MODELING AND CONTROL OF DUAL MOTOR BALL & BEAM SYSTEM

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To my beloved mother, father and family

谨此献给我所爱的父母，家人

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ABSTRACT

Ball and beam balancer system is very popular and widely used in control system engineering due to its simple modeling and easy understanding. The conventional ball and beam balancer system is with a single motor (SMBB) and recently a new variant of ball and beam balancer system with dual motors (DMBB) has come up. The purpose of DMBB is similar to SMBB, which is to control the position of the ball on the beam. Compared with SMBB, DMBB use two motors to work together in order to achieve a satisfied control of the ball position. Before the controller design, the mathematical model of the system needs to be derived. PD controller and lead compensator are designed to perform the simulation with MATLAB/Simulink. Two DC motors integrated with reduction gearbox is used as the actuator in the prototype design and two incremental encoders work to form the motor feedbacks. Interfaced with the computer through DAQ card, the designed prototype is verified by LabVIEW. This prototype can be used to test certain control strategies that SMBB cannot.

ABSTRAK

Sistem bola dan pelantar seimbang sangat popular dan sering digunakan dalam kejuruteraan sistem kawalan kerana rekabentuknya yang mudah. Konvensional sistem bola dan pelantar seimbang adalah motor tunggal (SMBB) dan baru-baru ini, sistem bola dan pelantar seimbang dengan dua motor (DMBB) telah dibentuk. Tujuan DMBB lebih kurang sama dengan SMBB, iaitu untuk mengawal kedudukan bola di atas pelantar. Berbanding dengan SMBB, DMBB mengguna dua motor untuk mengimbang kedudukan bola dan mencapai kawalan yang memuaskan. Sebelum pengawal direka, model matematik sistem harus diperoleh terlebih dahulu. Kawalan PD dan kompensator direka untuk menjalankan simulasi dengan MATLAB/Simulink. Dua DC motor integrasi dengan gearbox sebagai penggerak dalam rekabentuk prototaip dan dua pengekod tambahan dijalankan untuk membentuk tindakbalas motor. Rekabentuk prototaip disahkan melalui LabVIEW dan hubung kait prototaip dengan komputer adalah melalui kad DAQ. Prototaip ini boleh digunakan untuk menguji strategi kawalan tertentu yang SMBB tidak boleh laksanakan.

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LIST OF ABBREVIATIONS

SMBB	-	Single Motor Ball & Beam Balancer System
DMBB	-	Dual Motor Ball & Beam Balancer System
DC	-	Direct Current
PC	-	Personal Computer
SISO	-	Single Input, Single Output
MIMO	-	Multiple Input, Multiple Output
P	-	Proportional
PD	-	Proportional-Derivative
PID	-	Proportional-Integral-Derivative
LQR	-	Linear Quadratic Regulator
MATLAB	-	Matrix Laboratory
LabVIEW	-	Laboratory Virtual Instrumentation Engineering Workbench
KVL	-	Kirchhoff's Voltage Law
EMF	-	Electromotive Force
PM	-	Phase Margin
GM	-	Gain Margin
DIY	-	Do It Yourself
IC	-	Integrated Circuit
CMOS	-	Complementary Metal Oxide Semiconductor
DMOS	-	Double Diffused MOSFET
PWM	-	Pulse Width Modulation
Ch	-	Channel

Ref	-	Reference
CCP	-	Capture/Compare/PWM
ECCP	-	Enhanced CCP
A/D	-	Analog to Digital
DAQ	-	Data Acquisition
AO	-	Analog Output
AI	-	Analog Input
DO	-	Digital Output
DI	-	Digital Input
DAS	-	Data Acquisition System
PCI	-	Peripheral Component Interconnect
SCSI	-	Small Computer System Interface
CD	-	Compact Disc
DLL	-	Dynamic Link Library
VI	-	Virtual Instrument
MOT	-	Motor

LIST OF SYMBOLS

U_i	-	Input voltage to DC motor
R_a	-	Armature resistance of DC motor
L_a	-	Armature inductance of DC motor
U_a	-	Armature voltage of DC motor
i_a	-	Armature current of DC motor
K_t	-	Torque constant of DC motor
K_b	-	Back EMF constant of DC motor
τ_m	-	Torque at the motor shaft
τ_l	-	Torque from load
K_g	-	Gear ratio of reduction gearbox
J_m	-	Effective moment of inertia
D_m	-	Viscous friction coefficient
$\dot{\theta}_i$	-	Motor shaft angle speed output
$\ddot{\theta}_i$	-	Motor shaft angle acceleration
K_m	-	Gain constant of DC motor model
T_m	-	Time constant of DC motor model
F_B	-	Force on ball
m	-	Mass of the ball
r	-	Distance of the ball on the beam
g	-	Acceleration of gravity
β	-	Beam's tilt angle from the horizontal position
F_f	-	Friction force

γ	-	Rotational angle of the ball
R	-	Radius of the ball
R_r	-	Rotational radius of the ball
τ_B	-	Torque on the ball
J_B	-	Inertia of the ball
$\ddot{\gamma}$	-	Angular acceleration of the ball
θ_1	-	Rotary angle of motor1
θ_2	-	Rotary angle of motor2
θ_{g1}	-	Rotary angle of motor1 gear shaft
θ_{g2}	-	Rotary angle of motor2 gear shaft
θ	-	Sum of the rotary angle of motor1 and motor2
L	-	length of the beam
l	-	Length of the arm
K_c	-	Gain constant of ball beam model refer to the tilt angle of beam
G_M	-	Transfer function of DC motor integrated with gearbox
G_B	-	Transfer function of the ball position refer to gear shaft output
K'_m	-	New gain constant of DC motor after reduction.
K'_c	-	New Gain constant of ball beam model refer to the gearbox shaft angle
G_{MV}	-	DC motor speed transfer function
u	-	Output of PID controller
e	-	Error signal
K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
G_{pid}	-	Transfer function of PID controller
T_i	-	Integral time constant
T_d	-	Derivative time constant
G_{MC}	-	Transfer function of motor controller

G_{MO}	-	Open loop transfer function for DC motor
G_{lead}	-	Transfer function of lead compensator
K	-	Gain constant of lead compensator
z	-	Zero of lead compensator
p	-	Pole of lead compensator
α	-	The specific value of p and z
$\phi_\alpha(PM_{added})$	-	Necessary additional phase is required to give the desired phase margin
G_{inner}	-	The inner loop transfer function
$PM_{desired}$	-	Desired phase margin
PM_{makeup}	-	Makeup value of the phase margin
$OS\%$	-	Overshoot
T_s	-	Settling time
C_{max}	-	Peak value
C_{final}	-	Final value
V_{out}	-	Output voltage from position sensor
V_{in}	-	Voltage applied to position sensor
f_{PWM}	-	Frequency of the PWM feedback signal from encoder
n	-	Rotary speed of the code disk
$R_{encoder}$	-	Resolution of encoder

CHAPTER 1

INTRODUCTION

1.1 Background

The ball and beam balancer system is a typical control system. It is also called 'balancing a ball on a beam'. This system can usually be found in most university control labs. With the associated control design, it is an excellent platform for testing and evaluating different control techniques (Rosales, R. A. 2004).

It is related to real control problems such as horizontally stabilizing an airplane during landing or in turbulent airflow. The fundamental principles within this control system can also be found in many industrial applications, such as precise position control in production line (Wei Wang 2006).

The ball and beam balancer system has been built previously by many organizations. Normally the system is with a single motor, also can be named as single motor ball & beam system (SMBB). This application has been studied for years and methods of control techniques have been discussed in many literatures. There are two different basic models of SMBB dependent on the position of the motor used to regular the beam position. For the first kind, the motor was amounted in the middle of the beam; for the second kind, the motor was amounted in one of the end of the beam.

Recent years, a new variant of this system has come up: system with dual motors, dual motors ball & beam system (DMBB). This topic first appeared in Aalborg University Esbjerg (2005). They have built the first DMBB prototype. DMBB is a ball-beam system regulated by dual motors. In contrast to the SMBB, each end of the beam in DMBB is driven by a motor. The two motors cooperatively work to regular the beam angular which can control the ball position.

Figure 1.1 Designed DMBB Prototype

As shown in Figure 1.1, each end of the beam hangs from a level beam. The level beam hangs from an arm. The arm is fixed with the shaft of the planetary gear. Each planetary gear is amounted on the shaft of each of the two DC motors.

Such a setup can serve as a learning stage, for example, for the more difficult dual-manipulator cooperative control task (Hisashi Osumi ans Tamio Arai 1994), and for the more general multi-agent cooperative control (Daniel Cruz, James Mcclintock 2007).

1.2 Statement of the Problem

Same as SMBB, the aim of DMBB is to control the position of the ball to a desired reference point. The control signal can be derived by feeding back the position information of the ball. The angle signal from compensator goes to the two DC motor controllers then generate voltage signal to go to the DC motors. At last the torques generated from the two motors cooperatively drive the beam to rotate to the desired angle. Thus, the ball can be located at the desired position. In contrast to the SMBB, the difference is the two motors need to work cooperatively to achieve the aim.

It is important to point out that the open loop of the system is unstable and nonlinear. The problem of 'instability' can be overcome by closing the open loop with a feedback controller. The nonlinear property is not significant when the beam only deflects a small angle from the horizontal position. In this case, it is possible to liberalize the system. However, the non-linearity becomes significant when the angle of the beam from the horizontal is larger than 30 degrees, or smaller than -30 degrees. In this case, a simple linear approximation is not accurate.

1.3 Objectives of the Project

The major job of the project is to model DMBB and design controller for the DMBB model. Then build the prototype and verify it. Specifically, the aims are listed in the following:

- To derive the mathematical model of DMBB and build a simulation model for this system.
- To design controller for the DMBB model and see the simulation results.
- To design the prototype of the DMBB.

1.4 Scope of project

Two DC motors of the DMBB system will control the ball position. It's a cooperative problem between both DC motors. In this project, the cooperative control is without information exchange between the two motors and is accomplished through predefined workload sharing.

Some assumptions are made when deriving the mathematic model of the DMBB. And linear model is used. PD controller and lead compensator are used to apply control to the DMBB model in simulation.

The DMBB prototype is built in this project and interfaced with PC by PCI-1711 from Advantech.

1.5 Research Methodology

1. Literature review to understand the concept of a ball and beam balancer system is conducted.

2. Search out previous and current projects of a ball and beam balancer system and get ideas for designing the DMBB.

3. Derive mathematical model for DMBB and define mathematical model of the controllers.

4. Perform simulation using MATLAB/SIMULINK.

5. Design the prototype and test it with labVIEW program.

6. Future work to test different kinds of control strategies.

All the methodology above can be summarized as shown Figure 1.2.

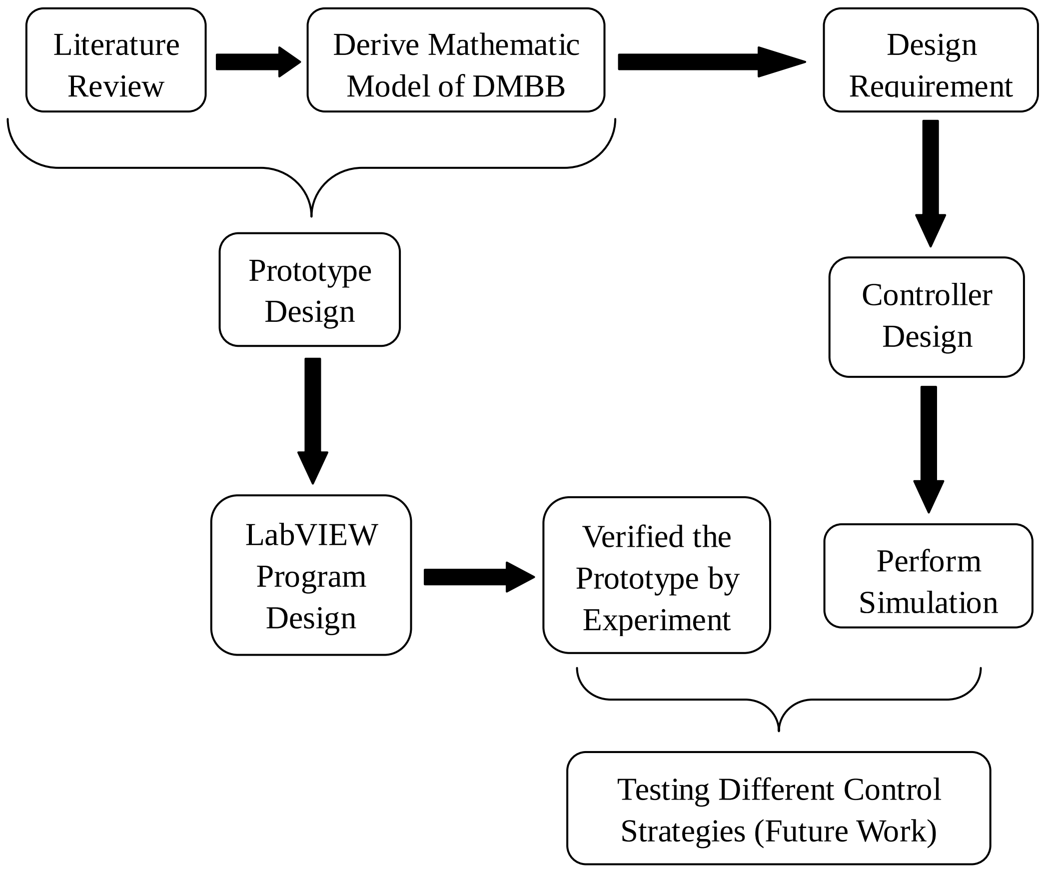

Figure 1.2 Flow Chart of Research Methodology

1.6 Thesis Outline

This project consists of six chapters including this chapter. The scope of each chapter is explained as stated below:

Chapter 1

This chapter gives an introduction to the project report, objectives, problem statement, scope of work and methodology adopted.

Chapter 2

This chapter discusses the previous design of ball and beam system and also the concept of synchronization and cooperative control.

Chapter 3

This chapter gives the analysis and modeling of the DMBB. With the designed controller, simulation is performed.

Chapter 4

This chapter presents the design of DMBB prototype including the mechanical parts and the electrical parts. The key components to construct the prototype are given here.

Chapter 5

This chapter the connections between PC and prototype are given. And also the designed DMBB prototype is verified by developing a program with LabVIEW.

Chapter 6

This last chapter presents the overall discussion and conclusion of this project. Some recommendations and suggestions have been included for future works.

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