CONTROLLER DESIGN OF A TWO-WHEELED SELF BALANCING MOBILE ROBOT BASE ON A SIMULATION VIEW POINT

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Robotics & Automation) (Hons.).
The member of the supervisory committee are as follow:

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(**En. Shariman bin Abdullah**)

ABSTRAK

Sebuah robot mudah alih beroda dua tidak dapat mengangkut dirinya dari satu tempat ke tempat lain tanpa bantuan seorang pengawal kerana sifat ketidakstabilan itu. Tujuan projek ini adalah untuk mereka bentuk pengawal yang mampu untuk mengelakkan robot dari jatuh ke bawah ke tanah dan keteguhan pengawal direka akan diuji melalui co-simulasi Adams dan Matlab. Keberkesanan pengawal direka akan disahkan dengan menganalisis keputusan daripada co-simulasi. Terdapat pada asasnya tiga jenis robot mudah alih beroda dua: sentroid tetap, sentroid bergerak dan dengan bar pemegang. Sebuah robot mudah alih beroda dua dengan sentroid bergerak dipilih untuk projek ini kerana sifat tidak stabil itu. Selepas membuat keputusan mengenai reka bentuk, model 3D adalah bermula pada SolidWorks. Kemudian, model itu dipindahkan ke persekitaran Adams untuk konfigurasi dan mengeksport data ke Matlab untuk reka bentuk pengawal. Dalam Matlab, pengawal yang direka berdasarkan algoritma PID. Cara penalaan manual digunakan pada penalaan pengawal untuk mencapai hasil yang dikehendaki. Selepas itu, kedua-dua perisian simulasi disambungkan menggunakan modul Adams dan kemudian co-simulasi boleh dimulakan. Terdapat tiga simulasi akan dijalankan dalam projek ini: keseimbangan diri ketika berehat, bergerak ke hadapan pada sudut kecondongan tertentu dan bergerak merentasi benjolan tanpa kehilangan keseimbangan. Keputusan yang diperolehi daripada co-simulasi akan dianalisis untuk mengetahui keupayaan pengawal yang direka. Keputusan daripada co-simulasi menunjukkan bahawa pengawal yang direka mampu mengekalkan kestabilan robot mudah alih dan memudahkan proses reka bentuk pengawal. Untuk kajian masa depan, pengawal PID yang digunakan dalam projek ini boleh digantikan dengan pengawal yang lain untuk mencapai prestasi dan keputusan yang lebih baik.

ABSTRACT

A two-wheeled mobile robot is not able to transport itself from one place to another without the aid of a controller due to its unstable nature. The aim of this project is to design a controller that is able to prevent the robot from falling down to the ground and the robustness of the designed controller will be tested through co-simulation of Adams and Matlab. The effectiveness of the designed controller will be confirmed by analyzing the result obtain from the co-simulation. There are basically three type of two-wheeled mobile robot: fixed centroid, moving centroid and with handle bar. A two-wheeled mobile robot with moving centroid is chosen for this project due to its unstable nature. After making decision on the design, 3D modelling is start in SolidWorks. Then, the model is transferred to Adams environment for configuration and export the data to Matlab for controller design. In Matlab, a controller is designed based on PID algorithm. Manual tuning method is applied while tuning the controller to achieve the desired result. Afterward, both simulation software are connected using Adams control interface module and the co-simulation can be initiated. There are altogether 3 simulation is going to carry out in this project: self-balance while at rest, move forward at certain tilt angle and move across bump without losing balance. The obtained result from the co-simulation is analyzed to know the capability of the designed controller. The co-simulation results showed that the controller is able to maintain the stability of the mobile robot and simplify the controller design process. For future study, the PID controller that was used in this project could be replaced other type of controllers to achieve better performance and results.

DEDICATION

This project is dedicated to my final year project supervisor, my beloved family and friends for giving me moral support, cooperation, encouragement and also understandings

Thank You So Much

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LIST OF ABBREVIATIONS, SYMBOLS AND NOMENCLATURES

3D	-	3 Dimension
TWSBMR	-	Two-Wheeled Self-Balancing Mobile Robot
PID	-	Proportional-integral-derivative
Kp	-	Proportional Gain
Ki	-	Integral Gain
Kd	-	Derivative Gain
CAD	-	Computer-aided design

CHAPTER 1

INTRODUCTION

1.1 Background of Study

A two-wheeled mobile robot is defined as the combination of wheeled mobile robot and inverted pendulum system. An inverted pendulum is a pendulum whose centroid is above its pivot point and a system that equipped with inverted pendulum will become unstable. The inverted pendulum system of a two-wheeled mobile robot is not self-actuated, on the contrary, it is actuated by the movement of the robot. For example, when the two-wheeled mobile robot is moving forward, the inverted pendulum system will lean to backward and the robot have to do something to prevent itself from toppling. Therefore, in order to help the robot to regain its stability, it is always mounted with sensors like gyroscopes and accelerometers whose task is to sense detect the inclination off the vertical axis. After that, the degree of inclination will be sent as feedback to the controller. Based on the received feedback, the controller will sent torque signal to each motor to prevent the system from losing its balance and eventually fall down to the ground. Thus, the two-wheeled mobile robot will have a to and fro movement to overcome its unstable nature (An & Li, 2013).

The increase in popularity of two-wheeled self-balancing among researchers is not only because of its non-linear nature, but also some of its superiorities compared to other mobile robots. Based on the review done by Chan *et al.* (2013), while comparing to a statically stable mobile robot like four-wheeled mobile robot, a two-wheeled robot is more difficult to control for sure, however, it is still much simpler to be controlled compared to a legged robot. Besides, due to the wheel configuration of two-wheeled mobile robots, the robot is very flexible and highly maneuverable and this allow the robot to turn on the spot in a more precise manner compared to other wheeled mobile robot. Despite having unstable nature, two-wheeled mobile robot is able to maintain its stability on inclined plane by leaning into the slope. Furthermore, a two-wheeled mobile robot is mounted with only two wheels, and this feature allow it to equip with bigger wheels. Two-wheeled mobile robot with bigger wheels has the potential to traverse rougher terrain (Chan *et al.*, 2013).

1.2 Problem Statement

Two-wheeled self-balancing mobile robots are widely implemented as human transportation vehicles that provide another form of transportation for human to travel from one place to another especially while doing sightseeing. Due to the increasing popularity, many researchers are interested in finding various ways and methods to balance the non-linear and unstable characteristics of a two-wheeled mobile robot.

In conventional method of producing a two-wheeled mobile robot, 3D-Modelling of the robot will be first carried out in modelling software like Solidworks, Catia etc. and followed by the controller design. The controller design of the robot is started by developing the mathematical model. This mathematical model is developed based on the free body diagram of the robot that was previously designed in the 3D-modelling software. The controller design will become very complex if all the real world physic are taken into account in the mathematical model. Therefore, to simplify the controller design, there are always some assumptions made while developing the mathematical model.

Afterward, the controller that designed based on the mathematical model can be tested through simulation in simulation software like Matlab. However, the success in simulation does not prove that the controller is confirmed to able to maintain the stability of the designed two-wheeled mobile robot, it only indicates that the controller is capable of stabilize the robot under the assumptions that made while developing the mathematical model. In real environment, there are many external disturbances such as friction that need to be considered. Because of this weakness, the actual performance of the designed controller can only be tested when the real prototype of the two-wheeled is produced and the this largely increase the cost of a research because actual prototyping can be costly.

In order to overcome such issue, there are a number of researcher come up with idea of simplify the controller design process by implementing a simulation that combine the advantages two virtual prototyping software. Such technique is named as co-simulation. Co-simulation has the capability of testing the robustness of the designed controller through simulation on an imitated real environment that is simulated by another software. By doing so, the actual performance of the designed controller can be tested in the simulated model without the need to wait for the prototype of the robot. Besides, the complexity of the mathematical model within the controller design will be reduced because the some transfer function that are developed in the mathematical model to represent the actual model of the robot is no longer required as the model of the robot can be imported to simulation environment while running co-simulation.

In this study, co-simulation of two virtual prototyping software was suggested to simplify, accelerate and thus improve the design process of a two-wheeled self-balancing mobile robot as well as minimize the cost for developing the real prototype.

1.3 Objectives

1. To develop the design of a two-wheeled self-balancing mobile robot by using 3D-modelling software and design a controller that enable the designed two-wheeled mobile robot to
    i. Self-balance while at rest
    ii. Move forward at certain tilt angle on a flat platform and
    iii. Move across bump in simulation environment
2. To simplify the controller design process by using co-simulation.
3. To analyze the effectiveness of the designed controller based on the result obtained from the co-simulation of Adams and

1.4 Scopes

1. The 3D-modelling of two-wheeled self-balancing mobile robot is constructed in Solidworks and there is no involvement of fabrication of real model in this project.
2. The controller design process is carried without the need of developing complex mathematical model
3. The slope of the bump is about 10 degree.
4. PID controller is chosen to implement the control of two-wheeled self-balancing mobile robot.
5. The effectiveness of the designed controller is tested through co-simulation in term of rise time, settling time, percent overshoot and steady state error.
6. The maximum tilt angle of the robot is 3 degree.
7. The speed of the robot is depend on the tilt angle
8. Manual tuning method is used to tune the PID controller

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are many research study on the two-wheeled self-balancing mobile robot due to its unstable state for controlling. The robot has to moves back and forth in order to maintain its balance through the use of certain controller. Although the literature covers a huge variety of such researches, this emphasis of this review will be placed on 5 major themes that will be discussed repeatedly throughout the literature reviewed. These themes are:

i. Mobile Robot
ii. Basic design of the two-wheeled self-balancing mobile robot.
iii. Mathematical Model of two-wheeled self-balancing mobile robot.
iv. Existing control system of the two-wheeled self-balancing mobile robot.
v. Simulation

Most of the simulation in the researches are carried out using Matlab to test the effect of the designed controller on the stability of two-wheeled self-balancing mobile robot. However, this kind of simulation is only done based on the dynamic equation and kinematic model of the robot. Some changes may have to be made on the controller in real environment variable such as inertia, friction and weight of the robot are taken into account. In fact, the simulation can be further improved through the use of ADAMS that create a simulation which imitates the condition of real environment. There are already some researches done based on the co-simulation of Adams and Matlab that will be further discussed in the following section. Although these themes are presented in a variety of contexts, this paper will primarily focus on the controller design of two-wheeled self-balancing mobile robot and the co-simulation of the designed robot and controller using Adams and Matlab.

Most of the information in this literature review is obtained from journal articles, relevant research paper, online articles and books. Majority of the references are the similar projects done by other researchers which are related to two-wheeled -self balancing mobile robot. Some of the references provide basic concept and knowledge about certain topic that are required this project for clearer understanding.

2.2 Mobile Robot

A mobile robot is an automatic machine that is capable of transport themselves from one place to another. The collective name this capability is called locomotion. The superiority of a mobile robot can be seen clearly while comparing it to a fixed manipulator or robot arm. A robot arm is usually bolted at its shoulder to a specific position in the assembly line and it is able to moves with great speed and accuracy to perform repetitive task. However, this situation shows the obvious weakness of a fixed manipulator: lack of mobility. It has a limited range of motion that is dependent on the location where it is bolted down. On the contrary, a mobile robot is able to travel throughout the manufacturing plant and such talent can be applied flexibly wherever it is most effective (Roland Siegwart, 2004).

Mobile robots can be differentiated based on their locomotion. Typically, there are two major type of mobile robot: legged mobile robots and wheeled mobile robots. Figure 2.1 shows the of a legged mobile robot. Legged mobile robot possesses high adaptability and maneuverability in rough terrain but it is mechanically more complex than a wheeled robot. Although a wheeled mobile will not have the adaptability and maneuverability as high as legged mobile robots in rough terrain, it is able to move faster than a legged mobile robot on a flat or smooth terrain. In addition, a wheeled mobile robot is simpler to be used, easier to be programed and easier to be maneuvered compared to a legged mobile robot (Roland Siegwart, 2004). Since the focus of this project about one kind of the wheeled mobile robot, therefore, the emphasis of this section will only place on the wheeled mobile robot. The following section consist of history of wheeled mobile robot, type of wheeled mobile robot and the application of wheeled robot.

Figure 2.1 Legged Mobile Robot (Horsey, 2011)

2.2.1 History of Wheeled Mobile Robot

After the invention of wheels, humans used the wheel to create wheeled vehicles like carriage, bicycle etc. to transport humans or goods from one place to another. Those wheeled vehicles were unpowered and usually operated manually or drawn by animals. This situation changed when the steam engine and the internal combustion engine were invented during 19^{th} and 20^{th} century. These inventions gave a tremendous increase in mobility, both with regard to speed and terrain capabilities. The idea of continuous tracks arose through the presence of wheel and wheeled vehicle. The main principle of a continuous track was that the tracks were making their own way or "track" in front of the wheeled vehicle so that the wheels can run on that track continuously (Nils Brynedal Ignell, 2004).

The drawings of the first manufactured robot are biologically inspired or in other word, they are largely resembled the human or animal body. This was, without doubt, a common phenomenon that will occur during the development of robot because the aim of the robot was to perform tasks that humans would rather skip such as carrying heavy loads or other tedious jobs and therefore, there would be no surprise that people would think of an autonomous, mechanical body of human while considering or building a robot. The development of robot was moved to the next stage when it was realized that the robot's appearance of a human was not entirely necessary, unlike its function (Nils Brynedal Ignell, 2004). For example, a robot arm may not look as if human arm from its appearance or move like human arm, but it is able to pick and load an object from one place to another just like a human arm. According to Buckley (1997), the first autonomous wheeled robot was created in 1912. It was an electric dog named “HM” that was technologically advanced for its time and could follow a light source. Figure 2.3 shows the design of the electric dog.

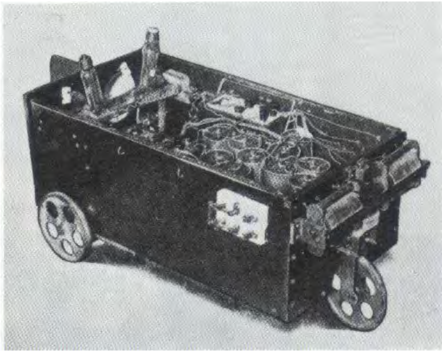

Figure 2.2 Electric Dog (Buckley, 1997)

2.2.2 Type of Wheeled Mobile Robot

Wheeled robots are the robots that can transport themselves form one place to another with the help of their wheels. A robot with wheeled motion can achieve mechanical term easily and with low cost compared to legged mobile robot. In addition, the control of wheeled moving is generally simpler. Due to these reasons, wheeled robots are becoming one of the most frequently seen robots. The types of wheeled mobile robot that have been developed by other researchers will be introduced at the following section.

2.2.2.1 Single Wheeled Mobile Robot

Single-wheel mobile robot are extremely challenging and difficult to keep balance because there is one single point of contact with the ground (Ruan *et al.*, 2014). In addition, all material of the robot would have to be packed inside a single wheel (Ha & Jung, 2015). According to the research done by Ha and Jung (2015), three actuators are used for the balancing and driving control. One of the actuator is for the driving, another one is for the flywheel spinning and the last one is for tilting the flywheel to generate the gyroscopic effect. The gyroscopic effect plays a role in making turn of the whole system in the roll direction by preventing the robot from falling down. Hence, the most important part in the balancing performance of a single-wheel mobile robot system is the tilting angle control of the flywheel