Universiti Malaysia PAHANG

RESEARCH REPORT UMP GRANT
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Final	/	Progress	

Progress Period : 05/10/2017 – 4/10/2019
√ Please tick

Status ✓

COMPLETED
(KPI PARTIALLY ACHIEVED)
(Publications)

PROJECT DETAILS *(Keterangan Projek)*

A		
	Grant No	RDU1703315
	Faculty/CoE	FKEE
	Project Title	THE DEVELOPMENT OF ROBUST AND FAST RESPONSE CONTROL ALGORITHM FOR UAV CROP DUSTER
	Project Leader	DR. MOHAMMAD FADHIL BIN ABAS
	Project Member	1. DWI PEBRIANTI 2. NORHAFIDZAH BINTI MOHD SAAD 3. HAMZAH BIN AHMAD

PROJECT ACHIEVEMENT *(Pencapaian Projek)*

B

ACHIEVEMENT PERCENTAGE				
Project progress according to milestones achieved up to this period	**0 - 25%**	**26 - 50%**	**51 - 75%**	**76 - 100%**
Percentage (please state %)				100%

EXPENDITURE *(Perbelanjaan)*

C

Budget Approved *Peruntukan diluluskan*	**Amount Spent** *Jumlah Perbelanjaan*	**Balance** *Baki*	**% of Amount Spent** *Peratusan Belanja*
RM 20,000.00	**RM 17,341.15**	**RM 2,658.85**	**86.7%**

RESEARCH OUTPUT *(Output Penyelidikan)*

D

NO OF PUBLICATION

KPI FOR NO OF PUBLICATION

	ISI	Scopus	Index Proceedings	Others
KPI		1	1	2
Achievement		2		

The contribution of funder (UMP, MOHE, MOSTI, Industry etc.) as the fund provider must be acknowledged at all times in all forms of publications. Please state the grant number (RDU/UIC) and grant name.

	ISI	Scopus
Number of articles/ manuscripts/books *(Please attach the First Page of Publication)*	1. 2.	1. Balya Bin Darohini, Muhammad Izzat Faez Bin Yusuf, M. F. Abas, N. Md. Saad, Dwi Pebrianti, M. Z. Ibrahim, 2018, Blackbox Modelling of a 6 Rotor Helicopter, Journal of

		Telecommunication, Electronic and Computer Engineering, e-ISSN: 2289-8131, Vol. 10, No. 1-3, pg(s): 99-102. 2. Balya Darohini, M. F. Abas, N. Md. Saad, Dwi Pebrianti, H. Ahmad, M.H. Ariff, M. R. Arshad, 2019, Optimization of Quaternion Based on Hybrid PID and Pw Control, InECCE 2019.
Conference Proceeding *(Please attach the First Page of Publication)*	**International** 1. 2.	**National** 1. 2.

HUMAN CAPITAL DEVELOPMENT

KPI FOR HUMAN CAPITAL DEVELOPMENT

	PhD Student	Master Student
KPI		**1**
Achievement		**1**

Human Capital Development	**Number**				**Others** (please specify)
	On-going		**Graduated**		
Citizen	Malaysian	Non Malaysian	Malaysian	Non Malaysian	
PhD Student					
Masters Student	1				
Undergraduate Student					
Total					

Name of Student: **ID Matric No:** **Faculty:** **Thesis title:** **Graduation Year:** **Name of Student:** **ID Matric No:** **Faculty:** **Thesis title:** **Graduation Year:** *** enter for more space*	Balya Bin Darohini MEL16017 FKEE Robust Control Of Flood Drone For Search And Rescue On Going

INTELECTUAL PROPERTIES

KPI FOR INTELECTUAL PROPERTIES

Patent, Copyright, Trademark,Industrial Design: ____________

Patent, Copyright, Trademark, Industrial Design ect	None

OTHERS

KPI FOR OTHERS

Prototype, Technology,Collaborations etc: ____________

Prototype, Technology, Collaborations etc	**None**

COMMENTS, IF ANY/ ENDORSEMENT BY FACULTY (*Komen, sekiranya ada / Pengesahan oleh Fakulti*)	
J	**Recommend / Not Recommend / KIV / Need Ammendment** .... **Name:** *Nama:* CERTIFIED COPY **Signature:** *Tandatangan:* **Date:** *Tarikh:* 10/12/2019 DR. MOHD MAWARDI BIN SAARI, DEPUTY DEAN (RESEARCH & POSTGRADUATE STUDIES), FAKULTI TEKNOLOGI KEJURUTERAAN ELEKTRIK DAN ELEKTRONIK, UNIVERSITI MALAYSIA PAHANG **** Dean/TDR/Director/Deputy Director**
COMMENTS, IF ANY/ ENDORSEMENT BY RMC PNI (*Komen, sekiranya ada / Pengesahan oleh RMC PNI*)	
K	**Recommend / Not Recommend / KIV / Need Ammendment** KPI partially achived Need to ~~ces~~ complete publication KPI and then close this project **Name:** *Nama:* **Signature:** *Tandatangan:* **Date:** *Tarikh:* 31/12/19 PROFESOR DR. MD. MUSTAFIZUR RAHMAN, Dekan Penyelidikan, Jabatan Penyelidikan & Inovasi, Universiti Malaysia Pahang, 26600 Pekan, Pahang

RDU 1703315

THE DEVELOPMENT OF ROBUST AND FAST RESPONSE CONTROL ALGORITHM FOR UAV CROP DUSTER

(PEMBANGUNAN ALGORITMA KAWALAN TEGUH DAN PANTAS UNTUK KEGUNAAN UAV)

MOHAMMAD FADHIL BIN ABAS
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MOHD RIZAL BIN ARSHAD / USM

RESEARCH VOTE NO:
RDU1703315

Fakulti Kejuruteraan Elektrik & Elektronik
Universisi Malaysia Pahang

2019

DEDICATION

Firstly, I would like to thank the Most Gracious the Most Magnificent Allah for His mercy and giving me the strength to undergo this research and life itself. It is a very difficult and stressful but with His guidance and blessing, I was able to complete the reseach.

I would also like to thank my parents who have brought me into this life, who has raised me and taught me. Without their support, blessing and prayers, I could not be here. Thanks also to my beloved wife, Norhafidzah Binti Mohd Saad, my two sons and daughter, Muhammad Hafizul Ilmi Ridwan, Mohammad Ilmi Ar-Rayyan and Nur Adhwa Azalea for being patient and supportive. I would like to thank my fellow researches for contributing their knowledge and hardwork in this research.

Finally, I would like to thank the University Malaysia Pahang for giving me the funds for this research.

Dr. Mohammad Fadhil Bin Abas

ABSTRACT

In realizing a high crop yield/year, the possibility of deploying a highly robust, fast response with gimbal lock problem free controller in an underactuated unmanned system is a possibility. The gimbal lock problem is solved via UAV model and control using quaternion angle instead of cartesian angle. By evaluating quaternion UAV model, nonlinear P^2 controller is used as the robust control. Original P2 controller is upgraded to include optimize gain which has been optimize using GA. Based on the simulation result, the controller has promising result.

ABSTRAK

Dalam merealisasikan hasil tanaman / tahun yang tinggi, kemungkinan untuk menggunakan respon yang sangat teguh dan pantas dengan pengendali masalah masalah kunci gimbal dalam sistem tanpa pemandu yang kurang aktif adalah kemungkinan. Masalah kunci gimbal diselesaikan melalui model UAV dan kawalan menggunakan sudut quaternion bukan sudut cartesian. Dengan menilai model UAV quaternion, pengawal P2 tak linear digunakan sebagai kawalan yang mantap. Pengawal P2 asal ditingkatkan untuk memasukkan mengoptimumkan keuntungan yang telah dioptimumkan menggunakan GA. Berdasarkan hasil simulasi, pengawal mempunyai hasil yang menjanjikan.

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Chapter 1

INTRODUCTION

1.1 Introduction

The need for a control system which is highly robust and fast response for an underactuated system in plantation crops area is high. Besides highly robust and fast response, the controller needs to be free from gimbal Lock problem.

Current research on this area has led to many control algorithms. One type of control algorithm is the PID controller and its hybrids are very well known. Abdulkerim Fatih Șenkul et. Al. in [1] has design a cascaded PID controller with adaptive correction for inner and outer loop control to control a Tilt-Roll Rotor Quadrotor UAV. The simulation result shows good reliability and robustness compared to ordinary adaptive control algorithm. Ning Cao et. Al. in [2] has design an inner and outer loop PID controller on a mathematical model from the body frame representation of the translational dynamics. The body frame representation of the translational dynamics allows independent bound on roll and pitch. Based on mathematical proof, the proposed method is globally asymptotically stable assuming no inner loop tracking error. Hardware testing has shown that the strategy is robust hovering and tracking control objectives. LQR based control algorithm is also researched on in paper [3] by Yuki Kawai et. Al. The author has designed an optimal regulator based on frequency shaping LQR controller. The simulation and experimental test shows the controller performed well. Nonlinear Integral-Backstepping technique (NIB) and the Model Free Control (MFC) have been researched on by Younes Al Younes et. Al. The author designed a controller based on NIB and MFC to increase the robustness of the underactuated system under fault-free and actuator fault conditions. Based on experimental test, NIB-MFC shows superior performance compared to LQR, NIB and LQR-MFC. Fuyang Chen et. Al. in [5] and Kaijia Xue et. Al. in [6] has design a controller using hybrid sliding mode control with backstepping and error compensation support vector machine (SVM) respectively. Both designs have shown improvement in efficiency and robustness. The above control scheme has its advantages and disadvantages. The advantages have been discussed. One of the disadvantages is that all of the above control uses EULER angle in its control design. EULER angle is prone to gimbal lock.

To solve the gimbal lock problem, many researches has replace EULER angle based control with quaternion angle based control. Quaternion angle based control has been researched by Yihong Mou et. Al. in paper [7]. The author proposed a quaternion based double-loop PID control with digital filter algorithm for stabilizing a multirotor dynamics. The proposed controller has shown good experimental result for stable attitude control. Other controller which uses quaternion angle has also been researched by Maria Eusebia Guerrero-Sanchez et. Al. in paper [8]. The author proposed a quaternion-based passivity-based control to stabilize the attitude. Passivity-based control does not compute excessive and complex PDEs in obtaining the control law. Remon Damen et. Al. in paper [9] also designed a passivity based control based on quaternion with successful result. Simulation and experimental result shows that the quaternion-passivity-based control perform with good results for the control objectives. Kaddouri Djamel et. Al. in paper [10] has also designed attitude optimal backstepping controller which is combined with H infinity technique. The resultant controller demonstrate local stabilizability/ detectability condition. The controller also emphasize robustness with adaptation matrix. Walter Benitez et. Al. in paper [11] also design quartanion based PIDT (Proportional, Integral, Derivatives with a low-pass filter) for stability augmented system. Simulation results shows the algorithm showed satisfactory. Adnan Jafar et. Al in paper [12] designed H infinity control for altitude and attitude control against Atmospheric Turbulence. Based on the paper, the controller is highly robust but unfortunately the response time is slow. A. Chovancová et. Al. in paper [13] compares various controller based on quaternion. The paper states that backstepping lack fast response. Quaternion based output feedback observer-based dynamic surface controller have been designed by Jingxin Dou et. Al. in paper [14]. The Lyapunov stability analysis shows attitude tracking performance is ensured. Simulative and experimental results show better performance than other observer-based controller.

Based on the literature done, a fast response P^2 nonlinear controller with optimized gain will be developed. The inclusive of quaternion will enhance the controller so that to avoid gimbal lock problem.

1.2 Problem Statement

In realizing the ideal control system for an underactuated system in highly disturbance area such as large variation of wind, the control system should be highly robust, very responsive and gimbal lock free. This will enable the underactuated system such as a UAV based crop duster to operate in any climate.

However, current control system that has been formulated for an underactuated could not assure highly robust, very responsive and gimbal lock free. Many Euler based control has been research on which varies from simple PID to robust control system such as robust model free controller [1-6]. Control algorithm based on Euler angle is prone to gimbal lock. In order to overcome this problem, much research on quaternion based control algorithm is being research on. The control algorithm specifically deals to increase robustness, adaptability, stabilizability/detectability or accuracy [7-14]. Since there is not yet any controller which can produce high robustness, fast response and gimbal lock free response, an underactuated system could not be used in highly disturbance situation.

a fast response P^2 nonlinear controller with optimized gain will be developed. The inclusive of quaternion will enhance the controller so that to avoid gimbal lock problem.

1.3 Objective

The scope of work for this research is as follow.

1. To develop a robust and fast response control algorithm based on quaternion and quaternion feedback linearization for UAV crop duster.

2. To analyze the control algorithm for its applicability and performance through simulation and experimentation.

1.4 Scope of work

1. Only MATLAB simulation will be done
2. Multirotor is used as the UAV

Chapter 2

BLACKBOX MODELLING OF A 6 ROTOR HELICOPTER

Blackbox Modelling of a 6 Rotor Helicopter

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***Abstract*—Aerial robotics have received a considerable interest in both private builders and research laboratories for several years. In this respect, modeling is needed in the first step of developing aerial robotics or multi-rotor UAV and there are various methods that can be used for modeling. In this paper, the authors discussed and compared two types of blackbox modeling method that is the Continuous State Space using PEM method and the commonly used Second Order Underdamped System with Delay process model. Based on a comparison analysis of the two methods drawn from experimental data, it was found that the Second Order Underdamped System with Delay Modeling gives better similarity for a hexarotor pitch angle model. In contrast, the Continuous State Space model using PEM method in Polynomial gives better similarity to the hexarotor roll angle model. Finally, both tested methods deliver similar similarity for hexarotor yaw angle model.**

***Index Terms*—Blackbox; Hexarotor; Polynomial Model; Second Order System.**

I. Introduction

Aerial robotics have received a considerable interest in both private builders and research laboratories for several years. This interest is motivated by recent technological advances that make it possible to design efficient systems endowed with real autonomous navigation capabilities with no prohibitive costs. Unlike to terrestrial mobile robots for which it is often possible to be limited to a kinematic model, the control aerial robots require knowledge of a dynamic model. This is due to the effects of gravity and aerodynamic forces. These systems, for which the number of control inputs is less than the number of degrees of freedom, are expressed by under-actuated. The control mechanism usually provides one or two control inputs for the dynamics of translation and two or three control inputs for the rotational dynamics. The modeling of an autonomous helicopter has been assessed in numerous articles and journals directly and indirectly.

Oualid Araar et al. in their paper [1] modeled their quadrotor (four rotors autonomous helicopter) using a mathematical modeling. The authors found that the overall equation governing the model is the drag and lift factor, in which the trust factor is then identified using experimental data. Based on the experimental data, it is found that even if all of the four motors are identical, the PWM to speed is not similar to the motors. Thus, the controller which is built upon the model is influenced by the asymmetry of the PWM to speed graph.

Wojciech Giernacki et al. in their paper [2] use a black box modeling for estimating multi-rotor motor-rotor system. The input and output experimental data were inputted into the MATLAB System Identification Toolbox. The system output is the first-order model with pure time delay. This model is then used to design a Coefficient Diagram Method (CDM) and PID pole placement control with anti-windup compensation.

Similar to paper [2], Przemysław Gasior et al. in their paper [3] used experimental data to model their X8 configuration multi-rotor aerial system. The experimental data is fed into an Open Curve Fitting Tool and Fuzzy Modeling using Takagi-Sugeno Interface in MATLAB. Results show that the thrust estimated values are satisfactory and very similar for each approach.

Karima Benzaid et al. in the paper [4] presents a generalized dynamic modeling of a multi-rotor aerial system. The multi-rotor was first mathematically modeled to obtain a non-linear model. Then, the model is generalized for N numbers of '+' and 'X' configuration multi-rotor aerial vehicles. The results show that the generalized model is validated. Besides, the designed PID and integral backstepping control, the performance of 3D trajectory tracking of quadrotor, hexarotor and octorotor is considered good.

Similar to Karima Benzaid, Jae-Gyun Han et al. in paper [5] uses mathematical modeling in modeling their hexarotor aerial vehicle. By implementing PD controller on the model, the hexarotor simulation results were found good with minor fluctuation in the roll and pitch control.

Dafizal Derawi et al. in paper [6] modeled and designed a controller for hexarotor. The mathematical modeling is similar to Karima Benzaid et al. and Jae-Gyun Han et al. although it focused specifically on hexarotor. The model is then controlled using PID controller. The outdoor test result shows a good performance.

In this paper, the author will discuss a comparison study of black box modeling using two methods. The first was an underdamped second order system with delay process model, while the second was continuous State Space model using PEM method in Polynomial Modeling.

II. Methodology

The data acquisition setup for a hexarotor can be seen in Figure 1. A Radiolink AT9 Transmitter was used to control the hexacopter, in which the hexacopter was expected to capture the input signal from the radiolink and the output roll, pitch, yaw and throttle. The data was then downloaded to the computer.

The data was collected when the hexarotor was flying in roll, pitch, yaw and throttle condition. Every data was collected for 4 set per condition. 4 set for roll, 4 set for pitch, 4 set for yaw, and 4 set for throttle. Therefore, the total set of data for all conditions to be collected was 16 sets of data. Each set of data was collected by flying the hexarotor for 5 minutes according to the desired condition to get the required data. For example, to collect the data for a roll set, the hexarotor will be flying in the left and right movement repeatedly for 5 minutes, as depicted in Figure 2.

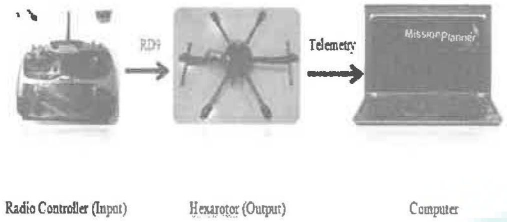

Figure 1: Data collection setup

Figure 2: Hexarotor flying in sinewave form for 5 minutes

After the hexarotor was flown for 5 minutes, the data was stored directly onto the hexarotor. This data was then downloaded from the mission planner software. The mission planner software was used to collect the data from Arducopter Autopilot APM by using telemetry transmitter or by USB data cable. The data received was entered into the log data in the mission planner program. Then, the data were downloaded and created in the file MATLAB. Figure 3 shows the sample of the output data. As can be seen in Figure 3, there are 3 conditions that include the Up condition (a condition where the hexarotor is initially flown to a preset height), Flying Condition (hexarotor is flown from left to right) and Down Condition (the hexarotor is landed). Only the flying condition data were used for modeling.

The modeling was done by using MATLAB's System Identification Toolbox. Two methods of black box identification were used. The first was an underdamped second order system with delay process model, and the second was continuous Continuous State Space model using PEM method in Polynomial.

III. Result and Discussion

The experimental data have been acquired and inputted into MATLAB's identification toolbox. Two blackbox methods modeling used were the Second Order Underdamped System with Delay process model and the Continuous State Space model using PEM method in Polynomial. Table 1, 2 and 3 show the model output for the pitch, roll and yaw respectively.

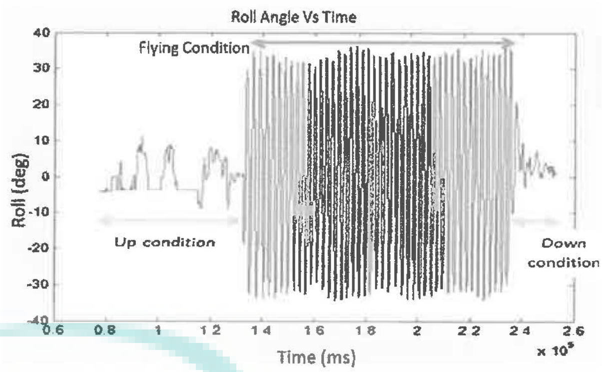

Figure 3: Sample data

Table 1
Pitch Model

No.	Modelling Type	Model Output
1	Second Order Underdamped System with Delay	$G(s) = \frac{0.9555}{0.0066s^2 + 0.1438s + 1} \times e^{-0.018s}$
2	Continuous State Space Model Using PEM Method	$\frac{dx}{dt} = Ax(t) + Bu(t)$ $y(t) = Cx(t)$

Matrix A, B and C are defined as follow.

$$A = \begin{bmatrix} -1.34 & -1.5 & -2.06 & -0.26 & 0.03 & 0.02 & 3.83 \\ 2.01 & -1.35 & 0.57 & 0.59 & -0.43 & 0.61 & -0.50 \\ 1.16 & -0.06 & -1.81 & -4.23 & -0.20 & -3.70 & 0.26 \\ -0.32 & 0.59 & 2.52 & -2.01 & 6.53 & -0.74 & 5.51 \\ -0.66 & -0.43 & 0.62 & -3.50 & -1.80 & 10.27 & -1.10 \\ -0.41 & 0.43 & 0.15 & -0.39 & -3.22 & -1.85 & 16.80 \\ -0.19 & 0.59 & -0.25 & -0.01 & -0.94 & -2.61 & -3.18 \end{bmatrix}$$

$$B = \begin{bmatrix} -0.61 \\ 0.53 \\ -0.39 \\ -0.77 \\ 0.46 \\ 0.52 \\ -0.02 \end{bmatrix}$$

$$C = [-3.33 \quad 2.65 \quad -1.08 \quad -2.46 \quad 1.55 \quad -3.82 \quad 2.91]$$

Table 2
Roll Model

No	Modelling Type	Model Output
1	Second Order Underdamped System with Delay	$G(s) = \frac{0.8289}{0.0056s^2 + 0.5014s + 1} \times e^{-0.017s}$
2	Continuous State Space Model Using PEM Method	$\frac{dx}{dt} = Ax(t) + Bu(t) + Ke(t)$ $y(t) = Cx(t)$

Matrix A, B, K and C are defined as follow.

$$A = \begin{bmatrix} -1.73 & 3.99 & 5.63 & -2.96 \\ -9.58 & -2.34 & -9.85 & 4.61 \\ -12.45 & -1.55 & -14.41 & 12.51 \\ -2.70 & -1.15 & -6.61 & 0.06 \end{bmatrix}, B = \begin{bmatrix} -0.06 \\ 0.27 \\ 0.35 \\ 0.12 \end{bmatrix}$$

$$K = \begin{bmatrix} 0.18 \\ 0.37 \\ -0.07 \\ -0.09 \end{bmatrix}, C = [54.66 \quad 8.45 \quad 1.19 \quad 0.06]$$

Table 3
Yaw Model

No.	Modelling Type	Model Output
1	Second Order Underdamped System with Delay	$G(s) = \frac{0.9513}{0.0028s^2 + 0.0651s + 1} \times e^{-0.026s}$
2	Continuous State Space Model Using PEM Method	$\frac{dx}{dt} = Ax(t) + Bu(t)$ $y(t) = Cx(t)$

Matrix A, B and C are defined as follow:

$$A = \begin{bmatrix} -7.49 & -5.99 & 9.261 & -1.90 \\ 7.11 & -11.08 & 0.83 & -2.65 \\ -5.36 & 0.04 & -6.93 & 12.02 \\ 2.83 & 0.36 & -1.38 & -12.10 \end{bmatrix}, B = \begin{bmatrix} -6.81 \\ 3.60 \\ -1.50 \\ 1.76 \end{bmatrix}$$

$$C = [-2.22 \quad -3.39 \quad -3.03 \quad -5.01]$$

An experimental input is fed into both of the model output from the Second Order Underdamped System with Delay and Continuous State Space Model using PEM method for each channel. The output result was compared with the measured output. Figure 4, 5 and 6 show the comparison between the three outputs for pitch, roll and yaw channel.

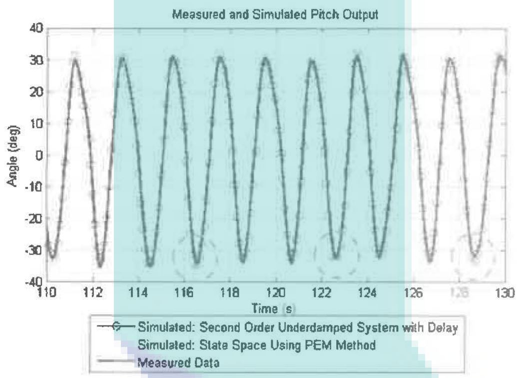

Figure 4: Measured and Simulated Pitch Output

Based on Figure 4, the three outputs waveform show similar result with minor overshoot (circled), as can be seen at t=117s, t=123s and t=129s. Based on MATLAB identification toolbox output comparison, the pitch model based on Continuous State Space using PEM method delivers 89.5% similarity with the measured data. For the Second Order Underdamped System with Delay, the model output delivers 2% more similarity than that of the previous method, which results in 91.5%. Based on this result, the pitch model using Second Order Underdamped System with Delay gives better similarity.

Based on Figure 5, the Continuous State Space Using PEM Method results in a good similarity to the measured data. Unfortunately, the Second Order Underdamped System with Delay output results poorly at the sharp movement (circled), which can be seen clearly at t=215s, t=231s, t=241s and t=247s. Based on MATLAB identification toolbox output comparison, the pitch model based on Continuous State Space using PEM method delivers 90.3%% similarity with the measured data. For the Second Order Underdamped System with Delay, the model output delivers 30.9% less similarity than that of the previous method which results in 59.4%. Based on this result, the pitch model using the Continuous State Space using PEM method gives better similarity.

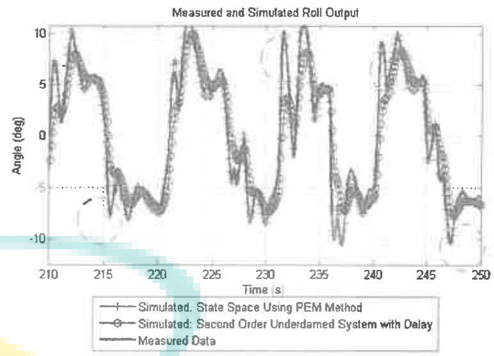

Figure 5: Measured and Simulated Roll Output

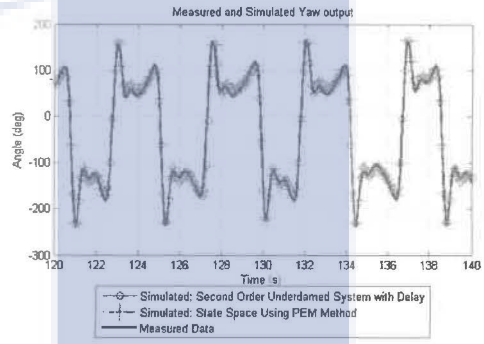

Figure 6: Measured and Simulated Yaw Output

With reference to Figure 5, both the Continuous State Space Using PEM Method and the Second Order Underdamped System with Delay Modeling resulted in a good similarity to the measured data. There is no clear indication that any of the method's outputs have deviated from the measured data. Based on MATLAB identification toolbox output comparison, the yaw model based on the Continuous State Space using PEM method and the Second Order Underdamped System with Delay delivers similar similarity with the measured data, which result in 87.2% similarity.

IV. Conclusion

Modeling of a hexarotor's attitude has been established via two approaches. The first approach was by using a Second Order Underdamped System with Delay and the second approach is using Continuous State Space PEM method.

For the pitch angle, modeling the channel using Second Order Underdamped System with Delay produces a better result. However, for the roll angle, Continuous State Space PEM method produces a better result. For the yaw angle, both simulated model give equal results.

A precise linear modellng using blackbox method needs to be done using multiple techniques. The best result will be used for the final modeling, although there is no one method that fits all.

Future testing is necessary for other linear modeling using blackbox methods, such as non-linear ARX, neural-network and others.

ACKNOWLEDGMENT

The authors would like to thank UMP for financing the research through final year student project fund and Research & Innovation research fund. RDU no . X

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Chapter 3

OPTIMIZATION OF QUATERNION BASED ON HYBRID PID AND P_W CONTROL

Optimization of Quaternion Based on Hybrid PID and P_ω Control

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***Abstract* — The aim of this article is to present an optimization of full non-linear quaternion based on hybrid control scheme using Genetic Algorithm (GA). A wider objective is used to find novel solutions to design hybrid controller based on PID and Pω control so that system functionality and performance may be compromised. In the presented approach both the quadrotor's attitude model and the proposed hybrid control algorithm have been implemented in the fully quaternion space without any transformations or conversion and calculations in the Euler's angles. In this paper, the optimized quaternion with fitness function composed of K_P, K_I, K_D and P_ω are proposed, and its effectiveness is shown by simulations using MATLAB.**

***Index Terms* — Genetic Algorithm; Quaternion; UAV; PID Controller; Crossover; Mutation.**

I. Introduction

Research on UAV has begun in the 20th century but in the form of model testing. After successful flight, the model would be used to build the full size aerial vehicles. An early usable UAV was built nearly at the end of Second World War. Early UAV uses bats which are bombs attached for bombardment. Since then, numerous configuration of UAV has developed and deployed. Among the UAV is a balloon type, fix-wing type and rotary-wing type. Rotary-wing type is associated with vertical take-off and landing (VTOL). VTOL aircraft has many advantages compared to the balloon type and fix-wing. Among them are the capabilities to hover and very maneuverable in crowded spaces. Numerous tasks do need the capability to hover in a given special point and maneuver aggressively when needed. In the past, the UAV has been used only in military application but it also has a wide area of application in civil aviation.

Quadrotor has become very popular and its use has spread throughout all areas of life. Some of the required tasks can be complicated and require faster, more efficient and reliable control algorithms under windy, uncertain and changing conditions as well. It is becoming very popular nowadays to use a quaternion instead of Euler angles to describe the dynamics and design controllers for a quadrotor. It is possible to use a feedback signal in the form of a quaternion to design linear and non-linear controllers of attitude and position. In the last decade, numerous new small flying unmanned vehicles have appeared. Among them are the mini UAVs of fix-wing type [1]. This type of UAVs is light enough to be handled with a single hand. VTOL based UAVs have also appeared which includes conventional helicopter [2], duct type [3], tilt-rotor [4], tri-rotor [5], six-rotor [5] and eight-rotor [6]. The increase of the amount of rotor in a single VTOL aircrafts enables more weight to be carried.

For an under-actuated system, the control algorithm should be highly robust and fast response. Many Euler angle based control has been research on which varies from simple Proportional Integral Derivative (PID) to hybrid nonlinear control system such as sliding mode control with back-stepping control [7][8][9][10][11][12]. Control algorithm based on Euler angle is prone to gimbal lock. In order to overcome this problem, many research on Quaternion angle based control algorithm which specifically deal to increase robustness, adaptability, stability/detectability and accuracy [13] [14] [15] [16][17].

In this paper, we propose a new approach for the full nonlinear quaternion based on hybrid PID and P_ω by optimization using GA, where K_P, K_I, K_D and P_ω are considered. First, we introduce the evaluating value about K_P, K_I, K_D and P_ω to the fitness function in order to get an optimized model. Then GA can autonomously synthesize a model that is equivalent in functionality, but is simpler and has better performance than a previous design.

In the next section, the fundamental properties and the corresponding algebra of the quaternion mathematics are being presented, while in Section III the quaternion based quadrotor modeling is analyzed. In Section IV the full quaternion based control scheme is established and in Section V a brief overview of GA is described. Therefore, in Section VI shows the simulation result of a new approach for the full nonlinear quaternion of an optimized model. Finally, Section VII concludes.

II. Quaternion Math

The basic algebraic concept of quaternion going to be presented in this section for building the mathematical background for following the previous modeling as stated in [18] and the proposed control scheme. The reader is referred to the publications [18] for a more depth description and comprehensive analysis of this mathematical tool.

A quaternion is a rank 4 number hyper-complex that can be represented in many ways, while equations (1) and (2) represent two of the most popular approaches. The $\boldsymbol{q_1}$ to $\boldsymbol{q_3}$ quaternion units are called the quaternion vector part, whereas $\boldsymbol{q_0}$ is the scalar part.

$$\boldsymbol{q} = q_0 + q_1\boldsymbol{i} + q_2\boldsymbol{j} + q_3\boldsymbol{k} \qquad (1)$$
$$\boldsymbol{q} = [q_0\ q_1\ q_2\ q_3]^T \qquad (2)$$

The result of Kronecker product, denoted as $\otimes$ are the multiplication of two quaternions $\mathbf{p}$ and $\mathbf{q}$ are presented in the following equations. Whereas, **p** represents one rotation and **q** represents another rotation, while **p** ⊗ **q** represents the combined rotation. Multiplication of quaternion is non-commutative.

$$\boldsymbol{p} \otimes \boldsymbol{q} = \begin{bmatrix} p_0q_0 - p_1q_1 - p_2q_2 - p_3q_3 \\ p_0q_1 + p_1q_0 + p_2q_3 - p_3q_2 \\ p_0q_2 - p_1q_3 + p_2q_0 + p_3q_1 \\ p_0q_3 + p_1q_2 - p_2q_1 + p_3q_0 \end{bmatrix}$$

$$\boldsymbol{p} \otimes \boldsymbol{q} = Q(p)q = \begin{bmatrix} p_0 & -p_1 & -p_2 & -p_3 \\ p_1 & p_0 & -p_3 & p_2 \\ p_2 & p_3 & p_0 & -p_1 \\ p_3 & -p_2 & p_1 & p_0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

$$= \bar{Q}(p)q = \begin{bmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & q_3 & -q_2 \\ q_2 & -q_3 & q_0 & q_1 \\ q_3 & q_2 & -q_1 & q_0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix}$$

The norm/length of a quaternion is defined as shown in equation (3), for any complex number. Plus, the unit quaternion are unitary length of all presented quaternion approached.

$$Norm\ (\boldsymbol{q}) = \|\boldsymbol{q}\| = \sqrt{q_0{}^2 + q_1{}^2 + q_2{}^2 + q_3{}^2} \tag{3}$$

Meanwhile, quaternion complex conjugates are the same as normal complex numbers. The sign of the complex part is switched as in equation (4).

$$Conj\ (\boldsymbol{q}) = \boldsymbol{q}^* = [q_0\ -q_1\ -q_2\ -q_3]^T \tag{4}$$

The inverse of a quaternion is defined as in equation (5), as the normal inverse of a complex number. Moreover, the inverse is the same as its conjugate if quaternion is unitary.

$$Inv\ (\boldsymbol{q}) = \boldsymbol{q}^{-1} = \frac{q^*}{\|q\|^2} \tag{5}$$

The derivative of a quaternion requires some algebraic manipulation: a) as in equation (6) in case that the angular velocity vector is in the fixed frame of reference, and b) as in equation (7) if the angular velocity vector is in the body frame of reference.

$$\dot{\boldsymbol{q}}_\omega(\boldsymbol{q}, \omega) = \frac{1}{2} q \otimes \begin{bmatrix} 0 \\ \omega \end{bmatrix} = \frac{1}{2}(Q)\boldsymbol{q} \begin{bmatrix} 0 \\ \omega \end{bmatrix} \tag{6}$$

$$\dot{\boldsymbol{q}}_{\omega'}(\boldsymbol{q}, \omega') = \frac{1}{2} q \otimes \begin{bmatrix} 0 \\ \omega' \end{bmatrix} = \frac{1}{2}(\bar{Q})\boldsymbol{q} \begin{bmatrix} 0 \\ \omega' \end{bmatrix} \tag{7}$$

where $\omega = [\omega_x\ \omega_y\ \omega_z]^T$. Quaternion can be used as a rotation operator if it's a unit quaternion. However the transformation is built up by multiplication of normal quaternion and conjugated quaternion as depicted in equation (8). Thus, **q** are the rotated vector **v** from the fixed frame to the body frame.

$$\omega = \boldsymbol{q} \otimes \begin{bmatrix} 0 \\ \mathbf{v} \end{bmatrix} \otimes \boldsymbol{q}^* \tag{8}$$

The equations (9), (10) and (11) below are the rewritten of **v** in equation (8) with the x, y and z axis.

$$R_x(\boldsymbol{q}) = \boldsymbol{q} \otimes \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \otimes \boldsymbol{q}^* = \begin{bmatrix} q_0{}^2 + q_1{}^2 - q_2{}^2 - q_3{}^2 \\ 2(q_1q_2 + q_0q_3) \\ 2(q_1q_3 - q_0q_2) \end{bmatrix} \tag{9}$$

$$R_y(\boldsymbol{q}) = \boldsymbol{q} \otimes \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \otimes \boldsymbol{q}^* = \begin{bmatrix} 2(q_1q_2 - q_0q_3) \\ q_0{}^2 - q_1{}^2 + q_2{}^2 - q_3{}^2 \\ 2(q_2q_3 + q_0q_1) \end{bmatrix} \tag{10}$$

$$R_z(\boldsymbol{q}) = \boldsymbol{q} \otimes \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \otimes \boldsymbol{q}^* = \begin{bmatrix} 2(q_1q_3 + q_0q_2) \\ 2(q_2q_3 - q_0q_1) \\ q_0{}^2 - q_1{}^2 - q_2{}^2 + q_3{}^2 \end{bmatrix} \tag{11}$$

It should be noted that equation (12) are the extracted of quaternion vector in rotation matrix that rotates a point in a fixed coordinate system. Note that, the angle sign will be change whenever a coordinate system is rotating as in equation (13), so that the same outcomes for the conjugating of quaternion in equation (8).

$$R(\boldsymbol{q}) = [R_x(q)\quad R_y(q)\quad R_z(q)] \tag{12}$$

$$R(\boldsymbol{q}) = \begin{bmatrix} R_x(\boldsymbol{q})^T \\ R_y(\boldsymbol{q})^T \\ R_z(\boldsymbol{q})^T \end{bmatrix} \tag{13}$$

Specify a reference or creates error can be done by using the notation denotes in equation (14) that represent the rotation of rotation vector as it has a direct physical connection, where **u** is the rotation axis (unit vector) and **α** is the angle of rotation.

$$\boldsymbol{q} = \cos(\tfrac{\alpha}{2}) + \boldsymbol{u}\sin(\tfrac{\alpha}{2}) \tag{14}$$

Finally, utilizing equation (15) and (16) respectively can be performed for the conversion from Euler angles to quaternion and from quaternion to Euler angle. If the aim is to represent an orientation in angles, this property is very useful, while retaining the overall dynamics of the system in a quaternion form.

$$\boldsymbol{q} = \begin{bmatrix} \cos\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\psi}{2}\right) + \sin\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\psi}{2}\right) \\ \sin\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\cos\left(\frac{\psi}{2}\right) - \cos\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{\psi}{2}\right) \\ \cos\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\psi}{2}\right) + \sin\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\psi}{2}\right) \\ \cos\left(\frac{\phi}{2}\right)\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\psi}{2}\right) - \sin\left(\frac{\phi}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\psi}{2}\right) \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} \boldsymbol{\phi} \\ \boldsymbol{\theta} \\ \boldsymbol{\psi} \end{bmatrix} = \begin{bmatrix} \operatorname{atan2}(2(q_0q_1 + q_2q_3), q_0{}^2 - q_1{}^2 - q_2{}^2 + q_3{}^2) \\ \operatorname{asin}(2(q_0q_2 - q_3q_1)) \\ \operatorname{atan2}(2(q_0q_3 + q_1q_2), q_0{}^2 + q_1{}^2 - q_2{}^2 - q_3{}^2) \end{bmatrix} \tag{16}$$

III. QUATERNION BASED QUADROTOR MODELLING

Figure 1 depicted the modelling of quadrotor's attitude dynamics which been assumed as rigid and symmetrical. The effects of gravity are neglected while the differential forces will affect the rotation created by the propeller.

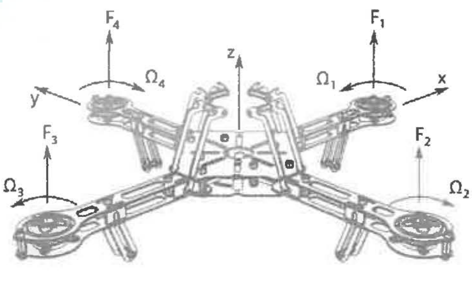

Figure 1: A sketch of Quadrotor without propeller attached [18]

Chapter 4

CONCLUSION AND FUTURE WORKS

4.1 Conclusion

Multi-rotor Unmanned Aerial Vehicles (UAV) with high duration flight capability for the use in crop dusting application. Modelling of the UAV based on black box modelling has been done in chapter 2. The black box model and the quaternion modelling has been done. Based on nonlinear P2 controller, the quaternion model with the controller has been developed in MATLAB Simulink. Genetic algorithm has been inserted into the controller to optimize it. The quaternion model with the optimized P2 controller has been written in chapter 3. The simulation result shows promising result.

4.2 Future Work

Although the controller has been done, further work is still needed. Among the work that is needed are as follow:

1. To include controller which can cater for high gust is needed.
2. Testing on hardware is also needed.

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