Developing an Autonomous Mobile Robot and a Study of Navigation Towards Nonholonomic Problems

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Abstract **– In this paper, we present the first stage of developing mobile robot for use in a study of mobile robot navigation and its stability. Three basic navigation problems for Nonholonomic mobile robot are tracking a reference trajectory, path following and desire posture stabilization. In this study, we will focus on the trajectory tracking which means tracking reference trajectories predefined or given by path planners. The kinematics controller is usually applied to control the robot position and motion path. It is assumed that masses as well as inertias of the robot and wheels are negligible. Therefore the stability and robustness of the wheeled mobile robot cannot be analyzed. Furthermore, in many research and developments of mobile robot in trajectory tracking stability, one of the problems faced by the researches was sudden increase in motor speed (also known as speed jump or velocity jump) during the first few moments of motor's rotation which results in the tracking error occurred during the trajectory. Above drawbacks can be overcome by including a dynamic modeling in the motion controller.**

I. Introduction

Mobile Robot is a robot likes a vehicle that can move around in their environment where it needs all devices such as power sources, computational resources, sensors and actuators to be equipped and mounted on the robot. In this study, we are going to use an autonomous mobile robot which nonholonomic constraint as an experiment tool. In an Autonomous Mobile robot system, one of the important aspects is related to its motion and navigation control. Autonomous mobile robot navigation is a navigation of mobile robot in the unknown environment to achieve a given task with a lesser control by the human or without interaction with the human. The issue of navigation control becomes more complex when the mobile robot has a nonholonomic system (also called as *Anholonomic* system) where the system is described by a set of parameters subject to differential constraints, such that when the system evolves along a path in its parameter space, the parameters varying continuously in values but finally returns to the original set of values at the start of the path [1]. In a simple word, the nonholonomic constraint states that the mobile robot can only move in the direction normal to the axis of the driving wheel where it is satisfies the condition of pure rolling without slippage.

II. Literature Study

Control of nonholonomic system can be divided into 2 types of control method: Kinematics control and Dynamic control. On the early research, many researchers worked focusing on only kinematics control but in recent years, a number of researches have investigated the application of the dynamic control. Some literature study on both of these control methods is described below:

In most of literatures, the nonholonomic tracking problem is simplified by neglecting the dynamics constraint and considering only on the steering system which is the control input are the velocities – linear velocity, v and angular velocity, ω. In the kinematics control, it is often to assume that the mobile robot fulfills perfect velocity tracking. Even in general, the proposed controller has successfully convergence the trajectory tracking error to zero but the use of kinematics control remains a drawback in terms of providing good stability when the mobile robot is to operate in the presence of disturbances and in unknown environments.

Kanayama *et al.* [2] proposed a stable tracking control method for a nonholonomic mobile robot using Lypunov function. The main purpose of this control rule is to find a reasonable target for linear velocity and angular velocity (v, ω). The control algorithm has been proven in its ability by determine reasonable and best value for the parameters K_x, K_y and K_θ .

A lot of research demonstrated the stable tracking control law for mobile robots focusing only on the tracking error convergence and system stability but neglect the smoothness of the velocity signal and dynamics constraints. Generation of robot velocity commands using kinematics model controllers approaches always start with a very large value and suffer from speed jumps when sudden tracking errors occur, which is impossible in actual application.

To solve the speed jumps problem, recent years, an increasing amount of research is examining the combination of kinematics model and dynamic model. One of the first publications which tried to integrate kinematics controllers with a torque controller into the nonholonomic mobile robot system is by Fierro and Lewis [3] in year 1995.

A dynamical controller provides a rigorous method of taking in account the specific vehicle dynamics (mass, inertia factor, torque) to convert steering system command into control input for the actual mobile robot. The advantage of this control algorithm is that, it is approaching closer to the real system compared to the kinematics model.

Dynamic controller is the most popular control method among the researcher. Many dynamic controllers have been developed that include neural dynamics based controller [4], Neural dynamics based full-state tracking controller [5], Neuro-cascade approach controller [6] and so on.

Besides Kinematics and Dynamics control, the tracking and stability controller for the mobile robot also can be classified into Predictive control model and Adaptive control model. One example of the predictive controller was brought by the research of mobile robot predictive trajectory tracking by Martin Seyr and Stefan [7] in year 2005. The control concept employs a linear state feedback law with integration of the velocity errors to control the velocity, *v(k)* and a nonlinear predictive controller using the closed loop of the inner loop in the prediction of the positions *x(k)*, as shown in figure 1.

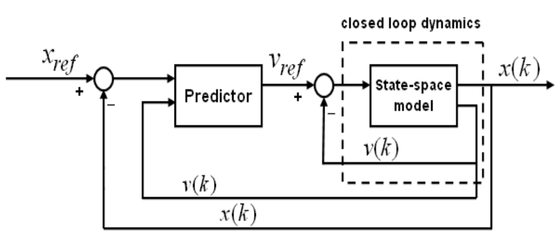

Fig.1. Sample of predictive algorithm.

This predictive algorithm performs very well in simulation even under severe disturbances. The state feedback controller with integration of the control error of the inner loop and the optimization in the outer loop makes the system very robust against modeling inaccuracies and very robust against changing ground conditions.

In adaptive control approach, it is assumed that the model can be fit to uncertain function. But, Ortega and Astolfi [8], instead of struggling fit a parameter function to the uncertainties was generated a stable error equation with a perturbation term that can be driven to zero.

Most popular adaptive controller is Backstepping technique where the stability is proved by the Lyapunov theory. One example is presented by Fukao, Nakagawa and Adachi [9]. They proposed that if an adaptive tracking controller for the kinematics model with unknown parameter exists, so an adaptive tracking controller for the dynamic model also can be designed by using an Adaptive backstepping approach. In this design, a new kinematics' adaptive controller is proposed and a torque adaptive controller is derived using this kinematics controller. The torque controller is designed using back-stepping method.

The mobile robot control technique was developed and progress started by the kinematics control model to dynamics control model and hence, there were many approaches in dynamics control model incorporate with Adaptive, Predictive, Intelligent element and so on. For the best of our knowledge, we think that a combination of kinematics control and dynamics control model could achieve a better stability of robot posture and improve the convergence of the trajectory tracking for the mobile robot.

III. KINEMATICS MODEL DESCRIPTION

A differential steering system of the mobile robot is shown in figure 2 [10]. It consists of a vehicle with two driving wheels mounted on the same axis and one front caster wheel. The motion and orientation of the mobile robot are achieved by individual DC motors providing the necessary torque to the rear wheels. A front caster wheel is not considered in creating kinematics model and dynamics model. It is assumed that the body is rectangular though any polygonal shape would lead to similar results.

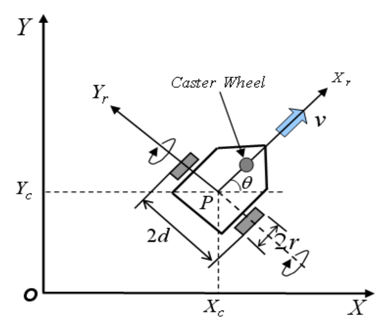

Fig.2. Differential steering system of a Nonholonomic mobile robot

Ignoring the wheel slip during the robot's roll, the kinematics model can be described as,

$$\left.\begin{aligned} \dot{x} &= v \cos\theta \\ \dot{y} &= v \sin\theta \\ \dot{\theta} &= \omega \end{aligned}\right\} \qquad (1)$$

where (*x*,*y*) is the coordinates of point P, θ is the angle between x coordinates and robot's forwards direction, v, ω are the linear velocity and angular velocity of mobile robot at P, respectively.

For a nonholonomic mobile robot, the relationship of velocity in the world coordinate $\dot{p}_c$ and velocity q_c in the local coordinate can be described by a Wheel Jacobian Matrix denoted as J_c.

$$\dot{p}_c = \begin{bmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{\theta}_c \end{bmatrix} = \begin{bmatrix} \cos\theta_c & 0 \\ \sin\theta_c & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_c \\ w_c \end{bmatrix} = J_c q_c \qquad (2)$$

The reference posture and reference velocity vectors are given as below.

$$p_r = \begin{bmatrix} x_r \\ y_r \\ \theta_r \end{bmatrix}, \quad q_r = \begin{bmatrix} v_r \\ \omega_r \end{bmatrix} \qquad (3)$$

The nonholonomic constraint arises from zero sideways velocity of the wheel can be described by;

$$\dot{y}\cos\theta - \dot{x}\sin\theta = 0 \qquad (4)$$

and the tracking error posture is described as;

$$p_e = \begin{bmatrix} e_x \\ e_y \\ e_\theta \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{bmatrix} (p_r - p_c) \qquad (5)$$

where e_x, e_y, e_θ are the errors in the driving direction, lateral direction and orientation direction of the mobile robot, respectively; and the mobile robot's current posture is given as follows:

$$p_c = \begin{bmatrix} x_c \\ y_c \\ \theta_c \end{bmatrix} \qquad (6)$$

Above kinematics model formulations can be described in simple block diagram as shown in below figure (Fig.3).

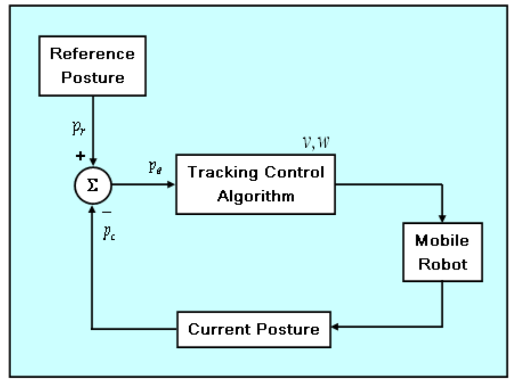

Fig.3. Mobile robot Control block diagram.

IV. Developing An Autonomous Mobile Robot

In this study, we have developed a Nonholonomic Mobile robot called as 'AMAD-R' as an experiment tool and is shown in figure 4.

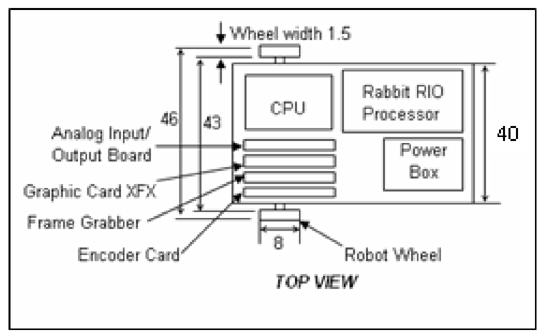

Fig.4. Structure of the mobile robot.

Table I shows the mechanical specification of the robot. The robot is equipped with encoder sensor on the both side of the rear wheel connected by the rubber chain in order to decode the position of the mobile robot and the speed of the wheels. The resolution of the optical quadrate encoder is 1024 pulse/ rev. The mobile robot uses 8cm in diameters' of wheel so that the each pulse of the encoder could counter a distance of 8 x 3.1415 / 1024 = 0.02454cm per pulse.

Two units of optical quadrature encoders were attached at mobile robot connected with the rubber chain or drive belt to each of the output shaft for the right side DC motor and left side DC motor, respectively. These encoders are used to measure wheel rotation which equals to 1024 counts of encoder pulse for revolution. A quadrature encoder (also known as an incremental rotary encoder) has two outputs called quadrature outputs. It has two gray coded tracks which phase out in 90 degrees. These signals are decoded to produce a count up pulse or count down pulse. These encoders are used to track motion and can be used to determine position and velocity. Because of the direction can be determined, very accurate measurement can be made so as it is widely use in industrial control, robotic, rotating radar platform and so on.

TABLE I
MECHANICAL SPECIFICATION

Height	14 cm
Width	40 cm
Length	45 cm
Radius of 2 driving wheels: r	4 cm
Circumference of wheel: $2\pi r$	25.1327 cm
Distance between 2 wheels: 2d	43 cm

An ultrasonic sensor is installed in-front of the mobile robot for the purpose of detecting obstacle during tracking. More sensors will be installed later to increase the capability in obstacle avoidance. Sensor used in this mobile robot is a type of LV-MaxSonar-EZ1® from MaxBotic™. It is very important in selecting sensor that reliable and has range stability, fast measurement and flexibility in sensor output method. For LV-MaxSonar®-EZ1™, it could detect an object included zero range object up to 6.45 meters and provides sonar range information from 15 centimeters to 6.35 meters with 2.5cm resolution (objects between 0 to 15cm range detected as 15cm), wider power range (lowest by 2.5V up to 5.5V) and three different output methods – pulse width output, analog voltage output and serial digital output. Besides that, LV-MaxSonar®-EZ1™ provides continuous variable gain, high quality beam shape, easy to use and very important also, low cost.

All signals from the various sensors will be processed by the Interface™ Analog Input-Output PCI-A3521 card. Interface™ encoder PCI-A6205C card is mounted on the computer motherboard ASUS® M4A78 PRO for converting the encoder signal data before the data can be sent via RS-232 port to secondary processor Rabbit RIO 4100 and converting it to PWM signal, control the voltage and speed of the DC motors.

V. SOFTWARE DEVELOPMENT AND SUMMARY

An algorithm designed for mobile robot posture's stability and trajectory tracking will be developed by using Dynamic C software integrated in Rabbit® RIO processor. The selection of using Rabbit® RIO processor and Dynamic C is due to its features of multitasking environment; more than one task (each representing a sequence of operations) can appear to execute in parallel. In reality, a single processor can only execute one instruction at a time. If an application has multiple tasks to perform, multitasking software can usually take advantage of natural delays in each task to increase the overall performance of the system. Each task can do some of its work while the other tasks are waiting for an event, or for something to do. In this way, the tasks execute almost in parallel [11].

The advantage of multitasking is very important in this mobile robot development and its navigation since, in the future, the mobile robot is planned for further developments to perform multitask in actual applications.

High-end processor and High CPU capacity are used in this mobile robot in order to cope with the multitasking, real-time motion control and trajectory tracking.

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