

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

MUHAMMAD FAIZ RAMLI

A thesis submitted in  
fulfilment of the requirement for the award of the  
Doctor of Philosophy

Faculty of Mechanical and Manufacturing Engineering  
Universiti Tun Hussein Onn Malaysia

APRIL 2020

## ACKNOWLEDGEMENT

In the name of Allah, the most Gracious and the most Merciful. Without guidance from Him, I certainly will not be able to complete this thesis. I would like to express my deepest gratitude to my main supervisor Dr. Syariful Syafiq and co-supervisor Assoc. Prof. Dr. Ari Legowo for passing on valuable knowledge about research. It will be a very difficult research journey without them.

Thank you to Ministry of Higher Education (MOHE), Malaysia and Universiti Tun Hussein Onn (UTHM) for providing the scholarship and financial support during my doctoral studies. Special thanks to Fahmi, my research partner for helping me a lot in administration work and it means the world to me.

I would like to convey my gratitude and thanks to my family. They are the ones who always taught me to never give up and be patient in life. Also gratitude and salute to my wife, who always cheers me on and whispers encouraging words during my studies especially in my difficult times. Finally, I would to give love and hugs to my son, who always be the reason for me to wake up and keep working every day. I am now very happy because all hardship I had to go through finally paid off.



## 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 sekeliling yang tidak menyerupai persekitaran sebenar. Sementara itu, kebanyakan 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 boleh 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 halangan 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.

## CONTENTS

<b>TITLE</b>	<b>i</b>
<b>STUDENT’S DECLARATION</b>	<b>ii</b>
<b>ACKNOWLEDGEMENT</b>	<b>iii</b>
<b>ABSTRACT</b>	<b>iv</b>
<b>ABSTRAK</b>	<b>v</b>
<b>LIST OF TABLES</b>	<b>ix</b>
<b>LIST OF FIGURES</b>	<b>x</b>
<b>LIST OF SYMBOLS AND ABBREVIATIONS</b>	<b>xiii</b>
<b>LIST OF APPENDICES</b>	<b>xvi</b>
<b>CHAPTER 1 INTRODUCTION</b>	<b>1</b>
1.1 Background Study	1
1.2 Problem Statement	4
1.3 Objectives	7
1.4 Scope of Study	8
1.5 Significance of Study	9
1.6 Thesis Organisation	10
<b>CHAPTER 2 LITERATURE REVIEW</b>	<b>12</b>
2.1 Introduction	12
2.2 Characteristic of Small-sized UAV	13
2.3 Obstacle Detection and Avoidance System Identification	15
2.4 General Obstacle Detection and Avoidance System Schemes	18
2.4.1 Navigation System Structure	19
2.4.2 Sensing Technologies	21
2.5 Survey of Obstacle Detection and Avoidance System	26

2.5.1 Vision-Based Sensor	26
2.5.2 Range-Based Sensor	36
2.5.3 Multiple Sensors Integration Based	39
2.6 Computer Vision Technique	41
2.6.1 Interest Local Feature Detection	42
2.6.2 Motion Detection	47
2.7 Summary	50
<b>CHAPTER 3 RESEARCH METHODOLOGY</b>	<b>52</b>
3.1 Introduction	52
3.2 UAV Platform	54
3.2.1 AR Drone 2.0 Proposed Configuration	56
3.3 Speeded Up Robust Feature (SURF)	58
3.3.1 Feature Detection	59
3.3.2 Feature Description	63
3.3.3 Feature Matching	65
3.4 Distance Detection	65
3.4.1 Obstacle Distance Detection Process	67
3.5 Image Frame Properties	69
3.5.1 Camera Calibration	69
3.5.2 Image Resolution	76
3.6 Depth Perception Technique	78
3.7 Region Classification	85
3.7.1 Region Detection Operation	88
3.7.2 Safe Avoidance Path Identification	101
3.8 Unexpected Situation	107
3.8.1 Sudden Obstacle Appearance Detection Operation	109
3.9 AR Drone 2.0 Controller	116



3.10 Obstacle Avoidance System Operation	121
3.11 Experiment Setup	128
3.11.1 UAV Operational Framework	131
3.11.2 Scenarios	132
3.12 Summary	136
<b>CHAPTER 4 RESULT AND DISCUSSION</b>	<b>138</b>
4.1 Introduction	138
4.2 Single Obstacle	139
4.3 Multiple Obstacle	145
4.3.1 Side Obstacle Aligned with Frontal Obstacle	146
4.3.2 Side Obstacle 60 cm Away from Frontal Obstacle	152
4.3.3 Side Obstacle 120 cm Away from Frontal Obstacle	158
4.4 Sudden Introduced Obstacle	161
4.5 Research Work Findings	164
4.6 Summary	168
<b>CHAPTER 5 CONCLUSION AND FUTURE WORKS</b>	<b>170</b>
5.1 Thesis Contribution	172
5.2 Future Works	174
<b>REFERENCE</b>	<b>176</b>
<b>APPENDIX</b>	<b>183</b>
<b>PUBLICATIONS</b>	<b>188</b>
<b>VITAE</b>	<b>189</b>



## LIST OF TABLES

1.1	Summaries of UAVs capabilities	2
1.2	Classification of UAV by weight	3
2.1	UAV classification based on weight and range.	13
2.2	Commercial UAV available in global market	14
2.3	Summary of sensing technologies	25
3.1	LIDAR Lite v3 Specification	57
3.2	Additional component on the UAV	58
3.3	Result of the expansion ratio for distorted images	73
3.4	Parameter of the camera sensor	75
3.5	Result of the expansion ratio for undistorted images	76
3.6	Result of scale changes experiment	82
3.7	Image frame division	86
3.8	$dR$ for 30 cm distance separation	87
3.9	Template for $dR$ of 30 cm distance separation	91
3.10	Template for $dR$ of 15 cm distance separation	91
3.11	Result from computation of distance ratio $dRnL15$	92
3.12	Thresholding process for region classification	94
3.13	AR Drone 2.0 Controller gain	120
3.14	Summary of avoidance operation for predictable obstacle appearance situation	127
4.1	Result of feature points detection for single obstacle situation	143
4.2	Result of feature points detection for multiple obstacles situation with aligned side obstacle	149
4.3	Result of feature points detection for multiple obstacles situation with '60 cm' side obstacle	155
4.4	Result of feature point detection for multiple obstacles situation with '120 cm' side obstacle	160



4.5 Result of unpredictable obstacle appearance situation

162



## LIST OF FIGURES

1.1	Categories of UAVs platform. (a) Fixed wing (b) Hybrid (c) Single rotor (d) Multiple rotor	2
2.1	Maximum altitude of UAVs. (Weibel & Hansman, 2004)	14
2.2	Generic process model of collision avoidance system (Lacher <i>et al.</i> , 2007)	15
2.3	Surrounding environment as viewed from the UAV (Albaker & Rahim, 2010)	17
2.4	The structure overview of guidance, navigation and control system for UAV (Kendoul, 2012)	19
2.5	TCAS operation	22
2.6	ADS-B operation	23
2.7	Characteristic of detection by the sensor	25
2.8	Relative size depth cue	27
2.9	Stereo cameras geometry (Adi & Widodo, 2017)	28
2.10	Perspective lines in the indoor environment (Bills <i>et al.</i> , 2011)	29
2.11	Texture variations across images (Croon <i>et al.</i> , 2011)	30
2.12	Size expansion cue. (a) Distance vs Scales. (b) Feature detection previous image. (c) Feature detection current image. (Mori & Scherer, 2013)	31
2.13	Convex shape feature detection. (a) Feature points. (b) Convex hull constructed from feature points. (c) Avoidance path created from tolerance. (Al-Kaff <i>et al.</i> , 2017)	32
2.14	Divergence pattern of the optical flow. (Zufferey & Floreano, 2006)	34
2.15	Distance derivation from the optical flow. (Zingg <i>et al.</i> , 2010)	35
2.16	Obstacle detection and avoidance system and Landing system. (Whalley <i>et al.</i> , 2009)	37

2.17	Threshold value from the range sensor based. (Kim <i>et al.</i> , 2014)	38
2.18	Obstacle distance estimation using sensor fusion. (Rambabu <i>et al.</i> , 2015)	40
2.19	Switching action between two sensors. (Tomi <i>et al.</i> , 2012)	41
2.20	Image pairs with extracted patches. (Szeliski, 2010)	42
2.21	Aperture problem	43
2.22	Fundamental idea of Harris corner detector through shifting the small window	44
2.23	Invariant attributes. (Lowe, 2004)	46
2.24	Motion detection from image frames sequence. (a) First image frame. (b) Second image frame. (c) Displacement vector. (Bors & Pitas, 2000)	48
2.25	Optical flow principal	48
3.1	Framework of the proposed obstacle detection and avoidance system	53
3.2	AR Drone 2.0 Platform	55
3.3	Configuration of the frontal camera sensor	55
3.4	UAV platform configuration. (a) AR Drone 2.0. (b) Lidar Lite v3. (c) Camera sensor. (d) Arduino nano. (e) Xbee Pro s1	56
3.5	Gaussian approximation kernels. Top row: The cropped second order derivatives in the x, y, and xy directions. Bottom row: Box filter approximations in the x, y and xy-directions. Refer them as $D_{xx}$ , $D_{yy}$ , and $D_{xy}$ respectively from left to right. (Evans, 2009)	60
3.6	Integral image operation. (a) Original image. (b) Integral image. (c) Box area region	61
3.7	Scale space function. (Bay <i>et al.</i> , 2006)	62
3.8	Non-maximal suppression	63
3.9	SURF descriptors. (a) Haar wavelets. (b) Square windows around interest points. (c) Sub regions in the square windows. (Evans, 2009)	64
3.10	Feature points matching across image frames	65
3.11	Sensors performance on various situations. (C.Gianni <i>et al.</i> , 2017)	67

3.12	Series of distance detection and image frames captured by the camera sensor	68
3.13	Type of lens distortions from the camera sensor	71
3.14	Ratio of expansion for distorted image frame where left and right pictures represent the distance of the object from the camera sensor which is 150 cm and 120 cm respectively. (a) Object located at the centre of the image. (b) Object located at the edge of the image.	72
3.15	Lens distortion correction principal. (a) Checkerboard pattern as the input image for the lens distortion correction process. (b) Set of test collinear points where $p^n$ represent the points and $d$ represent the error from the estimated straight line.	74
3.16	Ratio of expansion for undistorted image frame where left and right pictures represent the distance of the object from the camera sensor which is 150 cm and 120 cm respectively. (a) Object located on the centre of the image. (b) Object located on the edge of the image.	75
3.17	Image resolution. (a) Original image resolution, $1280 \times 720$ . (b) Proposed image resolution, $640 \times 360$	77
3.18	Distance feature point experiment. (a) Set of feature points distance. (b) Distance ratio cue result	79
3.19	Matched image frames. (a) Image frame 1. (b) Image frame 2. (c) Image frame 3	81
3.20	Scale changes observation. (a) Object captured at 300 cm. (b) Object captured at 180 cm. (c) Object capture at 90 cm	83
3.21	Image frame areas (left, middle, and right)	86
3.22	Overview of the process for region detection operation. (a) Region detection level 1. (b) Region detection level 2. (c) Region detection level 3.	89
3.23	Illustration of detected region in the image frame	94
3.24	Classification of true obstacle region and free region in the image frame	95
3.25	Uncover true identity of the area by changing the reference distance ratio. (a) Reference distance ratio = 1.05.	

	(b) Reference distance ratio = 1.06. (c) Reference distance ratio = 1.07.	98
3.26	Free region feature points combination. (a) Feature points in 15 cm matched image frame. (b) Feature points in 30 cm matched image frame. (c) Combination of feature points from both of matched image frames	100
3.27	Overview of the process for safe avoidance path detection	102
3.28	Cluster the free region feature points. (a) Computed free region feature points. (b) Free region feature points clustering	104
3.29	Isolation technique for the detected feature points. (a) Convex hull is formed from the obstacle region feature points. (b) The free region feature point inside the convex hull is removed.	106
3.30	No intersection between the convex hull and free region feature points.	107
3.31	Framework of sudden obstacle appearance detection operation	110
3.32	Sudden obstacle appearance in front of the UAV. (a) The obstacle stop from moving right after the detection is initiated. (b) The detection is activated before the obstacle is detected by the LIDAR Lite v3. Red arrow indicates the movement of the obstacle throughout the image frame sequence.	111
3.33	Selected ROI in the image frame for sudden appearance of the obstacle situation	112
3.34	Safe avoidance path when encountering the sudden appearance obstacle situation	113
3.35	FOE in the observed environment. (a) UAV moves forward with the object is static in the environment. (b) UAV moves forward with the object moves towards the UAV. (c) Observed FOE	114
3.36	Direction of the optical flows from the selected ROI	115
3.37	AR Drone 2.0 controller channel	116
3.38	AR Drone 2.0 software development kit	117
3.39	AR Drone 2.0 proposed controller system. (a) Forward velocity controller. (b) Lateral velocity controller. (c) Forward position controller. (d) Lateral position controller.	119

3.40	AR Drone 2.0 controller experiments. (a) Result of forward velocity controller. (b) Result of lateral velocity controller. (c) Result of position controller	120
3.41	Obstacle avoidance system operation	122
3.42	Tracking the safe avoidance path feature points by bringing the green feature points towards the centre of the image frame (red box)	124
3.43	Scanning process and view of the threshold value set during avoidance manoeuvre	124
3.44	Stages in the avoidance operation for predictable obstacle appearance situation	127
3.45	Streaming live video from the AR Drone 2.0. (a) Decode by FFmpeg. (b) Transfer the live video into webcam video by using ManyCam. (c) Read in MATLAB through webcam function	129
3.46	Marvelmind sensor configuration. (a) Position of the marvelmind beacons in the experiment room. Green circle and blue circle represent the stationary beacon and mobile beacon respectively. (b) Marvelmind sensor device.	130
3.47	UAV operation during experiments	131
3.48	Obstacles used in the experiment. (a) Obstacle 1(good texture). (b) Obstacle 2 (good texture). (c) Obstacle 3 (poor texture). (d) Obstacle 4 (texture-less)	133
3.49	Scenarios in the performed experiment. (a) Predictable obstacle appearance situation where the yellow box, black box and red box represent the frontal obstacle, side obstacle and fixed obstacle respectively. $d$ is the distance between frontal obstacle and side obstacle (b) Unpredictable obstacle appearance situation	135
4.1	Result of the avoidance path for single obstacle situation. Black box represents frontal obstacle and red boxes represent fixed obstacles (a) Single obstacle Case 1. (b) Single obstacle Case 2. (c) Single obstacle Case 3. (d) Single obstacle Case 4.	141

4.2	Result of the avoidance path for multiple obstacle situation with aligned side obstacle. (a) Side obstacle Case 1. (b) Side obstacle Case 3. (c) Side obstacle Case 4.	148
4.3	Finding the least resistance path for the safe avoidance path. (a) Reference distance ratio is 1.05. (b) Reference distance ratio is 1.03	151
4.4	Different situation in creating the Safe avoidance path. (a) Side obstacle fills up the area in the left side of the image frame. As a result, safe avoidance path is created on the right side. (b) Frontal obstacle detected at the side of the image frame caused by orientation of the camera sensor.	151
4.5	Result of the avoidance path for multiple obstacles situation with side obstacle located 60 cm away from the frontal obstacle. (a) Side obstacle Case 1. (b) Side obstacle Case 3. (c) Side obstacle Case 4.	154
4.6	Safe avoidance path on the same side as the introduced side obstacle. (a) Reference distance ratio is 1.10. (b) Reference distance ratio is 1.06	157
4.7	Result of the avoidance path for multiple obstacles situation with side obstacle located 120 cm away from the frontal obstacle. (a) Side obstacle Case 1. (b) Side obstacle Case 3. (c) Side obstacle Case 4.	159
4.8	Unpredictable obstacle appearance situation. Left figure and right figure represent the actual image frame of the sudden obstacle appearance and flow field vector generated, respectively. (a) Texture-less obstacle appearance. (b) Textured obstacle appearance	163
4.9	Obstacle does not appear in the image frame sequence	164
4.10	Obstacle cannot be detected by the LIDAR Lite v3 due to the narrow beam divergence	168

## 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
$\alpha$	- 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
$L_{xx}(x, \sigma)$	- Convolution of image with second order Gaussian derivative at x-direction
$L_{yy}(x, \sigma)$	- Convolution of image with second order Gaussian derivative at y-direction
$\sigma$	- Scale value of the Gaussian kernel
$D_{xy}, D_{yx},$ $D_{xy}$	- Box filters in SURF method
$k_n$	- Distortion coefficient
$D^{If}$	- Distance between feature points
$fp_n$	- Feature points in respective $n$ image frame



- $mf p_n^{if}$  - Matched feature points from respective  $if$  image frame
- $mf \hat{p}_n^1$  - Filtered matched feature point from image frame 1
- $mf \hat{p}_n^2$  - Filtered matched feature point from image frame 2
- $mf \hat{p}_n^{30}$  - Filtered matched feature point from image frame 3 with 30 cm distance separation
- $mf \hat{p}_n^{15}$  - Filtered matched feature point from image frame 3 with 15 cm distance separation
- $mf \hat{p}_n^{L(if)}$  - Filtered matched feature point of respective  $if$  image frame from left section
- $mf \hat{p}_n^{M(if)}$  - Filtered matched feature point of respective  $if$  image frame from middle section
- $mf \hat{p}_n^{R(if)}$  - 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)
- $mf \hat{p}_n^{Lo(r)}$  - Left section obstacle feature points ( $r = 15$  cm or 30 cm distance separation)
- $mf \hat{p}_n^{Mo(r)}$  - Middle section obstacle feature points ( $r = 15$  cm or 30 cm distance separation)
- $mf \hat{p}_n^{Ro(r)}$  - Right section obstacle feature points ( $r = 15$  cm or 30 cm distance separation)
- $mf \hat{p}_n^{Lf(r)}$  - Left section non-obstacle feature points ( $r = 15$  cm or 30 cm distance separation)
- $mf \hat{p}_n^{Mf(r)}$  - Middle section non-obstacle feature points ( $r = 15$  cm or 30 cm distance separation)
- $mf \hat{p}_n^{Rf(r)}$  - 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



**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Region Detection Operation Algorithm	183
B	Safe Avoidance Path Identification Algorithm	185
C	Sudden Obstacle Appearance Detection Algorithm	186
D	Interface of the FFmpeg Software	187



**PTTA UTHM**  
PERPUSTAKAAN TUNKU TUN AMINAH

## 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.

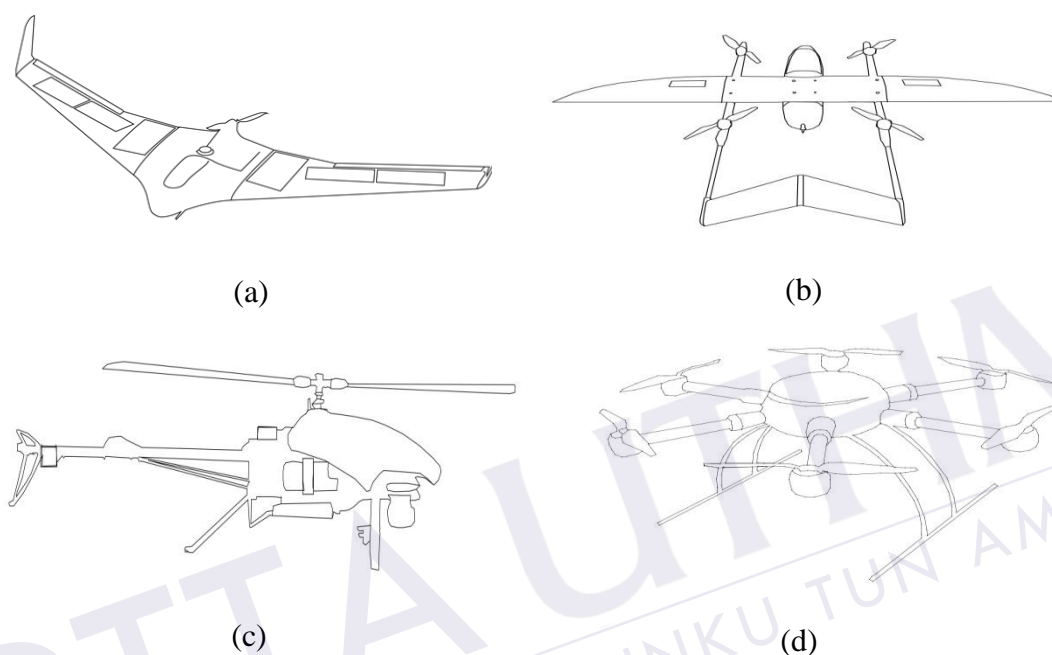


Figure 1.1: Categories of UAVs platform. (a) Fixed wing (b) Hybrid (c) Single rotor (d) Multiple rotor

Table 1.1: Summaries of UAVs capabilities

Category	Advantages	Disadvantages	Operation
<b>Fixed-wing</b>	<ul style="list-style-type: none"> <li>• Long endurance</li> <li>• Large area coverage</li> <li>• Higher speed</li> </ul>	<ul style="list-style-type: none"> <li>• Require space for take-off and landing</li> <li>• No VTOL and Hover flight</li> <li>• Expensive</li> </ul>	<ul style="list-style-type: none"> <li>• Aerial Mapping</li> <li>• Power line inspection</li> <li>• Agriculture activities</li> </ul>
<b>Hybrid</b>	<ul style="list-style-type: none"> <li>• VTOL</li> <li>• Long endurance</li> </ul>	<ul style="list-style-type: none"> <li>• Not mature yet</li> </ul>	<ul style="list-style-type: none"> <li>• Delivery</li> <li>• Aerial mapping</li> </ul>
<b>Single Rotor</b>	<ul style="list-style-type: none"> <li>• VTOL</li> <li>• Hover flight capability</li> <li>• More payload capability</li> </ul>	<ul style="list-style-type: none"> <li>• Dangerous</li> <li>• Expensive</li> <li>• Require training</li> </ul>	<ul style="list-style-type: none"> <li>• Aerial photography</li> <li>• Surveillance</li> </ul>
<b>Multi-Rotor</b>	<ul style="list-style-type: none"> <li>• Easy to operate</li> <li>• Accessibility</li> <li>• VTOL</li> <li>• Hover flight capability</li> <li>• Stable in attitude</li> </ul>	<ul style="list-style-type: none"> <li>• Short endurances</li> <li>• Limited payload capacity</li> <li>• Small physical size</li> </ul>	<ul style="list-style-type: none"> <li>• Aerial photography</li> <li>• Surveillance</li> <li>• Building inspection</li> </ul>

Table 1.2: Classification of UAV by weight

Category	Gross weight (Kg)
Super heavy	$\geq 2000$
Heavy	200 - 2000
Medium	50 - 200
Light	5 - 50
Micro	$\leq 5$

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 utilise 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.



## REFERENCES

- Adi, K., & Widodo, C. E. (2017). Distance measurement with a stereo camera. *International Journal of Innovative Research in Advanced Engineering (IJIRAE)*, 4, pp. 24–27.
- Administration, F. A. (2009). *Risk Managment Handbook*.
- Aguilar, W., Casaliglla, V., & Pólit, J. (2017). Obstacle Avoidance Based-Visual Navigation for Micro Aerial Vehicles. *Electronics*, 6(1), pp. 10.
- Al-Kaff, A., García, F., Martín, D., de la Escalera, A., & Armingol, J. M. (2017). Obstacle detection and avoidance system based on monocular camera and size expansion algorithm for UAVs. *Sensors (Switzerland)*, 17(5), pp. 1061.
- Al-kaff, A. H. (2017). *Vision-Based Navigation System for Unmanned Aerial Vehicles*.
- Albaker, B. M., & Rahim, N. A. (2010). Unmanned Aircraft Collision Detection and Resolution : Concept and Survey. *Industrial Electronics and Applications (ICIEA)*, pp. 248–253.
- Andert, F., Adolf, F., Goormann, L., & Dittrich, J. (2011). Mapping and path planning in complex environments: An obstacle avoidance approach for an unmanned helicopter. *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 745–750.
- Bachrach, A., He, R., & Roy, N. (2009). Autonomous Flight in Unknown Indoor Environments. *International Journal of Micro Air Vehicles*, 1(4), pp. 217–228.
- Badrloo, S., & M, V. (2017). Vision Based Obstacle Detection In UAV Imaging. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 21.
- Baker, S., & Matthews, I. (2004). *Lucas-Kanade 20 Years On : A Unifying Framework*. 56(3), pp. 221–255.
- Bay, H., Tuytelaars, T., & Van Gool, L. (2006). SURF: Speeded up robust features. *In European Conference on Computer Vision*, 404–417.

- Bharathraj, Razeen Ridhwan, Aasish, C. A. (2015). Collision Avoidance System Of An UAV. *International Journal of Application or Innovation in Engineering & Management (IJAIEM)*, 4(2), pp. 20–28.
- Bills, C., Chen, J., & Saxena, A. (2011). *Autonomous MAV Flight in Indoor Environments using Single Image Perspective Cues*. pp. 5776–5783.
- Bin Ramli, M. F., Shamsudin, S. S., & Legowo, A. (2018). Safe avoidance path detection using multi sensor integration for small unmanned aerial vehicle. In *2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 101–106.
- Blyenburgh, P. van. (2006). UAV Systems : Global Review. *Avionics '06 Conference Amsterdam*.
- Boonsuk, W. (2016). Investigating Effects of Stereo Baseline Distance on Accuracy of 3D Projection for Industrial Robotic Applications. *5th IAJC/ISAM Joint International Conference*, pp. 9. Retrieved from
- Bors, A. G., & Pitas, I. (2000). Prediction and Tracking of Moving Objects in Image Sequences. *IEEE Transactions on Image Processing*, 9(8), 1441–1445.
- Bouguet, J.-Y. (2001). *Camera Calibration Toolbox for Matlab*.
- Byrne, J., Cosgrove, M., & Mehra, R. (2006). Stereo based obstacle detection for an unmanned air vehicle. In *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006*, 2830–2835.
- C.Gianni, Balsi, M., Esposito, S., & Fallavollita, P. (2017). Obstacle Detection System Involving Fusion of Multiple Sensor Technologies. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 127.
- Chand, B. N., Mahalakshmi, P., & Naidu, V. P. S. (2017). *Sensors for Sense and Avoid Technology in Miniature Unmanned Aerial Vehicles*. 1(5), pp. 45–55.
- Chandwadkar, R., Dhole, S., Gadewar, V., Raut, D., & Tiwaskar, S. (2013). *Comparison Of Edge Detection Techniques*. (6), pp. 133–136.
- Corral, L., Fronza, I., & Ioini, N. El. (2017). The incorporation of drones as object of study in energy-Aware software engineering. *ICEIS 2017 - Proceedings of the 19th International Conference on Enterprise Information Systems*, 2(Iceis), pp. 721–726.
- Croon, G. C. H. E. De, Weerdt, E. De, Wagter, C. De, Remes, B. D. W., & Ruijsink, R. (2011). The Appearance Variation Cue for obstacle avoidance. *IEEE*

*Transactions on Robotics*, 28(2), pp. 529–534.

- Debevec, P. E. (1996). *Modeling and Rendering Architecture from Photographs*.
- Deng, C., Wang, S., Huang, Z., Tan, Z., & Liu, J. (2014). Unmanned aerial vehicles for power line inspection: A cooperative way in platforms and communications. *Journal of Communications*, 9(9), pp. 687–692.
- Desa, H., & Azfar, A. Z. (2009). Study of inertial measurement unit sensor. *International Conference on ManMachine Systems ICoMMS*, 11–13. Retrieved from
- Dorst, M. (2011). *Distinctive Image Features from Scale-Invariant Keypoints Abstract*.
- Drap, P., & Lefevre, J. (2016). An Exact Formula for Calculating Inverse Radial Lens Distortions. *Sensor*, (1), pp. 1–18.
- Erdos, D., Erdos, A., & Watkins, S. E. (2013). An experimental UAV system for search and rescue challenge. *IEEE Aerospace and Electronic Systems Magazine*, 28(5), pp. 32–37.
- Eschmann, C., Kuo, C.-M., & Boller, C. (2012). Unmanned Aircraft Systems for Remote Building Inspection and Monitoring. *Proceedings of the 6th European Workshop on Structural Health Monitoring*, 2, pp. 1–8.
- Evans, C. (2009). *Notes on the OpenSURF Library*.
- Fetić, A., & Jurić, D. (2012). The procedure of a camera calibration using Camera Calibration Toolbox for MATLAB. *Proceedings of the 35th International Convention MIPRO*, 1752–1757.
- Gageik, N., Benz, P., & Montenegro, S. (2015). Obstacle detection and collision avoidance for a UAV with complementary low-cost sensors. *IEEE Access*, 3, pp. 599–609.
- Gageik, N., Müller, T., & Montenegro, S. (2012). Obstacle Detection and Collision Avoidance Using Ultrasonic Distance Sensors for an Autonomous Quadcopter. *International Journal of Engineering Trends and Technology*, 17(2), pp. 1–6.
- Green, B. Y. W. E., & Oh, P. Y. (2008). Optic-Flow-Based Collision Avoidance. *IEEE Robotics & Automation Magazine*, pp. 96–103.
- Greenfield, J. S. (1990). *A Proof for a QuickHull Algorithm A Proof for a QuickHull Algorithm*.
- Gupta, N., Singh Makkar, J., & Pandey, P. (2015). Obstacle detection and collision

- avoidance using ultrasonic sensors for RC multirotors. *2015 International Conference on Signal Processing and Communication (ICSC)*, pp. 419–423.
- Habsi, S. Al, Shehada, M., Abdoon, M., Mashood, A., & Noura, H. (2015). Integration of a Vicon Camera System for Indoor Flight of a Parrot AR Drone. *10th International Symposium on Mechatronics and Its Applications (ISMA)*, 1–6.
- Harris, C., & Stephens, M. (1988). A Combined Corner and Edge Detector. *In Alvey Vision Conference*.
- Horn, B. K. P., & Schunck, B. G. (1981). Determining Optical Flow. *Artificial Intelligence*, 17, pp. 185–203.
- Hrabar, S. (2008). 3D path planning and stereo-based obstacle avoidance for rotorcraft UAVs. *In 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 807–814.
- Juan, L., & Gwun, O. (2009). A comparison of sift, pca-sift and surf. *International Journal of Image Processing (IJIP)*, 3(4), pp. 143–152.
- Kendoul, F. (2012). Survey of Advances in Guidance , Navigation , and Control of Unmanned Rotorcraft Systems. *Journal of Field Robotics*, 29(2), pp. 315–378.
- Kim, J., Song, S., Kim, S., & Suk, J. (2014). Collision Avoidance System for Agricultural Unmanned Helicopter using LIDAR Sensor. *Asia-Pacific International Symposium on Aerospace Technology*.
- Krajnik, T., Vonasek, V., Fiser, D., & Faigl, J. (2011). AR-Drone as a Platform for Robotic Research and Education. *International Conference on Research and Education in Robotics*, 172–186.
- Lacher, A. R., Maroney, D. R., & Zeitlin, A. D. (2007). Unmanned Aircraft Collision Avoidance Technology and Evaluation Methods. *FAA EUROCONTROL ATM R&D Symposium*, pp. 1–10.
- Likas, A., Vlassis, N., & Verbeek, J. (2003). The global k-means clustering algorithm. *Pattern Recognition*, 36(2), pp. 451–461.
- Lobry, S. (2012). *Improving Horn-Schunck*.
- Lowe, D. G. (2004). Distinctive Image Features from Scale-Invariant Keypoints. *International Journal of Computer Vision*, pp. 1–28.
- Lu, Y., Xue, Z., Xia, G., & Zhang, L. (2018). Geo-spatial Information Science A survey on vision-based UAV navigation. *Geo-Spatial Information Science*, 5020, pp. 1–12.

- Mahjri, I., Dhraief, A., & Belghith, A. (2015). A Review on Collision Avoidance Systems. *In International Workshop on Communication Technologies for Vehicles*, pp. 203–214.
- Majumder, S., Shankar, R., & Prasad, M. S. (2015). Obstacle size and proximity detection using stereo images for agile aerial robots. *2nd International Conference on Signal Processing and Integrated Networks, SPIN 2015*, pp. 437–442.
- Marvelmind. (2018). *Hardware interface and protocol of data exchange with mobile beacon via USB , UART and SPI interfaces .*
- Mori, T., & Scherer, S. (2013). First results in detecting and avoiding frontal obstacles from a monocular camera for micro unmanned aerial vehicles. *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 1750–1757.
- Murugan, S. (2010). TCAS Functioning and Enhancements. *International Journal of Computer Applications*, 1(8), pp. 46–50.
- Oyallon, E., & Rabin, J. (2015). An Analysis of the SURF Method. *Image Processing On Line*, 5(2004), pp. 176–218.
- Park, J., Byun, S., & Lee, B. (2015). Lens Distortion Correction Using Ideal Image Coordinates. *IEEE Transactions on Consumer Electronics*, 55(3)(2009), pp. 987–991.
- Patel, D., & Saurabh, U. (2013). Optical Flow Measurement using Lucas kanade Method. *International Journal of Computer Applications*, 61(10), pp. 6–10.
- Pedersen, J. T. (2011). *Study group SURF : Feature detection & description*.
- Petrou, M., & Bosdognianni, P. (2010). *Image Processing: the fundamentals*. John Wiley & Sons.
- Pham, H., Smolka, S. A., Stoller, S. D., Phan, D., & Yang, J. (2015). A survey on unmanned aerial vehicle collision avoidance systems. *ArXiv Preprint ArXiv*.
- Prayitno, A., Indrawati, V., & Utomo, G. (2014). *Trajectory Tracking of AR . Drone Quadrotor Using Fuzzy Logic Controller*. 12(4), pp. 819–828.
- Radke, R. J. (2013). *Computer Vision for Visual Effects*.
- Rahman, M. F., & Sasongko, R. A. (2018). Obstacle Avoidance for Quadcopter using Ultrasonic Sensor. *Journal of Physics: Conference Series*, 1005.
- Rambabu, R., Bahiki, M. R., & Azrad, S. (2015). Multi-sensor fusion based UAV collision avoidance system. *Jurnal Teknologi*, 76(8), pp. 89–93.

- Rudol, P., Doherty, P., & Science, I. (2008). Human Body Detection and Geolocalization for UAV Search and Rescue Missions Using Color and Thermal Imagery. *IEEE Aerospace Conference*, 1–8.
- S, A., Kaleemuddin S, M., Bose, D., & Ramachandran, K. I. (2016). Performance comparison of Infrared and Ultrasonic sensors for obstacles of different materials in vehicle / robot navigation applications. *IOP Conference Series: Materials Science and Engineering*, Vol. 149.
- Sabikan, S., Nawawi, S. W., & Sudin, S. (2017). A survey of onboard sensors for quadrotor's collision avoidance. *Journal of Engineering and Applied Sciences*, 12(16), pp. 4138–4143.
- Saxena, A., Chung, S. H., & Andrew Y. Ng. (2008). 3-D Depth Reconstruction from a Single Still Image. *International Journal of Computer Vision*, 76(1), pp. 53–69.
- Saxena, A., Jamie, S., & Ng, A. Y. (2007). Depth estimation using monocular and stereo cues. *IJCAI International Joint Conference on Artificial Intelligence*, pp. 2197–2203.
- Scherer, J., Rinner, B., Yahyanejad, S., Hayat, S., Yanmaz, E., Andre, T., ... Hellwagner, H. (2015). An Autonomous Multi-UAV System for Search and Rescue. *Proceedings of the First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use - DroNet '15*, pp. 33–38.
- Šilar, Z., & Dobrovolný, M. (2011). Comparison of two optical flow estimation methods using Matlab. *International Conference on Applied Electronics*, (1), pp. 1–4.
- Singhal, G., Bansod, B., & Mathew, L. (2018). Unmanned Aerial Vehicle classification , Applications and challenges : A Review. *Preprint*, (November).
- Srinivasan, M. V, Zhang, S. W., Lehrer, M., & Collett, T. S. (1996). Honeybee Navigation En Route To The Goal: Visual Flight Control And Odometry. *Journal of Experimental Biology*, 199(1), pp. 237–244.
- Szeliski, R. (2010). *Computer Vision : Algorithms and Applications*.
- Thompson, S. D., & Sinclair, K. A. (2008). Automatic Dependent Surveillance – Broadcast in the Gulf of Mexico. *Lincoln Laboratory Journal*, 17(2), pp. 1–15.
- Thota, S. D., Vemulapalli, K. S., Chintalapati, K., & Srinivas, P. S. (2013). *Comparison Between The Optical Flow Computational Techniques*. 4(10), pp. 4507–4511.

- Tomi, B. T., Kassecker, M., Schmid, K., Lutz, P., Mair, E., Grixia, I. L., ... Burschka, D. (2012). Research Platform for Indoor and Outdoor Urban Search and Rescue. *Robotics and Automation Magazine*.
- Torrero, L., Molino, A., Spa, T. E., Giordan, D., National, I., & Manconi, A. (2014). The Use of Micro-UAV to Monitor Active Landslide Scenarios. *Engineering Geology for Society and Territory - Volume 5.*, (September), 701–704.
- Tuytelaars, T., & Mikolajczyk, K. (2008). *Local Invariant Feature Detectors : A Survey*. 3(3), pp. 177–280.
- Weibel, R. E., & Hansman, R. J. (2004). Safety considerations for operation of different classes of UAVs in the NAS. In *AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum*, 1(September), 6244.
- Whalley, M., Takahashi, M., Schulein, G. J., & Goerzen, C. (2009). Field-testing of a helicopter UAV obstacle field navigation and landing system. *65th Annual Forum of the American Helicopter Society, Grapevine, TX*. Retrieved from
- Wijesinghe, A. (2016). *Speed up Robust Features in Computer Vision Systems Literature Survey*.
- Williamson, T., & Spencer, N. A. (1989). Development and Operation of the Traffic Alert and Collision Avoidance System (TCAS). *Proceedings of the IEEE*, 77(11), pp. 1735–1744.
- Xiang Yu, Y. Z. (2015). Sense and avoid technologies with applications to unmanned aircraft systems: Review and prospects. *Progress in Aerospace Sciences*, (April), pp. 152–166.
- Yoo, D., Won, D., & Tahk, M. (2011). Optical Flow Based Collision Avoidance of Multi-Rotor UAVs in Urban Environments. *International Journal of Aeronautical and Space Sciences*, 12(3), pp. 252–259.
- Zhang, Z. (2008). *A Flexible New Technique for Camera Calibration* (Vol. 1998).
- Zhang, Z., & Way, O. M. (1999). Flexible Camera Calibration By Viewing a Plane From Unknown Orientations. *Iccv*, 99, pp. 666–673.
- Zingg, S., Scaramuzza, D., Weiss, S., & Siegwart, R. (2010). MAV navigation through indoor corridors using optical flow. *Proceedings - IEEE International Conference on Robotics and Automation*, 3361–3368.
- Zufferey, J. C., & Floreano, D. (2006). Fly-inspired visual steering of an ultralight indoor aircraft. *IEEE Transactions on Robotics*, 22(1), pp. 137–146.

## PUBLICATIONS

- 1 Ramli, M. F. B., Legowo, A., & Shamsudin, S. S. (2017, March). Development of Sense and Avoid system based on multi sensor integration for unmanned vehicle system. In *IOP Conference Series: Materials Science and Engineering* (Vol. 184, No. 1, p. 012006). IOP Publishing.
- 2 Ramli, M. F. B., Legowo, A., & Shamsudin, S. S. (2017, November). Object Detection Technique for Small Unmanned Aerial Vehicle. In *IOP Conference Series: Materials Science and Engineering* (Vol. 260, No. 1, p. 012040). IOP Publishing.
- 3 Ramli, M. F. B., Shamsudin, S. S., & Legowo, A. (2017). Obstacle Detection Technique Using Multi Sensor Integration for Small Unmanned Aerial Vehicle. *Indonesian Journal of Electrical Engineering and Computer Science*, 8(2), 441-449.
- 4 Ramli, M. F. B., Shamsudin, S. S., & Legowo, A. (2018, June). Safe avoidance path detection using multi sensor integration for small Unmanned Aerial Vehicle. In *2018 5th IEEE International Workshop on Metrology for AeroSpace Rome, Italy (MetroAeroSpace)* (pp. 101-106). IEEE.



## VITAE

The author, Muhammad Faiz Bin Ramli was born in Kajang, Malaysia on February 2<sup>nd</sup>, 1989. He went to Technical Institute of Kuala Lumpur for his secondary school in 2005. He then completed his Bachelor Degree (Hons) in Aircraft Maintenance Engineering in 2012 before pursuing his Masters of Science in Aerospace Mechanics and Avionics at Institut Supérieur de l'aéronautique et de l'espace (ISAE) in Toulouse, France. He then joined the industry as an Aerospace Engineer focusing on military aircraft structural integrity for 2 years.

