VELOCITY PROFILE COMPLIANCE FOR A WHEELED MOBILE ROBOT

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ABSTRACT

Mobile robots can be used in many applications, such as exploration, search and rescue, reconnaissance, security, and cleaning. Mobile robots usually carry batteries as their energy source and their operational time is restricted by the finite energy available from the batteries. With great advancements in application of Wheeled Mobile Robots (WMRs), concern of energy grew. Most of (not all) research and work done on the field of robotics is developed with no relation to 'life' of the robot. Specially, mobile robots use batteries to power themselves. So, the 'lifespan' of these robots is limited. So, the investigations on energy-related concepts are also of great importance. The energy is dissipated mostly in the motors, which strongly depends on the velocity profile. This paper investigates energy efficiency for trapezoidal velocity profile to minimize a new energy object function which considers practical energy consumption dissipated in motors related to motor dynamics, velocity profile, and motor control input. This paper will perform the analyses on energy consumption for trapezoidal velocity profile by using the Pulse Width Modulation (PWM) method as the controller. The goals of this project are by getting the energy optimization and the best velocity profile generation. Through the project, it can be concluded that the main factors in energy optimization based on the velocity profile generation are the election of PWM duty cycle and the time to complete the task. The higher the duty cycle of PWM and the shorter time we gain to complete the task will be result more energy saving in battery consumption. The velocity Profile 3 is chosen as the best velocity profile compared to Profile 1 and Profile 2 in terms of energy efficiency consumption which it gives us 2.48% and 1.95% differences between Profile 1 and Profile 2 respectively.

ABSTRAK

Robot mobil boleh digunakan dalam banyak aplikasi seperti penerokaan, pencarian dan penyelamatan, peninjauan, keselamatan dan pembersihan. Robot mobil kebiasaannya membawa bateri sebagai punca tenaga dan masa pengoperasian mereka adalah terhad ke[ada tenaga yang ada daripada bateri tersebut. Dengan kemajuan yang kian pesat dalam pengunaan robot mobil beroda, perkembangan tenaga dititikberatkan. Hampir ke semua penyelidikan dan kerja-kerja yang telah siap dalam bidang robotik ini telah dibangunkan dengan tiada hubungkait tentang 'nyawa' kepada robot ini. Terutamanya, robot mobil menggunakan bateri untuk menghidupkan mereka. Jadi, 'jangka hayat' robot-robot ini adalah terhad. Jadi, adalah penting untuk menyelidik tentang penggunaan tenaga. Kebanyakannya tenaga dilesapkan dalam motor yang mana bergantung kepada profil halaju. Kertas ini menyelidik keberkesanan tenaga kepada profil halaju trapezoid untuk meminimumkan satu fungsi tenaga baru yang mana dianggap penggunaan tenaga dilesapkan dalam motor yang berkaitan dengan dinamik motor, profil halaju dan kawalan kemasukan motor. Kertas ini akan menunjukkan analisis dalam penggunaan tenaga untuk profil halaju trapezoid dengan menggunakan teknik *PWM (Pulse Width Modulation)* sebagai pengawal. Sasaran projek ini adalah untuk mendapatkan tenaga yang optimum dan profil halaju yang terbaik. Melalui projek ini, dapat dirumuskan di sini bahawa faktor utama dalam mengoptimumkan tenaga adalah berhantung kepada pemilihan kitar tugas *PWM* dan masa yang diambil untuk melengkapkan tugas. Semakin tinggi kitar tugas *PWM* dan semakin pendek masa yang diambil untuk menamatkan tugas akan memberikan keputussan semakin berlaku penjimatan dalam penggunaan tenaga bateri. Profil halaju 3 dipilih sebagai profil yang terbaik berbanding dengan Profil 1 dan Profil 2 dari segi keberkesanan penggunaan tenaga di mana memberikan kita perbezaan sebanyak 2.48% dan 1.95% di antara Profil 1 dan Profil 2.

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LIST OF SYMBOLS AND ABBREVIATIONS

WMRs -	Wheeled Mobile Robots
WMR -	Wheeled Mobile Robot
PIC -	Programmable Interface Controller
PWM -	Pulse Width Modulation
RC -	Racing Car
PLL -	Phase-Locked Loop
SCR -	Silicone Control Rectifier
A -	Acceleration
C -	Cruise
D -	Deceleration
NRZ -	Non Return to Zero
GUI -	Guide User Interface
PC -	Personal Computer
d -	Distance per Meter

CHAPTER I

INTRODUCTION

1.1 Project Background

Nowadays mobile robots are in research laboratories as well as in industry, hospitals, museums, and it is important issues to have a powerful and reliable mobile robots.

Mobile robots have the capability to move around their environments and are not fixed to one physical location. They are a class of robots that move use wheels that control by motor. A robot can be seen as a machine with three characteristics:

(i) Input (sensors or stored information)

(ii) Intelligence (interpretation, brains – affected by the presence of a central processing unit)

(iii) Actuators (controlled motion systems or other output devices)

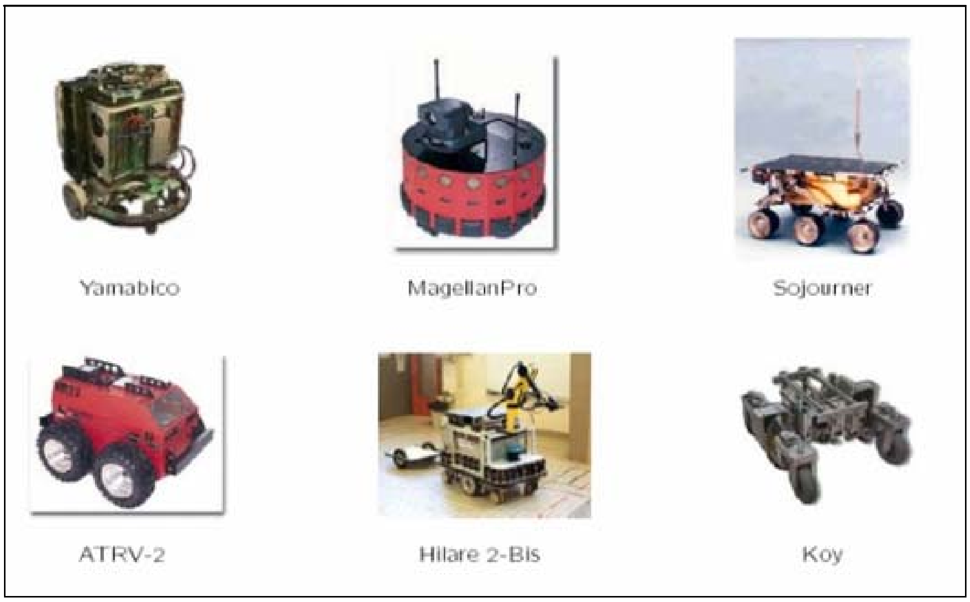

Figure 1.1 : Various Types of Mobile Robots

Figure 1.1 shows that various types of mobile robots where various tasks that applied by the robots. Wheeled mobile robots (WMRs) usually carry batteries to power on them and successful execution of mission is limited by finite amount of energy.

Commonly, many researchers are concerned about the energy consumption on path planning for a wheeled mobile robot [1], [6]. They come out with many methods and algorithm which are very useful for the manufacturer. Some of them also concerned the energy saving on the battery consumption [1], [2], [4], [7]. From these researches, it is very important for us also to take our responsibility to concern about the energy consumption for wheeled mobile robots that can be vary from a velocity profile.

1.2 Problem Statements

In the new era technology, WMRs require various robotics technologies to perform the task successfully. Many researchers concern about the path planning, motor control, sensing, obstacle avoidance and so on.

Mobile robots usually carry their energy source as batteries to power them which are have limitation on the energy consumption. Unfortunately, most of research and work done on the field of robotics is developed with no relation to 'life' of the robot. So, the 'lifespan' of mobile robots are limited.

So, this is very relate with the concept and idea of this research because the idea of this research are concerning about the energy consumption of wheeled mobile robot which is related to the velocity profile that produce from the control speed of DC motor.

Perhaps that from this concept and idea, the Robotic community members will have an easy way to understand about the issue of the energy consumption of mobile robot and will be applied to their projects or research.

1.3 Project Objectives

The major objective of this research is to investigate the velocity profile of wheeled mobile robot in relative to the energy optimization. The data will be taken from the control speed of DC motor and furthermore related to the energy consumption of WMRs where the goal is to have the minimum-energy saving.

Its measurable objectives are as follows:

(i) To control the speed of WMR by using the Pulse Width Modulation technique according to the desired velocity profile
(ii) To implement the wheeled mobile robot by using the PIC implementation
(iii) To study and analyze the velocity profile in order to reach the energy consumption of a wheeled mobile robot

1.4 Project Scopes

This project is primarily concerned with the velocity profile of mobile robot which is furthermore concern about the minimum-energy saving too. In order to achieve the objectives of the project, several scopes had been outlined. The scopes of this project are:

(i) Use PWM technique to control the speed of DC motor
(ii) The distance of the path planning of mobile robot is 10m and it is straight way (no obstacle avoidance)
(iii) The hardware will be interfaced to the personal computer by using RS232 serial communication
(iv) Use existing mobile robot which is a model from RC car is selected to be a model for the mobile robot where it is consists of four wheels

1.5 Summary

This section explains the objective as well as the scope of the project in order to give the sense of direction of this project. The next subsequent chapter will be literature review section, discussing the research works previously done by other researchers concerning on the energy-efficient of mobile robot due to velocity profile.

CHAPTER II

LITERATURE REVIEW

2.1 Technology Developments

The development of robotics technology is a great effort since the application of robots is expanding more and more for human welfare. Especially, mobile robots have been seen used in many applications. Many researchers concern about the energy consumption of mobile robots since the energy of each mobile robot is limited by the finite amount of energy in the batteries they carry. It is become a big issue in robotic field. Here, the research activities that related to the effort in investigate the energy-saving of the mobile robot due to the velocity profile.

2.2 The Development In Energy Saving For A Wheeled Mobile Robot

Generally in evaluating the machine performances, the question is raised to ask about how efficient that machine is. Efficiency is a measure to show roughly, how much input is utilized to produce the output. So, in the process of designing the machine and designing the operation of the machine, we want to have the most utilization of input to output.

Here in this section, a quick overview of different examples work those were done. In [18], energy consumption enters the problem as limit constraints. As we know, the time and energy are conflicting objectives. Here, the problem tries to maximize the distance covered with time and energy constraints. An energy constraint resembles the energy stored in the battery.

In [19], case study of how mobile robots consume energy. Here we mentioned only two issues. In order to improve energy efficiency of motion of mobile robots, we can develop the strategies of dynamic power management where this concept is to programme the robot computer to organize power management across all components of the robot.

A timeout rule should be maintained to avoid rapid switching on and off which consume a great deal of energy. The others issues is, by develop the scheduling of the real-time. Here, the computer would be responsible of arranging different task according to some rule. In relation to energy, the scheduling is done according to duration of the task. So, higher priorities will be given to shorter and faster tasks.

Another set of work done in investigating the energy-minimization are work of Kim and Kim [8]. They considered a differential-driven wheeled mobile robot. The circuit driving the wheels motor is shown in Figure 2.1.

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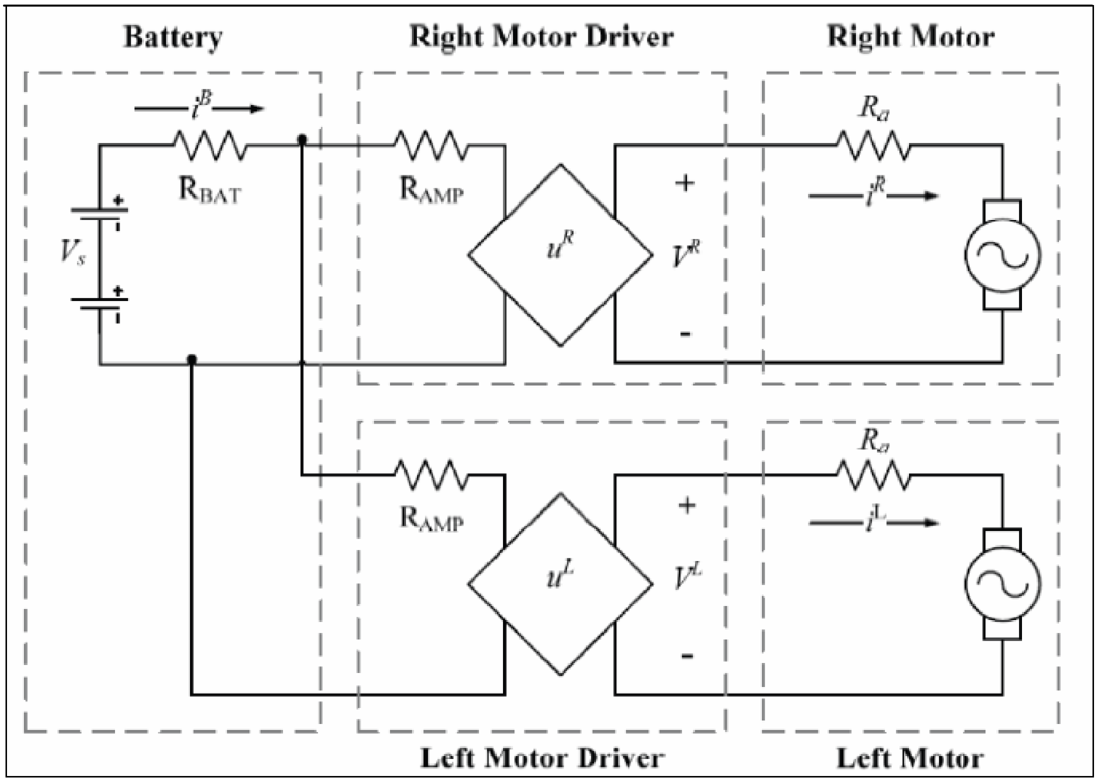

Figure 2.1 : Motor Driver Circuit

A complete derivation of the problem is done in the paper. The optimization cost function considered includes also the wheel friction and inertia along with the loss-minimization objective.

Another interesting work of Kim and Kim [7] is in designing velocity profile in 3-step fashion. The 3-step fashion of velocity profile is including the acceleration, cruise and deceleration state. So it is obvious that for any stage of motion there will be an acceleration phase followed by constant cruise speed and ending by deceleration to zero. In [7], different kinds of accelerations and decelerations are investigated. The optimization problem is solved numerically with a search algorithm explained in paper. The paper claims to have a most efficient solution with efficiency of 30%.

2.3 DC Motor Speed Controller

For precise the speed control of DC motor system, closed loop is normally used. Basically the block diagram is shown in Figure 2.2.

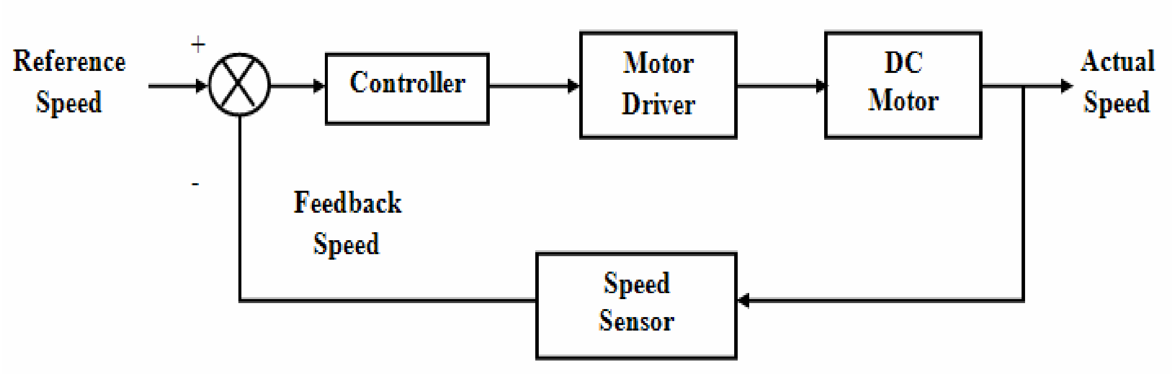

Figure 2.2 : Basic Block Diagram For DC Motor Speed Control

There are several controllers that can be used to control the speed of motor such as by using thyristor, phase-locked-loop control, chopper circuit, Fuzzy Logic controller and etc. Here, we will discuss the methods that had been used by the others researchers.

The block diagram of a converter-fed dc motor drive with phase-locked-loop control is shown in Figure 2.3. In a phase-locked-loop (PLL) control system, the motor speed is converted to a digital pulse train by using a speed encoder. The output of the encoder acts as the speed feedback signal of frequency f_0.

The phase detector compares the reference pulse train (or frequency) f_r with the feedback frequency f_0 and provides the pulse-width-modulated (PWM) output voltage V_e that is proportional to the difference in phases and frequencies of the reference and feedback pulse trains. The phase detector (or comparator) is available in integrated circuits. A low-pass loop filter converts the pulse train V_e to continuous dc level V_c which varies the output of the power converter and in turn the motor speed.

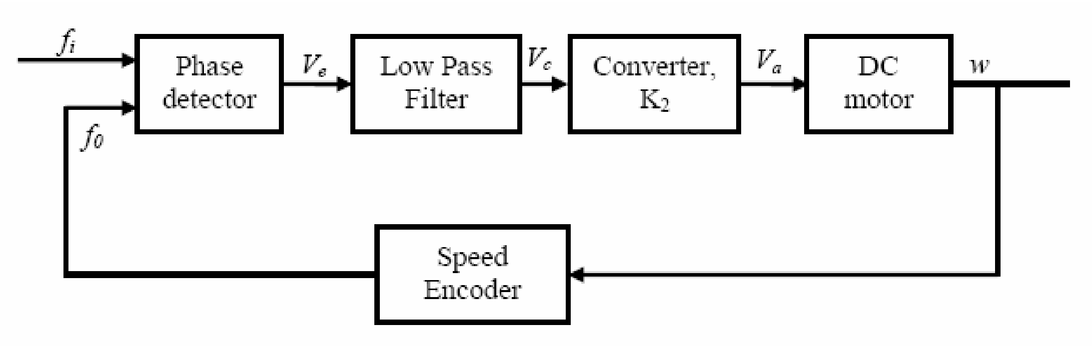

Figure 2.3 : Phase-Locked Loop Control System

When the motor runs at the same speed as the reference pulse train, the two frequencies would be synchronized together with phase difference. The output of the phase detector would be a constant voltage proportional to the phase difference and the steady state motor speed would be maintained at a fixed value irrespective of the load on the motor.

Any disturbances contributing to the speed change would result in the phase difference and the output of the phase detector would respond immediately to vary the speed of the motor in such direction and magnitude as to retain the locking of the reference and feedback frequencies. The response of the phase detector is very fast.

In journals by A. Adkins and Moore respectively, it has developed a model for the components of PLL servo control system using both linear and nonlinear techniques [20]. However, PLL controlled motor drives have the following shortcoming.

(i) PLL controlled motor system tend to be unstable for low-speed operation
(ii) PLL controlled motor system have large response time
(iii) PLL controlled motor system may get out of synchronization for an abrupt load variation

Figure 2.4 shows the block diagram for DC motor speed control by using thyristor. This method has been used by P. C. Sen and M. L. MacDonald in their research [21]. The thyristor is used to supply a variable DC voltage to motor, thus it can control the speed of motor. The average output of voltage is given by

$$V_{ave} = \frac{V_m}{2\pi}(1 + \cos\alpha) \quad (1.1)$$

Where V_m = peak of voltage supply of thyristor

α = firing angle of thyristor

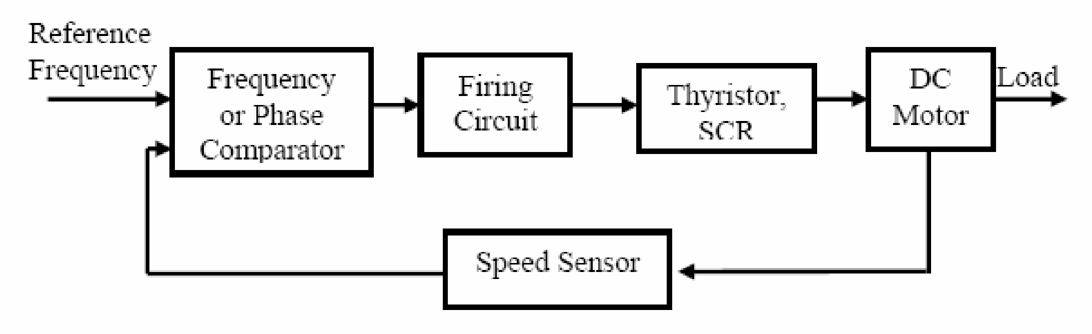

Figure 2.4 : Block Diagram of DC Motor Speed Control By Using Thyristor

From Equation 1.1, by controlling the firing angle α average output of DC voltage can be varied. If the motor speed is low, the speed sensor frequency will be below the reference frequency. The frequency differences produce a change in firing circuit that causes the thyristor, SCR to fire sooner. There is a resulting increase in motor speed which brings the output speed back up to the value which is equal to the reference signal.

Conversely, if the speed sensor output frequency is above the reference, then the firing circuit will be modified to allow the SCR to conduct for a shorter period of time, the decrease in conduction reduces the DC motor speed.

2.4 Summary

In the view of the previous research, there are several methods had been used and been investigated in the application of mobile robot. Therefore the methods which are related to this project had been identifying to ensure that the objective of this project can be archived. The chapter 3 will be describing the method that we can used to investigate the energy-saving due to the velocity profile.

CHAPTER III

METHODOLOGY

3.1 Introduction

This project is concerning about the energy consumption of mobile robot which is gain from the produce velocity profile. In this chapter, we cover the methods applied throughout study and steps taken during the development of this project.

3.2 Overall Process

The purpose of a control system is to achieve the desired output from a physical system by controlling the input to a system. The components of a control system include sensors which measure system output, actuators which generate the input to the system, and the controller which is responsible for deciding what input will be sent to the system based upon the measured output. The figure 3.1 shows the flowchart of the overall methods that have been applied throughout the project.

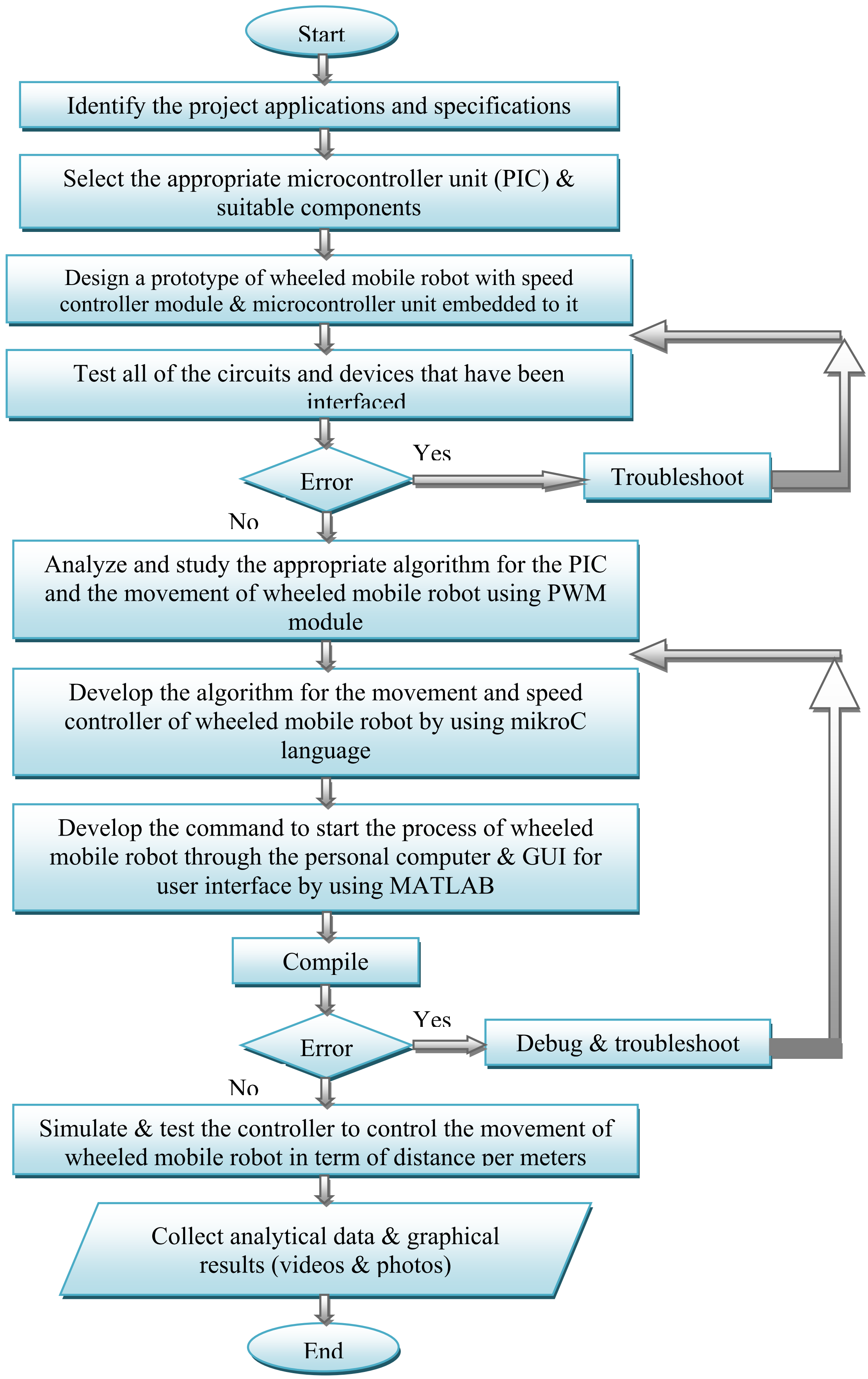

Figure 3.1 : Flowchart of Overall Method

3.3 Project Block Diagram

In this project, we will discuss the methods for delivering the control signal from the controller to the actuator. We will also detail the measurement of system output by using encoder. Figure 3.2 shows the block diagram for this project.

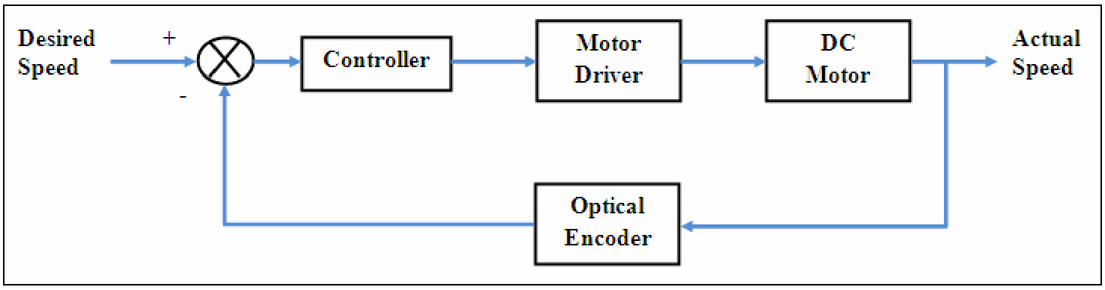

Figure 3.2 : Block Diagram for Velocity Compliance of A Wheeled Mobile Robot

Figure 3.2 is a basic structure of a feedback control system. The first input signal for the controller is a desired input a signal where the signal is in a command form for the controller. The controller will be use the command signal into a module what we called the Pulse Width Modulation (PWM) module plus with the Timer module to control the speed of motor. Then it will send to the motor driver where is the H-Bridge module has been used. DC motor will received the signal and moved as desired. From this, the output signal that come out from the movement of DC motor will be measured by the optical encoder where is it will be enumerate the distance of the wheeled move. Then it will give a feedback to the controller to calculate the error between the input signal and the feedback signal. The error will determine the actual output for the DC motor to move by using the PWM technique. This process will be continuing until we get the desired velocity profile. The details for each part in this block diagram will be explained on the next chapter.

3.4 Velocity Control System

In concerning about the energy-efficient of mobile robot, we will investigate first about the velocity profile control system which is most dissipated in DC motor. This robot will use four wheels but only two will driven by DC Motor. The motor are located first on left rear side of the body and the second one is on right front side of the body. The Figure 3.3 shows the proposed schematic diagram of the velocity control systems for this project.

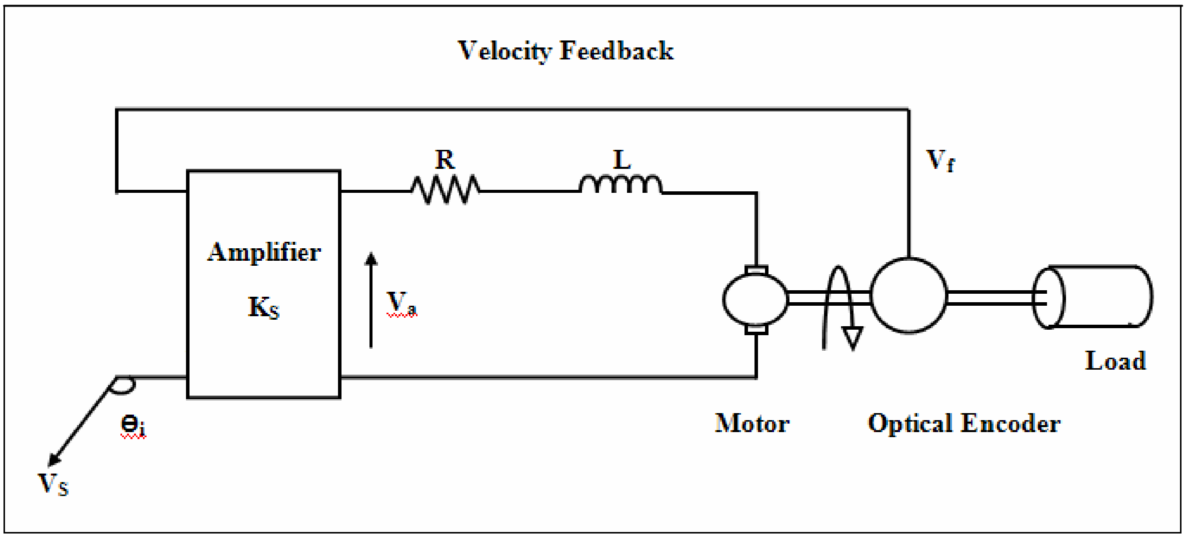

Figure 3.3 : Schematic Diagram of Velocity Control System

Hence that the input voltage, $V_i \, \alpha \, \theta_i \, \alpha \, \omega_i$ (Input Velocity)

Precision control of the angular velocity $\omega_m(t)$ of an inertia load driven directly by an armature controlled DC motor can be achieved by comparing an input voltage, V_i representing a demanded speed ω_i and derived from a source of constant voltage V_i via a potentiometer with a feedback voltage V_f derived from a optical encoder coupled to the shaft of wheeled mobile robot.

This means that:

$$V_e(t) = V_i(t) - V_f(t) \tag{3.1}$$

and $$V_a(t) = K_s V_e(t) \tag{3.2}$$

The Figure 3.4 shows the block diagram for the velocity control system [11].

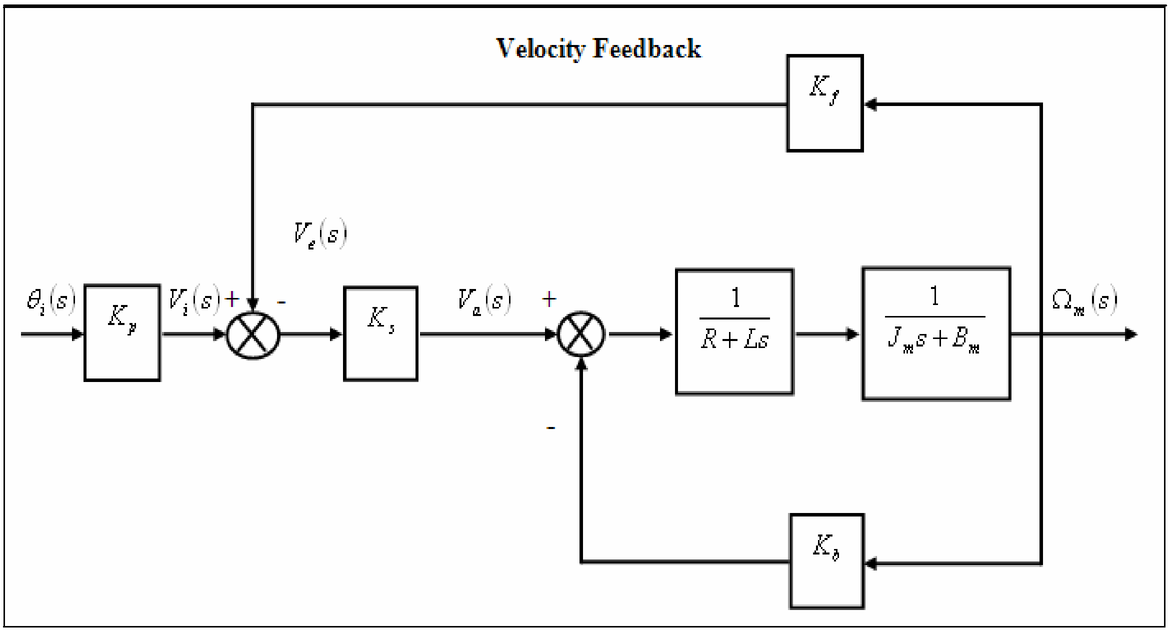

Figure 3.4 : Block Diagram for Velocity Control System

From the block diagram above, we obtained the transfer function of this system:

$$\frac{\Omega_m(s)}{V_a(s)} = \frac{K_t}{(R + L_s)(J_m s + B_m) + K_t K_b}$$

Where

K_b back emf constant

K_f optical encoder constant

For small motors, the armature inductance L can be neglected.

~L = 0

So,

$$\frac{\Omega_m(s)}{V_a(s)} = \frac{K_t}{(R + L_s)(J_m s + B_m) + K_t K_b}$$

$$= \frac{K_t}{RJ_m s + (RB_m + K_t K_b)}$$

$$= \frac{\frac{K_t}{RB_m + K_t K_b}}{\frac{RJ_m}{RB_m + K_t K_b}(s+1)}$$

Let K_m be the motor gain and τ_m be the motor constant time then we get,

$$\frac{K_t}{RB_m + K_t K_b} = K_m$$

$$\frac{RJ_m}{RB_m + K_t K_b} = \tau_m$$

Therefore,

$$\frac{\Omega_m(s)}{V_a(s)} = \frac{K_m}{1 + s\tau_m}$$

The block diagram of the simplified velocity control system is,

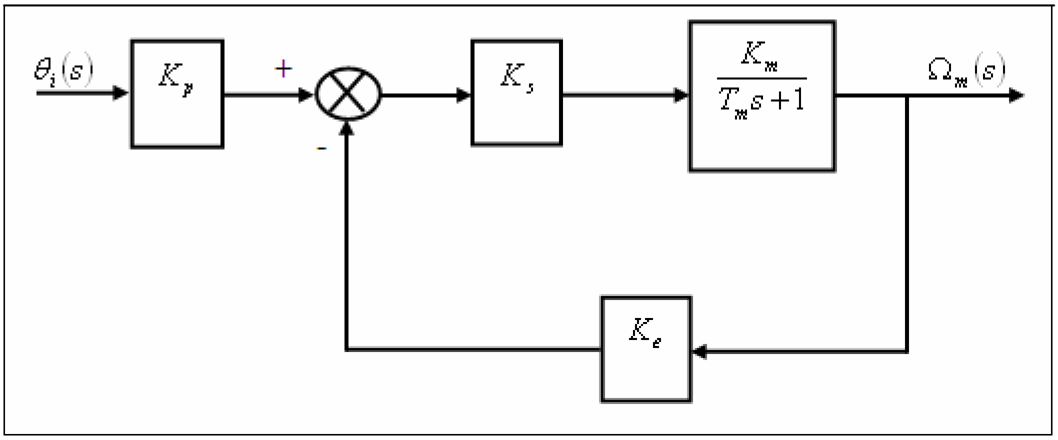

Figure 3.5 : Block Diagram of the Simplified Velocity Control System

The overall transfer function,

$$\frac{\Omega_m(s)}{\theta_i(s)} = K_p \times \frac{\dfrac{K_s K_m}{1+s\tau_m}}{1+\dfrac{K_s K_m}{1+s\tau_m}}$$

$$\frac{\Omega_m(s)}{\theta_i(s)} = \frac{K_p K_s K_m}{s\tau_m + \left(1 + K_s K_m K_f\right)} \qquad (3.3)$$

For a unit step input for example $\theta_i(t) = r(t)$ where it transform $\theta_i(s) = \frac{1}{s}$, then the angular velocity of the system can be shown to vary as in Figure 3.6.

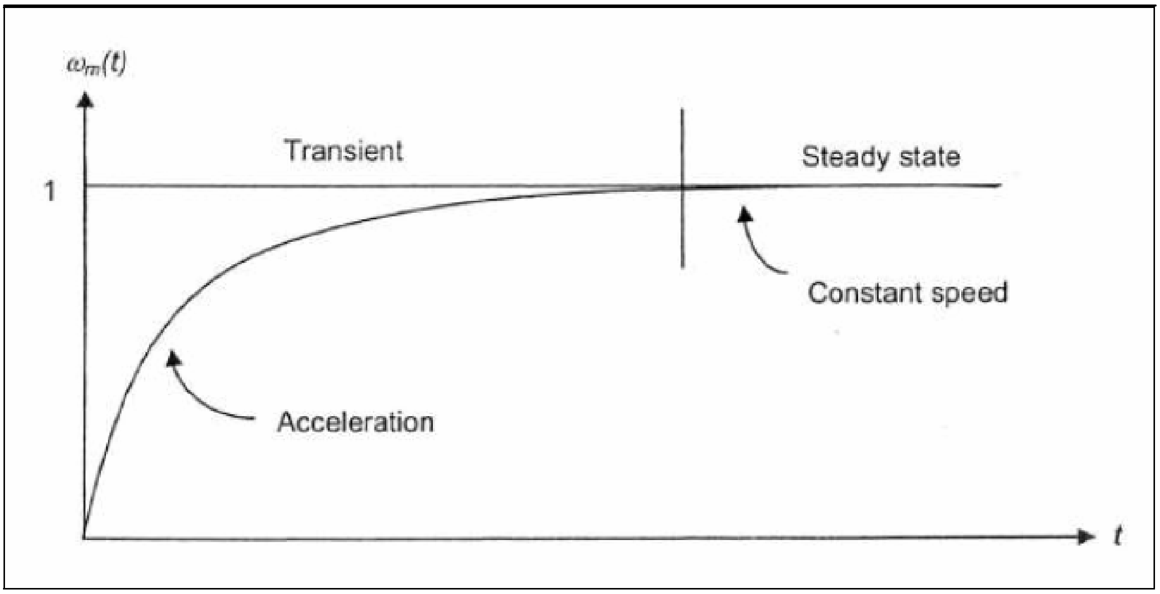

Figure 3.6 : Response of the Simplified Velocity Control System

3.5 Kinematics Wheeled Mobile Robot

Kinematics is the most basic study of how mechanical behave. In mobile robotics, we need to understand the mechanical behavior of the robot both in order to design appropriate mobile robot for tasks and to understand how to create control software for an instance of mobile robot hardware.

Figure 3.7 represent of a wheeled mobile robot. Mathematically the configuration of the mobile robot can be described by $q = [x, y, \theta, \phi]^T$, where x and y are the point at the centre of rear axle, θ is the headling angle and ϕ is the steering angle as shown in Figure 3.7. The rolling without slipping constraints is found by the setting sideways velocity of the front and rear wheels to zero.

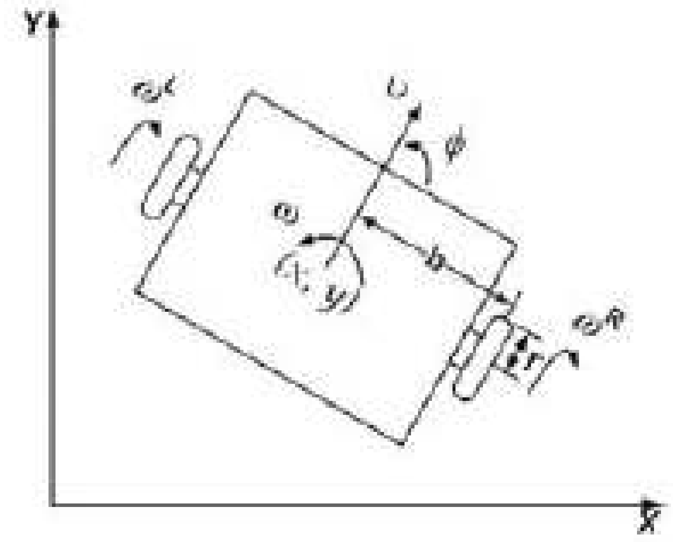

Figure 3.7 : Structure of Wheeled Mobile Robot

From the figure, this leads to

$$\begin{aligned} &\sin\theta x - \cos\theta y = 0 \\ &\sin(\theta+\phi)x - \cos(\theta+\phi)y - d\cos\theta\phi = 0 \end{aligned} \qquad (3.4)$$

This can be written as

$$\begin{aligned} &[\sin\theta \quad \cos\theta \quad 0 \quad 0]q =< \omega_1, q >= 0 \\ &[\sin(\theta+\phi) \quad -\cos(\theta+\phi) \quad -d\phi \quad 0] =< \omega_2, q >= 0 \end{aligned} \qquad (3.5)$$

It is thus straight forward to the control system.

$$g_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}; g_2 = \begin{bmatrix} \sin\theta \\ \sin\theta \\ \frac{1}{d}\tan\phi \\ 0 \end{bmatrix} \qquad (3.6)$$

Assume that the wheeled mobile robot has a symmetrical structure driven by DC motor. Also assume the DC motor has the armature resistance, R_a, back emf constant, K_b, torque constant, K_t, and gear ratio, ρ. For simpler dynamics, neglect the inductance of armature circuits since electrical response is generally much faster than mechanical response. Letting the V_s be the battery voltage supplied, armature circuits of DC motor are described by

$$R_a i = V_s u - K_t \rho \omega \tag{3.7}$$

Where $i = [i^R \quad i^L]^T$ is the armature current vector, $\omega = [\omega^R \quad \omega^L]^T$ is the angular velocity vector of wheels, and $u = [u^R \quad u^L]^T$ is the normalize input voltage vector. Superscript R and L correspond to the right and left of motor shaft. In addition, dynamic relation between angular velocity and motor current considering inertia and viscous friction becomes

$$J \frac{dw}{dt} + F_v w = K_t \rho i \tag{3.8}$$

Where F_v is the viscous friction coefficient and J is the equivalent inertia matrix motors. Then obtain the following differential equation:

$$w + Aw = Bu \tag{3.9}$$

Where

$$A = \begin{bmatrix} a_1 & a_2 \\ a_2 & a \end{bmatrix} = J^{-1} \left[F_v + \frac{K_t K_b \rho^2}{R_a} \right] \text{ and } B = \begin{bmatrix} b_1 & b_2 \\ b_2 & b \end{bmatrix} = J^{-1} \frac{K_t \rho}{R_a} V_s$$

Define the state vector as $z = [v \quad w]^T$, translational velocity of WMR as v, and rotational velocity of WMR as w. Then v and w are related with w^R and w^L as

$$\begin{bmatrix} v \\ w \end{bmatrix} = T_q \begin{bmatrix} w^R \\ w^L \end{bmatrix}, \; T_q = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{2b} & \frac{-r}{2b} \end{bmatrix} \tag{3.10}$$

Using similarity transformation (3.9) and (3.10), we get the following equation:

$$z + \overline{A}z = \overline{B}u \tag{3.11}$$

Where

$$\overline{A} = T_q A T_q^{-1} = -\begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} = \begin{bmatrix} a_1 + a_2 & 0 \\ 0 & a_1 - a_2 \end{bmatrix}$$

$$\overline{B} = T_q B = -\begin{bmatrix} \beta_1 & \beta_1 \\ \beta_2 & -\beta_2 \end{bmatrix} = \begin{bmatrix} \frac{r(b_1 + b_2)}{2} & \frac{r(b_1 + b_2)}{2} \\ \frac{r(b_1 - b_2)}{2b} & \frac{-r(b_1 - b_2)}{2b} \end{bmatrix}$$

Define posture as *[x(t)   y(t)   Ø(t)]*^{T}. Then WMR kinematics is define as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos & \sin & 0 \\ \phi & \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} \tag{3.12}$$

When WMR moves a long straight line path, angular velocity Ǿ is zero since the same control input is applied to motor. Hence (3.12) can be written in the simple form

$$\begin{bmatrix} \dot{x} & \dot{y} & \dot{\phi} \end{bmatrix}^T = \begin{bmatrix} v & 0 & 0 \end{bmatrix}^T \tag{3.13}$$

3.6 Typical Velocity Profiles

Typical velocity profiles of WMR are consisting of three sections: acceleration (A), cruise (C) and deceleration (D). Certainly, there are many profile types for acceleration and deceleration depends on the motor control input. In this project, we investigate the trapezoidal velocity profile. Figure 3.8 shows the typical trapezoidal velocity profile.

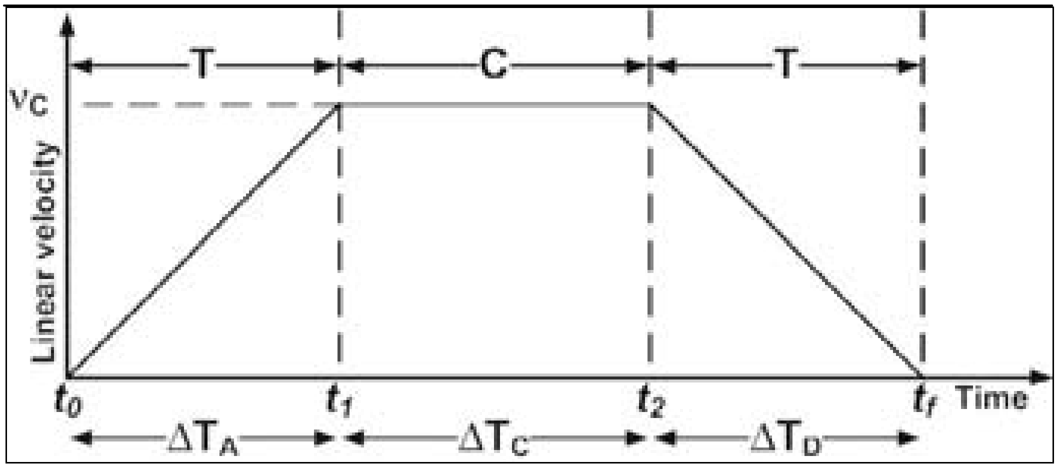

Figure 3.8 : Typical Trapezoidal Velocity Profile

Trapezoidal velocity profile provides smooth motion for starting and stopping motor control system. Figure 3.9 shows a velocity profile sections to be implemented in software that we can used to provide digital or analogue control to a motor. In the figure, $\dot{\theta}$ represents the desired motor velocity (trapezoidal velocity profile) and $\dot{\theta}_{MAX}$ represents the maximum motor velocity. We can predetermine the velocity profile based on the load accelerations and decelerations requirements. To apply this method to wheeled mobile robot, we need to design what is the desired velocity profile that we want to implement into the system.

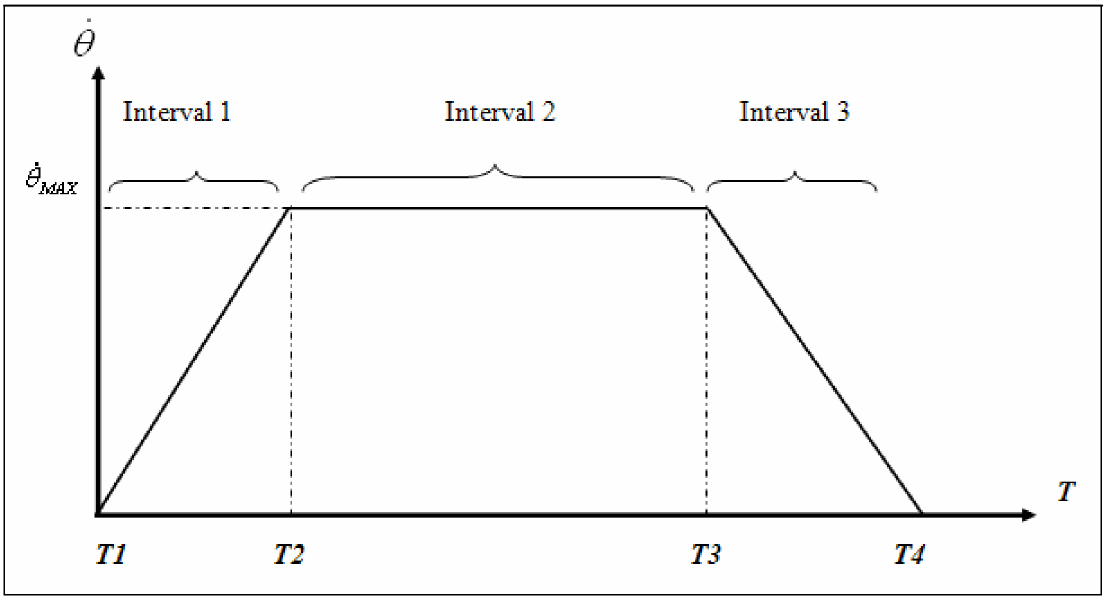

Figure 3.9 : Velocity Profile Sections To Be Implemented in Software

From figure we get,

$$\theta_D = \underbrace{\int_{T_1}^{T_2} \frac{\dot{\theta}_{MAX} \times t}{(T_2 - T_1)} dt}_{Interval\ 1} + \underbrace{\int_{T_2}^{T_3} \dot{\theta}_{MAX}\, dt}_{Interval\ 2} + \underbrace{\int_{T_3}^{T_4} \frac{\dot{\theta}_{MAX} \times t}{(T_4 - T_3)} dt}_{Interval\ 3} \qquad (3.14)$$

Equation 3.14 shows the calculation of the desired position, θ_D or the distance that the motor needs to travel as the area under the curve of Figure 3.9 which is an integral of the velocity. For example, if we want the interval 1 to travel for a certain distance we need to vary the *T1* and *T2* for the system to accelerate. Then the system will calculate the position every *T* sampling period. The sampling period that we choose in this project is 0.5s. From this, the velocity for every sampling period will be determined from the rotation of optical encoder. The optical encoder gives us the pulses signal to vary the speed of the motor. From these speeds of motor, we may use Equation 3.15 to calculates the $\dot{\theta}$.

$$\dot{\theta} = \frac{d}{t + T} \qquad (3.15)$$

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