DYNAMIC MODELLING AND CONTROL OF HEXAROTOR SYSTEM USING PORT CONTROL HAMILTONIAN (PCH) AND PID APPROACH

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DYNAMIC MODELLING AND CONTROL OF HEXAROTOR SYSTEM USING PORT CONTROL HAMILTONIAN (PCH) AND PID APPROACH

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2021

DECLARATION

I declare that this thesis entitled "DYNAMIC MODELLING AND CONTROL OF HEXAROTOR SYSTEM USING PORT CONTROL HAMILTONIAN (PCH) AND PID APPROACH" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this report entitled "DYNAMIC MODELLING AND CONTROL OF HEXAROTOR SYSTEM USING PORT CONTROL HAMILTONIAN (PCH) AND PID APPROACH" and in my opinion, this thesis it complies the fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

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DEDICATIONS

To my beloved mother and father, thank you for your support on me to finish this study. During these time, the financial and mental support from both of you has been assisting me go through this journey. Your great contributions will not be forgotten.

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ABSTRACT

In recent years, the rapid development of technology and internet has made drones a commercial commodity. The engineer always finds a way to optimize drone models with various classical mechanics methods and Hamiltonian is well known for energy conservation with its powerful geometric techniques for studying dynamical systems. Hence, the applicability of the Hamiltonian model on hexarotor system is awaited to be examined. Therefore, this study was developing a mathematical model of hexarotor system using port control Hamiltonian (PCH) and Proportional-Integral-Derivative (PID) approach. To investigate this statement, the vertical take-off landing experiments were conducted in a controlled environment by simulate hexarotor operate on the desired path and observe its translational and rotational dynamics. PI, PD, and PID controller were implemented into hexarotor system, and PID controller obtained 30% better stability than PD controller, 70% less error than PI controller. In comparison to other controllers, the overall performance of PID controller is excellent.

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ABSTRAK

Dalam tahun-tahun kebelakangan ini, perkembangan pesat teknologi dan internet telah menjadikan drone komoditi komersial. Jurutera sentiasa mencari cara untuk mengoptimumkan model dron dengan pelbagai kaedah mekanik klasik dan Hamiltonian terkenal dengan pemuliharaan tenaga dengan teknik geometri yang kuat untuk mengkaji sistem dinamik. Oleh itu, kebolehgunaan model Hamiltonia pada sistem heksarotor dinanti-nantikan untuk diperiksa. Oleh itu, kajian beliau adalah membangunkan model matematik sistem heksarotor menggunakan kawalan pelabuhan Hamiltonian (PCH) dan pendekatan Proportional-Integral-Derivative (PID). Untuk menyiasat kenyataan ini, eksperimen pendaratan berlepas menegak telah dijalankan dalam persekitaran kawalan yang diketuai oleh simulasie heksarotor beroperasi di laluan yang dikehendaki dan memerhati dinamik terjemahan dan bergilir-gilir. Pi, PD, dan pengawal PID telah dilaksanakan ke dalam sistem heksarotor, dan pengawal PID memperoleh 30% kestabilan yang lebih baik daripada pengawal PD, 70% kurang kesilapan daripada pengawal PI. Berbanding dengan pengawal lain, prestasi keseluruhan pengawal PID sangat baik.

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LIST OF SYMBOLS AND ABBREVIATIONS

ζ	-	Angular velocity around x, y, z axis
ω	-	Angular velocity of rotor
D	-	Drag coefficient
F	-	Force
g	-	Gravity constant
H	-	Hamiltonian value
I	-	Inertia
T	-	Kinetic energy
L	-	Lagrangian value
l	-	Length of the hexarotor arms
m	-	Mass of the hexarotor
θ	-	Pitch angle
PCH	-	Port Control Hamiltonian
V	-	Potential energy
PID	-	Proportional-Integral-Derivative
ϕ	-	Raw angle
η	-	Rotational coordinate (roll, pitch, yaw)
C_T	-	Thrust coefficient
τ	-	Torque
C_Q	-	Torque coefficient
ξ	-	Translational coordinate (x, y, z)
VTOL	-	Vertical take-off landing
ψ	-	Yaw angle

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CHAPTER 1

INTRODUCTION

1.1 Background

Unmanned aerial vehicle, or more commonly called as drone, is a type of aircraft without a human pilot operating physically in it. The drone can be designed in various structures according to the requirement, the number of rotors is a consideration in the product design stage. There are four types of drones with three, four, six, and eight rotors on them, the arrangement of the rotor must be symmetrical to create a balanced structure. Hexarotor is the six rotors drone with the six V-arrangements lines up together in a circle, as shown in Figure 1.1.

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Figure 1.1: Hexarotor structure

Drone creates lift force from the rotors to elevate the whole body, controlling each rotor spinning rate and direction can even achieve translational and rotational dynamics. To design a functional and controllable drone, dynamic model and control system is the foundation. Classical mechanics can further describe the motion of drones by deriving the dynamic model of it, Newtonian mechanics is often used in the earlier time. Lagrangian and Hamiltonian mechanics are later introduced into the classical mechanic to describe the motion of drones by a different approach. Control system design on the drone can achieve precise and stable flight, classical controller like PID controller is common for the drone control system.

1.2 Motivation

In the research area, there are not many breakthroughs in the dynamic model of drones. Many journal papers can be found using these two mechanics, Newtonian and Lagrangian mechanics to describe their motion of drone. In (Lee, 2018), (Fernando et al., 2013) and (Ding et al., 2016) papers used Newtonian mechanics due to its simplicity advantage to describe the motion of drones. In contrast, (Walid et al., 2014) and (Jithu & Jayasree, 2016) accomplished Lagrangian mechanics on quadrotor modelling because Lagrangian involves much comprehensive consideration than Newtonian mechanics.

Recently, Hamiltonian mechanics started to adopt and used as a system framework called port control Hamiltonian. The concept of port control Hamiltonian concentrate on preserving system energy because of its formalism. This model slowly began to implement in many other dynamic systems, such as electrical circuits by (Adibi et al., 2017). Again, (Meng et al., 2020) applied the port control Hamiltonian model on their tank system to utilize its characteristics. Since port control Hamiltonian is a relatively new model and the mathematical field of the drone is waiting to be developed. Hence, using port control Hamiltonian to derive the dynamic model of the drone can be considered as a breakthrough to better interpret the motion of the drone.

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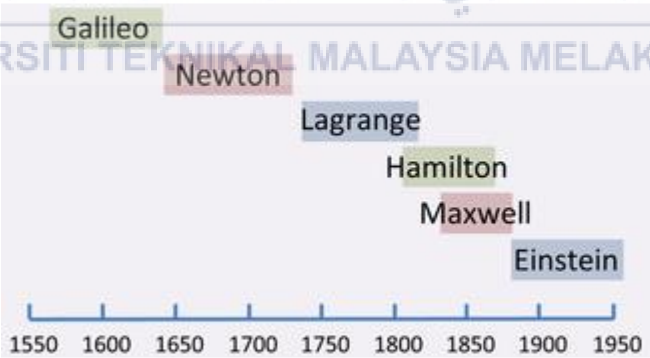

Figure 1.2: Development of classical mechanics

1.3 Problem statement

In (Wu et al., 2018) paper, they used the port control Hamiltonian model to derive the dynamic model of a quadrotor and claimed that there are few advantages over Newtonian and Lagrangian mechanics. In Newtonian mechanics, there is an inefficient method to describe the attitude system for the drone. The other is Lagrangian mechanics are too complicated to design a controller with its model. These facts prompt the author to introduce a new approach to the drone which is port control Hamiltonian.

The statements on the Hamiltonian model claimed in this paper believed that it could bring great efficiency on controller design due to its former states consist of generalized momentum. This information can better describe the attitude system of the drone from a control aspect. In addition, the Hamiltonian model has related more aptly to the idea of energy than the Lagrangian model. Thus, the Hamiltonian is a compact model. Nevertheless, this paper is focused on quadrotor modelling with no other multirotor aerial vehicles. This project is to investigate the applicability of the port control Hamiltonian model on the hexarotor system whether identical to the quadrotor system.

1.4 Objective

The objectives of this project are:

1. To derive the mathematical dynamic model of hexarotor by port control Hamiltonian approach.
2. To design PI, PD, and PID controller for the hexarotor system.
3. To compare and analyse the outcome from different controllers in terms of stability and performance.

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1.5 Scope

In this project, the hexarotor aerial vehicle will become the only focus area to study with the port control Hamiltonian model. The hexarotor model is derived with a mathematical approach and using Legendre transform to obtain the Hamiltonian model. Hence, the control system of hexarotor can be designed with the Hamiltonian model. PI, PD, and PID controller will be implemented into the hexarotor system to conduct each vertical take-off landing experiment under a software environment. In this case, MATLAB is a suitable computational software that manages to perform numerical simulations. Modelling and control of the hexarotor system are extended to Simulink, a graphical extension to MATLAB. The outcome from these controllers is taken in the form of graphical representation which can be further analysed and make comparisons from a different aspect.

1.6 K-chart

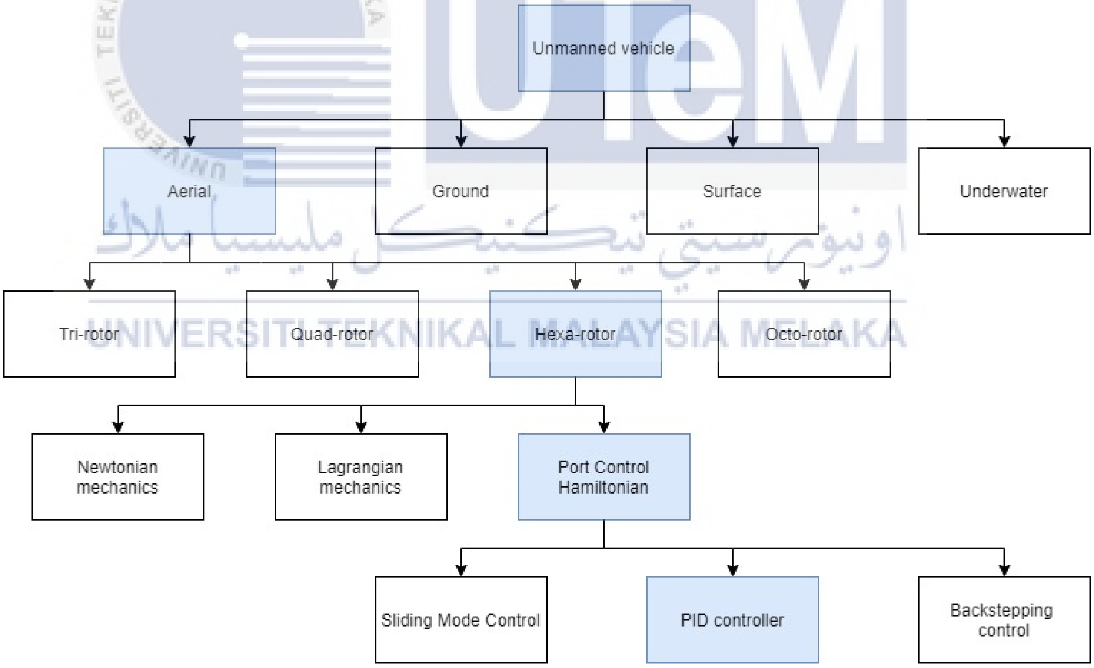

Figure 1.3: K-chart

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CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, various related articles and journal papers are reviewed then synthesis on the pros and cons of each highlight to formulate the framework for this project. Past studies on the multirotor aerial vehicle, mathematical modelling, and controller design will be collected and summarized in each table. Journal papers and articles are getting from IEEE Xplore, Scopus, and ScienceDirect that are reliable and trustable scientific publication websites.

2.2 Past studies on multirotor aerial vehicle

(Ireland et al., 2015), the paper compared different multirotor configurations in closed-loop performance, hexarotor with unusual design affords great manoeuvrability over the other configurations and claimed it is possible to achieve horizontal flight capability. There are less distinctive in quadrotor and octorotor, with extra rotor configuration generate additional thrust but consume significantly more power.

(Rashad et al., 2020) conclude that hexarotor structure has mechanical simplicity and ease of transforming into a fully actuated vehicle and (Magnussen et al., 2014) paper shows 6 rotors drone have the longest flight time. However, (Benzaid et al., 2016a) paper reveals no difference in behaviour and have good stabilization between three multirotor aerial vehicles in 3D trajectory tracking experiment. The great efficiency of controller application with the dynamic model is regardless of the number of rotors.

Table 2.1: Past studied on multirotor aerial vehicle

<table>
<tr><th>Keyword</th><th>Type</th><th>Characteristics</th></tr>
<tr><td rowspan="3">Multirotor aerial vehicle</td><td>Quadrotor (Magnussen et al., 2014)</td><td>✓ Ease of design
✓ Best dynamic performance</td></tr>
<tr><td>Hexarotor (Ireland et al., 2015; Magnussen et al., 2014; Rashad et al., 2020)</td><td>✓ Longest flight time
✓ Great manoeuvrability
✓ Mechanical simplicity</td></tr>
<tr><td>Octorotor (Ireland et al., 2015)</td><td>✓ More thrust generated
✗ More power consumed</td></tr>
</table>

2.3 Past studies on dynamic modelling of drone

In a past study, (Benzaid et al., 2016b) concluded that the same mathematical model applied on the different multirotor aerial vehicles does not make any difference on performance and stability. Therefore, (Mersha et al., 2011) study focus on port-based modelling and control of the drone without mention a specific type of multirotor. This study design the port-Hamiltonian system for the underactuated aerial vehicle, well demonstrate the effectiveness of the proposed model on trajectory tracking which is similar to (Wu et al., 2018) research. The experiment result of these two papers shows the consistent drone navigation in pre-set trajectory.

Poor consistency of drone navigation happens in (Ding et al., 2016) research when his mathematical model is derived by the Newton-Euler method. However, (Walid et al., 2014) use the Euler-Lagrange method to derive and obtain a better result than the Newton-Euler method in terms of stability and consistency. Unlike many others, (Alaimo et al., 2013) accomplished simplicity computation and numerical stability on hexarotor by quaternion parametrization to avoid gimbal lock configuration because it is more efficient and stable from a computational point of view.

Table 2.2: Past studied on mathematical modelling of drone

Keyword	Type	Characteristics
Dynamic modelling	Port control Hamiltonian (Mersha et al., 2011; Wu et al., 2018)	✓ Compactness ✓ Easiness of controller design ✓ Energy conservation
	Newton-Euler (Ding et al., 2016)	× Poor consistency in navigation
	Euler-Lagrange (Walid et al., 2014)	✓ Stability ✓ Consistency
	Quaternion parametrization (Alaimo et al., 2013)	✓ Simplicity computation ✓ Numerical stability

2.4 Past studies on controller design on drone

Controller design of drone in past studies are the main focus research area, few advancements are made on developing non-linear controller. (Salim et al., 2015) research indicates the advantage of the proposed robust controller in minimizing external disturbance, but poor stability would be the disadvantage. In opposite, (Han & Jin, 2015) propose a linear controller, PD with an external P controller on hexarotor helicopter and acquire reasonable outcomes in regulating overshoot.

In (Mallavalli & Fekih, 2018) paper also present a great performance by sliding mode controller on quick fault accommodation to prevent performance degradation. However, (Ahmad et al., 2020) focus on improving the sliding mode control system by implementing an improved double integral method. This integrates controller technique shows strong chattering-free characteristics when compared to normal sliding mode controller. Furthermore, (Arellano-Muro et al., 2013) integrate backstepping control and sliding mode estimation into hexarotor to withstand external disturbances and parameter variations.

Table 2.3: Past studied on controller design of drone

Keyword	Type	Characteristics
Controller design	Non-linear (Salim et al., 2015)	✓ Minimize external disturbance ✗ Poor stability
	Linear (Han & Jin, 2015)	✓ Regulate overshoot
	Sliding mode (Mallavalli & Fekih, 2018)	✓ Quick fault accommodation
	Sliding mode & double integral (Ahmad et al., 2020)	✓ Strong chattering-free characteristic
	Backstepping & sliding mode (Arellano-Muro et al., 2013)	✓ Withstand external disturbance ✓ Parameter variations

2.5 Summary

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Table 2.4 summarize on past studies and categorised by keywords, then list out their advantage and disadvantage. The determined relation from many past studies on drone is predictable. Many researchers used integrate technology on drone such as integrate controller to minimize the external disturbance and advancing drone performance. But the correlation between mathematical model and control system on drone is concrete and complementarity. Therefore, studies of introduce new system design on drone can be ground-breaking for the drone design topic. New system design method associates with the hexarotor structural advantage brings great value to drone innovation. So, the complementarity characteristics between different systems embed and external layout is essential correspondingly.

Table 2.4: Literature review table

Keyword	Type	Advantages
Multirotor aerial vehicle	Hexarotor	✓ Longest flight time(Magnussen et al., 2014) ✓ Great manoeuvrability(Ireland et al., 2015)
Dynamic modelling	Newton-Euler method	✓ Simplicity model
	Euler-Lagrange method	✓ Consistency & stability(Walid et al., 2014)
	Port control Hamiltonian system	✓ Compactness & energy-efficient(Wu et al., 2018)
Controller design	PID controller	✓ Simplicity design
	Nonlinear controller	✓ Minimize disturbance(Salim et al., 2015)
	Integrated controller	✓ Chattering-free characteristic(Ahmad et al., 2020)

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