UNIVERSITI PUTRA MALAYSIA

AVIAN-INSPIRED FEATURE-BASED RELATIVE POSITIONING STRATEGY FOR FORMATION CONTROL OF MULTIPLE UNMANNED AERIAL VEHICLES

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By

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Chair: Syaril Azrad Md. Ali, PhD
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As a new era of flying machines intersected autonomous and semi-autonomous machines, resulted in the birth of Unmanned Aerial Vehicles (UAVs). It has changed the way human beings travel, transport objects, surveillance execution, emergency response, and other things which time will reveal. Among the various types of UAVs, the Multi-rotor UAVs attained the most attention due to its advantages such as: ease of use, Vertical Take Off and Landing capability, hover flight, and ability to operate in confined area. However, small payload capacity is one of the most discerning disadvantage. Due to limited capability and performance of single Multi-rotor UAVs, interest to overcome this through flight formation and formation control of UAVs has grown significantly over the past few years. One of the key aspects of flight formation is spatial coordination or relative positioning between UAVs flying in close proximity in order to avoid collision and achieve collective operation.

In spatial coordination of UAVs flying in the swarm, using the vision-based technique for on-board computation, there have been two main approaches, which are; Color-based (artificial marker detection) and Motion-based (Optical Flow). The Color-based approach performance is highly affected by misdetection for indoor application and light intensity variation for outdoor application. The Motion-based or Optical Flow approach for both indoor and outdoor application suffers from lack of precision and high sensitivity to noise. To the best of our knowledge at the time of writing this thesis, there are nearly no studies which focused on the use of feature-detection approach in real-time and on-board of UAVs for the collision-free flight formation.

As inspired by birds flying in flocks, vision is one of the most critical component for them to be able to respond to their neighbor’s motion. Thus, in this thesis a novel approach in developing a Vision System as a primary sensor for relative positioning in flight formation of Leader-Follower scenario is introduced. The developed Vision System is based on Feature-Detection and stereo vision. It utilizes the On-Line Machine Learning approach for tracking the Leader in Leader-Follower flight formation. The NVIDIA JETSON TX1 is used as a computing platform for processing the Vision System data in real-time and on-board of DJI MATRICE 100 quadcopter.

In order to evaluate the Vision System performance, three flight-formation scenarios which are *tracking the Leader in motion*, *following the Leader in motion* and *tracking the Leader in presence of obstacle* were introduced. The test results from the first flight-formation show the 99% success in tracking the Leader in motion when approximately 3600 training sample photo of the leader provided and 83% accuracy in calculating the location of the Leader. The second flight-formation test results show the ability of the Follower to follow the Leader with roughly 2 seconds delay by utilizing the Vision System. The results of third flight-formation show 85% success in tracking the Leader with 30% occlusion, 75% success in case of 50% occlusion and poor performance in case of 100% occlusion. The obtained test results show the developed Vision System which is based on Feature-Detection to be a better alternative to the existing approaches which are Color-based and Motion-based.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
Sebagai memenuhi keperluan untuk ijazah Master Sains

STRATEGI PENENTUKEDUDUKAN RELATIF BERASASKAN PENGLIHATAN BERINSPIRASIKAN UNGGAS BAGI KAWALAN FORMASI BERBILANG PESAWAT UDARA TANPA PEMANDU

Oleh

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Dalam era baharu ini kita sedang menyaksikan berlakunya penggabungan antara konsep jentera terbang dan jentera berautonomi separa dan penuh yang telah melahirkan pesawat udara tanpa manusia (UAV). Seiringan dengan masa, teknologi ini telah mengubah bagaimana manusia bergerak, mengangkut barangan, melakukan pemantauan, berespon terhadap kecemasan dan sebagainya. Di antara pelbagai jenis UAV yang berbeza, UAV multi-rotor mendapat perhatian yang terbesar disebabkan oleh beberapa kelebihan yang ditawarkan seperti mudah digunakan, kebolehan berlepas dan mendarat secara menegak (VTOL), penerbangan hover dan kemampuan untuk beroperasi pada kawasan yang tertutup. Walaubagaimanapun UAV dalam kelas ini mempunyai kelemahannya yang ketara kerana kapasiti muatannya adalah amat terhad.

Minat terhadap penerbangan berformasi dan kawalan formasi UAV multi-rotor meningkat mendadak beberapa tahun kebelakangan ini sebagai satu cara untuk menampung keupayaannya yang terhad. Salah satu aspek utama penerbangan dalam formasi ialah pengkoordinasian ruang atau penentukedudukan relatif antara UAV yang terbang berdekatan antara satu sama lain, bagi mengelakkan berlakunya perlanggaran serta bagi mencapai operasi secara kolektif.

Dalam pengkoordinasian ruang oleh UAV yang terbang secara kerumunan, yang menggunakan teknik berasaskan visi bagi pemprosesan di atas pesawat, terdapat dua pendekatan berbeza, iaitu Berasaskan Warna (pengesanan penanda buatan) dan Berasaskan Pergerakan (alur optik). Prestasi pendekatan menggunakan Berasaskan Warna banyak dipengaruhi oleh kesilapan pengesanan bagi aplikasi dalam bangunan. Ia juga amat terkesan dengan keamatan cahaya jika diaplikasi di luar bangunan. Pendekatan Berasaskan Pergerakan atau alur optik bagi aplikasi dalam dan luar

bangunan mempunyai masalah disebabkan kurangnya kepersisan dan amat sensitif terhadap hingar. Sehingga kini iaitu semasa penulisan tesis ini, didapati hampir tiada penyelidikan yang telah dijalankan bagi menggunakan pendekatan Berasaskan Fitur bagi menghasilkan penerbangan formasi yang bebas dari pelanggaran sesama UAV pada masa nyata serta data yang diproses menggunakan peranti yang dipasang pada pesawat.

Seperti yang diinspirasikan oleh burung-burung yang terbang secara berkelompok, visi adalah merupakan komponen yang paling penting bagi haiwan itu supaya dapat beriak balas terhadap pergerakan burung yang terbang berhampiran. Maka dengan itu dalam tesis ini satu pendekatan baru telah diperkenalkan bagi membangunkan Sistem Visi sebagai sensor utama bagi penentukedudukan relatif UAV yang terbang menggunakan formasi Ketua-Pengikut. Sistem Visi yang dibangunkan adalah berasaskan Pengesanan Berasaskan Fitur dan visi stereo. Ia menggunakan pendekatan Pembelajaran Mesin Dalam Talian bagi menjejak Ketua dalam penerbangan formasi Ketua-Pengikut. NVDIA JETSON TX1 telah digunakan sebagai platform komputer bagi memproses data Sistem Visi pada masa nyata dan dipasangkan pada pesawat helikopter empat rotor DJI MATRICE 100.

Untuk menilai prestasi Sistem Visi, tiga senario formasi penerbangan telah diperkenalkan, iaitu pertama penjejakan Ketua yang sedang bergerak, kedua mengekori Ketua yang sedang bergerak dan ketiga menjejak Ketua ketika terdapatnya taupan. Hasil ujian dari formasi penerbangan pertama menunjukkan peratusan kejayaan sebanyak 99% dalam penjejakan pesawat Ketua yang sedang bergerak, apabila kira-kira 3600 gambar sampel pesawat Ketua disediakan, dan 83% ketepatan dalam pengiraan lokasi pesawat Ketua. Keputusan penerbangan formasi kedua menunjukkan kemampuan pesawat Pengikut untuk mengekori pesawat Ketua menggunakan Sistem Visi dengan kelewatan secara kasarnya sebanyak 2 saat. Keputusan pernerbangan formasi ketiga menunjukkan kejayaan 85% dalam menjejak pesawat Ketua dengan taupan sebanyak 30%, 75% kejayaan dalam kes 50% taupan dan prestasi yang lemah bagi taupan 100%. Keputusan ujian menunjukkan Sistem Visi yang dibangunkan yang berasaskan Pengesanan Fitur adalah alternatif yang lebih baik berbanding pendekatan yang sedia ada iaitu Berasaskan Warna dan Berasaskan Pergerakan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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UAV	Unmanned Aerial Vertical
VTOL	Vertical Take Off and Landing
IMU	Inertial Measurement Unit
P3P	Perspective -3- Point Problem
PID	Proportional Integral Derivative
LED	Light Emitting Diode
PnP	Perspective -n- Point Problem
2D	2 Dimension
3D	3 Dimension
GPS	Global Positioning Unit
RADAR	RAdio Detection And Ranging
LIDAR	Laser Imaging Detection And Ranging
RGB	Red, Green, Blue
RGB-D	Red, Green, Blue, Depth
FOV	Field Of View
MOG	Mixture Of Gaussian
OpenCV	Open Source Computer Vision
ML	Machine Learning
MIL	Multiple Instance Learning
KCF	Kernelized Correlation Filter
TLD	Tracking, Learning and Detection
ROI	Region Of Interest
TM	Tracking Module
RPM	Relative Positioning Module
DETM	Data Extraction and Transfer Module
VS	Vision System
ISU	Image Sensor Unit
CCD	Charged Coupled Device
CMOS	Complementary Metal Oxide Semiconductor
PCM	Pinhole Camera Model
IP	Internet Protocol
UDP	User Datagram Protocol
TCP	Transmission Control Protocol
OBPU	On-Board Processing Unit
ASC	Active Stereo Camera
PSC	Passive Stereo Camera
SDK	Software Development Kit
FPS	Frame Per Second
GPU	Graphic Processing Unit
CPU	Central Processing Unit
ESC	Electronic Speed Control
FC	Flight Controller
GCS	Ground Control Station
PC	Personal Computer
IR	Infra-Red

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Background of Study

As a new era of flying machines decussating with autonomous and semi-autonomous machines, it's resulting in birth of Unmanned Aerial Vehicles (UAVs) which going to change the way human beings travel, transport their stuffs, carry the surveillance, emergency respond, and other things which time will reveal.

In the beginning of any new potential era, there would be generally lots of interest in different aspect of that technology or idea. As of this norm, there have been huge attention and vast researches in the field of UAVs. In order to categorize the UAVs, they come under four main categories, which are: Multi-rotor, Fixed-wing, Single-rotor, Fixed-wing hybrid. Each of these types of UAVs have their own advantage and disadvantages, and among the above mentioned types, the Multi-rotor UAVs get the most attentions due to their advantages such as: ease of use, Vertical Take Off and Landing (VTOL), hover flight, and ability to operate in confined area. On the other side, their small payload capacity is one the concerned disadvantage [1].

Due to limited capability and performance of single Multi-rotor UAVs, interest in the flight formation and formation control of UAVs has grown significantly over past few years [2]. One of the key aspect of flight formation is Spatial Coordination or Relative Positioning between UAVs flying in close proximity in order to avoid collision and achieve collective operation.

As inspired by birds flying in flocks, vision is one of the most critical component for the birds in order to be able to respond to their neighbor's motion [3]. Thus, this thesis's focus is on the vision aspect of the UAVs as a primary sensor for relative positioning in flight formation of Leader-Follower scenario.

1.2 Problem Statements

In spatial coordination of UAVs flying in the swarm, using the vision-based technique for on-board computation, there has been two main approaches, which are: Color-based (artificial marker detection), and Motion-based (Optical Flow). R. Jin et al. [4] presented a vision tracking system which detects color LED markers installed in advance on a hexarotor. The LED markers size are 6cm x 6cm and placed 40cm apart in horizontal and vertical directions forming a 40cm square. Their vision system used single monocular camera to detect the markers and relative distance and pose estimation were calculated by solving Perspective-3-Point Problem (P3P). They have reported the ability of their system to detect the marker up to 6.58m distance. However, they need to adjust the LED markers light intensities for different situations such as day time and night time and even indoor and outdoor flights due to the sensitivity of the camera to color of markers. The other problem they have faced was the higher relative distance the more difficult to detect the markers as it sizes gets smaller and smaller in binary image.

A Leader-Follower flight formation scenario has been tested by D. Dias et al. [5] which consists of three Hummingbird quadrotors. All the quadrotors are equipped with active LED markers. The Leader is kept static and the Followers which use a 320x240 resolution camera on-board form a triangle flight formation. They have reported a successful flight formation using camera as a main vision sensor by keep all the quadrotors in the same flight altitude level. Although, this has been achieved in the laboratory environment, in reality it's a very difficult task to maintain the leader in static position and all the UAVs in the same height level. These difficulties make the detection of LED markers in desired orientation to be of great challenge, thus, making it not applicable in real applications.

R. Tron et al. [6] presented a flight formation using three Hummingbird quadrotors. Each of them is equipped with 13cm diameter circular color pad as an artificial marker. Although, in this approach the UAVs consume less energy in contrast with active LED markers, still the vision system is required to be calibrated in advance due to sensitivity of the cameras to detect the desired colors.

The other approach of the vision-based UAV navigation which has been used so far, is Motion-based or Optical Flow approach. N. Gageik et al. [7] used the Optical flow data fused with Inertial Measurement Unit data for an autonomous UAV navigation system and they could achieve the position error of 20cm in flight over eight set points. J. Qi et al. [8], also used the same approach for both indoor and outdoor and they have got the position error of 1.41m. In both cases [7, 8], they have reported a high sensitivity of their system to the noise.

In summary, the Color-based approach performance is highly affected by misdetection for indoor application and light intensity variation for outdoor application. The Motion-based or Optical Flow approach for both indoor and outdoor application suffers from lack of precision and high sensitivity to noise.

There are nearly no researches which focusing on the use of Feature-detection approach for the collision-free UAV flight formation.

1.3 Research Objective(s)

The main objectives of the present work are:

i. To develop a vision system which is capable of acquiring, processing and reacting to visual sensor's data for relative positioning between members of flocking UAVs.

ii. To evaluate the accuracy/effectiveness of the developed vision system in real-time data processing on-board of UAVs.

1.4 Scope of Work

The present work mainly focuses on development of vision-based algorithm which is Feature-based rather than Color-based or Motion-based. The range estimation and relative positioning will be calculated purely by Vision System through stereo vision techniques rather than utilizing any other sensors such as Infrared or Ultrasonic.

In order to get the best out of the given time frame of this project, well stablished techniques for Feature-Detection vision-based navigation will be studied to adopt the most suited one. As the developed Vision System is intended to be processed on-board the UAV, available On-Board Processing platform will be investigated to select the best suited.

The vision algorithm will be run on-board DJI MATRICE 100 which is available in the Satellite and Space System Laboratory of Department of Aerospace, Universiti Putra Malaysia. The developed Vision System will be tested for the Leader-Follower flight formation consists of two quadcopters, DJI MATRICE 100 as a Follower and DJI F450 as a Leader. The flight formation test will be carried on in the above mentioned laboratory which is equipped with 16 OptiTrack *Flex13* motion capture camera covering an area of 16 m^2.

Since the main focus of this work is on developing a Vision System for the UAVs, the research would not be involved in the areas such as:

- Formation flight controller of leader-follower, hence, simple and established control strategy will be used;
- Power efficiency of the UAV involved. Power is expected to be largely consumed due to computational cost of the strategy;
- Navigation of UAVs in complex and cluttered environment, such as through a building, forest etc., high-speed and acrobatic flight.

1.5 Thesis Outline

In chapter 2, nature of flocking birds and prior works in the area of flight formation is reviewed. Chapter 3, describes the Vision System requirements and its architecture. It discusses in details the flight scenarios and their objectives, the development process and platforms including Programming, UAVs and Testing platforms. The results obtained from testing of Vision System in real-time flight formation is presented and discussed in chapter 4. The conclusion of this project achievements and recommendations for future works is discussed in chapter 5.

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