DIGITAL VIDEO BROADCASTING SATELLITE-BASED PASSIVE FORWARD SCATTER RADAR FOR DRONE DETECTION BASED ON MICRO DOPPLER ANALYSIS

SURAJO ALHAJI MUSA

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By

SURAJO ALHAJI MUSA

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

December 2019

DEDICATION

This thesis is dedicated to:
My Parents and Family

Abstract of thesis presented to the Senate of University Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Raja Syamsul Azmir Raja Abdullah, PhD
Faculty : Engineering

The exponential growth of drone usage and the posing threats by the users such as unauthorized imaging and filming in restricted areas, illegal surveillance, air collision, drugs smuggle, terrorist attacks, RF jamming among others, became alarming. Several efforts were made to detect the drone to curtail the menace. Attempt such as acoustic, camera, cascaded audio-visual, radio frequency (RF) and other non-technical approaches were among the efforts made in detecting a drone. Radar system is another method used for surveillance, detection and tracking of ground moving and airborne targets. This thesis presented a micro-Doppler analysis for drone detection and identification by using digital video broadcasting satellite (DVB-S) based passive forward scatter radar (PFSR) systems.

The passive radar ability to exploit the available illuminators for targets' detection and its key benefits were the motivating factor of its implementation. Besides, FSR as a special mode of bistatic radar with an enhanced performance and attracting features, making it a good candidate for this work. Thus, this thesis, described how a DVB-S based PFSR system, for drone detection based on its micro-Doppler was implemented. A theoretical model was designed, simulated, and validated experimentally, for both the Doppler due to drone linear motion and the micro-Doppler signature in FSR geometry. The results were promising especially for the "Facing-Rx" scenario and can serve as a model for Doppler analysis of the drone in FSR geometry.

In a feasibility study, the DVB-S signal ambiguities guarantees a good range resolution of 4.17m that can differentiate a velocity of 0.027m/s. Irrespective of the blade material and orientation, an appreciable RCS was achieved in FS mode with highest RCS whenever the blade is facing e-field direction e.g. 0.736 dBm for Perfect Electrical

Conductor (PEC) material. A SNR of 4 dB above the bistatic threshold of 13 dB was achieved hence, with the FSR receiving system, a reasonable processing gains (<normal i.e. 55-75 dB) is enough to achieve the sensitivity level of the receiver. The direct power (P_{dir}) arriving the antenna front-end is -112.1324 dBw, which is within the practical value.

A Measat3a/3/3b signal was acquired and used for actual detection of the drone over a 40 m target-receiver distance. An empirical mode decomposition (EMD) algorithm was then used to extract the feature vectors present in the acquired signature. This involve the Doppler and the micro-Doppler component due to the rotating blades. The results were promising and conformed with the theoretical assumptions and that of the FSR system. The extracted micro-Doppler served as a strong hold for the identification of the detected drone. It is also used to identify the direction of flight of the drone. The PFSR system is therefore considered efficient in detecting a low profiled airborne target.

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

VIDEO DIGITAL PENYELESAIAN SATELIT BERDASARKAN KE HADAPAN RADAR SCATTER UNTUK DETEKSI DRON BERDASARKAN ANALISIS DOPPLER MICRO

Oleh

SURAJO ALHAJI MUSA

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Pertumbuhan eksponen penggunaan drone dan ancaman yang ditimbulkan oleh pengguna seperti pengimejan tidak sah dan penggambaran di kawasan laranga, pengawasan haram, pertembungan udara, penyeludupan dadah, serangan pengganas, gangguan frequency radio antara lain, menjadi membimbangkan. Beberapa usaha dibuat untuk mengesan drone untuk mengurangkan ancaman. Percubaan seperti akustik, kamera, audio visual, frekuensi radio (RF) dan cara bukan teknikal lain seperti penembakan dan penjelasan adalah antara beberapa usaha yang dibuat pengesanan drone ini. Sistem radar adalah kaedah lain yang digunakan untuk pengawasan, pengesanan dan pengesanan sasaran bergerak dan udara. Tesis ini mempersembahkan analisis mikro-Doppler untuk pengesanan drone dengan dan pengenalan menggunakan sistem radar pasif hadapan DVB-S (PFSR).

Keupayaan radar pasif untuk mengeksploitasi pencahayaan yang atas sasaran ada untuk pengesanan sasaran dan manfaat utamanya adalah faktor pemotivasi pelaksanaannya. Selain itu, FSR sebagai mod khas radar bistatik dengan prestasi yang dipertingkatkan dan yang menarik ciri-ciri, menjadikannya ciri yang baik untuk kerja ini. Oleh itu, tesis ini, menggambarkan bagaimana sistem PFSR berasaskan DVB-S, untuk pengesanan drone berdasarkan mikro-Dopplernya dilaksanakan. Model teori telah direka, disimulasikan, dan disahkan secara eksperimen, untuk kedua-dua Doppler dibuktikan gerakan linear drone dan pelambangan mikro Doppler dalam geometri FSR. Hasilnya menjanjikan terutamanya senario "Facing-Rx" dan boleh menjadi model untuk analisis Doppler drone dalam geometri FSR.

Dalam kajian kebolehlaksanaan, kekeliruan isyarat DVB-S menjamin resolusi jarak yang baik 4.17m yang boleh membezakan halaju 0.027m/s. Tanpa mengira bahan dan

orientasi pisau, RCS yang cukup dapat dicapai dalam mod FS dengan RCS tertinggi setiap kali bilah menghadap arah e-lapangan misalnya. 0.736 dBm untuk bahan konduktor elektrik yang sempurna. SNR 4 dB di atas ambang bistatik 13 dB dicapai dengan itu, dengan sistem penerimaan FSR, keuntungan pemprosesan yang berpatutan (<normal iaitu 55-75 dB) cukup untuk mencapai tahap kepekaan penerima. Kuasa langsung (Pdir) yang tiba di hadapan antena adalah -112.1324 dBw, yang berada dalam nilai praktikal.

Isyarat Measat3a/3/3b telah diperolehi dan digunakan untuk mengesan drone sebenar pada jarak penerima sasaran 40 m. Algoritma penguraian mod empirikal (EMD) kemudian digunakan untuk mengekstrak vektor ciri yang terdapat dalam tandatangan yang diperolehi. Ini melibatkan Doppler dan komponen mikro-Doppler disebabkan oleh bilah berputar. Hasilnya menjanjikan dan menepati dengan andaian teori dan sistem FSR. Mikro-Doppler yang diekstraksi berkhidmat sebagai pemegangan yang kuat untuk mengenal pasti drone yang dikesan. Ia juga digunakan untuk mengenal pasti arah penerbangan drone tersebut. Oleh itu, sistem PFSR dianggap efisien dalam mengesan sasaran udara yang berprofil rendah.

ACKNOWLEDGEMENTS

In the name of Allah, the most beneficent the most merciful

My appreciation and deepest gratitude goes to my supervisor Prof. Raja Syamsul Azmir bin Raja Abdullah for his guidance, suggestions, and encouragement throughout the conduct of this work. Without his helping hand, this might have not been a success.

I would not forget the kind gestures received from my co-supervisors in person of Prof. Ir. Dr. Aduwati bt Sali and Prof. Dr. Alyani bt Ismail for their overwhelming support and guidance through the conduct of this research. I would also like to extend my thanks to some other academic and non-academic staff of Universiti Putra Malaysia for their support in the conduct of this work like Dr. Zuraida Zan, Mr. Zulkhair, Mr. Hisham, Mr. Hakim to mention but few. Thanks and gratitude are extended to all my research team, friends and other colleagues especially Abdelmajid Husam Hussein Habush for their support throughout the research period. Special thanks goes to the Faculty of Engineering, University Technology Mara, (UiTM) Sha'alam, especially the Electrical Engineering Department for the use of their anechoic chamber during the conduct of this work.

Finally, I am highly grateful to my mother Haj. Amina, and my wife Samina, for their patience, encouragement, support and unconditional love throughout the period of my stay in Malaysia.

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

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TABLE OF CONTENS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABS-S	Advanced Broadcasting System Satellite
ADC	Analog Digital Converter
ARL	Army Research Laboratory
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPF	Band Pass Filter
BSS	Broadcasting Satellite Services
CNN	Convolutional Neural Network
CST	Computer simulation Technology
DBS	Digital Broadcasting Satellite
DBN	Deep Belief Network
dBW	Decibel Watt
DAB	Digital Audio Broadcast
DTH	Direct to Home
DVB-S	Digital Video Broadcast Satellite
DVB-T	Digital Video Broadcast Terrestrial
EIRP	Effective Isotropic Radiated Power
EMD	Empirical Mode Decomposition
eNB	e-Node Base Station
FAA	Federal Aviation Administration
FM	Frequency Modulation
FSR	Forward Scatter Radar
FSS	Fixed Satellite Services
GEO	Geostationary Earth Orbit
GHz	Giga Hertz

GNSS	Global Navigation Satellite System
GMM	Gaussian Mixture Model
GPS	Global Positioning System
GSM	Global System Mobile
HHT	Hilbert Huang Transform
HPF	High Pass Filter
ISAR	Synthetic Aperture Radar
IMF	Intrinsic Mode Function
LEO	Lower Earth Orbit
LNA	Low Noise Amplifier
LNB	Low Noise Block
LoS	Line of Sight
LPF	Low pass filter
LSS	Low Slow and Small Target
LTE	Long Term Evolution
MCMC	Multimedia Communication Malaysian Company
MEASAT	Malaysian East Asia Satellite
MSS	Mobile Satellite Services
NLD	Non-linear Device
PBR	Passive Bistatic Radar
PCL	Passive Coherent Locator
PEC	Perfect Electrical Conductor
PFSR	Passive Forward Scatter Radar
PRF	Pulse Rate Frequency
PSD	Power spectral density
QFD	Quality Function Deployment

QPSK	Quadrature Phase Shift Keying
RCS	Radar Cross Section
RCP	Remote Controlled Piloted
RF	Radio Frequency
RNN	Recurrent Neural Network
RRC	Root Raised Cosine
RPAS	Remotely Piloted Aircraft Systems
RPM	Revolution Per Minute
SAI	System Architecting using Ilities
SAR	Synthetic Aperture Radar
SCF	Spectral Correlation Function
SMR	Surface Movement Radar
SNR	Signal to Noise Ratio
SoS	System of System
SPC	Stationary Point Concentration
STFT	Short Time Frequency Transform
SVD	Singular Value decomposition
SVM	Support Vector Machine
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
WIFI	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER 1

INTRODUCTION

1.1 Background

The use of a drone by civil society is exponentially increasing due to its low cost and operational flexibility, thus, became vulnerable and alarming, making its detection necessary [1]. Although drone is been used for good in areas like aerial imaging, monitoring, search and rescue, security surveillance, hobbyists entrepreneurial [2], enhancing agriculture [3] and wildlife monitoring [4], yet, it is considered an emerging threat [5] due to the users' abuse.

Drone was involved in activities such as drugs smuggling, conveyance of contraband materials like weapons [6] and other significant vulnerability like privacy violation, anti-social and other unsafe acts [7] and terrorist attack [8]. Drones equipped with RF jammers posed challenges to GPS receivers and cell phones, and at the same time can launch a long distance attacked for the criminals to remain un-noticed (Hoffmann, et al. 2016). A drone can also be used to crash aircraft while taking off or landing if collided (Sziill, et al., 2017), or getting into a jet engine, the damage caused may be no difference to collision with birds. The Technical Cooperative Committee (TTCP) attempt of address the critically identified potential dangers posed by small UAVs [11] further stress the foreseen threats. Recently, drone was sighted over the Gatwick airport London causing havoc and much distressful situation, that resulted to incoming flight diversions (BBC, 2018), the drone penetration into the highest level of security [8] and other already proven incidences was a clear indication of mandating a drone detection a priority. Figure 1.1 illustrated some identified threats of a smuggled package through a prison cell window [13] in 1.1a, a spotted drone near New York airport [14] in 1.1b and a crashed drone with suspicious items [15] in 1.1c.

(a)

(b)

(c)

Figure 1.1 : **(a) Smuggled package [13], (b) Spotted UAV drone [14] (c) Crashed drone [15].**

Attempts were made by different researchers to find suitable technique for drone detection, ranging from non-radar systems such as acoustic, video, hybrid systems, radio frequency (RF), thermal and other unclassified systems like shooting and netting. Despite the recorded achievements by these methods, some unresolved challenges were faced. For instance, the drone-generated audio frequencies usually approximately equal to 40 kHz may be difficult to detect, due to a higher noise ratio in urban cities. Some drones are designed to follow a predefined GPS path, hence, there is no link to trace the RF link. Many unlicensed WIFI-RF bands suffers noise effect due to many users; this of course affect the system performance. A target with a dynamic or blurred background may affect the camera-based detection which may also have difficulty in differentiating a drone from flying birds. The drone's plastic nature and the frames make and a minimal heat exhaust rendered thermal detection obsolete. Thus, a radar system was considered as an alternative and equally important due to its capability in automotive and military applications, and in the dark, noisy and blurred or misty environments.

In line of the above, radar system was equally explored by many researchers to detect the drone**.** The history of radar according to [16] can be traced as far back as eighteen (1800) century, from Michael Faraday who proved that an electric current produced a magnetic field, and returns the energy contained in this field even if the current was absent. James Maxwell, Christian Hulls Meyer and Gughelmo Marconi formed the frontiers of this magnetic field and its application (e.g. radar) up to the finding in a research made by Dr Albert Taylor of the Naval Research Laboratory (NRL) in Washington D.C in 1922 on the observed issues on radar effect. The emergence of using co-located transmitter and receiver became breakthrough of tracking aircraft and ships after an observation resulted from NRL test conducted in 1930, that a plane flying through a beam generated by a transmitter distorts the signal. Thus, the finding leads to an aggressive experimental approach amongst the USA, UK, Soviet Union, France, Italy, Germany and Japan.

World War II was the exploring avenue of radar application as a defensive weapon at the beginning, after which it turns to an automatic aircraft tracking device [17], [16] and [18]. Despite the low frequency and other attributed limitations of the very high frequency (VHF) band, it forms the basic building blocks of radar technology before the war application. Although military applications explored radar application, yet, the progress in radar technology was diversified to civil marine and other civilian applications [16].

Radar system can either be monostatic or bistatic, passive or active techniques. The monostatic and bistatic radars had their transmitters openly seen and discovered their location, this make it simple to an enemy to jam them. A passive radar was therefore introduced to minimize such occurrences. A passive radar is a bistatic radar that essentially used a non-cooperative transmitter usually known as "illuminator of opportunity". It offers many advantages when compared with normal conventional radars such as low-cost due to saving on expensive transmitters, no restriction to spectrum allocation, robustness, low environmental impact, covert operation and increase of commercial networks by years.

Many illuminators were explored for passive radar application in various researches such as global navigation satellite system (GNSS) by [19] & [20], Long Term Evolution (LTE) signal [21] & [22], WIFI in [23] & [24], Digital Video Terrestrial Broadcast (DVB-T) [25], [26], Digital Audio Broadcast (DAB) [27], FM in [28]. However, the use of digital video broadcasting satellite (DVB-S) was among the early illuminators explored as far back as 90's by [29] and [30]. The DVB-S signal offers many advantages when used for passive applications such as:

i. The signal footprint, signal availability at all times and is deployable worldwide.
ii. The satellite signal had a fixed system structure, a large frequency band ranging from 10.7 – 12.75 GHz and strong radiated power.
iii. Apart from high transponder power, it also have high receiving antenna gain due to narrow beam and less vulnerability to ground microwave interference effects [31].
iv. The DVB-S had a good spectrum capability, coverage area and position, leading to a larger target RCS, this resulted in reliable detection of a low-profile target [32].

In contrast, forward scattering radar (FSR) is special mode of bistatic radar that enhances the radar performance by improving the target RCS irrespective of its surface shape and have a relatively simple hardware [17], [18] and [33]. The major difference between the FSR from the monostatic and the bistatic systems is that, the FSR utilizes the effect due to electromagnetic waves of the target shadow rather than reflecting from the target. The identified FS features of an active radars such as appreciable RCS [34] simple receiver [20] counter to stealth technology; and high power yield [35], make it accessible and an option especially when dealing with low profile target like the drone.

Although achievements were made by the attempted methodologies, yet, some information was missing due to the target characteristics of low altitude, slow speed, and smaller RCS (LSS). This thesis investigated the potentiality of implementing a DVB-S based passive FSR system, such that the robustness features of passive radars [36] compensated the absence of range resolution in FSR. This enhances the current radar capability and simplify target detection [19]. Other implemented passive FSR system other than DVB-S based, also had their recorded achievements, but none of the illuminators can be guaranteed for all applications.

The WIFI-based system suffers background noise due to too many users resulted from its free nature [37]. A high integration gain required to detect a manoeuvring target for broadcasting-based illuminators [38], for their pronounced clutter interference due to the line of sight between ground clutter and the antenna[39]. This can be compensated using a high gain receiver coupled with long integration time to improve the SNR [34]. This thesis further proposed the use of additional information generated by the rotating blades called the micro-Doppler, to detect the drone. It is a Doppler generated from different parts of the moving body that involved rotation or vibrations [19] & [40]. This micro-Doppler was exploited by many civilian and military applications for target detection and recognition. In this study, a satellite (DVB-S) based passive FSR radar system is used to detect a drone by utilising the micro-Doppler generated by the rotating blades.

1.2 Problem Statement

The main goal of proposing the DVB-S based passive FSR system is to address some of the challenges faced by the limitation of conventional radars especially for low-profiled airborne target detection. These are as follows:

a) The low profile nature of drone, makes its micro-Doppler analysis difficult, hence, there is a need of a model to be used for easy analysis of micro-Doppler of a quadcopter drone in FSR geometry.
b) The flying altitude of a drone is outside the range of a conventional radar, making the drone surveillance area penetrative: A drone has a maximum allowable flying altitude of vertical height of 400 feet above the sea-level, which is outside the range of conventional radars, thus, the need for an illuminator within the area of surveillance, with good spectrum capability**.**
c) There is need for an implementation of an enhanced and inexpensive radar system that addressed a quadcopter drone detection by utilising its micro-Doppler due to rotating blades: This is due to the drone existence in the same surveillance volume with other small targets like birds and having a slow speed and a very low RCS, thus, the micro-Doppler helps in identifying the target.

To the best of our knowledge, there is no experimental study that has been published that implemented a DVB-S based passive FSR system, and detected a quadcopter drone via its micro-Doppler., except the one published by UPM under this work.

1.3 Aim and Objectives

This study aimed at implementing a DVB-S based passive FSR for drone detection by utilising the micro-Doppler scattered from the rotating blade. The objectives are as follows:

1. To design a framework that may serve as a model for micro-Doppler signature analysis of a quadcopter drone, comparable to an experimental response in FSR geometry.
2. To investigate the feasibility of using DVB-S signal as an illuminator for radar application and its implementation into FSR geometry for drone detection.
3. To implement an enhanced system by using DVB-S satellite signal for passive FSR system and detect a drone based on its micro-Doppler scattered by the rotating blade.

1.4 Scope of the Study

The scope of this work is to detect a quadcopter drone based on its micro-Doppler generated by the rotating blades, by using DVB-S based PFSR radar. Although the drone may be ambiguous and synonymously used for unmanned aerial/aircraft vehicle (UAV) due to the fact that every drone can be regarded as UAV, but not every UAV is considered to be a drone. Regulatory agencies, aircraft engineers and other stake holders, each viewed drone and UAV in their perspective. The agency considered several terms such as Unmanned Aircraft Systems (UAS), Remotely Piloted Aircraft Systems (RPAS) which is an UAS sub-category. Aircraft engineers viewed drone and UAV as interchangeable terms, but normally UAV is used to differentiate the military drone from hobbyist drone. Federal Aviation Administration (FAA) designated UAS to describe remote controlled helicopter and the department of defence used UAV to define software controlled aircraft or balloon from a distance [41].

In this study, drone is viewed as a hobbyist drone or copter drone characterized by multiple rotors like quadcopter, hexacopter, octocopter etc. (unlike UAV with fixed wings), be controlled by remote [42] and/or mobile apps, can have a programmable GPS route to follow, usually have video camera with live view to mobile phones and can carry payload [6]. Figure 1.2a-c illustrated some typical example of copter drones, and a fixed wing UAV in1.2d.

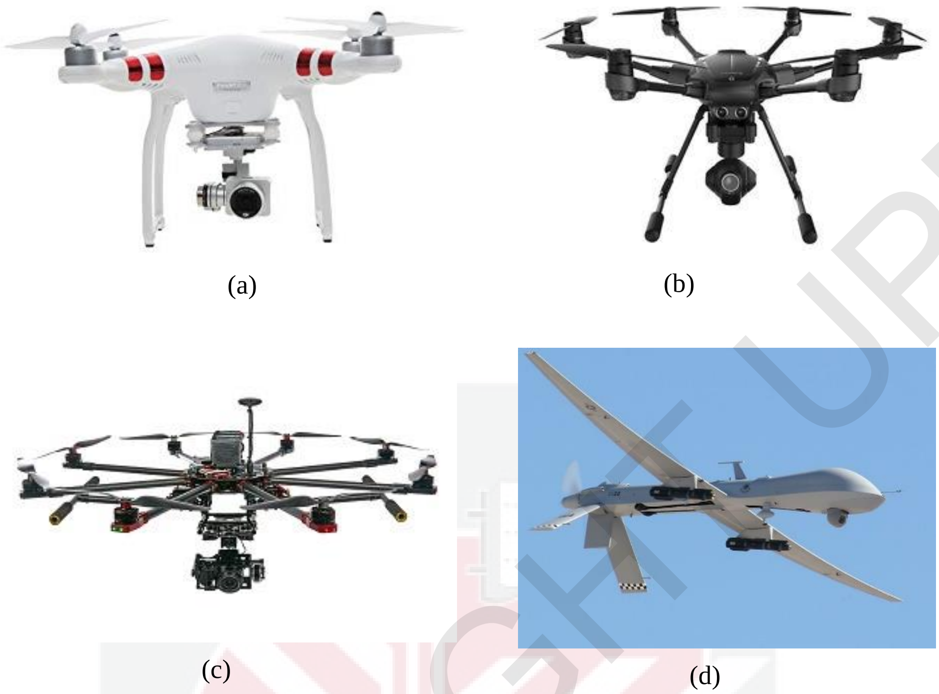

Figure 1.2 : (a) DJI Phantom (b) Yuneec typhoon (c) Octocopter (d) Fixed wing UAV. [13], [42]

In addition to the detection as said earlier, the micro-Doppler features due to the rotating blades was extracted to help identify the detected target. This work therefore, does not involve the classification aspect of the drone. Figure 1.3 illustrate a flow of the scope of this work.

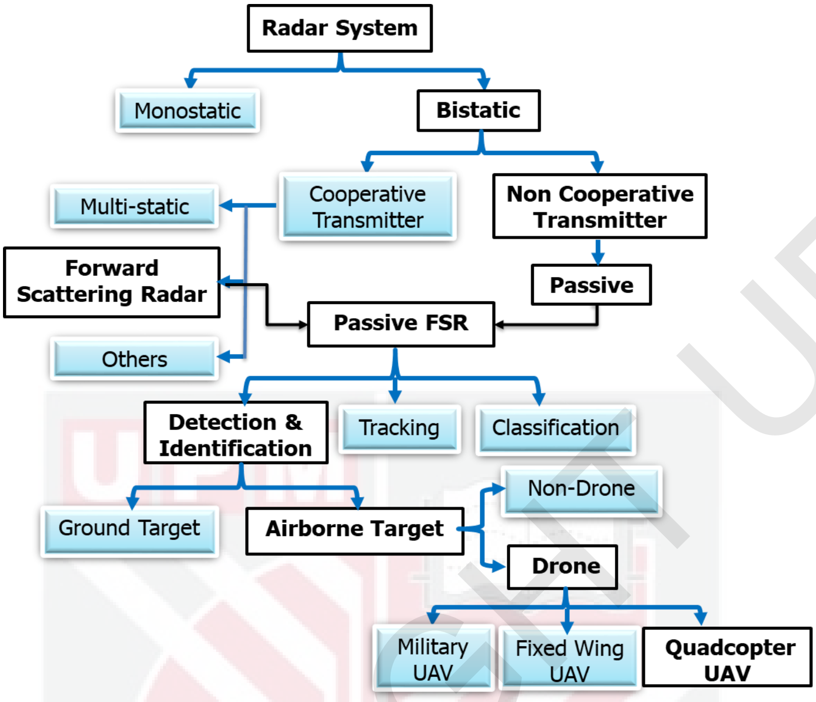

Figure 1.3 : **Scope of the study chart**

1.5 Significance of Studies

This study may open up a basis for counter measures of minimising the potential dangers and damages that may be caused as a result of drone misuse or other deliberated attempt. The system could be utilised but not limited to the following applications: protections for our homes, offices, recreational centres public places like banks and all other volatile environment that may suffer the consequences of drone attack or misuse.

Figure 1.4 : **Satellite based forward scattering radar (PFSR) potential application**

It can also serve as a surveillance measures for border monitoring and protection, security agencies, data centres, rehabilitation centres like prisons and other high profiled organisation governing the affairs of a nation. Figure 1.4 illustrated some potential application of our proposed system.

1.6 List of Contributions

The research contributions are listed as follows:

- Designed a model for micro-Doppler analysis of quadcopter drone in FSR geometry.
- Investigated the possibility of using Measat3a/3/3b, Malaysian satellite for radar application and airborne target detection.
- The system confirmed the FSR ability of improving detection of low profiled target characterised as LSS target.
- A commercial drone was successfully detected via its micro-Doppler features by using a complete DVB-S based passive FSR system.

1.7 Thesis Organization

Subsequently, this thesis was organised as follows: Chapter two presented the literature review of essential parameters involved in this study. It reviewed the literature that addressed drone detection by using non-radar, radar-based and the PFSR approach and the micro-Doppler analysis due to a rotating part of a target, precisely on airborne targets. Chapter three described the materials and methods used in the conduct of this study. Chapter four addressed the framework design of the quadcopter blade model for the analysis of micro-Doppler in FSR geometry. It further presented how a commercial phantom drone was detected in FSR geometry with parabolic dish antenna as the receiver; this served as the basis for the feasibility of using our developed receiving system. Chapter five presented a feasibility study of using Measat3a/3/3b Satellite signal into FSR geometry for drone detection. It also presented a step-by-step implementation of the complete DVB-S based passive FSR system for drone detection based on its micro-Doppler features. Chapter six finally, summarised the achievement made in this study and highlighted the limitation for future studies.

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