



Universiti Teknikal Malaysia Melaka

Fakulti Kejuruteraan Elektrik

**FINAL YEAR PROJECT REPORT**

**TITLE: MODELING AND PSO-BASED LQR CONTROLLER DESIGN  
FOR COUPLED TANK SYSTEM**

**FIONA SERINA DAUD**

**B011110074**

**BACHELOR OF ELECTRICAL ENGINEERING**

**(Control, Instrumentation and Automation)**

“I hereby declare that I have read through this report entitle “Modeling and PSO-based LQR Controller Design for Coupled Tank System” and found out that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation)”

Signature : .....

Supervisor's Name : .....

Date : .....

**MODELING AND PSO-BASED LQR CONTROLLER DESIGN FOR  
COUPLED TANK SYSTEM**

**FIONA SERINA DAUD**

**A report submitted in partial fulfillment of the requirements for the degree of  
Bachelor of Electrical Engineering (Control, Instrumentation and Automation)**

**Faculty of Electrical Engineering  
UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2014**

I declare that this report entitle “*Modeling and PSO-based LQR Controller Design for Coupled Tank System*” is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : .....

Name : .....

Date : .....

To my beloved father and mother

## ACKNOWLEDGEMENT

A major research project like this is never the work of anyone alone. The contributions of many different people, in their different ways, have made this possible. I would like to extend my appreciation especially to the following.

I would like to express my sincere gratitude to my supervisor Miss Nur Asmiza Binti Selamat for the continuous support on my final year project research, for her patience, motivation, enthusiasm, and immense knowledge. Her guidance helped me in all the time of research and completing this project. I could not have imagined having a better supervisor, mentor and guidance in completion of my final year project in Universiti Teknikal Malaysia Melaka.

Besides my supervisor, I would like to thank all the lecturers that helped me throughout the completion of the project and always willing to share and gives their best suggestions. Without their support and guidance, this project will not complete as what I wanted.

Moreover, I would like to express my gratitude to all my fellow friends who always there cheering me up and stood by me through the good and bad times. Completing this project would not have been possible without their helps and support.

Finally, I would like to thank my parents, three elder brothers and sister. They were always supporting me and encouraging me with their best wishes. My research would not have been possible without their encouragement and helps.

## ABSTRACT

Industrial application for liquid level and flow control is used tremendously in a process control industries such as the water treatment industries, paper making industries and petrochemical industries. Level and flow control is important to ensure the quality and performance of the system can be maintained. This project is related on how to control the water level in the coupled-tank while both tanks is still regulating. It can be classified as Single-Input Single-Output (SISO) system as the process of this system only control one output using one input. Mathematical model can be obtained based on the experimental data collected from the coupled-tank system. The data will be loaded in a process called system identification where the mathematical representation or transfer function of the system can be determined. The validity of the transfer function will be verified before proceeds to controller design. Controller is used as a tool to improve the stability and performance of the transient response of the system. Hence, for this project LQR controller was selected as the controller to control and improve the transient response of the system. The LQR parameter is obtained using the optimization technique called Particle Swarm Optimization (PSO). To validate the result, system performance using LQR controller will be compared with PID controller.

## ABSTRAK

Penggunaan industri berkaitan dengan paras cecair dan kawalan aliran adalah amat diperlukan terutamanya dalam industri kawalan proses seperti industri rawatan air, industri membuat kertas dan industri petro-kimia. Pengawalan paras air dan kawalan aliran adalah penting untuk memastikan kualiti dan prestasi sesuatu sistem dapat dikekalkan. Projek ini berkaitan tentang bagaimana untuk mengawal paras air dalam tangki walaupun pengaliran air untuk tangki berkembar ini masih berjalan. Ia boleh diklasifikasikan sebagai sistem satu masukan satu keluaran (SISO) dimana ia hanya mengawal proses yang mempunyai satu keluaran menggunakan satu masukan. Model matematik boleh diperolehi berdasarkan data yang dikumpul daripada pelaksanaan eksperimen terhadap sistem tersebut. Data ini akan dimuatkan di dalam proses yang dipanggil pengenalan sistem di mana perwakilan matematik atau fungsi pindah sistem tersebut boleh ditentukan. Kesahihan fungsi pemindahan akan diperiksa sebelum beralih ke langkah seterusnya yang merupakan reka bentuk pengawal. Pengawal digunakan sebagai alat untuk meningkatkan kestabilan dan prestasi sesebuah sistem. LQR pengawal dipilih untuk mengawal dan meningkatkan prestasi sistem tersebut. Parameter LQR akan diperolehi dengan menggunakan teknik pengoptimuman yang dipanggil PSO. Untuk mensahihkan prestasi sistem, LQR pengawal akan dibandingkan dengan prestasi sistem daripada pengawal PID.



## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	iii
	<b>DEDICATION</b>	iv
	<b>ACKNOWLEDGEMENT</b>	v
	<b>ABSTRACT</b>	vi
	<b>ABSTRAK</b>	vii
	<b>TABLE OF CONTENTS</b>	viii
	<b>LIST OF TABLES</b>	xi
	<b>LIST OF FIGURES</b>	xii
	<b>LIST OF APPENDICES</b>	xiii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of Study	1
	1.2 Problem Statement	2
	1.3 Objectives	3
	1.4 Project Scopes	3
	1.5 Project Outline	4
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>6</b>
	2.1 Overview	6
	2.2 Control Principle of Coupled Tank System	7
	2.3 Mathematical Model	9

2.3.1	First-Order Single-Input Single-Output Plant	13
2.3.2	Second-Order Single-Input Single-Output Plant	14
2.4	System Identification	16
2.5	Linear Quadratic Regulator (LQR)	17
2.5.1	Performance of LQR Controller	17
2.6	Types of Controller	19
2.6.1	Proportional Integral Derivative Controller (PID)	19
2.6.2	Fuzzy Logic Controller (FLC)	20
2.6.3	Sliding Mode Controller (SMV)	21
2.6.4	Direct Model Reference Adaptive Control (DMRAC)	21
2.7	Optimization Technique	25
2.8	Summary of review	26
<b>3</b>	<b>METHODOLOGY</b>	<b>27</b>
3.1	Overview	27
3.2	Project Flow Chart	28
3.3	Integrate Hardware and Software	29
3.3.1	Coupled Tank Model (Operation)	30
3.3.2	Calibration of Coupled Tank	31
3.4	Modeling of Coupled Tank	35
3.4.1	Pseudorandom Binary Sequence (PRBS)	35
3.4.1.1	PRBS stages	37
3.4.2	System Identification	39
3.5	Design LQR and PID Controller	45
3.5.1	LQR Controller	45
3.5.2	PID Controller	48
3.6	Particle Swarm Optimization (PSO) technique	50
<b>4</b>	<b>RESULT AND DISCUSSION</b>	<b>55</b>
4.1	Overview	55
4.2	Transfer function verification	56

4.3	Characteristic of system	57
4.4	Selection of PSO parameter	59
4.4.1	Number of particles	59
4.4.2	Number of iteration	61
4.5	PSO for LQR and PID	62
4.5.1	Statistical estimation from ITSE	66
4.5.2	ITSE for LQR and PID	66
4.6	Parameter for PID and LQR	68
4.7	Comparison between LQR and PID	69
4.8	Robustness of LQR and	71
4.8.1	ITSE for LQR and PID (with disturbance) PID using PSO	71
4.8.2	Parameter for PID and LQR (with disturbance)	73
4.9	Comparison between LQR and PID (with disturbance)	74
<b>5</b>	<b>CONCLUSION AND FUTURE WORKS</b>	<b>77</b>
5.1	Overview	78
5.2	Conclusion	79
5.2	Recommendation for future works	80
	<b>REFERENCES</b>	<b>81</b>
	<b>APPENDICES</b>	<b>84</b>

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	SISO steady state condition for coupled-tank system	8
2.2	Comparison of coupled tank water level control method	22
2.3	Types of optimization technique	25
3.1	PRBS input table	37
3.2	Set value of initialization in PSO	52
4.1	Transient response for open loop system	58
4.2	Transient response for closed loop system	59
4.3	ITSE value when number of particles increases	60
4.4	Stopping criteria characteristics	61
4.5	LQR data with 20 times execution using PSO at 2 <sup>nd</sup> simulation	64
4.6	PID data with 20 times execution using PSO at 9 <sup>nd</sup> simulation	65
4.7	Comparison of statistical estimation	66
4.8	Parameter value for PID and LQR	68
4.9	Comparison between LQR and PID	70
4.10	Parameter value for PID and LQR (with disturbance)	73

4.11	Comparison between LQR and PID (with disturbance)	75
------	---	----

## LIST OF FIGURES

<b>FIGURE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Schematic diagram for CTS-001 coupled tank	7
2.2	Diagram of the coupled tank control apparatus	9
2.3	Block diagram of 2 <sup>nd</sup> order process	15
3.1	Flow chart for project development	28
3.2	Coupled tank control apparatus model CTS-001	30
3.3	The relationship between the water level and the corresponding voltage in Tank A	33
3.4	The relationship between the water level and the corresponding voltage in Tank B	33
3.5	The relationship between the pump voltage and the corresponding voltage in Tank A	34
3.6	The relationship between the pump voltage and the corresponding voltage in Tank B	34
3.7	General form of PRBS waveform	36
3.8	Shift register for generation of PRBS	36
3.9	Data obtained from CAIRO CTS001	38
3.10	Input and Output used for system identification method	38

3.11	Flow chart of System Identification	40
3.12	Import 1 <sup>st</sup> data from workspace	41
3.13	Import 2 <sup>nd</sup> data from workspace	42
3.14	Save data for Working Data and Validation Data	42
3.15	Select estimation as transfer function models	43
3.16	Best fit percentage and transfer function obtained	44
3.17	Schematic diagram for LQR	45
3.18	Schematic diagram for PID	49
4.1	Best fit percentage	56
4.2	Transfer function obtained	56
4.3	Open loop step response	57
4.4	Closed loop step response	58
4.5	Graph of ITSE versus number of particles	60
4.6	Graph of ITSE versus number of simulation for LQR	62
4.7	Graph of ITSE versus number of simulation for PID	63
4.8	Graph of ITSE versus iteration for LQR	67
4.9	Graph of ITSE versus iteration for PID	67
4.10	Responses for LQR and PID controller	69
4.11	Performance comparison between LQR and PID controller	70
4.12	Graph of ITSE versus number of simulation for LQR (with disturbance)	72
4.13	Graph of ITSE versus number of simulation for PID (with disturbance)	72
4.14	Responses for LQR and PID controller	74

	(with disturbance)	
4.15	Performance comparison between LQR and PID controller (with disturbance)	75

\



**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	LQR parameter data	84
B	PID parameter data	90
C	Gantt Chart	96
D	Turnitin Report	97

## CHAPTER 1

### INTRODUCTION

#### 1.1 Background of Study

Coupled tank system plays important role in industrial application such as in petrochemical industries, paper making industries, medical industries and water treatment industries. The coupled tank system consists of two vertical tanks which are joined together with an orifice and has an inlet liquid pumps and outlet valves. Each tank has its own inlet pump and output valve where the valve will regulate continuously. The coupled tank system can be configured as a Single-Input Single-Output (SISO) or as a Multiple-Input Multiple-Output (MIMO) system via manipulation of pumps input and sectional area of rotary valves. In industries, the liquid in the tank will go through several processes or mixing treatment whereby the level of liquid needs to be controlled and maintained. The flow between tanks must be continuously regulated. The basic control principle of the coupled tank system is to maintain the level of liquid in the tank when there is a process of inflow of liquid into the tank and output of liquid out of the tank.

## 1.2 Problem Statement

There are differences between real-time control and simulation control. Real-time is related to the surrounding where all of the parameters and condition need to be considered whereas simulation is an imitation of the operation of real process. All of the parameters can be controlled by human. To study the performance of the real-time implementation in a system, the coupled-tank system is chosen. In industries, there are problems faced related to the level of liquid in tank and the flow between the tanks. Most of the time, liquid level in the tanks needs to be controlled while regulating the flow in the tank. Common controller used to control the system is PID controller and Fuzzy Logic Control (FLC) controller. However in several cases, the conventional PID controller is not suitable for a controlled object with variable parameter or when there is existence of external disturbances in the system. One of the solutions to achieve high performance of the system is to apply state feedback controller to the system. There are several controllers that have been applied to control the system of the coupled tank. In this project, Linear Quadratic Regulator (LQR) controller will be selected as the state feedback controller for the system. The LQR controller approach will be tested to verify the improvement related to the performance of the system.

### 1.3 Objectives

The aim of this project is to obtain the modeling and controller design for coupled tank system. The main objectives of this project are:

- 1) To obtain transfer function of the coupled tank using system identification method
- 2) To implement LQR controller on coupled tank system and obtain its parameter using particle swarm optimization (PSO) technique
- 3) To compare the system performance of LQR and PID controller

### 1.4 Project Scopes

There are limitations to the completion of this project. The scopes of the project only cover:

- 1) Interface the coupled tank CTS-001 with DAQ card and use personal computer to stimulate data using software MATLAB
- 2) The experimental of coupled tank process is using single-input single-output (SISO) control system
- 3) System Identification used to generate the transfer function of the coupled tank
- 4) The parameter of LQR controller and PID controller will be determined using PSO optimization technique.

## **1.5 Project outlines**

This report basically divided into five chapters:

### **CHAPTER 1 Introduction**

This chapter allows the readers to visualize the basic aspects of the research done, such as the overview of the coupled tank system, problem statements, objectives and scopes of the project.

### **CHAPTER 2 Literature Review**

This chapter reviews on the basic modeling for a coupled tank, previous controller used for the coupled tank system, several types of optimization techniques use for the system and other reviews that related to this project.

### **CHAPTER 3 Design Methodology**

This chapter consists of the flow related to the study and methodology used for this project. The control principle for coupled tank system, modeling of the coupled tank and the design technique for PSO-based LQR controller will be explained in this chapter. The implementation of system identification to obtain the transfer function will also be included in this chapter.

## **CHAPTER 4 Result and Discussion**

This chapter shows the characteristic of the system, the fitness function of each controller and the result of the transient response performance using the LQR and PID controller to the system.

## **CHAPTER 5 Conclusion & Future Works**

This chapter consists of the conclusion based on the overall works and results. It also includes some future improvement that can be done in the system.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Overview

This chapter will review on research which focuses on mathematical model, LQR controller, previous controller used for coupled tank, system identification and optimization method used for the system. Coupled tank system is common in process industries as it need to be pumped from one tank to another. Somehow, the liquid needs to be monitored and the flow and level of liquid need to be controlled although the tank need to be continuously regulated. There are many types of controller use to control the coupled tank system such as the LQR, PID, Fuzzy Logic and Slide Control. The controllers have similar objective which are to improve the system performance. System identification is a tool that produces a transfer function from data collected in the coupled tank. From the transfer function obtained using the system identification, the optimization method is applied to find the best value for Q and R matrix in easier way compared to the trial and error method.

## 2.2 Control Principle of Coupled Tank System

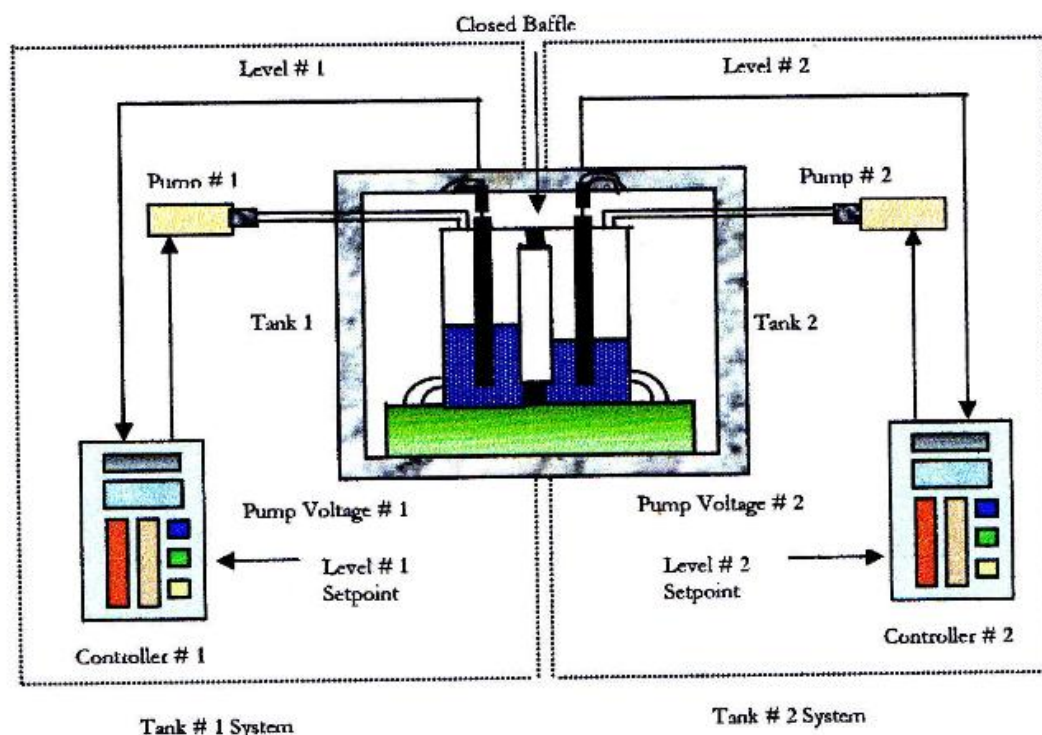


Figure 2.1: Schematic diagram for CTS-001 coupled tank [1]

Figure 2.1 shows the schematic diagram for CTS-001 coupled tank. The basic control principle of the coupled tank system is to maintain the water level in both tanks at a desired point value while the inflow and outflow of water tank keep regulating. Disturbance may be caused by variation in the rate flow from the baffle gap or the changes in the outlet of the tank. When disturbances occur, the water level in the tank will change and settle at a different steady-state level [1].

The control variable involve in the process control of this system is the water level in the coupled tank system. In order to control and maintain the water level at a desired point, the inlet flow rate needs to be adjusted. The pump voltage will become the device to adjust the inlet flow rate. The manipulated variable for this system is the input flow rate because it is the variable needs to maintain the process variable at the desired point.