# FLAPPING WING MECHANISM DEVELOPMENT AND CONTROL

# NURASYEERA BINTI ROHAZIAT

# RESEARCH PROJECT SUBMITTED TO THE INSTITUTE OF GRADUATE STUDY FACULTY OF ENGINEERING UNIVERSITY OF MALAYA, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR DEGREE OF MASTER OF MECHATRONIC ENGINEERING

2018

### ACKNOWLEDGEMENT

Alhamdulillah. Praises be to Allah.

I would like to express my truthful appreciation to my supervisor, Dr Mohamad Azlin bin Ali, for his guide, support and encouragement on this project.

Regardless of the many challenges and obstacles throughout this project, it would not be completed without the help and support from numbers of brilliant persons – my gratitude to all of them for helping to make this project possible.

Finally, special thanks to my beloved family members for their enduring motivation. Thank you for all your encouragement!

## FLAPPING WING MECHANISM DEVELOPMENT AND CONTROL

## ABSTRACT

Developing a dragonfly robot and reproducing the flapping mechanism involve challenging tasks particularly in terms of design and control to achieve high flapping frequency. Therefore, the purpose of this study is to develop a rigid flapping mechanism of a dragonfly robot. As such, the flapping mechanism of a dragonfly robot was modelled and a working prototype was then assembled. An open-loop control system of using an Arduino Uno microcontroller board was established with embedded radio frequency (RF) communication protocol to wirelessly control the robot from a personal computer. Moreover, an ultrasonic sensor was implemented as well for future development. Based on several experimental results, the developed flapping mechanism has worked reasonably well with the addition of greases on adjoining parts of the dragonfly robot. At 3V motor input voltage, the mechanism was able to produce a flapping frequency of 10Hz. On the other hand, the incorporation of an ultrasonic sensor offered an accuracy of up to 97.21%. when being tested with 3-15cm distances object. In conclusion, the work presented in this study serves as a basis understanding to develop an overall better flapping mechanism for a dragonfly robot in the future.

Keywords: dragonfly robot, flapping mechanism, Arduino Uno, ultrasonic sensor

#### ABSTRAK

Membangunkan robot pepatung dan meniru mekanisme pengepakan melibatkan tugastugas yang mencabar terutamanya dari segi reka bentuk dan kawalan untuk mencapai frekuensi mengapungkan tinggi. Oleh itu, tujuan kajian ini adalah untuk membangunkan mekanisme yang menggerunkan robot robot hingar. Oleh itu, mekanisme pengepakan robot pepatung telah dimodelkan dan prototaip yang berfungsi telah dipasang. Sistem kawalan gelung terbuka menggunakan mikrokontroler Arduino Uno telah ditubuhkan dengan protokol komunikasi frekuensi radio (RF) untuk mengawal robot tersebut secara tanpa wayar dari komputer peribadi. Selain itu, sensor ultrasonik juga telah dibangunkan untuk pembaharuan pada masa hadapan. Berdasarkan beberapa keputusan eksperimen, mekanisme pengepakan yang dicipta telah berjalan dengan baik dengan penambahan gris pada bahagian-bahagian robot yang bercantum. Pada voltan masukan motor sebanyak 3V, mekanisme tersebut dapat menghasilkan frekuensi pengepakan sehinnga 10Hz. Selain itu, penggabungan sensor ultrasonik menawarkan ketepatan sehingga 97.21%, apabila diuji dengan objek pada jarak 3-15cm. Kesimpulannya, hasil kerja yang dibentangkan dalam kajian ini menyediakan pemahaman asas untuk membangungkan mekanisme pengepakan untuk robot pepatung yang lebih baik pada masa hadapan.

Kata kunci: robot pepatung, mekanism pengepakan, Arduino Uno, sensor ultrasonik

# TABLE OF CONTENTS

ACKNOWLEDGEMENTii
ABSTRACTiii
ABSTRAKiv
TABLE OF CONTENTS
LIST OF FIGURES
LIST OF TABLEx
LIST OF SYMBOLS AND ABBREVIATIONSxi
CHAPTER 1 : INTRODUCTION
1.1 Introduction
1.2 Problem statement
1.3 Aim and objectives2
1.4 Scopes2
1.5 Contributions
1.6 Thesis outline
CHAPTER 2 : LITERATURE REVIEW
2.1 How dragonfly flies
2.2 Ornithopter flying robot
2.3 Flapping mechanism7
2.4 Flapping control & flight control12
CHAPTER 3 : METHODOLOGY16

3.1 I	Research plan16
3.2 \$	System architecture
3.3 I	Hardware design19
3.3.1	Flapping mechanism19
3.3.1	Arduino Uno development board20
3.3.2	XBee RF module21
3.3.3	DC motor and motor shield23
3.3.4	HC-SR04 ultrasonic sensor
3.3.5	Device connections
3.4 \$	Software design
3.4.1	Wireless communication
3.4.2	Arduino program
CHAPTER	R 4 : RESULT AND ANALYSIS
4.1 I	Hardware development
4.2 N	Motor voltage input test
4.3 I	Flapping frequency
4.4 U	Ultrasonic sensor performance
CHAPTEF	R 5 : CONCLUSION42
5.1 (	Conclusion42
5.2 I	Recommendations43
REFEREN	JCES44
APPENDI	X A

APPENDIX B	
APPENDIX C	50

University Malay

## LIST OF FIGURES

Figure 2.1: Ornithopter design (Jackowski, 2009)7
Figure 2.2: Experimental lift acquisition setup (Arabagi, Hines, & Sitti, 2013)
Figure 2.3: Completed MAV test fixture mounted to a high sensitivity force transducer
(Wood, 2007)
Figure 2.4: Illustration of the micro air vehicle (Yoon, Kang, & Jo, 2011)10
Figure 2.5: Flapping motion of a double hinged wing (Choi, Joung, & Lee, 2012)10
Figure 2.6: Mechanism assembly of a flapping wing (Yang et al., 2015)
Figure 2.7: Experimental prototype of miniature flapping wing robot (Arabagi, Hines, &
Sitti, 2012)14
Figure 2.8: Block diagram of the overall electronics system configuration for a wireless
flapping robot (Tandon, Vajpai, & Mishra, 2013)15
Figure 3.1: Research plan flowchart
Figure 3.2: Device interface with Arduino Uno microcontroller
Figure 3.3: Prototype design of dragonfly robot flapping mechanism with views on the
(a) front and the (b) back
Figure 3.4: Arduino Uno microcontroller (Arduino, 2018)
Figure 3.5: XBee Series 1 1mW Wire Antenna (Sparkfun, 2018b)22
Figure 3.6: XBee shield (Cytron, 2018b)
Figure 3.7: DC motor (Autobotic, 2018)
Figure 3.8: Equivalent DC motor circuit
Figure 3.9: DC motor torque-speed curve
Figure 3.10: Cytron 2A motor shield (Cytron, 2018a)27
Figure 3.11: HC-SR04 ultrasonic sensor (Sparkfun, 2018a)27
Figure 3.12: Device connections of the overall electronics components

Figure 3.13: XCTU software	
Figure 3.14: Console mode in XCTU	31
Figure 3.15: Flowchart of Arduino program	32
Figure 4.1: Prototype of a dragonfly robot	
Figure 4.2: User input voltage vs measured voltage	36
Figure 4.3: Testing setup for flapping frequency measurement	37
Figure 4.4: Voltage vs frequency of dragonfly robot flapping mechanism	
Figure 4.5: Testing setup for ultrasonic sensor	40
Figure 5.1: Efficiency versus voltage graph	42

## LIST OF TABLE

Table 3.1: Arduino Uno microcontroller specification	21
Table 4.1: Motor voltage input test measurement	
Table 4.2: Flapping frequency test measurement	
Table 4.3: Ultrasonic sensor test measurement	40

university children

## LIST OF SYMBOLS AND ABBREVIATIONS

3D	-	Three Dimensional
А	-	Amp
AOA	-	Angle of Attack
BMAV	-	Biomimetic Micro Air Vehicle
CAD	-	Computer-Aided Design
cm	-	Centimeter
DH	-	Destination Address High
DL	-	Destination Address Low
DOF	-	Degree of Freedom
G		Gram
GHz	-	Gigahertz
Hz	-	Hertz
I/O	-	Input/Output
М	-	Meter
MAV	-	Micro Air Vehicle
MHz	-	Megahertz

ММ	-	MAC Mode
mW	-	Milliwatt
PID	-	Proportional, Integral and Derivative
PLA	-	Polylactic Acid
PWM	-	Pulse Width Modulation
PSU	-	Power Supply Unit
RF	-	Radio Frequency
rpm	-	Revolutions Per Minute
Rx	-	Receiver
SH	-	Serial Number High
SL	-	Serial Number Low
Тх		Transmitter
UART	-	Universal Asynchronous Receiver-Transmitter
USB	-	Universal Serial Bus
V	-	Volt
VCM	-	Voice Coil Motor

#### **CHAPTER 1: INTRODUCTION**

#### 1.1 Introduction

Dragonfly is one of the ancient insect that evolve through the centuries. There are many species of dragonflies found all over the world. The structure of the body and wings differ from each species, but they mostly share a common characteristic which is possessing two sets of wings. Amazingly, each of these wings maneuver independently with each other. Its ability to fly swiftly makes it capable of migrating, performing multidirectional flight (upward, downward, forward, backward, left, right), and sudden directional changes.

Dragonflies are also able to fly in four different flight styles (Rowe, Richard J. 2015) (Waldbauer, Gilbert, 2006). The flight modes include the counter-stroking (for hovering and slow flight) and synchronous-stroking (for direction change and gliding). The lift of dragonflies is generated in several techniques at different times that involve classical lift and supercritical lift. Furthermore, the dynamic flight of the dragonflies is supported by the flexible wing movement that is able to generate a maximum flapping frequency of 50Hz and a flying speed of up to 97km/h.

Through previous study of dragonfly's flights model, a biomimetic micro air vehicle (BMAV) can be developed based on the dragonfly structure (Usherwood, 2001),. As a side note, a BMAV is a technology that develops a micro animal (mostly insect). This include replicating of life-like movement such as walking, climbing and in this case, flying.

This research mainly focused on the dragonfly flapping mechanism and its speed control. Initially, the research started with developing one pair of wing. For future development, the second pair can be cooperated in the system. The movement mechanism of each wing is designed by integrating numbers of gears and cranks. One of the desired flapping characteristics includes a 50Hz flapping frequency and at least a 45° flapping angle. The flapping wing frequency can be control by controlling the speed of motor.

#### **1.2 Problem statement**

Developing a dragonfly robot and replicating the flapping mechanism involve challenging tasks especially in terms of design and control of the flapping mechanism to achieve high flapping frequency (Hsiao, Yang, & Lin, 2012). Likewise, if the objective is to make a flying dragonfly robot, several extended variables need to be tackled; overall mass of the system, required surface area of the flaps in order to produce enough force to lift the body, selections of lightweight material and selections of suitable motor. Such combination of exhaustive requirements is crucial so that the dragonfly robot is able to fly.

## 1.3 Aim and objectives

This research aims to develop a rigid flapping mechanism of a dragonfly robot. The objectives of this research are as follows:

- 1. To design a flapping mechanism of a dragonfly robot.
- 2. To control the speed of the flapping mechanism of a dragonfly robot.
- 3. To establish a wireless communication between a dragonfly robot and a computer.
- 4. To test the performance of the developed system.

## 1.4 Scopes

The scopes and limitations of this research are given as below:

- 1. This study focuses on the development of dragonfly robot flapping mechanism.
- Arduino Uno microcontroller board was utilized for embedding the control program.
- The wireless system module was implemented by using XBee Series 1 1mW Wire Antenna with ZigBee 2.4GHz radio frequency (RF) protocol.

- Communication between the computer and the dragonfly robot was conducted wirelessly from within the X-CTU program.
- 5. The dragonfly robot used a direct current (DC) controlled motor for the flapping mechanism.

## 1.5 Contributions

In summary, contributions in this study are listed as follows:

- This study contributes on a functional flapping mechanism of a dragonfly robot. A DC-controlled motor was used on the gears-driven flapping movement. In addition, lightweight yet rigid structures from using 3D printed polylactic acid (PLA) based components were constructed for the overall body and mechanism of the robot.
- 2. This study presents a fully wireless communication between the PC and the dragonfly robot to control the speed of the flapping mechanism. A 2.4GHz RF protocol was employed to bridge the connection between two XBee modules; one connected to the computer while the other connected to the dragonfly robot. X-CTU program was utilized to send input signals to the robot.

## **1.6** Thesis outline

The structure of this thesis is organized as follows. Chapter 1 discusses the motivation and background of this research. The problems in dragonfly mechanism are identified and explained. The research objectives are then presented along with the research contributions.

Chapter 2 gives a deeper look on what makes a dragonfly fly, existing flying robots, flapping mechanism, and flapping control and flight control.

Determination of hardware and software is laid out in Chapter 3, where it discusses the overall research plan and designs for both hardware and software control system.

The outcomes and findings on the overall development of a dragonfly robot flapping mechanism in this research is presented in Chapter 4 with detailed analysis on the flapping movement.

Finally, Chapter 5 summarises this research along with recommendation for future development.

university

#### **CHAPTER 2: LITERATURE REVIEW**

#### 2.1 How dragonfly flies

Flying insects are capable of maneuvering in many distinct type of flights, which many differ according to which activity they intended to do (Wakeling & Ellington, 1997). for example, a constant velocities flight is required during their migration and scavenging in great distance. However, most of the flight type are naturally unstable. Accelerations took place during the prey hunting and predators avoiding, while inconsistent flight paths are implemented during the escape. In early study of dragonfly flight, it was found that all wing beating frequency of a dragonfly is 41.5Hz (Azuma et al., 1985). On the other hand, the flapping angles can be obtained as follows:

$$\psi = \psi_0 + \sum_{n=1}^{\infty} \psi_n \cos(n\omega t + \delta_n)$$

Which signify as:

$$\psi_f = -3 - 43\cos(\omega t)$$

$$\psi_h = 2 - 47 \cos(\omega t + 77)$$

From the above equation, it can be concluded that the angular speed is  $\omega = 2\pi \times 41.5$ rad s<sup>-1</sup> which approximately equal to  $15000^{\circ}$ s<sup>-1</sup>. Furthermore, the phase different between fore and hind wing was  $\Delta \delta = \delta_{1,h} - \delta_{1,f} = 77^{\circ}$ .

Previous researchers had derived the aerodynamic force and power of the dragonfly's wing motion as the phase function (Wang & Russell, 2007). It was proven that minimal power was required in the out of phase motion to produced force that able to balance out the weight of the dragonfly. At the same time, greater force was needed during in phase motion (take off) to accelerate. It was also stated that the phase dependence was caused by the main hydrodynamic interaction.

A structural analysis of the dragonfly wing had been studied (Jongerius & Lentink, 2010). The dragonfly's forewing and hindwing anatomy were scanned using a 3D micro-CT scanner and the architecture was approximated using 3D beam and shell model. The research showed that the inertial loads were up to 3 times higher than the aerodynamic pressure loads. In addition, the down stroke wing deformation was found to be smaller than during the upstroke because of the structural asymmetry. The natural frequency of the dragonfly wing structural was 154Hz in vacuum and 32.3Hz in hovering flight mode.

## 2.2 Ornithopter flying robot

Ornithopter is one of the bio inspired flying robot which took the impression of a wing flapping flight (birds, bats, and insects). In this research, the mechanism of the flapping wing was design based on the ornithopter concept. In the year of 2009, Jackowski had developed a large ornithopter (named Phoenix) and had studied its control system (Jackowski, 2009). The prototype was able to carry a full system that included a small computer and sensor set with a weight of 400gram. The machine pitch was stabilized using the PD controller during the testing. They developed a large scale of ornithopter design due to the manageable size of components that must be included onboard (computer, sensors, power supply). It was also designed to be repairable and adjustable for future improvement or damage. A manual test was performed and proved that it was able to sustain the flight with heavy load. The flight also was stabilized by a simple common aircraft controller.



Figure 2.1: Ornithopter design (Jackowski, 2009)

In 2005, a butterfly-like ornithopter flight dynamics had been studied (Tanaka et al., 2005). The ornitopter weighed 4.0g with a wing span of 140mm and 10Hz flapping frequency. A high-speed video camera was used to capture the flight of the butterfly ornithopter and the longitudinal motion was analyzed. The outcome of the study were the total aerodynamic force produced by the cyclic change of the angle of attack. The obtained result from the visualized air flow was that the free body motion produced a stable attachment of leading edge vortex which aided to smooth out the wing upstroke.

## 2.3 Flapping mechanism

The mechanism of the dragonfly wings depends on the biometric model of the wing itself which is determined by the kinematics of the wing model. To develop the particular type of kinematics, the structure and motion of the wing have to be determined, such as the motion of flapping, gliding and twisting. Alternatively, a simpler mechanism could be designed by only taking into consideration the flapping motion which only consisted of one degree of freedom (DOF) movement. Nevertheless, this design produced less efficiency in aerodynamic performance compared with the real dragonfly (Hsiao, Yang, & Lin, 2012).

Previous researches had designed a numerical simulation tool in order to develop a passive rotation mechanism of a flapping wing (Arabagi, Hines, & Sitti, 2013). The quasistatic model of the piezoelectric actuator bending, transmission kinematics and the small Reynolds number aerodynamic forces governing from wing dynamics were included in the simulation tool. Consequently, two single wing systems with different resonant frequency were fabricated to test the simulation tool. The simulation was able to be used as an optimization tool for mechanical design that included wing shape, actuator with four bar geometry and dual wing flapping as shown in Figure 2.2. However, the system performance is not so robust and consistent. To compensate this design issues, an adequate controller is required.



Figure 2.2: Experimental lift acquisition setup (Arabagi, Hines, & Sitti, 2013)

Other researcher had also developed a miniature wing design with two passive DOF (Wood, 2007). A flapping wing micro air vehicle (MAV) presented in Figure 2.3 was designed and manufactured based on the biology of the Dipteran insects. The transmission system of the wing comprised of one actuated and two passive DOF. The study highlighted two main elements which were the wing trajectory as well as the generated thrust. The downside of the project was that the wing motion control system was limited by both transmission and actuation size and overall complexity. The reason was because, to produce high efficient flapping control, the system would be massive.

Hence, the developed MAV was unable to create arbitrary body torques. At the end, they planned to add smaller actuators to the system so that the dynamic tuning would be possible.



Figure 2.3: Completed MAV test fixture mounted to a high sensitivity force transducer (Wood, 2007)

In 2011, a group of researchers explained about the essential of wing root rotation to allow the body to lift and hover in mid-air (Yoon, Kang, & Jo, 2011). The micro vehicle had to be attached to a compact actuator and in order to reduce the size and weight, a voice coil motor (VCM) was developed. The research proposed a linkage mechanism to convert the linear motion of VCM into wing twisting and flapping motions that used ball joint for the twisting motion.

The 2.86g air vehicle as displayed in Figure 2.4 created a vertical force that was proportional to the twisting angle. Based on the figure, the mechanism was designed with two actuators attached to a ball joint on its front and rear sides. Both coils moved simultaneously to flap, while asynchronously to twist. The front coil was static whereas during the beginning of the upstroke, the rest moved downwards.



Figure 2.4: Illustration of the micro air vehicle (Yoon, Kang, & Jo, 2011)

Another biomimetic flying robot researchers had studied about the relationship between flight parameters (Choi, Joung, & Lee, 2012). They had designed and modelled a bird-like wing mechanism in the MATLAB/Simulink environment as shown in Figure 2.5 which focused on the flapping and tilting motion.



Figure 2.5: Flapping motion of a double hinged wing (Choi, Joung, & Lee, 2012)

In the simulation tool, the flapping angle of the outer wing was designed to synchronize with the inner wing. The dimension of the effective wingspan can then be calculated together with the force and the required power, while the lift force and thrust were able to be computed in the modelling system. The results presented from the simulation were possible to be implemented in the real-time system of a flying robot.

In 2015, several researchers had studied a mechanical design of a flapping wing using various types of fabrication materials (Yang et al., 2015). They had tested a number of materials to achieve an energy efficient, compact and light flapping model. A 20cm wing span was fabricated using an electrical discharge wire cutting and injection moulding. The model as presented in Figure 2.6 was able to attain 100° flapping angle, low transverse vibrations and also both wings were close to no phase lag.

Their simulation results on the mechanism design showed that it was able to achieve zero phase lag and a symmetrical flapping stroke. The performance of the fabricated design was tested by its torque and aerodynamic characteristics at different angle of attack (AOA) and wind speeds. This results in flapping maximum lift and thrust at AOA of 70° with 26.67 gear reduction. This admirable result provided a potential for future micro vehicle with high transmission effectiveness.



Figure 2.6: Mechanism assembly of a flapping wing (Yang et al., 2015)

## 2.4 Flapping control & flight control

There are many ways to control the flapping frequency and the flight. The main element that has to be included is the total weight of the robot. Based on the flight equation, higher weight will require greater force to lift. Other controlling elements are the processor, sensor and actuator that can be used for a closed-loop control system.

Previous researchers had developed a 10g ornithopter robot which comprised of a camera from a cellphone as the main sensor and a wireless controller (Bermudez & Fearing, 2009). The optical flow algorithm was implemented in the research to manipulate the data captured by the camera. In the optical flow algorithm, the net motion direction was extracted by computing the average value of the flow field in entire sensor. It showed the importance of the pitch oscillations based on the wing flapping in the direction of the estimation technique. The research resulted in a high optical flow signal due to the frequency of the flapping wing it produced and they were able to be separated by a notch filter Another method of controlling a flapping wing was introduced (Baek, Garcia Bermudez, & Fearing, 2011). A micro size flapping mechanism that weighs 13g was constructed. The ornithopter design had been proved to be able to fly to target destination without being remotely controlled. The flight controller that only weighs 1g consisted of microcontroller integrated circuit, inertial sensor, visual sensors, electronics communication and motor drives. A simple structure design was developed to make the control system less complex.

The ornithopter was claimed to be able to fly to the marked area by only computation and on-board sensor. In a narrow view field, the target might be undetectable. Consequently, a dead-reckoning computing method was implemented to recuperate the temporary target loss. The method presented in the study successfully measured the current position of the ornithopter through calculating the previous exact position. The research proved an 85% efficiency for a 28cm wing-span ornithopter that could fly and landed within a 0.5m radius from the target point.

The idea in building a controllable miniature flapping wing robot was presented by a team of researchers in 2012 (Arabagi, Hines, & Sitti, 2012). They had developed a mechanism which included spherical four-bar transmission and a single wing. A dual wing mechanism was manufactured by using the technique of smart composite microstructures. A finite element analysis was applied to assure the vibration mode of the airframe were out of the operation range of the platform while maintaining high rigidity. The prototype was later tested to describe the production of the robot lift capabilities and also to minimize the wing coupling. Consequently, they were able to reduce the size of the prototype for half of its initial scale with a lift to weight ratio of 3:8.



Figure 2.7: Experimental prototype of miniature flapping wing robot (Arabagi, Hines, & Sitti, 2012)

A wireless communication flapping robot was once developed and controlled by an Arduino as the main control unit (Tandon, Vajpai, & Mishra, 2013). They had developed an autonomous ornithopter equipped with a live video capturing features for surveillance purposes. The electronics control system included servo motor driver, transmitter and receiver, and also a live camera. The system was able to broadcast while flying in mid-air.



Figure 2.8: Block diagram of the overall electronics system configuration for a wireless flapping robot (Tandon, Vajpai, & Mishra, 2013)

#### **CHAPTER 3: METHODOLOGY**

This section explains the research plan, hardware design and software design implemented in this study. The research plan is divided into project plan structure, speed and control flow, lastly the interfacing plan.

#### 3.1 Research plan

The research plan flowchart is shown in Figure 3.1. There are two parts of the system part A and part B. Generally, part A is more to understanding the basic concept of this research, from planning, theory, and hardware/software. The planning of this research is tabulated in the Gantt chart which show the time allocation for different type of tasks that had to be done. The theory and related research reviews will be explained in the literature review part and based on books, lecture notes, conference papers, journals and articles. A critical review had been made to compare related topics such as motor theory and types of controllers.

For part B, it started with building the prototype and carry out a low-level software. The mechanical part of this research consists of designing the gear wing mechanism, fuselage, and wing structure. In electronics and control elements, this research required to make a power circuit, and motor gear connection. Along with that, the software part is to generate PWM signal in Arduino design tool by using Arduino Uno board and acquire data from sensor. After completing both hardware and software, the system is ready to interface and proceed to high level software. If the system has no problems occurred, the next step can be proceeded. However, if there are problems occurred at any points, the system will be verified at either hardware or software part. After completing both hardware and software, the system will be verified at either hardware is developed into high level software which include more advance features in the system like controlling the motor speed and wireless control (if

needed). Next, the whole system is ready for performance test which include varying of loads at constant speed.



Figure 3.1: Research plan flowchart

## **3.2** System architecture

Figure 3.2 displays the interface between all of the devices used in the development of the dragonfly robot flapping mechanism which involved a master and slave setup. Controlling the speed of the motor that drives the flapping mechanism was done within the X-CTU program by a user with a personal computer. Connection between the master and slave control mode was made by using XBee Series 1 RF modules. The computer is serially connected to the SKXBee board while it simultaneously received data and feedback from the onboard XBee module of the dragonfly robot. The ZigBee compliant module was chosen considering that it provides low transmission power rate and is well-suited for short range data transmission.



Figure 3.2: Device interface with Arduino Uno microcontroller

## 3.3 Hardware design

The hardware design section provides detail explanations on both mechanical prototype of the dragonfly robot flapping mechanism and electronics components that are involved in this study.

## 3.3.1 Flapping mechanism

The flapping mechanism of the dragonfly robot in this research was designed by using SolidWorks with every details and considerations taken into account. The overall body and mechanism is provided in Figure 3.3 with the exception of the DC motor and other electronics components. Since this research is mainly concerned on the development of the dragonfly robot flapping mechanism and not to actually making it able to fly, therefore the prototype design may not be ideal in terms of weight distribution, practicality of the moving parts, and the overall performance of the flapping itself.



Figure 3.3: Prototype design of dragonfly robot flapping mechanism with views on the (a) front and the (b) back

In this prototype design, the DC motor is located at the back of the robot in which it is attached to a small 10-teeth red gear. This gear will then drive a bigger 50-teeth white gear to have a gear setup of 5:1 ratio. The reason is for the small DC motor to produce large enough torque to compensate for the friction of the moving red flaps of the robot. Additionally, both flaps are designed to move accordingly with the linear movement of the white slider gear at the front where it can produce approximately 45° flapping angle.

#### 3.3.1 Arduino Uno development board

The Arduino Uno as shown in Figure 3.4 is an open-source microcontroller board based on the ATmega328P microcontroller chip. The mainboard is equipped with 14 digital input/output (I/O) pins of which 6 can be used as pulse width modulation (PWM) outputs, 6 analogue inputs, a 16MHz crystal oscillator, a universal serial bus (USB) connector to download a program, a power jack, and a reset button. The main specification of the development board is summarized in Table 3.1. Essentially, the board is well-known and is highly recommended for fast prototyping of a system as it contains adequate features and is particularly sufficient for the research presented in this study.



Figure 3.4: Arduino Uno microcontroller (Arduino, 2018)

Microcontroller	ATmega328		
Operating Voltage	5V		
Input Voltage (recommended)	7-12V		
Input Voltage (limits)	6-20V		
Digital I/O Pins	14 (of which 6 provide PWM outputs)		
Analog Input Pins	6		
DC Current per I/O Pin	40mA		
DC Current for 3.3V Pin	50mA		
Clock Speed	16MHz		

Table 3.1: Arduino Uno microcontroller specification

## 3.3.2 XBee RF module

Figure 3.5 shows the XBee Series 1 1mW Wire Antenna RF module from Digi. The module takes the standard IEEE 802.15.4 protocol and utilized it into a simple to use serial command set. The module allows for a straightforward, reliable and wireless communication between microcontrollers and computer systems with a serial port. Besides, the 100m communication range is excellent for such a low powered device that only consumes 1mW. The small form factor is also suitable for the kind of application in this research.



Figure 3.5: XBee Series 1 1mW Wire Antenna (Sparkfun, 2018b)

In order to have the XBee module connected to the Arduino Uno development board, the use of an expansion board as shown in Figure 3.6 is necessary. The shield design enables it to be stackable on top of the Arduino Uno along with other types of shield as well. This feature makes the entire experience hassle-free and less time consuming to add additional devices.



Figure 3.6: XBee shield (Cytron, 2018b)

### **3.3.3** DC motor and motor shield

A DC motor as presented in Figure 3.7 is used to drive the gears that move the flapping mechanism of the dragonfly robot. The motor has a normal operating voltage ranging from 1 to 3V but yet can handle a maximum load of up to 12V. It weighs about 26g and has a no-load speed of  $6600\pm10\%$  rpm at 1V.



Figure 3.7: DC motor (Autobotic, 2018)

The equivalent DC motor circuit and equations are shown as in Figure 3.8:



Figure 3.8: Equivalent DC motor circuit

$$V = I.R + L\frac{dI}{dt} + E$$

Where,

V = applied voltage

I = current

L =Inductance

R =Resistance

E = Back EMF

Assuming that the current is constant, thus the inductance can be disregarded. The simplified voltage equation is as:

$$V = I.R + E$$

The voltage that is produced by the coil rotation is called back electromotive force which oppose the supplied voltage. Hence, the voltage across motor is reduced. The back EMF equation is given as:

$$E = k_E . \omega$$

Where,

 $k_E$  = Electrical constant, inherent to the motor

 $\omega$  = Angular velocity of the motor

Therefore, the voltage equation would be,

$$V = I.R + k_F.\omega$$

The current flow is directly proportional to the torque of the motor.

$$T = k_T I$$

and the current equation is,

$$I = \frac{T}{k_T}$$

Where,

T = Motor torque

 $k_T$  = Motor torque constant

Consequently, the voltage equation become,

$$V = \frac{T}{k_T} \cdot R + k_E \cdot \omega$$

From the above equation, the relationship between the applied voltage and the angular velocity is directly proportional. In DC motor, the electrical constant and the torque constant are equal, therefore the equation of the angular velocity will be as,

$$\omega = \frac{V}{k} - \frac{T}{k^2} \cdot R$$

This shows that the motor will achieve its maximum speed when there is zero load torque applied at the motor's shaft and vice versa. The torque equation can be obtained by rearrange the equation. This show that when the angular velocity is zero, the torque will be at its maximum state.

$$T = \frac{V - \omega . k}{R} . k$$

The relationship between the motor torque and rotational speed in most DC motor is plotted as shown in Figure 3.9.



Figure 3.9: DC motor torque-speed curve

Based on the above analysis, it has been proved that when the motor torque (load) is constant, the generated speed is directly proportional to the supply voltage. Meanwhile, when the voltage is constant, the speed will be decreased as the load increase.

To have the motor connected with the Arduino Uno, a motor shield as given in Figure 3.10 is used which can be stacked on top of the development board. The motor driver shield is needed since the Arduino pin can only supply up to 40mA for each of the I/O pins. The shield utilizes L298P chip that allows control of two 5-26V DC motors with a maximum of 2A current for each channel. Furthermore, users have the option to configure it to become Locked-Anti Phase which uses PWM signal to decide on the motor direction, speed and start/stop of the motor. This control mode can be configured from the on-board jumpers and also within the program.



Figure 3.10: Cytron 2A motor shield (Cytron, 2018a)

## 3.3.4 HC-SR04 ultrasonic sensor

A distance measuring sensor for the purpose of detecting the height of the dragonfly robot when it flies is added for future research and development. The sensor used is a low-cost ultrasonic range finder that uses Sharp infrared sensor as shown in Figure 3.11. The HC-SR04 ultrasonic sensor has a ranging distance of 2-400cm with a resolution up to 0.3cm. The sensor also has an effective measuring angle of less than 15° as rated by the manufacturer. The build dimension on the other hand is rather small at only 45 x 20 x 15mm.



Figure 3.11: HC-SR04 ultrasonic sensor (Sparkfun, 2018a)

#### **3.3.5** Device connections

Figure 3.12 visualizes the device connections of the entire electronics components used for the development of dragonfly robot flapping mechanism in this study. The ultrasonic sensor, XBee shield (with attached XBee module), and 2 Amp motor shield are all connected to the Arduino Uno. The shields are stacked on top of the Arduino and therefore share the same power supply. Meanwhile, the power supply used to turn ON the whole system is an external 12V DC adapter connected to the input voltage supply of the Arduino.



Figure 3.12: Device connections of the overall electronics components

The speed control of the DC motor is achieved through conventional PWM which can be obtained from Arduino's analog pin 5 while the enable/disable function of the motor is controlled by Arduino's analog pin 4. For the ultrasonic sensor, the input echo pin is connected to the Arduino's digital pin 8 while the output trigger pin is connected to the

Arduino's digital pin 12. The XBee shield on the other hand has its universal asynchronous receiver-transmitter (UART) connection set to digital pin 0 and pin 1 of the Arduino.

### 3.4 Software design

#### **3.4.1** Wireless communication

Every XBee modules have unique addresses assigned to them from the factory. In order to establish successful communication between two XBees, both Serial Number High, SH and Serial Number Low, SL of one XBee need to be transferred to the Destination Address High, DH and Destination Address Low, DL of the partner XBee. Such procedure can be accomplished by using XCTU utility software provided by Digi International as shown in Figure 3.13. Additionally, the PAN ID of the XBee can be in any numbers while the Mac Mode, MM needs to be set to 802.15.4 with ACKs from the drop-down menu to enable proper data transmission between the two XBees.



Figure 3.13: XCTU software

The provided XCTU utility is a free tool that not only can be operated to define the communication parameters, but also as a control and monitoring platform to transmit and receive data between two or more XBee modules. This can be done by first securing the connection between the XBees and switching to the Console working mode on the XCTU. The Console command window as presented in Figure 3.14 can then be used to transmit data and displays the receive data as well.



Figure 3.14: Console mode in XCTU

## 3.4.2 Arduino program

Figure 3.15 provides the flowchart of the Arduino program for the dragonfly robot. The program firstly performs system initialization that includes classifying the enable/disable pin that is connected to the motor shield as output and then disabling the motor so that it will not radically turned ON while system startup. Afterwards, the system enters a standby mode and waits for user input that comes from the XBee signal connected to the XCTU.



Figure 3.15: Flowchart of Arduino program

Once a signal is received, the system will see whether it is within a valid range of input for the motor voltage before proceed with turning ON the motor. Otherwise, the system will return the proper range of input that will be displayed in XCTU and goes back to the standby mode. On the occasion that the user input voltage is relevant, the motor will simply run continuously based on the input value until the reset button is pressed.

## **CHAPTER 4: RESULT AND ANALYSIS**

## 4.1 Hardware development

The final version of the prototype dragonfly robot flapping mechanism is given in Figure 4.1. Each individual parts of the body of the dragonfly robot were 3D printed from using PLA material and fixed to each other by sets of screws, nuts and washers. The material was chosen as it is the easiest to print, lightweight, biodegradable and rigid enough for this application. This approach makes the overall rapid prototyping possible while being cost effective at the same time. Moreover, by taking advantage of using 3D printing technology in prototyping development, it opens up branches of opportunity as objects can be of almost any shape or geometry. Unlike material removed from a stock in the conventional machining process, 3D printing builds a three-dimensional object from CAD model layers by layers and therefore produces no unwanted waste.



Figure 4.1: Prototype of a dragonfly robot

At the tail of the robot, a DC motor was attached while an ultrasonic sensor was mounted to the head. All other electronic components were separated from the body of the robot. The entire components were then powered by a 12V DC external power supply unit (PSU) to the Arduino. Due to the stackable design of the motor shield and the XBee shield, each of these expansion boards drew power from the same power source of the Arduino. For the XBee shield, power was taken from the 5V pin of the Arduino for the logic controls and regulated on-board to 3.3V DC before being supplied to the XBee module. Similar condition can be said for the motor shield, except the motor was directly driven by the Vin power supply of the Arduino.

The gear equation is illustrated as below:

Gear ratio, 
$$\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} = \frac{50}{10}$$

Secondary gear rotational speed, 
$$\omega_2 = \frac{6600}{5} = 1320 rpm$$

Assuming that the rated speed of the motor has a no-load speed of  $6600\pm10\%$  rpm at 1V. Thus,  $\omega_1 = 6600$  rpm. From the equation, the rotational speed of the secondary gear is 13520 rpm. Next, the secondary gear is connected to the 6.45 mm and 24.00 mm crank to move the slider. The speed of the slider can be obtained as:

Slider velocity,  $V_D$ = (length of small crank)(rotational speed of the secondary gear) = (6.45)(1320) 0.10472 = 891.6mms<sup>-1</sup>

Then, the slider with 5 number of tooth at each side is link to the wing gear (red) which has 5 number of tooth as well but only within a 140° angle of radius 11.5mm. Thus, the gear ratio between the slider (white) and the wing gear (red) is equal to one.

Linear velocity,  $v = r. \omega$ 

Rotational speed, 
$$\omega = \frac{v}{r}$$

$$\omega_W = \frac{V_D}{r} = \frac{891.6}{11.5} = 77.53rpm$$

Wing gear rotational speed,  $\omega_W = 2\pi f_W$ 

Runs only from  $0^{\circ}$  to  $140^{\circ}$ ,

$$\omega_W = (140) \frac{\pi}{180} f_W = 2.44346 f_W$$

Flapping wing frequency, 
$$f_W = \frac{77.53}{2.44346} = 31.73Hz$$

## 4.2 Motor voltage input test

A series of evaluation has been conducted to obtain the actual voltage the motor is running when being supplied with different level of input voltages. Such findings are given in

Table 4.1 and Figure 4.2. Based on the results, it can be seen that all of the measured voltages from the motor fluctuated and did not even reach the desired voltage input being supplied to the motor. This is mainly due to the motor load that has to drive the mechanical gears of the flapping mechanism.

Test	Input Voltage, V	Measured Voltage, V	Average Measured Voltage, V	Average Error
1	1.7	0.98 - 1.14	1.06	0.64
2	1.8	1.06 - 1.10	1.08	0.72
3	1.9	1.13 - 1.22	1.18	0.73
4	2	1.34 - 1.40	1.37	0.63
5	2.1	1.36 - 1.42	1.39	0.71
6	2.2	1.40 - 1.50	1.45	0.75
7	2.3	1.49 - 1.54	1.52	0.79
8	2.4	1.57 - 1.62	1.60	0.81
9	2.5	1.67 – 1.69	1.68	0.82
10	2.6	1.73 – 1.79	1.76	0.84
11	2.7	1.81 - 1.90	1.86	0.85
12	2.8	1.91 - 2.00	1.96	0.85
13	2.9	1.99 - 2.04	2.02	0.9
14	3	2.09 - 2.16	2.13	0.88
			Total Average	0.78

 Table 4.1: Motor voltage input test measurement



Figure 4.2: User input voltage vs measured voltage

## 4.3 Flapping frequency

The flapping mechanism of the dragonfly robot has been assessed with motor input voltages that varied from 2-10V. Figure 4.3 shows the testing setup with the body of the dragonfly robot simply held by hand. To capture and count the number of flaps the robot was making, a smartphone that was capable to record videos in slow motion was used. Due to the use of a smartphone, a limiting voltage of 10V was administered since the smartphone was not able to capture faster frequencies the mechanism produced at higher voltages.



Figure 4.3: Testing setup for flapping frequency measurement

The outcomes of the experiment are provided in Table 4.2. For every assessments, a minimum operation period of at least 5s was implemented to get the proper frequency for each input voltages. From the visualization in Figure 4.4, it can clearly be seen that the number of frequency or flaps per second gradually increases together with the increases of the motor supply voltage. By manipulating the motor input voltage from 2 to 10V with an increment of 0.5V, the flapping frequency of the dragonfly robot was measured at up to 26Hz.

Test	Voltage (V)	Frequency (Hz)
1	2	6
2	2.5	6
3	3	8
4	3.5	10
5	4	13
6	4.5	15
7	5	18
8	5.5	20
9	6	23
10	6.5	23
11	7	23
12	7.5	24
13	8	24
14	8.5	25
15	9	25
16	9.5	26
17	10	26

**Table 4.2: Flapping frequency test measurement** 



Figure 4.4: Voltage vs frequency of dragonfly robot flapping mechanism

#### 4.4 Ultrasonic sensor performance

A simple experiment to test the precision and accuracy of the ultrasonic sensor has been conducted as shown in Figure 4.5. The body of the dragonfly robot was turned upside down and a piece of cardboard was manually placed by hand at certain pre-determined distances away from the sensor to serve as a reverberation wall. Such findings are presented in Table 4.3.



Figure 4.5: Testing setup for ultrasonic sensor

	Actual Distance (cm)						
	3	5	7	9	11	13	15
No. of Test			Measu	red Distan	ce (cm)		
1	3.12	5.05	6.74	8.88	11.48	13.93	15.78
2	3.12	5.21	6.22	9.00	11.90	13.52	15.78
3	3.02	4.71	6.33	8.28	11.90	13.57	15.78
4	3.12	5.40	6.24	8.64	11.48	13.59	15.31
5	3.12	5.41	6.79	8.48	11.90	13.17	15.72
6	3.02	5.31	6.69	8.33	12.78	13.17	15.78
7	3.12	5.41	6.79	8.48	12.78	13.17	16.12

 Table 4.3: Ultrasonic sensor test measurement

#### Table 4.3 (continued)

8	3.12	4.90	6.69	8.43	13.17	13.17	15.67
9	3.02	5.47	6.79	8.33	13.59	13.17	15.72
10	3.07	5.26	6.71	8.43	13.07	13.17	15.72
Mean Error (%)	2.83	5.82	5.73	5.24	12.72	2.79	4.92

During the experiment, 7 distances of the cardboard were specified within a range of 3-15cm and 10 number of measurements data were collected. It was discovered that the sensor has the lowest mean error of 2.79% when the cardboard was placed with a distance of 13cm from the sensor. In comparison, the highest mean error was 12.72% when the gap was 11cm. This large error could be due to several reasons, such as inaccurate placement of the cardboard and a slight movement of the cardboard that resulted in a nonparallel surface to the sensor.

For the rest of the measurement distances, the mean error was roughly around 5% with the 3cm distance being the second lowest error at 2.83%. In summary, the overall results were considered to be satisfactory since the sensor used is low-priced and non-industrialized, yet is adequate for applications that do not require high precision measurement.



## 5.1 Conclusion

Figure 5.1: Efficiency versus voltage graph

Efficiency, 
$$\eta = \frac{P_{out}}{P_{in}}(100)$$

In this study, a flapping mechanism of a dragonfly robot has been successfully developed. A CAD model was designed by using SolidWorks and then 3D printed in multiple parts before they are combined together. An Arduino Uno was used and other essential electronics components were integrated as well. Subsequently, in order to operate the robot, a program was created and wireless communication was implemented to control the robot wirelessly from a computer. Finally, several experiments have been conducted which consisted of observing the performance of the flapping mechanism when it is turned ON, evaluating the input voltage of the motor, calculating the flapping frequencies on different input voltages, testing the behaviour of the ultrasonic sensor and calculating the efficiency of the whole system. Even though it has a lower efficiency (40%), it provides wide opportunity for future improvement.

## 5.2 Recommendations

Current design of the prototype dragonfly robot flapping mechanism did not move smoothly due to the absence of bearings for each joints of the printed parts. Consequently, some greases were applied to alleviate such issue. Nevertheless, overall design modifications and the use of bearings are essential for all the mechanical components to move freely without much friction.

For future development, a closed-loop control system will be crucial for the dragonfly robot to move and maintain its course at specific heights. Different type of controllers such as proportional, integral and derivative (PID), intelligent fuzzy logic control or the combination of both can be implemented and tested to see which controller provides better performance.

#### REFERENCES

- Arabagi, V., Hines, L., & Sitti, M. (2012). Design and manufacturing of a controllable miniature flapping wing robotic platform. *International Journal of Robotics Research*, 31(6), 785–800. https://doi.org/10.1177/0278364911434368
- Arabagi, V., Hines, L., & Sitti, M. (2013). A simulation and design tool for a passive rotation flapping wing mechanism. *IEEE/ASME Transactions on Mechatronics*, *18*(2), 787–798. https://doi.org/10.1109/TMECH.2012.2185707
- Arduino. (2018). Arduino Uno Rev3. Retrieved January 12, 2018, from https://store.arduino.cc/usa/arduino-uno-rev3
- Autobotic. (2018). Hobby Motor Gear. Retrieved from https://www.autobotic.com.my/hobby-motor-gear
- Azuma, B. Y. A., Azuma, S., Watanabe, I., & Furuta, T. (1985). FLIGHT MECHANICS OF A DRAGONFLY, *107*, 79–107.
- Baek, S. S., Garcia Bermudez, F. L., & Fearing, R. S. (2011). Flight control for target seeking by 13 gram ornithopter. *IEEE International Conference on Intelligent Robots and Systems*, 2674–2681. https://doi.org/10.1109/IROS.2011.6048246
- Bermudez, F. G., & Fearing, R. (2009). Optical flow on a flapping wing robot. 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009, 5027–5032. https://doi.org/10.1109/IROS.2009.5354337
- Choi, Y., Joung, J., & Lee, D. (2012). Flapping-wing Model for Aerial Robot, (Urai), 180–181.

Cytron. (2018a). Cytron 2A Motor Shield.

- Cytron. (2018b). Cytron XBee Shield. Retrieved January 12, 2018, from https://www.cytron.io/p-shield-xbee
- Hsiao, F., Yang, L., & Lin, S. (2012). Lightweight Robotic Birds, (October), 35-48.
- Jackowski, Z. (2009). Design and construction of an autonomous ornithopter. *Thesis*. Retrieved from http://18.7.29.232/handle/1721.1/52809
- Marconi, L., Naldi, R., & Gentili, L. (2011). Modelling and control of a flying robot interacting with the environment. *Automatica*, 47(12), 2571–2583. https://doi.org/10.1016/j.automatica.2011.09.020
- Pérez-Arancibia, N. O., Duhamel, P. E. J., Ma, K. Y., & Wood, R. J. (2013). Model-free control of a flapping-wing flying microrobot. 2013 16th International Conference on Advanced Robotics, ICAR 2013. https://doi.org/10.1109/ICAR.2013.6766538
- Putri, F. T., Ariyanto, M., Haryanto, I., Arozi, M., Caesarendra, W., & Hanan, M. R. I. (2017). Development of Unmanned Aerial Vehicle (UAV) ornithopter with wireless radio control. *Proceedings - 2016 3rd International Conference on Information Technology, Computer, and Electrical Engineering, ICITACEE 2016*, 79–84. https://doi.org/10.1109/ICITACEE.2016.7892415
- Sankarasrinivasan, S., Balasubramanian, E., Yang, L. J., & Hsiao, F. Y. (2015). Autonomous control of Flapping Wing Vehicles using graphical user interface. 2015 International Conference on Advances in Computing, Communications and Informatics (ICACCI), 2217–2220. https://doi.org/10.1109/ICACCI.2015.7275946
- Sparkfun. (2018a). Ultrasonic Sensor HC-SR04. Retrieved from https://www.sparkfun.com/products/13959

- Sparkfun. (2018b). XBee 1mW Wire Antenna Series 1 (802.15.4). Retrieved January 12, 2018, from https://www.sparkfun.com/products/8665
- Tandon, A., Vajpai, A., & Mishra, A. N. (2013). Design of an Autonomous Ornithopter With Live Video Reception for Military Surveillance, 489–493.
- Usherwood, J. R. (2001). AERODYNAMICS AND ENERGETICS OF ANIMAL FLIGHT BASED ON PROPELLER MODELS, (May).

Wakeling, J. M., & Ellington, C. P. (1997). Dragonfly flight, 582, 557–582.

- Wang, Z. J., & Russell, D. (2007). Effect of Forewing and Hindwing Interactions on Aerodynamic Forces and Power in Hovering Dragonfly Flight a ) b ) c ) d ), 148101(October), 1–4. https://doi.org/10.1103/PhysRevLett.99.148101
- Wood, R. J. (2007). Design, fabrication, and analysis of a 3DOF, 3cm flapping-wing MAV. 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1576–1581. https://doi.org/10.1109/IROS.2007.4399495
- Yang, L., Esakki, B., Chandrasekhar, U., Hung, K., & Cheng, C. (2015). Practical Flapping Mechanisms for 20 cm-span Micro Air Vehicles, 7(2), 21–22.
- Yoon, S., Kang, L., & Jo, S. (2011). Development of Air Vehicle with Active Flapping and Twisting of Wing. *Journal of Bionic Engineering*, 8(1), 1–9. https://doi.org/10.1016/S1672-6529(11)60007-3