Geometric Kinematics and Applications of a Mobile Robot

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Abstract: In this paper, the simple geometric kinematics of a three-wheeled holonomic mobile robot is proposed. Wheel architecture is developed for the holonomic mobile platform in order to provide omni-directional motions by three individually driven and steered wheels. Three types of basic motions are proposed for the path generation of the developed mobile robot. All paths of the mobile robot can be achieved through a combination of the proposed basic motion trajectories. The proposed method is verified through computer simulations and the developed mobile robot.

Keywords: Geometric kinematics, three-wheeled mobile robot, basic motion trajectory.

1. INTRODUCTION

Numerous types of kinematics modeling and platform designs have been studied for wheeled mobile robots [1-3]. For large and heavy outdoor mobile robots, car-like driving mechanisms or skid-steer platforms have been used. However, these mobile robots are quite restricted in their motion by non-holonomic constraints on their wheel mechanism in tight indoor environments.

One way to reduce these restrictions on four-wheeled mobile robots is to replace the coupled steering wheels with one wheel, as in the case of three-wheeled mobile robots. The three-wheeled mobile robot has the advantage that wheel-to-ground contact can be maintained on all wheels without any suspension system. In [4], the single wheel is the drive wheel as well as the steering wheel, enabling all other wheels to be idle. Some mobile robots have three wheels controlled by a synchronous drive system. In those systems, all the wheels are utilized for both driving and steering [5]. However, in the case of these mobile robots, wheels are coupled with a belt drive or gears, allowing them to be steered by a single motor. This three-wheeled mobile robot allows rotation of the mobile robot around any point, but does not allow sideways and full mobility by non-holonomic constraints [4,5].

In general, there are two types of three-wheeled mobile robots: non-holonomic and holonomic [6]. A non-holonomic mobile robot has the ability to reach an arbitrary position and orientation, but it is unable to rotate while simultaneously moving in an arbitrary direction. In contrast, a holonomic mobile robot is able to rotate while simultaneously translating in a free direction. To achieve full mobility in the design of the omni-directional mobile robot, the holonomic property was adopted as a design goal.

For the support of the holonomic property, certain types of mechanisms for an omni-directional holonomic mobile robot have been considered [6,7]. In these papers, the wheels are designed to operate as driving and steering wheels, using motors on concentric shafts. Three wheels are mounted 120° apart on a circular platform. As they are all driven, they must rotate at different speeds when turning in order to provide omni-directional motion. However, the kinematics of this model are known to be complex and furthermore that the controllers are unable to control each wheel efficiently. This design used three complex assemblies, each having an independent degree of freedom. There was some difficulty in controlling six degrees of freedom in the wheel for practical implementation in [8,9]. This was due to the complex kinematics modeling that caused problems during operation.

In this paper, a kinematics modeling based on a simple geometric approach for an omni-directional three-wheeled mobile robot is proposed. It is applied to reduce the kinematics complexity and to simplify the modeling method, in that all three wheels operate as both driving and steering wheels simultaneously. Independent flexible wheel architecture is applied to achieve omni-directional motions of the holonomic

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mobile platform. The proposed kinematics (divided into inverse kinematics and forward kinematics) are applied to the developed omni-directional holonomic mobile robot, and its usefulness is proved by computer simulations and practical implementations.

This paper is organized as follows. In the next section, the mobile robot's architecture and the wheel architecture are described. In Section 3, the proposed inverse and forward kinematics are described. Next, the three basic motions of the proposed mobile robot are discussed in Section 4. Section 5 presents applications of the proposed kinematics through computer simulations and the practical model. Finally, conclusions are drawn in Section 6.

2. MOBILE ROBOT ARCHITECTURE

The developed mobile robot is shown in Fig. 1. There are three levels that comprise the mobile robot. The first level is composed of three wheels, batteries, and gear housing. The second level consists of six servo motors with drivers, AC-DC converters, and digital I/Os. The third level is composed of 24 ultrasonic sensors, an omni-directional vision sensor, and control units.

2.1 Wheel architecture

The wheel architecture is shown in Fig. 2. There are two motors connected to each wheel, one for steering and the other for driving. Therefore, each wheel has the capability of steering and driving independently. The driving motor is offset from the steering motor in order to prevent wires from becoming entangled. The large spur gear is used to reduce the speed of the motor, and the power is transferred through the second spur gear to the bevel gear box. The housing of the wheel is connected directly to the steering motor. Therefore, the wheel rotates along with the housing. The speed of the steering motor is also reduced by a larger gear, and the gear housing is designed in order to prevent tangling of the wire when the wheel is rotated 360°. For the wheel architecture, the non-deformed planar circle type is used.

Fig. 1. An overview of the developed mobile robot.

To avoid cumulative mechanical errors of wheels in the mobile robot, the wheel alignment process is implemented. This process enables all three wheels to align, making it easier for the mobile robot to navigate. he wheel alignment process is made possible by a luminary point marked on the wheels and the photo sensor. The wheel line-up process is shown in Fig. 3 using the installed sensor system.

3. GEOMETRIC KINEMATICS MODELLING OF THE MOBILE ROBOT

This section deals with the geometric kinematics modeling of the developed three-wheeled omni-directional mobile robot. The kinematics modeling is divided into two parts, inverse kinematics and forward kinematics. Inverse kinematics is used to solve the angular velocities and steering angles of each wheel. Forward kinematics is used to estimate the position and heading angle of the mobile robot using

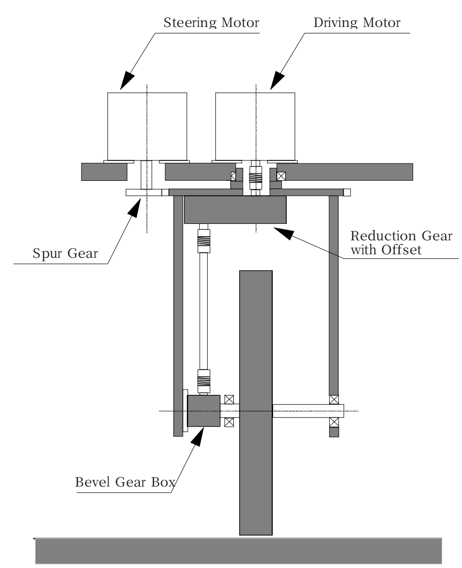

Fig. 2. Wheel architecture.

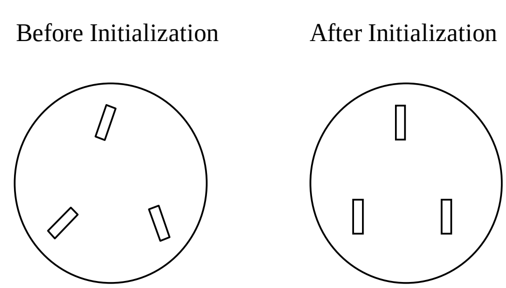

Fig. 3. Wheel alignment process for alignment.

the wheel measurement from the encoder.

An assumption and basic concepts are introduced to describe the kinematics model of the mobile robot [9, 10].

Basic Concept:

- All motions of the mobile robot can be divided into translation and rotation components.
- Translation is the displacement of the mobile robot's center.
- Rotation concerns the rotational movement of each wheel's axis.

Assumption:

- There is no wheel slippage during the movement of the mobile robot.

3.1. Inverse kinematics

Inverse kinematics is used to solve the angular velocities (ω_R) and steering angles of each wheel (θ_r).

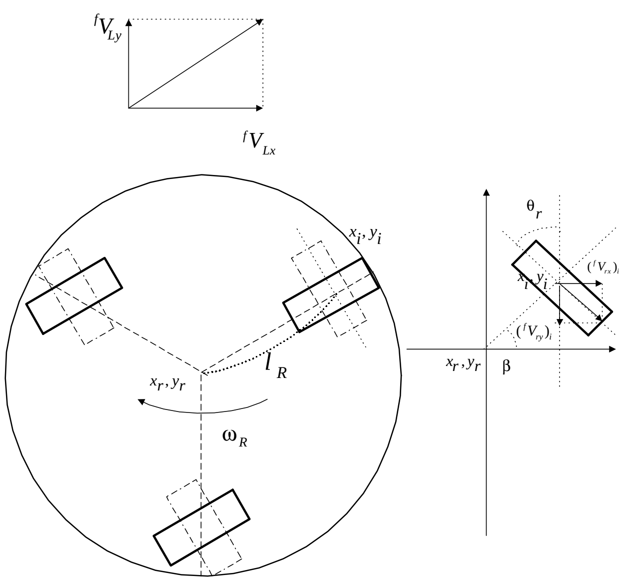

Fig. 4. Notation for the geometry of the mobile platform.

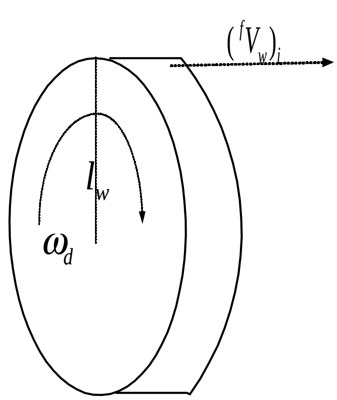

Fig. 5. Notation for the geometry of each wheel.

Input parameters are linear velocities of the mobile robot in X, Y directions $(^fV_{lx})_i, (^fV_{ly})_i$, the angular velocity of the mobile robot ω_R, and the iteration number. Three coordinate systems are used in inverse kinematics: the floor coordinate system; the mobile robot coordinate system with its origin at the center of the mobile robot; and, the wheel coordinate system with its origin at the center of each wheel. Each coordinate system consists solely of translation components, with no rotation components. A wheeled mobile robot's motion can be expressed in terms of translational and rotational motion. The translational component is the displacement of the center of the mobile robot, and the rotational component is the rotational movement of the axis of each wheel. Rotation components are expressed as follows:

$$\theta_r = \tan^{-1}\left(\frac{y_i - y_r}{x_i - x_r}\right). \tag{1}$$

The parameter θ_r is the angle displacement of each wheel in respect to the center of the mobile robot coordinate. The rotational velocity of each wheel $(^fV_{rx})_i$ can be calculated

$$(^fV_{rx})_i = l_w \omega_R \sin\theta_r , \tag{2}$$

$$(^fV_{ry})_i = l_w \omega_R \cos\theta_r . \tag{3}$$

Combining rotation and translation components, the velocity of i-th (i = 1, 2, 3) wheel is expressed as:

$$(^fV_{wx})_i = (^fV_{Lx}) + (^fV_{rx})_i \ , \tag{4}$$

$$(^fV_{wy})_i = (^fV_{Ly}) + (^fV_{ry})_i \ . \tag{5}$$

Using (1), (3), and (4), the steering angles of each wheel are obtained as shown in (6):

$$(\theta_s)_i = -\tan^{-1}\left[\frac{(^fV_{wx})_i}{(^fV_{wy})_i}\right] + \omega_R \mathrm{t_s} . \tag{6}$$

The velocities of each wheel can be obtained by combining the wheel velocity of *x*, *y* directions as follows:

$$(^fV_w) = \sqrt{(^fV_{wx})_i^2 + (^fV_{wy})_i^2} \ . \tag{7}$$

Once the velocity of the wheels is obtained, angular velocities of the i-th wheel can be obtained:

$$(\omega_d)_i = \frac{(^fV_w)}{l_w} . \tag{8}$$

3.2. Forward kinematics

Forward kinematics is used to estimate the position and heading angle of the mobile robot using the wheel measurement. At first, the rotation and steering values of the wheels are measured and obtained from translational and rotational components at the center point of the mobile robot. Velocity components of each wheel with respect to the frame coordinate system are given as

$$({}^{f}V_{wx})_i^m = -({}^{f}V_w)_i^m \sin[({}^{f}\theta_s)_i^m + \omega_R^m (k-1)t_s], \quad (9)$$

$$({}^{f}V_{wy})_i^m = ({}^{f}V_w)_i^m \cos[({}^{f}\theta_s)_i^m + \omega_R^m (k-1)t_s]. \quad (10)$$

Using the property that the rotational components are canceled if the velocities of three wheels are added together, the translational components are obtained as:

$${}^{f}V_{Lx}^m = \sum_{i=1}^{3} \frac{({}^{f}V_{wx})_i^m}{3}, \quad (11)$$

$${}^{f}V_{Ly}^m = \sum_{i=1}^{3} \frac{({}^{f}V_{wy})_i^m}{3}. \quad (12)$$

Using (8)-(12), the coordinates of the mobile robot's center and each wheel's center are obtained as follows:

$$x_R(k) = ({}^{f}V_{Lx})^m t_s + x_R(k-1), \quad (13)$$

$$y_R(k) = ({}^{f}V_{Ly})^m t_s + y_R(k-1), \quad (14)$$

$$\begin{bmatrix} x_i(k) \\ y_i(k) \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} x_i(k-1) - x_R(k-1) \\ y_i(k-1) - y_R(k-1) \end{bmatrix} + \begin{bmatrix} x_R \\ y_R \end{bmatrix}. \quad (15)$$

The angular velocity of the mobile robot is obtained from the amplitude and its directions as follows:

$$\omega_R^m = \frac{\sqrt{[({}^{f}V_{rx})_i^m]^2 + [({}^{f}V_{ry})_i^m]^2}}{l_w}, \quad (16)$$

where

$$({}^{f}V_{rx})_i^m = ({}^{f}V_{wx})_i^m - {}^{f}V_{Lx}^m, \quad (17)$$

$$({}^{f}V_{ry})_i^m = ({}^{f}V_{wy})_i^m - {}^{f}V_{Ly}^m. \quad (18)$$

In this case, the direction of the angular velocity should be determined considering positions of each wheel by the mobile robot's coordinate system.

4. BASIC TRAJECTORIES

All movements of the developed mobile robot can be achieved by combining three types of basic motions. This section deals with calculations of translational and rotational components to accomplish each motion segment. Details are provided in the following section.

4.1. Straight line with orientation angle (Basic Motion 1).

First, as shown in Fig. 6, straight line movement can be achieved by means of a changed orientation angle. The desired displacement (D) is expressed as:

$$D = \sqrt{(x_r - x_c)^2 + (y_r - y_c)^2}. \quad (19)$$

The steering angle of each wheel is expressed in (20). It maintains the following constant value during movement:

$$\alpha_r = \alpha_c = \tan^{-1}\left(\frac{y_r - y_c}{x_r - x_c}\right), (\alpha_1 = \alpha_2 = \alpha_3). \quad (20)$$

Fig. 6 shows the straight line movement of the mobile robot by changing the orientation angle. The steering angle of each wheel is continuously changed during the movement to change the orientation angle. The desired displacement (D) is shown in (19) and the desired moving time (T_1) is expressed as:

$$T_1 = \frac{D}{V_r}. \quad (21)$$

The translational and rotational components are obtained as follows:

$$V_{Lx} = \frac{\Delta x}{D} \cdot V_r, \; V_{Lx} = \frac{\Delta y}{D} \cdot V_r, \; \omega_r = \frac{\theta_R - \theta_c}{T_1}. \quad (22)$$

The orientation angle of the mobile robot is fixed in the case of θ_R equals θ_c. The orientation angle of the mobile robot can be changed without the movement of the center point of the mobile robot. The mobile robot moves only with the commanded rotational angular velocity. In this case, the mobile robot's translational velocities are zero, and the rotational component is expressed as follows:

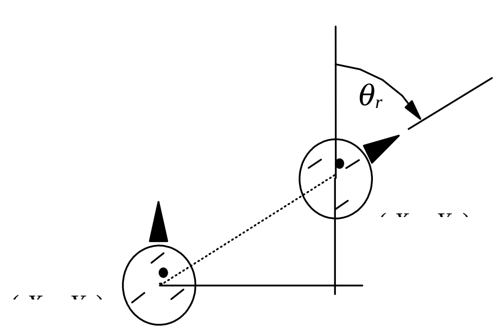

Fig. 6. Diagram of straight line with fixed orientation.

$$V_{Lx} = V_{Ly} = 0, \omega_R = \omega_r \,. \tag{23}$$

4.2. Arc with orientation angle (Basic Motion 2)

The arc movement with a constant radius and a fixed orientation angle is described in Fig. 7. The steering angles of each wheel are changed with the same values. The distance (d) between two positions is given in (24) and the desired displacement (D) is obtained as follows:

$$d = \sqrt{(x_r - x_c)^2 + (y_r - y_c)^2} \,, \tag{24}$$

$$d^{2} = R^2 + R^2 - 2R^2 \cos(\Delta r) \,, \tag{25}$$

$$\Delta r = \cos^{-1}(1 - 0.5\left(\frac{d}{R}\right)^2) \,, \tag{26}$$

$$D = R \cdot \Delta r. \tag{27}$$

The translational and rotational components and the desired moving time (T_2) are given as:

$$V_{Lx}(t) = V_r \cdot \sin(\frac{\Delta r}{T_2} \cdot t + \tan^{-1}(\tan \alpha_{ci})) \,, \tag{28}$$

$$V_{Ly}(t) = V_r \cdot \cos(\frac{\Delta r}{T_2} \cdot t + \tan^{-1}(\tan \alpha_{ci})) \,, \tag{29}$$

$$\omega_R = 0, T_2 = \frac{D}{V_r}(+ : C.W, - : C.C.W) \,. \tag{30}$$

It is arc movement that has a constant radius with the changing orientation angle. It is only the mobile robot's orientation angle that changes compared to the third segment. The desired moving time (T_2), translational and rotational components are obtained as follows:

$$\omega_r = \frac{\theta_R - \theta_c}{T_2}, T_2 = \frac{D}{V_r}. \tag{31}$$

4.3. Wheel steering (Basic Motion 3)

Wheel steering is used to change the steering angle without altering the mobile robot's center point or the orientation angle. This is a mode for changing the steering angle to the next moving direction. The mobile robot has neither translational nor rotational components and the command for the steering angle is given as:

$$\Delta\alpha_{\max} = \max(\Delta\alpha_1, \Delta\alpha_2, \Delta\alpha_3), \quad T_3 = \frac{\Delta\alpha_{\max}}{\omega_r}, \tag{32}$$

$$\alpha_{ri}(t) = \alpha_{ci} + \frac{\Delta\alpha_i}{T_3} \cdot t. \tag{33}$$

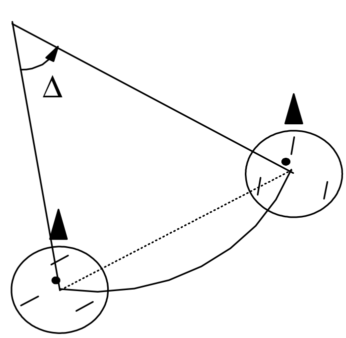

Fig. 7. Diagram of arc with fixed orientation.

5. IMPLEMENTATION RESULTS

5.1. Simulation of path error control

Forward kinematics calculates the position of the mobile robot from the measurements of encoders. Encoders connected to both the steering and driving motors record the rotation of the motor and this combined information is used to calculate the position and velocity of each wheel. Therefore, there is a path control error between the calculated position of the mobile robot and the measured position of the mobile robot. Errors in x and y directions are as follows:

$$e_x = (x_r - x_m), \tag{34}$$

$$e_y = (y_r - y_m). \tag{35}$$

The angle displacement error is shown in

$$e_h = \theta_R - \theta_m. \tag{36}$$

The velocity errors in both *x* and *y* directions are calculated as follows:

$$e_{xv} = (V_{rx})_r - (V_{rx})_m, \tag{37}$$

$$e_{yv} = (V_{ry})_r - (V_{ry})_m \,. \tag{38}$$

The values $(V_{xr})_c$, $(V_{yr})_c$ are 5 m/sec, the value ω_{Rc} is 5 rad/sec, the iteration number is 1000, and the constant values $c_1, c_2, c_3, c_4,$ and c_5 are 0.1 in the simulation. After calculating the errors, corrected values can be obtained using the following equations.

The angular velocity is calculated as follows:

$$\omega_{Rc} = \omega_{Rr} + c_1 e_h \,. \tag{39}$$

Linear velocities of X, Y direction are calculated as follows:

$$(V_{xr})_c = (V_{xr})_r + c_2 e_x + c_3 e_{xv} \,, \tag{40}$$

$$(V_{yr})_c = (V_{yr})_r + c_2 e_y + c_3 e_{yv} \,. \tag{41}$$

These values are used for calculating the steering angle and driving angle velocity through inverse kinematics. The mobile robot follows the desired motion trajectory by using a path error controller. Fig. 8 represents the motion trajectory when following the path error control method. The parameters, $\omega_{Rc}, (V_{xr})_c$, $(V_{yr})_c$ are control commands and $\omega_{Rr}, (V_{xr})_r,$ $(V_{yr})_r$ are reference commands in the path error controller.

5.2. Controller design and simulation for wheel slip error

Even if command signals to the steering and driving motors are exact, the mobile robot's wheels will show slippage due to imperfection of the wheel geometry and floor conditions [10-12]. The wheel model we drive is based on the no deformable planar circle rolling with no slip on the ground. The relationships between forces on wheels and slip angles are described by the following equations:

$$F_{lo} = \mu_p F_A - \frac{\lambda(\mu_p F_A - K_1 S)}{2lK_1 S}, \tag{42}$$

$$F_l = \mu F_A (1 - e^{-k\alpha}) \ . \tag{43}$$

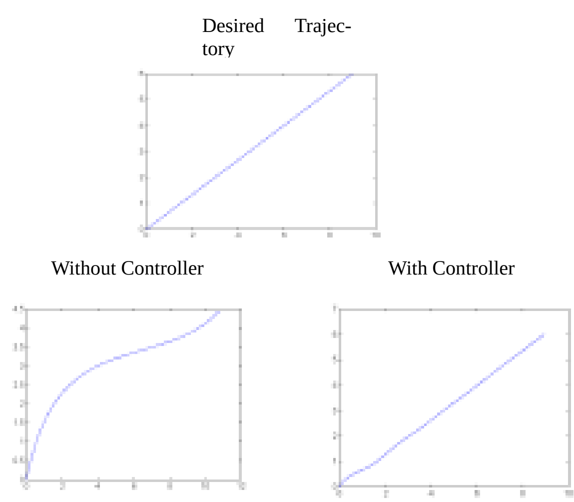

Fig. 8. Motion trajectory with path error control.

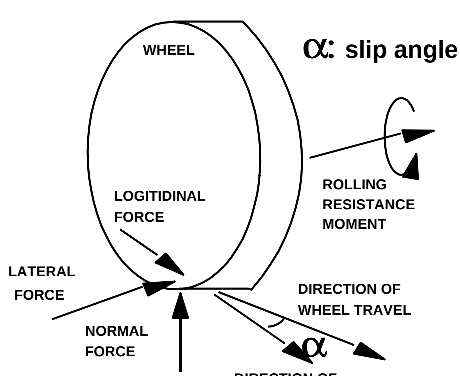

Fig. 9. Slipping model of wheel.

And the slip angle is given as

$$\alpha = K \cdot \ln\left[\mu \cdot \frac{F_A}{\mu F_A - F_l}\right]. \tag{44}$$

Using (44), the slip angle can be obtained from lateral force, and by compensating this slip angle at the steering motor, additional torque on the driving motors can be reduced. The mobile robot's wheels can then be steered so that they demonstrate the least slip. The proposed controller scheme is shown in Fig. 10. Inverse kinematics, forward kinematics, wheel slip model and torque-minimizing control algorithm are integrated into a single computer simulation model. Simulation results are given in Fig. 11. As in Fig. 11, if any disturbance is present, the commanded steering angle from inverse kinematics will exhibit further oscillation. However, this oscillation can be reduced by using a torque minimizing algorithm.

5.3. Navigation test with integrated sensor system

The navigation and obstacle avoidance algorithm have been studied [13-15]. In this paper, we test a simple navigation algorithm for proving the availability of the proposed kinematics. The applied algorithm is shown below. If it is not necessary for the mobile

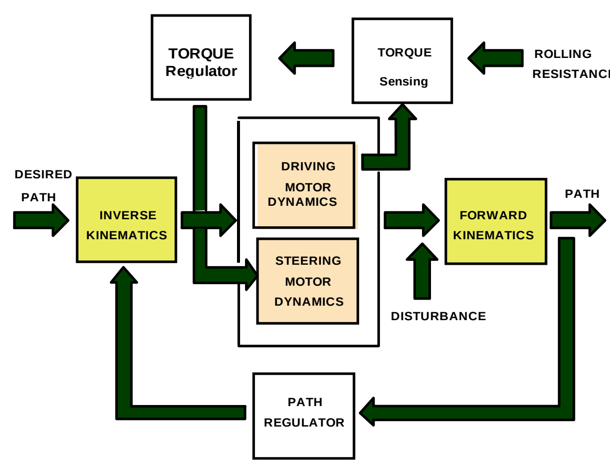

Fig. 10. Applied control scheme .

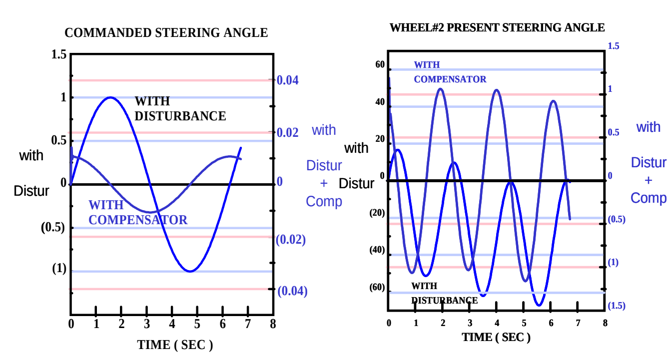

Fig. 11. Wheel slippage simulation.

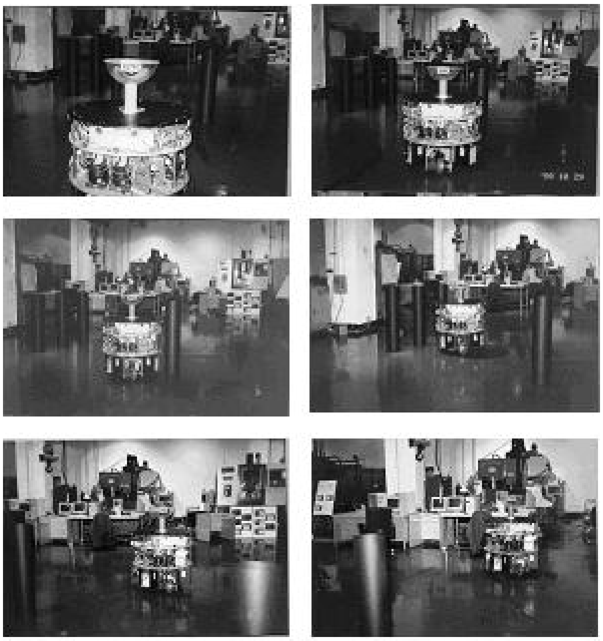

Fig. 12. Navigation test using the developed mobile robot.

robot to avoid present obstacles, the mobile robot calculates a straight course between the algorithm is shown below. If it is not necessary for the mobile robot to avoid present obstacles, the mobile robot calculates a straight course between the present position and the target and then proceeds directly through that path. If the mobile robot locates an object in close proximity, the mobile robot calculates the optimal moving direction considering both the present position and the target position data [16]. During navigation, 24 ultrasonic sensors and a vision sensor are used for detecting obstacles and correcting direction errors [17]. Fig. 13 contains a selection of scenes from an actual experiment using the developed mobile robot. The task in the experiment was to determine the destination (NC Lathe in Fig. 13) in a FMS pilot plant. After receiving its task, the mobile robot proceeds toward a target point by the path generation. In Scenes 1 and 2, the robot establishes a starting point and finds an obstacle within its calculated path. In Scenes 3 and 4, the mobile robot first detects the obstacle and then changes direction so as to avoid it. In Scenes 5 and 6, the mobile robot arrives at its destination.

6. CONCLUSIONS

In this paper, the kinematics modeling of a three wheeled omni-directional mobile robot based on a geometric approach is proposed. Inverse kinematics, forward kinematics and basic motions of the developed mobile robot are proposed and integrated into a computer simulation model. For these simulations, a three wheeled mobile robot platform with all wheels having the capability of both steering and driving is used. In the simulations, a control method for a mobile robot is presented in that the mobile robot's driving energy can be made efficient by reducing wheel slip. Because it is necessary to simulate uneven floor conditions that effect wheel slip, sinusoidal slip angles are added to the wheel steering motors as disturbances. In addition, a path error control method is applied to compensate for errors between the calculated position and the measured position of the mobile robot. Results of this research can be applied to areas in the automotive industry, especially to all-wheel drive electric vehicles. As a future direction of this work, one may consider analyzing the mechanical structure, efficiency power transfer and minimization of gear usage.

Nomenclature

$x_{i,} y_i$: X, Y coordinates of the i-th wheel

$x_{r,} y_r$: commanded X, Y coordinates of the mobile robot's center

$x_{c,} y_c$: current X, Y coordinates of the mobile robot's center

$x_{R,} y_R$: X, Y coordinates of the mobile robot's center

$x_{m,} y_m$: measured X, Y coordinates of the mobile robot's center

V_r : reference velocity of the mobile robot

$({}^f V_{rx})_{i,} ({}^f V_{ry})_i$: instantaneous X, Y velocity of the i-th wheel for the mobile robot rotation with respect to the frame coordinates

$({}^f V_{Lx})_{i,} ({}^f V_{Ly})_i$: instantaneous X, Y velocity of the wheel for the mobile robot translation with respect to the frame coordinates

$({}^f V_{wx})_{i,} ({}^f V_{wy})_i$: instantaneous X,Y velocity of the i-th wheel for the mobile robot displacement with respect to the frame coordinates

θ_r : angle displacement of each wheel

l_W : radius of the wheel

l_R : radius of the mobile robot

α_i : steering angle of the i-th wheel

$(\omega_d)_i$: driving angular velocity of the i-th wheel

ω_R : angular velocity of the mobile robot

t_s : sampling time

$(\theta_s)_i$: steering angle of the i-th wheel

ϕ : $\omega_r^m \cdot t_s$

K : lateral static stiffness of the wheel

μ : resultant friction coefficient

μ_p : maximum friction coefficient

F_A : normal force on the wheel

F_{lo} : longitudinal force on the wheel

F_l : lateral force on the wheel

λ : longitudinal deformation of the wheel at the wheel's front end

K_L : $K_l \cdot \lambda_l$

S : degree of wheel slip

l : contact length between the floor and the wheel

θ_c : current rotation angle of the mobile robot

θ_R : reference orientation angle of the mobile robot

(α_c, α_r): current and reference steering angles of the mobile robot

D: desired displacement of the mobile robot

d: distance between two points during Arc movement

e_x : error in x direction

e_y : error in y direction

e_h : error in angle displacement

e_{xv} : velocity error in x direction

e_{yv} : velocity error in y direction

T_1 : desired moving time in basic motion 1

T_2 : desired moving time in basic motion 2

T_3 : desired moving time in basic motion 3

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