DEVELOPMENT OF TEST RIG FOR QUADROTOR FLIGHT TESTING INSIDE WIND TUNNEL USING MOTION CAPTURE SYSTEM

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UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

2022

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Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional Malaysia, in fulfilment of the requirements for the Degree of Master of Science (Electric & Electronic Engineering)

2022

ABSTRACT

The study of station keeping of a hovering quadrotor under various turbulent wind conditions has gained a lot of attention these days due to its potential application in complex environments. Different kind of control algorithm has been developed to increase the performance of the quadrotor under such wind condition and need to be tested and verified by actually flying the quadcopter itself. One of the quick and low-cost solution would be to set up a test rig by modifying an existing wind tunnel to recreate such wind conditions. By attaching the open jet wind tunnel which has a diverged shape integrated with Settling Chamber, a new flight space with turbulence wind flow constructed. The maximum wind speed at the opening is 8 m/s. The extended wind tunnel's flow characteristics are analyzed by the anemometer for velocity distribution in four different distances from the opening Augmented with Motion Capture System provide real time pose and velocity information of quadrotor hovering at rate of 120Hz. Quadrotor flight performance been tested indoor lab and new flight space of UPM wind tunnel either with and without wind rejection algorithm. Maintaining hovering in constant position in turbulence wind condition can be endured by utilize existing Extended High Gain Observer (EHGO) as wind rejection algorithm. The replicate real world turbulence wind is measured and wind profile recorded. The wind rejection algorithm measure real time tracking quadrotor hovering been showing rare data in turbulence wind. This test rig will be unique capability in creating turbulence wind condition for flight test of quadrotor hovering embedded existing wind rejection algorithm.

ABSTRAK

Pemanduan kuadrotor akan terganggu disebabkan oleh pelbagai keadaan angin yang bergelora telah mendapat perhatian berpotensi semasa terhadap persekitaran yang kompleks. Pelbagai kawalan algoritma diciptakan untuk meningkatkan prestasi kuadrotor dengan angin sedemikian dan perlu diuji, disahkan. Salah satu penyelesaian yang cepat dan murah adalah memasang rentetan ujian dengan mengubah terowong angin sedia ada untuk menciptakan keadaan angin tertentu. Terowong angin jet terbuka tambahan berbentuk menyimpang ditambah dengan dewan penempatan, dapat memberi ruang penerbangan yang baru dengan aliran angin pergolakan. Kelajuan angin maksimum ialah 8 m/s. Ciri aliran terowong angin tambahan dianalisis oleh anemometer untuk halaju angin dari empat jarak yang berbeza dari bukaan. Sistem Tangkap Gerak dipasang dan memberikan maklumat masa sebenar quadrotor berlegar pada kadar 120Hz. Prestasi penerbangan kuadrotor akan diuji makmal tertutup dan terowong angin UPM ruang baru dengan atau tanpa algoritma penolakan angin. Mengekalkan kedudukan tetap dalam keadaan angin pergolakan dibantu oleh Pemerhati Keuntungan Tinggi yang Dipanjangkan (EHGO) yang sediaada sebagai algoritma penolakan angin. Replika angin putaran pada 100m di atas tanah diukur dan profil angin direkodkan. Algoritma penolakan angin mengukur penjejakan masa nyata kuadrotor terbang telah menunjukkan data yang jarang berlaku dalam angin pergolakan. Pelantar ujian ini adalah unik mampu mewujudkan keadaan angin pergolakan bagi ujian penerbangan kuadrotor secara melayang bersama dengan algoritma penolakan angin tersedia ada di dalamnya.

ACKNOWLEDGEMENTS

Alhamdulillah, praise be to Allah the Almighty upon the completion of Master of Science Project and Thesis during Pandemic Covid-19. The author would like to express his deep gratitude to the following people for their support and assistance during this project. Foremost, the author would like to extend the special thanks to the supervisor, Dr. Elya binti Mohd Nor for her patient guidance, enthusiastic encouragement, together with supporting in a harsh time in the current pandemic. With her proper guidance, the author managed to understand well and teach more about the non-linear equation, high-gain observers, and flight algorithms in turbulence conditions also MATLAB Simulink. For co-supervisor Dr. Syaril Arzad bin Md Ali (UPM) and Assoc. Prof. Ir. Ts. Dr. Mohd Rashdan bin Saad give motivation, support, and emphasis to do this project until publishing research paper, great guideline, and learning a lot of new software in aerospace. This author would like to thanks to Ministry of Higher Education give an opportunity and supported this project thru the Fundamental Research Grant Scheme, FRGS (grant no: FRGS/1/2018/TK09/UPNM/03/3).

The author would also like to acknowledge, Mr. Muhammad Rijaluddin bin Bahiki and Mr Azizie for support on the project programming language in Visual Studio software. Huge thanks go to Assoc. Prof. Dr. Azmin Shakrine and Mr. Saiffairus give UPM Wind Tunnel facilities and coach in this project, without them the research would not have been completed.

Finally, an honorable mention goes to the author's family especially his mother and friends, for their support and encouragement throughout his study. Praise be to Allah, who made all things possible.

APPROVAL

The Examination Committee has met on **1st September 2021** to conduct the final examination of **Muhammad Zufar Bin Jurij** on his degree thesis entitled '**Development of Test Rig for Quadrotor Flight Testing inside Wind Tunnel using Motion Capture System'.**

The committee recommends that the student be awarded the Master of Science (Electric and Electronic Engineering).

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This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Electric & Electronic Engineering)**. The members of the Supervisory Committee were as follows.

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Date of birth : 18 November 1988

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Academic session : 2019-2021

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LIST OF ABBREVIATIONS

UPNM	Universiti Pertahanan Nasional Malaysia
MINDEF	Ministry of Defence
STRIDE	Science and Technology Research Institute for Defence
ARMA	Autoregressive Moving-average
CAN	Controller Area Network
CCD	Charge-coupled Device
CFD	Computational Fluid Dynamic
ComPort	Communication Port
DOB	Disturbance Observer Based
DOF	Degree of Freedom
EHGO	Extended High Gain Observer
EKF	Extended Kalman Filter
ESC	Electronic Speed Control
FMU	Flight Controller Unit
FPU	Floating-Point Unit
GCS	Ground Control Station
GNC	Guidance, Navigation and Control
GPS	Global Positioning System
GUI	Graphical User Interface
HC	Hierarchical Controller
I2C	Inter-Integrated Circuit
IIUM	International Islamic University Malaysia
IMU	Inertial Measurement Unit
IOD	Internet of Drone
IR	Infrared
JAXA	Japan Aerospace Exploration Agency
LIDAR	Light Detection and Ranging
LiPo	Lithium-ion Polymer
m	Mass
MAV	Micro Aerial Vehicle
MAVLink	Micro Air Vehicle Link
MAVSec	MAVLink Security
MCS	Motion Capture System
MLP	Multi-Layered Perceptron
ONERA	Office National d'Etudes et de Recherches Aérospatiales
OVLI-TA	Objet Volant Leger Instrumenté–Turbulence Atmosphérique
PC	Personal Computer
PID	P = Proportional, I = Integral, and D = Derivative
PIV	Particle Image Velocimetry
PWM	Pulse Width Modulation
RANS	Reynolds-averaged Navier–Stokes

RC	Remote Control
RX	Receiver
SDK	Software Development Kit
SIRIM	Standard and Industrial Research Institute of Malaysia
SMC	Sliding Mode Controller
TX	Transmitter
UART	Universal Asynchronous Receiver-Transmitter
UAV	Unmanned Aerial Vehicle
UiTM	Universiti Teknologi MARA
UPM	Universiti Putra Malaysia
UPNM	Universiti Pertahanan Nasional Malaysia
USA	United State of America
UTM	Universiti Teknologi Malaysia
VTOL	Vertical Take-off and Landing

LIST OF ANNOTATIONS

z	z coordinate of the quadrotor
θ	Roll angle of quadrotor
τ	Torque
ψ	Yaw angle of quadrotor

CHAPTER 1

INTRODUCTION

The Quadrotor is one of part of Unmanned Aerial Vehicle (UAV) in under vertical take-off and landing (VTOL) that utilize 4 rotors to perform the stable flight. In natural wind environment there are 2 types of wind conditions, laminar flow like a linear free stream flow and turbulence flow in which there is no fixed pattern and high irregularity. This will be challenging for the quadrotor to fly in stable condition if wind becomes certain high turbulence air flow. There are many cases of UAV crashes due to turbulence airflow even the UAV is equipped with the latest firmware or algorithm. This thesis presents an experimental setup for the development and testing of quadrotor flight in an open jet wind tunnel with turbulence flow.

1.1 Introduction

Robotic replace a human for working in a dangerous situation, complex and high repeatability and high precision. Unmanned Aerial Vehicle (UAV) which is one of robotics for aerospace application, has become the top choice technology of many researchers nowadays. UAVs can either be controlled autonomously through on-board computers or by the remote control of a pilot on the ground. UAV has huge benefits for the military section, photographer, aerospace industry, surveillance, air

racer sport, and entertainment shows. Quadrotor is one type of the VTOL UAVs current researcher make for their study as priority compares to others such as hexarotor and trirotor due to lack of servo-controlled trust vectoring [1], .

In recent years, many efforts have been put to further investigate flight UAVs in real environments [2]–[6]. Many methods have been addressed to solve this problem such as putting additional sensors to quadrotors, designing failsafe programming to control the quadrotor, or adding an emergency button that triggers when the abnormal wind occurs. This approach was introduced in several applications on firmware for UAVs its safety flight, avoiding properties losses and unexpected incident. Thus, researchers are now trying to expose several approaches, techniques, programming, and algorithm to obtain the best technique to be used.

In terms of low cost, the Optitrack Motion Capture System capable to capture the quadrotor system with position and angular output data. Since this project will be conducted in a wind tunnel, the current position sensor of the quadrotor that uses GPS will not function. The data is using longitude and latitude which low accuracy and low precision compared to the Motion Capture System. The advantages of using Motion Capture System will give data of sub-20 μm accuracy in optimal conditions but in this project only using meter.

In quadrotor especially for Pixhawk flight controller consist own controls system and the controls system can tune and calibration using Mission Planner Software or Qgroundcontrol. In extreme wind condition that produce by wind tunnel another set of control system or additive control system need to validate in certain

wind condition with certain wind estimator to cater a better quadrotor flight testing in wind tunnel with turbulence intensity.

1.2 Problem Statement

The experiment setup has three main components which are a wind tunnel, a motion capture system, and a quadrotor. The wind tunnel represents wind condition. Meanwhile, the motion capture camera is to gather quadrotor motion data and a quadrotor that able to integrate all components with support by an external computer. Due to limitation of wind tunnel to create turbulent wind, other method is using outdoor wind and portable fans as experiment study of UAV in turbulent wind condition. In order to replicate the outdoor wind environment condition for future applications, modifying an existing wind tunnel their limited wind tunnel capable to create turbulence flow due to many factors cause this restriction of design and this will first problem need to solve. To understand turbulence flow as a new study, need to understand how much turbulence applied for UAV to get flight stability and hovering inside wind tunnel secondary problem. Further studies in wind rejection algorithm need to conduct to relate between control parameters such as gain with the wind characteristics by using this test rig as a platform capable to validate performance of wind rejection algorithm. Since the existing wind rejection such as EHGO will be third problem for this test rig capable to validate one of wind rejection algorithm. Last, allocation to fix quadrotor in wind tunnel is importance for better safety flight and data collection.

1.3 Objective of the Research

The aim of this research is to develop, and this study aims to achieve an autonomous flight of UAVs hovering in turbulence conditions on a relative positioning system using a low-cost motion camera. This is accomplished through three research objectives:

1. To develop Motion Capture System (MCS) inside wind tunnel for that is able to capture motion of quadrotor UAV in presence of wind generated by wind tunnel.
2. To demonstrate the capability of the developed system through a stability study of quadrotor flight hovering in x and y axis positioning under turbulent wind.
3. To validate wind rejection algorithm by using EHGO under turbulent wind condition generated by the wind tunnel.

1.4 Scope of Study

This study focuses on development of experiment setup that integrates open jet wind tunnel, quadrotor, and motion capture camera and ground station computer. Using Universiti Putra Malaysia Open Jet Wind Tunnel and their new attachment capable to create turbulence flow needs to be verified and validate with turbulence under 30% and wind speed under 9 m/s. The test section for flight test must over 1m x 1m for suitable quadrotor hovering. The quadrotor is DJI 450 with Pixhawx 2.1 flight controller and attach with telemetry for making a stream connection to ground control computer. For motion capture system is, 6 units Optitrack camera model Flex13 with

Motive Software to capture motion and stream data. All component integration as known as test rig will be streaming data to each other and able to insert new algorithm for flight testing as a future development.

1.5 Contribution

The completion of this thesis has yielded a number of contributions to the new approach of flight characteristic for quadrotor in turbulence wind condition. In particular, the following milestones have been achieved:

• Development of a turbulence wind tunnel which nearly to 30% of turbulence intensity suitable to replicate a real environment turbulence intensity wind speed of the exhaust and normal wind speed in Malaysia [7].

• The design and development of Motion Capture System in the outdoor environment integrated with Wind Tunnel that is attached with test section or outdoor test section by consideration of field of view infrared camera, vibration, disturbance, transmissive, and other constraint in Chapter 3.

• The design and evaluate test subject (quadrotor) for the best flight testing instead of making a strut or safety cable that will create certain limitation of quadrotor flight characteristic, presented in Chapter 3.

• The validation of the adaptive EHGO techniques, through a real flight-testing experiment in the new development of turbulence wind tunnel presented in Chapter 4.

CHAPTER 2

LITERATURE REVIEW

This chapter describes some studies that have been done to study the 6 main components of the development of the UAV significant effect experiment in the Wind Tunnel. Special emphasis was given to the research carried out in the wind tunnel experiment using quadrotor. A literature review on the development of Quadrotor Experiment Method, Wind Tunnel Experiment Setup, Replicate Real World Wind Characteristic, Motion Capture System, Programming Language, Telemetry Communication and Disturbance Estimation will be discussed in term of development the new test rig.

2.1 Introduction of UAV

Over the decade, Unmanned Arial Vehicles (UAV) has attracted a great interest among practitioner owing to its numerous applications in civilian sectors to replace human. These include assessment of damage caused by natural or manmade hazards, terrain monitoring for agriculture, exploration of remote and inaccessible. fix wing and Vertical Take-off and Landing (VTOL) are two main types of UAV. The fix wing

UAV is most likely operational as an aeroplane. Unlike VTOL UAV which have various type depend on it rotor attached on it, especially quadrotor (4 rotor attached) is growing rapidly as a popular platform in the UAV research. This is because of the vehicle have capability to fly and hover at very low altitudes and speeds, good manoeuvrability, and its superiority over other VTOL type in terms of simplicity in the mechanical structure Elya *et. al* [8].

UAV work advancing and becoming a phenomenon for both UAV VTOL and Fix Wing in 2007 and the researcher continues the Wind Tunnel experiment by Sikkel *et. al*, [9] to increase their efficiency and future development. Among the problems related to the determination of wind characteristics, many researchers have based their work on the development of wind engineering and aerodynamics applied to UAVs with Wind Tunnel, Outdoor and Simulation experiments.

Wind is one of the major concerns in many aerospace industries, such as aircraft, space exploration, wind turbine energy systems, hot air balloons, helicopters, rockets, jet-fighters, gliders, drones, shuttles, and many more. Researchers believe that UAVs capable of countering the uncertainty of the wind tunnel will become the main subject of a wind experiment capable of generating laminar flow and turbulence Waslander & Wang, [10]. Since the first attempt to study the wind tunnel, Francis H. Wenham, Horatio F. Phillips and Hiram S. Maxim have been built in the United Kingdom; then Ludwig Mach in Austria; Charles Renard and Etienne Marey in France; H.C. Vogt and Paul LaCour in Denmark; and USA reviewed by Gorbushin *et. al*, [11]. The proposed wind tunnel at that time is used to test the air drag and

stability of the axisymmetric bodies, to develop a study on the design of helicopters and kites, and finally to investigate the high atmospheric layers.

One important strategy to deal with turbulent wind conditions would be to use a robust control algorithm compared to a linear and non-linear control algorithm to deal with unpredictable wind conditions. To test the performance of the control strategy, the first method is to use computer-based simulations instead of using the UAV itself to generate high costs and require the Wind Tunnel to validate the data. Many research groups have used this approach to simulate UAVs in turbulent condition such as using ONERA simulation by Perozzi *et. al*, [12], using both computer simulation and outdoor tests by Ke *et. al* [13] and Joyo *et. al* [14] using MATLAB.

Another concern in flight in turbulence flow is forces and moments experienced by the vehicle there will create variable position control law. Turbulent wind effect is difficult to model even with detailed of Computational Fluid Dynamics (CFD) analysis and by creating assumptions such as constant wind fields are often used and have been considered more closely. The main reason for these assumptions is that short term and this approach is impractical from a control point of view that study by Waslander & Wang, [10]. The main contribution of this work is the use of the Dryden gust model in simulation and outdoor wind to study the effectiveness of their estimation of wind disturbance and rejection strategy. Bannwarth *et. al* [15] and Elya *et. al* [8] applied portable fan to generate indoor wind disturbances to study wind rejection. Even both are using same methodology using motion capture system, but the algorithm outcome is different which Bannwarth attempt to make 2 types of