DEVELOPMENT OF OBSTACLE DETECTION AND AVOIDANCE SYSTEM BASED ON INTEGRATION OF DIFFERENT BASED-SENSOR FOR SMALL-SIZED UNMANNED AERIAL VEHICLE USING CUES FROM EXPANSION OF FEATURE POINTS AND DIRECTION OF FLOW FIELD VECTORS

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ABSTRACT

Achieving a reliable obstacle detection and avoidance system that can provide an effective safe avoidance path for small unmanned aerial vehicle (UAV) is very challenging due to its physical size and weight constraints. Prior works tend to employ the vision based-sensor as the main detection sensor but resulting to high dependency on texture appearance while not having a distance sensing capabilities. Besides, vision-based sensor detection system suffers from creating a trusted safe avoidance path due to inability to detect the free region. The previous system only focused on the detection of the frontal obstacle without observing the environment as a whole which is strictly not resemble the real environment. On the other hand, most of the wide spectrum range sensors are heavy and expensive hence not suitable for small UAV. In this thesis, integration of different based-sensor was proposed for a small UAV obstacle detection and avoidance system. Cues from expansion of the features points are used to extract the depth information of the environment and classify the region in the predictable obstacle appearance situation. In the unpredictable obstacle appearance situation, the detection of the obstacle is done by analysing the flow field vectors in the image frames sequence. The proposed system was evaluated by conducting the experiments in a real environment for both of the observed situations, which consisted of different configuration of the obstacles. The results show that the proposed system able to create the safe avoidance path regardless of the texture appearance (e.g. poor texture or textureless) and size of the obstacle. It also able to handle multiple obstacles with the distance of the introduced side obstacle was up to 270 cm from the UAV platform. In addition, the success rate for the sudden introduced obstacle experiments is high which is 70 % and above. It is also found that the safe avoidance path by the proposed system will depend on the situation and position of the obstacle in the environment. Finally, the obstacle appearance in the image views plays a critical role in deciding the direction of the safe avoidance path.

ABSTRAK

Merangkakan Sistem pengesanan dan penghindaran halangan bagi pesawat tanpa pemandu yang (UAV) bersaiz kecil adalah sangat mencabar kerana kekangan saiz fizikal dan jumlah berat yang boleh dibawa. Kerja-kerja penyelidikan yang lepas sering menggunakan sensor berasaskan penglihatan sebagai sensor asas tetapi daya sensor ini bergantung kepada penampilan tekstur sementara tidak mempunyai kebolehan untuk menentukan jarak. Selain itu, sensor ini tidak mampu menghasilkan laluan penghidaran yang selamat kerana ketidakbolehan untuk mengesan ruang bebas. Sistem sebelumnya hanya mengfokuskan kepada mengesan halangan hadapan tanpa memerhatikan keadaan di sekiling yang tidak menyerupai persekitaran sebenar. Sementara itu, kebanyakkan sensor jarak yang berspektrum luas adalah sangat berat dan mahal, oleh itu, ia tidak sesuai untuk UAV bersaiz kecil. Kerja penyelidikan ini menggunakan gabungan daripada kedua-dua sensor yang disenaraikan di atas tadi. Isyarat-isyarat daripada pengembangan titik ciri digunakan untuk mengekstraksi maklumat jarak persekitaran dan mengklasifikasikan rantau bagi situasi halangan yang bole diramal. Bagi situasi halangan yang tidak diramal, halangan dikesan melalui analisa vektor medan aliran dalam susunan gambar yang diambil. Sistem yang dicadangkan telah dinilai dengan menjalankan eksperimen dalam persekitaran yang nyata yang terdiri daripada pelbagai keadaan halangan. Keputusan menunjukkan sistem ini mampu menghasilkan laluan penghidaran yang selamat tanpa mengira keadaan tekstur (cth. kurang tekstur atau tanpa tekstur) dan saiz halangan. Ia juga mampu mengendalikan halagan berganda dengan jarak halangan tepi mencecah 270 cm dari UAV. Tambahan pula, kadar kejayaan bagi halangan muncul secara tiba-tiba adalah tinggi iaitu 70 % dan ke atas. Ia juga mendapati bahawa laluan penghidaran yang selamat akan bergantung kepada situasi dan lokasi halangan di dalam persekitaran tersebut. Akhirnya, penampilan halangan di dalam pandangan imej memainkan peranan yang penting untuk menentukan arah laluan penghindaran yang selamat.

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LIST OF SYMBOLS AND ABBREVIATIONS

D	- Distance value derived from the LIDAR sensor
d	- Disparity of stereo cameras
X_L	- Coordinate on the left image
X_R	- Coordinate on the right image
f	- Focal length
b	- Baseline length
$\propto$	- The angle between direction of travel and the obstacle
E	- Change of intensity in Harris corner detector
I	- Intensity of the image
v	- Shift of window in y-direction
u	- Shift of window in x-direction
f_x	- Image gradient in x-direction
f_y	- Image gradient in y-direction
f_t	- Image gradient along time space
U	- Optical flow vector in x-direction
V	- Optical flow vector in y-direction
$L_{xx}(\mathrm{x}, \sigma)$	- Convolution of image with second order Gaussian derivative at x-direction
$L_{yy}(\mathrm{x}, \sigma)$	- Convolution of image with second order Gaussian derivative at y-direction
σ	- Scale value of the Gaussian kernel
D_{xy}, D_{xy}, D_{xy}	- Box filters in SURF method
k_n	- Distortion coefficient
D^{If}	- Distance between feature points
fp_n	- Feature points in respective *n* image frame

mfp_n^{if}	-	Matched feature points from respective *if* image frame
$m\hat{f}p_n^1$	-	Filtered matched feature point from image frame 1
$m\hat{f}p_n^2$	-	Filtered matched feature point from image frame 2
$m\hat{f}p_n^{30}$	-	Filtered matched feature point from image frame 3 with 30 cm distance separation
$m\hat{f}p_n^{15}$	-	Filtered matched feature point from image frame 3 with 15 cm distance separation
$m\hat{f}p_n^{L(if)}$	-	Filtered matched feature point of respective *if* image frame from left section
$m\hat{f}p_n^{M(if)}$	-	Filtered matched feature point of respective *if* image frame from middle section
$m\hat{f}p_n^{R(if)}$	-	Filtered matched feature point of respective *if* image frame from right section
$dR_n^{L(r)}$	-	Distance ratio of left section for matched image frame (*r* = 15 cm or 30 cm distance separation)
$dR_n^{M(r)}$	-	Distance ratio of middle section for matched image frame (*r* = 15 cm or 30 cm distance separation)
$dR_n^{R(r)}$	-	Distance ratio of right section for matched image frame (*r* = 15 cm or 30 cm distance separation)
$m\hat{f}p_n^{Lo(r)}$	-	Left section obstacle feature points (*r* = 15 cm or 30 cm distance separation)
$m\hat{f}p_n^{Mo(r)}$	-	Middle section obstacle feature points (*r* = 15 cm or 30 cm distance separation)
$m\hat{f}p_n^{Ro(r)}$	-	Right section obstacle feature points (*r* = 15 cm or 30 cm distance separation)
$m\hat{f}p_n^{Lf(r)}$	-	Left section non-obstacle feature points (*r* = 15 cm or 30 cm distance separation)
$m\hat{f}p_n^{Mf(r)}$	-	Middle section non-obstacle feature points (*r* = 15 cm or 30 cm distance separation)
$m\hat{f}p_n^{Rf(r)}$	-	Right section non-obstacle feature points (*r* = 15 cm or 30 cm distance separation)
$dR_{(r)}$	-	Reference distance ratio of matched image frame (*r* = 15 cm or 30 cm distance separation)

$LR_{(r)}$ - Left ratio of the matched image frame (*r* = 15 cm or 30 cm distance separation)

$RR_{(r)}$ - Right ratio of the matched image frame (*r* = 15 cm or 30 cm distance separation)

$MR_{(r)}$ - Middle ratio of the matched image frame (*r* = 15 cm or 30 cm distance separation)

$Ffp_n^{(j)}$ - Free region feature points (*j* = side section, *s* or middle section, *m*)

$Ffp_n^{(j)I}$ - Intersect Free region feature points (*j* = side section, *s* or middle section, *m*)

$Ofp_n^{(j)}$ - Obstacle region feature points (*j* = side section, *s* or middle section, *m*)

$Cv_{(j)}$ - Convex hull (*j* = side section, *s* or middle section, *m*)

Sfp_n - Safe avoidance path feature points

$Vx_n^{(p)}$ - Direction of optical flow in x-direction (*p* = Right section or left section)

Lv_K - Dominant direction of flow field vector for left section

Rv_K - Dominant direction of flow field vector for Right section

Ld - Total number of positive flow field vector in x-direction for left section in previous five image frames

Rd - Total number of negative flow field vector in x-direction for right section in previous five image frames

Ds - Direction of sudden obstacle

dA_n - Scanned distance data at stage (a) of the avoidance operation

dB_n - Scanned distance data at stage (c) of the avoidance operation

dT - Distance value derived by Trigonometry principal

ADS-B - Automatic Dependant Surveillance Broadcast

DOF - Degree of Freedom

DFOV - Diagonal Field of View

EO - Electro optical

FOV - Field of View

FPS Frame per Second

GPS - Global Positioning System

GNSS - Global Navigation Satellite System

IR	-	Infra-Red
KLT		Kanade-Lucas-Tomasi Tracker
LIDAR	-	Light Detection and Ranging
MTOW	-	Maximum take-off weight
MFR	-	Ratio of middle section free region feature points
MOR	-	Ratio of middle section obstacle region feature points
ORP	-	Obstacle reference points
PD		Proportional Derivative Controller
QVGA		Vertical Quarter Video Graphic Array
ROI	-	Region of Interest
SURF	-	Speeded Up Robust Feature
SIFT	-	Scale Invariant Feature Transform
SLAM	-	Simultaneous Localization and Mapping
SFR	-	Ratio of side section free region feature points
SOR	-	Ratio of side section obstacle region feature points
TCAS	-	Traffic Collision Avoidance System
UAV	-	Unmanned Aerial Vehicle
VTOL	-	Vertical Take-off and Landing

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CHAPTER 1

INTRODUCTION

1.1 Background Study

In recent years, the application of Unmanned Aerial Vehicle (UAV) has experienced tremendous growth in the civilian application and it is not merely restricted to the military environment application. As the name implies, UAV is a powered air vehicle that does not require an onboard pilot. It can fly autonomously by pre-programmed the embedded system of the UAV or through manual control by a human pilot on the ground. Generally, there are four main categories of the UAV platform, which are the fixed-wing, single rotor, multi-rotor, and fixed-wing hybrid as illustrated in Figure 1.1.

This categorisation is purely based on the body structure and flying principles of the UAV platform. Each category of the UAV contains its own advantages and disadvantages. For example, fixed-wing UAV has long endurance of flying. Thus, this type of UAV can cover a large area of the environment and is commonly used for aerial mapping activities. However, fixed-wing UAV requires a great space for Take-off and Landing operations. On the other hand, the multi-rotor UAV has short endurance and limited payload capacity compared to the fixed-wing UAV. On the brighter side, this type of UAV is very easy to operate and has good accessibility towards any area in the surrounding environment. In addition, the multi-rotor UAV possess the ability to Vertical Take-off and Landing (VTOL) which theoretically they can take-off and land almost anywhere, making them far more flexible.

The advantages and disadvantages of each category of UAVs are summarised in Table 1.1 (Al-kaff, 2017). Other than categorisation based on the physical structure of the UAV, the simplest way to categorise UAVs is by measuring the overall weight of the UAV (Xiang Yu, 2015) as illustrated in Table 1.2. Blyenburgh (2006) classifies the UAV into more detailed characteristics, which include the Maximum take-off weight (MTOW), flight altitude, endurance and the range that the UAV can fly.

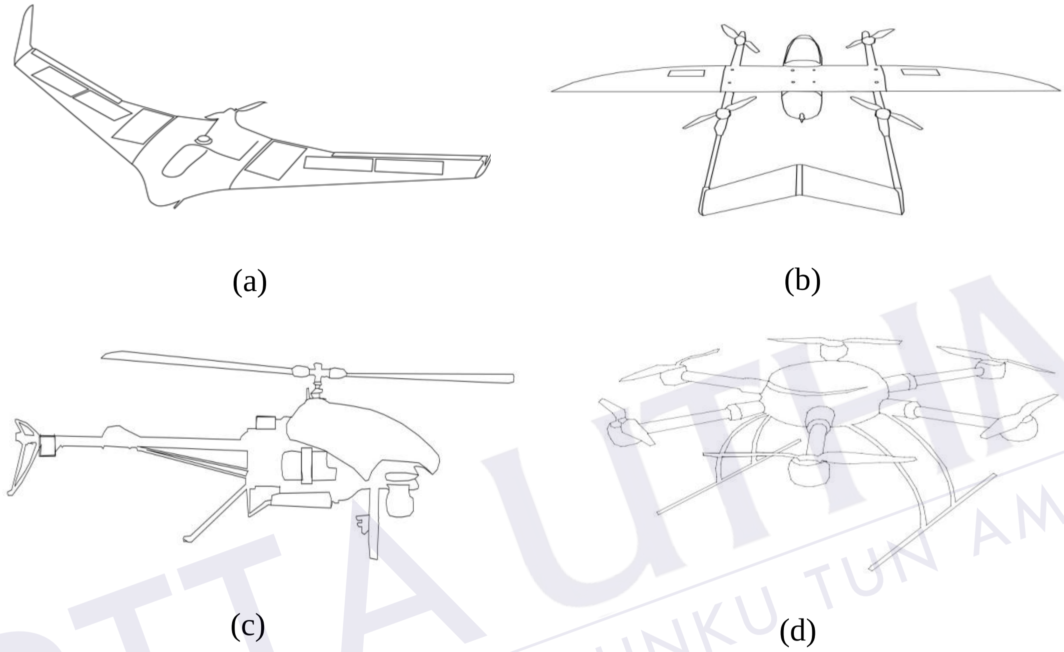

Figure 1.1: Categories of UAVs platform. (a) Fixed wing (b) Hybrid (c) Single rotor (d) Multiple rotor

Table 1.1: Summaries of UAVs capabilities

Category	Advantages	Disadvantages	Operation
Fixed-wing	• Long endurance • Large area coverage • Higher speed	• Require space for take-off and landing • No VTOL and Hover flight • Expensive	• Aerial Mapping • Power line inspection • Agriculture activities
Hybrid	• VTOL • Long endurance	• Not mature yet	• Delivery • Aerial mapping
Single Rotor	• VTOL • Hover flight capability • More payload capability	• Dangerous • Expensive • Require training	• Aerial photography • Surveillance
Multi-Rotor	• Easy to operate • Accessibility • VTOL • Hover flight capability • Stable in attitude	• Short endurances • Limited payload capacity • Small physical size	• Aerial photography • Surveillance • Building inspection

Table 1.2: Classification of UAV by weight

Category	Gross weight (Kg)
Super heavy	≥ 2000
Heavy	200 - 2000
Medium	50 - 200
Light	5 - 50
Micro	≤ 5

Hypothetically, the UAV platform has great potential to perform numerous tasks such as monitoring the environment (Torrero et al., 2014), massive building and structure inspection (Deng, Wang, Huang, Tan, & Liu, 2014; Eschmann, Kuo, & Boller, 2012), search and rescue activities (Scherer et al., 2015; Rudol, Doherty, & Science, 2008; Erdos, Erdos, & Watkins, 2013) and others. Most of these tasks require the UAV to achieve a higher level of autonomy in its embedded system. The critical element in any autonomous system of the UAV platform is the navigation system and its system components. Al-kaff (2017) has stated that the autonomous navigation system will utilises the data or information from the system components to accomplish vital tasks in the autonomous navigation operation. One of the tasks in the autonomous system for the UAV is the operation to identify the appearance of any obstacles that are being introduced to the UAV and ultimately create a manoeuvre action plan or safe avoidance path. The obstacle detection and avoidance operation can be very challenging to the UAV platform, especially for a small-sized UAV. This is due to the payload capacity and physical size constraints of the UAV. Nowadays, the production of the UAV or commercial UAV follows these mentioned constraints, which means that the size of these air vehicles is getting smaller and the weight is getting lighter. As a result, these properties can straightaway lead to the significant limitation of the payload capabilities by the UAV. Therefore, mounting additional sensors to the on-board system of the UAV platform will pose a great and challenging problem to the user.

Typically, the obstacle detection system for UAV depends on the type of sensors being installed onboard the UAV, which is either vision-based sensors or range-based sensors. Selecting the proper sensors to be placed onboard the UAV plays a critical role in the system operation, where each of the aforementioned techniques has its own advantages and disadvantages. For example, the vision-based sensor method can provide rich information regarding the bearing of the detected obstacles in the operating environment. However, the distance from the UAV to obstacles are poorly recognised and estimated. Conversely, range-based sensor is excellent in determining the distance value of the detected obstacle, but there is a lack of information about the location of the detected obstacle in the surrounding environment. Other than the type of sensor used in the system, the obstacle detection techniques used in the obstacle detection and avoidance system will determine the accuracy and reliability of the detection operation. There are many obstacle detection techniques that have been developed by researchers, such as distance threshold value, motion parallax, a perspective cue from an image frame, and more. Section 2 will cover the details about the obstacle detection techniques for the UAV. The work presented in this thesis will focus on the development of obstacle detection and avoidance system for small-sized UAVs, which is still an open problem for the robotics or UAV community.

1.2 Problem Statement

The obstacle detection and avoidance system is regarded as an important element in the autonomous navigation system. It enables the UAV to execute the intended mission safely across the operating environment. However, there are lots of gaps to be filled in this study because most of the previous obstacle detection and avoidance systems developed by researchers still contain weaknesses and disadvantages that can ultimately jeopardise the robustness and reliability of the system. Obstacle detection and avoidance system for the UAV is crucial for all types of environment, which are either in the Global Position System (GPS)-friendly environment or GPS-denied environment. Since most of the commercial UAVs at present are small and miniature in size, the development of the obstacle detection and avoidance system becomes more complicated due to the payload capacity and physical size constraints. As a result, the researchers need to find a balanced line between the performance of the system and the mentioned constraints by the UAV platform.

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VITAE

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