The Developments of Proportional-Double Derivative-Linear Quadratic Regulator Controller for Attitude and Altitude Motions of a Quadcopter

ABSTRACT

Unmanned Aerial Vehicle (UAV), in this case, a quadcopter, is a small-scale UAV that has been widely used in the recent years due to its capability to perform a various application either in the military or civilian application such as environment monitoring, surveillance, and inspection. In order to guarantee a high performance of the quadcopter in the various mission applications, it needs reliable hardware and control systems. Therefore, it is important to developing an effective control algorithm for the controller for the performance and application of the quadcopter. In this thesis, studies of the attitude control and stabilization of the quadcopter through a simulation in Matlab/Simulink software has been done. First, several controllers, Proportional-Integral-Derivative (PID), Proportional-Derivative (PD), Linear Quadratic Regulator (LQR), Proportional-Linear Quadratic Regulator (P-LQR), and Proportional-Derivative-Linear Quadratic Regulator (PD-LQR) controller have been chosen to be studied and analyzed. After that, from the analysis obtained another controller was proposed to improve the performance of the quadcopter control. It is found that by adding another Derivative gain in the PD-LQR control system, the performance can be improved further. Thus, a Proportional-Double Derivative-Linear Quadratic Regulator (PD2-LQR) controller has been designed and developed. The mathematical model of the quadcopter using the Newton-Euler approach is applied to the controller system illuminate the attitude and altitude motions of the quadcopter. The simulation results of

the proposed PD2-LQR controller have been compared with the PD, PID, LQR, P-LQR, PD-LQR controller. The comparative study of the response plots reveals that the proposed PD2-LQR controller significantly improves the performance of the control system in almost all responses. In pitch motion, the PD2-LQR controller can improve the rise time up to 82.9% in average compared to other controllers, settling time improved by 86.58% in average, overshoot improved by 39.16% in average, steady-state error improved by 39.2% in average, and RMSE improved by 28.32% in average. In roll motion, rise time improved by 63% in average, settling time improved by 65.5% in average, overshoot improved by 57.7% in average, steady-state error improved by 32.82% in average, and RMSE improved by 29.4% in average. In yaw motion, rise time improved by 41.8% in average, settling time improved by 41.5% in average, overshoot improved by 34.3% in average, the improvement of steady-state error in yaw motion is very small it can be approximately equal to zero, and RMSE improved by 19.4% in average. In altitude motion, rise time improved by 31.7% in average, settling time improved by 52.7% in average, overshoot improved by 75.7% in average, and RMSE improved by 10.2% in average. Therefore, the proposed PD2-LQR controller is best-suited for the modelled quadcopter in all four motions, pitch, roll, yaw, and altitude.

Pembangunan Pengatur Kuadratik Linier Dua Terbitan Berkadar untuk Pengawalan Quadcopter dalam Sikap Gerakan dan Ketinggian

ABSTRAK

Kenderaan Pengangkut Tanpa Pemandu (UAV), dalam kes ini, sebuah quadcopter, adalah sebuah UAV berskala kecil yang telah banyak digunakan pada tahun-tahun kebelakangan ini kerana ia mampu melaksanakan pelbagai aplikasi sama ada dalam aplikasi tentera atau awam seperti pemantauan alam sekitar, pengawasan, dan pemeriksaan. Untuk menjamin prestasi quadcopter yang tinggi dalam pelbagai aplikasi misi, ia memerlukan sistem perkakasan dan kawalan yang boleh dipercayai. Oleh itu, adalah penting untuk membangunkan algoritma kawalan yang berkesan untuk pengawal untuk prestasi dan penggunaan quadcopter. Dalam tesis ini, kajian terhadap kawalan sikap dan penstabilan quadcopter melalui simulasi dalam perisian Matlab/Simulink telah dilakukan. Pertama, beberapa pengawal, Terbitan Integral Berkadar (PID), Terbitan Berkadar (PD), Pengatur Kuadratik Linier (LQR), Pengatur Kuadratik Linear Berkadar (P-LQR) dan Pengatur Kuadratik Linear Terbitan Berkadar (PD-LQR) telah dipilih untuk diteliti dan dianalisis. Selepas itu, dari analisis yang diperolehi satu lagi pengawal telah dicadangkan untuk meningkatkan prestasi kawalan quadcopter. Ditemukan dengan menambahkan satu lagi keuntungan Terbitan (D) dalam sistem kawalan PD-LQR, prestasi dapat ditingkatkan lagi. Oleh itu, Pengatur Kuadratik Linier Dua Terbitan Berkadar (PD2-LQR) telah direka dan dibangunkan. Model matematik quadcopter menggunakan pendekatan Newton-Euler diterapkan pada sistem pengawal menerangi gerakan sikap dan ketinggian quadcopter. Hasil simulasi

pengawal PD2-LQR yang dicadangkan dibandingkan dengan pengawal PD, PID, LQR, P-LQR, PD-LQR. Kajian perbandingan plot tindak balas menunjukkan bahawa pengendali PD2-LQR yang dicadangkan dapat meningkatkan prestasi sistem kawalan dalam hampir semua respon. Dalam gerakan pitch, pengawal PD2-LQR boleh mengurangkan masa kenaikan sehingga 82.9% secara purata berbanding dengan pengawal lain, masa penyelesaiannya berkurang sebanyak 86.58% secara purata, penyingkiran terlebih tembakan meningkat dengan purata 39.16%, kesilapan keadaan mantap berkurang sebanyak 39.2% secara purata, dan RMSE berkurang sebanyak 28.32% secara purata. Dalam gerakan roll, peningkatan masa berkurang sebanyak 63% secara purata, masa penyelesaian berkurang sebanyak 65.5% secara purata, penambahbaikan terlebih tembakan sebanyak 57.7% secara purata, kesilapan keadaan mantap berkurang sebanyak 32.82% secara purata, dan RMSE berkurang sebanyak 29.4% secara purata. Dalam gerakan yaw, peningkatan masa berkurang dengan 41.8% secara purata, masa penyelesaian berkurang sebanyak 41.5% secara purata, penambahbaikan terlebih tembakan sebanyak 34.3% secara purata, pengurangan kesilapan keadaan mantap dalam gerakan yaw adalah sangat kecil ia boleh disamakan dengan sifar , dan RMSE berkurang sebanyak 19.4% secara purata. Dalam gerakan ketinggian, peningkatan masa berkurang sebanyak 31.7% secara purata, masa penyelesaian berkurang sebanyak 52.7% secara purata, penambahbaikan terlebih tembakan sebanyak 75.7% secara purata, pengurangan kesilapan keadaan mantap meningkat sebanyak 38.3% secara purata dan RMSE berkurang sebanyak 10.2% secara purata. Oleh itu, pengawal PD2-LQR yang dicadangkan paling sesuai untuk quadcopter model di semua empat gerakan, pitch, roll, yaw, dan ketinggian.

CHAPTER 1

INTRODUCTION

1.1 Overview of Quadcopter

Unmanned Aerial Vehicle (UAV) technology was first introduced in the early 1900s. The UAVs can be described in terms of fixed-wing and rotary that can be either remotely or autonomously controlled. In the initial stage, these UAVs are mainly used in military application purposes such as surveillance and attack. As the technology advancing, the research in the area of UAVs is continually increased because of their interesting application; the UAVs have been widely used in civilian applications to perform a variety of environmental, commercial and scientific purposes. For instance, wildfire surveillance (Khatoon et al., 2017), search and rescue mission and hazardous environment monitoring (Wei et al., 2013). With these UAVs, the risk of human lives in a dangerous scenario can be minimized or avoided (Khatoon et al., 2017).

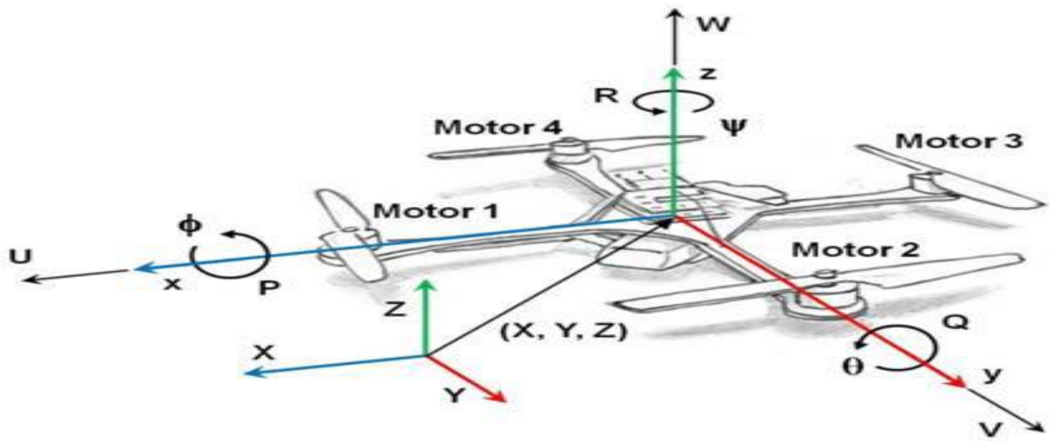

Figure 1.1.1: Quadcopter rotation convention (Numan, 2017)

Compared to fixed-wing UAVs, rotary UAVs called quadcopter or quadrotor is more interest to the researchers due to its particular advantages over the fixed-wing UAVs. A quadcopter has the ability to do a vertical take-off and landing (VTOL), or short take-off and landing (STOL) and hovering flight capabilities. With these capabilities, the quadcopter does not require a runaway for take-off and landing like a fixed-wing UAVs it just simply direct vertical take-off and landing in a limited space, plus the hovering capability give a great advantage if static image capturing is needed (Han et al., 2014).

A quadcopter is a type of multirotor helicopter that is lifted and propelled by four rotors that equally spaced; the arrangement of the rotors is usually at the corners of the square body. They are low cost, small-sized UAVs that have unique abilities for vertical, stationary and low-speed flight (Khatoon et al., 2017). A quadcopter uses two pairs of identical fixed pitch propellers that spin in an opposite direction; one pair in a clockwise direction and one pair in a counter-clockwise direction to counteracting the torque produced by each pair of the rotor. The controls of these types of UAVs use an independent variation of the speed of the rotor. A desired specific total thrust can be generated by changing the speed of each rotor. The fundamental configuration of the quadcopter is shown in Figure 1.1.1 and 1.1.2.

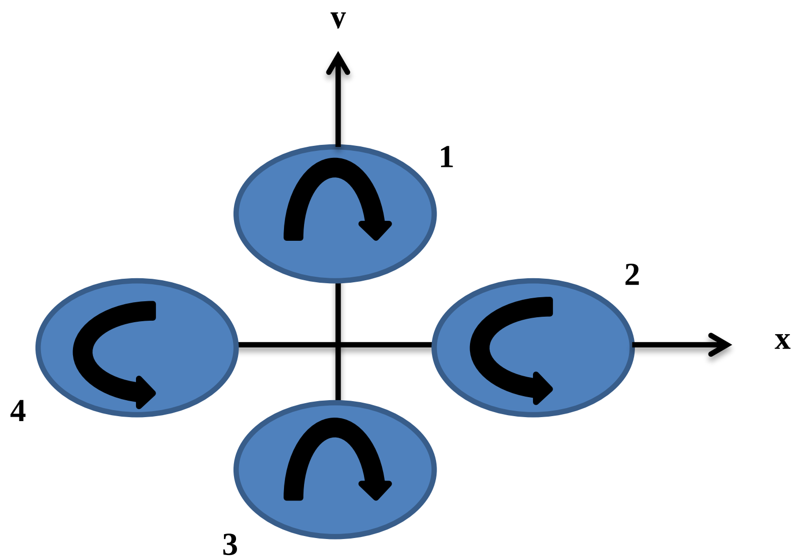

Figure 1.1.2: Configuration of quadcopter's propeller rotation

The four basic types of motion of the quadcopter by the differential rotation speed of each propeller are illustrated in Figure 1.1.3 to 1.1.6 below. The control of a quadcopter is achieved by differential control of the thrust generated by each rotor (Mahony et al., 2012). The exerted force by each of the propeller was along the z-axis in the body frame (pointing toward you) and the sum of all four thrusts will give the total thrust of the quadcopter (Figure 1.1.2). From Figure 1.1.2 and 1.1.3, if all four propellers from 1 to 4 are rotated at the same speed the total thrust produced will balance the weight of quadcopter. This is called hovering motion, where the sum of propeller forces and torque compensating the weight of the quadcopter, in simple terms the lift and the weight of the quadcopter is equal.

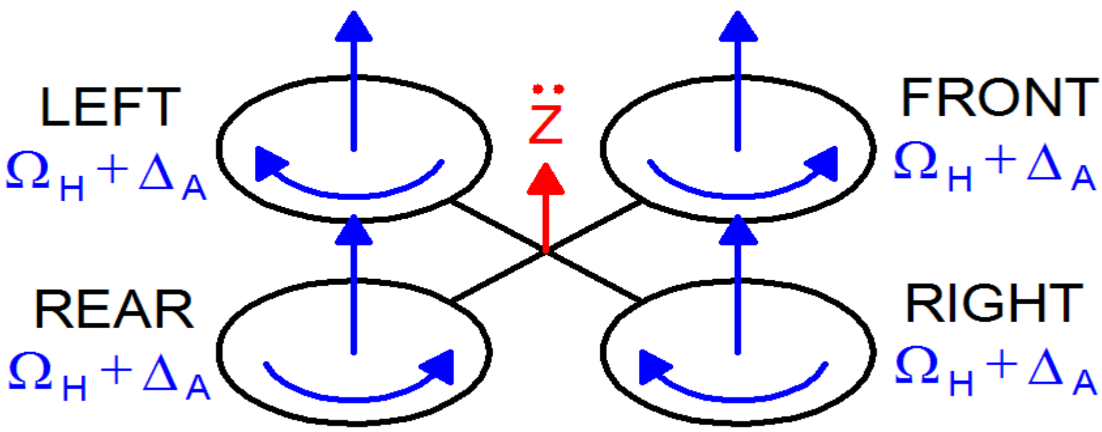

Figure 1.1.3: Hovering motion or vertical motion (Numan, 2017)

For pitch motion, the principle is almost the same and is straight forward to conceptualize. Let say rotation around y-axis is corresponds to the pitching axis as shown in Figure 1.1.2 and 1.1.4, to get a pitching moment propeller 2 and 4 must create a different thrust by spinning with a different speed while propeller 1 and 3 stay in the same speed. For example, if you increase the speed for propeller 2 while other propellers stay in same the speed you will get a negative pitch, the quadcopter will fly toward negative x-direction. Conversely, reduce the speed will make the quadcopter to generate an appositive pitch.

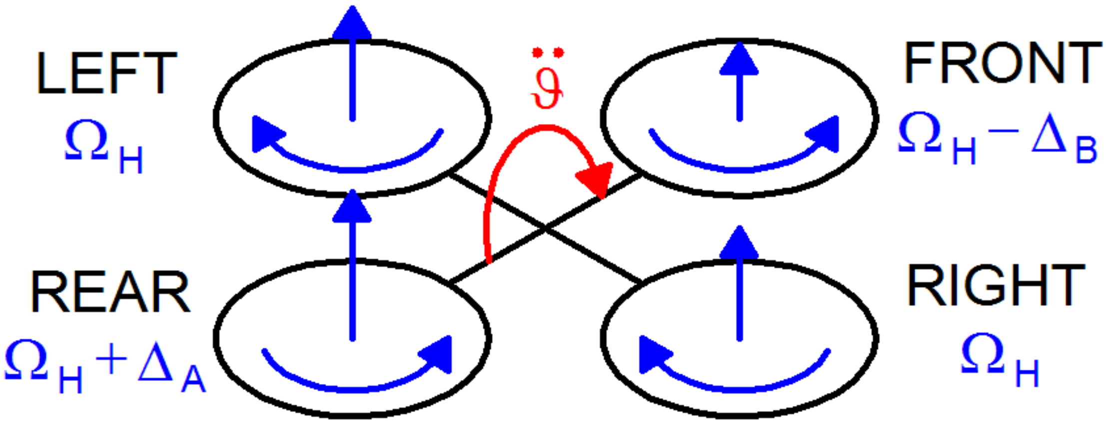

Figure 1.1.4: Pitching motion (Numan, 2017)

After that, for the rolling motion, we can just simply change the speed of either propeller 1 or 3. Rotation about the x-axis will be corresponding as the rolling moment axis of the quadcopter as shown in Figure 1.1.2 and 1.1.5. Increase the speed of propeller 1 will give positive roll and vice versa. For heave condition, all propellers from 1 to 4 must have the same amount of thrust. The final speed of all propellers must be higher than the initial velocity so that the quadcopter will lift upward in the z-direction.

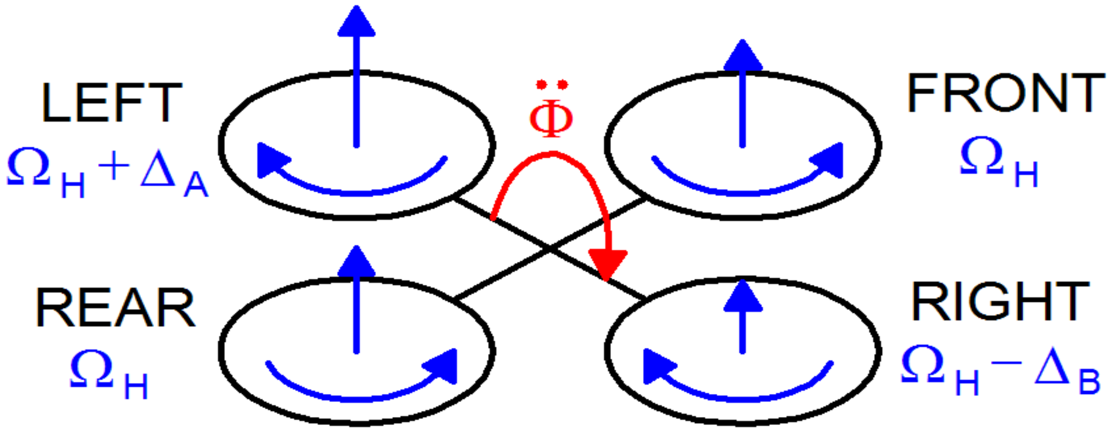

Figure 1.1.5: Rolling motion (Numan, 2017)

For the yaw motion, it is obtained by adjusting the average speed of the clockwise (1 and 3) and anti-clockwise (2 and 4) propeller rotating rotors as shown in Figure 1.1.2 and 1.1.6 (Mahony et al., 2012).

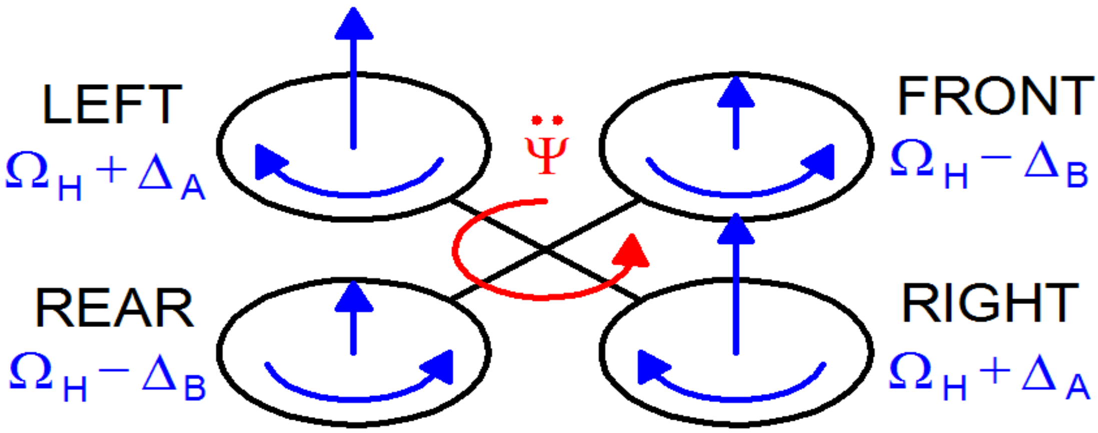

Figure 1.1.6: Yawing motion (Numan, 2017)

A quadcopter control system is a fundamentally difficult and challenging problem because its dynamics modelling is highly nonlinear, especially after accounting for the complicated aerodynamic effects. Plus, its variables are highly interdependent and coupled in nature. The system of the quadcopter is severely under-actuated since it has six degrees of freedom (three translational and three rotational) that need to be controlled by only four independent inputs (rotor speeds), which brings about the complexity in its position and attitude control (Khatoon et al., 2017), (Xiu et al., 2018), (Kuantama et al., 2017).

The precise controller design is needed to control the quadcopter system because of its high maneuverability capability. Parameter perturbation and model uncertainties have brought another difficulty with the quadcopter control system. Besides, stabilization within a short period of time with an acceptable level of precision is needed for all parameters due to its fast dynamics model of the quadcopter. Controller design with an effective attitude stabilizer is important for maintaining the desired orientation and hovering throughout the flight duration. In order to obtain attitude tracking control in all motion, the speed of all four rotors of the quadcopter must be synchronized perfectly (Khatoon et al., 2017).

In this thesis, the dynamic modelling of the quadcopter was done using the Newton-Euler formulation approach. The nonlinear model of the quadcopter was simplified into the linear system in order to comply with the linear conventional controller. The simulation was done by using the Matlab/Simulink software and all the essential parameter needed to design the dynamic model of the quadcopter was determined and collected. The overshoot requirement of the system must be less than 10% (Wael and Quan, 2011) and the control precision must be lower than ±1% (Gong et al., 2013). Moreover, the ideal performance for rise time, settling time, overshoot, steady-state error, and root mean square error (RMSE) should be close to zero as much as possible. Since the size of the quadcopter is small, the expected level of precision should be ±0.001s (Austin, 2010).

A hybrid PD2-Linear Quadratic Regulator (PD2-LQR) controller has been proposed and developed. The dynamic characteristic of the proposed controller is compared with the conventional PD, PID, LQR, P-LQR and PD-LQR controller. All simulation results show that all the techniques were able to stabilize the quadcopter, but the proposed controller is best-suited to robustly stabilize the quadcopter with a better dynamic performance in terms of rise time, settling time, percentage overshoot, steady-state error, and RMSE.

1.2 Problem Statement

This research is done based on work done by (Kok Kai et al., 2016) and (Kok Kai and Rajendran, 2015). These papers have only studied and designed the controller of the fixed-wing UAVs, while in this thesis rotary UAVs were studied.

The quadcopter is an under-actuated system that has six degree of freedom which needs to be controlled by only four actuators. Thus, a precise controller design is needed due to its high manoeuvrability capability. Stabilization of the parameters within a very short period of time is crucial. To maintain the attitude and altitude of the quadcopter throughout the flight duration, an effective attitude stabilizer plays a vital role in designing the controller of the quadcopter.

Hence, it is essential to developing an autonomous flight control system that has excellent performance for the quadcopter. The development of these systems will take complete advantages of the quadcopter. For instance, intelligence computational algorithm can be studied in order to achieve the goals.

1.3 Research Objectives

The research work in this thesis was performed based on the following objectives:

1. To study various types of controller for longitudinal, lateral, directional, and altitude motions of the quadcopter.
2. To develop a new type of controller for longitudinal, lateral, directional, and altitude motions of the quadcopter.
3. To improve the performance of longitudinal, lateral, directional, and altitude motions of the quadcopter.
4. To recommend a suitable controller for longitudinal, lateral, directional, and altitude motions of the quadcopter.

1.4 Thesis Layout

In this thesis, there are 5 main chapters that will be discussed which are Introduction, Literature Review, Methodology, Result and Discussion, and Conclusion.

In Chapter 1, the overview of the quadcopter, problem statement and the objective of this research work will be discussed. Chapter 2 will be presents the literature review and theoretical background for the thesis from the previous researches and the studies on the quadcopter control system. This chapter consists of a review of the quadcopter dynamic model and quadcopter control techniques. In Chapter 3, the methodology of the project will be explained. This chapter will be divided into 3 sections which are Dynamic Modelling of Quadcopter, the Performance Indexes and Controller Design Techniques. The derivation of the mathematical model and the parameters needed of the quadcopter are discussed in the dynamic modelling of the quadcopter section. In this work, Newton-Euler formalism was used to model the quadcopter system. Next, the performance index of the quadcopter control will be explained. In the controller design technique section, the controller design technique, control strategy in designing the quadcopter controller, evaluation of several control techniques, tuning the parameters and evaluate the finding was done. After that, the best and mature controller design with better performance will be applied to the quadcopter system.

In Chapter 4, the result obtained from the simulation of the various control techniques applied to the modelled quadcopter are further discussed. Justification and reason are stated based on the findings. The last Chapter 5 will conclude the research project and some recommendations are included for future work development of the project.

CHAPTER 2

LITERATURE REVIEW

The advancement of technologies today has raised the potential application of the quadcopter in various fields. Today many developments related to the quadcopter has been done to improve the performance of the quadcopter control system. Most of the developed quadcopter projects are now available in the market as toys armed with various sensors and communications capabilities (Khatoon et al., 2017).

In this chapter, the literature review about the dynamic model and the control techniques of the quadcopter done by other researchers will be presented.

2.1 Quadcopter Dynamic Model

Modelling the quadcopter body dynamic is an essential work to do before designing the control techniques for the quadcopter because these mathematical models will need to be applied to the controller system. For the past years, lots of different methodologies have been used to model quadcopter model dynamics (Khatoon et al., 2017). In Mohammadi and Shahri (2013), the dynamic model of the quadcopter based on the Lagrange-Euler formalism is presented. Alkamachi and Erçelebi (2017) describe the nonlinear mathematical model of the quadcopter based on the Newton-Euler approach as a common technique used in quadcopter modelling. The dynamic model based on Quaternion formulations is used in Ki-Seok and Youdan (2003) to modelled the quadcopter dynamic model. In Das et al. (2009), backstepping was applied to the coupled Lagrangian form of the dynamics. In this paper neural network was used to conflict with the unknown nonlinearities to estimate the unknown nonlinear terms and the aerodynamic forces and moments of the quadcopter. Bjorn et al. (2007) presented the nonlinear mathematical model of the quadcopter with the application of the propulsion system. Identification of the dynamical model of the UAVs by using an integrated approach was provided in Ma et al. (2019). A hybrid algorithm was used to obtain the unknown parameter of the linear model of the UAVs.

Quadcopter dynamic modelling with the complete mechanical and electrical system was described in Oliveira (2011), where it shows the work of a gearing system connected to the motor to reduce the speed of the propellers. Propeller modelling is one of the important works to do because it consists of the aerodynamic equation that models lift, drag and moment based on the coefficient of aerodynamics and the rotor speed. From the researches done by the past researchers, it shows that ducted propeller has more advantages compare to the ordinary propeller in terms of its efficiency. In Luque-Vega et al. (2012), a comparison between ducted and ordinary propeller was discussed. In addition, ducted propeller UAVs present many unique challenges because of the complex aerodynamics of the propeller itself and usually these UAVs are highly unstable. The mathematical modelling of this type of propeller was presented in Johnson and Turbe (2006).

Besides all these researches work that focused on the dynamic modelling of the quadcopter, there are some researchers that also focusing on modelling the quadcopter for a specific task application. In Barikbin and Fakharian (2019), modelling of the quadcopter system was done with the present of cable-suspended payload that acts as an unknown disturbance. The equation of motion of the quadcopter was design to suit with the payload that connected with an arbitrary number of quadcopter via rigid links. The unique feature between the rigid body payload, links and quadcopters are explicitly incorporated into control system design and stability analysis in Lee (2018). Guerrero-Sánchez et al. (2017) presents the mathematical model of the quadcopter integrated with the dynamics of the cable and payload. An Interconnection and Damping Assignment-Passivity Based Control (IDA-PBC) was chosen because of its inherent robustness against parametric uncertainty and un-modelled dynamics. An enhanced coupling hierarchical control scheme for both quadcopter positioning and payload swing elimination was described in Liang et al. (2019).

In Wu et al. (2018), a new design of the mathematical model of the quadcopter system was designed and implemented. The equation was derived by using the Hamiltonian approach, this model has proven to be a more compact, simple structure and easier to use than Newtonian and Lagrangian formulation. The model is a first-order differential equation.

2.2 Quadcopter Control Techniques

Designing and modelling the quadcopter control system is a well-known field of research and was used in many applications either in civil or military purposes. Studies show there is an extensive literature review of the quadcopter control system that has been done by these researchers for the past years. Designing the control system should be simple and precise for better performance. Thus, by studying the computational algorithm of the control system such as PID, PD, LQR and etc, the desired performance of the quadcopter control system can be achieved.

The PID controller is used the most in the industry due to easy to implement with adequate performance (Kok Kai and Rajendran, 2015). As mention by Khatoon et al. (2017), the popularity of the classical PID also because of their advantage like simple design, the gains can be easy to adjust and very good robustness. The gains of the PID controller can be determined by using the Ziegler and Nichols method. The improvement of the response time of the system is one of the reasons that the PID controller is widely used (Kok Kai and Rajendran, 2015). Besides, the PID controller can keep the quadcopter operating close to the stationary state and eliminates error in a stable state (Castillo-Zamora et al., 2018), (Badr et al., 2019). However, the nonlinearity of the quadcopter dynamic model and other major challenges like inaccurate mathematical modelling of some of the dynamic will limit the performance of the PID controller if it is applied to this system (Khatoon et al., 2017). Salih et al. (2010), Badr et al. (2019), and Ahmad et al. (2018) in their study revealed that the PID controller is able to robustly stabilize the quadcopter to its desired position. They also stated that the controller is easy to design and give a fast response time as well as good performance in term of the speed of the response of the quadcopter. In Erkol (2018), a study was done on the classical PID controller tuning with an optimization algorithm. The Artificial Bee Colony (ABC), Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) were used to determine the optimum parameter for the controller. The result shows that in regard to the IAE and RMSE, the ABC- and GA-based PID controller give a better performance. In terms of overshoot and settling time, the ABC-based PID controller has proven to be the best due to its lowest overshoot and shortest settling time. From the point of reliability and repeatability, the ABC-based PID shows the best performance. However, if the criterion is the speed, the GA-based PID gives a better result.

The control algorithm of the dynamic system of the LQR controller is run by optimizing the suitable cost function. As studied by Bouabdallah et al. (2004), the LQR and PID control technique was applied to the quadcopter model then the result was compared. They discovered that the result was satisfactory if the Pearson method is considered in the LQR control technique, the model without the actuator was used to perform the simulation. On the other hand, if comparing the previous method with the Sage-Eisenberg method it gives the new method a better result than the Pearson method since the cost function was optimized in every sub-trajectory. However, the control technique was failed in the real system. From the experiment, the average result was obtained for the LQR controller but the steady state error remained the same since the actuator did not take into account. Contrarily, the PID controller gives a better success than the LQR controller.

In Hajiyev (2013), a combination of the LQR control system with the Kalman filter has been studied. The test was done for all state condition and the result shows that the LQR controller with the Kalman filter added to the system in the presence of disturbance has increased the effectiveness of the LQR controller in controlling the vertical flight motion. However, to implement such a system in the real cases are not generally possible due to insufficient robustness. Plus, this system also has a lower stability margins and slower response time compared to the traditional LQR controller.

A hybrid P-LQR controller has been proposed in Kok Kai and Rajendran (2015). In this report, the P-LQR controller was designed to improve the performance of the UAVs in the longitudinal motion over the PID and LQR controller. The result from the simulation shows this approach was able to improve the rise time, settling time, and RMSE but overshoot and steady state error are slight increases within the acceptable limit constraint. The PD-LQR is another type of hybrid controller that being studied by Kok Kai et al. (2016), the result shows the PD-LQR controller performs with great success. The improvement of the controller in terms of rise time, settling time, RMSE, and steady-state error is 95.6%, 95.5%, 49.3%, and 0% respectively. In terms of overshoot, PD-LQR still lags behind the P-LQR controller with just only 0.001% different and the LQR controller has the lowest percentage of overshoot with 0.351%.

Takagi and Sugeno (1985) in their report present a way to build a fuzzy model of the system, the mathematical tool of the system was presented. The report shows the identification of the system using its input-output data and the application of such a system was discussed further. In Kuantama et al. (2017), a hybrid Fuzzy-PID controller was designed to demonstrate a circular trajectory of the quadcopter with and without disturbance. Through the finding, the Fuzzy-PID controller has a better performance in terms of reducing the error and better capability to reject disturbance than the traditional PID controller, the position shift is less than 0.05m and flight stability is better on the circular motion for the Fuzzy-PID controller. The Fuzzy-PID controller can maintain the position on the trajectory even when the disturbance is added. Moreover, the Fuzzy-PID controller has a higher anti-jamming capability with a high precision of response speed which means it can still perform better in the presence of disturbance by eliminating the overshoot in the system. Meanwhile, the PID controller produces a relatively large error with a severe bending trajectory (Yong et al., 2016). The same conclusion can be seen in Tiep and Ryoo (2017), Laith Jasim and Rasha Shehab (2017), and Mardan et al. (2017) where the performance of the Fuzzy-PID controller is superior to traditional PID and Fuzzy controller.

Kayacan and Maslim (2017) in their report has studied the comparison and the contrast of the Type-1 and Type-2 Fuzzy Neural Network with optimal tuning algorithm. In this report, the trajectory tracking problem of the quadcopter in term of their tracking accuracy and control effort are discussed and appreciated. The efficiency and efficacy of the Type-2 Fuzzy Neural Network with tuning algorithm are better by 50% to compare to the conventional PD controller. However, in terms of control effort, the PD controller has better performance. In addition, the comparison between the Type-1 and Type-2 controller reveals that Type-2 has better noise reduction properties than the Type-1 when the noise and disturbance are present.

In another research work done by Khoud et al. (2018), the quadcopter control was done by co-simulation of a Fuzzy Gain-Scheduled Proportional-Integral-Derivative (GS-PID) controller based on Particle Swarm Optimization (PSO) algorithm. They propose the PSO with variable inertia weight (PSO-In), PSO with constriction factor (PO-Co) and PSO with the possibility of updating strategies (PSO-gbest) tuning algorithm to improve the controller performance. Simulation reveals that the PSO-In speed response greatly outperforms other algorithms, and then the comparison of the proposed controller has been made with the conventional Fuzzy and Fuzzy-PID controller.

An adaptive control strategy is one of the techniques used by the researchers to adopt the changing of the quadcopter system by automatically adjust the controller in real time. The control parameters are updated based on the error between the output and the desired response. Ramiro Ibarra et al. (2018) presented an adaptive technique using Model Reference Adaptive Control (MRAC) schema with Lyapunov's theory to improve the stability of the system. From the simulation, it proves that the adaptive control technique has a good performance in tracking the reference output. However, this technique can be particularly susceptible to time delay. In another work by Thu and Gavrilov (2017), the control method of the quadcopter was done by using the L1 adaptive control technique, a filtered version of MRAC. The advantage of the L1 is that it cleanly separates performance and robustness (Kharisov et al., 2010). The performance of the L1 method improved for attitude and trajectory tracking, plus L1 is easier to be applied to the real-world flight.

Control using the Backstepping technique was presented in the thesis by Numan (2017), control law of such control technique is designed by using a recursive control algorithm for certain states. In his finding, a comparison of the Backstepping and the conventional PID controller has been made. The results obtained show that the Backstepping controller is better than the PID controller in terms of its rise time, settling time and overshoot. Moreover, disturbance of the wind shear effect up to 6m/s can be rejected by the Backstepping controller. However, it is worth to mention that Backstepping is computationally intensive while the PID controller is easy to implement and less time is taken to compute. The combination of a robust Backstepping-based controller with sliding mode control for trajectory tracking was proposed in Fethalla et al. (2018), the controller was able to follow the desired trajectory correctly in the presence of disturbances.

In Xiu et al. (2018), a controller named Improved Global Sliding Mode Control (IGSMC) was proposed. The controller was designed based on the conventional Global Sliding Mode Control (GSMC). In the report, both of GSMC and IGSMC are implemented to rectangular, square cross and square X structure of the quadcopter. The result shows that the control effectiveness of IGSMC in position and attitude are proven to be effective and the performance of the system can be improved.

The effectiveness of the nonlinear controller is proven to be great by taking advantage of the nonlinearity of the quadcopter system. According to Ye (2018) in his thesis, the Nonlinear Feedback control was proposed. Dynamic performance and the robustness of the system against the wind disturbance give a satisfactory result. The minimization of the cost function of the system is the reason why the optimization technique was developed. Optimization techniques such as the L1, $H\infty$, and Kalman filter are the most commonly used in designing the control system. The robustness of the system using the optimization technique is low (Khatoon et al., 2017). Satici et al. (2013) in their study indicated that the L1 controller is robust and relatively optimal for the attitude and altitude tracking. The result gives a very small error and the controller was able to persistently reject the disturbance. An integral predictive and nonlinear H∞ controller is presented in Raffo et al. (2010) for path following problems. The robustness and smoothness of the proposed controller were validated by the simulation; the trajectory tracking of the quadcopter has proven to be excellent.

Direct Inverse Control with Artificial Neural Network (DIC-ANN) was presented by Jemie and Benyamin (2018) to overcome the limitations faced with the conventional control method. By using the DIC-ANN control system, a better result in the altitude dynamics was achieved compared to the conventional PID controller. However, the problem arises in the overshoot of the system. DIC-ANN experienced a slight overshoot compared to the PID controller, but the error is within an acceptable limit and it tends to be decreased.

An Adaptive Neural Network control approach was designed to improve the performance and stabilized the quadcopter system. From the experimental and simulation data, this approach has been proven to be effective in reducing the tracking error and zero weight drift. From the past researches, even the best control techniques have limitation in quadcopter application. Thus, a hybrid ANN and Fuzzy Inference System called ANFIS has been developing. In Jang (1993), the architecture and learning procedure of the control system was described and presented. The applications of such a control system also have been discussed. Another improvement approach was made in getting a better result for the control technique. For instance, Khatoon et al. (2017) has developed a control system that combined the ANFIS with conventional PD control. The proposed control technique was compared with the conventional PD, PID and Fuzzy logic controller, and it reveals that the PD-ANFIS controller was able to achieve better results in terms of response time, robustness and able to reject disturbance with better quality.

Other than that improving the quadcopter attitude and altitude control, other researchers also have designed and studied a controller that can tolerate with the actuator faults. One of the examples is done by Ahmet Ermeydan and Emre Kiyak (2017). In this report, the enhanced PID controller has used to handles the loss of effectiveness in the motors of the quadcopter. A 20 percent loss in control effectiveness in the first and third motor in the system are simulated, the result shows the quadcopter is able to follow the command given successfully except in psi state. There is a steady-state error that occurs in psi state, however the quadcopter system still stable.

Different control algorithm and control theory have been studied and developed by many researchers in the past years, the main goal of these researches is all the same which is to be able to stabilize and improve the performance of the UAVs in all motions within an acceptable limit constraint. Precise and instantaneous responses are the key factor in designing the UAVs controller. The performance of the system can be said to be improved if these factors are achieved. Even a 0.1s improvement in the response like rise time can lead to a better result (Kok Kai and Rajendran, 2015). The remarkable contribution of these researchers in the field of modelling and stabilizing the UAVs have led to the increasing development of these technologies today.

CHAPTER 3

METHODOLOGY

In this chapter, the dynamic modelling of the quadcopter using the Newton-Euler approach will be presented. The lift forces produced by the four rotating propellers create the motion of the quadcopter in translational or rotational achieved by means of differences in the counter-rotating propeller.

The overall flows of the project are illustrated in the Figure 3 below:

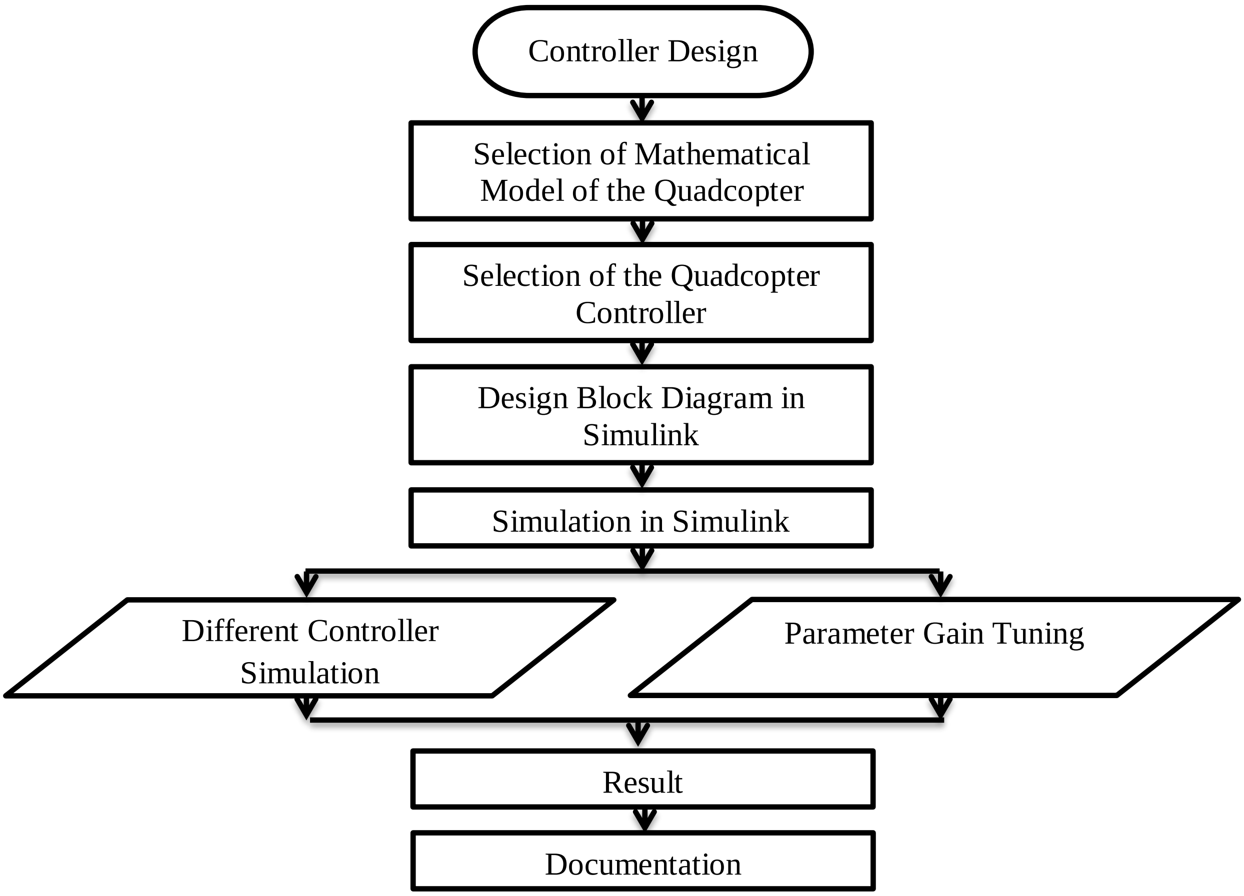

Figure 3: Overview of the project flow chart

From Figure 3, in order to develop a new controller the following process was done. First, the study about the quadcopter model is done. There are several model from the literature review have been consider for example the Newton-Euler approach, Lagrange approach and etc. After so much study, the model with Newton-Euler approach was choosing due to its simplicity. Next, in order to use the quadcopter model, several controller techniques have been choose to simulate namely, PD, PID, LQR, P-LQR, PD-LQR, and PD2-LQR. After that, block diagram of the controller have been design in Simulink and the simulation of each of the controller was done to obtain the step response of the controller. In the simulation phase, the parameter gain was tuned automatically within the specified value to get the optimum gain. Lastly, the result of the simulation was recorded and discussed.

3.1 Dynamic Modelling Of Quadcopter

The first step in designing the dynamic model of the quadcopter is to define the inertial frame and body frame in the three-dimensional space, each with its defined right-handed coordinate system. In this way, the attitude and the position of the quadcopter are able to be controlled in a three-dimensional space.

3.1.1 The Inertial Frame and Body Frame

As shown in Figure 3.1.1, the inertial frame or earth frame, denoted by E, is used to describe the absolute position in the space. The origin of the coordinate system E is fixed on a ground surface or a specific point in space and the initial position of the quadcopter. The designated of the quadcopter heading is in the positive direction of the OX-axis and perpendicular to the OYZ plane. The OY-axis is perpendicular to the OXZ plane and the OZ-axis perpendicular to the OXY plane and pointing vertically upward.

The relative movement of the ground and the quadcopter is studied using this coordinate system.

The centre of the quadcopter is the origin of the quadcopter coordinate system $Oxyz$ denoted by B. The positive Ox-axis is pointing toward rotor 1, the positive Oy-axis is pointing toward rotor 4 and Oz-axis is pointing vertically upward against the gravity. These two coordinate systems can be converted to each other through transition matrix R. Based on this reference frame, $[x\ y\ z]^T$ is defined as the translational position and $[\phi\ \theta\ \psi]^T$ is defined as angular position. The location of the quadcopter with respect to the inertial frame is indicated by the translational position. The angular position is defined by the Euler angle. Roll angle, ϕ, is referred to rotating angle around the OX-axis, pitch angle, θ, is refer to rotating angle around the OY-axis and yaw angle, ψ, is refer to rotating angle around the OZ-axis.

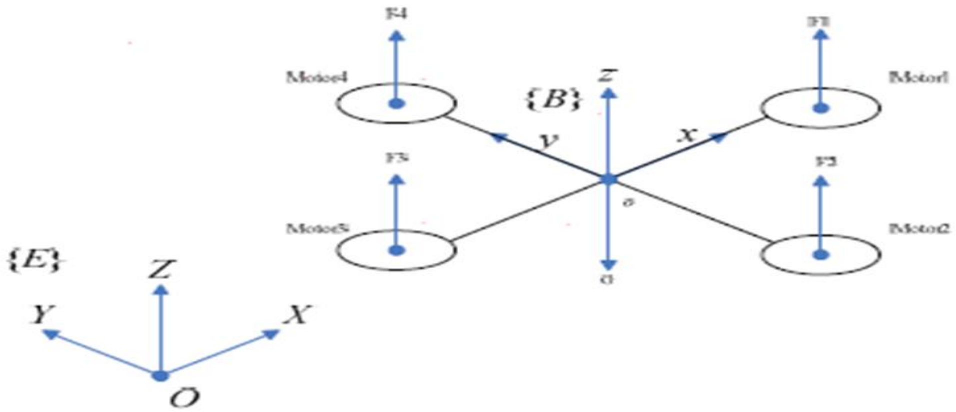

Figure 3.1.1: Structure model of the quadcopter with a reference frame (Li and Li, 2011)

Thus, rotational matrix R_x, R_y, and R_z from the body frame B to the inertial frame E can be obtained as in equation (1), (2), and (3) below (Li and Li, 2011).

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\phi & -sin\phi \\ 0 & sin\phi & cos\phi \end{bmatrix} \quad (1)$$

$$R_y = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \quad (2)$$

$$R_z = \begin{bmatrix} cos\psi & -sin\psi & 0 \\ sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

By multiplying these three rotational matrix R_x, R_y, and R_z, we finally can obtain the rotational matrix R of the body frame relative to the inertial frame as in equation (4) below (Li and Li, 2011).

$$R = R_x.R_y.R_z$$

$$= \begin{bmatrix} cos\psi cos\phi & cos\psi sin\theta sin\phi & cos\psi sin\theta cos\phi + sin\psi sin\phi \\ sin\psi cos\theta & sin\psi sin\theta sin\phi & sin\psi sin\theta cos\phi - sin\phi cos\psi \\ -sin\theta & cos\theta sin\phi & cos\theta cos\phi \end{bmatrix} \quad (4)$$

3.1.2 Mathematical Derivation

Before the derivation of the mathematical model of the quadcopter can be model, the following assumptions need to be made (Li and Li, 2011).

I. The structure of the quadcopter is asymmetrically rigid.

II. The geometric centre and centroid of the quadcopter are in the same position with the origin of the inertial coordinate system.

III. Flight altitude and other factor do not affect the resistance and gravity of the quadcopter.

IV. Tensions in all directions are proportional to the square of the propeller speed.

Fx, Fy, and Fz are the components of external force, $\bar{F}$ on the three coordinate axes of the quadcopter coordinate system. Component of body angular rate, $\bar{\omega}$ on the three coordinate axes of the quadcopter coordinate system are p, q, and r.

The stress analysis of the quadcopter is defined as in equation (5), (6), and (7) below (Li and Li, 2011):

$$Gravity, G = mg \tag{5}$$

$$Resistance, D_i = \frac{1}{2}\rho C_d \omega_i^2 = k_d \omega_i^2 \tag{6}$$

$$Lift\ of\ a\ single\ rotor, T_i = \frac{1}{2}\rho C_t \omega_i^2 = k_t \omega_i^2 \tag{7}$$

where, m is the mass of the quadcopter, g is the gravitational constant, ρ is the air density, C_d is the drag coefficient, ω is the angular speed of the rotor, k_d is the drag factor, C_t is the thrust coefficient, and k_t is the thrust factor.

Newton's second law and dynamics equation of the quadcopter can be defined as in equation (8) and (9) below (Li and Li, 2011):

$$\bar{F} = m\frac{d\bar{V}}{dt} \tag{8}$$

$$\bar{M} = \frac{d\bar{H}}{dt} \tag{9}$$

where, $\bar{F}$ is the external force acting on the quadcopter, $\bar{V}$ is the speed of the quadcopter, $\bar{M}$ is the moment of the quadcopter, and $\bar{H}$ is the angular momentum of the quadcopter.