y_b(t) = y(t). \tag{24}$$

Using that assumption, the robot position during the simulation can be expressed as follows:

$$x_b(t) = 2\cos(kt) + 5\cos\left(\frac{2}{3}kt\right) \tag{25}$$

$$y_b(t) = 2\sin(kt) - 5\sin\left(\frac{2}{3}kt\right), \tag{26}$$

where $x_b(t)$ and $y_b(t)$ represent the robot's position at simulation time t with respect to the inertia coordinate system.

For this simulation, define that the robot requires 108 seconds to move a completed cycle of the path such that the constant k can be calculated as follows:

$$k = \frac{6\pi}{108}, \tag{27}$$

where 6π is the value of α for one cycle and 108 is the simulation time for completing one cycle. The simulation is carried out and the result is shown in Figure 4. The robot moved exactly on the defined path with the correct orientation at each position. Postures of the robot are displayed every 2 seconds such that 54 different postures of the robot are shown

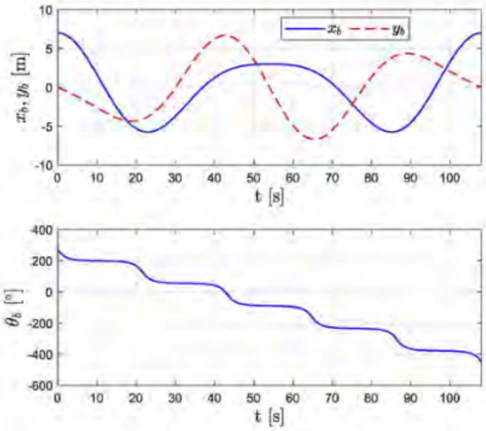

Fig. 5: The position and orientation of the robot versus the time resulted in the simulation of robot movement for completing one cycle of the route.

in the figure. The Figure 4 shows that the distances between the robots at the time interval are not equal. The robots are shown rarely at the straight track, but denser at the turning track. This indicates that the robot's velocities are varying, where the longer distances implicate the higher linear velocities of the robot.

Figures 5 shows the robot posture, including the robot position x_b and y_b and the robot orientation θ_b. At $t = 0$, the robot position is $(7, 0)$ and orientation $270°$ that describes the initial robot posture. After the simulation began, the posture changed as shown by variations on the position and orientation values. The graph of robot orientation includes some flat curves and descending curves periodically. The flat curve of $\theta_b(t)$ shows a constant orientation angle that indicates a straight line movement. The descending curve of $\theta_b(t)$ shows a decreasing orientation angle that indicates a left turn movement. For an example, let consider the $\theta_b(t)$ at the beginning of simulation, $t = 0$ to $t = 15$ seconds. The orientation angle decreased significantly from $\theta_b = 270°$ to $\theta_b = 200°$ at $t = 0$ to $t = 5$ seconds. This indicates the robot was turning left. After that, at $t = 5$ to $t = 15$ seconds, the orientation angle did not change significantly and almost constant that indicates the robot moved in almost straight line. These movements are visualized in the Figure 4, where the robot turned left after the departure and moved on a slightly straight track before made the next left turning.

Figures 6 show the robot's velocities, including linear and angular velocities, and angular velocities of the active wheels. It was mentioned that the robot made a small forward movement and large left-turn immediately after the simulation starts. This is confirmed by Figures 6 where the robot had linear velocity $1.34\ m/s$ and angular velocity -31.63 $°/s$ at

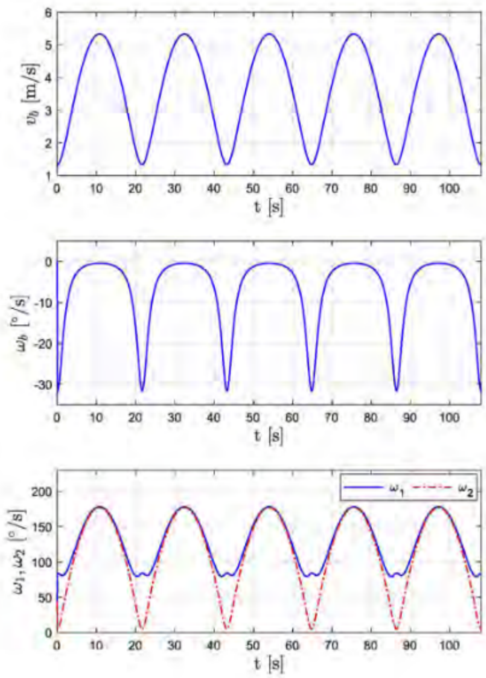

Fig. 6: The linear and angular velocities of the robot and the angular velocity of the active wheels versus the time resulted in the simulation of robot movement for completing one cycle of the route.

the beginning of simulation. The Figures 6 exhibits the robot's velocities changed periodically with time period 21.6 seconds. An example of the velocities change cycle is shown in the simulation result at 0 to 21.6 seconds. Both linear velocity and turning rate of the robot increased at 0 to 10.8 seconds and then decreased at 10.8 to 21.8 seconds. The robot reached the maximum linear velocity 5.33 m/s at 10.8 second where the robot was moving turning rate $-0.42°/s$ at that time. The turning rate $-0.42°$ was being the smallest of the turning rate magnitude in the simulation.

IV. Conclusion

Kinematics modeling of a four-wheeled mobile robot has been presented. The robot is a non-holonomic robot as it can only move in two DOF of motions instead of three on the ground. The movements include translation and rotation. The kinematics model resulted in mathematics equations representing the robot motions. The robot motions were numerically analyzed using the calculus of parametric equations. This resulted in numerical data of the robot motions. Computer simulation presented a demonstration of the robot motions based on the kinematics model and numerical data. The simulation results confirmed the robot motions based on the kinematics model and numerical data were matched.

This study was done by assuming that the robot had an ideal controller to reach any desired position at a certain time. Obtaining the ideal controller is a remaining work. The ideal controller may not exist, but can be approached by a controller with sufficient performance. Designing such kind of controller is taken into account as a continuation of this study.

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