CHAPTER I

INTRODUCTION

1.1 Research Motivation

A bicycle was first introduced in the 19th century [1] and still popular over the world up to now. The bicycle has attractive performances. It has light-weight, narrow body, ability to travel to a steeper and rough terrain with also lower installation and maintenance costs. In the environment-friendly aspect, bicycles produce low noise pollution and no CO_2 emission from the organic fuel. Various types of bicycles have been conventionally manufactured without consideration on their dynamics. However, as the advent and evolution of the computer and electronic sensors, the complex control system becomes more feasible.

Bicycle researches induce a rich problem in the area of mechanics (modeling technique) and nonlinear control (control technique). Moreover, the method to control the bicycle can be divided by taking the actuator type into account. For example, it is obvious to see how we control the bicycle by steering the handlebar and balancing our bodies. Another method which cannot be realized by a human rider is to use the flywheel with high spinning rate and precessing about another perpendicular axis. By exploiting the gyroscopic effect, the flywheel generates the torque to help stabilize the bicycle. Since the technique is possible both when the bicycle stands at zero-speed and on moving, we decide to tackle this bicycle control problem with this type of actuator.

The derivation of the bicycle control has 2 main approaches which are the Newtonian approach (Force/Torque balance) and the Lagrangian approach (Conservation of Energy). We have selected the model that mostly fits our aim of research. Our model is from Spry and Girard (2008) [2] which is mainly concerning the model derivation and verification. This model describes the dynamics of bicycle at a constant forward and rotating speed of the bicycle with gyroscopic flywheel and was derived through the Lagrangian method. For our research, the parameter size is on the larger scale comparing with the experiment in [2]. Our parameters are based on the human size bicycle, not a toy size as presented in [2]. The proposed control method was a simple selection of the appropriate gain to satisfy the stability condition of the linearized model. This motivates our research to develop the nonlinear control algorithm for this model.

The bicycle with gyroscopic flywheel model is in fact nonlinear and usually linearized about its operating point to make it possible for using linear control method. To our knowledge, there is no effective result on the nonlinear control of this model type. Therefore, it is an advantage to extend the operating range of bicycle rolling angle while keeping less model error as much as possible by using the new method based on linear models. This results in our proposed control method, the Piecewise Affine (PWA) Control.

PWA systems belongs to the promising class of representation of nonlinear systems by approximating the nonlinearity with linear or affine functions. It can be considered as a natural model class for nonlinear systems since it has been used to represent a range of nonlinearities such as dead zones, saturations, and hysteresis with arbitrary accuracy. Our research will focus on approximating the nonlinear model to PWA model and deriving the control law based on Piecewise Quadratic (PWQ) criteria. We mainly refer the theory of PWA control to the results in [3].

1.2 Literature Review

The structure of the literature review will be presented in 2 parts: the bicycle part and the PWA control part.

Many researches on the bicycle dynamics model and stability analysis and control were done since the late of 19th century. Many papers discussed about the analysis of bicycle with rider control qualitatively. Some did the analysis with a bunch of equations to study its dynamics. The nearly perfect review of bicycle model history was done by A. Schwab *et al.* [4].

Various types of the bicycle model were presented along the century. Every type is concerning with the rolling angle or leaning angle because we are talking about the stability of the upright standing bicycle. Human exploits the advantage of a steering handlebar and body leaning himself to control the path and stabilize the rolling angle. Most of researchers present the interaction between rolling angle and steering angle and use the rolling angle to act like a feedback controller for stabilizing the bicycle. N. Getz presented the nonlinear dynamic model with steering and forward velocity input [5], [6], [7], [8]. His model was derived by constrained Lagrangian method and improved in [9] with additional issue of non-zero front fork angle. M. Defoort [10] applied sliding-mode control scheme to Getz's model. Other works in [11], [12], [13] neglected the front fork angle. Franke *et al.* derived the equation of motion by Newton's formulation [14]. In 2005, Åström [15] released a good summary of bicycle dynamic and control and also the simple linearized second-order model with derivation. One year later, Limebeer and Sharp [16] wrote the more exhaustive models for bicycles and motorcycles including inside analysis of pneumatic tire deflation, flexible frame, etc. A series of paper from Guo showed the different types of control method to this kind of model; nonlinear stabilization [17], LQR [18], fuzzy sliding-mode [19], DFL nonlinear control [20]. Moreover, it was proved that the bicycle with a positive front-fork can be self-stabilized at a specific interval of speed where the real part of eigenvalues were investigated to stay in the left-half plane [4], [21].

The bicycle robot with balancer control was presented in [22] and also balancer together with steering control [23], [24] to enlarge the region of stability. This type of model is not widely investigated as well as the gyroscopic stabilization [2], [25], [26], [27], [28]. Parnichkun (2008) [25] applied the particle-swarm optimization to the proposed model from Gallaspy (1999) [27]. This model captures the bicycle dynamics at the zero forward velocity. The model in [28] incorporated the forward moving velocity but lacked of simulation to verify the model validation. The recent gyroscopic stabilization from [2] is more reliable since it is presented with the clear derivation and model validation by both simulation and real hardware implementation. It included the forward moving velocity and rotating velocity, and left the higher-level study in control part for further development.

The guideline for bicycle project and hardware design can be found in Michini (2006) [29] and a very completed instructive hardware project report "Experimental Validation of a Model for the Motion of an Uncontrolled Bicycle" by Kooijman (2006) [30].

The Piecewise Affine Control or sometimes called Piecewise Linear Control are presented as a kind of hybrid system and the model is varied according to the region which the state is staying. The circuit theory community was said to be the first who recognized PWA systems as an interesting system class [3]. At the beginning, the research on PWA systems considered the model representation [31], [32], especially on the electric network [33]. Model approximation of Nonlinear system by linear model in each region is still be an interesting problem as well. This problem tends to be more complicated when the number of partitioned states is increasing and also more constraints are added to made the smooth continuity at the boundary. The research on PWA model approximation can be found in [34], [35], [36]. To guarantee the stability of the PWA systems, the studies on finding the Quadratic Lyapunov function were proposed by Hassibi and Boyd [37]. This stability problem was also covered the hybrid system and solved via LMIs approach [38]. The PWA optimal control can be found in [39]. The summarize of Piecewise Linear Control was done by Johansson [3]. Besides, one interesting branch of research on PWA is PWA Identification which can be found in [40], [41], [42].

The applications of PWA control are continue to release: Anti-Wind up controller [43], PWA control of a boiler-turbine unit [44], MPC [45], etc. There is not much papers published about PWA applying with vehicle dynamics control application. However, we have found some application to a vehicle yaw control in [46], [47].

This thesis mainly follows the PWA system theory presented extensively in [3].

1.3 Thesis Objective

The main objective of this research is to design a piecewise affine controller based on piecewise quadratic stability criteria for the autonomous bicycle with gyroscopic flywheel stabilization and to build a start-up prototype bicycle for the future implementation work on the bicycle robot. We first obtain the bicycle dynamics model from the previous work and then approximate the nonlinear model into the form of a piecewise affine model. The controller based on a global piecewise quadratic Lyapunov function is derived by solving the semidefinite programming problem.

1.4 Scope of Thesis

1. To derive Piecewise affine bicycle with gyroscopic flywheel model

2. To design the feedback controller based on the Piecewise Quadratic criteria

3. To build a physical prototype of the bicycle robot for retrieving the practical bicycle parameters and for a future research

1.5 Methodology

1. Literature review on Bicycle model and PWA systems.
2. Select an autonomous bicycle robot model with gyroscopic stabilization.
3. Do parameter measurement from the real bicycle.
4. Derive the PWA model from the selected nonlinear dynamics bicycle model.
5. Design the Piecewise Quadratic controller for PWA bicycle model.

1.6 Contributions

1. A Piecewise Affine bicycle with gyroscopic flywheel model.
2. A Piecewise Affine controller for bicycle with gyroscopic flywheel.
3. A start-up prototype of experimental bicycle with gyroscopic flywheel.

1.7 Structure of Thesis

The organization of the thesis is as follows. In the next chapter, the related theories, which are the primary knowledge and some are considered to be in bicycle robot environment, are presented. Chapter 3 presents Experimental Bicycle. Chapter 4 presents the bicycle dynamic model. Chapter 5 presents PWA model for the bicycle robot. Chapter 6 presents piecewise affine control for bicycle robot. In the last chapter, conclusions are given.