



**UNIVERSITI PUTRA MALAYSIA**

**A VARIABLE RATE PULSED WIDTH MODULATED NOZZLE VALVES  
ALGORITHM FOR A BOOM SPRAYER SYSTEM**

**ALI RAFIEISHAHEMABADI**

**FK 2008 31**



**A VARIABLE RATE PULSED WIDTH  
MODULATED NOZZLE VALVES ALGORITHM  
FOR A BOOM SPRAYER SYSTEM**

**ALI RAFIEISHAHEMABADI**

**MASTER OF SCIENCE  
UNIVERSITI PUTRA MALAYSIA**

**2008**



**A VARIABLE RATE PULSED WIDTH MODULATED NOZZLE VALVES  
ALGORITHM FOR A BOOM SPRAYER SYSTEM**

**By**

**ALI RAFIEISHAHEMABADI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in  
Fulfilment of the Requirements for the Degree of Master**

**April 2008**



**This thesis is dedicated to the author's beloved wife, Seyedeh Zahra Seyed  
Abrishami, and my parents who are always in the author's mind**



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

**A VARIABLE RATE PULSED WIDTH MODULATED NOZZLE VALVES  
ALGORITHM FOR A BOOM SPRAYER SYSTEM**

By

**ALI RAFIEISHAHEMABADI**

**April 2008**

**Chairman: Samsul Bahari bin Mohd Noor, PhD**

**Faculty: Engineering**

Agricultural sprayers are used for applying pesticides, fertilizer and other chemicals in the field. A control algorithm to precisely vary the application rate of fertilizer across the fields using low cost components is desired.

A variable rate sprayer control system was developed using a combination of boom flow rate variation and pulse width modulation of solenoid nozzle valves. The combination makes it possible for variable rate broadcast application of chemicals and/or variable rate application over the length of the boom. Matlab 7.1 was used to simulate the performance of the combination. To specify dynamic characteristics of the sprayer components, the sprayer was assembled and its components were calibrated. The given characteristics were used in simulation program. Process identification technique was used to estimate response time of the sprayer flow rate changes to control signals. A look ahead strategy was used for navigation system to minimize misapplication along the direction of travel from a simulated preloaded geographical information map with positioning constantly updated and corrected for variation in forward velocity. This



strategy was verified by simulation program used sample GIS data and assumed AGPS coordinates. Misapplication over the width of the boom is minimized by precomputing the pulse width modulation algorithm to use on the nozzle valve when variation in application rate along the boom is desired. The simulation used a 1 second cycle to change control parameters thus effectively minimizing misapplication. The pulse width modulation algorithm was modified to pulse width activation algorithm to compensate for errors due to fall and rise time of non expensive normally closed solenoid shut off valve.

The experiments estimate average dead time and time constant of 0.1095 and 0.4225 for the sprayer. A flow control range of 34:1 was achieved by the given control algorithm. The average estimated flow rate error in manifold for two different random desired application rate data and each four different random range were 1.356% and 1.211% for constant velocity and 2.651% if the velocity changes within a limited range. The simulated results showed that the pulse width activation algorithm reduces average error of non expensive normally closed solenoid shut off valve with opening and closing time of 20 ms and 30 ms to 2.555% for constant velocity and 3.084% if the velocity changes within a limited range compared to ideal expensive shut off valve with response time of zero.



Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master

**ALGORITMA BAGI INJAP KADAR BERUBAH MODULASI LEBAR  
DENYUTAN BAGI SISTEM BOOM PENYEMBUR**

Oleh

**ALI RAFIEISHAHEMABADI**

**April 2008**

**Pengerusi: Samsul Bahari bin Mohd Noor, PhD**

**Fakulti: Kejuruteraan**

Penyembur pertanian digunakan untuk aplikasi racun makhluk perosak, baja dan bahan-bahan kimia lain di dalam ladang. Sebuah algoritma kawalan untuk mengubahsuai kadar aplikasi baja dalam ladang dengan jitu menggunakan komponen yang berkos rendah diperlukan.

Sebuah sistem kawalan penyemburan berkadar ubah telah dimajukan, menggunakan kombinasi perubahan kadar aliran pada boom, dan juga dengan menggunakan modulasi lebar denyutan pada injap solenoid yang dipasang pada nozel. Kombinasi ini membolehkan aplikasi kimia pertanian dengan tebaran kadar berubah dan/atau aplikasi kadar berubah bagi keseluruhan panjang boom. Matlab 7.1 telah digunakan untuk simulasi pencapaian sistem kombinasi tersebut. Untuk menentukan pencirian dinamik komponen-komponen penyembur, penyembur tersebut telah dipasang dan komponennya telah dikalibrasi. Pencirian tersebut telah digunakan di dalam pengaturcaraan simulasi tersebut. Teknik pengenalpastian proses telah digunakan untuk menganggar waktu tindakbalas perubahan kadar aliran penyembur terhadap perubahan isyarat kawalan.



Strategi pandang depan telah digunakan untuk sistem navigasi bagi meminimalkan ralat aplikasi sepanjang arah pergerakan traktor penyembur, menggunakan kadar yang ditentukan sebuah peta GIS yang disimulasi, di mana kedudukan sentiasa dikemaskini dan diperbetulkan bagi variasi dalam halaju. Strategi ini telah disahkan secara simulasi dengan menggunakan data GIS yang telah disampel, dan koordinat AGPS yang telah diandaikan. Ralat aplikasi sepanjang boom diminimakan dengan lebih awal algoritma modulasi lebar denyutan untuk digunakan pada injap nozel apabila variasi dalam aplikasi sepanjang boom diingini. Simulasi tersebut menggunakan kitar masa 1 saat untuk untuk mengubah parameter- parameter kawalan bagi meminimakan ralat aplikasi. Algoritma modulasi lebar denyut telah diubahsuai kepada modulasi lebar denyutan aktivasi untuk mengurangkan ralat daripada waktu naik dan turun bagi injap solenoid biasanya tertutup yang berkos rendah.

Ujikaji mendapati nilai anggaran purata masa mati dan masa malar sebanyak 0.1095 dan 0.4225 bagi sistem penyembur tersebut. Julat nisbah kawalan aliran sebanyak 34:1 telah dicapai menggunakan algoritma tersebut. Anggaran ralat purata kadar aliran dalam perecik bagi dua data kadar aplikasi pilihan rawak dan empat julat rawak adalah 1.356% dan 1.211% bagi halaju malar, dan 2.651% jika halaju berubah dalam julat yang kecil. Hasil dari simulasi menunjukkan bahawa algoritma aktivasi lebar denyut ini mengurangkan ralat purata bagi injap solenoid biasanya tertutup berkos rendah dengan waktu bukaan dan tutupan sebanyak 20ms dan 30 ms kepada 2.555% bagi halaju malar dan 3.084% jika halaju berubah dalam julat yang kecil, berbanding dengan injap ideal berkos tinggi dengan waktu tindakbalas sifar.



## ACKNOWLEDGEMENTS

Praise be to Allah for giving me the strength and wisdom to complete this work. Without Allah's help and blessing, I would not have succeeded.

Firstly, I would like to thank my supervisor for his invaluable discussion, commentary, support and encouragement and also my co-supervisors for their useful advice.

The author would like to thank all the project members, Mohd. Rozni Md. Yusof, Hishamudin bin Jamaludin, and Chan Chee Wan. This study was supported by the University Putra Malaysia, MARDI, and the Ministry of Science, technology and Innovation.

I would also like to express my thanks to my friends and colleagues for their support and advice. Your help will not be forgotten.

Finally, I would like to thank my family, specially my wife, for giving me the motivation and moral support needed to complete this thesis. Only Allah can truly reward what they have done.



## APPROVAL

I certify that an Examination Committee met on \_\_\_\_\_ to conduct the final examination of Ali Rafieishahemabadi on his Master Degree thesis entitled “A Variable Rate Pulsed Width Modulated Nozzle Valves Algorithm for Boom Sprayer System” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher degree) Regulations 1981. The Committee recommends that the student be awarded the relevant degree.

Members of the Examination Committee were as follows:

**Mohamad Hamiruce Marhaban, Ph.D**

School of Graduate Studies  
Universiti Putra Malaysia  
(Chairman)

**Wan Ishak Wan Ismail, Ph.D**

Professor  
School of Graduate Studies  
Universiti Putra Malaysia  
(Internal Examiner)

**Ishak Aris, Ph.D**

Associate Professor  
Faculty of Graduate Studies  
Universiti Putra Malaysia  
(Internal Examiner)

**Yahya Md. Sam, Ph.D**

Associate Professor  
School of Graduate Studies  
Universiti Putra Malaysia  
(External Examiner)

---

**HASANAH MOHD GHAZALI, Ph.D**

Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: \_\_\_\_\_



This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master Science. The members of Supervisory Committee were as follows:

**Samsul Bahari bin Mohd Noor, PhD**

Assistant Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Anuar bin Abdul Rahim, PhD**

Associate Professor  
Faculty of Agriculture  
Universiti Putra Malaysia  
(Member)

**Seyed Javid Eghbal, PhD**

Assistant Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

---

**AINI IDERIS, PhD**  
**Professor and Dean**  
**School of Graduate studies**  
**Universiti Putra Malaysia**

**Date : 10 July 2008**



## **DECLARATION**

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

---

**ALI RAFIEISHAHEMABADI**

Date: \_\_\_\_\_



## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	v
<b>ACKNOWLEDGEMENTS</b>	vii
<b>APPROVAL</b>	viii
<b>DECLARATION</b>	x
<b>LIST OF TABLES</b>	xiv
<b>LIST OF FIGURES</b>	xv
<b>LIST OF ABBREVIATIONS</b>	xx
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 Overview	1
1.2 Research Problems in Sprayer	2
1.3 Aim and Objectives	3
1.4 Scope and Limitation	4
1.5 Thesis Layout	5
<b>2 LITERATURE REVIEW</b>	<b>7</b>
2.1 Definition of Precision Agriculture	7
2.2 Technology behind Variable Rate Application Control System and its Benefits	8
2.3 Technology to Control Application Rate	11
2.3.1 Direct Chemical Injection System	11
2.3.2 Pulse Width Modulation (PWM) Flow Control System	15
2.4 Background of Variable Rate Application System	15
2.5 Summary	26
<b>3 METHODOLOGY</b>	<b>28</b>
3.1 Introduction	28
3.2 Describing Model of PWM Boom Sprayer System	28
3.3 System Components Calibration Tests	31
3.3.1 Calibration Frequency to Voltage Converter	32
3.3.2 Flow Meter Calibration	32
3.3.3 By-Pass Control Valve Calibration	34
3.3.4 Calibration Test for Extracting Dynamic Characteristics of Manifold Total Flow Rate	35



	<b>Page</b>	
3.4	Response Time of the System Based on Process Identification Technique	37
3.5	Extract the Application Rate Based on Nearest Point in Look up Table	40
3.6	Estimate Orientation of the Tractor	42
3.7	Valves Positions	43
3.8	Modifying Position of the Shut off Valves	44
3.9	Algorithm to Determine the Best Possible Duty Cycle Setting	47
3.10	Pressure Fluctuation Problem in the Sprayer System	52
3.11	Algorithm for Pulsed Activation of Solenoid Valves for Variable Rate Application	53
3.12	Simulation Program to Evaluate Performance of the Sprayer	59
<b>4</b>	<b>RESULTS AND DISCUSSION</b>	<b>61</b>
4.1	Calibration Experimental Result of Signal Conditioner (Frequency to Voltage Converter)	61
4.2	Calibration Experimental Result of Flow Meter	63
4.3	Calibration Experimental Result of By-Pass Control Valve	65
4.4	Experimental Result of Dynamic Characteristics of Manifold Total Flow Rate	69
4.5	Experimental Result to Determine Dead Time and Time Constant	71
4.6	Orientation of the Tractor and Valves Positions versus Look Ahead Prediction Strategy	72
4.7	Analyzing and Simulating of the Pulse activation Algorithm for Solenoid Shut- off Valves	77
4.8	Effect of Velocity Alternations to Sprayer Operation	99
4.9	Summary	119
<b>5</b>	<b>CONCLUSION AND RECOMMENDATION</b>	<b>121</b>
5.1	Conclusion	121
5.2	Recommendation and Future Work	122
	<b>REFERENCES</b>	<b>124</b>
	<b>APPENDICES</b>	<b>127</b>
A	Source of Simulation Program	128
B	Step Response of the System	143
C	The Predicted Shut off valves Results	146
D	GIS Preload Data	147
E	LUMARK Calibration Table	175
F	Estimated Total Flow Rate and Percentage of Error	177
G	Simulated Results	179
H	AGPS Data	182



**BIODATA OF STUDENT**

**Page**

184



## LIST OF TABLES

<b>Table</b>	<b>Page</b>
3.1 Assumed Preload GIS Data	41
4.1 Flow Meter Calibration Test Result	64
4.2 Bypass Calibration Result	68
4.3 Bypass Actuation Signal versus Total Flow Rate for LUMARK 03 F110	70
4.4 Measured Time Constant and Dead Time	72





## LIST OF FIGURES

Figure	Page
2.1 The Main Components of a Variable Rate Application System	8
2.2 Variable Rate Sprayer Scenario	12
2.3 Experimental Layout for Droplet Travel Time	22
2.4 Real-time, Variable Rate Herbicide Applicator Using Machine Vision	23
2.5 PWM Flow Control System	25
3.1 The Model of PWM Boom Sprayer System	29
3.2 Flow Meter Calibration Diagram	33
3.3 By-Pass Calibration Diagram	35
3.4 Dynamic Characteristics of Manifold Total Flow Rate	36
3.5 Step Test Diagram	38
3.6 Fitting a FOPDT to A Step Response	39
3.7 Distances from AGPS Coordinate to All GIS Coordinates	41
3.8 Tractor Orientation and Valves Positions	43
3.9 Look Ahead Strategy	45
3.10 The Boom Covered Area by Tractor Travel Distance	48
3.11 Algorithm to Determine the Best Possible Duty Cycle Setting	51
3.12 Solenoid Valve Attached to Sprayer Nozzle	53
3.13 Pulse Width Modulation	54
3.14 Minimum Nonzero Flow	56
3.15 Maximum Flow Rate	56
3.16 Flow Rate is 97.5% of the Maximum Flow	57



<b>Figure</b>	<b>Page</b>
3.17 Flow Rate is 95% of the Maximum Flow	58
3.18 Flow Rate is 60% of Maximum Flow, at 16 Pulses per Second	58
3.19 Pulse Omission, Flow Rate Reduced by 3.75% to 56.25% of Maximum Flow Rate	59
3.20 Pulse Omission, Flow Rate Reduced by 7.5% to 52.5% of Maximum Flow Rate	59
3.21 The Employed Algorithm Flowchart to Survey Performance of the Sprayer	60
4.1 Experimented Set-up of Signal Conditioner	61
4.2 Graph of Voltage versus Frequency for Signal Conditioner	62
4.3 Experimented Set-up of Flow meter	63
4.4 Graph of Flow Rate versus Voltage for Flow Meter Calibration Test	65
4.5 Experimented Set-up of by-pass control valve	66
4.6 The Control Signals are being sent to By-Pass control Valve and Shut-off Valves	67
4.7 Bypass Actuation Voltages versus Flow Rate at 4 Different Duty Cycles	69
4.8 Bypass Setting Versus Flow Rate for LUMARK 03F110 Tip Valve Nozzle at Different Duty Cycles	70
4.9 The Total Flow Rate Response to Step Signal	71
4.10 Orientation of the Tractor with Sample Position	73
4.11 Orientation of the Tractor and Predicted Coordinates	74
4.12 Predicted Coordinates of Shut off Valves and Middle of the Boom	76
4.13 Tractor Displacement among Sampled GIS Data and Predicted Shut off Valves Coordinates	78
4.14 The Predicted Points for Spraying	79

<b>Figure</b>	<b>Page</b>
4.15 Desired Flow Rates for the Shut off Valves Installed on Right Side of the AGPS Antenna	80
4.16 Desired Flow Rates for the Shut off Valves Installed on Left Side of the AGPS Antenna	81
4.17 Desired Total Flow Rates for 12 Shut off Valves	82
4.18 Setting the Bypass Control Valve	83
4.19 Extracting the Average Percent of Duty Cycle	83
4.20 Estimated Total Flow Rates	84
4.21 Percentage of Estimated Total Flow Rate Error	85
4.22 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a1	87
4.23 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a2	88
4.24 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a3	89
4.25 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a4	90
4.26 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a5	91
4.27 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a6	92
4.28 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b1	93
4.29 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b2	94
4.30 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b3	95



<b>Figure</b>	<b>Page</b>
4.31 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b4	96
4.32 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b5	97
4.33 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b6	98
4.34 Alternations of Average Velocity during Spraying Time	100
4.35 Desired Flow Rates for the Shut off Valves Installed on Right Side of the AGPS Antenna	101
4.36 Desired Flow Rates for the Shut off Valves Installed on Left Side of the AGPS Antenna	102
4.37 Setting the Bypass Control Valve	103
4.38 Extracting the Average Percent of Duty Cycle	103
4.39 Desired Total Flow Rates for 12 Shut off Valves	104
4.40 Estimated Total Flow Rates	105
4.41 Percentage of Estimated Total Flow Rate Error	106
4.42 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a1	107
4.43 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a2	108
4.44 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a3	109
4.45 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a4	110
4.46 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a5	111



<b>Figure</b>	<b>Page</b>
4.47 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve a6	112
4.48 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b1	113
4.49 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b2	114
4.50 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b3	115
4.51 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b4	116
4.52 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b5	117
4.53 Comparison of PWM Algorithm and Pulsed Activation Algorithm for Valve b6	118



## LIST OF ABBREVIATIONS

VRT	Variable Rate Technology
LPM	Litter Per Minute
GPM	Gallon Per Minute
PWM	Pulse Width Modulation
PSI	Pound Per Square Inch
GPS	Global Positioning System
AGPS	Assisted Global Positioning System
GIS	Geographic Information System
DC	Duty Cycle
FOPDT	First Order Plus Dead Time Model
SOPDT	Second Order Plus Dead Time Model
MATLAB	Matrix Laboratory
PTO	Power Takeoff
RPM	Revolutions (or Rotations) Per Minute
gpa	Gallon Per Acre (4046.86 square meter)
CV	Coefficient Value
PRV	Pressure Relief Valve
VRA	Variable Rate Application



# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

Precision farming is a farming system concept which involves the development and adoption of knowledge-based technical management systems with the main goal of optimizing profit. This management system will enable micro- management concepts, that is, the ability to appropriately manage every field operation at each location in the field, if it is technically and economically advantageous to manage at that level. The system will likely include the ability to vary or tailor the application rate of all inputs such as seeds, weed, insect, and disease control. It has become feasible because of several new technologies like fast computers, geographical information system, remote sensing, and geographical positioning system. Fast computers and powerful graphical and information management software are among the technologies which are making precision farming a reality.

Variable rate technology (VRT) plays an important role in precision farming. It involves the use of historical and/or real-time site-specific information in applying a desired rate of an agriculture input such as pesticides, herbicides and fertilizers at a specific site within a field.



Technically, one important aspect of the development of precision farming concepts is the development of the hardware and software necessary to vary the rate of the application of agricultural inputs.

Control systems fitted to agricultural boom sprayers should guarantee control of delivered dose rates in order to achieve optimum use of fertilizer, pesticide and herbicide. Precision farming approaches are likely to require application rates to be varied to match the fertilizer requirements of different parts of a field and this will require control systems that have a rapid response to change requirements. Control parts are devices that change the application rate of products being applied real time.

A new development in variable flow rate application is the use of variable flow rate from the nozzle by pulse width modulation. Some shut off valves installed on a boom mounted on the rear of the vehicle, usually tractor, with a control system to make a sprayer apply the desired application rates by pulse width modulation.

## **1.2 Research Problems in Sprayer**

Nowadays, the precision farming is able to access information of agricultural fields by employing new technologies. The micromanagement process in agricultural field management affords ability to extract required application rates of chemical fertilizers with accuracy of less than a meter. However, the technology required to vary application rate of fertilizer across the fields with a given precise micro amounts in each part of the



land is a challenge to researchers. The new sprayers play an important role to distribute chemical precisely on the farm.

The PWM (pulse width modulation) sprayer is a new design of sprayer developed by Han et al. (2001). The flow control range of 9:1 was achieved under constant supply pressure for PWM sprayer (Ess et al., 2001) which is not a wide range of control compatible with preload GIS data. The fast-acting electrical solenoid valves with response time of 4 ms and operation frequency of 10 Hz used in given sprayer system. The high speed solenoid valves used in this system is quite costly, adding to the expense of the hardware, especially since the valves are likely to require replacement as they wear out. If lower cost industrial solenoid valves could be used instead, the initial cost of the hardware could be brought down. The penalty in using lower cost valves is their slower opening and closing time compared to high speed valves.

This study offers a control system design for pulse width modulation sprayer with low cost components. This sprayer was assembled by contribution of mechanical and GIS group in instrumentation laboratory of Engineering, University Putra Malaysia.

### **1.3 Aim and Objectives**

The aim of this project is to design and simulate a control system for the sprayer fitted with low cost PWM (pulse width modulation) nozzle valves. In order to have a control system for PWM sprayer that will be able to spray with high accuracy, the following objectives have been set: