ANTI-WINDUP COMPENSATOR DESIGN FOR IMPROVED TRACKING PERFORMANCE OF DIFFERENTIAL DRIVE MOBILE ROBOT

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ANTI-WINDUP COMPENSATOR DESIGN FOR IMPROVED TRACKING PERFORMANCE OF DIFFERENTIAL DRIVE MOBILE ROBOT

by

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LIST OF SYMBOLS & ABBREVIATIONS

ABBREVIATIONS

AWC	Anti-Windup Compensator
DC	Direct Current
DDR	Differential Drive Robot
EMF	Electromotive Force
IO	Input Output
IVWAN	Intelligent Vehicle with Autonomous Navigation
Li-Po	Lithium Polymer
MIMO	Multiple Input Multiple Output
NPV	Nonlinear Parameter Varying
OLED	Organic Light-Emitting Diode
P	Proportional
PD	Proportional Derivative
PI	Proportional Integral
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
SISO	Single Input Single Output
UART	Universal Asynchronous Receiver/Transmitter

WMR	Wheel Mobile Robot

SYMBOLS

ω	Angular Velocity
θ	Angular Position
s	Linear Displacement
u	Input Speed Command
u_{ms}	Saturation Bound
A	AWC Gain
v	Linear Velocity
r	Radius of The Wheel
D	Distance between Two Wheels of The Robot
c	Coordinate of The Center of The Shaft
x	Coordinate of Robot in X-Axis
y	Coordinate of Robot in Y-Axis
∧	Transpose of X and Y Coordinates
J	Moment of Inertia of The Rotor
B	Viscous Friction Coefficient
K_t	Torque Constant
K_b	Back-EMF Constant

R	Armature Resistance
L	Armature Inductance
K_P	Proportional Gain
K_I	Integral Gain
K_D	Derivative Gain
Δt	Time Taken to Move from One Point to Another Point
K	Steady State Gain
τ	Time Constant
ζ	Damping Factor
ω_n	Natural Frequency of The System
C_D	Dynamic Controller
G_K	Forward Kinematic Plant
G_{KIN}	Inverse Kinematic Plant
G_D	Dynamic Plant

REKA BENTUK PEMAMPAS ANTI-BELITAN UNTUK PENINGKATAN PRESTASI PENGESANAN ROBOT MUDAH ALIH KEBEZAAN PACU

ABSTRAK

Robot mudah alih beroda (WMR) telah digunakan secara meluas untuk tujuan navigasi dan aplikasi industry seperti pengesanan jalan dan pengesanan halangan. Robot kebezaan pacu (DDR) merupakan salah satu jenis WMRs dengan konfigurasi roda tertentu di mana dua roda tetap dikawal oleh motor dan satu roda kastor ditambah untuk sokongan mekanikal semasa pergerakan translasi dan putaran. Untuk tujuan pengesanan, pengawal telah memainkan peranan yang amat penting untuk memastikan robot tersebut tidak menyimpang jauh dari lokasi sasaran atau jalan. Dalam projek ini, DDR telah dibina dengan menggunakan dua motor DC. Oleh sebab kebanyakan motor menunjukkan tingkah laku nonlinear, mereka telah dimodelkan dalam struktur Hammerstein-Wiener pembolehhubah yang mengandungi tak lelurus statik dan sistem linear secara siri dengan satu sama lain. Pengenalan model linear telah dijalanakan melalui analisis tindak balas masa dengan pelbagai jenis input, sedangkan tak lelurus adalah dianggar melalui beberapa ujian dalam MATLAB Simulink. Kerja ini juga memberi tumpuan kepada kedua-dua model dinamik dan kinematik DDR di mana pengawal PI telah direka supaya mencapai spesifikasi yang dikehendaki dalam lingkungan linear. Dalam usaha untuk mengambil kira kesan ketidaklinear model motor DC yang biasa dipengaruhi oleh keupayaan halaju bersempadan mereka, pemampas anti-belitan statik (AWC) telah dilaksanakan yang akan diaktifkan semasa output pengawal melebihi sempadan tersebut. Dengan menggunakan strategi ini, peningkatan prestasi pengesanan DDR yang ketara telah ditunjukan melalui simulasi terumatanya semasa jalan yang dikehendaki mempunyai sudut tajam atau belok.

ANTI-WINDUP COMPENSATOR DESIGN FOR IMPROVED TRACKING PERFORMANCE OF DIFFERENTIAL DRIVE MOBILE ROBOT

ABSTRACT

Wheeled mobile robots (WMRs) have been widely used for navigation purposes as well as industrial applications such as path tracking and obstacle detections. Differential drive robot (DDR) is one type of WMRs with a specific wheel configuration where two fixed wheels are controlled by the motors and a castor wheel is added to mechanically support its translational and rotational movements. For tracking purposes, the controller plays a very important role to ensure it does not deviate far from the targeted locations or path. In this project, a DDR is built with two DC motors. As most motors exhibit nonlinear behavior, they are modeled as a multivariable Hammerstein-Wiener structure which contains static nonlinearities and a linear system in series with each other. The identification of the linear model is performed via time response analysis with different types of inputs, whereas the nonlinearities are estimated via several tests in MATLAB Simulink. This work also focuses on both dynamic and kinematic models of the DDR where a proportional-integral (PI) controller is designed to achieve the desired specifications in the linear region. In order to account for the nonlinear effects from the DC motor model which is mainly influenced by its bounded velocity capability, a static anti-windup compensator (AWC) is implemented which is activated when the controller output exceeds the bound. Via this strategy, a significant improvement on the tracking performance of the DDR can be observed via simulations especially when the desired path involves sharp corners or turns.

CHAPTER 1
INTRODUCTION

1.1 Background

Recently, wheel mobile robots (WMR) are getting more attention from many researchers due to their numerous application. Unlike robotic arm which is mainly used in the production site for industrial purposes, wheel mobile robots are autonomous and can move freely within the predefined workspace to achieve specific goals. This mobility capability of the WMR makes them suitable to be used in vast applications both in structured or unstructured environment [1].

There are many types of WMR available such as differential drive robot [2,3], car-like robot [3] and omnidirectional robot [4]. Differential drive robot (DDR) is considered as one of the common wheel configurations and can execute the defined trajectories [5]. In DDR, two motors are used to provide motion control while the other one or two castor wheels are used as a mechanical support for the robot. The locomotion of the DDR is achieved by controlling the speed of the left and right wheel respectively. For translation movement, both motors will move in the same speed. For rotational movement, both motors will move at different speed.

WMRs are extensively used for tracking and path following missions. The former one involved point-to-point approach (classic control), as the path between the starting point and destination is not a priority. The latter is more difficult than the tracking as not only the robot has to arrive at the desired coordinate, it also needs to track or follow a predefined trajectory [6]. This is particularly useful when used for navigation in the presence of obstacles.

1.2 Problem Statement

A WMR consists of kinematic and dynamic models where they are cascaded together to control its position. Many tracking control strategies only consider the kinematic model of the robot to simplify the design procedure [7]. Such a design may seem to work perfectly if the DC motors are assumed to be linear and time invariant. In practice, however, the motors exhibit nonlinear properties which may affect the overall performance of the robot. The physical limitation of the motors, for instance, leads to actuator saturations which can cause windup effects. This phenomenon, in the worst case, will drive the closed loop system into unstable region. By involving the dynamic model inside the control loop, improvements on the tracking can be made especially when the desired path involves sharp corners or turns. Modeling the WMR's motor models are nonetheless not straightforward due to the presence of nonlinearities. A general nonlinear system can be restructured into the so-called Hammerstein-Wiener structure where the system can be decomposed into linear and nonlinear blocks. Identifications of each block, however, remain a technical challenge. With the inclusion of the nonlinear blocks into the model, the dynamic controllers need to be optimized to account for the nonlinear effects to ensure a smooth tracking behavior.

1.3 Objectives

1) To build a differential drive robot (DDR) for tracking purposes with two DC motors, two fixed wheels and a castor wheel for mechanical support
2) To model the DC motors of the DDR into a multivariable Hammerstein-Wiener structure and to estimate the linear and nonlinear blocks via time response method
3) To implement an optimized control strategy for improved trajectory tracking behavior
4) To reduce the effect of nonlinearities in the Hammerstein-Wiener model by the inclusion of a static anti-windup compensator

1.4 Scope of The Project

The scope of this project is limited to the construction of DDR, modeling of the DC motors and simulation of the results via MATLAB. The dynamic model is built based on the time domain response via MATLAB System Identification toolbox with no-load condition and the wheels of the robot are free running without any interaction with the surface. When tested experimentally, the additional electronic components and battery used usually will add extra load to the motors. The modification of the result presented in this thesis when the load is considered will be done in future. Thus, the dynamic model of the DDR mentioned in this project refers to the dynamic model of the motor without considering the coupling effects of the motor in load condition. Apart from that, this work also focuses on point-to-point tracking where only the initial and final coordinates are prioritized, but not the angles of departure and arrival of the robot and its nonholonomic constraints [3]. This robot is also assumed to have no wheel slippage during the tracking.

1.5 Project Outline

This report consists of five chapters in total, including this chapter. This chapter introduces the background of DDR, the nonlinear issues in DDR models, and the motivation of the research. In Chapter 2, the literature reviews of previous works related to path tracking of DDR are presented. The anti-windup schemes that have been developed are briefly explained with their suitability to use. The kinematic model of the DDR is discussed together with commonly used kinematic controllers. Chapter 3 presents the methodology, which includes the DDR hardware implementation and modeling of both dynamic and kinematic models via MATLAB Simulink. With regard to the dynamic models, the methods used to estimate the Hammerstein-Wiener structure are also discussed. In chapter 4, the results and discussions of the project are presented. Multivariable Hammerstein-Wiener model with non-invertible nonlinearities of a DDR is estimated via time response method in MATLAB System Identification toolbox. Cascade controller with position loop and velocity loop is implemented to improve the trajectory tracking behavior of DDR. A static anti-windup compensator is implemented to reduce the effect of nonlinearities in the Hammerstein-Wiener model and the corresponding results are shown. The final chapter concludes the research work and discusses possibilities to extend the results for further improvements.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In this chapter, the papers on the WMR especially the research on the DDR has been extensively studied. The locomotion of DDR has been summarized which give a general idea on how the movement of the robot been performed. Previous works on the control design of tracking and path following of DDR have been compared and analyzed especially whether to take the dynamic model of the motor of DDR into consideration. In addition, the linear controller such PID controller used for the cascade control of DDR has been studied. The effect of changing each of the PID parameters on the closed loop response of the system has been tabulated. Equations concerning the kinematic model of DDR and dynamic model of the motor of DDR have been analyzed and studied which will be needed during the design process for cascade control of DDR. The Hammerstein-Wiener model which used to represent the dynamic model of the motor of DDR has been studied along with the modeling method to estimate the dynamic model of the motor. From the previous works, the coupling effects of left and right motors of DDR have been studied. Finally, due to the actuator saturation, the previous work on the design of static anti-windup compensator has been studied to help to alleviate the nonlinearity effects on the closed loop response of the system to reduce undesired effect such as overshoot, undershoot and more seriously instability of the system.

2.2 Differential Drive Wheel Mobile Robot

The mobility of WMR can be classified into five generic structures corresponding to a pair of indices (*m*, *s*): where *m* is the mobility degree and *s* is the steerability degree [8]. The mobility degree refers to the number of degree of freedom the mobile robot could have instantaneously from its current position without steering any of its wheel. The steerability degree refers to the number of the steered wheels that the robot has that can be oriented independently.

In paper [8,9,10], different configurations of WMR have been studied. As mentioned before, the configurations are categorized into 5 different classes. Class 1 referred to the type of the mobile robot that uses three Swedish wheels actuated by 3 motors that provide the rotating speed of each wheel. This type of configuration allows the WMR to be omnidirectional. Class 2 mobile robot or commonly known as DDR contains two fixed wheels and a third castor wheel for support. Further explanation on the configuration and locomotion of DDR are discussed in next few paragraphs.

Class 3 mobile robot referred to the mobile robot that does not have any fixed wheels but has at least one conventional centered orientable wheel. This configuration allows the robot to move in any direction. Class 4 mobile robot referred to the mobile robot that has two fixed wheels on the same axle and a centered steerable wheel. The steering angle of this robot are constrained and thus make it as a nonholonomic vehicle. Finally, class 5 mobile robot referred to the mobile robot that have two centered orientable wheels and mechanically supported by a third off-centered orientable wheel. This type of configuration makes class 5 robot to be nonholonomic.

There are numerous advantages of choosing omnidirectional robot as the robot configuration to perform the tracking and path following such as the robot can move in any direction directly without making any reorientation of the body. However, it is costly and time consuming to build the omnidirectional robot. On the other hand, the kinematic model of the nonholonomic robot is easier to be understood and involved less mathematical equations as compared to omnidirectional robot. The nonholonomic robot can also be built easier and the material cost is cheaper as compared to omnidirectional robot. Thus, nonholonomic robot with class 2 configuration is chosen due to its simpler structure and commonly used among the nonholonomic robot.

DDR is considered as Type (2,0) robots, which refers to the mobile robot that have no steering wheel (*s*=0) with either one or several fixed wheels in a common axle [9]. The common axle restricts mobility to a two-dimensional plane (*m*=2). The popular two wheels' differential-drive model is obtained using the general two-active fixed wheels and one passive-caster wheel structurer. The differential drive structure of type (2,0) robot is shown in the Figure 2-1.

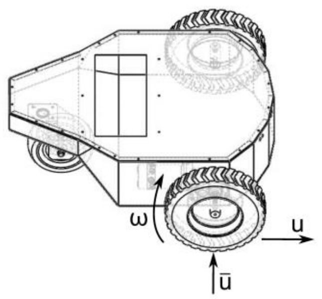

Figure 2-1 The differential drive structure of type (2,0) WMR IVWAN (Intelligent Vehicle with Autonomous Navigation) [9]

In paper [10], the locomotion of the DDR is extensively explained. If the angular velocities of the left and right motors are the same, the pure translational movement is generated. If the angular velocity of the left motor is opposite of the angular velocity of the right motor, pure rotational is produced. If the angular velocity of the right motor is more than left motor, then anticlockwise rotation is generated. On the other hand, if the angular velocity of the left motor is more than the right motor, then clockwise rotation is generated. If both motors are moving in the same direction but different angular velocities, heading orientation is modified and a turning action is done.

2.3 Control Design of Tracking and Path Following of Differential Drive Mobile Robot

There are numerous works related to DDR's control design for tracking and path following. Path following refers to the capability of the mobile robot to follow as closely as possible through a previously defined reference path. The path is usually specified as either a set of consecutive reference points or a set of geometrical primitives such as straight lines, curve, etc. [11]. Some of the researches only include the kinematic model in their design while other researchers will integrate both the kinematic model and dynamic model during the design process. If only the kinematic model is considered in the path tracking control design, the implementation will be relatively simpler and the control problem is easier to solve. By including the dynamic model into consideration, the speed mobile robot can be increased, here it is more convenient for tasks that require quick movement.

In paper [11], the cascaded PID control is proposed for path tracking of the mobile robot to improve the dynamic response to disturbances. This is because corrective action for disturbances by the conventional feedback control only starts after the controlled variables deviated from the set point. Thus, cascade control is implemented which include slave controllers to control the angular velocities of left and right motors respectively and master controller to control the orientation of the robot. The corresponding block diagram of proposed cascade control is shown in the Figure 2-2.

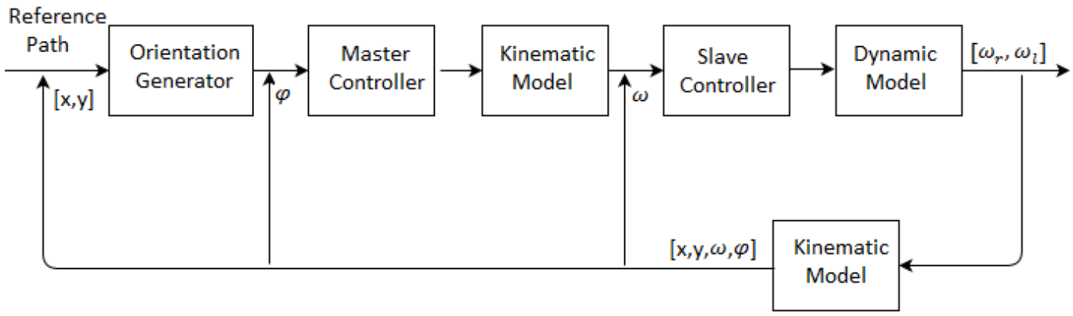

Figure 2-2 Block diagram of the proposed cascade controller [11]

With the implementation of the PID controller in the velocity loop and position loop, the tuning of the PID parameters will be more complicated since more tuning parameters are involved. In paper [3], similar cascade controller is implemented. The velocity loop of the robot is controlled by the low-level PI controller while the position loop of the robot is controlled by PD controller. By using PI or PD controller, the parameters involved can be estimated by using the second order control theory.

In book [12], similar cascade control structure has been proposed and shown in Figure 2-3. There is a total of three distinct control loops presented in the design which is current loop (innermost), followed by speed loop and finally position loop (outermost). In cascade control, the speed of response of each distinct control loops increase towards the inner loop, with the current loop being the fastest and position loop being the slowest.

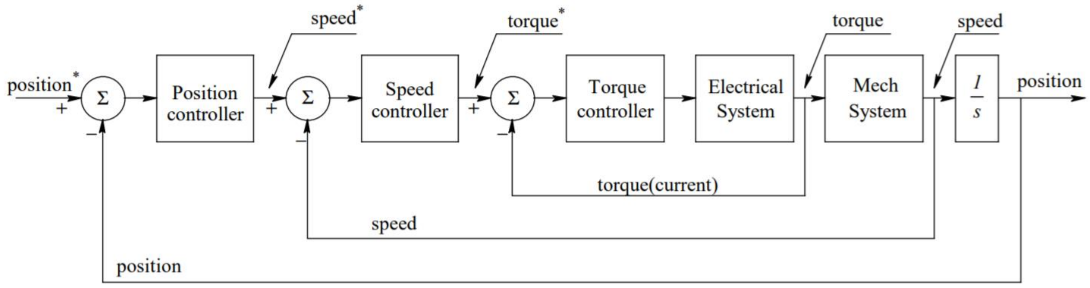

Figure 2-3 Cascade control of a motor drive [12]

2.4 PID Controller

The cascade control design mentioned in the previous section, PID controller is used to control the angular velocity of the motor in velocity loop and control the orientation of the robot in position loop. It is important to have a better understanding of the effect of each parameter so that it helps to improve the tuning on the closed loop stability. In paper [13], the effects of each PID parameter has been well explained in controlling the angular velocity of the motor. Proportional control will make the control input to increase when the angular velocity is too low. Derivative control will make the control input to decrease when the angular velocity increases quickly. Integrating control will make the control input to increase when the angular velocity has been consistently too low over a period. Basically, the overall effect of each PID parameter is tabulated in Table 2-1.

Table 2-1 The effect of changing PID parameters in general

PID controller parameter	Rise time	Overshoot	Steady state error
Proportional, K_P	↓↓	↑	↓
Integral, K_I	↓	↑	↓↓
Derivative, K_D	-	↓↓	-

2.5 Kinematic Model of Differential Drive Mobile Robot

From Figure 2-4, coordinate (X, Y) refers to the world coordinate system while coordinates (X_R, Y_R) refers to the local coordinate system. The parameter D refers to the distance between two wheels of the robot. The parameter r refers to the radius of the wheel. The parameter θ refers to the angular position of the robot. The parameter c refers to the coordinate of the center of the shaft.

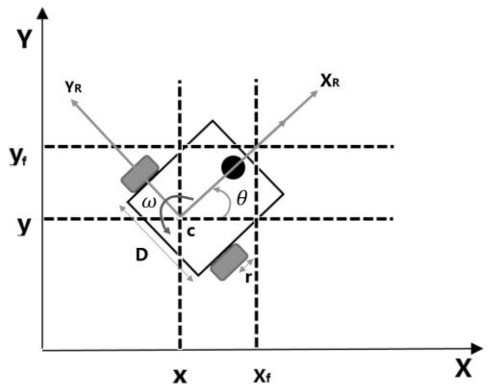

Figure 2-4 Diagram of differential drive mobile robot

In paper [1,14], the kinematic differential drive configuration is discussed and shown from equations (2.1) to (2.6).

$$\omega = \frac{(\omega_R - \omega_L) r}{D} \tag{2.1}$$

$$v = \frac{(w_r + w_l) r}{2} \tag{2.2}$$

$$\dot{x} = v \cos\theta \tag{2.3}$$

$$\dot{y} = v \sin\theta \tag{2.4}$$

$$\dot{\theta} = \omega \tag{2.5}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{2.6}$$

The position of the mobile robot in the local reference frame [X_R, Y_R] need to map to world reference frame [X, Y] using the transformation matrix. The transformation is done to bring every variable associated with the system to a common plane. Let $R(\theta)$ be the transformation matrix such that

$$\dot{\wedge} = R(\theta)\, \dot{\wedge}_R \tag{2.7}$$

Where $\wedge = [x, y]^T$ and $\wedge_R = [x_R, y_R]^T$. From Figure 2-4, the new pose of the robot can be expressed as below

$$\dot{x} = \dot{x}_R \cos\theta - \dot{y}_R \sin\theta \tag{2.8}$$

$$y = \dot{x}_R \sin\theta + \dot{y}_R \cos\theta \tag{2.9}$$

Hence,

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{2.10}$$

2.6 Dynamic Model of The DC Motor of Differential Drive Mobile Robot

In paper [11], the dynamic model of the motor of differential drive mobile robot is acquired by knowing the relationship between the input voltage and torque produced by the DC motor. This modeling method will include the mechanical dynamics and electrical dynamics of the system into the transfer function of the motor which shown in Figure 2-5.

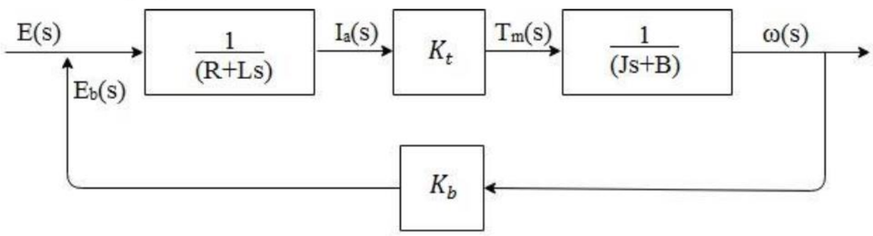

Figure 2-5 Block diagram of DC motor [15]

The transfer functions of the DC motor can be represented as below,

$$\frac{T_m(s)}{E(s)} = \frac{K_t(J_s+B)}{(R+L_s)(J_s+B)+K_tK_b} \tag{2.11}$$

where,

J is the moment of inertia of the rotor,

B is the viscous friction coefficient

K_t is the torque constant

K_b is the back-emf constant

R is the armature resistance

L is the armature inductance

In paper [10], the dynamic model of the DDR is suggested to be modeled through the approach of a set of linear transfer functions that include the nonlinearities of the whole system. The parameter identification is based on black box modeling technique. Black box modeling technique refers to the technique of acquiring the dynamic model based on input-output data without knowing the underlying physics structure of the motor. In practice, however, it is not easy to identify all the parameters as in equation (2.11) accurately. Hence, in many literatures, a more suitable method to facilitate the modeling process is proposed which can be done MATLAB system identification toolbox.

When a system exhibit nonlinear behavior, it can be generalized into a nonlinear model, which is termed Hammerstein-Wiener structure. This structure describes the system's dynamic using two static nonlinear blocks in series with a linear block as shown in the Figure 2-6. The nonlinear block before the linear block referred to Hammerstein model while the nonlinear block after the linear block referred to Wiener model [16].

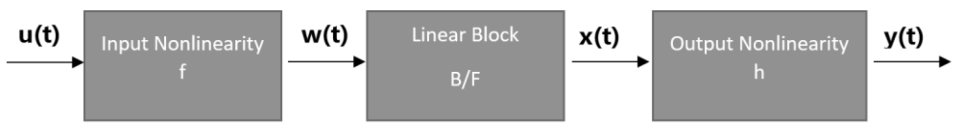

Figure 2-6 Block diagram of Hammerstein-Wiener model [17]

where

1. f is referred to nonlinear static function which transforms the input u(t) as w(t)= f(u(t))
2. B/F referred to linear transfer function which transform w(t) as x(t)= (B/F) w(t) (B – order of zeros and F – order of poles)

3. H referred to nonlinear static function which transforms the input x(t) as y(t)= h(x(t))

The angular velocities of the left and right motors are calculated based on the encoder positions with the change of time. By using such approximation method, high noise results are produced. In this paper, Laplace domain is considered to prevent the angular velocity approximation. Instead of using Laplace domain in this project, a filter is used to filter the high frequency noise present in the angular velocity data.

The modeling methods suggested by the papers [10,13] are more suitable to use to find the linear model of the motors since the primary interest of this project is to explore the method to improve the path tracking of differential drive mobile robot with a better control strategy. With these modeling techniques, the mechanical dynamics and electrical dynamics of the motors can be ignored. In MATLAB Simulink, there is a lot of nonlinear discontinuity blocks available to be used in Simulation. The nonlinear discontinuity blocks can be added into the estimated linear model to form the Hammerstein-Wiener model.

2.6.1 Coupling Effects of The Motors

In paper [10], the coupling effects of the left and right motors are mentioned. Since there are left and right motors involved in the differential drive mobile robot, the nonholonomic system dealt in the control design is considered as a multiple input multiple output (MIMO) system. Each left and right motor are considered as single input single output (SISO) system with coupled connection. The two DC motors will have the dynamic influence on each other which can be represented in transfer function (2.12),

$$\begin{bmatrix} V_R \\ V_L \end{bmatrix} = \begin{bmatrix} G_{RR} & G_{LR} \\ G_{RL} & G_{LL} \end{bmatrix} \begin{bmatrix} U_R \\ U_L \end{bmatrix} \tag{2.12}$$

where

V_R and V_L refer to the angular velocities of the motor

U_R and U_L refers to the corresponding speed command

G_{LL} refers the transfer function of left motor angular velocity with left motor speed command

G_{RR} refers the transfer function of right motor angular velocity with right motor speed command

G_{LR} and G_{RL} are coupling terms which refer to the transfer function of right motor angular velocity with left motor speed command and the transfer function of left motor angular velocity with right motor speed command

From the paper, the coupling dynamics of the motors are neglected based on the experimental results. Thus, in this project, experiment on the coupling effect of the motors will be done to justify the significance of the effect even though the contribution of effect is negligible when the DDR is tested in no load condition.

2.7 Static Anti-Windup Compensator

The actuator of a linear or nonlinear system is subjected to the lower and upper magnitude limits which will cause the saturation of a control signal [18]. If the saturation issue is ignored during the control design, then it will induce undesirable effects to the system such as overshoot, undershoot and more seriously instability of the system. To reduce the nonlinearity effect on the system, a scheme named anti-windup compensator (AWC) is required, which is usually included in the main controller's structure. Figure 2-7 shows an example of block diagram with the proposed AWC structure and controller for their nonlinear parameter varying (NPV) system.

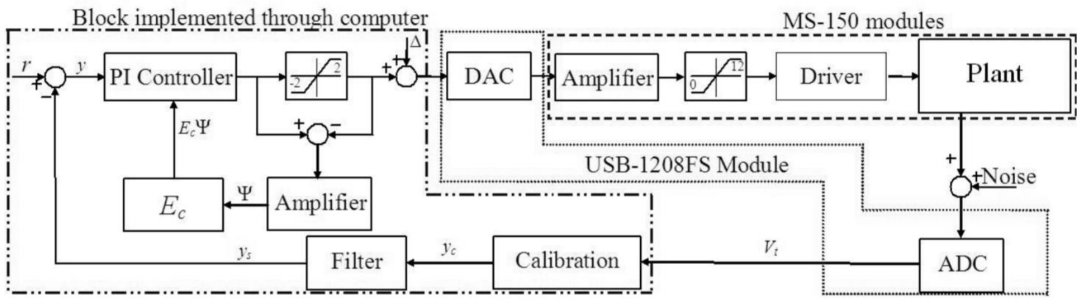

Figure 2-7 Block diagram of the proposed AWC structure and controller of nonlinear parameter varying (NV) system [18]

From the proposed AWC structure, the difference between the output right after the PI controller and the output after the saturation block is obtained and amplified. Later, the amplified signal will pass through the AWC gain E_C block before feedbacking to the PI controller. In the paper, they also mentioned that the proposed AWC design approach can also be applied to the other complicated nonlinear system. Inspired by this approach, an AWC design structure is implemented in this research project with slightly different strategies and objectives, which is targeted to improve the tracking performance of DDR.

2.8 Summary

Based on the literature reviews, there are numerous papers concerning on the control design of tracking and path following of DDR. From the previous works, dynamic model of the DDR has been decided to take into consideration so that the speed of the mobile robot can be increased and improve the tracking and path following performance of DDR. In addition, the dynamic model of the DDR will be modeled in the form of Hammerstein-Wiener model structure through the black box modeling technique since this technique required no knowledge of the underlying physics structure of the motor but purely based on the input-output data. The control design on the tracking and path following of the DDR will be in cascade control form. The significance of the coupling effect of the motors will still be verified even though the test on the DDR is in no-load condition. Finally, static anti-windup compensator has been implemented to reduce the actuator saturation effects on the closed loop response of the system.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter consists of four main parts which are hardware implementation, software implementation, hardware modeling and model simulation. The hardware implementation of the DDR includes the construction of the robot using the listed components and explanations on how the components interact with each other. In software implementation, the algorithm used to read the encoder counts and how to process the counts into the motion information are discussed.

In hardware modeling, the dynamics of the DC motors will be observed and analyzed. The modeling of the DC motors is based on the black-box modeling methods which are estimation of the model from the time domain response via MATLAB System Identification toolbox. All the generated models are closely examined to estimate the nonlinearities in the Hammerstein-Wiener structure, and the best dynamic are selected for further analysis and controller design.

In model simulation, the kinematic and dynamic control loops are cascaded to represent the actual structure of the DDR. A static anti-windup compensator is then implemented to account for the nonlinearities in the motor models.

3.2 Hardware Implementation of Differential Drive Mobile Robot

The Figure 3-1 and Figure 3-2 show the assembled differential drive mobile robot with the capability of being remoted controlled via UART transceiver. The core voltage of the microcontroller chip ESP8266 is 3.3V but is 5V tolerant so it able to take the input from most of the modules which operated at 5V. The motor driver can only accept 5V PWM input thus a 3.3V to 5V logic converter is used to translate the 3.3V PWM output from the microcontroller chip to the driver. Since the voltage of Li-Po battery is around 12V, a voltage regulator is used to supply 3.3V to the microcontroller chip. The OLED display used in the robot will display the motion information of the robot such as encoder count, angular velocity and angular displacement of the robot. Due to limited IO pins by the microcontroller chip ESP8266, there are two microcontrollers used to implement the hardware design which is master controller and slave controller. Slave controller controls the speed of the DC motors through PWM via full H-bridge motor driver. The master controller sends the required speed command to slave controller via the UART protocol.

The whole hardware architecture is illustrated in Figure 3-3 to show the interconnection of the electronic components. Further explanations on the functionality of electronic components such as microcontroller chip, ESP8266, Li-Po battery, battery checker and full H-bridge motor driver are presented in the Appendix A, B, C and D respectively. The motor encoders used in DDR are crucial to measure the angular velocities of the motors. Thus, the functionality of motor encoder is further explained and discussed in the Chapter 3.2.1.

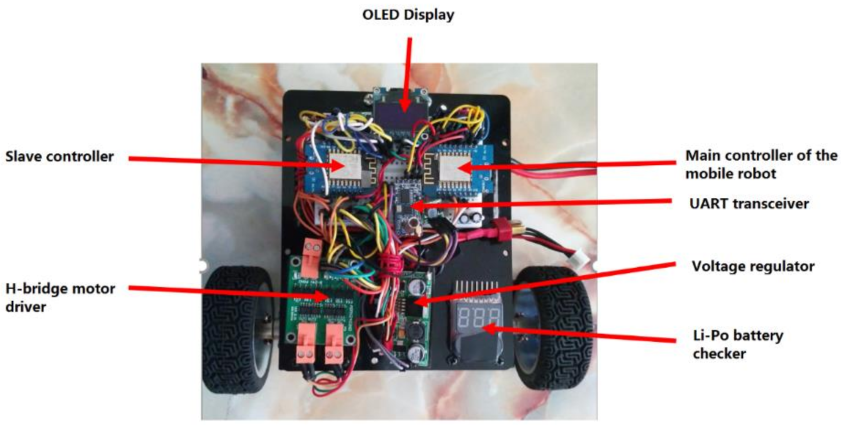

Figure 3-1 Differential drive mobile robot (top view)

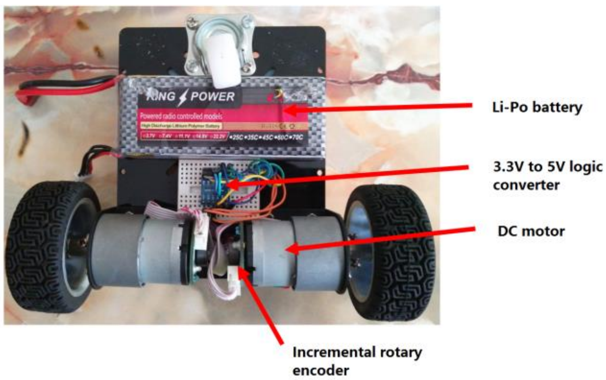

Figure 3-2 Differential drive mobile robot (bottom view)

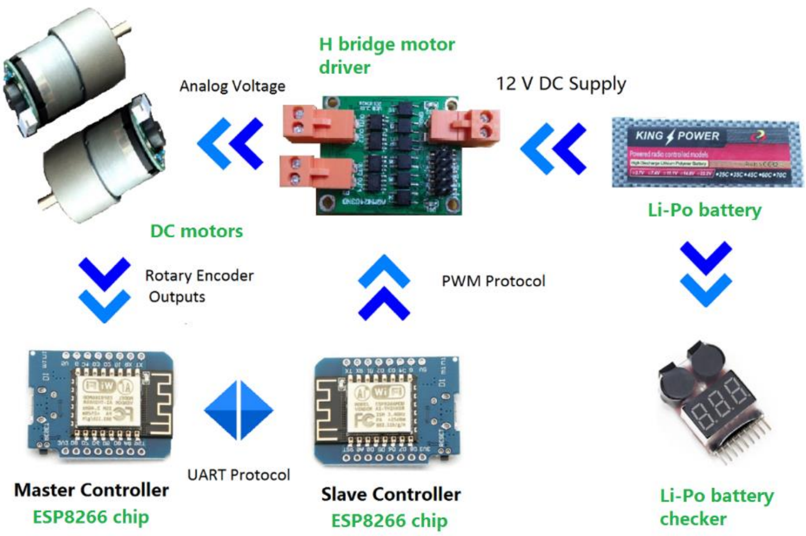

Figure 3-3 Hardware architecture of the differential drive mobile robot

3.2.1 Motor Encoders

The encoder used in this project is a rotary type. A rotary encoder is an electro-mechanical device that is used to measure the angular motion of the motor. There are two main types of rotary encoder which are absolute and incremental. The absolute rotary encoder will return the absolute angular position of the motor shaft. The incremental rotary encoder will only provide information on the motion of the shaft which need to be further processed to obtain the motor information such as angular displacement and angular velocity.

The incremental rotary encoder can be either mechanical, optical and magnetic. The mechanical rotary encoder can handle limited rotational speed since the mechanical switches require debouncing. In this project, the rotary encoder used must be able to handle high speed rotation, only optical and magnetic rotary encoder will be considered. The optical rotary encoder can measure the speed of motor with higher accuracy but still magnetic rotary encoder is chosen. There are many advantages of using magnetic rotary encoder over optical rotary encoder which are excellent reliability, high resistance to shock and vibration, lack of breakable parts, lower assembly cost, insensitive to dirt and moisture.

The magnetic rotary encoders used contain two hall sensors which enable the sensor to produce quadruple cyclical outputs which are 90 degrees to each other. These signals are later decoded to become a count-up pulse or count-down pulse depending on the direction of quadruple outputs change which is shown in the Figure 3-4.

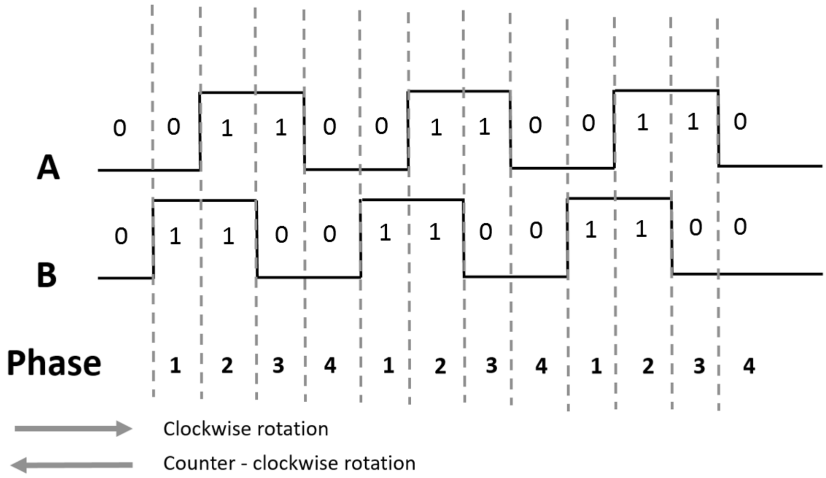

Figure 3-4 Quadruple output waveforms generated by the rotary encoder with gray encoding

When the motor shaft is turning in clockwise rotation, the quadruple outputs of incremental rotary encoder will change from 00 > 01 > 11 > 10 which is gray code encoding. On the other hand, when the motor shaft is turning in the counter-clockwise rotation, the quadruple output of the incremental rotary encoder will change from 10 > 11 > 01 > 00. In short, when the output A leads output B, the motor shaft is turning in clockwise direction. When the output B leads output A, the motor shaft is turning in counter-clockwise direction.

The hall effect magnetic encoder that uses a wheel that magnetized with north and south poles around its perimeter to attach to the motor shaft is illustrated in Figure 3-5. In this project, the magnetic encoder wheel is magnetized with 780 poles (390 north, 390 south) which gives a resolution of 390 lines per rotation. There are two hall effect sensors that will place 180 degrees from each other. The hall effect sensor will act like a switch inside the magnetic encoder which will turn on and off based on the detected field. When the detected flux density of the magnetic field exceeded the critical threshold level, the magnetic encoder will turn on. Once the detected flux density falls below the critical threshold level, the magnetic encoder will turn off. Since each of the hall sensors gives a resolution of 390 lines per revolution, quadruple outputs from the two hall sensors give an effective resolution of 1560 lines (390 lines multiplied by 4) per revolution.

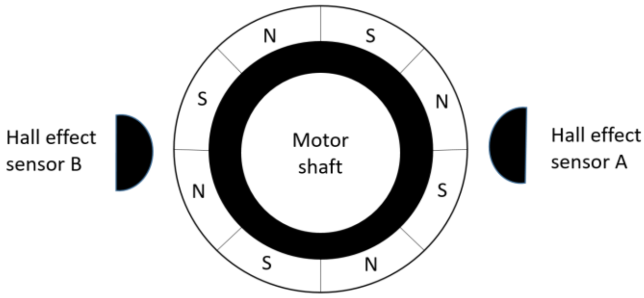

Figure 3-5 Hall effect sensing componentry

3.3 Software Implementation

The central discussion in this section is the algorithm used to read the encoders pulses from the incremental rotary encoders of the motor. Besides this, another algorithm is implemented to process the encoders pulses to obtain the angular information such as angular velocities of the left and right motors.

3.3.1 Encoder Pulse Acquisition

As mentioned previously, the encoders pulses are read by using the pin change interrupt to prevent any missing counts. The algorithms used to read the encoders pulse are illustrated in Figure 3-6 and Figure 3-7. The incremental rotary encoder used in