UNIVERSITI PUTRA MALAYSIA

MODELLING THE DYNAMICS AND CONTROL SYSTEM OF HYBRID AIRSHIP UAV (HAU-3)

MOHD FAZRI BIN SEDAN

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By

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

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DEDICATIONS

I dedicated this thesis to my parents Sedan Ila and Mainas Tatar, with love: It takes a single step to begin a successful journey… stay strong, be patient and preserved, and everything will be right where it belongs…

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

MODELLING THE DYNAMICS AND CONTROL SYSTEM OF HYBRID AIRSHIP UAV (HAU-3)

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April 2022

Chair : Ahmad Salahuddin Mohd Harithuddin, PhD
Faculty : Engineering

In this thesis, a 3.3 m length, finless hull airship called HAU-3 is presented. Four vector thrusters arranged in H-Frame configurations were attached to the hull, which enable the airship to maneuver in 5DOF. To allow a deeper understanding of the HAU-3 motion behavior and to design a flight controller, a reliable dynamics model representation and simulator of HAU-3 are developed. A six-degrees of freedom (6DOF) non-linear mathematical model representation is constructed using the Newton-Euler approach. The dynamics model parameters were identified via semi-empirical, computer-aided modelling (CAD) and experimental approaches. The HAU-3 dynamics model was then integrated into Simulink and MATLAB to construct a closed-loop simulator to analyze the airship's behavior. Five separate Proportional, Integral and Derivative (PID) controllers were designed using the developed non-linear dynamic model. A series of indoor static tests and outdoor flight tests were conducted to evaluate the controller performance and to validate the simulator response. A dynamic response model of the vector thrusters developed provides excellent agreement with the actual thrust and motor transient response with 0.29 s delay and 0.2 N steady-state error. The indoor static test of the yaw controller shows an adequate yaw state change tracking performance with a 9.5% average difference in maximum overshoot and approximately 30% settling time difference by comparison of actual and simulated responses. The controller is able to suppress the pendulum oscillation in pitch and roll with 0.165 Hz and 0.3 Hz oscillation frequency, respectively and at least 20° maximum angle deviation. The altitude controller also shows an excellent performance in tracking the change in altitude

during outdoor flight tests with an average 0.5 m altitude difference between simulation and actual recorded altitude. The developed HAU-3 simulator provides a reasonable estimate of the airship's attitude and translational states for modelling and simulation purposes.

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

PEMODELAN DINAMIK DAN SISTEM KAWALAN UAV PESAWAT HIBRID (HAU-3)

Oleh

MOHD FAZRI BIN SEDAN

April 2022

Pengerusi : Ahmad Salahuddin bin Mohd Harithuddin, PhD
Fakulti : Kejuruteraan

Tesis ini membincangkan mengenai sebuah pesawat tanpa sirip sepanjang 3.3 meter yang dikenali sebagai HAU-3. Empat penujah vektor yang disusun dalam konfigurasi H-Frame telah dipasang pada badan pesawat yang membolehkan pesawat bergerak dalam sistem 5DOF. Bagi pemahaman yang lebih mendalam tentang tingkah laku gerakan HAU-3 dan bagi tujuan mereka bentuk alat pengawal penerbangan, perwakilan model dinamik yang boleh dipercayai dan simulator HAU-3 dibangunkan. Pewakilan model matematik bukan linear enam darjah kebebasan (6DOF) dibina menggunakan pendekatan Newton-Euler. Parameter model dinamik dikenal pasti melalui pendekatan semi-empirikal, reka bentuk berbantu komputer (CAD) dan eksprimen. Model dinamik HAU-3 kemudiannya disepadukan ke dalam Simulink dan MATLAB untuk membina simulator gelung selanjar rapat untuk menganalisis tingkah laku pesawat. Lima alat kawalan *Proportional, Integral dan Derivative (PID)* berasingan telah direka bentuk menggunakan model dinamik bukan linear yang telah dibangunkan. Satu siri ujian statik dalaman dan ujian penerbangan luar telah dijalankan untuk menilai prestasi alat kawalan dan untuk mengesahkan tindak balas simulator. Model tindak balas dinamik penujah vektor yang dibangunkan memberikan keserasian yang sangat baik dengan tujahan sebenar dan motor sambutan fana dengan lengah 0.29s dan ralat keadaan mantap 0.2 N. Ujian statik dalaman alat kawalan rewang menunjukkan prestasi pemacu perubahan keadaan rewang yang mencukupi dengan perbezaan purata 9.5% dalam melewati maksimum dan kira-kira 30% perbezaan masa enapan dangan perbandingan tindak balas simulasi dan tindak balas sebenar. Alat kawalan mampu menahan ayunan bandul dalam anggul dan beroleng dengan ayunan 0.165 H dan 0.3 Hz frekuensi

ayunan masing-masing sekurang-kurangnya 20° sudut sisihan maksimum. Alat kawalan altitud juga menunjukkan prestasi cemerlang dalam menjejaki perubahan altitud semasa ujian penerbangan luar dengan purata perbezaan ketanggian 0.5 m antara simulasi dan ketinggian sebenar yang direkodkan. Simulator HAU-3 yang dibangunkan menyertakan anggaran yang munasabah tentang sikap pesawat dan keadaan translasi untuk tujuan pemodelan dan simulasi.

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Thank you to The Almighty, Allah S.W.T for giving me the strength and willpower to complete this research and thesis. First, I would like to take this opportunity to express my gratitude to the individuals who contributed to the completion of this research work and inspired me during the up and down of this journey. Foremost, thanks to my beloved family who always be there to give me moral support throughout my Master's Studies. Without them, it is impossible for me to achieve this stage.

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

Ahmad Salahuddin bin Mohd Harithuddin, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ermira Junita binti Abdullah, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 08 September 2022

Declaration by Members of the Supervisory Committee

This is to confirm that:

- the research and the writing of this thesis were done under our supervision;
- supervisory responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) are adhered to.

Signature: _____
Name of Chairman of Supervisory Committee: Dr. Ahmad Salahuddin bin Mohd Harithuddin

Signature: _____
Name of Member of Supervisory Committee: Dr. Ermira Junita binti Abdullah

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
ALTAV	Almost lighter than air vehicle
BR	Buoyancy ratio
CAD	Computer aided design
CCW	Counter clockwise rotation
CFD	Computational fluid dynamics
CG	Center of gravity
COB	Center of buoyancy
CV	Center of volume
CW	Clockwise rotation
DCM	Direct cosine matrix
DOF	Degree of freedom
ESC	Electronic speed controller
FF	Form factor
FOPD	First order plus delay
FR	Finesse ratio
GDOP	Geometric dilution of precision
GNSS	Global navigation satellite system
GPS	Global positioning system
HAU	Hybrid airship unmanned aerial system
HDOP	Horizontal dilution of precision
HLA	Heavy lifting airship

HTA	Heavier than air
IMU	Inertial measurement units
LED	Light emitting diode
LIPO	Lithium polymer
LLC	Low level controller
LTAV	Lighter-than-air vehicle
MAVLINK	Micro air vehicle link
METAR	Meteorological Aerodrome Reports
MPC	Model predictive controller
PCB	Printed circuit board
PID	Proportional, integrator and damping
PVC	Polyvinyl chloride
PWM	Pulse width modulation
RC	Radio controller
RGB	Red, green, blue
SISO	Single input, single output
STOL	Short take-off and landing
TPU	Thermoplastic polyurethane
UART	Universal asynchronous receiver/transmitter
UAV	Unmanned aerial vehicle
VTOL	Vertical take-off and landing

LIST OF SYMBOLS

r(x)	Radius of the hull relative to the distance from COB
M	Inertia matrix of the airship
$\boldsymbol{\nu}_B$	Velocities expressed in body frame
$\dot{\boldsymbol{\nu}}_B$	Acceleration expressed in body frame
λ	Rotation matrix
$\mathbf{F}_{external}$	Total external force and moment
$\mathbf{F}_R$	Restoring force and moment
$\mathbf{F}_P$	Propulsion force and moment
$\mathbf{F}_A$	Aerodynamic force and moment
$\mathbf{F}_C$	Coriolis and centripetal force and moment
p	Roll rate expressed in body frame
q	Pitch rate expressed in body frame
r	Yaw rate expressed in body frame
q_0	Quaternion constant
q_1	Quaternion constant 1
q_2	Quaternion constant 2
q_3	Quaternion constant 3
ε	Norm of the quaternion state vector
X	Vehicle position expressed in NED
$\dot{\mathbf{X}}_B$	Vehicle velocity and rotation rates expressed in body frame
$\mathbf{M}_{RB}$	Rigid body inertia matrix
M	Apparent inertia matrix

$\mathbf{M}_A$	Added mass inertia matrix
$\mathbf{r}_{CG}$	CG position vector
$r_{z,CG}$	Vertical position of CG relative to COB
k_1	Longitudinal added-mass factor
k_2	Lateral added-mass factor
k'	Ratio of apparent moment of inertia to the moment of inertia of displaced air
I_{zh}	Moment of inertia of the displaced air
a_1	Semi-major axis first ellipsoid
a_2	Semi-minor axis of the second ellipsoid
a_{mean}	Mean of semi-major axis of a double-ellipsoid
b	Semi-minor axis of the ellipsoid
F_g	Gravity force
F_b	Buoyancy force
V	Hull volume
g	Gravitational acceleration
ρ_{air}	Air density
ρ_{He}	Helium gas density
f	Force matrix
n	Moment matrix
η	Position and orientation of the airship relative to NED
m	The total airship mass
$C_{D\circ}$	Axial drag coefficient
S_{ref}	Aerodynamic drag reference area

S_{wet}	Wetted area for a body of revolution
S_{C_D}	The total drags area of the airship's hull
C_A	Aerodynamic axial force
C_N	Aerodynamic normal force
C_M	Pitching-moment coefficient
η	Crossflow drag proportionality factor
A_b	Base area
$\mathbf{v}$	Airship translational body velocity
$\boldsymbol{\omega}$	Airship rotational body rates
α	Angle of attack
A_p	Planform area
x_p	Centroid of the planform
T_V	Vertical thrust
T_h	Horizontal thrust
T_ϕ	Roll thrust
T_θ	Pitch thrust
T_ψ	Yaw thrust
T_R	Resultant thrust
I_{xx}	Moment of inertia in x-direction
I_{yy}	Moment of inertia in y-direction
I_{zz}	Moment of inertia in z-direction
I_{xy}, I_{xz},I_{yz}	Product of inertia
L,M,N	Roll, pitch and yaw moment

ϕ,θ,ψ	Euler angles (Roll, pitch, yaw)
u,v,w	Translational velocity in the body-fixed frame
p,q,r	Euler angle angular rate in the body-fixed frame

SUBSCRIPT

R	Restoring force dynamics model associate
x	Surge displacement
y	Sway displacement
z	Vertical (Heave) displacement
ϕ	Roll
θ	Pitch
ψ	Yaw
A	Aerodynamic dynamics model associate
a.c	Aerodynamic center parameter associate
C	Coriolis and Centripetal force dynamics model associate
P	Propulsion dynamics model associate
w	Wind disturbance associate parameters
z_{CG}	Vertical displacement of CG respect to COB

CHAPTER 1

INTRODUCTION

1.1 Research Background

After being neglected for a few decades, airships are now again a source of high interest, and new research programs are being launched around the world. This new airship trend is mainly due to three main reasons: A major concern for sustainable growth, increasing need for carrying heavy loads, and new expectations for survey and monitoring means. Their use represents a niche in the aeronautical market. LTAs are aerial platforms that get some or all of their lift from a lifting gas like helium, hydrogen, or hot air. Examples of this class of vehicle include airships, hot-air balloons and, tethered aerostats. There has been a resurgence of interest in Lighter-Than-Air Vehicle (LTAV) technology in recent decades, particularly in the advancement of autonomous technology in air vehicles. The rising of interest in LTA vehicle also due to its low energy consumption and long endurance capability (Li et al., 2011).

The autonomous airship, which is propelled by the buoyancy of lighter-than-air gases, has enormous potential as an aerial platform for a variety of applications including telecommunication relay, broadcasting relay, monitoring, experimental platform, and public security. Currently, most of the existing airship is classified as Heavy Lifting airship (HLA) where the payload is measured in tonnes. With the miniaturization of electronic technology, the scaling capability of airship can be improved from the HLA class to smaller design that can carry less than hundreds of kilograms of payload. Smaller airships that able to carry payloads ranging from 20-100 kg is suitable to extend the mission capacity of multi-copter drones, especially for missions that need more flight endurance and lifting capacity. The system of classification of airship size based on payload is depicted in Figure 1.1 and a commonly known commercial airship is presented in Figure 1.2.

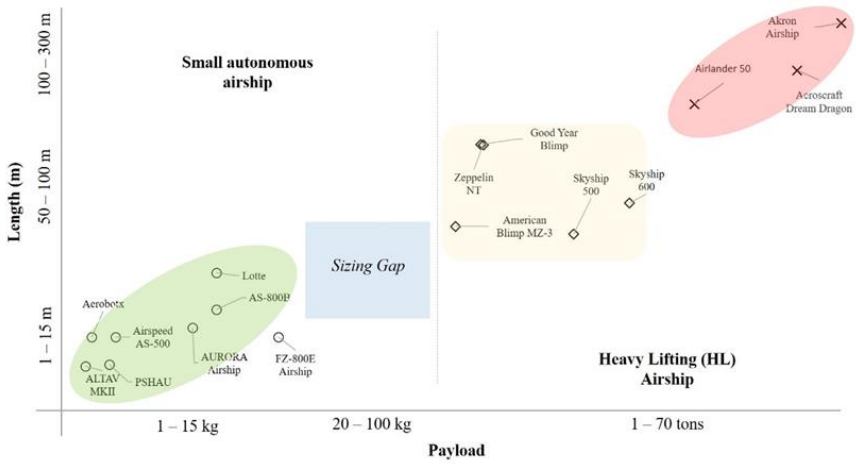

Figure 1.1: Current available airships size and payload capacity ranged from small to heavy lifting airship

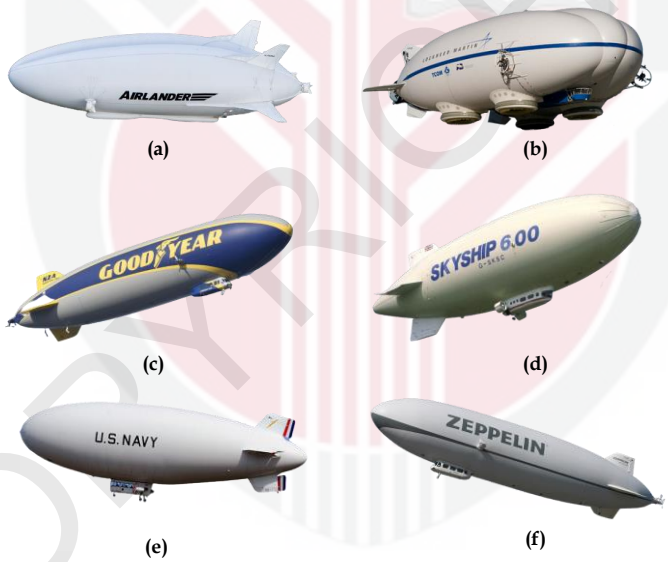

Figure 1.2: Common commercial airship. Airlander 10 (a) (Block, n.d.)**, Lockheed P-791 (b)** (*Lockheed Martin P-791 - Lockheed*, 2006)**, Goodyear Wingfoot One (c) (Goodyear, n.d.), Skyship 600 (d)** (*Airship Industries Skyship 600 - Airship Industries*, n.d.)**, US Navy MZ-3 airship (e) (Peek, 2013) and LZ N07-101 – Zeppelin (f)** (*Zeppelin NT*, n.d.)**.**

Currently, a major key area of interest for a buoyant vehicle is unmanned and autonomous airships. The application of this area is widely conducted all over the world, such as the ALTAV Quanser MkII that developed by Quanser Inc

(Liesk et al., 2012) as shown in Figure 1.3 these can be used for wide variety of application such as wildlife monitoring and surveillance due to the ability to relatively stealthy due to their lower heat and noise signature, aerial photography, atmospheric measurements, civil safety and security mission are major area of application.

Figure 1.3: ALTAV Quanser MkII airship (Liesk et al., 2012)

Due to the low mass of the typical payload, unmanned, autonomous airship is generally much smaller than airship for cargo or passenger transportation, making them more susceptible to atmospheric disturbances. As they float in the surrounding air, they tend to follow every movement of the air, such as wind gusts or thermals, unless measures are taken to counter these effects. To overcome the problem of poor ground handling and manoeuvrability at low speed, a combination between the lighter-than-air technology and the heavier than air technology such as fixed wing and rotary wing have been applied. This combination is called Hybrid Airship, the advantages of this configuration is the airship does not fully depend on the lifting gas to create lift (Khoury, 2012). The lift can be generated partially from the buoyancy force which from lifting gas and also generated dynamically from different of airflow pressure acting on the hull of the airship. Usually, the hybrid airship has unconventional shape which is the merging of several lobes body (Khoury, 2012). The application of vectored thrusters has improved the low-speed manoeuvring performance of hybrid airship which has been shown to be beneficial by number of researchers (Chen et al., 2015) (Nong, 2012). In the following section, a triangular shaped hybrid airship with axial coupling vector thrust configuration concept is presented that attempts to address the shortcomings of conventional airship design.

1.2 Hybrid Airship UAS (HAU-3)

Figure 1.4: HAU-3 prototype

The hybrid airship unmanned aerial system (HAU) is a finless airship that has a thruster configuration that enables this airship to move in biaxial direction without changing its heading. The objective of this axial-coupling thruster configuration is to improve the manoeuvrability and agility of small airships with payloads ranging from 10-100 kg. HAU-3 is the third prototype of the HAU airship series that replaced HAU-2. Its 3.3 m length, and 1.7 m hull made of lightweight material which is TPU film sheet. The vehicle consists of three major components which is the hull, thrusters and gondola as in Figure 1.4. The most distinctive feature of the HAU-3 compared to most conventional airship is its lack of aerodynamics control surface such as rudder and elevator due to its finless design. The airship becomes highly manoeuvrable in this case, but at the expense of stability due to the lack of restoring forces provided by the fins (Peddiraju et al., 2009). As a result, the airship's stability is primarily dependent on the artificial stability provided by its controller. Four vector thrusters mounted along the hull's equator provide stability control and actuation as shown in Figure 1.4. A servo tilts the motor allowing the vector thrust direction change from $+90^{o}$ to -90^{o} make this thruster able to produce upward and downward thrust for vertical take-off (VTOL) and vertical landing. Another distinguishing feature of this airship is that, in normal operation, the airship's weight exceeds the lift generated by the helium, indicating that the airship is negatively buoyant. The excess weight will be compensated with additional lift provided by the thrusters to keep the airship airborne. The benefits of having negative buoyant are that if all of the thrusters fail, the airship will slowly sink to the ground rather than floating away with the wind, making this configuration one of its safety features.

Apart of the features that offered by this vehicle and its successful prototype construction previously, there is lack of work to understand the underlying dynamics behaviour of this vehicle. The first attempt to develop this vehicle dynamics and control system is conducted by Sedan, (2018), using a black-box modelling approach of the second HAU prototype (HAU-2). However, to develop a robust mathematical representation using experimental approach increase the project cost and duration due to the needs to conduct multiple flight test of the actual vehicle. Furthermore, the experimental approach model does not accurately represent the underlying dynamics and is only valid in the region where the vehicle is tested. In addition, to reduce the logistics cost of flight test and rapid controller design optimization a platform which enable the developed HAU-3 dynamics model to be simulated is required. The need to develop a mathematical model and a functional flight simulator in LTA and UAV vehicle study also addressed by a number of author in their work such as Alsayed (2017), Navajas (2021), Peddiraju et al. (2009) and Frye et al. (2007).

1.3 Research Objectives

Hence, in order to allow a deep understanding of the HAU-3 motion behaviour and to design its attitude controller, a robust and reliable mathematical dynamics model representation and a closed-loop simulator needs to be developed.

Thus, three objectives of the research are as follows,

1. To build a working prototype of HAU-3 to be applied as a functional experimental platform.
2. To develop a six degree of freedom (6DOF) dynamics model for the HAU-3 prototype.
3. To develop closed-loop six degree of freedom (6DOF) simulator using Simulink and MATLAB for HAU-3.

1.4 Research Scope and Limitation

The research work involved in the fabrication and construction of the HAU-3 airship. The airship is built from scratch based on its previous prototype design (HAU-2) that involved the fabrication of its hull, electronic board and the thruster's module. Physical parameter experiments also conducted to measure the physical parameter needed in the dynamics model. A major work involves in the development of the mathematical model of HAU-3 based on its prototype

and model implementation to build its closed-loop non-linear simulator using Simulink and MATLAB. The simulator then used to develop its flight controller. Finally, the controller and some of the dynamic parameters is validated using static and outdoor flight tests. To sum up, the scope of the research is summarized as follows:

1) HAU-3 prototype fabrication and assembly
2) Dynamics modelling of HAU-3 using Newton-Euler approach
3) Closed-loop simulator with PID controller development using Simulink and MATLAB
4) HAU-3 flight test for some of dynamics parameter validation and controller response evaluation. The test divided into two part which is static indoor test which focuses more on the evaluation of yaw controller and outdoor flight test to evaluate the controller performance and dynamics parameters validation.

In order to simplify the vehicle modelling in this research, some assumption is made before the development of HAU-3 mathematical model. The modelling assumption is as follows:

1) The airship hull is modelled as a rigid body, as the hull is pressurized.
2) The COB is the point of origin of the airship.
3) CG is the centre of mass of the airship.
4) Hull elasticity skin properties is ignored.
5) The airframe is symmetric about X-Z plane such that both the COB and CG lie in the plane of symmetry.
6) The CG is located under the COB where horizontal displacement, x_{CG} is considered relatively small and y_{CG} assumed to be zero.
7) Airship is neutrally buoyant in open-loop simulation. Heaviness only introduced in closed-loop simulation.

The limitation of the conducted study is laid out to provide initial insight of the study outcomes and applicability. Since the study is based on one specific vehicle design called HAU-3, thus the 6DOF mathematical model obtained from this study is applicable to HAU-3 only, however general expression of the model is still applicable for a finless airship application. Part of propulsion dynamic model is derived using black-box modelling where the model only applicable to vehicle which utilize a compatible vectored thruster configuration. The thrust mixing methodology developed in this study is specifically constructed for vehicle which utilise similar vector thruster configuration. The PID controller developed in this study is tuned based on Zigeler-Nichols's method with non-linearized plant, hence the PID gain obtained is not optimal but sufficient to make the vehicle as a functional experimental platform to analyse HAU-3

responses. HAU-3 closed loop simulator is build based on no wind disturbance assumption hence this simulator only can estimate HAU-3 states for minimal to no wind flight condition. The no wind assumption is only valid in HAU-3 simulator as the wind disturbance is not incorporated in the HAU-3 dynamics model. For actual flight test of HAU-3 prototype this ideal case is considered applicable with relatively low wind speed condition of <2 m/s based on the work that conducted in this study.

1.5 Thesis Organization

The thesis is divided into five chapters which begins with Chapter 1 that describes the introduction of the conducted study, introduction of the vehicle used in this study and laid out of research objectives and problem statement which drives the research work. Major research related concept and previous related work is reviewed in Chapter 2.

Chapter 3 where the methodology to carried out this research is discussed in details. This chapter is divided into six sections where the first section described the overall work research flow. Section 3.2 discussed the constriction of HAU-3 prototype. The development of HAU-3 dynamics model is discussed in the third and fourth section.

The simulator construction based on dynamic model integration to SIMULINK and MATLAB is described in section five and finally the flight test setup is laid out in the last section of Chapter 3. Result and findings of the research is discussed in detail in Chapter 4, where this Chapter is divided into three major parts which is the dynamics modelling experimental result discussion.

Second part of the result, presented the finding of the developed simulator responses based on open and closed loop simulation of HAU-3 and the final part of this Chapter is a discussion on the simulator response validation based on comparison between simulation and actual vehicle response during flight test. The final Chapter of this thesis, laid out the conclusion made based on research findings and objectives also the future work recommendations.

REFERENCES

Abdallah, F. Ben, Azouz, N., & Beji, L. (2019). *Modeling of a heavy-lift airship carrying a payload by a cable-driven parallel manipulator*. *August*, 1–17. https://doi.org/10.1177/1729881419861769

Air - Density and Specific Weight. (2018). https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html

Air - Dynamic and Kinematic Viscosity. (2003). Engineering Toolbox. https://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html

Airship Industries Skyship 600 - Airship Industries. (n.d.). 1984. https://www.airliners.net/photo/Airship-Industries/Airship-Industries-Skyship-600/2042487

Alsayed, A. (2017). *Pitch and altitude control of an unmanned airship with sliding gondola*. University of Ottawa.

Aviation Weather Center. (n.d.). National Oceanic and Atmospheric Administration (NOAA). Retrieved January 16, 2021, from https://aviationweather.gov/metar/data/

Azouz, N., Chaabani, S., Lerbet, J., & Abichou, A. (2012). Computation of the Added Masses of an Unconventional Airship. *Journal of Applied Mathematics*, *2012*, 19. https://doi.org/10.1155/2012/714627

Battipede, M., Gili, P. A., Massotti, L., & Vercesi, P. (2003). Dynamic Modelling of a Non Conventional Thrust-Vectored Airship. *AIAA Modeling and Simulation Technologies Conference and Exhibit*, *August*, 1–11.

Block, I. (n.d.). "Flying bum" airship concept updated with motors powered by fuel cells alongside diesel engines. *Dezeen*. https://www.dezeen.com/2021/06/18/airlander-electric-airship-hav-sustainable/

Bosma, A. (2017). *Datasheet SDP3x-Digital*. *December*, 1–14. https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/0_Datasheets/Differential_Pressure/Sensirion_Differential_Pressure_Sensors_SDP3x_Digital_Datasheet.pdf

Boyle, A. (2018). *Egan Airships floats a sales campaign to get its Plimp hybrid aircraft off the ground*. GeekWire. https://www.geekwire.com/2018/egan-airships-floats-sales-campaign-get-plimp-hybrid-aircraft-off-ground/

Carichner, G. E., & Nicolai, L. M. (2013a). *Fundamental of Aircraft and Airship Design Volume 2 - Airship Design and Case Studies* (Vol. 2). American Institute of Aeronautics and Astronautics, Inc.

Carichner, G. E., & Nicolai, L. M. (2013b). *Fundamentals of Aircraft and Airship Design, Volume 2--Airship Design and Case Studies*. American Institute of Aeronautics and Astronautics, Inc.

Carrión, M., Steijl, R., Barakos, G. N., & Stewart, D. (2016). Analysis of hybrid air vehicles using computational fluid dynamics. *Journal of Aircraft*, *53*(4), 1001–1012. https://doi.org/10.2514/1.C033402

Chen, L., Wen, Y. B., Zhou, H., Wang, X. L., Zhou, P. F., & Duan, D. P. (2015). Design and control of a multi-vectored thrust airship. *22nd AIAA Lighter-Than-Air Systems Technology Conference, 2015*, *October*. https://doi.org/10.2514/6.2015-3228

Cho, S., Mishra, V., Tao, Q., Vamell, P., King-Smith, M., Muni, A., Smallwood, W., & Zhang, F. (2017). Autopilot design for A class of miniature autonomous blimps. *1st Annual IEEE Conference on Control Technology and Applications, CCTA 2017*, *2017-Janua*, 841–846. https://doi.org/10.1109/CCTA.2017.8062564

Cook, M. V. (2007). Flight Dynamics Principles. In *Elsevier Ltd.* (2nd ed.). Elsevier. https://doi.org/10.1016/B978-0-7506-6927-6.X5000-4

Corona DS-236MG Metal Gear Servo 7.0kg / 0.12sec / 27g. (n.d.). Retrieved January 20, 2021, from https://hobbyking.com/en_us/corona-ds-236mg-metal-gear-servo-7-0kg-0-12sec-27g.html?queryID=9f3f3a23ba6efedaa94170928274c6ca&objectID=82&indexName=hbk_live_products_analytics

Duun-henriksen, A. K., Sc, M., Schmidt, S., Røge, R. M., & Sc, M. (2013). Model Identification Using Stochastic Differential Equation Grey-Box Models in Model Identification Using Stochastic Differential Equation Grey-Box Models in Diabetes. *Journal of Diabetes Science and Technology*, *7*(2). https://doi.org/10.1177/193229681300700220

Fossen, T. I. (1987). *Nonlinear modelling and control of underwater vehicles*. Norwegian Instutite of Technology.

Fossen, T. I. (1995). *Guidance and control of ocean vehicles*. John Wiley and Sons Ltd.

Frye, M. T., Gammon, S. M., & Qian, C. (2007). The 6-DOF dynamic model and simulation of the tri-turbofan remote-controlled airship. *Proceedings of the American Control Conference*, 816–821.

https://doi.org/10.1109/ACC.2007.4283087

Funk, P., Lutz, T., & Wagner, S. (2003). Experimentelle investigations on hull-fin interferences of the LOTTE airship. *Aerospace Science and Technology*, *7*(8), 603–610. https://doi.org/10.1016/S1270-9638(03)00058-0

Gao, W., Nelias, D., Liu, Z., & Lyu, Y. (2018). Numerical investigation of flow around one finite circular cylinder with two free ends. *Ocean Engineering*, *156*(May), 373–380. https://doi.org/10.1016/j.oceaneng.2018.03.020

Goodyear. (n.d.). *Current Blimps - Wingfoot One*. https://www.goodyearblimp.com/behind-the-scenes/current-blimps.html

H. Julian Allen, E. W. P. (1951). A study of effects of viscosity on flow over slender inclined bodies of revolution. *National Advisory Committee for Aeronautics (NACA)*, *NACA-RM-A9*.

Han, D., Wang, X. L., Chen, li, & Duan, D. P. (2016). Command-filtered backstepping control for a multi-vectored thrust stratospheric airship. *Transactions of the Institute of Measurement and Control*, *38*(1), 93–104. https://doi.org/10.1177/0142331214568237

Haranen, M. (2016). White , Grey and Black-Box Modelling in Ship Performance Evaluation White , Grey and Black-Box Modelling in Ship Performance Evaluation. *1st Hull Performence & Insight Conference (HullPIC)*, *April*, 115–127.

Helium - Density and Specific Weight. (2018). https://www.engineeringtoolbox.com/helium-density-specific-weight-temperature-pressure-d_2090.html

HEX/ProfiCNC Here2 GPS. (2020). https://docs.px4.io/master/en/gps_compass/gps_hex_here2.html

Hex Cube Black Flight Controller. (2020). https://docs.px4.io/master/en/flight_controller/pixhawk-2.html

Hoerner, Sighard F. (1965). Fluid dynamic drag: practical information on aerodynamic and hydrodynamic resistance. In *Copyright by: SF Hoerner Fluid Dynamics, Vancouver, Printed in the USA, Card Number 64-19666*.

Hopkins, J., & Field, M. (1951). A semiemprical method for calculating the pitching moment of bodies of tevolution at low mach numbers. In *National Advisory Committee for Aeronautics (NACA)*.

HT 1890 Manometer. (n.d.). Retrieved January 22, 2021, from https://hti-instrument.com/products/ht-1890-manometer

Hygounenc, E., Jung, I. K., Souères, P., & Lacroix, S. (2004). The autonomous blimp project of LAAS-CNRS: Achievements in flight control and terrain mapping. *International Journal of Robotics Research*, *23*(4–5), 473–511. https://doi.org/10.1177/0278364904042200

Jorgensen, H. (1973). Prediction of Static Aerodynamic Characteristics for Space Shuttle Like and Other Bodies At Angle of Attack From 0 degree to 180 degree. *Nasa Technical Note*.

Kantue, P. (2018). Grey-box modelling of an Unmanned Quadcopter during Aggressive Maneuvers. *2018 22nd International Conference on System Theory, Control and Computing (ICSTCC)*, 640–645.

Kellock, R. E., & Miller, P. H. (1971). *Aerodynamic Characteristics of Basic Nose-cylinder Bodies for Large Ranges of Angle of Attack*.

Khoury, G. A. (2012). *Airship technology* (Vol. 10). Cambridge university press.

Kukillaya, R. P. (2017). Simulink model development , validation and analysis of high altitude airship. *PD-FMC/2017/1000. National Aerospace Laboratories, Flight Mechanics and Control Division, Bangalore, India.*, *March*. https://doi.org/10.13140/RG.2.2.11844.22400

Lamb, H. (1895). *Hydrodynamics* (2234 (Ed.)). Princeton University Press.

Lamb, H. (1918). The inertia coefficients of an ellipsoid moving in fluid. *Advisory Committee for Aeronautics, Reports and Memoranda No. 623, London, UK.*, *623*.

Lanteigne, E., Alsayed, A., Robillard, D., & Recoskie, S. G. (2017). Modeling and Control of an Unmanned Airship with Sliding Ballast. *Journal of Intelligent and Robotic Systems: Theory and Applications*, *88*(2–4), 285–297. https://doi.org/10.1007/s10846-017-0533-6

Li, Y., & Nahon, M. (2007). Modeling and Simulation of Airship Dynamics. *Journal of Guidance, Control, and Dynamics*, *30*(6), 1691–1700. https://doi.org/10.2514/1.29061

Li, Y., Nahon, M., & Sharf, I. (2009). *Dynamics Modeling and Simulation of Flexible Airships*. *47*(3). https://doi.org/10.2514/1.37455

Li, Y., Nahon, M., & Sharf, I. (2011). Progress in Aerospace Sciences Airship dynamics modeling : A literature review. *Progress in Aerospace Sciences*, *47*(3), 217–239. https://doi.org/10.1016/j.paerosci.2010.10.001

Liesk, T., Nahon, M., & Boulet, B. (2012). Design and experimental validation of a controller suite for an autonomous , finless airship. *American Control Conference*, 2491–2496.

Liesk, T., Nahon, M., & Boulet, B. (2013). Design and Experimental Validation of

a Nonlinear Low-Level Controller for an Unmanned Fin-Less Airship. *IEEE Transactions on Control Systems Technology*, *21*(1), 149–161.

Ljung, L. (2011). System identification toolbox. *The Matlab User's Guide*, *1*, 237.

Ljung, Lennart. (2001). Black-box Models from Input-Output Measurements. *18th IEEE Instrumentation and Measurement Technology Conference Budapest*, *1*, 138–146. https://doi.org/10.1109/IMTC.2001.928802

Lockheed Martin P-791 - Lockheed. (2006). https://www.airliners.net/photo/Lockheed/Lockheed-Martin-P-791/1153517

Ltd, Rfd. P. (n.d.). *Antenna 900MHz 3dBi Dipole (RPSMA)*. https://store.rfdesign.com.au/antenna-900mhz-3dbi-dipole-rpsma/

Luo, S. C., Gan, T. L., & Chew, Y. T. (1996). Uniform flow past one (or two in tandem) finite length circular cylinder(s). *Journal of Wind Engineering and Industrial Aerodynamics*, *59*(1), 69–93. https://doi.org/10.1016/0167-6105(95)00036-4

M.M. Munk. (1934). *Fluid Mechanics, 2nd Part* (In. W.F Durand (Ed.)). Julius Springer.

Mazhar, H. (2012). *Dynamics , Control and Flight Testing of an Unmanned , Finless Airship*. McGill University, Montreal.

Mazhar, H., Nahon, M., & Liesk, T. (2013). Validation of a dynamics model and controller for an unmanned, Finless Airship. *AIAA Lighter-Than-Air Systems Technology (LTA) Conference 2013*, *February*. https://doi.org/10.2514/6.2013-1300

Mikegrusin, B. J. (n.d.). *Hobby Servo Tutorial*. Retrieved June 7, 2020, from https://learn.sparkfun.com/tutorials/hobby-servo-tutorial

Mission Planner. (2020). https://ardupilot.org/planner/index.html

Moutinho, A. B. (2007). Modeling and Nonlinear Control for Airship Autonomous Flight. In *Praca doktorska, Universidade Técnica de Lisboa, Lisbona, Grudzień.* https://doi.org/10.13140/2.1.1333.8568

Mueller, J., Paluszek, M., & Zhao, Y. (2004). Development of an aerodynamic model and control law design for a high altitude airship. *AIAA 3rd" Unmanned Unlimited" Technical Conference, Workshop and Exhibit*, 6479.

Munk, M. M. (1931). The aerodynamic forces on airship hulls. In *National Advisory Committee for Aeronautics* (Vol. 211, Issue (No. NACA-TR-184)). https://doi.org/10.1016/s0016-0032(31)90371-2

Navajas, G. T. (2021). *Modelling and Pitch Control of a Re-configurable Unmanned Airship*. University of Ottawa.

Nicolai, L. M., & Carichner, G. E. (2010). *Fundamentals of aircraft and airship design, volume 1--aircraft design*. American Institute of Aeronautics and Astronautics.

Nong, Y. (2012). *Design of Small Highly Maneuverable Airships*. McGill University, Department of Mechanical Engineering.

Ogata, K. (2010). *Modern Control Engineering* (Fifth). Pearson Education Inc.

Pais, A. R., & Pais, A. R. (2006). *Project AURORA : Infrastructure and Flight Control Experiments for a Robotic Airship*. *23*(December 2005), 201–222. https://doi.org/10.1002/rob

Park, S. (2013). *RFD900 Radio Modem Data Sheet*. http://files.rfdesign.com.au/Files/documents/RFD900 DataSheet.pdf

Paul Scherz, & Monk, S. (2016). *Practical Electronics for Inventors* (Fourth). McGraw-Hill Education.

Peddiraju, P. (2010). *Development and validation of a dynamics model for an unmanned finless airship*. McGill University.

Peddiraju, P., Liesk, T., & Nahon, M. (2009). Dynamics modeling for an unmanned, unstable, fin-less airship. *18th AIAA Lighter-than-Air Systems Technology Conference, May*. https://doi.org/10.2514/6.2009-2862

Peek, D. (2013). *Navy manned airship lands at Dobbins*. 94th Airlift Wing Public Affairs. https://www.dobbins.afrc.af.mil/News/Article-Display/Article/561962/navy-manned-airship-lands-at-dobbins/

Peterson, M. A. (2002). Galileo's discovery of scaling laws. *American Journal of Physics*, *70*(6), 575–580. https://doi.org/10.1119/1.1475329

RFD 900+ Modem. (n.d.). Retrieved January 22, 2021, from https://store.rfdesign.com.au/rfd-900p-modem/

S. B. V. Gomes. (1990). *An Investigation of the Flight Dynamics of Airships with Application to the YEZ-2A*. Cranfield Institute of Technology.

Sagatun, S. I., & Fossen, T. I. (1991). Lagrangian formulation of underwater vehicles' dynamics. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, *2*, 1029–1034. https://doi.org/10.1109/icsmc.1991.169823

Sebbane, Y. B. (2019). *Lighter Than Air Robots Guidance and Control of Autonomous Airships* (Vol. 53, Issue 9). Springer.

https://doi.org/10.1017/CBO9781107415324.004

Sedan, M. F. (2018). *Flight Control System Perfoemance Analysis of Finless Hybrid Airship (PSHAU-2)*. Universiti Putra Malaysia.

Series 1585 Test Stand Datasheet. (2022). Tyto Robotics. https://cdn.rcbenchmark.com/landing_pages/Manuals/Series 1585 Datasheet.pdf

STM32F103x8, STM32F103xB. (2022). https://www.st.com/resource/en/datasheet/stm32f103c8.pdf

Tischler, M. B., Ringland, R. F., & Jexj, H. R. (1983). Heavy-Lift Airship Dynamics. *Journal of Aircraft*, *20*(5), 425–433.

TPS56637 4.5-V to 28-V input, 6-A Synchronous Buck Converter. (2019). https://www.ti.com/lit/ds/symlink/tps56637.pdf?ts=1619973800610&ref_url=https%253A%252F%252Fwww.google.com%252F

Tuckerman, L. B. (1926). *Inertia factors of ellipsoids for use in airship design*.

Turnigy 3200mAh 4S 20C LiPoly Pack w/ EC3. (2022). https://hobbyking.com/en_us/turnigy-3200mah-4s-20c-lipoly-pack-w-ec3-e-flite-compatible-eflb32004s.html?queryID=c0dc728da04eff5c481ff62d9c4367e0&objectID=45413&indexName=hbk_live_products_analytics

Tuveri, M., Ceruti, A., & Marzocca, P. (2014). *Added masses computation for unconventional airships and aerostats through geometric shape evaluation and meshing*. *15*(3), 241–257. https://doi.org/10.5139/IJASS.2014.15.3.241

Windy.com. (n.d.). Retrieved January 16, 2021, from https://www.windy.com

Zdravkovich, M. M., Brand, V. P., Mathew, G., & Weston, A. (1989). Flow past short circular cylinders with two free ends. *Journal of Fluid Mechanics*, *203*.

Zdravkovich, M. M., Brand, V. P., Weston, A., & Mathew, G. (1989). Flow past short circular cylinders with two free ends. *Journal of Fluid Mechanics*, *203*(557), 557–575. https://doi.org/10.1017/S002211208900159X

Zeppelin NT. (n.d.). Airships.Net. https://www.airships.net/zeppelin-nt/

Zhang, L., Lv, M., Sun, C., & Meng, J. (2018). Flight performance analysis of hybrid airship considering added mass effects. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, *140*(11), 1–13. https://doi.org/10.1115/1.4040220

Zufferey, J. C., Floreano, D., Van Leeuwen, M., & Merenda, T. (2002). Evolving vision-based flying robots. *Lecture Notes in Computer Science (Including*

Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), *2525*, 592–600. https://doi.org/10.1007/3-540-36181-2_59

Zufferey, J. C., Guanella, A., Beyeler, A., & Floreano, D. (2006). Flying over the reality gap: From simulated to real indoor airships. *Autonomous Robots*, *21*(3), 243–254. https://doi.org/10.1007/s10514-006-9718-8