Chapter 1

INTRODUCTION

1.1 Motivation

Researches on balancing a Mobile Inverted Pendulum (MIP) have gained momentum over the last decade in a number of robotics laboratories around the world [1–8]. This is due to the inherent unstable dynamics of the system. Such robots are characterized by the ability to balance on its two wheels and spin on the spot. This additional maneuverability allows them to navigate easily on various terrains, turn sharp corners, and traverse small steps or curbs. These capabilities have the potential to solve a number of challenges in industry and society. For example, a motorized wheelchair utilizing this technology gives operators greater maneuverability and thus they can access it to places most able-bodied people take for granted [9–11]. Prototyping and utilizing this technology allow humans to travel short distance in a small area or factories as opposed to using cars or buggies which emit more pollution [12]. A gyroscope and an accelerometer are used to measure the tilt of the robot and the encoders on the motors to measure the wheel's rotation. Apart from the above, this thesis will delve into the suitability and performance of linear state-space controllers, namely, the linear quadratic regulator (LQR) and a Pole-placement controller in balancing the system. In an additional study the $\mathcal{H}_\infty$ controller is designed to balance the MIP using linear parameter varying control technique with a full block multiplier and it was also implemented in XPC-target.

1.2 Literature Review

Conducting literature review prior to undertaking research projects is critical as this will provide the researcher with much needed information on the technology available and methodologies used by other research counterparts around the world on the topic. This chapter provides a condensed summary of literature reviews on key topics related to balancing a two-wheeled autonomous robot.

1.2.1 Balancing Mobile Inverted Pendulum

The inverted pendulum problem is not uncommon in the field of control engineering. The uniqueness and wide application of technology derived from this unstable system have drawn interests from many researchers and robotics enthusiasts around the world. In recent years, researchers have applied the idea of a mobile inverted pendulum model to various problems like designing walking gaits for humanoid robots [13], robotic wheelchairs [14] and personal transport systems [2]. Researchers at the Industrial Electronics Laboratory at the Swiss Federal Institute of Technology have built a scaled down prototype of a Digital Signal Processor controlled two-wheeled vehicle based on the inverted pendulum with weights attached to the system to simulate a human driver (Figure 1.1). A linear state-space controller utilizing sensory information from a gyroscope and motor encoders is used to stabilize this system [1]. A similar and commercially available system, "SEGWAY HT" has been invented

Figure 1.1: JOE: mobile inverted pendulum.

by Dean Kamen, who holds more than 150 U.S. and foreign patents related to medical devices, climate control systems, and helicopter design. The "SEGWAY HT" is able to balance a human standing on its platform while the user traverses the terrain with it (Figure 1.2). This innovation uses five gyroscopes and a collection of other tilt sensors to keep itself upright. According to Segway Inc (2005), only three gyroscopes are needed (one on each axes), the extra sensors are included as yet another redundancy system [2]. M. A. Clark et al [3] designed and built a self-balancing scooter (EDGAR) that similar to the Segway Human Transporter (Figure 1.3). EDGAR's design drew upon the successes and failures of the Segway HT and other attempts at producing self-balancing scooters which utilized various automatic control methods. Angular feedback from a gyroscopic sensor and PWM output to

Figure 1.2: SEGWAY HT.

motors were used in a control system to achieve the balance of EDGAR. Another example

Figure 1.3: EDGAR, a two-wheeled balancing robot.

is Nbot, a two-wheeled balancing robot similar to JOE built by D. P. Anderson (Figure 1.4). This robot used a commercially available inertial sensor and position information from motor encoder to balance the system [4]. Steven Hassenplug successfully constructed a balancing robot called Legway using the LEGO Mindstorms robotics kit (Figure 1.5). Two Electro-Optical Proximity Detector (EOPD) sensors was used to provide the tilt angle of the robot to the controller which was programmed in Brick OS, a C/C++ like programming language specifically for LEGO Mindstorms [5]. The paper "Cooperative Behavior of a Wheeled Inverted Pendulum for Object Transportation" presented by Shiroma et al (Figure 1.6) in 1996

Figure 1.4: Nbot, a two wheel balancing robot.

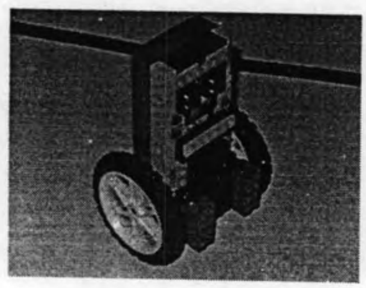

Figure 1.5: Legway, a two wheel balancing robot.

shows the interaction of forces between objects and the robot by taking into account the stability effects due to these forces. This research highlights the possibility of cooperative transportation between two similar robots and between a robot and a human [6]. The rapid

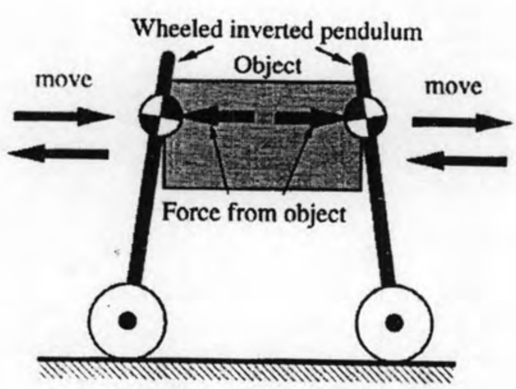

Figure 1.6: The concept of the cooperative transportation by two wheeled inverted pendulums.

increase of the aged population in countries like Japan has prompted researchers to develop robotic wheelchairs to assist the infirm to move around (Figure 1.7). The control system for an inverted pendulum was applied when the wheelchair manoeuvres a small step or road curbs [11].On a higher level, Sugihara et al. modeled the walking motion of a human as an

Figure 1.7: Robotic wheelchair.

inverted pendulum in designing a real time motion generation method of a humanoid robot (Figure 1.8) that controlled the center of gravity by indirect manipulation of the Zero Moment Point (ZMP). The real time response of the method provided humanoid robots with high mobility [13].

1.2.2 Kalman Filter

In 1960 R.E Kalman published a paper entitled "A New Approach to Linear Filtering and Prediction Problems" [15]. His research intended to overcome the limitations of the "Weiner-Hopf" filter in solving problems of statistical nature which seriously curtailed its practical usefulness. The process described within came to be known as Kalman filtering. The Kalman filter is a set of mathematical equations that provides an efficient computational solution of the least square method. The filter is very powerful as it supports estimations of past, present and even future states, and it can do so even when the precise nature of the modeled system is unknown. There have been a number of texts written about Kalman filtering since Kalman's original paper. One of the complications in understanding the filter methodology is that there seems to be a lack of standard notation for the filter equations. It is possible that the notations used by Kalman are too complex. Therefore, successive authors have simplified notation and expressed filter equations in different ways. This result in none of the books used identical

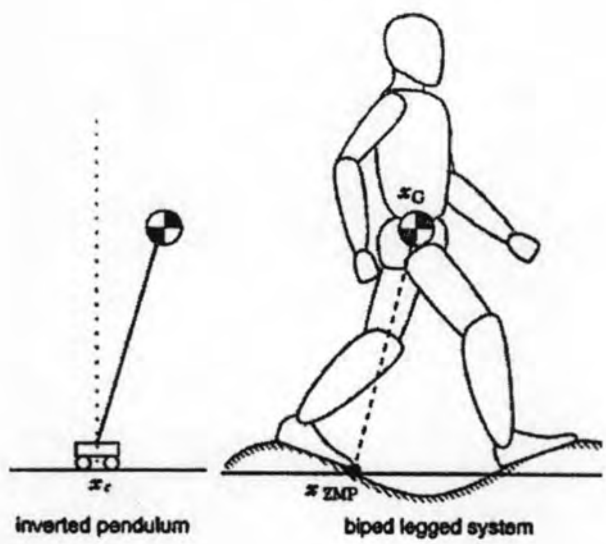

Figure 1.8: Inverted pendulum and legged system.

notation and authors of academic papers who use the Kalman filter usually follow the notation used by author's reference. As the subject of Kalman filtering was relatively new at that period of time, the lack of continuity in these books and the different notation used in some chapters have hindered the understanding of the material presented. Books by Gelb (1974) and Maybeck (1979) provided a comprehensive explanation on Kalman filtering in a very practical way. Although both books provided practical aspects of implementing the Kalman filter, Maybeck's complete work which consists of three volumes are superior and more modern than Gelb's as it covers a broader range of topics in more depth. Maybeck's book is aimed at engineers and could serve as a reference on the topic of stochastic estimation.

1.2.3 Sensor Fusion Using Kalman Filter

The accuracy and reliability of information regarding its operating environment for mobile robots is critical as these systems are usually unmanned. These requirements call for highly accurate sensors which are very expensive. Sensor fusion technology, where signal from several sensors are combined to provide an accurate estimate is the most widely used solution [16]. The Kalman filter is used in a number of multi-sensor systems when it is necessary to combine dynamic low-level redundant data in real time. The filter uses the statistical characteristics of a measurement model to recursively determine estimates for fused data that are optimal in a statistical sense. The recursive nature of the filter makes it appropriate for use in systems without large data storage capabilities. In 1993, Barshan and Durrant-Whyte published a paper on Inertial Navigation Systems for Mobile Robots. This pioneering research studies formed the building block for many other research applying sensor fusion technologies for mobile robot applications. The paper evaluated the performance of several sensors used in Inertial Navigation Systems and provided an outline for developing an Extended Kalman Filter for such systems [17, 18]. The wide applicability of sensor fusion technology has inspired the use in numerous configurations. Borenstein and Feng developed "Gyrodometry", which uses the Kalman filter for combining data from gyroscopes and odometry in mobile robots. This method effectively reduces odometry error which usually occurs when wheels of the robot slips on slippery surfaces [19]. In a similar development, Komoriya and Oyama utilized the Kalman filter to combine velocity information from the Optical Fibre Gyroscope with the position information obtained from the motor encoders for an optimal trajectory control of mobile robots [20]. The next section was introduced the control system in the previous works.

1.2.4 Control Systems

Control system development is vital to guarantee the success in balancing the robot, while there is abundance of control strategies that can be applied to stabilize the robot, the main aim is to build the control system with low cost and effective without sacrificing the robustness and reliability of the controller. The difference in balance control algorithm implemented depends mostly on how the system is modeled and how the tilt information is obtained. Nevertheless, a common approach separates the balancing and trajectory control of the mobile inverted pendulum. The control strategies for such system can be divided into two distinct methods, namely a linear control method and a nonlinear controller method. Linear control methods often linearize the dynamics about a certain operating point. This method is usually sufficient in balancing the system. Most researchers utilize the linear controller approach. A nonlinear controller uses the unscathed dynamics model of the system in designing a controller. Although these controllers can provide a more robust system, the complexity and implementation difficulties of these methods occur. A literature review found that nonlinear controllers are mostly implemented in solving the balance control problem of a simple pendulum on a cart model or a rotary inverted pendulum. Lahdhiri and Alouani developed a Fuzzy Logic controller for balancing an inverted pendulum on a cart. This approach is based on approximate reasoning and knowledge based control [21]. Williams and Matsuoka used the inverted pendulum model to demonstrate the ability of Neural Networks controller in controlling nonlinear unstable systems [22]. While simulation results proved that the system could be balanced with both controllers, there was no evidence of implementation of these ideas to verify their findings. Kajiwara et al [23] designed Linear Parameter-Varying (LPV) to control an inverted pendulum. LPV techniques allowed the construction of the global control law as a whole entity for all admissible angle. They furthermore provided theoretical guarantees in terms of both stability and performance in the presence of fast time-domain evolutions of the scheduled variables. The linear controllers are more popular among researcher designing similar balancing robots like JOE [1]. Linear state-space controllers like the Pole-placement controller and the linear quadratic regulators (LQR) are the two most popular control system schemes implemented. The implementation of these controllers can be seen in papers published by Shiroma [6], Takahashi [10, 11] and Grasser [1]. In the research entitled "Comparative Study of Control Methods of Single-Rotational Inverted Pendulum " conducted by Xu and Duan [24] showed that the LQR controller was far better than the Pole-placement controller in balancing an inverted pendulum mounted on a rotation arm. This is because the LQR controller offers an optimal control over the system input by taking the states of the system and the control input into account. The arbitrary placement of control poles for Pole-placement controllers might cause the poles to be placed too far into the left-half plane and cause the system susceptible to disturbances.

1.3 Objectives

The primary objectives of this research are to find the dynamic models, to design the controller and to implement an MIP.

1.4 Scope of Thesis

1. To build a physical prototype of an MIP.
2. To develop an accurate mathematical model by Newtonian approach and verify some parameters using system identification.
3. To design two control systems to be able to balance and rotating a robot under minimal disturbances.
4. To develop a Virtual Reality (VR) model of the prototype for the tuning of the control system.
5. To make it possible to control the MIP from a remote control via radio frequency.

1.5 Methodology

1. Design a prototype.

   Design an MIP in Solidworks then find the parameters center of mass and moment of inertia.

2. Derive a dynamic model.

   Derive a dynamic model using a Newtonian approach and the equations were linearized around an operating point to design controllers.

3. Build an interface circuit.

   To build an interface to capture good signals of angle and angular velocity of the pendulum with a treatment of the signal drift from sensor fusion using Kalman filter.

4. Design controllers.

   Design an LPV controller for an MIP and a linear state-feedback controller LQR or Pole-placement then compare the results.

5. Implement controller.

   Implement the LQR controller to the DSPIC to make the robot able to balance itself autonomously.

6. Build a user interface.

   Implement an user interface in MATLAB for an MIP and use XPC-Target to run the MIP with an LPV controller.

7. Build a remote control.

   Build a remote control to control the robot to move forward, backward, leftward or rightward.

8. Demonstrate the application.

   The demonstration of the plant aims to show the result already obtained. By this demonstration, developers could share the idea to allow other to use the plant in a laboratory.

9. Write the thesis

   The output is a complete, finalized thesis including all supporting documents in organized form.

1.6 Contributions

The expected contributions from this thesis are:

1. Dynamic model of an MIP.
2. LPV techniques to control of an MIP.
3. Linear state-feedback controller for an MIP.
4. User interface for an MIP.