VELOCITY CONTROL OF A CAR-LIKE MOBILE ROBOT

By

TOP SOKUNPHAL

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DC	Direct Current
GAs	Genetic Algorithms
IAE	Integral of Absolute Magnitude of the Error
ICC	Instantaneous Centre of Curvature
ICR	Instantaneous Centre of Rotation
ICSP	In-Circuit Serial Programming
IDE	Integrated Development Environment
LMS	Least Mean Square
NPN	Not Pointing In
PI	Proportional Integral
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
RMSE	Root Mean Square Error
USB	Universal Serial Bus

ABSTRAK

Kawalan halaju merupakan komponen yang sangat penting untuk setiap robot mudah alih. Kawalan halaju ini akan memberikan halaju yang stabil kepada sistem dan meningkatkan keupayaan pengiraan pergerakan robot mudah alih. Sementara itu, kawalan halaju robot mudah alih seperti-kereta ialah tajuk utama dalam disertasi ini. Tujuan utama kawalan halaju robot mudah alih seperti-kereta adalah untuk merekabentuk pengawal kelajuan dan menggunakan robot model kinematik seperti-kereta dalam usaha untuk mendapatkan pergerakan semasa menyelaras robot. Terdapat beberapa prosedur untuk mencapai objektif projek ini seperti mengesahkan model motor DC, merekabentuk pengawal kelajuan berdasarkan pengawal PI, dan melaksanakan dengan model robot kinematik. DC model motor boleh disahkan berdasarkan eksperimen masa nyata. Pengawal kelajuan boleh direka dengan menggunakan pengawal PI. Walau bagaimanapun, bahagian yang kritikal dalam pengawal kelajuan adalah untuk mengira parameter PI. Model robot kinematik seperti-kereta digunakan untuk menentukan pergerakan semasa menyelaras robot berdasarkan halaju linear dari pengawal kelajuan, dan sudut stereng bakal ditetapkan menjadi 30^{o}. Selain itu, sudut stereng yang ditetapkan menjadi 30^{o} ini membolehkan robot membelok sebelah kiri untuk 30^{o}. Keputusan akhir boleh diperolehi dengan melakukan simulasi dan ujian masa nyata bagi kaedah yang dicadangkan itu. Pengawal kelajuan berjaya direka yang memberikan kelajuan yang stabil kepada sistem. Model robot kinematik seperti-kereta juga berjaya dilaksanakan pada robot, tetapi peningkatan model ini diperlukan untuk membolehkan ia lebih tepat.

ABSTRACT

The velocity control is a very important component for every mobile robot. This velocity control will provide a stable velocity to the system, and increase the ability of calculation the movement coordinate of the mobile robot. Meanwhile, the velocity control of a car-like mobile robot is a main title in this dissertation. The main purpose of the velocity control of a car-like mobile robot is to design speed controller and apply the car-like robot kinematic model in order to obtain the current movement coordinate of the robot. There are some procedures to achieve the objective of this project such as to verify DC motor model, design the speed controller based on PI controller, and implement with car-like robot kinematic model. The DC motor model can be verified based on real-time experiment. The speed controller can be designed by using PI controller. However, the critical part of speed controller is to calculate the PI parameters. The car-like robot kinematic model is used to define the current movement coordinate of the robot based on the linear velocity from speed controller, and the fixed steering angle is set to be 30^o. Moreover, this fixed 30^o steering angle is made the robot turn left for 30^o. By doing the simulation and real-time testing for the proposed methods, the final result can be obtained. The speed controller is successfully designed which provides a stable velocity to the system. The car-like robot kinematic model is also successfully implemented on the robot, but the improvement of this model is needed in order to make it more accurate.

CHAPTER 1

INTRODUCTION

1.1. Overview

In the previous years, investigation and development of the autonomous mobile robot are increasing gradually in many fields such as in military, industries, and hospital. The concept of mobility which basically suggested whereby mobility is free-roaming robots move about with an integrated multifariousness fostering even more preponderant returns in extra range of application surpass that of the typical factor floor.

In the past years, mobile robots were designed with large size, heavy and require a high cost computer system which need to be connected via cable or wireless devices. Nowadays, the trend is to evolve with a small mobile robot which is reduced in size, weigh, and cost of the system by using sensors, numerous actuators, and the controller are carried on-board the robot (Bräunl, 2008). Mobile robots are built based on a good relation of both hardware and software. There is one more thing that mobile robot really needs is a good navigation system such as vision camera or sensor. (Chen & Agrawal, 2013).

In this project, the mobile robot is developed to move by using car-like robot kinematic model. This mobile robot will move forward with the stable speed which is provided by the speed controller. Moreover, car-like robot kinematic model will let the robot turn left or right according to the linear velocity provided by speed controller and a fixed steering angle. The speed is provided for the mobile robot in range between 9.99cm/s (0.36km/h) to 88.7cm/s (3.2km/h).

According to the mobile robot which is designed with a simple velocity control by adjusting the PWM faces the problem during movement such as the mobile robot cannot keep moving straight and difficult for direction control like turning left or right. Therefore, the speed controller and car-like robot kinematic model are introduced in this project to make the mobile robot has a high efficient on maneuver system.

Furthermore, this project also provides a lot of conveniences for development purpose to reach a high level mobile robot. The mobile robot can be developed by making a communication with various sensors and artificial intelligence. Moreover, the mobile robot can be interacted with human, wheelchair, and other mobile robots as well. Therefore, the project has many benefits for control system purpose and society.

1.2. Problem Statement

Nowadays, there are so many type of mobile robot. The movement and the constraint of development are very important for every mobile robot. Some mobile robots are designed by using the proper control method and the others comes with a simple control method by adjusting velocity to make the robot move which has many problems during movement of the robot.

There are some motion problems can be found on the mobile robot which is using a simple control method. Firstly, the mobile robot cannot keep moving straight line due to the speed provided by DC motor is not stable. This matter also makes the robot has the difficulty to turn left or right by direction set or by using various sensor.

Therefore, the speed controller and car-like robot kinematic model are being used in this project which known as the proper control system method. The speed controller will provide a stable velocity to the robot, and car-like robot kinematic model will control the movement of the robot by using the reference velocity from the speed controller and the steering angle to control the direction of the robot. The advantage of the car-like robot cinematic model is required only one DC motor and provides the current coordinate of the robot.

1.3. Objective

The car-like robot is a type of mobile robot where the velocity and steering angle are needed in order to get current coordinate of the robot. Therefore, there are two main objectives to control velocity for car-like robot.

- To design the speed controller by using PI controller for car-like mobile robot.
- To implement the maneuver control system by using car-like robot kinematic model.

1.4. Scope of Work

To achieve the objectives, DC motor model identification is needed to be done at the first place to define transfer function of DC motor in this project. The main goal is to define transfer function parameters such as DC gain and time constant. Another necessary part is to design speed controller for car-like mobile robot by using PI controller. This speed controller has enough ability to provide a stable velocity to the system. Therefore, experiments are carried out in order to verify that the speed controller is successfully designed.

Moreover, car-like robot kinematic model is used as a maneuver control method to calculate current coordinate of car-like robot based on the motion equation of car-like robot. By using car-like robot model, reference velocity and steering angle are needed to be input for the system. The distance between front wheels and back wheels is very necessary in this model due to the motion model of car-like robot.

Furthermore, the experiment for car-like robot model must be done to guarantee that the robot moves are matched with the defined coordinates on simulation. The calculation real-time coordinate of car-like robot is done by using Odomertry method. However, the comparison between simulation result and real-time testing of the robot are needed to be considered to verify that the car-like robot model can be used for this system.

1.5. Thesis Organization

There are five chapters in this dissertation such as introduction, literature review, methodology, result and discussion, and conclusion. The briefly explanation for every chapters can be found in this section, which start with chapter 1 until chapter 5. This section also show about the outline in this dissertation.

Chapter 1 is shown about introduction, which describes about the overview of related work, problem statement that express about the problem of using the simple velocity control to drive the robot, goal and objectives that need to achieve in this project, and scope of work which set to be done to achieve goal and objectives.

Chapter 2 shows literature review which provides some main information and result from relevant research. Those information is related to technique and method that have been using for relevant inventions. Moreover, this chapter will briefly explain about the result of those relevant research. According to those results, the contribution of those technique to this project can be confirmed.

Chapter 3 discusses about methodology, which describes about method and technique that have been used in this entire project. Furthermore, all concepts that show about how those techniques work and how to conduct the experiment are found in this chapter. Hardware and software section are also explained in this chapter.

Chapter 4 explains about results and discussion for velocity control of car-like mobile robot. All the completed results which is done by simulation and real-time testing are described in this chapter. Moreover, this chapter is also explained about how to the result contribute to the entire project.

Chapter 5 is a conclusion section, which concludes all the important information, and what have been done in this project. In addition, this chapter also provides some good idea to improve the ability of using car-like robot kinematic model as a main maneuver control method in this project.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The relevant theories and precious research available which related to velocity control of car-like mobile robot are described in this chapter. There are some important techniques and relevant research available such as proportional integral derivative (PID) controller, velocity control of DC motor by using both PI and PID controller, maneuver control system, and the relative error calculation. Moreover, car-like robot control system design, differential drive, and skid steering are found in maneuver control system.

2.2. Proportional Integral Derivative Controller Optimization

Proportional integral derivative (PID) control is one of the most efficient and commonly use in robotic field. PID controller compares the measure output and the speed. During the speed of the robot is low, the proportional control will increase the duty cycle. This proportional control is very important parameter in PID controller in order stable the system.

Derivative control will response to reduce the duty cycle, in case the speed raise too fast. Duty cycle will be effected by proportional, integral, and derivative control. According to the closed-loop control, the turning point must be very accurate based on the set points and the process variable (Saidonr et al., 2011).

According to the simple formation and implementation, PID controller is well known in control system field. The fundamental of PID controller is to define and optimize the PID parameters. Recently, there are a lot of researches introduce intelligent control to PID controller. This mean that the intelligence PID is built based on control process and control law, or optimal problems with a smooth space of continuous derivatives.

Furthermore, the PID parameters optimization using genetic algorithm technique has been applied to PID controller by many scholars (Aly, 2011). In addition, the optimization of the PID controller parameters using genetic algorithm is applied to control servo drive system of the mobile robot. The structure of DC motor position servo is shown in Figure 2.1.

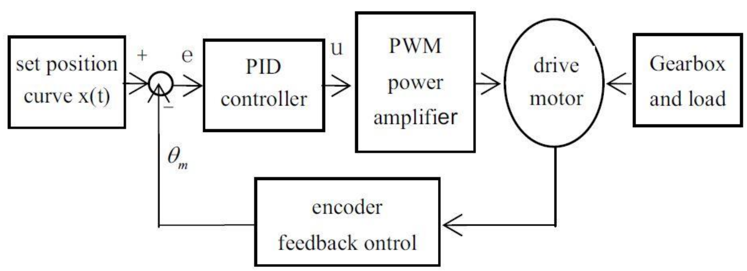


Figure 2.1. The structure of DC motor position servo

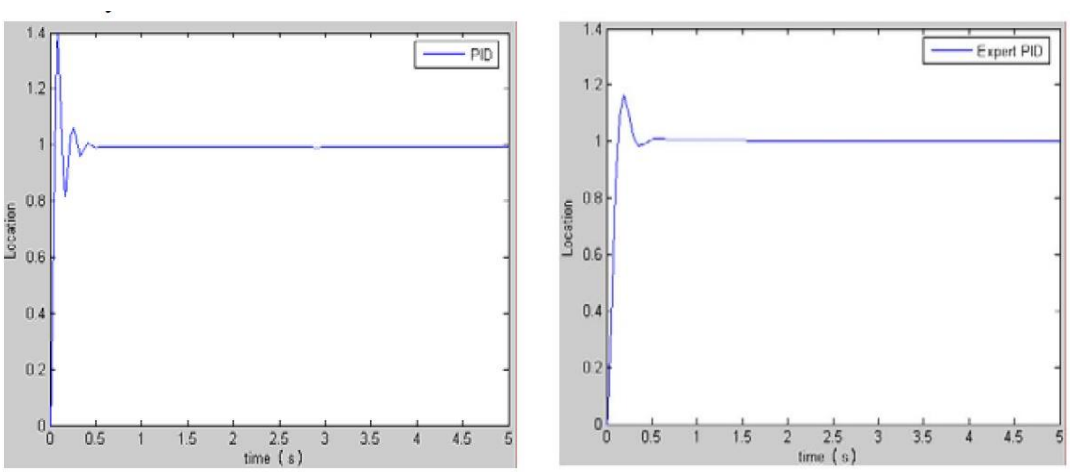
(Yan-hong et al., 2011)

In this research, the proposed method proved that the optimization of PID parameter for servo motor is solved. Furthermore, the intelligent algorithm is applied in PID controller for DC motor. There are three procedures to prove that the proposed method is right to apply to the whole system.

Firstly, reverse error neural network is adopted to identify the mathematical model of the robot drive. Secondly, the genetic algorithm is applied to define PID controller parameter based on the identification model. Finally, the proposed method is implemented to the mobile robot (Yan-hong et al., 2011).

Meanwhile, another method is proposed as an expert PID controller which combine the position error and error of change output to correct the PID parameters for mobile robot. The mobile robot is designed based on photoelectric sensor to detect the white background and black middle line to reach the goal stable and fast. MATLAB is a software which is used for simulation purpose (Luo & Li, 2014).

The simple output response curve using a simple PID control is shown in Figure 2.2 (a). By adding expert PID control to the system, the output response curve is presented in Figure 2.2 (b). As the result, an expert PID controller has a good performance, high reliability and good for tracking mobile robot automatically.



(a) (b)

Figure 2.2. (a) A simple PID output response curve, (b) An expert PID output (Luo & Li, 2014)

2.3. Velocity Control of DC Motor Based on PID Controller

The DC motor is a necessary component for every mobile robots. The velocity control is one of the most important part in order to provide a stable velocity to the system. According to the previous research, there are a lot of techniques which are used to control velocity of DC motor. However, PID controller is most common choice as a main controller for velocity control of DC motor. This section is described about velocity control of DC motor by using optimization techniques based on PID controller.

PID controller is well known as a control which is used to control speed and position of DC motor framework. In this research, genetic algorithms (GAs) are used to optimize the PID gains for speed controller of a DC motor. Genetic Algorithms are a stochastic general pursue procedure that simulate the strategy of standard change (Pavankumar et al., 2010). Moreover, PID controller is utilized due to its simple control structure is very simple and less expensive (Visioli, 2012).

According to the execution of generic algorithms, the best tuning of PID controllers parameters can be obtained. During the execution records, the ideal PID controller analyzed the extension values by using GAs. The Integral of Absolute Magnitude of the error (IAE) is settled to provide a best PID controller. The proposed method was demonstrated with a second request physical plant as DC motor, where the PID turning parameters calculations were driven for the most part.

2.3.1. Separately Excited DC Motor

The separately excited DC motor provide a speed to the system by using armature control and the voltage apply to armature. The best rate for outline, position, speed are given by DC motor. The block diagram of DC motor can be designed on MATLAB Simulink. Furthermore, MATLAB Simulink is also used to get a step response for DC motor. The parameters of DC motor is shown in Table 2.1.

Table 2-1 DC motor parameters (Suman & Kumar Giri, 2016)

Parameters	**Value**
Armature inductance	L_a=0.1215 H
Armature resistance	R_a=11.2 Ohm
Rotor inertia	J_m=0.02215 kg/m^2
Armature voltage	V_a=240 V
Viscous friction coefficient	B_m=0.002953 Nms/rad
Motor torque constant	K_m=1.28 Nm/A
Back EMF constant	K_b=1.28 Vs/rad
Speed	W=1500 rpm

2.3.2. Turning of PID Controller

In this research, the PID parameters can be calculated by using the Ziegler-Nichols tuning rules. By using the Ziegler-Nichols, the relative coefficient is known as a definitive addition the discrete reactions of a DC motor. Furthermore, the scattering and creation can fixed the execution of standard controllers. The Ziegler-Nichols tuning rule parameters based is shown in Table 2.2.

Table 2-2 Ziegler-Nichols turning rule based (Suman & Kumar Giri, 2016)

Controller Type	K_P	K_I	K_D
PID	K_u/1.7	T_u/2	T_u/8

The goal of this technique is to get the PID parameters which match the execution purpose such as settling time, rising time, overshoot, and the steady condition commit error. According to the relation between DC motor and PID controller, the block diagram of PID controller system can be designed as shown in Figure 2.3, which e is an error signal, K_P is a proportional gain, K_I is an integral gain, and K_D is a derivative gain. Moreover, the effect of increasing the PID controller parameters is shown in Table 2.3.

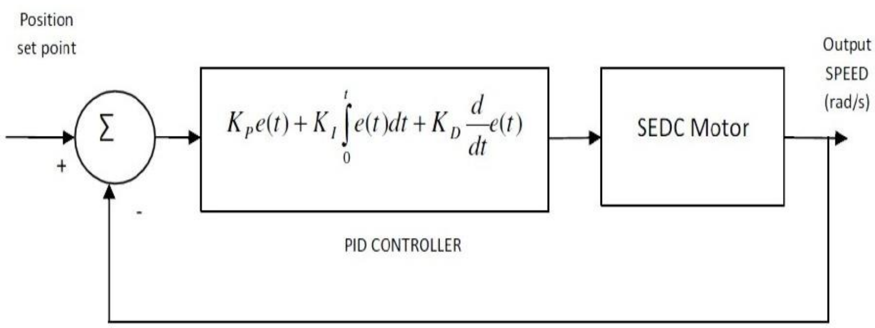


Figure 2.3. The PID controller system

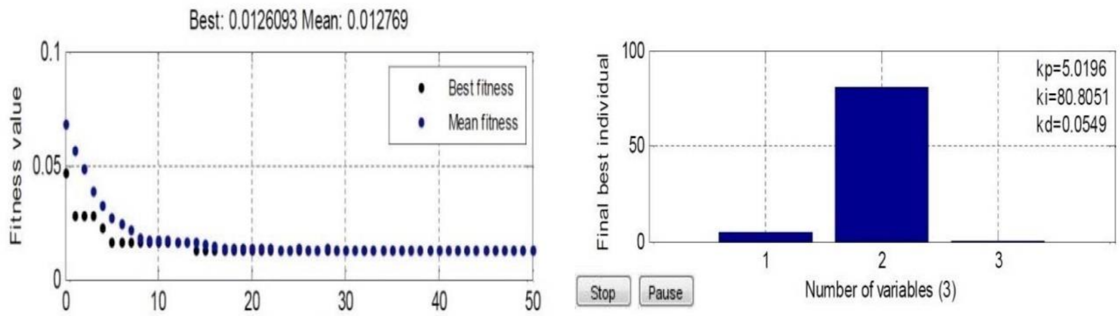
(Suman & Kumar Giri, 2016)

Table 2-3 The effect of increasing the PID parameters (Suman & Kumar Giri, 2016)

Parameter	**Rise Time**	**Overshoot**	**Settling Time**	**Steady state error**
K_P	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Reduce
K_D	Small change	Decrease	Decrease	Small change

However, the conventional PID controller tuning method which is used to obtained a standard parameters of PID controller can be demonstrated by using MATLAB.

Moreover, the genetic algorithms can be applied by using the fitness function. MATLAB coding is used to calculate the integral of the absolute error. The GA progress result based on integral of the absolute error can be shown in Figure 2.4. Moreover, the step input of controlled DC motor drive system can be shown in Figure 2.5.



(a) (b)

Figure 2.4. GA optimization progression based objective function (IAE) index (Suman & Kumar Giri, 2016)

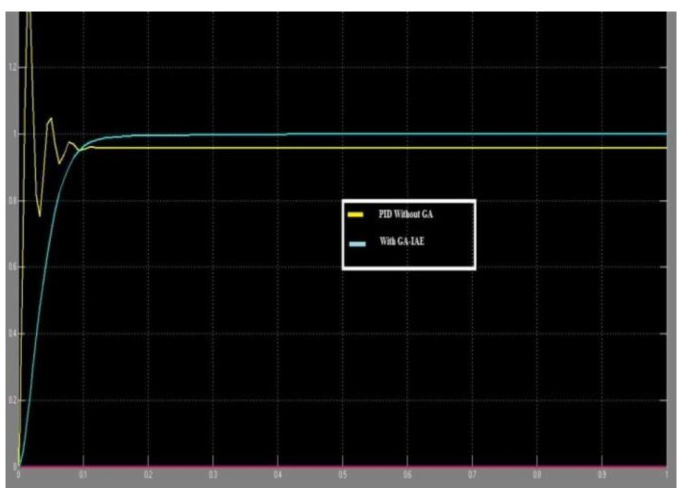


Figure 2.5. Step response of PID with GA and without GA

(Suman & Kumar Giri, 2016)

The final result in this research proved that the standard PID controller didn't provide the accurate result. The best result is obtained by using another technique to control velocity of DC motor which is called genetic algorithms based PID controller. By using GA based on PID controller, the PID parameters can be defined based on distinctive target work, this tuning technique to get least ascent time, and the small steady state error of settling time and overshoot (Suman & Kumar Giri, 2016).

2.4. Maneuver Control System

Recently, autonomous mobile robot provides a lot of advantages to industrial, military, home, and other research centers. Maneuver control system is well known as a main role to control the navigation of autonomous mobile robot. There are some researches that related to maneuver control method such as car-like mobile robot, differential kinematic, and skid steering, will be reviewed in this section.

2.4.1. Car-like Mobile Robot Control Design

Recently, the navigation of an autonomous mobile robot is the primary topic to consider in the robotic field. The collision between the desire position and obstacle is the matter of navigation (Kloetzer & Belta, 2008). The relevant researches such as a simple dynamic and complicated dynamic are appeared in this area. The most common of research on path planning for mobile robots is simple robot dynamic, either fully actuated or under actuated with differential-wheel drive concept.

According to a high efficiency result, a realistic idea from large scale mobile robots is to focus on car-like robots. Car-like robot is one of the most effective motion control method which is used to control the wheels of the robot. The mathematical models are usually used in a fixed frame environment or in frame where the robot moves to the desired path (Kloetzer & Ghita, 2010). According to linear control theory, the adaptive control system is designed to follow the path of car-like mobile robot. PID controller is used to control the path following of the robot (Sanchez-lopez et al., 2012).

However, the fuzzy PID controller for the path following of a Car-like mobile robot is proposed to improve performance of using only PID controller. To achieve this method, there are two important things need to consider which include the kinematic model of Car-like mobile robot, fuzzy PID controller and its features. The bicycle model of Car-like robot is presented in Figure 2.6.

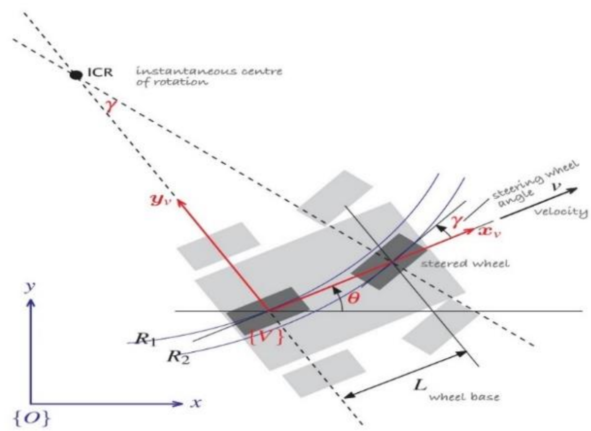


Figure 2.6. The bicycle model of Car-like mobile robot

(Siciliano, Khatib, & Groen, 2011)

MATLAB is used to design the Simulink block of the system. So, the block diagram of fuzzy PID controller can be designed as Figure 2.7. Based on the experiment result, the fuzzy PID controller has a better performance than the standard PID controller for mobile robot with any initial state (Talebi Abatari & Dehghani Tafti, 2013).

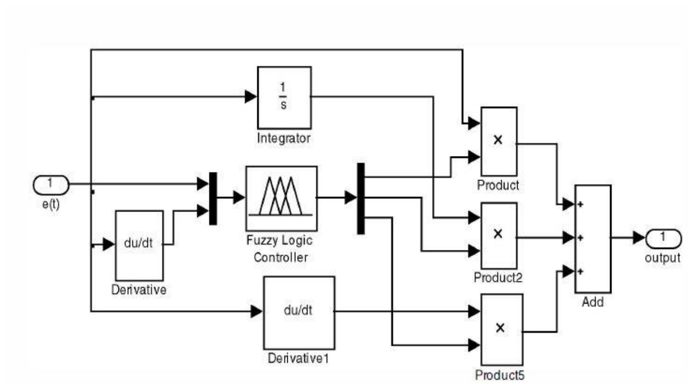


Figure 2.7. Simulink block of fuzzy PID controller

(Talebi Abatari & Dehghani Tafti, 2013)

2.4.2. Differential Drive

The motion control and orientation of a mobile robot are the problem for researcher. By the time, the solution has been proposed to solve the problem by using the kinematic model, PID controller (Abdalla & Abdulkareem, 2012), the parameters tuning using optimization method, and output feedback state tracking controller. The trajectory tracking of wheeled mobile robot is considered as a various control strategy for minimizing the tracking error.

The adaptive controller is required to address the pose error at every point of the given trajectory and should be validated on different polygon or fold line trajectories

(CAO, ZHAO, & WU, 2011). Differential drive for a mobile robot is used to control the direction of the robot based on the differential between the speed of left and right wheel.

Normally, the differential drive is applied to the three-wheel's robot which two wheels are drive the robot and another one wheel is for supporting the robot. The differential drive model is not based only on specific inputs and outputs, but also on how and where the frame coordinates are accomplished (Diaz & Kelly, 2016). The mobile robot configuration and motion coordinate are show in Figure 2.8.

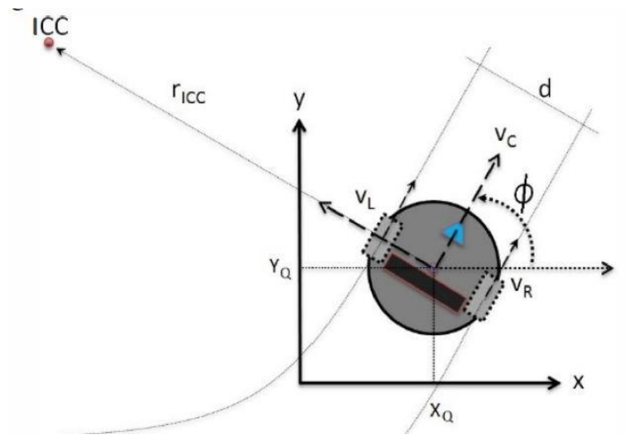


Figure 2.8. Mobile robot configuration and motion coordinate

(Chandra & Mija, 2016)

By using the proposed method, the result of trajectory tracking without controller in closed loop system is shown in Figure 2.9 (a). While the trajectory tracking with controller in the same closed loop system is presented in Figure 2.9 (b). Moreover, the trajectory tracking with controller and observer in closed loop system is obtained, as Figure 2.9 (c) (Anushree, 2016).

According to the final result in Figure 2.9 (a), (b), (c) in this research, the trajectory tracking with Least Mean Square-Lyapunov based controller has a good performance than the normal trajectory tracking without controller. Furthermore, the trajectory tracking with controller and observer is more precise and accurate than the other proposed method in this research.

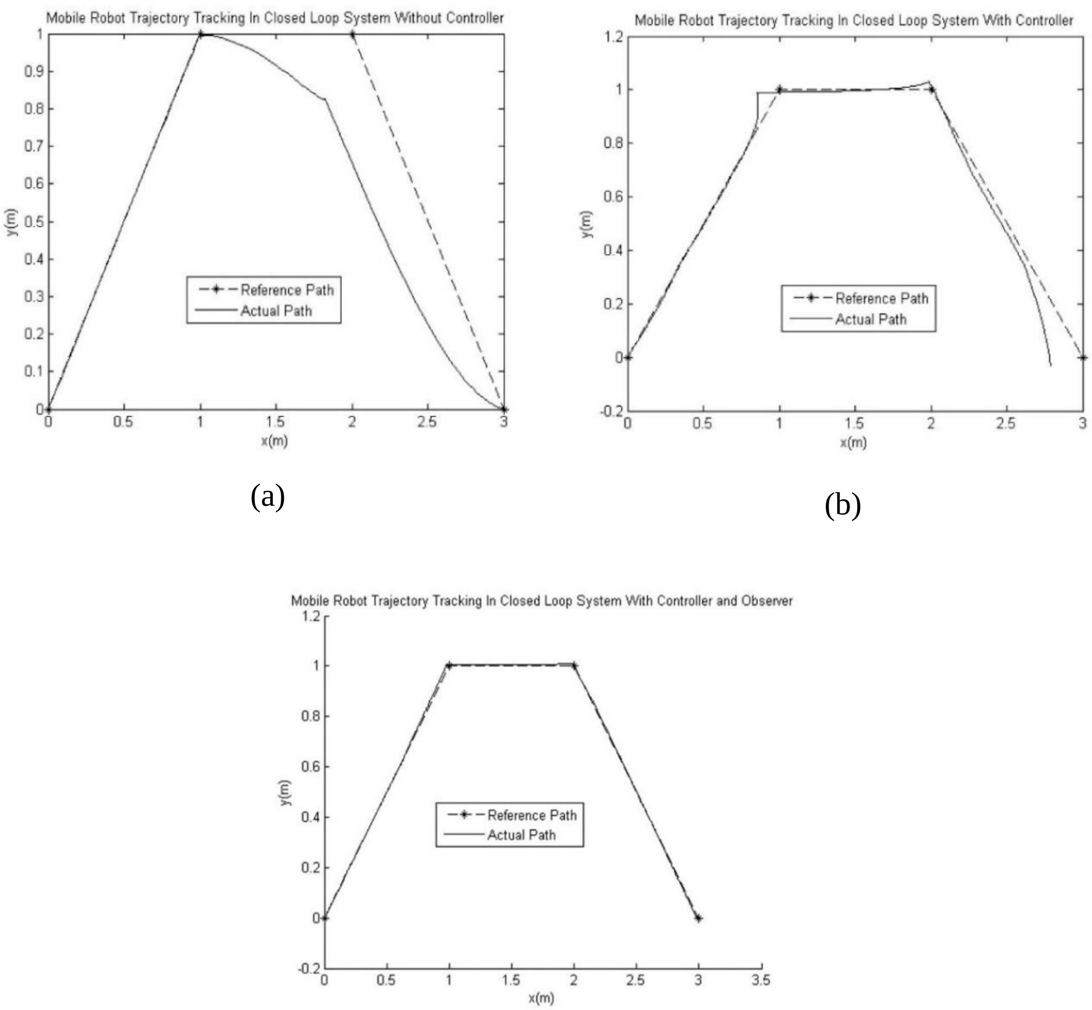


Figure 2.9. (a) Trajectory tracking without controller, (b) Trajectory tracking, (c) Trajectory tracking with controller and observer (Anushree, 2016)

2.4.3. Skid Steering

Recently, Skid steering motion has been used in mobile robot. Steering is done according to the controlling of relative velocities of left and right wheel. Skid steering is not really different from differential drive, since the high maneuverability is also found in skid steering (Yi, Member et al., 2009).

The advantages of using skid steering motion are based on the simple mechanism structure and validity. Furthermore, skid steering has a good mobility on a variety of terrain, which provide a desirable for all-terrain mission (Yi, Song, Zhang, & Goodwin, 2007). On the other hand, there are a few disadvantages of skid steering based on locomotion scheme, since the kinematic and dynamic models are very difficult to develop to describe the motion.

Meanwhile, the dynamic control of skid steering mobile robots has been discussed in various researches. During the movement of the robot, the no holonomic constraints of the robot is assumed that can calculate such as wheel angular velocities for a desired robot motion (Arslan & Temeltas, 2011). The wheel-ground interaction is captured by using a Coulomb friction model, while to track the path is based on the design of nonlinear feedback controller.

Moreover, Skid steering mobile robot dynamic model for 2D motion and linear 3D motion were developed by Yu and Ylaya Chuy (Yu & Chuy, 2009), which is different from the Coulomb friction based model but the model needs a lot of computational effort to calculate a complex dynamic model in real time (Yu, Chuy, Collins, & Hollis, 2010).

The new analysis and experimental kinematic scheme of the skid-steering robot by using a kinematic relationship between the instantaneous center of curvature (ICC) coefficient of the robot and the path parameters are proposed later based on laser scanner sensor. The laser scanner sensor is used to derive the ICR value of the robot and the other path parameters in the experiment (Wang et al., 2015). The Figure 2.10 shows about the laser scanner measurement during an entire cycle.

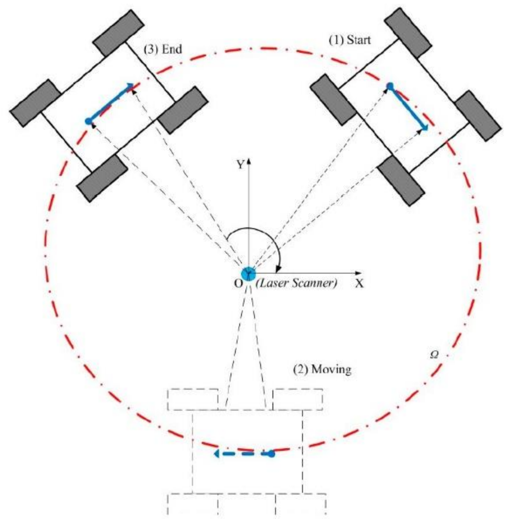


Figure 2.10. An entire cycle measurement using laser scanner

(Wang et al., 2015)

According to final of this research, the relationship between the skid steering kinematic model and ICC coefficient of the robot and the path parameters has been done by analysis and experimental. According to the experimental, the proposed model and the analysis can be used to control the robot. Furthermore, the kinematic model is verified that can be used for a skid steering robot system.

2.5. Relative Error Calculation

A relative error between absolute data and observe data is very important in every research. The goodness of fit is a statistical model describes how it fits a set of observation. The predicted values close to the observed data values is known as a well-fitting regression model. Normally, the fit of a proposed regression is better than the fit of the mean model. There are three goodness of fit statistical model are used in ordinary least squares (OLS) regression to evaluate the fitness of model such as R-Square, the overall F-test, and the root mean square error (RMSE) (R-squared & R-squared, 2012).

The RMSE is the square root which measure of how close a fitted line is to data points. This mean that the absolute fit of the model to the data and how observed data close to the model's predicted values. The RMSE is interpreted in term of measurement units, and is a better measure of goodness of fit compare to a correlation coefficient. Moreover, the RMSE has been used in many researches which the relative error is required to be found.

In the research of evaluation of inertial sensor fusion algorithms in grasping tasks using real input data, the RMSE is used to evaluate the algorithms in three scenarios such as the desired of an accuracy of 2^{o} in human grasping movement signification application, the estimation between Xsens sensor and Qualisys orientation. By using 24000 samples of data-set, the accuracy of sampling frequency is determined from 120 Hz to 15 Hz. The filter results before and after influenced with 120 Hz recorded Qualisys data are shown in table 2.1, and 2.2, respectively (Brückner, Spindeldreier, & Blume, 2012).

Table 2-4 The error in degree of RMS dependent on scenario (Brückner et al., 2012)

Filter	**Error in °RMS**		
	Arbitrary Rotation	***Static Orientation under Magnetic Disturbance***	***Grasping movement data***[a]
	roll, pitch, yaw ***average***	*roll, pitch, yaw* ***average***	*roll, pitch, yaw* ***average***
First order integration	96.9, 46.7, 57,1 **66.9**	22.9, 26.0, 2.4 **17.1**	12.2, 9.6, 17.0 **12.9**
Third order integration	43.5, 27.5, 38,1 **36.4**	15.8, 16.2, 6.9 **13.0**	5.7, 11.2, 16.7 **11.2**
QUEST	2.9, 2.1, 20.5 **8.5**	2.2, 1.4, 16.2 **6.6**	9.6, 8.1, 42.4 **20.0**
O2OQ	3.8, 3.4, 9.2 **5.5**	0.9, 1.0, 19.8 **7.2**	8.0, 9.2, 8.5 **8.6**
Roetenberg	59.0, 17.7, 56.6 **44.4**	10.3, 12.9, 4.3 **9.2**	12.2, 9.6, 17.0 **12.9**
Yun	3.2, 2.7, 11.9 **6.3**	1.9, 1.4, 15.7 **6.3**	8.3, 10.2, 42.8 **20.4**
Lee	2.5, 2.6, 6.0 **3.7**	1.5, 1.0, 17.9 **6.8**	7.2, 6.9, 6.6 **6.9**
Suh	41.4, 28.5, 38.3 **36.1**	13.5, 18.2, 8.4 **13.4**	4.6, 10.5, 19.8 **11.6**
Xsens	4.3, 2.9, 6.8 **4.7**	0.8, 0.8, 57.2 **19.6**	6.1, 5.8, 5.7 **5.9**

Table 2-5 The sampling frequency influence on accuracy (Brückner et al., 2012)

Filter	**Error in °RMS**			
	Roll	***Pitch***	***Yaw***	***Average***
Lee filter (120 Hz)	2,48	2,63	6,03	3,71
Lee filter (60 Hz)	2,47	2,43	6,18	3,89
Lee filter (30 Hz)	37,30	18,08	39,33	31,57
Lee filter (15 Hz)	56,20	20,85	53,12	43,39

In the result, eight algorithms for inertial sensor data fusion were evaluated using three different data sets. By using RMSE, the Lee Kalman filter features about 5 times different of the computation complexity of the O2OQ algorithm but this provided about 49% more accurate results. Therefore, in order to fulfill the application requirement best with the computation complexity, the RMSE is very necessary to calculate the estimation and the difference of the computation complexity.

2.6. Summary

This literature review chapter is a main basic part before starting the research. This chapter provided the relevant researches which all the techniques can be explained with the final result. There are three main sections in this chapter such as PID controller optimization, velocity control of DC motor using optimization based PID controller, maneuver control system, and the relative error calculation. Moreover, this chapter is contributed a lot to this project.

CHAPTER 3

METHODOLOGY

3.1. Introduction

The concept and design for velocity control of a car-like robot will be discussed in this chapter. Factors to consider on achieving the goal and objectives in this project included gathering of detail information about the cart design, hardware development, software development, programing with real-time testing, and verification. The process flow of the overall system is shown in Figure 3.1.

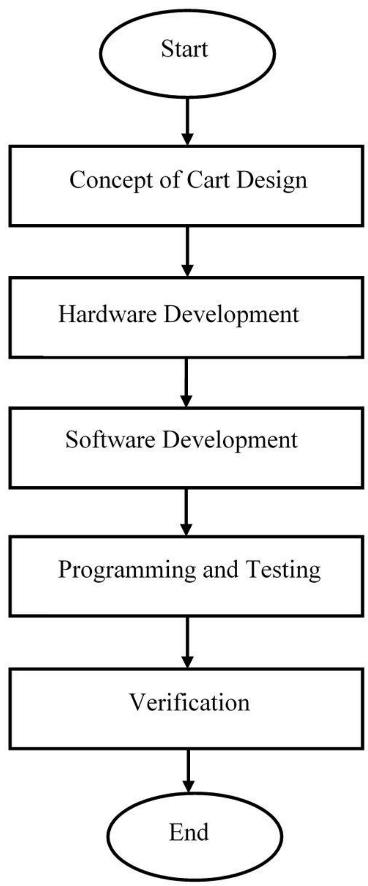


Figure 3.1. The process of overall system

The car-like mobile robot designed is a main source where all important information such as weight, width, length, height, and the distance between front wheels and back wheels can be found in this section. Moreover, those information are necessary for velocity control of a car-like mobile robot since car-like robot kinematic model is used as a main maneuver control design.

Furthermore, hardware and software development are the two main sections in this project. The hardware development covers development by adding some extra hardware to the robot, and choosing a proper microcontroller to control the car-like mobile robot. The software development included method or technique that can be used to the develop the car-like robot.

Programing with testing describes how the designs are computed by using a specific software, and verification of the design for velocity control of a car-like robot. Once the programing has been implemented, the testing or doing some experiments over the methods to the real-time robot need to be done to show the final output of using those methods.

In order to confirm that those designs can be used for velocity control of a car-like mobile robot, the verification section is necessary for every design. This verification section error calculation between simulation generated and real-time testing result. When error between simulation and real-time testing is high, the model can be define as failed to use or acceptable to use with condition.