# INTEGRATED PARAMETERS MEASUREMENT OF BRUSHLESS DIRECT CURRENT MOTOR AND CONTROL FOR QUADCOPTER APPLICATION

**by**

**LEONG YONG CHEE**

**Thesis submitted in fulfilment of the requirements for the**

**Bachelor's Degree of Engineering (Honours) (Aerospace Engineering)**

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## ENDORSEMENT

I, Leong Yong Chee hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

(Signature of Student)

Date:

(Signature of Supervisor)

Name: Ir. Dr. Ahmad Faizul Hawary

Date:

(Signature of Examiner)

Name: Ir. Dr. Parvathy Rajendran

Date:

## DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

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**INTEGRATED PARAMETERS MEASUREMENT OF BRUSHLESS DIRECT CURRENT MOTOR AND CONTROL FOR QUADCOPTER APPLICATION**

## ABSTRACT

The objective of this project is to measure and study the performance parameters of the BLDC motor. The parameters obtained in this project is propeller thrust, rotor speed and motor current, which is measured by HX711 load cell sensor, A3144 Hall effect RPM sensor and GY-712 Hall effect current sensor respectively. A motor-propeller testbed is set up with the electronic sensor modules and MCU embedded to perform the real-time signal processing in accessing the integrated performance parameters while increasing controlled throttle is applied. On the other hands, step responses of thrust generated by the rotor-propeller are acquired at different fixed throttle inputs. Before conducting the experiment, the sensor modules had been calibrated by comparing the reading with hand measuring tools to validate the accuracy of those sensors and find out that the output of current sensor exist an additional offset of 0.277 A that causing it to deviate from the actual value even though a moving average is applied into current measuring algorithms. The purpose of this experiment is to study the correlations between the measured parameters so as to identify the performance limitations and constraints within the open-loop control system. The results show that the BLDC motor start to toggle on at servo throttle of '46' and reach its maximum throttle at '135' while the motor stalling occurs at throttle percentage of 53.33%. The thrust generated using smaller size propeller is lower however higher rotor speed and lower current consumed is achieved on behalf of that. The step response of thrust at different throttle control is observed in verifying the stability performance of motor-propeller

when applying different speeds. The result shows that the motor losing efficiency at high steady throttle or whenever there is a throttle change as the settling time increases and the overshoot occurs in the waste of energy.

# PENGUKURAN PARAMETER BERINTEGRASI MOTOR ARUS TERUS TANPA BERUS DAN KAWALAN UNTUK APLIKASI QUADCOPTER

## ABSTRAK

Objektif projek ini adalah untuk mengukur dan mengkaji parameter hasil kerja motor BLDC. Parameter yang diperolehi dalam projek ini adalah kuasa kipas, kelajuan pemutar dan arus motor, yang diukur dengan pengesan sel beban HX711, pengesan A3144 Hall RPM dan pengesan arus GY-712 masing-masing. Tempat kajian propeller-motor disediakan dengan modul pengesan elektronik dan MCU tersambung untuk mejalankan pemprosesan isyarat masa nyata dalam mengakses parameter hasil kerja terintegrasi sambil meningkatkan pendikit terkawal yang diterapkan. Sebaliknya, tindak balas tindanan kuasa yang dihasilkan oleh kipas pemutar diperolehi dengan pemasukan pendikit tetap yang berlainan. Sebelum menjalankan eksperimen, modul pengesan telah dikalibrasi dengan membandingkan bacaan dengan alat pengukur tangan untuk mengesahkan ketepatan pengesan tersebut dan didapati bahawa keluaran pengesan arus mempunyai tambahan offset 0.277 A yang menyebabkannya menyimpang dari nilai sebenar walaupun purata bergerak telah digunakan ke dalam algoritma pengukur arus. Tujuan eksperimen ini adalah mengkaji hubungan antara parameter yang diukur untuk mengenal pasti batasan hasil kerja dan kekangan dalam sistem kawalan ulangan terbuka. Hasilnya menunjukkan bahawa motor BLDC mula bergerak pada pendikit servo '46' dan mencapai pendikit maksimum pada '135' manakala motor terhenti berlaku pada peratus pendikit 53.33%. Kuasa yang dijana menggunakan kipas saiz yang lebih kecil adalah lebih rendah tetapi kelajuan

pemutar yang lebih tinggi dan penggunaan arus yang lebih rendah telah dicapai bagi tujuan itu. Tindak balas langkah kuasa pada kawalan pendikit yang berlainan diperhatikan untuk mengesahkan prestasi kestabilan kipas motor apabila meggunakan kelajuan yang berbeza. Hasilnya juga menunjukkan bahawa motor mula kehilangan kecekapan pada pendikit tetap yang tinggi ataupun semasa mempunyai perubahan pendikit yang menunjukkan masa penetapan bertambah dan tembakan tindak balas berlaku dalam keadaan pembaziran tenaga.

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# LIST OF SYMBOLS

$I$ : Current through the circuit $[A]$

$I_M$ : Current through the motor $[A]$

$I_{M_{idle}}$ : No-load current of the motor $[A]$

$V$ : Potential difference across the load $[V]$

$V_M$ : Potential difference across the motor $[V]$

$V_m$ : Voltage potential after the motor $[V]$

$V_{esc}$ : Voltage potential after the ESC $[V]$

$V_b$ : Voltage supplied by the battery $[V]$

$V_{load}$ : Measured output voltage value of a load $[V]$

$V_H$ : Hall voltage $[V]$

$V_{CC}$ : Voltage at common collector (supplied voltage) $[V]$

$V_{IOUT(Q)}$ : Quiescent output voltage $[V]$

$V_{OE}$ : Electrical offset voltage $[V]$

$R$ : Resistance of the load $[\Omega]$

$R_M$ : Resistance of the motor $[\Omega]$

$R_{ESC}$ : Resistance of the ESC $[\Omega]$

$Sens$ : Sensitivity of sensor module $[mV/A]$

$E_{TOT}$ : Total output error

$RPM$ : Revolution per minute $[rev/min]$

$K_V$ : RPM constant of the motor $[rev/V]$

$N$ : Cumulative number of counts within the duration

$t$ : Cumulative time taken $[ms]$

$T_P$ : Propeller thrust $[kg]$

$W$ : Weight of load $[kg]$

$P_{p_{Out}}$ : Propeller output power $[W]$

$v_p$ : Propeller pitching velocity $[m/s]$

$g$ : Gravitational acceleration, $g = 9.81\ m/s^2$

$\rho$ : Density of air $[kg/m^{-3}]$

$d$ : Propeller diameter $[inch]$

$p$ : Propeller pitch $[inch]$

$M_{load}$ : Measured output mass value of a load

$M_{ref}$ : Reference output mass value at no load

$M_{sample}$ : Measured value of a sample with known mass

$m_{sample}$ : Mass of the sample

$k_m$ : Scale factor of load cell

$K_1$ & $K_2$ : Empirical constants in thrust measurement experiment

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

A drone, also technically called as an unmanned aerial vehicle (UAV), have been the focal point of aviation in the last two decades since the first flight of human being took place in the history. Quadcopter is one of the UAVs categorised as a rotorcraft as the lift is required for a quadcopter flight which is opposed to the fixed-wing aircraft, a more powerful motors are therefore needed to generate sufficient thrust to hover in the air. The commonly used motors used in drone are Brushless Direct Current (BLDC) motors as they are economical, lightweight, small but powerful. One of the advantages of this motor over the brushed motor is that there is absence of brushes inside BLDC motor hence it does not require periodic maintenance, replacement or repair and never a need to be concerned about the condition of the brushes. Therefore, the motor is more reliable and has a higher speed range since there is no mechanical limitation imposed by the interaction between brushes and commutator. However, BLDC motor cannot be operated unless an Electronic Speed Controller (ESC) is used to control the speed of motor. The ESC enables the voltage and current of the motors to be controlled based on the applied speed reference signal either in the form of servo signal or input of pulse width modulation (PWM) signal to control the motor speed by adjusting the duty cycle or switching the frequency of a network of field effect transistors (FETs). And the rapid switching of the transistors is what causes the motor itself to produce high pitched whine which is noticeable especially at low speeds. Therefore, there is a current issue being encountered during the drone design which is less information obtained from the operation of BLDC motor together with the embedded ESC such as how fast the response acting towards the input signal to accelerate the motor, the stability on motor signal responses, throttle level where the motor stalling, maximum throttle on motor control, correlation of motor rpm-current, etc.

## 1.2 Problem Statement

Quadcopter is mostly unstable because of its nonlinear model that consists of numerous variables within six degrees of freedom worked by four actuators to fly in symmetrical position. The system design of controller for the quadcopter positioning includes three translational and three rotational movement that are imperative for the manoeuvring stability. At this point, it is significant to carry out analyses to detect the possible obstacles encountered during the manoeuvre performance of the quadcopter, inspecting the cause of the circumstances and trying to maintain its typical operations. By adjusting the rotational speed of each rotor, the thrust of the motor-propeller performance can be controlled. To read continuously the thrust value of the rotor, load cell sensor and rpm sensor are used, and the movement error assessed by these sensors are sent to the microcontroller unit (MCU) to be corrected using Proportional, Integral, Derivative (PDI) algorithms. Every control system has the critical role in achieving a high stability and the capability of diagnosis as well as correction for the output errors is the important criteria for a precision controller. The basic open-loop algorithms are unsuitable to drive a motor accordingly hence the control system must be programmed to regulate the motor throttle repeatedly to retain the desired thrust in maintaining a stable flight position. Monitoring and control adjustment for the speed of the rotors are necessary and the performance in maintaining stability is depending on how fast and how accurate the control system diminishes the position error.

To achieve this, the characteristic of the motor is needed prior to design a motor controller. Usually a motor that is purchased in the market does not come with accurate specifications. Therefore, this study aims to develop and set up a system that can analyse the BLDC motor characteristic using experimental approach. The proposed system is expected to be able to extract the motor characteristic in terms of speed, current, thrust, etc. In this study, monitoring the thrust produced by the propeller will be the objective where the process of triggering and monitoring can be done at the same time. Hence, a motor-propeller testbed is set up with electronic sensor modules embedded onto it where the set up can read the thrust generated and other performance parameters while tuning the motor throttle.

## 1.3 Objectives

The overall purposes of this study are listed as below:

1. To study the characteristics of motor-propeller based on the correlations between thrust, speed and current at an increasing controlled throttle.
2. To observe the step response of thrust generated by the motor-propeller testbed at different fixed throttle input control.
3. To perform sensor calibration and data correlation for both current sensor and RPM sensor.

The purpose of this study is to collect the performance characteristics of the BLDC motor by controlling the motor throttle. A motor-propeller testbed with an MCU embedded is constructed to regulate and monitor the thrust generation by the rotor-propeller based on the developed control scheme. Thrust, speed and current are detected from the identification process on the motor-propeller performance using their respective sensors. The data collecting process is conducted based on signal processing in real-time after the diagnosis of electronic and mechanical errors is carried out for zero offset calibration. The results of experiments are provided in the chapter 4 with two different means of throttling control method and two different testbed models to demonstrate the difference in performance and response regarding the states output of rotor-propeller.

## 1.4 Research Approach and Scope

### 1.4.1 Research Approach

This study discusses the design of the system implementation method, mechanism and operating principles, including the system hardware structure, the selection of sensors and the flow chart of system operation. The purpose of the research is to retrieve various responses of performance parameters corresponding to the motor throttle in a control system via experimental approach. This study proposes two approaches about the throttle control method to visualise their responses of the thrust generation in a practical way. Data collecting process is built based on the altering of throttle controller parameter via a direct approach to access the sets of input-output data obtained from the system of motor propeller testbed. The experimental results will manifest on the proportionality of the thrust-current dynamics of motor-propeller performance, the settling time of the thrust generation at the specified throttle step input value and the stall limitation of the BLDC motor that may aid in the stability calibration drone control in further research. The set up will be operated by the control core unit which using Arduino Uno MCU as control module and sensors such as GY-712 current sensor, HX711 load cell sensor and Hall effect RPM sensor to test the relation of thrust with current and speed so as to determine the performance parameters of the motor-propeller. The control system is then being measured using different measuring tools to validate the accuracy of the data processing analysis. The research procedures can be summarised as the scope shown as below.

### 1.4.2 Scope

1. To study the use of GY-712 Hall effect current sensor to measure the current of the rotor.
2. To study the use of Servo.h library to control throttle of the BLDC motor.
3. To study the use of Hall effect RPM sensor to measure the speed of the motor-propeller.
4. To study the use of HX711 load cell sensor to measure the thrust generated by rotor-propeller.
5. To obtain the performance parameters and step response of the motor-propeller testbed at different means of throttle control.

## 1.5 Thesis Outline

The body of the study is organised into 5 chapters as the following. Chapter 1 is the introduction which includes overview, problem statement, objectives, research approach and scope. Chapter 2 presents the literature review and benchmarking of BLDC motor for multirotor operations. This chapter also explains mathematical modelling of algorithms for the motor-propeller testbed which involve of theory behind the electronic sensor modules embedded onto the system. The methodology on how to execute experiments including control strategies used to tune the controller parameters and the approach on how to validate the output signal processed by the MCU is elaborated in

Chapter 3, as well as the description of the testbed parameters used in this study involving the schematic configuration diagram, specification and performance characteristics. The implementation of results is discussed in Chapter 4 related to the evaluation and analysis of experimental test results from the controls of rotor-propeller testbed while finally the improvement and conclusions discussing the possible future works are provided in Chapter 5.

# CHAPTER 2

# LITERATURE REVIEW

Propulsion system of UAV is important to provide the necessary power to propel itself for forward flight or hover. Due to the high thrust-to-weight ratio, the vertical take-off and landing (VTOL) vehicles have become the focus of study especially on quadcopter since they have higher manoeuvrability advantages over the other types of UAVs.(Ermeydan and Kiyak, 2017) Electric propulsion systems are commonly used for quadcopter as they are scalability meaning that the thrust generated can be controlled precisely and respond faster to throttle input. Electric propulsion systems are crucial to provide consistent power control so to diminish the motor control failure as well as to minimize the battery consumption.(Griffis et al., 2009) Hence, the criteria needed to define a good control performance of quadcopter in throttling or hovering mode are the quick but minimum responses. However, the swift response tends to cause oscillation which leads to less stable control during the transient state and therefore extra control signalling is usually required to neutralise its effect.(Raharja et al., 2017)

There is another common issue about the stability of quadcopter, that is uneven thrust generated despite supplying the same magnitude of throttle input. During throttling and hovering, the flight stability of a quadcopter is obtained when the equal thrusts are generated by all the rotors-propellers. Even though the identical motors and propellers used at the same speed, the thrusts generated are not really to be balanced not to mention that a single rotor-propeller set up is not necessarily producing a stable thrust. The imbalances of propeller during vibration, the voltage input values of the pulse width modulation (PWM) or pulse position modulation (PPM) in ESC, the timing of remote control, as well as the sensitivity of the sensors used may be the reason for that. Hence, a closed-loop controller is normally required to encounter this problem by eliminating all these electronic and mechanical errors conceding that the correlation of thrust value as well as other performance parameters from the rotor-propeller are apparent beforehand.(Kuantama et al., 2018)

Generally, components selection for the electric propulsion system in designing an UAV has been a simple process due to recommendation of standard propulsion combination sets by manufacturers or suppliers based on weight and type of UAV. However, the recommended weight range may only suitable up to 25 % of the maximum take-off weight. Thus, analysis on the sizing model of propulsion system is essential to estimate the performance of an UAV design. The simulation for the performance of both solar UAV and non-solar UAV had been modelled in (Rajendran et al., 2016) by changing different propeller size and the performance comparison was done among those propeller sizes. The theoretical formulas and equations shown in this research was used in the Methodology to approximate the performance parameters of the motor-propeller testbed analytically from the specification datasheet of propulsion system sizing devices. The results from performance comparation showed that lowering propeller diameter and pitch increases the efficiency of electric motor but not grant enough thrust output. Instead, propeller with larger diameter and pitch generates higher thrust and power to weight ratio. Hence, the research concluded that the propeller tip static speed should be the key parameter for propeller sizing instead of power-to-weight ratio as lower propeller tip static speed allows higher endurance of UAV flight.

The testing for the precise selection of electric propulsion system which consists of BLDC motors and propeller for the use in multicopter or hovercraft had been done in (Patel et al., 2017) by comparing the results of both theoretical values given in the datasheet of the motors and the practical thrust calculation after conducting experiments on couple of motors. The sizing of the system considered the maximum take-off weight as the requirement so that the motors-propellers combination is able to produce thrust twice the flying weight of the multicopter system. The comparison showed the thrust difference in experimental analysis proving that there is always a loss in the motors during their practical operation that has to be included in calculation and consideration during the selection of propulsion system components.

To validate the accuracy of simple motor and propeller models as well as to facilitate the selection of appropriate BLDC motor and propeller combination for flight applications, the theoretical performance approximation for single motor and propellers can carried out solely based on data provided by manufacturers and then compared to the experimental results obtained in static thrust tests. The motor and propeller models can be decoupled as different single objects to study their respective results independently. The theoretical predictions in (Muzar et al., 2017) were distributed into two parts which are modelling of BLDC motors that quantify the speed-to-voltage as well as torque-to-current characteristics and modelling of propellers that focus on speed-torque-thrust characteristic. The relation between torque and speed was explained by using motor circuit analysis and the thrust coefficient was obtained as a function of propeller diameter and pitch to determine the static thrust. The experimental results showed that the speed and torque of BLDC motor models increase by increasing motor driving voltage. Increasing propeller diameter and pitch raises its output torque to provide higher propeller thrust but reducing the motor shaft speed. The findings also showed that all the propellers produce almost the same load of thrust at low speed. The propeller with the smallest pitch generates the most thrust output at high speed.

The design and simulation of an UAV highly depends on the thrust produced by a motor-propeller combination. A method was proposed in (Gupta and Abdallah, 2018) using the experimental data from 291 motor-propeller data points to verify a generalised mathematical relationship between the motor input RPM and the corresponding output thrust for the preliminary design process of low Reynold's number applications. The mathematical models comprised of the expression for inflow velocity ratio which is developed into a simplified form using the concept of Blade Element and Momentum Theory (BEMT), the force constant which defines each thrust-rpm mathematical model and the expression for coefficient of thrust which involves the effects of pitch variation and rotor diameter effectiveness. The process was different from curve fitting method as the discrepancy of thrust between the estimated data and the experimental data may occur over the high speed and huge range of propeller sizes where the aerodynamic phenomenon becomes difficult to be generalised. The findings showed that the validation of the small size UAV model is only applicable when using propellers of diameter ranging from 4 inches to 6 inches.

A similar experiment had been conducted in (Al et al., 2018) with empirical testing to collect the parameters and data related to the relationship between BLDC motor voltage supplied, rotor speed, air speed and rotor lift. The result proved that the air velocity measured using anemometer which is used to determine thrust coefficient is linearly proportional to the rotor speed measured using tachometer as according to the concept derived using Newton's law, Archimedes, Pascal, Bernoulli and the law of continuity. The results from measurement data also showed that the lift force generated relative to the rotational speed is not proportional. Nonlinearity occurs when the lift generated by the rotor reaches up to 1.5 N where the rotation speed is around 65 revolutions per second (rps), then the thrust surges up sharply with the increase of rotor speed rotation. The performance parameters obtained for a 1200 $K_V$ BLDC motor with

30 A ESC and a propeller blade with the radius of 12 cm at the input voltage of 12V in room temperature has the thrust coefficient of 1.732.

In terms of motor selection, the technical information of the motor parameters given in the motor specifications may not be sufficient, especially for cheaper motor tends to have high tolerances in their performance characteristics. Micro brushed and brushless motors used on micro-ground vehicles and micro-air vehicles were also been found to have low efficiencies and the efficiencies decreases significantly with motor size due to not only low manufacturing tolerances but also motors operation under high range of loading status causing them to operate off design conditions. A basis of simple motor analysis was explained in (Harrington and Kroninger, 2013) with comparation between the analysis and the actual motor test data in terms of operating torque and speed within different motors. The experiments were conducted to examine the efficiencies of off-the-shelf brushless motors in two approaches that is by observing the tendencies of motor overall efficiencies change without the use of brushless speed controller at different voltages with a constant throttle as well as at a constant voltage with varying throttle settings. The results showed that the overall efficiencies of brushless motors increase with the increase in motor power output as a result of increasing input voltage and the maximum efficiency from a brushless motor is obtained at 100 % throttle. The study also emphasized the importance in matching of motor design to the motor loading conditions in order to maximize power efficiency and it was found that the brushless speed controllers are the source in causing motor inefficiency as the efficiency drops linearly with increased motor load.

# CHAPTER 3

# METHODOLOGY

## 3.1 Throttle control of BLDC motor

A complete electric propulsion system for UAVs comprises of motors, propellers, ESCs and a battery. Electric motors in electric propulsion system serve as powerplants because they can be easily coupled with propeller as the propulsion effecter, creating rotational motion from electric power and all it needs is continuous source of electricity. Theoretically, the rotational speed of an electric motor is proportional to the voltage applied to it while the torque generated is proportional to the current flow.

Figure 3. 1: Set up of motor-propeller testbed

The experiment for the motor-propeller testbed is set up as shown in Figure 3.1 with all the electronic devices and sensor modules connected to the Arduino MCU for signal processing. The movement of motor is restricted at the set-up platform which is mounted at one leg of the load cell sensor and the motor is connected to an ESC which was connected in series with a LiPo Battery of 14.8 V and a Hall effect current sensor while the ESC unit was being controlled by Arduino Uno with throttling signals. On the body of the BLDC motor, there is a small neodymium magnet adhere on it and a Hall effect RPM sensor is fixed just beside the motor set up.

### 3.1.1 Motor sizing

A selected motor will have a huge impact on the payload where an UAV can support, as well as the flight time. A general rule in designing an UAV is that the thrust provided by the motors should compromises with the requirement of thrust-to-weight ratio. The brushless electric motors are commonly chosen based on how much thrust required by the motors to lift off and fly the quadcopter at speed. The image and specification of the BLDC motor used in this study is shown in Figure 3.2 and Table 3.1 respectively. The detailed technical information of O.S. Motor OMA-3825-750 is shown in Table I at Appendix B.

Figure 3. 2: O.S. Motor OMA-3825-750 brushless motor

Table 3. 1: Specification of O.S. Motor OMA-3825-750 brushless motor

| Specification | Description |
|---|---|
| Sort | Brushless |
| Operating voltage range | 14.8 V – 18.5 V |
| Rated current | 35 A – 40 A |
| No-load speed, rpm | 11100 |
| Max. output at nominal voltage | 625 W |
| Nominal voltage | 14.8 V |
| Thrust | 30 N (1 N = 100 g) |
| Maximum current | 75 A |
| No-load current | 2 A |
| Phase Resistance | 31 mΩ |
| RPM constant ($K_V$) | 750 rev/V |

### 3.1.2 ESC sizing

The brushless electric motor is powered by a Direct Current (DC) electric source via ESC which produces a three phase Alternating Current (AC) electrical signal to control and regulate the speed as well as the direction of the motor besides power supplying the motor. The ESC must be able to handle the maximum current in which the motor might consume and be able to provide it at the right voltage. The ESC used in this study is SKYRC Hornet Brushless Sensor ESC 60 A shown in Figure 3.3 which runs in correspond with the servo control command to operate the motor control in the experiment and the sets of data is concurrently being collected along the way. The ESC is connected to the MCU so to get supply of regular 5 V input voltage and to receive the servo PWM signal from the MCU which then makes motor moves. The downside of SKYRC Hornet 60 A ESC is that it can only allow the use of servo PWM signal but not digital PWM signal to control the motor as referred to Appendix A. The detailed feature specifications of the SKYRC Hornet 60 A ESC is shown in Table 3.2.


Figure 3. 3: SKYRC Hornet 60 A Brushless ESC

Table 3. 2: Specification of SKYRC Hornet Brushless ESC

| Specification | Description |
| --- | --- |
| Maximum operating current | 60 A |
| Operating voltage | 2 – 6 S LiPo / 6 – 20 Cell NiMH |
| Switching BEC | 5.7 V / 3 A |

### 3.1.3 Battery sizing

Batteries are crucial to sustain the quadcopter flight time and lift. Lithium polymer (LiPo) is used for the batteries in this study as it can supply maximum energy density with high discharge rates. The higher the capacity, the longer the operations of electric motors, but the heavier the battery pack will be. The selection of battery pack must be ensured that the maximum current supplied by the battery is lower than the ESC outburst current to prevent burn-out of the ESC. The battery used in this study is Fullymax 14.8 V 3000 mAh 4S 35 C LiPo Pack and its detailed specifications is shown in Table 3.3.

Table 3. 3: Specification of Fullymax LiPo Battery Pack

| **Specification** | **Description** |
|---|---|
| Capacity | 3000 mAh |
| Voltage | 4S1P / 4 cell / 14.8 V |
| Discharge rate | 35 |

## 3.2 Measurement of motor current

### 3.2.1 Theory

The approximation of motor current can be determined analytically based on motor voltage using the required data from the specification datasheet of motor, ESC and battery used in this study such as no-load current and resistance of the motor, resistance and maximum current limit of the ESC as well as operational voltage of the battery.

$$V_{esc} = V_b - I \times R_{ESC} \tag{1}$$

$$I = \frac{V_{ESC} - V_m}{R_M} \tag{2}$$

$$I_M = I - I_{M_{idle}} \tag{3}$$

### 3.2.2 Experimental approach

A Hall effect current sensor is used as the device to detect the electric current in a wire and produce a signal which is proportional to that current. The signal produced could be either analog voltage or current or even a digital output and is stored in a data acquisition system for further analysis or for the purpose of control. There are various types of current sensors and the current sensor used in this study is basically a Hall effect transducer in which the detection is based on the Hall Effect phenomenon and can be used to measure all types of current signals including AC, DC and pulsating current.

Working principle of Hall effect current sensor

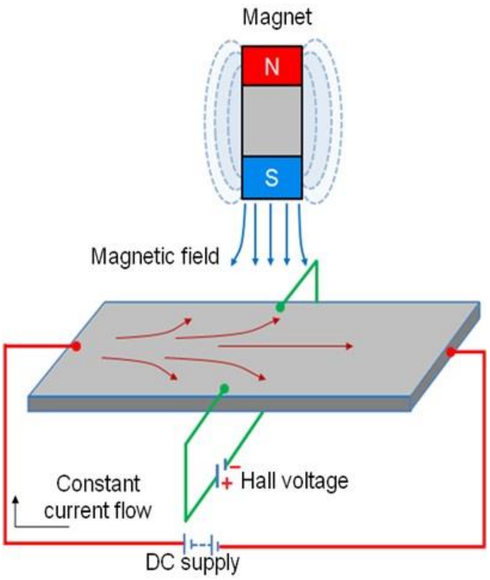


Figure 3. 4: Working principle of Hall effect current sensor(Joshi, 2013)

Inside a Hall effect sensor, there is a thin strip of metal attached along the circuit in a magnetic field as shown in Figure 3.4. In the existence of magnetic field perpendicular to the direction of electrons flow, the magnetic force acting on the particles causing the electrons beam in the metal strip will be averted from the straight path towards one edge. As the consequence, charge separation occurs when one edge of the metal strip will be negatively charged while the opposite edge become positively charged, resulting a voltage gradient perpendicular to the current feed called Hall voltage.

Specification of GY-712 module

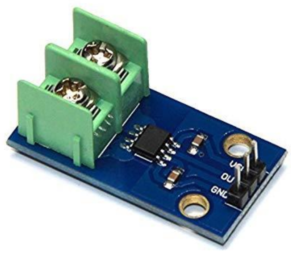

Figure 3. 5: GY-712 Hall effect current sensor module

The GY-712 current sensor as shown in Figure 3.5 is a positive-negative current measurement module that adopts ACS712ELCTR-30A-T Chip from Allegro Microsystems as module chipset, in which its detection range of current is from -30 A to 30 A. The operation principle of the current sensor is Hall effect based where it generates a linear output offset voltage proportional to the captured current. The specifications of the GY-712×30A module is shown in Table 3.4 and its detailed performance characteristics under effect of ambient temperature is shown in Table II at Appendix B.

Table 3. 4: Specification of GY-712 module

| **Specifications** | **Description** |
|---|---|
| Working temperature, $T_A$ | -40 °C to 85 °C |
| Operating voltage, $V_{CC}$ | 5 V |
| Optimized range, $I_P$ | ±30 A |
| Sensitivity, Sens | 63 mV/A to 69 mV/A |
| Total output error, $E_{TOT}$ | ±1.5 % |

While using Hall effect current sensor, there are additional terms about the accuracy characteristic of sensor need to be understood before constructing algorithms for current measurements.

Definitions of accuracy characteristics of Hall sensor

*Sensitivity (Sens)* is the response change in device output proportionate to a 1 A change through the primary conductor. The sensitivity is the product of the magnetic circuit sensitivity (G/A) and the amplifier gain (mV/G) of linear Integrated Circuit (IC).

The linear IC amplifier gain is the property programmed at factory to optimise the sensitivity (mV/A) for the full-scale current of the device.

*Quiescent output voltage* ($V_{IOUT(Q)}$) is the output of the device when the primary current is equal to zero. For a unipolar supply voltage, the output normally remains on $V_{CC}/2$. Hence, the operating voltage, $V_{CC}$ = 5 V is translated into $V_{IOUT(Q)}$ = 2.5 V. Variation in $V_{IOUT(Q)}$ can be associated to the resolution of quiescent voltage trim and thermal drift in the Allegro linear IC.

*Electrical offset voltage* ($V_{OE}$) is the actual device output differed from its ideal quiescent output value of $V_{CC}/2$ due to nonmagnetic causes. To obtain the measured current, this voltage is used to divide the device sensitivity, Sens.

*Total Output Error* ($E_{TOT}$) is the percentage of maximum discrepancy of the actual output from its ideal value and is also known as the total output error. Aside from nonmagnetic causes, temperature could also be a limiting factor that disturbs the device accuracy.

Implementation of GY-712 module

The hardware hook-up of GY-712 module is shown in Figure I at Appendix C. The output sensitivity of Hall effect current sensor means the output voltage relative to the measured current. For GY-712×30A module, the typical sensitivity is about 66 mV/A. The measurement offset voltage of the current sensor is roughly equal to 2.5 V which means the output is the power midpoint voltage when there are no currents flow through. Hence, when performing current calibration in Arduino algorithms, it is crucial to eliminate the multiplicative offset by deducting 2.5 V from the signal as described in Eq. 3 to attain actual reading at zero offsetting. Since the current sensor is connected to the analog pin in Arduino MCU, the voltage output signal is read through the Arduino

Analog-to-Digital Converter (ADC) in 10 bits number which displays the reading within 0 to 1023.(Boudiaf et al., 2018)

According to Ohm's law, current flowing through a load can be measured by dividing the voltage across the load with the load resistance which grants the equation:

$$I = \frac{V}{R} \tag{4}$$

For Hall effect current sensor, the current is determined by Hall voltage induced in accordance with current passing through which is constituted as the sensitivity of the sensor module.

$$V_H' = V_{load} \times \frac{V_{CC}}{2^{bit} - 1} \tag{5}$$

$$V_H = \left(V_H' - V_{IOUT(Q)}\right), \text{ where } V_{IOUT(Q)} = \frac{V_{CC}}{2} \tag{6}$$

$$I_M = \frac{1000\, V_H}{Sens} \tag{7}$$

## 3.3 Measurement of rotor speed

### 3.3.1 Theory

The approximation of motor speed can be determined analytically based on $K_V$ of the motor with the condition that the potential difference across the motor is obtained. $K_V$ refers to the velocity constant of a motor, measured in revolutions per minute (rpm) per volt. The $K_V$ rating of a brushless motor is the ratio of the motor's unloaded rotational speed to the peak voltage on the wires connected to the coils. By knowing the $K_V$ rating of a motor, the motor speed can be determined whether how fast it will rotate with a given voltage applied.

$$RPM = V_M \times K_V \tag{8}$$

### 3.3.2 Experimental approach

An RPM sensor is used in this study to measure the rotational motion of a part. It senses how fast one full revolution is completed by a rotating part which can be then converted to revolutions per minute, linear frequency, period of revolution and rotational speed. The RPM sensor used in this study is a Hall effect sensor where the measured output value detected is in the form of Hall voltage induced which is proportional to the current and magnetic field applied.

Working principle of Hall effect RPM sensor

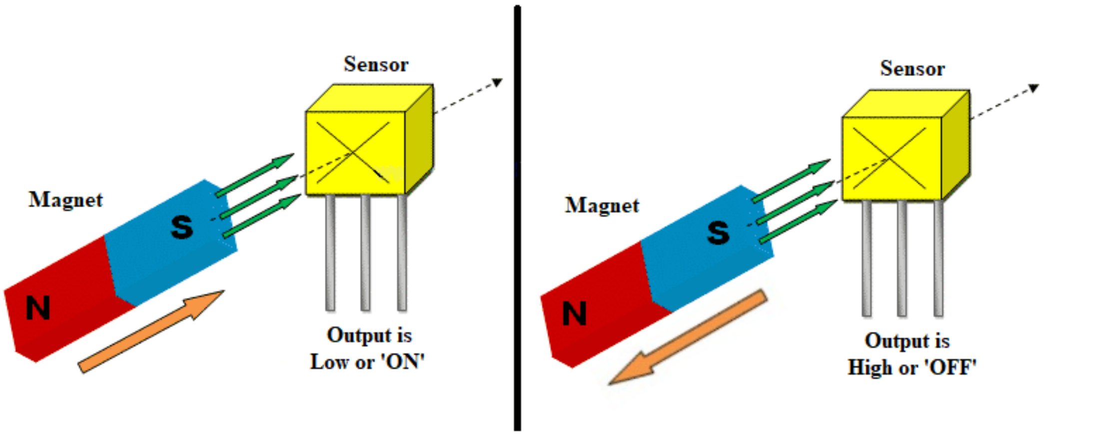


Figure 3. 6: Working principle of Hall effect RPM sensor(Electricalfundablog.com, 2015)

When the Hall effect sensor gets close enough to the magnet attached on the spinning shaft, the sensor is able to detect the presence of polarised magnetic field near its face. As shown in Figure 3.6, the latch signal pin will have the binary output change to LOW once it is triggered by a magnetic South pole of enough strength and its state is then restored back to its ordinarily binary signal of HIGH when the magnetic field is outside the detection range of the sensor. At the end of every loop, the sensor is turned off by discharging its supply voltage and then turned on at the beginning of the loop, hence registering its passing.

Specification of A3144 sensor

Figure 3. 7: A3144 Hall Effect RPM Sensor

Figure 3.7 shows the picture of A3144 Hall effect sensor and its detailed specification characteristics is shown in Table 3.5.

Table 3. 5: Specification of A3144 Hall effect sensor

| **Specifications** | **Description** |
|---|---|
| Operating voltage, $V_{CC}$ | 5 V |
| Open-collector output current | 25 mA |
| Output voltage | 5 V |
| Operating temperature | -40 °C to 85 °C |
| Turn on and Turn off time | 2 μs |

Implementation of A3144 sensor

The connection of A3144 RPM sensor to Arduino microcontroller pin is shown in Figure II at Appendix C. To measure the speed of the BLDC motor, a tiny neodymium magnet is fixed perpendicular to the rotation axis of the motor and the sensor is located just near enough to the motor so that the magnet attached to the motor can stay passing the sensor field. The set up need specific focus on the proximity between the A3144 Hall effect sensor and the neodymium magnet in which the sensor cannot be too distant away from the magnet that the sensor fails to detect the magnetic pole and cannot be too close to the motor that the sensor may crash with the magnet adhered on the circulating device. Hence, a small magnet is more advisable to be attached to the motor as small magnet generates less torque to the motor that may cause imbalance during spinning despite its smaller size.

When counting the number of counts the Hall effect sensor detect the magnetic pole, setting Interrupts in Arduino coding is necessary to allow the Arduino algorithms executing several operations in real-time. An Interrupt is a set of command that is executed interrupting the regular basis performed by the source coding instructions while here, Interrupts are called when the magnet passes through the sensor field. To perform the command during interrupt, the Interrupt Service Routine (ISR) is used outside the void setup() as well as void loop() and is being called whenever there is a Falling from HIGH (1) to LOW (0) in digital input pin to increase the counter value that makes a count. Since A3144 hall effect sensor is a unipolar sensor where only one pole of magnet is needed, every passing of the magnet will trigger the interrupt in the code and rpm count. The formula for speed measurement is based on simple calculation of number of rotations made by the turning shaft per time taken.

$$RPM = \frac{60000\ (N_n - N_{n-1})}{t_n - t_{n-1}} \tag{9}$$

## 3.4 Measurement of propeller thrust

### 3.4.1 Propeller sizing

In general, the selection of the propeller for an UAV depends on propeller diameter, propeller efficiency and tip static speed. A smaller diameter propeller provides less inertia to the UAV and is therefore easier to speed up or slow down which may help in acrobatic flight. Normally, the propeller manufacturers provide propeller data with thrust and power coefficients included. Hence, thrust can be partially obtained when choosing the suitable propeller. In this study, a propeller G/F 3 Series Master Airscrew KN1160 and a propeller K-Series K1260 K3015 which has the same pitch, but 1 inch longer than the former are used to monitor the generated thrust. The detailed dimensions of both propellers are shown in Table 3.6.

Table 3. 6: Dimension of propellers sizing

| Propeller type | Diameter | | Pitch | |
|---|---|---|---|---|
| | inch | mm | inch | mm |
| G/F 3 Series Master Airscrew KN1160 | 11 | 280 | 6.0 | 150 |
| K-Series K1260 K3015 | 12 | 304 | 6.0 | 152 |

### 3.4.2 Theory

In short, propeller moves air and converts the torque of its power source into thrust. The thrust generated by a propeller depends on the density of the air, propeller rotation speed, propeller diameter and pitch, chord length as well as the shape and area of the propeller blades.(cbenson, 2015)

$$P_{p_{Out}} = \frac{\rho}{2}\left(\frac{RPM}{60}\right)^3 (0.0254 \cdot d)^4 (0.0254 \cdot p) \tag{10}$$

$$v_p = \frac{RPM}{60}(0.0254 \cdot p) \tag{11}$$

$$T_P = \frac{P_{p_{Out}}}{g \cdot v_p} \tag{12}$$

The relation of thrust in terms of propeller diameter and pitch proposed by hobbyist Gabriel Staples in 2014, which is developed from simple momentum theory is shown in Eq. 13.

$$T_P = \rho\pi\left(\frac{0.0254 \cdot d}{2}\right)^2 \left(\frac{RPM}{60} \times 0.0254 \cdot p\right)^2 \left(\frac{d}{K_1 \cdot p}\right)^{K_2} \tag{13}$$

### 3.4.3 Experimental approach

A load cell is a transducer that is used to generate an electrical signal in which the magnitude of the signal is directly proportional to the force being measured. A strain gauge load cell which is also known as force sensor, will be discussed here. The strain gauge is used as a tool to detect changes in a physical phenomenon such as sheer force, bending movement, weight, vibration, motion and pressure. In this study, the load cell was used to measure thrust based on its correlation with weight as it detects only one degree of freedom along the z-axis with dynamic behaviour.

The strain gauge provides wide range, high precision and high integration degree of measurements, as well as high sensitivity of system contact points. The design concept of a strain gauge sensor is to change the stimulus received by the sensor from mechanical loadings into electrical signal by applying resistance modification measuring circuit based on theories of Wheatstone bridge.

Working principle of load cell

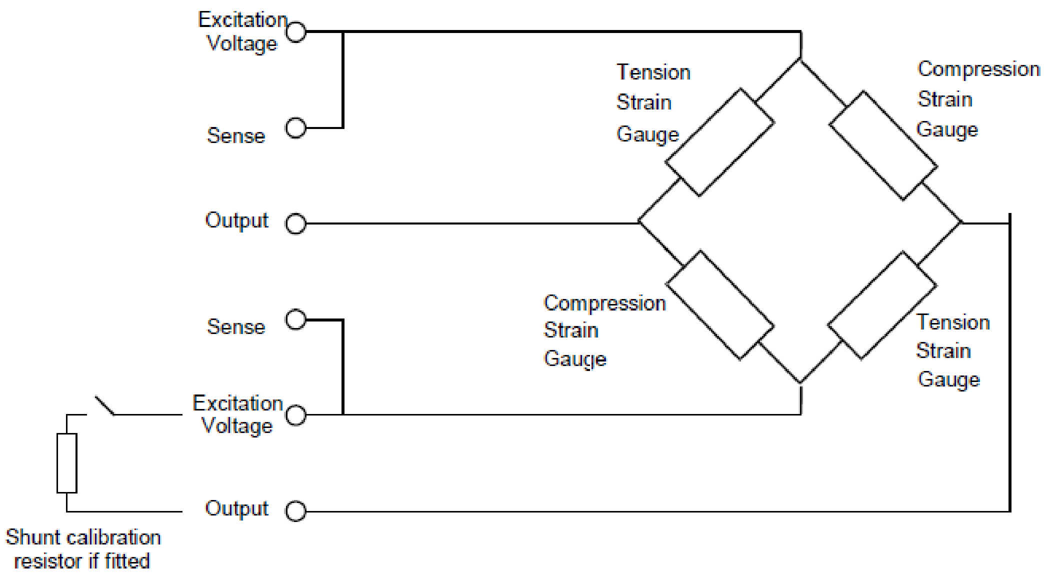


Figure 3. 8: Basic set up of a full-bridge configuration(Systems)

Generally, a Wheatstone bridge shown in Figure 3.8 is an electrical circuit used to determine an unknown electrical resistance as the means of calibrating measuring instrument. Wheatstone bridge is able to measure a very small values of resistance down in milli-Ohms range by balancing two legs of a bridge circuit in which one leg is placed with an unknown substance. The Wheatstone bridge of the load cell has four arms and its configuration depends on the number of strain gauges mounted onto a beam. The