A METAHEURISTIC OPTIMIZATION USING EXPLOSION METHOD ON A HYBRID PD2-LQR QUADCOPTER CONTROLLER

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by

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E	: The inertial/earth frame
B	: The body frame
x, y, z	: The linear position of the quadrotor in x, y, z axes
$\dot{x}, \dot{y}, \dot{z}$	: The rate of change of position of the quadrotor in x, y, z axes
ϕ, θ, ψ	: The roll, pitch, and yaw angle
$\dot{\phi}, \dot{\theta}, \dot{\psi}$	: The rate of change of roll, pitch, and yaw angle
$R_{x,y,z}$	: The elementary rotation matrix in x, y, z axes
T	: The transformation matrix
F	: The external force acting on the quadrotor body
M	: The moment/torque acting on quadrotor body
M_G	: The gyroscopic moment/torque
O	: The point of origin
$U_{1,2,3,4}$	: The control input of the quadrotor
$T_{1,2,3,4}$	: The thrust produced by the rotor
Q	: The positive semi-definite symmetric matrix
R	: The positive definite symmetric matrix
g	: The gravitational constant
m	: The mass of the quadrotor
l	: The distance of rotor to the center of gravity of the quadrotor
ρ	: The air density
$I_{x,y,z}$	: The inertia of the quadrotor
J_r	: The inertia of the rotor

ω : The angular velocity of the rotor

C_t : The thrust coefficient

C_d : The drag coefficient

A : The area of the rotor blade

r : The radius of the rotor blade

d : The desired reference point

e : The error between input/output reference point

u, v, w : The linear velocity in the body frame

p, q, r : The angular velocity in the body frame

C_M : The controllability matrix

O_M : The observability matrix

K_P, K_I, K_D : The proportional, integral, and derivative controller's gain

K : The optimal LQR controller's gain

J : The cost function in the LQR control system

R_F : The random location of the fragment

r_e : The explosion radius

X_P : The position of the parent particle

X_F : The position of the fragment produce

D : The distance between the fragment and global best position

GB : The global best solution

c : The parameter constant of the REA algorithm

n_F : The number of fragments

t_{ss} : The time at which the response reaches a steady-state

LIST OF ABBREVIASIONS

ABC	: Artificial Bee Colony
ACO	: Ant Colony Optimization
ACROA	: Artificial Chemical Reaction Optimization Algorithm
ADRC	: Active Disturbance Rejection Control
AEFA	: Artificial Electric Field Algorithm
ALO	: Ant Lion Optimizer
ANFIS	: Artificial Neural Fuzzy Inference System
ANN	: Artificial Neural Network
BA	: Bat Algorithm
BA	: Butterfly Algorithm
BBBC	: Big Bang Big Crunch
BBO	: Biogeography-Based Optimizer
BC	: Backstepping Control
BCPA	: Bee Collecting Pollen Algorithm
BH	: Black Hole
BLDC	: Brushless DC motor
BMO	: Bird Mating Optimizer
CA	: Cultural Algorithm
CFO	: Central Force Optimization
CS	: Cuckoo Search
CSA	: Crow Search Algorithm
CSO	: Curve Space Optimization

CSS	: Charge System Search
DA	: Dragonfly Algorithm
DE	: Differential Evolution
DIC	: Direct Inverse Control
DL	: Deep Learning
DOF	: Degree of Freedom
DPO	: Dolphin Partner Optimization
EA	: Evolutionary Algorithm
EMA	: Exchange Market Algorithm
EPO	: Emperor Penguin Optimizer
ES	: Evolutionary Strategy
ESO	: Extended State Observer
FA	: Firefly Algorithm
FL	: Feedback Linearization
FLC	: Fuzzy Logic Control
GA	: Genetic Algorithm
GBSA	: Galaxy-Based Search Algorithm
GE	: Grammatical Evolution
GOA	: Grasshopper Optimization Algorithm
GP	: Genetic Programming
GSA	: Gravitational Search Algorithm
GSO	: Galactic Swarm Optimization
GWO	: Grey Wolf Optimizer
HHO	: Harris Hawk Optimization

IAE	: Integral Absolute Error
ISE	: Integral Square Error
ITAE	: Integral Time Absolute Error
ITSE	: Integral Time Square Error
KGMO	: Kinetic Gas Molecule Optimization
LQR	: Linear Quadratic Regulator
MBO	: Marriage in Honeybee Optimization algorithm
MFO	: Moth Flame Optimization
MIMO	: Multi-Input Multi-Output
MPC	: Model Predictive Control
MRAC	: Model Reference Adaptive Control
MRFT	: Modified Relay Feedback Test
MS	: Monkey Search
MVO	: Multi-Verse Optimizer
NPID	: Nonlinear Proportional, Integral, and Derivative
NSO	: Neural State Observer
OIO	: Optic Inspired Optimization
OS	: Overshoot
PD	: Proportional-Derivative
PD2-LQR	: Proportional-Double Derivative-Linear Quadratic Regulator
PD-LQR	: Proportional-Derivative-Linear Quadratic Regulator
PID	: Proportional-Integral-Derivative
P-LQR	: Proportional-Linear Quadratic Regulator
PSO	: Particle Swarm Optimization

REA	: Random Explosion Algorithm
RM	: Reference Model
RMSE	: Root Mean Square Error
RO	: Ray Optimization
ROA	: Rainfall Optimization Algorithm
RT	: Rise Time
SA	: Simulated Annealing
SFO	: Sail Fish Optimizer
SHLNN	: Single Hidden Layer Neural Network
SHO	: Selfish Herd Optimizer
SI	: Swarm Intelligence
SMC	: Sliding Mode Control
SMO	: Sliding Mode Observer
SPNN	: Sigma Pi Neural Network
SSE	: Steady-State Error
STOL	: Short Take-Off and Landing
SWOA	: Small World Optimization Algorithm
TEO	: Thermal Exchange Optimization
T-S-K	: Takagi-Sugeno-Kang
UAV	: Unmanned Aerial Vehicle
VTOL	: Vertical Take-Off and Landing
WOA	: Whale Optimization Algorithm

PENGOPTIMUMAN METAHEURISTIK MENGGUNAKAN KAEDAH LETUPAN PADA PENGAWAL HIBRID PD2-LQR QUADCOPTER

ABSTRAK

Populariti UAV jenis bermotor, quadrotor, telah berkembang pesat sejak beberapa tahun kebelakangan ini kerana ia mempunyai kelebihan dan kemampuan untuk melakukan pelbagai aplikasi seperti pemantauan, pengawasan, dan pemeriksaan lingkungan. Walau bagaimanapun, dinamik quadrotor sangat tidak linier dan tidak stabil kerana mempunyai 6 DOF yang perlu dikendalikan oleh hanya 4 pengawal. Selain itu, sangat penting bahawa parameter pengawal ditala dengan betul kerana ia dapat mempengaruhi prestasi quadrotor. Kajian ini bertujuan untuk membangunkan teknik kawalan optimum yang berkesan untuk mengawal dan menstabilkan pergerakan ketinggian dan sikap quadrotor. Eksperimen berasaskan simulasi menggunakan MATLAB/Simulink dilakukan untuk menguji dan mengesahkan prestasi algoritma dan pengawal yang dicadangkan. Model matematik quadrotor diperoleh menggunakan pendekatan Newton-Euler dan dilinierkan menggunakan pendekatan sudut kecil. Dalam kajian ini, pengawal Hibrid PD2-LQR dicadangkan untuk kawalan dan penstabilan quadrotor. Secara konvensional, parameter pengawal ditala menggunakan kaedah percubaan dan ralat. Masalah dengan kaedah ini adalah bahawa ia sangat memakan masa, dan perancang kawalan tidak mengetahui parameter mana yang paling baik untuk pengawal tersebut. Oleh itu, algoritma pengoptimuman berdasarkan kaedah letupan yang dipanggil REA dicadangkan dan diterapkan pada struktur kawalan Hibrid PD2-LQR yang dicadangkan. Kajian perbandingan dengan 8 algoritma terkenal, PSO, ABC, GA, DE, MVO, MFO, FA, dan STOA, dilakukan untuk menilai prestasi algoritma yang dicadangkan. Begitu juga, pengawal yang dicadangkan dinilai dengan kajian perbandingan dengan 6 pengawal konvensional, PD, PID, LQR, Hibrid P-LQR, Hibrid PD-LQR, dan Hibrid PD2-LQR. Hasil kajian menunjukkan bahawa REA dapat memberikan prestasi yang baik dalam mengeksploitasi solusi optimum yang global dan menjelajahi ruang pencarian. Kelajuan penumpuan REA juga lebih cepat daripada algoritma yang lain. Begitu juga, bagi pengawal, hasil penemuan menunjukkan bahawa pengawal Hibrid PD2-LQR berasaskan REA mempunyai masa kenaikan yang lebih cepat dengan masa penyelesaian yang lebih pendek daripada pengawal konvensional, sementara itu tidak ada terlebih tembakan dan kesalahan keadaan mantap yang dihasilkan. Rata-rata, waktu kenaikan, masa penyelesaian, terlebih tembakan, ralat keadaan mantap dan RMSE ditingkatkan masing-masing sebanyak 95%, 95.3%, 100%, 100%, dan 43.5% untuk gerakan roll dan pitch, sementara 96.5%, 96.5%, 100%, 97.2%, dan 47.3% masing-masing untuk gerakan yaw. Untuk pergerakan ketinggian, masa kenaikan, masa penyelesaian, terlebih tembakan, dan keadaan mantap ditingkatkan masing-masing sebanyak 84.5%, 85.5%, 100%, dan 100%. RMSE untuk pergerakan ketinggian tidak meningkat tetapi masih dapat diterima kerana perbezaan dengan pengawal konvensional tidak terlalu banyak. Oleh itu, berdasarkan penemuan ini, ia dapat disimpulkan bahawa pengawal Hibrid PD2-LQR berasaskan REA yang dicadangkan adalah yang terbaik di antara pengawal yang diuji dan sesuai untuk mengawal dan menstabilkan pergerakan ketinggian dan sikap quadrotor kerana ia dapat meningkatkan prestasi tindak balas quadrotor.

A METAHEURISTIC OPTIMIZATION USING EXPLOSION METHOD ON A HYBRID PD2-LQR QUADCOPTER CONTROLLER

ABSTRACT

The popularity of the rotorcraft type UAV, the quadrotor, has grown rapidly in recent years due to its advantages and capability to perform various applications such as environment monitoring, surveillance, and inspection. However, the quadrotor's dynamics are highly nonlinear and underactuated since it has 6 DOF that need to be controlled by only 4 actuators. Besides, it is also crucial that the controller's gains are tuned appropriately since it can affect the quadrotor's performance. This study aims to develop an effective optimal control technique to control and stabilize the quadrotor's altitude and attitude motion. A simulation-based experiment in MATLAB/Simulink environment was conducted to test and verify the proposed algorithm and controller performance. The mathematical model of the quadrotor was derived based on the Newton-Euler approach and linearized using a small angle approximation. In this study, a Hybrid PD2-LQR controller was proposed for quadrotor control and stabilization. Conventionally, the controller's gains were tuned using the trial-and-error method. The problem with this method was that it very time-consuming, and the control designer could never tell which gains are the optimal solution for the controller. Therefore, an optimization algorithm based on the explosion method called REA was proposed and implemented on the proposed Hybrid PD2-LQR control structure. A comparative study with 8 well-known algorithms, PSO, ABC, GA, DE, MVO, MFO, FA, and STOA, was performed to evaluate the performance of the proposed algorithm. Similarly, the proposed controller was evaluated by a comparative study with 6 conventional controllers, PD, PID, LQR, Hybrid P-LQR, Hybrid PD-LQR, and Hybrid

PD2-LQR. The findings show that the REA could perform well in exploiting the global optimum and exploring the search space. The convergence speed of the REA was also faster than other algorithms. Similarly, for the controller, the findings show that the REA-based Hybrid PD2-LQR controller has a faster rise time with a shorter settling time than the conventional controllers, while there was no overshoot and steady-state error produced. On average, the rise time, settling time, overshoot, steady-state error and RMSE was improved by 95%, 95.3%, 100%, 100%, and 43.5% respectively for roll and pitch motion, while 96.5%, 96.5%, 100%, 97.2%, and 47.3% respectively for yaw motion. For altitude motion, the rise time, settling time, overshoot, and steady-state error were improved by 84.5%, 85.5%, 100%, and 100%, respectively. The RMSE for altitude motion was not improved but still could be accepted since the difference with the conventional controllers was not too much. Therefore, based on these findings, it could be concluded that the proposed REA-based Hybrid PD2-LQR controller was the best among the tested controller and suited for controlling and stabilizing the quadrotor's altitude and attitude motion since it could significantly improve the performance of the quadrotor's response.

CHAPTER ONE

INTRODUCTION

This thesis focuses on studying an optimal hybrid controller to control and stabilize the altitude and attitude motion of a vertical take-off and landing (VTOL) rotorcraft type Unmanned Aerial Vehicle (UAV) quadrotor. First, a brief introduction of the UAVs, their applications, and their classification were provided. Then, an overview of the quadrotor fundamental concept and architecture was presented. Additionally, a brief overview of the control system and the metaheuristic optimization algorithm were presented. Then, the issues in the quadrotor control area were addressed in the problem statement section. After that, the goals, the scope of this research, and the research approach were discussed in detail. Lastly, the structure of the thesis was outlined.

1.1 Unmanned Aerial Vehicles (UAVs)

In recent years, researchers and engineers from various fields have worked intensively to create an operational flying machine capable of conducting a mission with minimal or no human involvement. This type of vehicle was widely known as Unmanned Aerial Vehicle (UAV).

UAV is an aircraft designed and modified to be flown without a human pilot onboard. These types of aircraft could be remotely controlled by the human operator on the ground control station or autonomously controlled by an onboard computer that was pre-programmed to perform a specific task (Yang et al., 2018), (Alley-Young, 2020). UAVs could carry a variety of payloads (Najm et al., 2016), such as cameras, sensors, or packages for delivery according to their requirements. Furthermore, they could be expendable and/or recoverable.

Over the years, research in UAVs has become increasingly popular due to the new technology advancement. UAVs were mainly appreciated since they could successfully achieve a large group of civilian and military applications without putting human lives at risk when encountering a dangerous situation (Yit et al., 2016). Plus, since there is no human pilot onboard the aircraft, these aircraft could be designed to be smaller than manned aircraft, which benefits for easy storage and transportation.

In the initial stage of the UAV development, these aircraft were called drones because of their autonomy restrictions. These drones need to be supervised constantly by a pilot that controlled their flight via a radio command. Since the advanced progress of scientific knowledge within the UAV's embedded control and guidance systems permit them to be autonomously controlled to perform and carry out tasks such as take-off and landing, flight stabilization, and point-to-point navigation (Garcia Carrillo et al., 2012).

1.1.1 Applications

Since the pilot on the ground station could remotely control the UAVs, they have become significant in military and civilian applications. In military applications, UAVs were typically used to perform a mission such as reconnaissance which is the exploration outside an area occupied by friendly forces to gain information about natural features and other activities in the area, attack and combat roles, and border surveillance (Budiyono et al., 2015), (Kim et al., 2020).

Aside from the military applications, UAVs also has been used in various civil or commercial applications. Recent years and experiences have shown that UAVs were also being used for covert, diplomatic, research, and environmentally critical roles. Typical use of UAVs in civilian applications was aerial photography for mapping, wildfire surveillance, search and rescue missions, scientific research, and agriculture (Kim et al., 2020), (Khatoon et al., 2017), (Noormohammadi-Asl et al., 2020).

1.1.2 Classification

UAVs were designed for many different reasons. Thus, in the literature, many different ways to classify them, such as based on the range of the aircraft could fly, based on the configuration of the aircraft, based on the size and payload of the aircraft, or according to their levels of autonomy (Hassanalian and Abdelkefi, 2017), (Dalamagkidis, 2015), (Watts et al., 2012), (Singhal et al., 2018). However, for simplicity, the aircraft's classification based on their configuration was presented in this thesis since it is a better way to describe their characteristics (Garcia Carrillo et al., 2012).

The UAV configuration could be categorized into four main categories, which are 1) fixed-wing UAVs, 2) rotary-wing UAVs, 3) blimps UAVs, and 4) flapping-wing UAVs. Each of these UAVs types have their advantages and disadvantages.

1.1.2.1 Fixed-wing UAVs

Fixed-wing UAVs (Figure 1.1) were mainly used for long-distance, long-range, and high-altitude missions. The disadvantage of these UAVs is that they need a runway to take off, making it undesirable to be used in rural areas where limited or no runway is available. These UAVs were commonly used for scientific applications such as meteorological reconnaissance and environmental monitoring.

a) Northrop Grumman RQ-4 Global Hawk (Hassanalian and Abdelkefi, 2017)

b) Nasa Pathfinder (Gibbs, 2017)

Figure 1.1: Fixed-wing UAVs

1.1.2.2 Rotary-wing UAVs

Rotary-wing UAVs (Figure 1.2) are aircraft that generate lift using rotor blades shaped like a wing. These UAVs could perform vertical take-off and landing (VTOL) that is advantageous when no runway is available. They could also hover at specific places that make them suitable for capturing static images if needed (Han et al., 2014) and have high maneuverability.

a) Single rotor (Hassanalian and Abdelkefi, 2017)

b) Two rotor (coaxial) (Chen and McKerrow, 2012)

c) Four rotor (quadrotor) (Hassanalian and Abdelkefi, 2017)

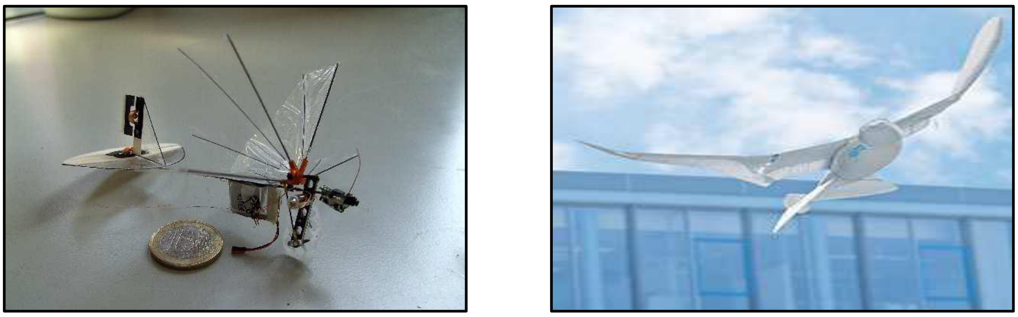
d) Multi rotor (octocopter) (ElKholy, 2014)

Figure 1.2: Rotary-wing UAVs

Usually, rotary-wing UAVs could be categorized based on their number of blades which is 1) single rotor, 2) two-rotor (tandem, transverse, coaxial, intermeshing), 3) three-rotor (uncommon configuration), 4) four-rotor (also called quadcopter/quadrotor that use pair of counter-rotating rotor), and 5) multi-rotor (more than four-rotor such as hexacopter or octocopter).

1.1.2.3 Flapping-wing UAVs

Flapping-wing UAVs (Figure 1.3) are usually aircraft that were inspired by the bird or insect. These UAVs are typically designed on a small scale with deficient payload capability and low endurance. However, it has a fascinating characteristic: they have low power consumption and could perform a VTOL. This class of UAVs was still under development since it is hard to imitate the flapping-wing flight of birds or insects properly.



a) DelFly (ElKholy, 2014)

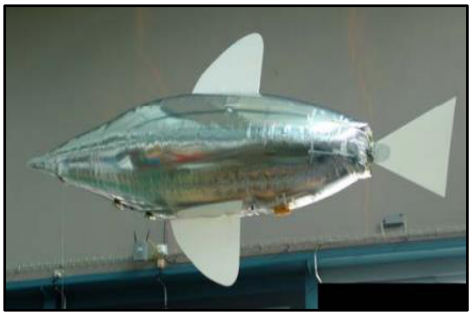
b) FESTO "SmartBird" (Hassanalian and Abdelkefi, 2017)

Figure 1.3: Flapping-wing UAVs

1.1.2.4 Blimps UAVs

Blimps or non-rigid aircraft (Figure 1.4) are aircraft that have no internal structural framework. The primary and only lifting mechanism of these UAVs was by pressurizing lifting gas (helium) inside the aircraft's body. They are very light and could fly for a long time at a low speed.

a) Typical blimp's design (Ruggiero et al., 2018)



b) Bio-inspired blimp design (Michel et al., 2007)

Figure 1.4: Blimps UAVs

1.2 Overview of the Quadrotor

A quadrotor is a type of rotorcraft UAV driven by four rotors located at the end of the body frame with equal distance from the centre mass of the quadrotor’s body. The quadrotor configuration could either be a plus or cross-style configuration, as shown in Figure 1.5. The main difference between these two styles depends on how the quadrotor's heading was defined and how the mathematical model was derived. In a plus style configuration, the heading is pointing toward the rotor 1 direction, while in a cross style configuration, the heading is pointing in between rotor 1 and rotor 2 direction. According to Ye (2018) and Partovi et al. (2012), the cross-style configuration was more stable and provides higher momentum than the plus-style configuration. The plus-style configuration was said to have more agility than the cross-style configuration.

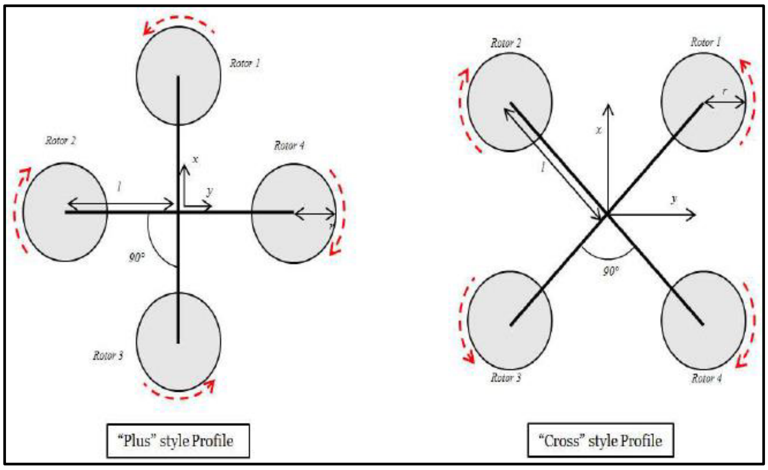


Figure 1.5: Quadrotor configuration with plus and cross style (Partovi, 2012)

A quadrotor is typically low-cost and small in size UAVs (except the transport UAVs) with a unique capability of vertical, stationary, and low-speed flight (Khatoon et al., 2017). Unlike most helicopters, the quadrotor uses two sets of identical fixed-pitch propellers that spin in the opposite direction; one pair rotates in a clockwise direction, and one pair rotates in a counter-clockwise direction (Burggräf et al., 2019). With this configuration, the torque produce by the rotor pairs could be eliminated. The quadrotor is an underactuated system because it has 6 degrees of freedom (DOF) (3 translational and 3 rotational) that need to be controlled by only 4 control inputs, the thrust force, and the aerodynamic torques (Nada El et al., 2019). Such systems bring about complexity in their position and attitude control. A good position and attitude controller are crucial to be designed to control and stabilize such a complex system which were discussed in the next section.

The quadrotor's position and attitude could be controlled by varying each rotor's speed (Mahony et al., 2012). The quadrotor's fundamental movements are the upward and downward movement, also known as altitude motion, rolling motion, pitching motion, and yawing motion, as illustrated in Figures 1.6 through 1.9 below. Note that the movement in X and Y direction could be achieved by determined the proper value of the pitch and roll angle, respectively.

To produce a vertical movement, the forces exerted by each of the rotors in the positive Z direction must be equal. The quadrotor's total thrust responsible for the vertical movement was produced by summing all the individual forces exerted by the individual rotor. Vertical acceleration could be obtained by changing all four rotor speeds by the same amount. Hovering motion could be achieved by balancing the total thrust produced with the weight of the quadrotor.

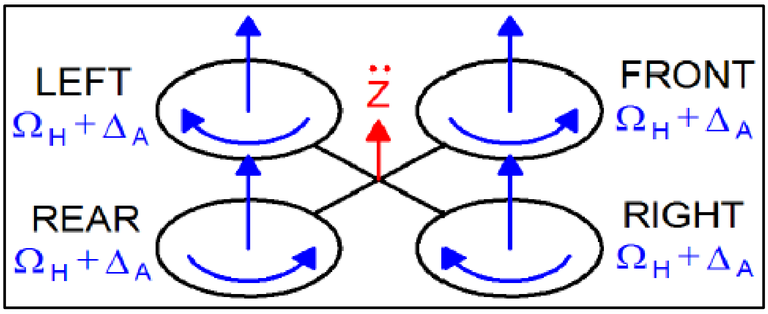


Figure 1.6: Hovering or vertical motion in Z direction (Sabatino, 2015)

Next, the rolling motion. The rolling motion could be achieved by simply rotating the quadrotor around its forward axis, the X axis. Rolling motion could be performed by increasing/decreasing the speed produce by rotor 2 or 4, as shown in Figure 1.7 below. For instance, increasing the speed of rotor 2 on the left side of the quadrotor and decreasing the speed of rotor 4 on the right side of the quadrotor will give a positive rolling motion and vice versa. If a proper value of the roll angle was obtained, one could produced a translational movement of the quadrotor in the Y direction.

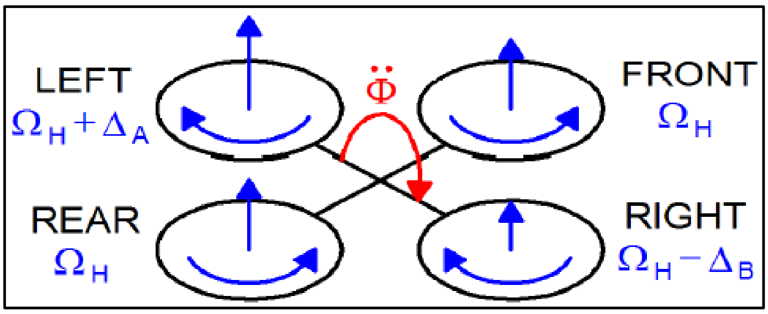


Figure 1.7: Rolling or horizontal motion in Y direction (Sabatino, 2015)

After that, the pitching motion. The mechanism of the pitching motion was very similar to the rolling motion, but the difference is that the rotation was around the Y axis instead of the X axis. Pitching motion could be performed by increasing/decreasing the speed produce by rotor 1 or 3, as shown in Figure 1.8 below. For instance, increasing the speed of rotor 3 on the quadrotor's rear side and decreasing the speed of rotor 1 on the quadrotor's front side will give a positive pitching motion and vice versa. Note that if one determines the proper value of the pitch angle, then one could produce a translational movement of the quadrotor in the X direction.

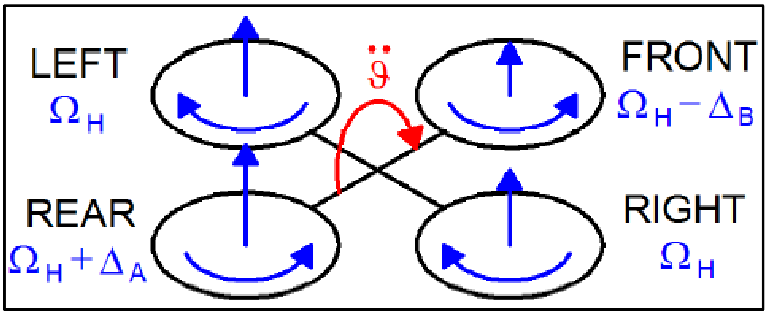


Figure 1.8: Pitching or horizontal motion in X direction (Sabatino, 2015)

Lastly, the yawing motion. The yawing motion could be achieved by rotating the quadrotor around its vertical Z axis. Yawing motion could be performed by increasing/decreasing the speed produce by the rotating pair of the two rotors, as shown in Figure 1.9 below. For instance, increasing the speed produced by one pair of the rotor that was rotating in the clockwise direction (2 and 4) while decreasing the speed produced by the other pair of the rotor that was rotating in an anticlockwise direction (1 and 3) gives a negative yawing motion and vice versa. Note that this movement was done to adjust the heading of the quadrotor.

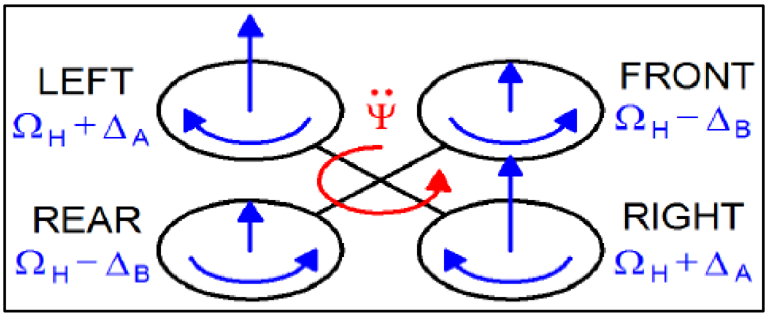


Figure 1.9: Yawing motion (Sabatino, 2015)

Nowadays, the increasing popularity of research in the area of the quadrotor cannot be denied. This trend was due to the advantages of the quadrotor over the conventional helicopter. First, since the quadrotor uses a fixed-pitch propeller, thus it makes the rotor mechanics much simpler. In contrast, the helicopter uses a variable pitch propeller that increases the complexity of its rotor mechanics; and therefore, making the quadrotor easier to manufacture and maintain. Besides, with a symmetrical configuration in the quadrotor's body, the gyroscopic effect was minimized, leading to easier control.

Other than that, the quadrotor could also provide more stability when hovering than the helicopter due to the four propeller's configuration. Four thrust forces shifted at a fixed distance from the center of gravity instead of only one propeller centered in the middle as in a helicopter. Moreover, it could carry a larger payload with a four-rotor propulsion system relative to its size, high maneuverability, and essentially more stable. However, since the quadrotor uses four propellers, it consumes more energy than the helicopter, and with increasing size, the quadrotor could get heavier due to its four propellers structure (Habib et al., 2014).

1.3 Overview of the Control System

Nowadays, control systems have become an integral part of modern society. The demand for automation was increasing correspondingly as human civilization was modernized day by day. Control of a device was highly needed for automation. Control systems have played a central role in developing and advancing modern technology and civilization in recent years. Practically, every aspect of our daily life was less or more influenced by some control system. There are countless applications all around us.

For example, the rocket's fire and the space shuttle lift off to the earth orbit, a self-guided vehicle delivering objects, automated machining robots, an air conditioner, and a refrigerator, to name a few. A control system consists of subsystems or processes (or plants) assembled to obtain the desired output with desired performance, given a specified input (Nise et al., 2011). Figure 1.10 shows a control system in its simplest form, where the input represents the desired output.

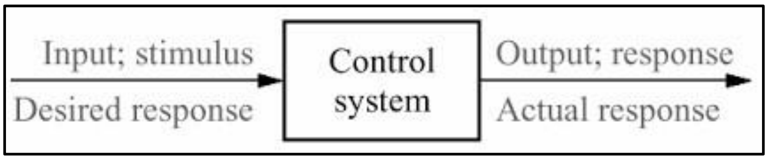


Figure 1.10: Simplified description of a control system (Nise et al., 2011)

The control theory was concerned with controlling the dynamic systems in engineered processes and machines. The goals were to develop a control model to optimally control such systems using a control action without a significant error or overshooting and ensure control stability. As for this purpose, a suitable controller with the necessary corrective action was needed. A controller is a method designed to decrease the difference between the actual value of the system (the process variable) and the desired value of the system (the setpoint). The controlled process variable was monitored by the controller and then compared with the reference or setpoint point. The difference between the process variable's actual and desired value, called an error signal, was used as feedback to generate a control action to bring the controlled process variable back to the same value as the setpoint (Åström and Murray, 2012).

The controller used to control the plant/system could be categorized as linear control and non-linear control. Most of the time, the linear controller was used to control the system since it could provide an adequate performance and is easy to design. In contrast, the non-linear controller is much complex to be design, and sometimes the performance was not significant from the linear controller. Every control system must guarantee specific requirements to become a good control system.

The ability to meet various requirements differs from the model considered and the control strategy selected. Nevertheless, all controllers were used for the same purposes, which is 1) to improve the transient response of the system, 2) to improve the accuracy by reducing the steady-state error of the system, 3) to improve the stability of the system, 4) to control the overshoot of the system, 5) to minimize the off-set and the noise signals produced by the system, and 6) to increase the speed of the response of the system (Abdelzaher et al., 2008).

1.4 Overview of the Metaheuristic Optimization Algorithm

Optimization could be defined in many terms. One of the most straightforward definitions for optimization, according to Gomez et al. (2012), was “doing the most with the least”. However, a suitable definition for optimization related to this study could be defined as “the process of finding the most effective or favourable value or condition” (Lockhart and Johnson, 1996), (Kelley, 2010). The purpose of optimization was to achieved the best possible or optimal solution to a problem from all feasible solutions in those problems relative to a set of prioritized criteria or constraints (Parkinson et al., 2018).

In many fields, optimization theory and techniques have been applied to deal with different practical problems. With the advanced progress in computing systems, optimization techniques were becoming increasingly important and common in various engineering applications (Tsai et al., 2014), (Yang, 2013).

Typically, two distinct types of optimization algorithms have been widely used today: deterministic algorithms and stochastic algorithms. A deterministic algorithm is an algorithm that, given a particular input, will always produce the same output, with the underlying machine always passing through the same sequence of states. Deterministic algorithms were the most studied and familiar kind of algorithm and one of the most practical since they could efficiently run on real machines.

On the other hand, the stochastic algorithm is an algorithm that exhibits a nature of randomness in its model. It uses a random iteration to solve a stochastic problem (Spall, 2003). It explicitly uses randomness to find an objective function's optimum or optimize an objective function with randomness (statistical noise). Stochastic algorithms commonly seek a balance between exploring the search space and exploiting what has already been learned about the search space to find the optima. The choice of the following locations in the search space was chosen stochastically, which was probabilistically based on areas that have been searched recently (Russell and Norvig, 2021), (Spall, 2012), (Graham and Talay, 2013), (Collet and Rennard, 2008).

In this field, various algorithms have been developed to solve the problems. Researchers may use algorithms that terminate in a finite number of steps, or iterative methods that converge to a solution (on some specified class of problems), or heuristics that may provide approximate solutions to some problems (although their iterates need not converge). However, this study focuses only on the heuristic algorithm, specifically the metaheuristic algorithm.

Metaheuristic optimization algorithms were often inspired by nature, and they are now among the popular and widely used algorithms for solving complex real-life optimization problems among researchers. The popularity of this type of algorithm was increasing since they have many advantages over conventional algorithms. The main reason was that they are relatively simple, flexible, non-transferable, and could avoid local stagnation (Mirjalili et al., 2014).

The simplicity of the metaheuristic algorithms was derived from a very simple concept that was typically inspired by physical phenomena, animal behavior, or evolutionary concepts. Flexibility refers to applying metaheuristic algorithms to different problems without any specific structural changes in its algorithm. Metaheuristic algorithms were easily applied to various problems since they are usually assuming the problems as black boxes.

Most metaheuristic algorithms have mechanisms that were free of derivation. In contrast to, for example, gradient-based optimization approaches these algorithms stochastically optimize the problems. This optimization process begins with a random solution(s), and there was no need to calculate the derivative of the search spaces to find the optimum value. This makes metaheuristic algorithms are highly suitable for real problems with expensive or unknown information on derivatives.

Compared to conventional optimization techniques, metaheuristic algorithms have a superior capability in avoiding local optima. Due to the stochastic nature of these algorithms, it is possible to prevent stagnation in local optima and search extensively throughout the search space. The actual problem area was usually unknown and complex with many local optima, so metaheuristic algorithms are excellent options for optimizing these challenging problems.

Generally, metaheuristic algorithms could be divided into two categories: single-solution and multi-solution-based. On a single-solution basis, the search process begins with one candidate solution that was improved throughout the iterations. Whereas multi-solution-based optimization was conducted using an initially random set of solutions called population, these populations were enhanced during the iterations. Multiple solutions (population) based optimization has some advantages over single-solution-based optimization. That is (Dhiman and Kumar, 2018), 1) there is multiple possible best solution, 2) there is information sharing between the multiple solutions that can assist each other to avoid local optima, and 3) exploration in the search space of multiple solutions is more significant than a single solution.

Furthermore, these metaheuristic algorithms could be classified further into three classes which are evolutionary-based, physical-based, and swarm-based methods (Dhiman and Kumar, 2017), as shown in Figure 1.11. The first class is a generic population-based algorithm based on biological evolution, such as reproduction, mutation, recombination, and selection. This method often provides close-to-optimal solutions to all types of problems as it does not make any assumptions about the basic fitness landscape.

Some of the popular metaheuristic algorithms based on the concept of evolution (EA) in nature are Genetic Algorithm (GA) (Holland, 1992), Differential Evolution (DE) (Storn and Price, 1997), Evolution Strategy (ES) (Rechenberg, 1978), (Beyer and Schwefel, 2002), Genetic Programming (GP) (Koza and Koza, 1992), and Biogeography-Based Optimizer (BBO) (Simon, 2008).

The second class of metaheuristic optimization is an algorithm based on physics. Such an optimization algorithm communicates with each search agent and moves across the search space according to physics rules, such as gravitational forces, electromagnetic forces, inertia, etc. These metaheuristic algorithms are Simulated Annealing (SA) (Kirkpatrick et al., 1983), Gravitational Search Algorithm (GSA) (Rashedi et al., 2009), Black Hole (BH) algorithm (Hatamlou, 2013), Ray Optimization (RO) algorithm (Kaveh and Khayatazad, 2012), Big-Bang Big-Crunch (BBBC) (Erol and Eksin, 2006), Central Force Optimization (CFO) (Formato, 2009), Charge System Search (CSS) (Kaveh and Talatahari, 2010), Small World Optimization Algorithm (SWOA) (Du et al., 2006), Artificial Chemical Reaction Optimization Algorithm (ACROA) (Alatas, 2011), Galaxy-based Search Algorithm (GbSA) (Shah-Hosseini, 2011), and Curve Space Optimization (CSO) (Moghaddam et al., 2012).

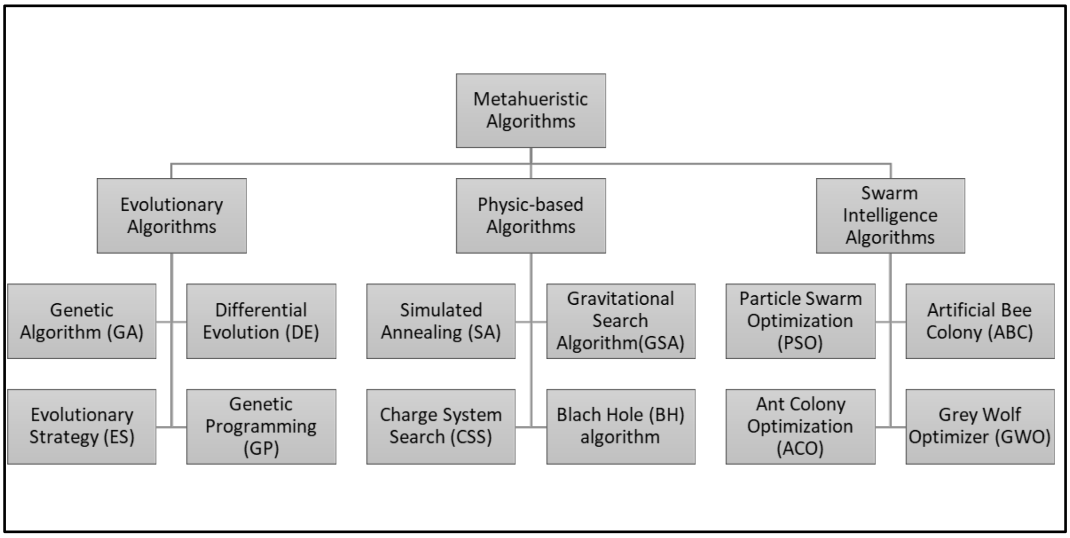


Figure 1.11: Classification of metaheuristic algorithms

The third class of metaheuristic optimization is swarm-based algorithms. These algorithms were based on the social creature's collective behavior. Collective intelligence was based on the interaction of the swarms with each other and their environment. A few well-known Swarm Intelligence (SI) techniques are Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995), Ant Colony Optimization (ACO) (Dorigo et al., 2006), Artificial Bee Colony (ABC) (Karaboga and Basturk, 2007), Monkey Search (MS) (Mucherino and Seref, 2007), Cuckoo Search (CS) (Yang and Suash, 2009), Bat-inspired Algorithm (BA) (Yang, 2010b), Dolphin Partner Optimization (DPO) (Shiqin et al., 2009), Firefly Algorithm (FA) (Yang, 2010a), Bee Collecting Pollen Algorithm (BCPA) (Lu and Zhou, 2008), and Marriage in Honey Bees Optimization Algorithm (MBO) (Abbass, 2001).

There are two crucial components in the metaheuristic algorithms that influence the solution's efficiency and accuracy: the phase of exploration and exploitation (Alba and Dorronsoro, 2005), (Olorunda and Engelbrecht, 2008). The exploration phase ensures that the algorithm moves and explores the other promising regions in the search space. In contrast, the exploitation phase ensures the search for the optimal solutions within the promising regions that have been achieved during the exploration phase (Lozano and García-Martínez, 2010). The fine-tuning of these two components was crucial to obtain an optimal solution for the given optimization problems. However, due to the stochastic nature of the optimization problem, it is challenging to balance these two components.

1.5 Problem Statement

The interest toward the rotary type of UAVs, especially the quadrotor, has grown rapidly in today's world. This increasing trend happens mainly because of its advantages over conventional fixed-wing UAVs and its various exciting applications. In the initial development, these UAVs were primarily used for military purposes such as surveillance and attack. However, as technology advances, UAVs have now also been used in civilian applications to perform various environmental, commercial, and scientific purposes.

However, certain problems need to be addressed before the use of these UAVs could be realized. The quadrotor's dynamics is a naturally unstable, underactuated system. It has 6 DOF that need to be controlled by only 4 actuators which are highly interdependent and coupled in nature (Noormohammadi-Asl et al., 2020). Therefore, controlling such a complex system was essentially challenging (Yazid et al., 2019). A suitable controller needs to be designed to control such a system to achieve a very satisfactory system's performance (Yit et al., 2016). It was also essential that the system stabilizes within a very short period without any problem, such as large overshooting or significant steady-state error (Yit and Rajendran, 2015).

Furthermore, fine-tuning the controller's gains was also crucial since it could affect the controller's performance and indirectly affect the performance of the quadrotor (Basri et al., 2015). Usually, for a conventional controller like PID, the controller's gains were adjusted manually using trial and error or Ziegler and Nichols method. Using these techniques sometimes was not appropriate because it is a time-consuming process, while the control designer does not know exactly which controller's gains are the optimal solution for the controller (Basri et al., 2015).

Other than that, it was found in many works of literature that the use of a single controller was not sufficient in achieving a good system's performance (Roy et al., 2021). Recently, many researchers have developed a type of controller that consists of two or more controllers called a hybrid controller to overcome the limitation of a single controller. This hybrid controller could work together as one entity to compensate each other disadvantages and ensure the stability and robustness of the system.

Therefore, in this work, a hybrid controller was developed and implemented, which is a combination of a conventional PD2 and LQR controller called a Hybrid PD2-LQR controller and fine-tuning the gains of the controller with the proposed optimization algorithm that was called Random Explosion Algorithm (REA), to find the best optimal solution for the gains so that it could effectively control and stabilize the altitude and attitude motion of the quadrotor with a better system's performance.

1.6 Research Objectives

The main objective of this research is to develop an effective optimal control technique to control and stabilize the altitude and attitude motion of the quadrotor UAV. The specific sub-objectives of this research are as follows:

I. To identify the standard type of mathematical model uses for quadrotor’s altitude and attitude control and stabilization.

II. To develop an optimization algorithm to implemented onto the proposed hybrid control structure.

III. To develop an optimal hybrid controller with an optimization algorithm for quadrotor’s altitude and attitude control and stabilization.

IV. To evaluate and compare the performance and the effectiveness of the proposed algorithm and optimal hybrid controller with various algorithms and controllers.

1.7 Scope of the Research

The scope of the research work in this thesis was limited by four factors. Firstly, this work was limited to designing and modelling the controller for control and stabilizing the quadrotor system using simulation in the MATLAB/Simulink environment. A comparative study with conventional controllers was made to validate the proposed controller's performance and effectiveness. Secondly, this research focuses only on the linearizedversion of the quadrotor’s dynamics using a linear control technique since it has been proven that in many works of literature, using a linear controller was sufficient to obtained an adequate performance for the system. Thirdly, since the quadrotor system is onlycomprising of 4 control inputs, thus the movement of the quadrotor was limited to 4 DOF only. In this study, only the altitude and the 3 attitude angles (roll, pitch, yaw) were chosen to be controlled. The translational movement in the X and Y direction was omitted from the quadrotor's dynamics. Lastly, the rotor's dynamic of the brushless DC motor (BLDC) was not considered. The controller was assumed to directly controlled the states of the quadrotor system.

1.8 Research Approach

The research was started by learning the basic concepts and topics concerned. The topics studied include the derivation of the mathematical modelling of the quadrotor, which consists of kinematics and dynamics model. The related articles and studies on linear and non-linear control systems in current literature have been extensively reviewed. The main emphasis was implementing an optimization algorithm onto the proposed control structure and applying it to the quadrotor model for the simulation.

Several objectives need to be completed from the previously mentioned targets. First, the mathematical equation of the quadrotor system was modelled based on the Newton-Euler formulation. Before any control technique was introduced, the quadrotor system's behavior was analyzed and understood carefully. Using the linearized equation of motion of the quadrotor, the linear PD2 control, and LQR control techniques are studied.

Besides, to use the advantages of the optimal control, an optimization algorithm was applied to the proposed control structure. Based on that, the combination of PD2 control and LQR control technique to become an optimal Hybrid PD2-LQR controller was developed to control and stabilize the altitude and attitude motion of the quadrotor. The simulation of the algorithms and the controllers in the MATLAB/Simulink environment was executed to obtain the comparison results and discuss the performance and effectiveness of the proposed algorithm and proposed controller. Several simulations were conducted, and the results and data were used to evaluate the performance of the algorithms and controllers. The algorithms were evaluated based on the exploitation and exploration capability, convergence speed, and algorithm's accuracy in finding the optimal solutions. In contrast, the controllers were assessed regarding the rise time, settling time, percentage overshoot, steady-state error, and root mean square error (RMSE) of the system's response.

1.9 Thesis Outline

This thesis was organized by the objectives and approaches as previously mentioned. Five main chapters were presented: the introduction, literature review, methodology, result and discussion, and conclusion and recommendation.

Chapter 1 briefly introduces the study's background, including an overview of the quadrotor system, control system, and metaheuristic optimization algorithm. It also briefly outlines the main problem statement, the primary and sub-objectives of the research, the research scope, and the research approach. Finally, the outline of the thesis was presented.

Chapter 2 provides an in-depth literature review and theoretical background of the thesis on the related subjects from the previous researchers, including enhancing the previous studies and explaining the previous concept and knowledge. The topic's discussed includes 1) the establishment of the dynamic model of the quadrotor, 2) linear and non-linear control techniques that were commonly used by the researchers in the quadrotor control area, 3) the optimization algorithm that was usually used for tuning the gains of the controller's, 4) the optimal controllers which uses the optimization algorithm in its structure, and 5) a summary of the review to highlights some of the important points in this research.

Chapter 3 presents a description of the proposed research methodology. This chapter was divided into 7 sections. In the first section, the chapter begins with a typical introduction. The second section covers the derivation of the mathematical model of the quadrotor using Newton-Euler formalism. The state-space representation of the linearized quadrotor's model was covered in the third section. Details of all controllers used in this study were discussed in the fourth section, including its control algorithm. The new optimization algorithm's development based on the explosion method called Random Explosion Algorithm (REA) was presented and explained in detail in the fifth section. The REA implementation on the Hybrid PD2-LQR controller was presented in the sixth section. Lastly, a summary of the chapter was discussed.

In Chapter 4, the results obtained from the MATLAB/Simulink simulation for the optimization algorithms and the controllers were discussed in detail, along with a reasonable justification to support the findings. This chapter was divided into 8 sections. In the first section, the chapter begins with the typical introduction, and the benchmark test function used for testing the algorithm's performance was presented in the second section. The third section discussed the comparative study of the proposed optimization algorithm with 8 other well-known algorithms. The comparative analysis of the other optimization-based controller with the proposed REA-based controller was discussed in the fourth section. In the fifth section, the comparative study of the conventional PD, PID, LQR, Hybrid P-LQR, Hybrid PD-LQR, and Hybrid PD2-LQR controller with the proposed controller, which is the REA-based Hybrid PD2-LQR controller, was presented. In the sixth section, the robustness of the proposed REA-based Hybrid PD2-LQR controller was tested using a modeled unknown external disturbance and sensor noise to simulate the real-world application and to compensate for the lack of experimental study. In the seventh section, the stability of the proposed controller was tested when the quadrotor's model was subjected to parameters uncertainty. Lastly, in the eighth section, the summary of the findings was presented to highlight the performance of the proposed algorithm and the proposed controller.

Chapter 5 presents the concluding remarks of the research work in this thesis, and some recommendations for the future research development of the project were also included.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The advancement of today's technologies has raised the popularity of quadrotor's control and stabilization area among researchers. This was due to the advantages and potential applications of the quadrotor in various fields in the community, either in civil or military. Today many developments related to the quadrotor control techniques have been done to improve the performance of the quadrotor's response. Most developed quadrotor projects are now available in the market as toys armed with various sensors and communications capabilities (Khatoon et al., 2017).

However, controlling the quadrotor system was not an easy task since its inherent complex non-linear dynamics that are highly unstable and exhibit an undesired flight characteristic in the absence of a flight controller. Moreover, the quadrotor is an underactuated system since it poses 6 DOF (3 translational and 3 rotational) that need to be controlled by only 4 control inputs. Having an underactuated system produces an additional challenge to control and stabilize the system's dynamics. Therefore, it was necessary to develop a proper mathematical model of the quadrotor's dynamics and an appropriate and effective control technique to overcome these problems so that the desired performance of the quadrotor's response could be achieved.

This chapter discussed some of the most commonly used control techniques in the works of literature. Since this work was based on the optimal (optimization-based) control, thus the main flow of this review are as follows; 1) a review of quadrotor's dynamics model, 2) a review of conventional controllers (without optimization), 3) a