DATA-DRIVEN TIME-TO-COLLISION MODEL FOR UNMANNED AERIAL VEHICLE CONTROL SYSTEM UNDER VARIOUS PAYLOAD AND SPEED CONDITIONS

SULAIMAN BIN SABIKAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2023

DEDICATION

To my father, wife and children
Sabikan bin Wagio
Hirne binti Saris
Syafiqah Hanan binti Sulaiman
Faizul Imaran bin Sulaiman
Sakinah Maisarah binti Sulaiman
Syifa Irdina binti Sulaiman

"Thank you for your patience and support"

ACKNOWLEDGMENT

In the name of Allah, the Beneficent, the Merciful. Praise Allah, the Almighty, on whom ultimately, we depend for sustenance and guidance. That is my first. Secondly, I wish to express my warmest gratitude to my supervisor, Dr. Sophan Wahyudi Nawawi, and my external co-supervisors, Dr. Nor Azlina Bt. Ab. Aziz for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study. Working with and learning something valuable from these amazing people has been a great honour. I am greatly indebted to the Government of Malaysia and Universiti Teknikal Malaysia Melaka (UTeM) for giving me the opportunity and financial support to pursue my doctoral study. I would like to thank ALL my family for supporting me spiritually throughout writing this thesis and my my life in general. Last, but certainly not least, I am indebted to the Universiti Teknikal Malaysia Melaka (UTeM) and the Ministry of Higher Education (MOHE) for their financial support and the opportunity to embark on my research journey.

ABSTRACT

Time-to-collision (TTC) can be defined as the time required for vehicles to collide with another vehicle or static obstacle if they continue at their present speed and on the same path. Hence, the mathematical model of TTC is useful to assist the collision avoidance system (CAS) in any type of autonomous vehicle. This thesis, presents the data-driven TTC model for unmanned aerial vehicles (UAV) control systems under various payloads and speeds condition. The research consists of three phases. The first phase involved the design and development of a data logging system in the multirotor UAV platform. The data acquisition process for model development requires a UAV system, which consists of the quadrotor vehicle structure, onboard flight mission controller and a ground control system. The open sources platform UAV system development and Proportional–Integral–Derivative (PID) controller used for position, altitude and attitude control have been implemented. Experiments are conducted to collect the required flight data in an uncontrolled environment using a developed platform that has been recognized for its performance. In the second phase involved modelling TTC. Controller time stamps, radio control signal magnitude, global positioning system platform and speed parameters are recorded from different payloads, ranging from 0g to 200g. A data filtering algorithm was applied to eliminate data that does not meet the specified minimum horizontal speed. Particles Swarm Optimization (PSO) algorithm was used for optimizing the model and validating with the real data from the experiment. The collected onboard real experimental data for five different payloads have been analysed to develop a mathematical model of TTC through the PSO approach. Based on the experimental data, the fitness function relationship is considered to solve optimization between speed (m/s), payload (g) and their time-to-collision (s). The TTC model predicts the time required for the collision with a static obstacle based on its current flight parameters, such as speed and payload. Finally, the third phase involved the evaluation of the UAV control system with the TTC model throughout the simulation. The TTC model has been implemented in the UAV's PID controller. Parameters such as initial speed, activation obstacle distances and final distance are introduced in the discussion of this thesis. Based on the workspace simulation environment that has been designed, the TTC model is applied to show the proposed speed based on the UAV's current speed. The activation obstacle distance obtained is a minimum of 5 metres with an initial speed of 2.0 m/s and the proposed speed will be given by the model, continuously. The distance between the obstacle and the reaching point is influenced by the payload. The distance without load is 2.589 metres, and the distance with a 200g load is 1.989 metres, both of which are safer than the specified final distance of 1 metre before a collision. In conclusion, the proposed TTC model has successfully determined the optimal proposed speed based on their current flight parameters under various payload and speed hence, it can be used as a risk assessment metric in UAV's CAS.

ABSTRAK

Masa-untuk-perlanggaran (TTC) boleh ditakrifkan sebagai masa yang diperlukan untuk kenderaan berlanggar dengan kenderaan lain atau halangan statik jika ia meneruskan pada kelajuan sekarang dan di laluan yang sama. Oleh itu, model matematik TTC berguna untuk membantu sistem mengelakkan perlanggaran (CAS) dalam mana-mana jenis kenderaan autonomi. Tesis ini membentangkan model TTC dipacu data untuk sistem kawalan kenderaan udara tanpa pemandu (UAV) di bawah pelbagai muatan dan keadaan kelajuan. Penyelidikan ini direka bentuk untuk terdiri daripada tiga fasa. Fasa pertama melibatkan reka bentuk dan pembangunan sistem pengelogan data dalam platform UAV multirotor. Proses pemerolehan data untuk pembangunan model memerlukan sistem UAV, yang terdiri daripada struktur kenderaan quadrotor, pengawal misi penerbangan atas kapal dan sistem kawalan darat. Pembangunan sistem UAV platform sumber terbuka dan pengawal Proportional–Integral–Derivative (PID) yang digunakan untuk kawalan kedudukan, ketinggian dan sudut telah dilaksanakan. Eksperimen telah dijalankan untuk mengumpul data penerbangan yang diperlukan dalam persekitaran yang tidak terkawal menggunakan platform yang dibangunkan yang telah diiktiraf prestasinya. Fasa kedua melibatkan pemodelan TTC. Setem masa pengawal, magnitud isyarat kawalan radio, sistem kedudukan global platform dan parameter kelajuan direkodkan daripada muatan yang berbeza, antara 0g hingga 200g. Algoritma penapisan data telah digunakan untuk menghapuskan data yang tidak memenuhi kelajuan mendatar minimum yang ditetapkan. Algoritma Pengoptimuman Kerumun Zarah (PSO) digunakan untuk mengoptimumkan model dan mengesahkan dengan data sebenar daripada eksperimen. Data sebenar eksperimen atas kapal yang dikumpul untuk lima muatan berbeza telah dianalisis untuk membangunkan model matematik TTC melalui pendekatan PSO. Berdasarkan data eksperimen, perhubungan fungsi kecergasan dipertimbangkan untuk menyelesaikan pengoptimuman antara kelajuan (m/s), muatan (g) dan masa-untuk-perlanggaran (s). Model TTC meramalkan masa yang diperlukan untuk perlanggaran dengan halangan statik berdasarkan parameter penerbangan semasanya, seperti kelajuan dan muatan. Akhir sekali, fasa ketiga melibatkan penilaian sistem kawalan UAV dengan model TTC sepanjang simulasi. Model TTC telah dilaksanakan dalam pengawal PID UAV. Parameter seperti kelajuan awal, jarak halangan pengaktifan dan jarak akhir telah diperkenalkan dalam perbincangan tesis ini. Berdasarkan persekitaran simulasi ruang kerja yang telah direka bentuk, model TTC digunakan untuk menunjukkan kelajuan yang dicadangkan berdasarkan kelajuan semasa UAV. Jarak halangan pengaktifan yang diperoleh adalah minimum 5 meter dengan kelajuan awal 2.0 m/s dan dan kelajuan yang dicadangkan akan diberikan oleh model, secara berterusan. Jarak antara halangan dan titik capai dipengaruhi oleh muatan. Jarak tanpa beban ialah 2.589 meter, dan jarak dengan beban 200 g ialah 1.989 meter, kedua-duanya lebih selamat daripada jarak akhir yang ditetapkan iaitu 1 meter sebelum perlanggaran. Sebagai kesimpulan, model TTC yang dicadangkan telah berjaya menentukan nilai optimum kelajuan yang dicadangkan berdasarkan parameter penerbangan semasa mereka di bawah pelbagai muatan dan kelajuan, oleh itu, ia boleh digunakan sebagai metrik penilaian risiko dalam CAS UAV.

TABLE OF CONTENTS

	TITLE	PAGE
DECLARATION		**iii**
DEDICATION		**iv**
ACKNOWLEDGMENT		**v**
ABSTRACT		**vi**
ABSTRAK		**vii**
TABLE OF CONTENTS		**viii**
LIST OF TABLES		**xi**
LIST OF FIGURES		**xii**
LIST OF ABBREVIATIONS		**xvi**
LIST OF SYMBOLS		**xvii**
LIST OF APPENDICES		**xviii**
CHAPTER 1	**INTRODUCTION**	**1**
1.1	Background of the Research	1
1.2	Motivation	2
1.3	Problem Statement	4
1.4	Research Objective	5
1.5	Scope of the Research	5
1.6	Contributions of Research Work	6
1.7	Thesis Organization	7
CHAPTER 2	**LITERATURE REVIEW**	**9**
2.1	Overview	9
2.2	Unmanned Aerial Vehicle Development	9
2.3	Collision Avoidance Control Strategy	11
2.4	Data-Driven Time-to-Collision Modelling	12
2.5	Time-to-Collision Model Optimization and Validation	17
2.6	Previous Research Work	19

	2.7	Summary	22
CHAPTER 3		**RESEARCH METHODOLOGY**	**25**
	3.1	Overview	25
	3.2	Phase 1: Development of UAV System	28
		3.2.1 Quadrotor Testbed Design and Development	28
	3.3	Phase 2: Data-driven Modelling of Time-to-Collision Using Particle Swarm Optimization	31
		3.3.1 Experimental Design and Data Collection	33
		3.3.2 Estimation of TTC using PSO Algorithm	37
		3.3.3 Model Validation	40
	3.4	Phase 3 : UAV Control System With TTC Model	40
		3.4.1 Quadrotor Modelling and Parameter Identification	40
		3.4.2 Stabilization Controller of Quadrotor	43
		3.4.3 Collision Avoidance Controller	45
		3.4.4 Collision Avoidance Controller with TTC Model	45
		3.4.5 Quadrotor Simulation	47
		3.4.6 Controller Algorithm with TTC Model	52
	3.5	Summary	55
CHAPTER 4		**RESULTS AND DISCUSSION**	**57**
	4.1	Overview	57
	4.2	Phase 1: Result of Development of UAV System	57
	4.3	Phase 2: Results of Modelling of Time-To-Collision Using Particle Swarm Optimization	60
		4.3.1 TTC Modelling	60
		4.3.2 Model Estimation	61
		4.3.3 Model Optimization	63
		4.3.4 Model Validation	72
	4.4	Phase 3: Result of UAV Real-Time Control System With TTC Model	75
		4.4.1 Mathematical Model of TTC	75
		4.4.2 TTC Controller Inputs	79

4.4.3 TTC Controller Outputs 79

4.4.4 Simulation Results of TTC Controller 80

4.4.5 Simulation of UAV Real-Time Control System with TTC Model for Obstacle Avoidance 89

4.5 Summary 103

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 105

5.1 Conclusion of Study 105

5.2 Summary of Original Contribution 107

5.3 Recommendation for Future Research 108

REFERENCES 109

LIST OF PUBLICATIONS 132

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 3.1	List of physical parameter of quadrotor	42
Table 3.2	The list and description of quadrotor physical model parameters	49
Table 4.1	Quadrotor test bed specification	59
Table 4.2	Data collection condition and setting	61
Table 4.3	Experiment setting	64
Table 4.4	Results of TTC coefficients	64
Table 4.5	Model Optimization for MSE and TTC model coefficients	71
Table 4.6	Model validation fitness error with different data size	74
Table 4.7	Activation obstacle distance and Initial Speed summary	84
Table 4.8	Reaching point with 0 ~ 200 gram payload	86

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Quadrotor testbed development approach	10
Figure 2.2	Vehicle latency and time to collision definition illustration	16
Figure 3.1	Flow chart of the research methodology	27
Figure 3.2	Flow of DDM – TTC modelling	32
Figure 3.3	TTC definition for quadrotor platform	33
Figure 3.4	RCIN signal and GPS speed to identify the t_{lb} parameter	35
Figure 3.5	Data Filtering Flow Chat	36
Figure 3.6	Flowchart of a PSO algorithm	39
Figure 3.7	Coordinate frames and force diagram of quadrotor	42
Figure 3.8	The structure of stabilization controller for quadrotor	44
Figure 3.9	The concept of collision avoidance controller	45
Figure 3.10	The block diagram of TTC Controller	47
Figure 3.11	The complete Simulink for PID quadrotor controller with position control	48
Figure 3.12	The position controller simulation block	51
Figure 3.13	Waypoints coordinates with 5 points and with 3 obstacles for position controller	51
Figure 3.14	TTC controller algorithm with TTC model algorithm flowchart	53
Figure 3.15	TTC model algorithm	54
Figure 3.16	The physical responses of the quadrotor	55
Figure 4.1	Configuration of an autonomous quadrotor test bed	58
Figure 4.2	Quadrotor testbed	60
Figure 4.3	Prove of linear relationship of five different payloads, speed and TTC	62
Figure 4.4	Data distribution plot of Speed vs TTC for different payload	62

Figure 4.5 Result of MSE vs Iteration using 70% data from each weight load 65

Figure 4.6 Result of TTC vs Speed using 70% data from each weight load 65

Figure 4.7 Result of MSE vs Iteration using 80% data from each weight load 66

Figure 4.8 Result of TTC vs Speed using 80% data from each weight load 67

Figure 4.9 Result of MSE vs Iteration using 90% data from each weight load 68

Figure 4.10 Result of TTC vs Speed using 90% data from each weight load 68

Figure 4.11 Result of MSE vs Iteration using 100% data from each weight load 69

Figure 4.12 Result of TTC vs Speed using 100% data from each weight load 69

Figure 4.13 The best MSE vs % of data used for modelling 71

Figure 4.14 Validation Fitness Error with different data size (70% to 100%) 75

Figure 4.15 Proposed Speed and Current Speed vs Obstacle Distance at 8 m/s initial speed and 0 gram payload 81

Figure 4.16 Proposed Speed and Current Speed vs Obstacle Distance at 9 m/s initial speed and 0 gram payload 82

Figure 4.17 Proposed Speed and Current Speed vs Obstacle Distance at 9 m/s initial speed ,0 gram payload and 30 meter activation obstacle distance 82

Figure 4.18 Proposed Speed and Current Speed vs Obstacle Distance at 2 m/s initial speed , 0 gram payload and 5 meter activation obstacle distance 83

Figure 4.19 The various payloads simulation results, 8 m/s initial speed,0 gram to 200 gram of payload and 5 meters activation obstacle distance 85

Figure 4.20 Trend line of reaching point for the payload increase 87

Figure 4.21 TTC model reaching point for 500 gram and 2000 gram payload, 8 m/s initial speed, and 5 meter activation obstacle distance 87

Figure 4.22	The reaching point at 2 meter and 0.5 meter final distance between quadrotor and obstacle, 8 m/s initial speed, 0 gram payload and 16 meter activation obstacle distance	88
Figure 4.23	***Obs_1*** location between $\boldsymbol{WP_2}$ and $\boldsymbol{WP_3}$	90
Figure 4.24	Waypoints arrangement, coordinates and their distance	91
Figure 4.25	Example of path trajectory generation between $\boldsymbol{WP_2}$ and $\boldsymbol{WP_3}$	92
Figure 4.26	3D flight mission trajectory without obstacles	93
Figure 4.27	The X, Y and Z flight mission coordinates without obstacles	93
Figure 4.28	Stabilization of quadrotor for flight mission 1	94
Figure 4.29	3D flight mission trajectory with obstacles between $\boldsymbol{WP_2}$ and $\boldsymbol{WP_3}$, simulation parameter are; ***sp*** = 3 m/s, ***w*** =0 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	95
Figure 4.30	Stabilization of quadrotor for flight mission 2, simulation parameter are; ***sp*** = 3 m/s, ***w*** =0 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	95
Figure 4.31	Flight mission 2 coordinates and stop at ***obs_1,*** simulation parameter are; ***sp*** = 3 m/s, ***w*** =0 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	96
Figure 4.32	3D flight mission trajectory, stabilization and XYZ coordinates for flight mission 2 and stop at ***obs_1,*** simulation parameter ; ***sp*** = 3 m/s, ***w*** =200 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	97
Figure 4.33	3D flight mission trajectory, stabilization and XYZ coordinates for flight mission 2 and stop at ***obs_1,*** simulation parameter ; ***sp*** = 5 m/s, ***w*** =200 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	98
Figure 4.34	3D flight mission trajectory, stabilization and XYZ coordinates for flight mission 2 and stop at ***obs_1,*** simulation parameter ; ***sp*** = 7 m/s, ***w*** =200 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	99
Figure 4.35	3D flight mission trajectory, stabilization and XYZ coordinates for flight mission 2 and stop at ***obs_1,*** simulation parameter ; ***sp*** = 9 m/s, ***w*** =200 gram, ***obs_d*** = 16 meter and ***min_d*** = 1 meter	100
Figure 4.36	Fail to reach reaching point with simulation parameter ***sp*** = 9 m/s	100

Figure 4.37 3D flight mission trajectory with obstacles between ***WP_2*** and ***WP_3*** without TTC controller and ***min_d*** = 1 meter 101

Figure 4.38 Stabilization of quadrotor for flight mission 3 without TTC controller 101

Figure 4.39 Flight mission 3 coordinates and stop at 1 meter from ***obs_1,*** without TTC controller 102

Figure 4.40 Comparison on the flight mission 3 coordinates and stop at 1 meter from ***obs_1,*** with and without TTC controller 103

LIST OF ABBREVIATIONS

CAS	-	Collision Avoidance System
DDM	-	Data-Driven Modelling
DR	-	Deceleration Rate
ET	-	Encroachment Time
EW	-	Empty Weight
GCS	-	Ground Control System
GPS	-	Global Positioning System
GT	-	Gap Time
IAPT	-	Initially Attempted Post-Encroachment Time
LQR	-	Linear Quadratic Regulators
MSE	-	Mean Square Error
MTOW	-	Maximum Take-Off Weight
OPS	-	Open-source Project
PET	-	Post-Encroachment Time
PID	-	Proportional–Integral–Derivative
PPM	-	Pulse Position Modulation
PSD	-	Proportion of Stopping Distance
PSO	-	Particles Swarm Optimization
RC	-	Radio Control
TTC	-	Time to Collision
UA	-	Unmanned Aircraft
UAS	-	Unmanned Aircraft (or Aerial) Systems
UAV	-	Unmanned Aerial Vehicle
USB	-	Universal Serial Bus
CAS	-	Collision Avoidance System

LIST OF SYMBOLS

V_b	-	Current quadrotor horizontal speed
V_f	-	Stop speed or hovering
v_{iw}	-	Average speed of wind
w_{io}	-	Quadcopter payload
t_{lb}	-	Time required for the quadrotor to hover
TTC_s	-	Time to collision from the TTC model
v_i^k	-	Particle velocities vector
x_i^k	-	Positions vector
TTC_d	-	Time to collision from the experiments
p_1	-	TTC mathematical model coefficients 1
p_2	-	TTC mathematical model coefficients 2
p_3	-	TTC mathematical model coefficients 3
p_4	-	TTC mathematical model coefficients 4
s	-	Horizontal speed of vehicle, m/s
w	-	UAV payload, grams
sp	-	Initial speed of quadrotor
WP	-	Flight waypoints
X_{in} Y_{in} Z_{in}	-	Quadrotor model and position timeseries
obs_d	-	TTC controller activation distances
min_d	-	Final distance between quadrotor and obstacle
current_speed	-	Real-time speed of quadrotor
proposed_speed	-	Proposed speed for the quadrotor controller

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
Appendix A	The State Equations Matlab Program Code	117
Appendix B	TTC Model Algorithm MATLAB Program Code	126
Appendix C	Attitude and position control in Simulink	129

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Unmanned Aerial Vehicles (UAV) are a class of aircrafts that can fly without the onboard presence of pilots. Quadrotor is a typical design for small UAV. It is a popular concept for a UAV. The major advantages for the quadrotor is its ability to hover, and take-off vertically. This makes the quadrotor useful for many tasks and allows it to be operated in nearly any environments. Powered by four high speed electrical rotors, it can manoeuvre in three-dimensional spaces, within tight space and relatively low altitude. Furthermore, it can navigate autonomously or controlled manually by an operator who can manoeuvre the vehicle to avoid collision. Dealing with unexpected environment and to realize autonomous flight mission, safe navigation capabilities remains a research challenge.

In recent years, there has been increasing interest in the implementations of quadrotor technology in the real world; for instance for real estate photography, aerial surveying, periodic forest monitoring, search/rescue missions [1] and IoT sensor networks [2]. Basic quadrotor helicopters platform consists of a flight controller, stabilization sensors [3], and propeller system powered either by four, six or eight Brushless DC electric motor. In addition, different types of external sensors are required for different situation of application, which should be installed on the vehicle. External sensors are used for additional tasks required for specific applications, such as global positioning, capturing images or video and obstacle detection.

For successful deployment of UAV, it is demanding to operate safely in the real world environment. Therefore, it requires a real-time quadrotor control system with have capability to manage collision avoidance algorithms. The control system with collision avoidance algorithm to avoid collisions is called as Collision Avoidance

System (CAS). Many research has been conducted in order to avoid collision with static objects such as trees or building walls, researchers develop CAS. That is one basic problem for UAV to be a fully autonomous vehicle. CAS involves multiple algorithms that have various advantages and disadvantages. Normally, the CAS methods require three stages, namely obstacle detection, collision recognition and obstacle avoidance path generation. The obstacle detection is a process of acquiring useful information about its surrounding environment. This function is carried out by a physical sensor that is integrated to the main controller circuits. Once a CAS receives information of the obstacles, collision recognition process occurs where the UAV determines if there are any imminent collisions. Finally, CAS path generation process need to perform collision avoidance new path to avoid a collision. Many methods have been proposed to perform collision avoidance in aerial vehicle, such as in [4] (collision avoidance layer), [5] (teleoperated obstacle avoidance), [6] (Bug algorithm), [7] (Artificial Potential Field algorithms), [7] (Vector Field Histogram algorithm), and [8] (Bubble Band Technique).

The main intent of this thesis is to design a UAV real-time control system by providing predefined information about Time-to-Collision (TTC) in the collision recognition stage of CAS. In case an obstacle is detected, collision recognition algorithm will be activated, with different strategies. At this point, the developed TTC model will be function as a matrix of speed to avoid a collision. That will improve the decision-making process and offer good perspectives in the understanding the navigation control algorithm to avoid a collision.

1.2 Motivation

For the ground vehicle, TTC parameters have often been used as a risk assessment metric for traffic safety analyses. TTC was introduced by Hayward [9] in 1972 and has been applied to identify traffic safety impacts, such as in [10] and [11]. Some research has been carried out on TTC with different terms, such as Gap Time (GT), Encroachment Time (ET), Deceleration Rate (DR), Proportion of Stopping

Distance (PSD) Ratio, Post-Encroachment Time (PET) and Initially Attempted Post-Encroachment Time (IAPT) . GT is similar to TTC [12].

According to Hayward and Federal Highway Administration, U.S. Department of Transportation (FHWA), for example, TTC can be defined as the time required for two vehicles to collide if they continue at their present speed and on the same path. In 2008, FHWA combined traffic simulation and automated traffic conflict analysis to develop a software utility referred to as a surrogate safety assessment model (SSAM) [13,14]. In freeway simulation models, TTC is often a critical element of a driver's trajectory management decision-making process and has been used as a cue for decision-making in traffic conflicts research and for activating a driver support system such as CAS [15], [16]. In addition, TTC has proven to be an effective measure for rating the severity of traffic conflicts and for discriminating critical from normal behavior. In principle, the lower the TTC, the higher the risk of a collision.

Any system with predefined information about TTC is an advantage in order to improve the decision-making process and offer good perspectives in the understanding the navigation control algorithm to avoid a collision. This information also helps to reduce dependency on physical information like distance and speed. For example in [15], proposed a collision warning algorithm based on the TTC estimation for traffic safety in the scenario of an arterial road with on-ramp under a connected environment. The Global Positioning System (GPS) based information of vehicles is assumed to be collected by the roadside device such as position, travelling direction and velocity. Then, the TTC of a pair of vehicles in arterial road and on-ramp is estimated based on their position, travelling direction and velocity difference. Besides that, visual control of vehicle braking based on TTC information was introduced by [17]. However, the implementation is limited only for the ground vehicles scenario.

In addition, there is an increasing demand for UAV to agility in complex environments. For instance, a deep learning-based TTC estimation algorithm proposed by train neural networks with real images from monocular camera in the indoor environment [18]. However, a vision-based approach required a large significant amount of datasets of collision cases are needed to compute average TTC estimation

[19], [20]. Moreover, the prediction of the time to collision parameter from a pre-defined avoidance map for a pair of UAV control inputs is proposed to solve conflict resolution among UAVs [21]. The time parameter obtained will be graded to provide alternative solutions for the UAVs to avoid conflict earlier.

From the previous works mentioned above, the TTC algorithm is an inessential method in traffic micro simulation modelling software. However, the use of a TTC algorithm model as a risk assessment matrix for CAS in an aerial vehicle, especially for a UAV has relatively little studies found. Most existing robotic applications of TTC simply control the TTC to be constant or constantly decreasing, without fully exploring the applicability of TTC [22]. The TTC model provides important parameters that can be utilized as a risk assessment matrix for CAS analyses in the UAV system as has been applied on the ground vehicle. Therefore, in this work, design and develop a method to create a model of TTC for the UAV control system.

1.3 Problem Statement

Issues related to TTC parameters for collision prediction and traffic simulation has often been used for ground vehicle situation [14],[23],[24],[25]. TTC can be defined as the time required for two vehicles to collide if they continue at their present speed and on the same path. TTC parameters has often been used as a risk assessment metric for traffic safety analyses TTC was introduced in 1972 and has been applied to identify traffic safety impacts. Until today, safety issues for navigating UAV become of significant importance. In order UAV to be able to navigate safely through complex environments, it would be useful to estimate accurate time-to-collision (TTC) to obstacles in their obstacle controller. The main issues in the use of TTC in previous research are related to vision based collision estimation [18],[19],[26]. Their study uses simple images from on-board cameras or from predefined operational maps, to develop a collision avoidance system. Given this point, the present study is limited to see the use of time to collision or time to contact parameter to assess their collision avoidance controller. In fact, none of the previous studies have examined the potential by building a TTC model and using it to help the existing controller. Model development based on real flight data in the real world requires an optimization algorithm method that is very necessary to reduce data noise and improve the analysis process to obtain optimal solutions in model development. Furthermore, the effect of speed and payload on TTC are also beneficial to be studied. TTC should not be constant or constantly decreasing, regardless of those factors. By developing a mathematical model that can predict an aerial vehicle collision with a static object, taking into account various speeds and payloads, the relationship between both parameters and TTC can potentially be found. By doing so, the model can be used to help obstacle avoidance controller decision-making.

1.4 Research Objective

The objectives of this research are as follows:

(a) To design a data-driven time-to-collision model based on UAV’s speed, and payload that can be useful to collision avoidance decision-making.

(b) To apply optimization algorithms to compute the optimal function of the time-to-collision of the model.

(c) To evaluate UAV control system with time-to-collision prediction capability for obstacle avoidance which considers speed and payload.

1.5 Scope of the Research

The scopes of this study is as follows:

(a) The research platform or testbed UAV system is based on the capacity of open-source project platform. ArduPilot open-source quadrotor UAV controller was chosen due to capability of the full range of flight requirements. In addition, the testbed must be capable of performing real-time onboard flight data recording, manoeuvring control and real-time monitoring.

(b) The modelling of UAV TTC model is based on data-driven approach by using the real platform in outdoor uncontrolled environments. The two considered UAV parameter is speed and payload. The range of parameter values studied is based on the capability limits of the platform used in this research. The maximum speed and payload for safe flight is 5 m/s and 200 g.

(c) Many swarm optimization algorithms have been introduced and all of these algorithms have demonstrated their potential to solve many optimization problems [27]. For example, Genetic Algorithms (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Differential Evolution (DE), Artificial Bee Colony (ABC), Swarm Optimization (GSO), and Cuckoo Search Algorithm (CSA). However, in this research, PSO swarm intelligence technique is used. It is simple to implement, has only a few parameters to be set, it is effective in global search, it is insensitive to scaling of design variables, and suitable to identify of the unknown parameters in the TTC model.

(d) The PSO algorithm, implemented in a MATLAB code and all simulation of UAV control system is done using the MATLAB/Simulink software.

1.6 Contributions of Research Work

Through this work, this thesis make contributions in the one major research areas;

The major contribution is proposed a data-driven TTC model under various payload and speed for aerial vehicle in order to evaluate and improve decision making of obstacle avoidance control system. The parameter is called “Time-to-Collision”. For successful deployment of UAV into a civil airspace, it is necessary to guarantee that they can operate safely in the environment. This requires robust collision avoidance algorithms. Therefore, the study has a potential to provide as an additional assessment matrix to CAS before making a decision. A PSO is used in the development of TTC mathematical model and simulated using MATLAB/Simulink.

Other than that, within this study, a complete quadrotor research platform is developed based on the Open-Source Project (OSP). This platform successfully developed, tested and implemented to be fulfil as a vehicle to collect a data required.

1.7 Thesis Organization

The overall structure of the study takes the form of seven chapters, including this introductory chapter.

The first chapter introduces the thesis which includes a problem statement, thesis objectives, the contribution of research and research scopes.

Chapter 2 gives the introduction to understand the TTC modelling, UAV system and CAS with focus on modelling of time-to-collision optimization and validation. This chapter also discusses the various exiting works related to UAV CAS control system.

Chapter 3 provides detailed descriptions of the research methodology.

Chapter 4 is concerned with results and discussion on each phase of the research mathodolgy.

The final chapter summarises the main findings of this project and recommendations.

REFERENCES

[1] D. Silver, D. Morales, Arc carving: obtaining accurate, low latency maps from ultrasonic range sensors, in: Int. Conf. Robot. Autom., IEEE, New Orleans,LA, 2004: pp. 1554–1561. https://doi.org/10.1109/ROBOT.2004.1308045.

[2] A. Censi, J. Strubel, C. Brandli, T. Delbruck, D. Scaramuzza, Low-latency localization by active LED markers tracking using a dynamic vision sensor, in: IEEE Int. Conf. Intell. Robot. Syst., 2013: pp. 891–898. https://doi.org/10.1109/IROS.2013.6696456.

[3] R. Lozano, P. Castillo, P. Garcia, A. Dzul, Robust prediction-based control for unstable delay systems: Application to the yaw control of a mini-helicopter, Automatica. 40 (2004) 603–612. https://doi.org/10.1016/j.automatica.2003.10.007.

[4] J. Müller, A.V. Ruiz, I. Wieser, M. Joachim, A.V. Ruiz, I. Wieser, Safe & sound: A robust collision avoidance layer for aerial robots based on acoustic sensors, Rec. - IEEE PLANS, Position Locat. Navig. Symp. (2014) 1197–1202. https://doi.org/10.1109/PLANS.2014.6851492.

[5] M. Odelga, P. Stegagno, H.H. Büthoff, Obstacle Detection , Tracking and Avoidance for a Teleoperated UAV, in: ICRA2016, 2016. https://doi.org/10.1109/ICRA.2016.7487464.

[6] F. Fraundorfer, L. Heng, D. Honegger, G.H. Lee, L. Meier, P. Tanskanen, M. Pollefeys, Vision-based autonomous mapping and exploration using a quadrotor MAV, in: IEEE Int. Conf. Intell. Robot. Syst., 2012: pp. 4557–4564. https://doi.org/10.1109/IROS.2012.6385934.

[7] M. Rezae, H. Boland, F. Jamaldoost, S. Sma, M.R. İ, H.B. İ, F. Jamaldoost, A New Obstacle Avoidance Algorithm for Quad rotors Group in the presence of Dynamic and Static Obstacles, Sci. J. 36 (2015).

[8] M. Zohaib, S.M. Pasha, N. Javaid, J. Iqbal, A. Salaam, An improved algorithm for collision avoidance in environments having U and H shaped obstacles, Stud. Informatics Control. 23 (2014) 97–106.

[9] H.C. Hayward, Near-miss determination through use of a scale of danger, Highw. Res. Rec. 384 (1972) 24–34.

[10] K.D. Kusano, H. Gabler, Method for Estimating Time to Collision at Braking in Real-World, Lead Vehicle Stopped Rear-End Crashes for Use in Pre-Crash System Design, SAE Int. J. Passeng. Cars – Mech. Syst. 4 (2011) 435–443. https://doi.org/10.4271/2011-01-0576.

[11] R. Van Der Horst, J. Hogema, Time-to-collision and collision avoidance systems, in: 6th Work. Salzbg., 1993: pp. 1–12.

[12] S. Sabikan, S.W. Nawawi, N.A.A. Aziz, Modelling of time-to collision for unmanned aerial vehicle using particles swarm optimization, IAES Int. J. Artif. Intell. 9 (2020) 488–496. https://doi.org/10.11591/ijai.v9.i3.pp488-496.

[13] P. St-Aubin, N. Saunier, L. Miranda-Moreno, Comparison of Various Time-to-Collision Prediction and Aggregation Methods for Surrogate Safety Analysis, {Transportation Res. Board 94th Annu. Meet. 1 (2015).

[14] J. Hou, G.F. List, X. Guo, New Algorithms for Computing the Time-to-Collision in Freeway Traffic Simulation Models, Comput. Intell. Neurosci. 2014 (2014).

[15] Y. Li, L. Zhang, Y. Song, A vehicular collision warning algorithm based on the time-to-collision estimation under connected environment, in: 2016 14th Int. Conf. Control. Autom. Robot. Vision, ICARCV 2016, 2017: pp. 13–15.

[16] R. Jiang, S. Zhu, H. Chang, J. Wu, N. Ding, B. Liu, J. Qiu, Determining an improved traffic conflict indicator for highway safety estimation based on vehicle trajectory data, Sustain. 13 (2021) 13169278. https://doi.org/10.3390/su13169278.

[17] D.N. Lee, A Theory of Visual Control of Braking Based on Information about Time-to-Collision, Perception. 5 (1976) 437–459.

[18] M. Kim, P. Ladosz, H. Oh, Monocular vision-based time-to-collision estimation for small drones by domain adaptation of simulated images, Expert Syst. Appl. 199 (2022) 116973. https://doi.org/10.1016/j.eswa.2022.116973.

[19] F. Gomes, T. Hormigo, R. Ventura, Vision based real-time obstacle avoidance for drones using a time-to-collision estimation approach, 2020 IEEE Int. Symp. Safety, Secur. Rescue Robot. SSRR 2020. (2020) 90–95. https://doi.org/10.1109/SSRR50563.2020.9292597.

[20] P. Bauer, A. Hiba, B. Vanek, A. Zarandy, J. Bokor, Monocular image-based time to collision and closest point of approach estimation, 24th Mediterr. Conf. Control Autom. MED 2016. (2016) 1168–1173.

https://doi.org/10.1109/MED.2016.7535965.

[21] L.A. Tony, D. Ghose, Time-Graded Avoidance Map for Constrained Aerial Traffi, AIAA Sci. Technol. Forum Expo. AIAA SciTech Forum 2022. (2022) 2514. https://doi.org/10.2514/6.2022-2158.

[22] H. Zhang, B. Cheng, J. Zhao, Optimal trajectory generation for time-to-contact based aerial robotic perching, Bioinspiration and Biomimetics. 14 (2019) 3190. https://doi.org/10.1088/1748-3190/aaeb13.

[23] A.J. Sanchez-Garcia, H.V. Rios-Figueroa, A. Marin-Hernandez, G. Contreras-Vega, Decision making for obstacle avoidance in autonomous mobile robots by time to contact and optical flow, 25th Int. Conf. Electron. Commun. Comput. CONIELECOMP 2015. (2015) 130–134. https://doi.org/10.1109/CONIELECOMP.2015.7086939.

[24] S.P. Venthuruthiyil, M. Chunchu, Anticipated Collision Time (ACT): A two-dimensional surrogate safety indicator for trajectory-based proactive safety assessment, Transp. Res. Part C Emerg. Technol. 139 (2022) 103655. https://doi.org/10.1016/j.trc.2022.103655.

[25] I. Arrouch, N.S. Ahmad, P. Goh, J. Mohamad-Saleh, Close Proximity Time-to-collision Prediction for Autonomous Robot Navigation: An Exponential GPR Approach, Alexandria Eng. J. 61 (2022) 11171–11183. https://doi.org/10.1016/j.aej.2022.04.041.

[26] M. Amrouche, T. Marinho, D. Stipanovic, Vision Based Collision Avoidance For Multi-Agent Systems Using Avoidance Functions, Eur. Control Conf. 2020, ECC 2020. (2020) 1683–1688. https://doi.org/10.23919/ecc51009.2020.9143739.

[27] M.N. Ab Wahab, S. Nefti-Meziani, A. Atyabi, A Comprehensive Review of Swarm Optimization Algorithms, PLoS One. 10 (2015). https://doi.org/10.1371/journal.pone.0122827.

[28] U.S. Army, Unmanned Aircraft Systems Roadmap 2010-2035, 2010.

[29] A. Uerkwitz, P. Dean, M. Yang, Drone Industry Report, 2016.

[30] C. Chen, M.W. Edwards, B. Gill, S. Smearcheck, T. Adami, S. Calhoun, M.G. Wu, A. Cone, S.M. Lee, Defining Well Clear Separation for Unmanned Aircraft Systems Operating with Noncooperative Aircraft, in: AIAA Aviat. 2019 Forum, American Institute of Aeronautics and Astronautics, 2019. https://doi.org/doi:10.2514/6.2019-3512.

[31] W. Dong, G.Y. Gu, X. Zhu, H. Ding, Development of a quadrotor test bed - Modelling, parameter identification, controller design and trajectory generation, Int. J. Adv. Robot. Syst. 12 (2015). https://doi.org/10.5772/59618.

[32] G. Hoffmann, D.G. Rajnarayan, S.L. Waslander, D. Dostal, J.S. Jang, C.J. Tomlin, The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control (STARMAC), in: AIAA/IEEE Digit. Avion. Syst. Conf. - Proc., IEEE, Salt Lake City, UT, 2004: pp. 12.E.4-1-12.E.4–10. https://doi.org/10.1109/DASC.2004.1390847.

[33] P. Castillo, A. Dzul, R. Lozano, Real-time stabilization and tracking of a four-rotor mini rotorcraft, in: IEEE Trans. Control Syst. Technol., 2004: pp. 510–516. https://doi.org/10.1109/TCST.2004.825052.

[34] M. Abdolhosseini, Y.M. Zhang, C. a. Rabbath, An efficient model predictive control scheme for an unmanned quadrotor helicopter, J. Intell. Robot. Syst. Theory Appl. 70 (2013) 27–38. https://doi.org/10.1007/s10846-012-9724-3.

[35] H. Lim, J. Park, D. Lee, H.J. Kim, Build your own quadrotor: Open-source projects on unmanned aerial vehicles, IEEE Robot. Autom. Mag. 19 (2012) 33–45. https://doi.org/10.1109/MRA.2012.2205629.

[36] Z. He, Y. Chen, Z. Shen, E. Huang, S. Li, Z. Shao, Q. Wang, Ard-mu-Copter: A Simple Open Source Quadcopter Platform, in: 2015 11th Int. Conf. Mob. Ad-Hoc Sens. Networks, 2015: pp. 158–164. https://doi.org/10.1109/MSN.2015.9.

[37] A. Manecy, N. Marchand, F. Ruffier, S. Viollet, X4-MaG : A Low-Cost Open-Source Micro-Quadrotor and Its Linux- Based Controller, Int. J. Micro Air Veh. 7 (2015) 89–109. https://doi.org/10.1260/1756-8293.7.2.89.

[38] R. Allen, M. Pavone, A Real-Time Framework for Kinodynamic Planning with Application to Quadrotor Obstacle Avoidance, in: AIAA Guid. Navig. Control Conf., San Diego, 2016: pp. 1–18. https://doi.org/10.2514/6.2016-1374.

[39] D. Antunes, C. Silvestre, R. Cunha, On the design of multi-rate tracking controllers:Application to rotorcraft guidance and control, Int. J. Robust Nonlinear Control. 20(16) (2010) 1879–1902. https://doi.org/10.1002/rnc.

[40] M. Leichtfried, C. Kaltenriner, A. Mossel, H. Kaufmann, Autonomous Flight using a Smartphone as On-Board Processing Unit in GPS-Denied Environments, in: Proc. 11th Int. Conf. Adv. Mob. Comput. {&} Multimed., 2013: pp. 341–350. https://doi.org/10.1145/2536853.2536898.

[41] H. Khandani, H. Moradi, J.Y. Panah, A real-time coverage and tracking

algorithm for UAVs based on potential field, in: 2014 2nd RSI/ISM Int. Conf. Robot. Mechatronics, ICRoM 2014, 2014: pp. 700–705. https://doi.org/10.1109/ICRoM.2014.6990985.

[42] T.T. Mac, C. Copot, A. Hernandez, R. De Keyser, Improved potential field method for unknown obstacle avoidance using UAV in indoor environment, in: 2016 IEEE 14th Int. Symp. Appl. Mach. Intell. Informatics, 2016: pp. 345–350.

[43] B. Xian, M. Di Xu, L. Wang, Distributed unmanned aerial vehicle platoon control with dynamic obstacle avoidance, Kongzhi Yu Juece/Control Decis. 37 (2022) 2226–2234. https://doi.org/10.13195/j.kzyjc.2021.0141.

[44] T. Wu, J. Wang, B. Tian, Periodic event-triggered formation control for multi-UAV systems with collision avoidance, Chinese J. Aeronaut. 35 (2022) 193–203. https://doi.org/10.1016/j.cja.2021.10.011.

[45] S. Feng, Y. Qian, Y. Wang, Collision avoidance method of autonomous vehicle based on improved artificial potential field algorithm, Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 235 (2021) 3416–3430. https://doi.org/10.1177/09544070211014319.

[46] J. Qi, J. Guo, M. Wang, C. Wu, Z. Ma, Formation Tracking and Obstacle Avoidance for Multiple Quadrotors with Static and Dynamic Obstacles, IEEE Robot. Autom. Lett. 7 (2022) 1713–1720. https://doi.org/10.1109/LRA.2022.3140830.

[47] I. Arrouch, N.S. Ahmad, P. Goh, J. Mohamad-Saleh, Close Proximity Time-to-collision Prediction for Autonomous Robot Navigation: An Exponential GPR Approach, Alexandria Eng. J. 61 (2022) 11171–11183. https://doi.org/https://doi.org/10.1016/j.aej.2022.04.041.

[48] M. Shahriari, M. Biglarbegian, Toward Safer Navigation of Heterogeneous Mobile Robots in Distributed Scheme: A Novel Time-to-Collision-Based Method, IEEE Trans. Cybern. (2021) 3110196. https://doi.org/10.1109/TCYB.2021.3110196.

[49] S. Ahmed, B. Qiu, C.W. Kong, H. Xin, F. Ahmad, J. Lin, A Data-Driven Dynamic Obstacle Avoidance Method for Liquid-Carrying Plant Protection UAVs, Agronomy. 12 (2022) 2022. https://doi.org/10.3390/agronomy12040873.

[50] X. Su, L. Tao, T. Zhang, Y. Cheng, J. Ma, C. Wang, A data-driven FCE method for UAV condition risk assessment based on feature engineering and variable

weight coefficients, 2020 Int. Conf. Unmanned Aircr. Syst. ICUAS 2020. (2020) 867–874. https://doi.org/10.1109/ICUAS48674.2020.9213943.

[51] B. Thomsen, M. Zhang, I. Sharf, Bio-inspired time-to-contact control for autonomous quadrotor vehicles, 2016 AIAA Guid. Navig. Control Conf. (2016) 2514. https://doi.org/10.2514/6.2016-0384.

[52] M.N. Ab Wahab, S. Nefti-Meziani, A. Atyabi, A comprehensive review of swarm optimization algorithms, PLoS One. 10 (2015). https://doi.org/10.1371/journal.pone.0122827.

[53] E.A. Chater, H. Housny, H. El Fadil, Adaptive proportional integral derivative deep feedforward network for quadrotor trajectory-tracking flight control, Int. J. Electr. Comput. Eng. 12 (2022) 3607–3619. https://doi.org/10.11591/ijece.v12i4.pp3607-3619.

[54] M.S. Can, H. Ercan, Real-time tuning of PID controller based on optimization algorithms for a quadrotor, Aircr. Eng. Aerosp. Technol. 94 (2022) 418–430. https://doi.org/10.1108/AEAT-06-2021-0173.

[55] A. Alkamachi, E. Erçelebi, Modelling and Genetic Algorithm Based-PID Control of H-Shaped Racing Quadcopter, Arab. J. Sci. Eng. 42 (2017) 2777–2786. https://doi.org/10.1007/s13369-017-2433-2.

[56] H. Housny, E.A. Chater, H. El Fadil, Fuzzy PID Control Tuning Design Using Particle Swarm Optimization Algorithm for a Quadrotor, 2019 Int. Conf. Optim. Appl. ICOA 2019. (2019) 2022. https://doi.org/10.1109/ICOA.2019.8727702.

[57] N. El Gmili, M. Mjahed, A. El Kari, H. Ayad, Particle swarm optimization based proportional-derivative parameters for unmanned tilt-rotor flight control and trajectory tracking, Automatika. 61 (2020) 189–206. https://doi.org/10.1080/00051144.2019.1698191.

[58] J. Kennedy, R. Eberhart, Particle Swarm Optimization, in: Proc. IEEE Int. Conf. Neural Networks, 1995: pp. 1942–1948.

[59] S. Bouabdallah, M. Becker, V. de Perrot, R. Siegwart, Toward obstacle avoidance on quadrotors, in: XII Int. Symp. Dyn. Probl. Mech., 2007: pp. 1–10.

[60] S. Bouabdallah, R. Siegwart, Full control of a quadrotor, in: 2007 IEEE/RSJ Int. Conf. Intell. Robot. Syst., IEEE, San Diego, CA, 2007: pp. 153–158. https://doi.org/10.1109/IROS.2007.4399042.

[61] J. Li, X.M. Li, Vision-based navigation and obstacle detection for UAV, in:

2011 Int. Conf. Electron. Commun. Control. ICECC 2011 - Proc., 2011: pp. 1771–1774. https://doi.org/10.1109/ICECC.2011.6066586.

[62] L.K. Kong, J. Sheng, A. Teredesai, Basic Micro-Aerial Vehicles (MAVs) obstacles avoidance using monocular computer vision, 2014 13th Int. Conf. Control Autom. Robot. Vision, ICARCV 2014. 2014 (1997) 1051–1056. https://doi.org/10.1109/ICARCV.2014.7064451.

[63] A. Budiyanto, A. Cahyadi, T.B. Adji, O. Wahyunggoro, J. Grafika, UAV Obstacle Avoidance Using Potential Field under Dynamic Environment, in: Int. Conf. Control. Electron. Renew. Energy Commun., 2015: pp. 187–192.

[64] O. Khatib, Real-Time Obstacle Avoidance for Manipulators and Mobile Robots, Int. J. Rob. Res. 5 (1986) 90–98. https://doi.org/10.1177/027836498600500106.

[65] K.-Y. Kim, J.-W. Park, M. Tahk, UAV collision avoidance using probabilistic method in 3-D, 2007 Int. Conf. Control. Autom. Syst. (2007) 826–829. https://doi.org/10.1109/ICCAS.2007.4407015.

[66] D. Tøttrup, S.L. Skovgaard, J.L.F. Sejersen, R.P. de Figueiredo, A Real-Time Method for Time-to-Collision Estimation from Aerial Images, J. Imaging. 8 (2022). https://doi.org/10.3390/jimaging8030062.

[67] R. Jiang, S. Zhu, H. Chang, J. Wu, N. Ding, B. Liu, J. Qiu, Determining an improved traffic conflict indicator for highway safety estimation based on vehicle trajectory data, Sustain. 13 (2021). https://doi.org/10.3390/su13169278.

[68] S. Badrloo, M. Varshosaz, S. Pirasteh, J. Li, Image-Based Obstacle Detection Methods for the Safe Navigation of Unmanned Vehicles: A Review, Remote Sens. 14 (2022) 3824. https://doi.org/10.3390/rs14153824.

[69] S.K. Fatima, S.M. Abbas, I. Mir, F. Gul, S. Mir, N. Saeed, A. Alotaibi, T. Althobaiti, L. Abualigah, Data Driven Model Estimation for Aerial Vehicles: A Perspective Analysis, Processes. 10 (2022) 2022. https://doi.org/10.3390/pr10071236.

[70] N. Azlina, A. Aziz, Z. Ibrahim, M. Mubin, S.W. Nawawi, Transitional Particle Swarm Optimization, Int. J. Electr. Comput. Eng. 7 (2017) 1611–1619. https://doi.org/10.11591/ijece.v7i3.pp1611-1619.

[71] T. Luukkonen, Modelling and Ccontrol of Quadcopter, J. Am. Soc. Mass Spectrom. 22 (2011) 1134–45. https://doi.org/10.1007/s13361-011-0148-2.

[72] S. Bouabdallah, Design and Control of Quadrotors With Application To

Autonomous Flying, École Polytechnique Fédérale De Lausanne, 2007. https://doi.org/10.5075/epfl-thesis-3727.

[73] K. Máthé, L. Buşoniu, Vision and Control for UAVs: A Survey of General Methods and of Inexpensive Platforms for Infrastructure Inspection., Sensors (Basel). 15 (2015) 14887–14916. https://doi.org/10.3390/s150714887.

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Sabikan, S.**, Nawawi, S.W., Sudin S. "A Survey of Onboard Sensors for Quadrotor Collision Avoidance System.", J Eng Appl Sci 2017;12:4138–43. https://doi.org/10.3923/jeasci.2017.4138.4143. **(Q3)**

Indexed Journal

1. **Sabikan, S.**, Nawawi, S.W., Aziz, N.A.A., (2020), "Modelling of time-to collision for unmanned aerial vehicle using particles swarm optimization." IAES International Journal of Artificial Intelligence (IJ-AI). 9. 488. 10.11591/ijai.v9.i3.pp488-496.

2. **Sabikan, S.**, Nawawi, S.W., "Implementation of Open-Source for Outdoor Multirotors Helicopter", Eng Technol Open Acc. 2018; 1(1): 555552. 10.19080/ETOAJ.2018.01.555552

3. **Sabikan, S.**, Nawawi, S.W.," Open-Source Project (OSPs) Platform for Outdoor Quadcopter". J Adv Res Des 2016;Volume 24:13–27.

Indexed Conference Proceedings

1. **Sabikan, S.**, Nawawi, S.W., Aziz, N.A.A., "UAV Control System with Time to Collision (TTC) Prediction Capability", International Conference on Robotics, Vision, Signal Processing and Power Applications (RoViSP 2021).

2. **Sabikan, S.**, Nawawi, S.W., Aziz, N.A.A., "Modelling Of Time To Collision For Unmanned Aerial Vehicle Using Particles Swarm Optimization", International Conference in Electrical Electronic Communication and Control Engineering (ICEECC 2019).

3. **Sabikan, S.**, Nawawi, S.W., “A Survey of Onboard Sensors for Quadrotor Collision Avoidance System.” Comput. Sci. Telecommun. Eng. Int. Conf. 2016, 2016.

4. **Sabikan, S.**, Nawawi, S.W., “A New Approach To Measure Outdoor Quadcopter System Latency Using Motion Analysis Sensor.” Asia Int. Multidiscip. Conf. (AIMC 2017), 2017.