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EXTENDED HIGH-GAIN OBSERVER-BASED OUTPUT FEEDBACK CONTROL OF UNDERACTUATED QUADROTOR

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EXTENDED HIGH-GAIN OBSERVER-BASED OUTPUT FEEDBACK CONTROL OF UNDERACTUATED QUADROTOR

By

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EXTENDED HIGH-GAIN OBSERVER –BASED OUTPUT FEEDBACK CONTROL OF UNDERACTUATED QUADROTOR

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October 2018

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Underactuated system is a nonlinear system having less actuators than the number of states to be controlled. The control for underactuated system is already a challenging task. It will be more difficult in the presence of external disturbances. Quadrotor is one example of an underactuated system. For quadrotor to overcome the external disturbance, it needs energy. However, energy limitation is the main challenges in quadrotor to serve the applications. An Extended High-gain Observer (EHGO) is proposed to stabilize the underactuated system in the presence of external disturbance with optimize energy consumption. In this study, the energy consumption is analyzed based on the control effort represented by control signal.

EHGO has shown good potential to handle disturbances in the fully actuated system and underactuated system. In most studies, EHGO was successfully implemented on established board, which is of good quality but high cost. The capability of EHGO in the low-cost off-the-shelf common board has a high interest in a wide group of practitioners, hence it is worth investigating. Therefore, a control design framework and validation of EHGO - output feedback control (EHGO-OFB) for quadrotor trajectory tracking under broader flight envelope that is implementable in real-time using off-the-shelf common quadrotor platform is presented.

A generalised closed-loop underactuated system model using EHGO-OFB in presence of disturbances was derived. An additional dynamic state equation is obtained which results in a closed-loop system in two-time-scale structure that is less complex. Consequently, this thesis extended the existing theorem of EHGO-OFB from fully-actuated to underactuated nonlinear system.

The validation was performed in simulation and experimental. In simulation, the overall performance of EHGO-OFB in hierarchical controller (HC) improves the control effort by 36% from the standard HC. Meanwhile, the EHGO-OFB in sliding mode control

(SMC) shows 15% improvement in the control accuracy achievable using smaller control effort compared to standard SMC. This simulation result provides an alternative to deal with chattering problem in SMC that has become the limitation of SMC when applied to a quadrotor.

In experiment, a 39.64% improvement in the control effort was obtained for proposed EHGO-OFB based on existing hierarchical flight controller (HFC). The flight test was performed in the Indoor Space flight arena in Universiti Putra Malaysia using low-cost off-the-shelf common components with sampling rate of 0.01s. An EHGO gain of 0.01 was able to achieve a good performance for the quadrotor. The existing HFC based on PID algorithm rejects the disturbance by physical means and consume more energy whereas the EHGO-OFB reject the disturbance internally. The controller able to maintain the quadrotor in a bounded area with notably smaller control effort even in the presence of wind as external disturbance. The work in this thesis is expected to enhance the performance of quadrotor in various fields.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKAAN ALAT KAWALAN EXTENDED HIGH GAIN OBSERVER UNTUK ‘UNDERACTUATED QUADROTOR’

Oleh

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Sistem underactuated adalah sistem tak linear yang mempunyai penggerak kurang daripada bilangan pembolehubah yang perlu dikawal. Kawalan untuk sistem underactuated adalah tugas yang mencabar. Ia menjadi lebih sukar dengan adanya gangguan luar. Quadrotor adalah satu contoh sistem underactuated. Quadrotor memerlukan tenaga untuk mengatasi gangguan luar. Namun, batasan tenaga merupakan cabaran utama dalam quadrotor untuk melayani aplikasi. “Extended High-Gain Observer (EHGO)” dicadangkan untuk menstabilkan sistem underactuated dibawah gangguan luar dengan mengoptimumkan penggunaan tenaga. Dalam kajian ini, penggunaan tenaga dianalisis berdasarkan magnitud usaha kawalan.

EHGO telah menunjukkan potensi yang baik untuk mengendalikan gangguan dalam sistem “fully-actuated” dan sistem underactuated. Namun dalam kebanyakan kajian, EHGO berjaya dilaksanakan menggunakan sistem yang berkuali tetapi kos yang tinggi. Keupayaan EHGO menggunakan system yang lebih murah mempunyai minat yang tinggi dikalangan kelompok pengguna yang lebih ramai, ia bernilai untuk disiasat. Oleh itu, rangka kerja reka bentuk kawalan dan pengesahan kawalan EHGO-OFB untuk lintasan quadrotor di bawah sampul penerbangan yang lebih luas boleh dilaksanakan dalam masa nyata menggunakan platform quadrotor biasa dipersembahankan.

Model sistem tertutup yang menggunakan EHGO-OFB di bawah gangguan luar diperolehi. Persamaan keadaan dinamik tambahan diperolehi yang menghasilkan sistem tertutup dalam struktur dua kali skala yang kurang kompleks. Hasilyna, tesis ini memperluaskan teorem EHGO-OFB yang sedia ada dari sistem nonlinear yang digerakkan sepenuhnya kepada system underactuated.

Pengesahan telah dilakukan dalam simulasi dan eksperimen. Dalam simulasi, prestasi keseluruhan EHGO-OFB dalam HC menambahbaik usaha kawalan sebanyak 36% daripada standard HC. Sementara itu, EHGO-OFB dalam SMC menunjukkan peningkatan 15% dalam ketepatan kawalan dicapai dengan menggunakan usaha kawalan yang lebih kecil berbanding SMC piawai. Hasil simulasi ini memberikan alternatif untuk menangani masalah perbualan di SMC yang telah menjadi batasan SMC apabila diterapkan pada quadrotor.

Dalam eksperimen, usaha kawalan sebanyak 39.64% diperolehi untuk EHGO-OFB yang dicadangkan berdasarkan pengawal penerbangan (HFC). Ujian penerbangan dilakukan di arena penerbangan Indoor Space di Universiti Putra Malaysia menggunakan komponen umum yang kurang mahal dengan kadar sampel 0.01s. EHGO bernilai 0.01 dapat mencapai prestasi yang baik untuk quadrotor tersebut. HFC sedia ada berdasarkan algoritma PID menolak gangguan dengan cara fizikal dan menggunakan lebih banyak tenaga manakala EHGO-OFB menolak gangguan dalaman. Pengawal mampu mempertahankan quadrotor menggunakan usaha kawalan yang lebih kecil walaupun berdepan gangguan angin. Kerja-kerja dalam tesis ini dijangka dapat meningkatkan prestasi quadrotor dalam pelbagai bidang.

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I certify that a Thesis Examination Committee has met on (date of viva voce) to conduct the final examination of (student's name) on his (her) thesis entitled ("Title of Thesis") in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the (insert the name of relevant degree).

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A	Frontal area perpendicular to the axis of motion
A_1	Translational A matrix for dynamic observer errors
A_2	Rotational A matrix for dynamic observer errors
A_T	Translational A matrix for tracking errors
A_R	Rotational A matrix for tracking errors
A_{TH}	Hurwitz matrix for translational tracking errors
A_{RH}	Hurwitz matrix for rotational tracking errors
A_ξ	Overall system uncertainty in the translational subsystem
A_τ	Overall system uncertainty in the rotational subsystem
$\mathcal{B}$	body-fixed frame
b	Thrust factor of the propeller
$C \in \mathbb{R}^3$	Centripetal force
C	Force – to – moment scaling factor
C_d	Drag coefficient
$D_x, D_y,$	Horizontal forces acting on the x- and y-axes (drag force)
D_z	Gravity force (drag force)
d	Disturbance state
$\hat{d}_i$	Estimated term by EHGO
e_{ξ_1}	Position error
e_{ξ_2}	Velocity error
e_{η_1}	Angular rotation error
$F_{ext} \in \mathbb{R}^n$	Translational forces
F_i	Thrust force generated by individual rotor

f_1, f_2	Known functions
f_d	Unknown and uncertain function
G_1	Coefficient of virtual control input
g	Gravity
H	Hub force
$\mathcal{I}$	Inertial frame
$I \in \mathbb{R}^{3x3}$	Moment Inertia
J	Rotor inertia
k	Controller gain
κ	Constant of propeller dynamic
l	Distance from the rotors to the centre of gravity
M	Pseudoinertial Matrix
M_i	Moments generated by individual rotor
m	Mass of vehicle
n	Dimension of states
$R(\eta_1)$	Rotation matrix
R_d	desired rotation matrix
R_{mxi}, R_{myi}	Rolling moment due to sideward flight
T	Thrust force
u	Control inputs
$\bar{u}$	Proposed controller in state feedback form
$\hat{u}$	Proposed EHGO-OFB controller
$\dot{V} = (u, v, w)$	Vehicle linear velocities in the three-dimensional axis, in frame $\mathcal{B}$
x	Position in x-axis

$x_i \in R^n$	System state
$\hat{x}_i \in R^n$	Estimated state by EHGO
y	Position y-axis
z	Position z-axis
α	Constant of EHGO
σ_x, σ_y	Friction in x, y -axis
$\xi_1 \in R^n$	Vehicle state position in x,y,z – axis, in frame $\mathscr{J}$
$\xi_2 \in R^n$	Vehicle state velocity in x,y,z – axis, in frame $\mathscr{J}$
ε	Observer gain of EHGO
$\eta_1 \in R^n = (\theta, \phi, \psi)$	Vehicle rotation angle in x,y,z -axis, in frame $\mathscr{J}$
$\eta_2 \in R^n = (\dot{\theta}, \dot{\phi}, \dot{\psi})$	Vehicle angular velocity in x,y,z -axis, in frame $\mathscr{J}$
η_{x1}	Position estimation error (fast variables)
η_{x2}	Velocity estimation error (fast variables)
η_{x2}	Extended velocity estimation error (fast variables)
$\eta_{\alpha 1}$	Rotation angle estimation error (fast variables)
$\eta_{\alpha 2}$	Angular velocity estimation error (fast variables)
$\eta_{\alpha 3}$	Extended angular velocity estimation error (fast variables)
Ω	Propeller angular rate
Ω_r	Propeller angular speed
ρ	Air density
$\mu_\xi \in \mathbb{R}^3$	Virtual force in the translational dynamics
τ	Control input torque
$\check{\tau}_\eta$	Intermediate control input torque
$\omega = (p, q, r)$	Vehicle angular velocities in the three-dimensional axis, in frame $\mathscr{B}$

ω_i	Individual rotor speed
$\Phi(\eta_1)$	Euler matrix
$\Psi(\eta_1)$	Inverse of Euler Matrix
θ	Angle rotation in x-axis
ϕ	Angle rotation in y-axis
ψ	Angle rotation in z-axis
Σ_T	Translational subsystem
Σ_R	Rotational subsystem

LIST OF ABBREVIATIONS

EHGO	Extended High-Gain Observer
EHGO-OFB in HC	Extended High-Gain Observer -based Output Feedback Control in Hierarchical Controller
EHGO-OFB in SMC	Extended High-Gain Observer -based Output Feedback Control in Sliding Mode Controller
EHGO-OFB in HFC	Extended High-Gain Observer -based Output Feedback Control in Hierarchical Flight Controller
GAS	Global asymptotic stable
HGO	High-Gain Observer
LES	Local exponential stable
MIMO	Multiple-input and Multiple output
OFB	Output feedback
SFB	State feedback
SISO	Single input and Single output
UA	Underactuated
UAV	Unmanned aerial vehicle
VTOL	Vertical Take-Off and Landing
3D	Three dimensional

CHAPTER 1

INTRODUCTION

1.1 Background

An underactuated system is of great interest in both theoretical and real applications. The growing interest in the research of the underactuated system can be attributed to its wide application in the industry, spanning from aerospace [2][3], ground robotics [4] to underwater vehicles [5].

Being a system having a smaller number of control inputs than the degrees of freedom to be controlled, the control design of an underactuated system is a challenging problem. The system model does not satisfy Brockett's necessary condition for feedback linearization [6]. For a fully-actuated system, a good number of control techniques are available which can be easily applied to the entire class of such systems. However, it is not the case for underactuated systems. The control technique for an underactuated system is unique in each application, since the control technique depends on the structure that varies among systems [7][8].

Vertical take-off and landing (VTOL) vehicles such as helicopters, ducted-fan and quadrotors are some of the examples of an underactuated system. In the VTOL family, the quadrotor and ducted-fan are commonly used as the platform for UAV control research. These vehicles are able take-off and land vertically and it is usually small in size with a physical weight ranging from 2 to 0.5 kg [2].

Over the decade, quadrotor has attracted a significant interest among practitioners owing to its numerous applications in civilian sectors to replace human. These includes terrain monitoring for agriculture, assessment of damage caused by natural or manmade hazards, exploration of remote and inaccessible [9]. Also, the quadrotor is emerging as a popular platform in the UAV research. This is due to the vehicle good manoeuvrability, its capability to hover and fly at very low altitudes and speeds, and its superiority over other types of VTOL in terms of simplicity in the mechanical structure.

Flight control is a fundamental problem for quadrotor. Linear flight controllers have been successfully applied to quadrotor such as by Bouabdallah et al.[10] and How et al.[11]. However, the stability achieved is limited to a small flight envelope. This is because linear control law is designed based on a linearized dynamic model. Alternatively, nonlinear flight controllers using technique such as backstepping [12], nested-saturation [13] and hierarchical controllers [14] were proposed [15] [16] [17]. The advantage of nonlinear approach is it considers the nonlinearities in the dynamic model. Hence, linearization of model is not required. Consequently, the system can be stabilized at wider flight envelope. Several nonlinear flight controller were successfully implemented to stabilize quadrotor [3][18][19]. However, the nonlinear flight controllers successfully stabilize the vehicle online in the hovering mode in which the presence of internal system uncertainties is small due to modelling errors and parameters uncertainties.

To accommodate the numerous applications of quadrotor as the UAV platform, there are many control problems that demand more robustness in the control approach that needs further study. For example, the robustness in the translational trajectory in the presence of external disturbance needs to be enhanced. Due to the quadrotor small size and low-level atmosphere flight operation, the vehicle is susceptible to unpredictable wind. An additional control functions, that increases the stability of quadrotor in much wider flight envelope is crucially needed. Generally, there are several approaches to the design of flight controllers to solve this problem, as listed below:

i. **Adaptive Control**: This approach solves the problem of the large range of uncertain parameters by an online parameter estimation. The drawback of this approach is that it requires the model to be known accurately. In addition, this control strategy involves complicated structures and high computational cost.

ii. **Robust Control** – This approach handles system uncertainties through dominating the terms using a high-gain switching. The drawback of this approach is that the control solution is conservative and constantly operating at "hard control" because the system uncertainties are dominated by a pre-defined upper-bound constant value.

iii. **Extended Observer-based Method**: This approach treated system uncertainties as an additional variable. It then handles the system uncertainties through estimating this term and feedback to the control.

The extended state observer (ESO) control is a feasible approach due to the following reasons. Firstly, the control law can be designed based on the system nominal model. Secondly, apart from estimating the extended state, ESO able to estimate the unmeasured states in the system. It is function as an output feedback control ~~to~~ that deal limitation of sensors in the actual physical system.

The concept of ESO as a disturbance estimator, with an additional high-gain component in the observer, known as the Extended High-Gain Observer (EHGO) was presented in 2008 by Freidovich & Khalil [20]. The robustness of a fully actuated nonlinear system against system uncertainties was successfully achieved and a theorem of the Extended High-Gain Observer - Output Feedback Control (EHGO-OFB) was developed. The line of study continue to grow [21] and recently in 2015, EHGO-OFB was extended to underactuated nonlinear system utilising dynamic inversion as the stabilizing control law [22]. In these works, EHGO was successfully implemented in the communication board that is well established and of good quality which is high cost.

On separate issue, there are a number of successful flight controllers that have been reported over the last decades [7][10]. However, existing flight controllers only solve the basic hovering flight problem. The range of system uncertainties that these flight controllers able to dominate is usually small, which is particularly due to parameter uncertainties or unmodelled dynamics. In this context, Kendoul et al.presented a flight controller based on the idea of hierarchical structure that achieves a global stability of the control system [18]. The control algorithm was successfully implemented into the low-cost communication devices that is commercially available and was able to give a good flight performance during hovering in a small flight envelope.

Meanwhile, the control robustness is usually achieved through conservative solutions in which the system uncertainties are dominated by sliding mode control (SMC) technique. This standard approach results in a hard control to the actuators and eventually leads to a faster mechanism degradation. The controller is likely to suffer as the vehicle starts to operate in a wide range of the flight domain.

Payload is a critical issue for a good flight performance, especially in the small-scale VTOL-UAV. In a UAV, the payload includes processing cards and sensors to provide the real-time pose estimation, which is necessary for the feedback loop implementation. Hence, this thesis focuses on EHGO-OFB to stabilize the quadrotor in the presence of external disturbance that is able to accommodate the limitation of energy from battery. A hybridization technique utilizing the EHGO-based output feedback control is proposed in the flight controller that achieves smaller control effort compared to the standard flight control.

1.2 Problem Statement

According to the Department of Civil Aviation (DCA) Malaysia Regulation [23], small aircraft is defined as any unmanned aircraft weighting less than 20kg, and flying not higher than 400 feet above surface. Due to its small and low-weight and flying at low-level atmosphere, the aerial vehicle of this size has issues to resist wind. It is generally known that flying the aerial vehicle on a windy day will drain the battery faster than normal because the actuators is working harder to control the vehicle body to maintain at the desired position in the air. This challenge is no exception for quadrotor vehicle.

Energy limitation is the main challenges in quadrotor to serve the applications in UAV. The internal controller that is available in the commercial quadrotor usually stabilizes the vehicle attitude at small flight envelope. The vehicle will be utilising using a lot of energy to stay afloat as the wind pushes against it.

In 2008, a hierarchical flight controller (HC) was proposed to stabilize the quadrotor. The HC was implemented on quadrotor and it was proven successful and it is widely used today in the quadrotor flight. The existing flight controller needs large control effort to stabilize the quadrotor during external wind. At some point, the controller may easily fail and lead to crash. Therefore, an additional control function to ensure stabilization of the vehicle in broader flight envelope is notably needed.

At the same year in 2008, an Extended High-Gain Observer -based output feedback control (EHGO-OFB) has shown good potential to handle disturbances and uncertainties in the fully actuated nonlinear system, more recently in 2015 in the underactuated system regardless of SISO or MIMO configurations. However, in most studies, EHGO was successfully implemented on an established acquisition board, which is of good quality but comes with high-cost devices. The capability of EHGO to estimate the fast dynamics of the quadrotor states and uncertainties using commercially available low-cost communication devices was not yet proven. Nevertheless, it has a high interest in a wide group of practitioners, hence it is worth investigating.

The past five years has seen the research trend on quadrotor control moving from stabilization, robust control tracking and now to disturbance rejection. However, the existing hierarchical flight controller able to tolerate small disturbances and uncertainties. Recently, the EHGO-OFB has been successfully implemented on quadrotor flight control and it were able to reject impulse disturbance. As stated previously, even though the theorem was successfully implemented, the application was done on established board which is high-cost. The capability of EHGO-OFB was not yet proven in the low-cost off-the-shelf controller board.

In terms of the fundamental control theory, the existing control design framework of EHGO-OFB for underactuated system produces a closed-loop system of multi-time scale structure. This introduces to complex stability analysis in which the user cannot simply adopt the established two-time-scale structure stability analysis which was initially developed in 2008 for fully actuated system.

A novel control based on sliding mode was proposed in 2008 to stabilize the quadrotor under robust condition. The control design framework was inspired by the general form of underactuated nonlinear system that been proposed in 2002. The sliding mode control (SMC) for the underactuated system that transformable into the general underactuated form has simple structure and it is an attractive design to robust flight control. However, the standard SMC is designed based on dominating the system uncertainties. The controller forced the actuators to constantly operate at its hard limit to ensure robustness. Furthermore, the standard SMC has chattering which make its application more challenging. In practical situation, these system uncertainties may not always be at the worst range. In the UAV flight, the presence of wind in the low-level atmosphere is uncertain and unpredictable.

1.3 Aim and Objectives

The primary aim of this work is on the control design of Extended High-Gain Observer Output-Feedback Control (EHGO-OFB) for quadrotor trajectory tracking under broader flight envelope that is implementable in real-time using off-the-shelf common platform UAV. There are four objectives to achieve this aim. The four objectives are:

1. To construct a simple closed-loop system for underactuated nonlinear system that is controlled by EHGO-OFB.

2. To design EHGO-OFB in the hierarchical controller (HC) for quadrotor forward and sideward motion that able to maintain performance specification at small control effort despite under presence of external force signal.

3. To design EHGO-OFB into the sliding mode control (SMC) that able to overcome large switching and chattering in the standard SMC.

4. To implement EHGO-OFB in the low-cost quadrotor platform for quadrotor real-time trajectory tracking in the presence of the continuous force disturbance.

1.4 Contribution

The main contributions of this work are:

- In the quadrotor control technology, the proposed EHGO-OFB integrated into the existing hierarchical flight controller able to reject disturbance with a smaller control effort (more than 36% improvement) compared to the existing hierarchical flight controller which uses PID algorithm to reject the disturbance by physical means. The proposed EHGO-OFB reject the disturbance internally. The controller able to produces similar performance at transient and steady-state with minimal control effort even when wind is pushing from opposite direction.

- The implementation of the Extended High-Gain Observer-based Output Feedback Control (EHGO-OFB) in the off-the-shelf common board that is low-cost aerial platform setup has been successfully conducted. The importance of tuning the observer gain to a high value for ESO-based control is shown. The performance is achieved at observer gain 0.01.

- The development of the discrete-time version of the EHGO. The quality of states estimated by EHGO is comparable to the standard numerical procedure for which Kalman filter are explicitly added to obtain smooth estimation data. The novelty of EHGO lies in its simplicity and minimal tuning of parameters.

- In the EHGO-OFB theorem, the proposed control design framework result in a closed-loop underactuated nonlinear system with two-time-scale structure. Therefore, this thesis extends the existing theorem of EHGO-OFB for fully actuated nonlinear system by Fredovich & Khalil (2008) [19] to underactuated nonlinear system. An additional dynamic state equation is emerged due to the proposed control design framework. However, stability analysis of the overall closed-loop system is simple and straightforward due to the two-time scale structure.

- The design of EHGO-OFB into sliding mode control (SMC) able to increase the control accuracy (small steady-state error) at minimal control effort which is a new way to deal with chattering.

1.5 Scope of the Work

The scope of the study is on the control framework and validation of proposed EHGO-OFB for underactuated nonlinear system. The testbed is quadrotor. This thesis focus on additional control function in quadrotor UAV that able to resist wind.

The control design focus on stabilization of underactuated quadrotor. In general, the system is classified as multi-input and multi-output (MIMO) underactuated nonlinear system. The size of system uncertainties is wider, extending from internal factor such as parameters uncertainties to external disturbances. Related to this point, the scope of the thesis is enhancing the trajectory tracking control in the forward (x-axis) and sideward (y-axis) motion of quadrotor UAV in the presence of wind disturbance. This is a control challenge because the forward and sideward is an underactuated motion. Its dynamic is manipulated by rotational angle.

The validation is mainly performed on the quadrotor UAV model and then on the actual quadrotor aerial platform. In the control design, the system model is assumed a minimum phase. Meanwhile, the system uncertainties comprising of external disturbances are of matched perturbation to the nominal system model.

The scope of study focuses on extended observer-based control in the translational subsystem. A translational observer is integrated into the subsystem. Therefore, the development of the closed-loop system mode of underactuated nonlinear system based on observer design emphasizes on the translational subsystem. The study does not really focus on the rotational observer. Nevertheless, the results from using the rotational observer may be included in part of the work in the experiment.

The system uncertainties comprising parametric uncertainties and external disturbances perturbing the vehicle are assumed bounded. In the simulation, the external disturbance is a continuously time-varying signal. In the flight experiment, the source of external disturbances will be generated artificially from a fan.

1.6 Thesis Organization

This thesis is divided into seven chapters. The first chapter begins with background of the research, followed by the problem statement and stated the objectives of the thesis. The thesis contributions are presented in this chapter.

Chapter 2 is the literature review underlying the research. The literature review is subdivided into four main sections. The first section starts with an overview of the underactuated quadrotor vehicle. It introduces the quadrotor physical structure, and described the mathematical model representing the vehicle. The third section review the existing quadrotor flight control technology. The fourth section review the hierarchical controller and the sliding mode control techniques. The fifth section reviews extended high-gain observer (EHGO) and the output feedback theorem (OFB). The limitations were highlighted in each section.

Chapter 3 comprise of three main sections. The first section presents the quadrotor dynamic model in the x, y and z -axis structure and the model of system uncertainties. The underactuated dynamic mainly the forward and sideward motion of the quadrotor model derived in this chapter will be used to solve the control problem in the subsequent chapters. The second section gives the control design framework of EHGO-OFB. This thesis extends the existing theorem of EHGO-OFB from nonlinear system to underactuated nonlinear system in which a two- time scale closed-loop system obtained in presented in this section. A state-feedback control law based on backstepping technique is intentionally derived even though it will not be used in the subsequent chapters. The objective is just to show the complexity of backstepping technique, hence not a good control law for MIMO system especially for embedded control. The third section validates the EHGO in estimating the unknown states from the underactuated dynamic.

Chapter 4 comprise of five sections. The first section provides background of Hierarchical Controller (HC). Second section formulates the problem. Third section presents the control design and analysis of EHGO- OFB in HC to solve the quadrotor problem during trajectory tracking under presence of external disturbance. The fourth section presents the remarkable performance of proposed EHGO-OFB in hierarchical controller shown in simulation using MATLAB/SIMULINK. The performance is compared to the standard hierarchical controller. The performance evaluated in terms of settling time, steady-state error, and control effort is described for quadrotor in this section. The last section summarizes the findings.

Chapter 5 consists of five sections. The first section provides background of sliding mode control (SMC) and highlighted the limitations in the standard SMC. Second section formulates the problem which outlined the dynamic of sliding surface as the control system. Third section delivers the control design framework of EHGO-OFB in continuous SMC. The fourth section provides the simulation results performed in MATLAB/SIMULINK and evaluates the performance of EHGO-OFB in SMC compared to the standard SMC. The last section summarizes the findings.

Chapter 6 presents the implementation of the EHGO-OFB in experimental flight test. This chapter comprise of four sections. The first introduces the layout of indoor space flight arena located at the Satellite & Space System Lab, Aerospace Department in UPM. The artificial generation of wind disturbance is shown. The second section provides the digital implementation of EHGO inside the ground station that is then communicated wirelessly to the low-cost embedded platform for control action. The third section presents the results of experimental flight-test. The real-time trajectory tracking performance were investigated under two case studies, i.e. tracking without external disturbance and trajectory tracking with external disturbance presence which is wind artificially generated by fan. Lastly, the flight test in terms of waypoint trajectory is presented. The last section provides summary of the chapter.

Chapter 7 gives the general conclusion of the overall thesis and state the possible directions of future research.

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APPENDICES

APPENDIX A

Mean Value Theorem to Obtain $G_1(y)$

Dynamic Model:

$$\dot{z_2} = \mathrm{f}_1(z_1, z_2, z_3, z_4) + A_\xi + \dot{d}_1$$

where f_1 is a continuously differentiable function over D={$\|x\| < r$} for some $r > 0$ and f_1(0,0,0,0)=0.

Let $J(yx)$ be the Jacobian matrix of $f_1(x)$, that is $J(x) = \frac{d\mathrm{f}_1}{dx}(x)$

$$\mathrm{f}_1(z_1, z_2, z_3, z_4) - \mathrm{f}_1(z_1, z_2, 0{,}0) = \frac{df_1}{dx}(z_3, z_4)$$

$$h(\sigma) = \mathrm{f}_1[(z_1, z_2, z_3, z_4) + \sigma(z_3, z_4)]; \qquad 0 \ll \sigma \ll 1$$

Differentiating $h(\sigma)$:

Chain rule : $h'(\sigma) = \frac{d\mathrm{f}_1}{dx}[(z_1, z_2, z_3, z_4) + \sigma(z_3, z_4)](z_3, z_4)$

$$\mathrm{f}_1(z_1, z_2, z_3, z_4) - f_1(z_1, z_2, 0{,}0) = h(1) - h(0)$$

$$\int_0^1 h'(\sigma) = h(1) - h(0)$$

$$= \int_0^1 \frac{df_1}{dx}[(z_1, z_2, z_3, z_4) + \sigma(z_3, z_4)](z_3, z_4)$$

$$f_1(z_1, z_2, z_3, z_4) = \int_0^1 \frac{df_1}{dx}[(z_1, z_2, z_3, z_4) + \sigma(z_3, z_4)](z_3, z_4) + f_1(z_1, z_2, 0{,}0)$$

Therefore, $G_1(z)z_3 = \int_0^1 \frac{df_1}{dx}[(z_1, z_2, z_3, z_4x_4) + \sigma(z_3, z_4)](z_3, z_4)$

The system Equation (3.12a) is replaced by Equation (3.13) and rewriting the system Equation (3.12a)-(3.12b) as

$$\begin{aligned} \dot{z_1} &= z_2 + d_1 \\ \dot{z_2} &= f_1(z_1, z_2) + G_1(z)z_3 + A_\xi + \dot{d}_1 \end{aligned} \tag{A.1a}$$

$$\begin{aligned} \dot{z_3} &= z_4 \\ \dot{z_4} &= f_2(z_1, z_2, z_3, z_4) + b(z_1, z_2, z_3, z_4)u + A_\eta \end{aligned} \tag{A.1a}$$

APPENDIX B

Derivation of Estimation Errors Dynamics

Based on the system model Equation (3.8) and the EHGO algorithm in Equation (3.22a) – (3.22b), the variables of estimation error for translational and rotational subsystems are defined as:

$$\eta_{x1} = \frac{x_1 - \hat{x}_1}{\varepsilon^2}, \quad \eta_{x2} = \frac{x_2 - \hat{x}_2}{\varepsilon}, \quad \eta_{x3} = \mathrm{A}_{\xi} - \hat{A}_{\xi}$$

$$\eta_{\alpha 1} = \frac{x_3 - \hat{x}_3}{\varepsilon^2}, \; \eta_{\alpha 2} = \frac{x_4 - \hat{x}_4}{\varepsilon}, \; \eta_{\alpha 3} = \mathrm{A}_{\eta} - \hat{A}_{\eta}$$

where $\eta = [\eta_x, \eta_\alpha]^T$, $\eta_x = [\eta_{x1}, \eta_{x2}, \eta_{x3}]^T$, $\eta_\alpha = [\eta_{\alpha 1}, \eta_{\alpha 2}, \eta_{\alpha 3}]^T$, $\mathrm{A}_\eta = \Delta_{f_2(x,d_3)} + \Delta_b(x,d) M g_\epsilon\left(\frac{\psi(x,\hat{A}_\eta)}{M}\right)$, where
$\Delta_{f_2(x,d_3)} = f_2 - \hat{f}_2(x)$
$\Delta_b(x,d) = b(x) - \hat{b}(x)$

The derivatives of η_x along the translational trajectories Equation (3.8) are:

$$\begin{aligned}
\varepsilon\dot{\eta}_{x1} &= -\alpha_{11}\eta_{x1} + \varepsilon\chi\eta_{x1} + \eta_{x2} \\
\varepsilon\dot{\eta}_{x2} &= -\alpha_{12}\eta_{x1} + \varepsilon\chi\eta_{x2} + \eta_{x3} + f_x - f_x(\hat{x}, \hat{A}_{\xi}) \\
\varepsilon\dot{\eta}_{x3} &= -\alpha_{13}\eta_{x1} + \varepsilon\dot{A}_{\xi}
\end{aligned}$$

The above equations are simplified into state-space form, given by:

$$\varepsilon\dot{\eta_x} = A_1\eta_x + \varepsilon d_1\eta_x + \varepsilon[B_1\Delta_1 + B_2\Delta_2]$$

where $A_1 = \begin{bmatrix} -\alpha_{11} & 1 & 0 \\ -\alpha_{12} & 0 & 1 \\ -\alpha_{13} & 0 & 0 \end{bmatrix}$, $d_1 = \begin{bmatrix} \chi & 0 & 0 \\ 0 & \chi & 1 \\ 0 & 0 & 0 \end{bmatrix}$, $B_1 = [0,1,0]^T, B_2 = [0,0,1]^T$,

The term Δ_1 and Δ_3 are defined by:

$$\Delta_1 = \frac{\mathrm{f}_1 - \hat{\mathrm{f}}_1(x, \alpha)}{\varepsilon} \qquad \text{(A.2a)}$$

$$\Delta_2 = \dot{A}_{\xi} \qquad \text{(A.2b)}$$

The derivatives of η_α along the rotational trajectories Equation (3.8) are:

$$\begin{aligned}
\varepsilon\dot{\eta}_{\alpha 1} &= -\alpha_{21}\eta_{\alpha 1} + \eta_{\alpha 2} \\
\varepsilon\dot{\eta}_{\alpha 2} &= -\alpha_{22}\eta_{\alpha 1} + \eta_{\alpha 3} + \Delta_0 \\
\varepsilon\dot{\eta}_{\alpha 3} &= [-1 - \Delta_3]\alpha_{23}\eta_{\alpha 1} + \varepsilon[\Delta_1]
\end{aligned}$$

The term Δ_0, Δ_1 and Δ_3 are defined by:

$$\begin{aligned}
\Delta_0 = \hat{\mathrm{f}}_2(x) - \mathrm{f}_2(\hat{x}) + a(x)M[g_\epsilon\left(\frac{\psi(\hat{x},\hat{d}_3)}{M}\right) &- g_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right) \\
&+ \hat{a}(x)Mg_\epsilon\left(\frac{(x,\hat{d}_3)}{M}\right) - \hat{a}(\hat{x})Mg_\epsilon\left(\frac{\psi(\hat{x},\hat{d}_3)}{M}\right) \\
&+ [a(x,d) - \hat{a}(\hat{x})]Mx[sat\left(\frac{\psi(\hat{x},\hat{d}_3)}{M}\right) \\
&- g_\epsilon\left(\frac{\psi(\hat{x},\hat{d}_3)}{M}\right)]
\end{aligned} \tag{A.2c}$$

$$\Delta_1 = \dot{\Delta}_b + \dot{\Delta}_a Mg_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right) + \Delta_a g'_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right)\frac{\partial\psi}{\partial x}(x,\hat{d}_3)\dot{x} \tag{A.2d}$$

$$\Delta_3 = \frac{\Delta_a(x,d_3)}{\hat{a}(x)}\ g'_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right) \tag{A.2e}$$

The fast subsystem for η_α is given by:

$$\varepsilon\dot{\eta_\alpha} = A_2\eta_\alpha - B_2\Delta_3\alpha_{23}\eta_{\alpha 1} + \varepsilon[B_1\Delta_4 + B_2\Delta_5]$$

$$\text{where } A_2 = \begin{bmatrix} -\alpha_{21} & 1 & 0 \\ -\alpha_{22} & 0 & 1 \\ -\alpha_{23} & 0 & 0 \end{bmatrix}, B_1 = [0,1,0]^T, B_2 = [0,0,1]^T,.$$

The term Δ_3, Δ_4 and Δ_5 are defined by:

$$\Delta_3 = \frac{\Delta_a(x,d_3)}{\hat{a}(x)}\ g'_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right) \tag{A.2f}$$

$$\Delta_4 = \frac{\Delta_0}{\varepsilon} \tag{A.2g}$$

$$\Delta_5 = \dot{\Delta}_b + \dot{\Delta}_a Mg_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right) + \Delta_a g'_\epsilon\left(\frac{\psi(x,\hat{d}_3)}{M}\right)\frac{\partial\psi}{\partial x}(x,\hat{d}_3)\dot{x} \tag{A.2h}$$

APPENDIX C

Coding for EHGO -based Hierarchical Flight Controller

```
//        Kalman Filter  //

MyKalman filter_k = new MyKalman();

//        Declare : EXTENDED High Gain Observer(EHGO)  //
double yhgo = 0;
double zhgo = 0;
double eps = 0.01                                        //user input

double[,] A_hgo = new double[3,
3]{{$a_{11,}a_{12,}a_{13}$},{$a_{21,}a_{22,}a_{23}$},{$a_{31,}a_{32,}a_{33}$}};
double[,] B_hgo = new double[3, 1] { { $b_{11,}$ }, { $b_{12,}$ }, { $b_{13}$ } };
                                                         // user input from
                                                     Matlab c2d command
double[,] q_hgo = new double[3, 1];                                //x
double[,] q_zhgo = new double[3, 1];                               //y
double[,] x_in = new double[3, 1] { { 0 }, { 0 }, { 0 } };         //x
double[,] z_in = new double[3, 1] { { 0 }, { 0 }, { 0 } };         //y
double[,] b_yhgo = new double[3, 1];                               //x
double[,] b_zhgo = new double[3, 1];                               //y
#endregion//        Update : Position and Velocity  //
MAV_DATA[rowIndex].xp = MAV_DATA[rowIndex].x;    // previous data
MAV_DATA[rowIndex].zp = MAV_DATA[rowIndex].z;
MAV_DATA[rowIndex].x = rb.x * m_ServerToMillimeters;// *= 1000.0;
MAV_DATA[rowIndex].z = rb.z * m_ServerToMillimeters;// *= 1000.0;
MAV_DATA[rowIndex].xv         =         (MAV_DATA[rowIndex].x         -
MAV_DATA[rowIndex].xp) / 0.01;
MAV_DATA[rowIndex].zv         =         (MAV_DATA[rowIndex].z         -
MAV_DATA[rowIndex].zp) / 0.01;
```

APPENDIX D

Coding of Extended High-Gain Observer (EHGO)

Matlab (.m)

Input : $\alpha_1, \alpha_1, \alpha_1, \varepsilon$

```
sys_ss=ss(A,B,C,D)
sys1 = c2d(sys_ss,0.01)
sim('discrete')
```

Output : $[a]_{3x3}$, $[b]_{3x1}$,c,d

**//	Update : EXTENDED High Gain Observer(EHGO) //**

% EHGO for x

```
yhgo = filter_k.update(MAV_DATA[0].x);          // x from Optitrack
xvh = filter_k.update(MAV_DATA[0].xv);          // xv from algorithm
```

in C#

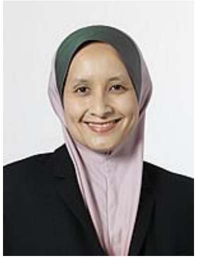
```
b_yhgo[0, 0] = B_hgo[0, 0] * (yhgo / eps);
b_yhgo[1, 0] = B_hgo[1, 0] * (yhgo / eps);
b_yhgo[2, 0] = B_hgo[2, 0] * (yhgo / eps);

double[,] A_hgo_xin = Multiplication(A_hgo, x_in);

q_hgo[0, 0] = A_hgo_xin[0, 0] + b_yhgo[0, 0];
q_hgo[1, 0] = A_hgo_xin[1, 0] + b_yhgo[1, 0];
q_hgo[2, 0] = A_hgo_xin[2, 0] + b_yhgo[2, 0];

x_in[0, 0] = q_hgo[0, 0];
x_in[1, 0] = q_hgo[1, 0];
x_in[2, 0] = q_hgo[2, 0];
```

BIODATA OF STUDENT



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LIST OF PUBLICATIONS

Elya M.N, S. B. M. Noor, R. Zafira, and S. Azrad, “Application of Sliding Mode Control with Extended High Gain Observer to Stabilize the Underactuated Quadrotor System,” *Pertanika J. Sci. Technol.*, vol. 25, no. S, pp. 343–352, 2017

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