DESIGN AND IMPLEMENTATION OF A COLLISION AVOIDANCE SYSTEM FOR UNMANNED AERIAL VEHICLES

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ABSTRACT OF THE THESIS

Design and Implementation of a Collision Avoidance System
for Unmanned Aerial Vehicles
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In order to address the Federal Aviation Administration’s (FAA) ban on the use of unmanned aerial vehicles (UAVs), in the National Air Space System (NAS) due primarily to their potential for mid-air collisions, this thesis investigates different collision avoidance methods for UAVs. After reviewing the benefits and limitations of a number of different collision avoidance methods, a sense-and-avoid solution is designed based on a Geometric Vector Algorithm and recommended herein as a collision avoidance system for development and prototyping.

The two-part solution proposed consists of (1) a radar system to be used to detect a potential target, and (2) a collision avoidance algorithm that changes the pre-planned path of a UAV. The collision avoidance algorithm designed and tested herein demonstrates the ability to determine a new flight trajectory for a UAV so that a head-on collision can be avoided. The scope of this research is limited only to the case of two aircraft on a collision path. Although, it is hypothesized herein that this research could ultimately be extended for use in the prevention of a collision involving multiple-aircraft.
TABLE OF CONTENTS

PAGE

ABSTRACT .......................................................................................................................... iv

LIST OF TABLES ................................................................................................................ ix

LIST OF FIGURES .............................................................................................................. x

CHAPTER

1 INTRODUCTION .............................................................................................................. 1

   1.1 Problem Statement ................................................................................................. 1

   1.2 Developing a Sense-and-Avoid Algorithm .............................................................. 2

   1.3 Constraints to Collision Avoidance Solutions ....................................................... 2

   1.4 Thesis Objective .................................................................................................... 3

2 LITERATURE REVIEW OF COLLISION AVOIDANCE SYSTEMS ....................... 4

   2.1 Sensor Technologies .............................................................................................. 4

      2.1.1 Optical Camera ............................................................................................ 4

      2.1.2 Acoustics .................................................................................................... 5

      2.1.3 Laser/LIDAR ............................................................................................... 5

      2.1.4 Transponders .............................................................................................. 5

      2.1.5 Thermal Sensors .......................................................................................... 6

      2.1.6 Radar .......................................................................................................... 6

   2.2 Collision Avoidance Methods ................................................................................ 7

      2.2.1 Astar (A*) Algorithm .................................................................................. 7

      2.2.2 Geometric Vector Algorithm ....................................................................... 9

      2.2.3 Protocol Based Decentralized Collision Avoidance .................................... 10

      2.2.4 Optimization Algorithm ............................................................................ 11

      2.2.5 Autonomous UAV Path Planning and Estimation .................................... 11

      2.2.6 Airborne Collision Avoidance System X (ACAS X) .................................. 12

      2.2.7 Summary ..................................................................................................... 12
2.3 Potential Solution ...........................................................................................................13

3 RESEARCH METHODOLOGY ........................................................................................16

3.1 What is Radar? .............................................................................................................16

3.2 Radar Classifications ..................................................................................................17

3.3 Radar System Composition ..........................................................................................17

3.3.1 Waveform Generator .............................................................................................18

3.3.2 Transmitter/Modulator ...........................................................................................18

3.3.3 Switch ......................................................................................................................18

3.3.4 Antenna/Antenna Controller ..................................................................................18

3.3.5 Propagation Medium ..............................................................................................18

3.3.6 Receiver ..................................................................................................................19

3.3.7 Analog to Digital Converter ...................................................................................19

3.3.8 Digital Signal Processor ........................................................................................19

3.3.9 Timing and Control Elements ................................................................................19

3.4 Radar Terminology and Concepts .................................................................................19

3.4.1 Signal-to-Noise Ratio (SNR) ..................................................................................20

3.4.2 Pulse Radar Concepts ............................................................................................20

3.4.3 Radar Range Measurement .....................................................................................21

3.4.4 Radar Bandwidth .....................................................................................................22

3.4.5 Detection of Signals in Noise ..................................................................................22

3.4.6 Pulse Integration .....................................................................................................23

3.4.6.1 Coherent Integration ..........................................................................................23

3.4.6.2 Non-Coherent Integration ................................................................................24

3.4.7 Target Radar Cross Section ....................................................................................24

3.4.7.1 Calculation of Radar Cross Section ..................................................................24

3.4.8 The Concept of a Matched Filter ..........................................................................25

3.4.8.1 Implementation of the Matched Filter .................................................................25

3.4.8.2 Match Filter Convolution Process .....................................................................26

3.4.9 Antennas: What is an Antenna? ..............................................................................26

3.4.9.1 Characteristics of an Antenna ............................................................................26

3.4.9.2 Isotropic Antenna ..............................................................................................27

3.4.9.3 Directional Antenna ...........................................................................................27
3.4.10 Characteristics of an Antenna Pattern..........................................................28
3.4.11 Phased Array Antennas..................................................................................28
3.4.12 Moving Target Indicator (MTI) Techniques...................................................29
  3.4.12.1 Relationship between Doppler Frequency and Radial Velocity..........................................................29
  3.4.12.2 Data Collection for Doppler Processing.......................................................30
  3.4.12.3 Pulse Doppler Processing Techniques.........................................................31
3.5 Design and Analysis of the Radar System............................................................32
  3.5.1 Design of an End-to-End Radar System (Isotropic Antenna)..........................32
  3.5.2 Configuration Process.......................................................................................33
    3.5.2.1 Generate a Waveform..................................................................................33
    3.5.2.2 Configure the Transmitter.........................................................................34
    3.5.2.3 Configure the Antenna..............................................................................34
    3.5.2.4 Configure the Receiver..............................................................................34
    3.5.2.5 Define the Targets.....................................................................................34
    3.5.2.6 Setup of Matched Filter............................................................................34
    3.5.2.7 Range and Reference Losses.................................................................34
    3.5.2.8 Detection Threshold.................................................................................35
  3.5.3 System Simulation............................................................................................35
3.6 Design of an End-to-End Radar (Phased Array Antenna)......................................35
  3.6.1 Problem Statement............................................................................................37
    3.6.1.1 Waveform Generation (Rectangular Waveform).........................................37
    3.6.1.2 Configure the Transmitter.........................................................................37
    3.6.1.3 Configure the Antenna..............................................................................38
    3.6.1.4 Configure the Receiver..............................................................................38
    3.6.1.5 Phased Array Antenna Design....................................................................38
    3.6.1.6 Creation of a Scanning Schedule............................................................38
  3.6.2 Target Location................................................................................................38
  3.6.3 Received Pulse Synthesis..................................................................................38
4  RESULTS AND CONCLUSIONS..............................................................................40
  4.1 Results of Radar System Design (Isotropic Antenna)..........................................40
    4.1.1 Waveform Generator......................................................................................40
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1. Characteristics of the Three General Classes of Commercial UAVs</td>
<td>3</td>
</tr>
<tr>
<td>Table 3.1. Radar Classifications Based on Operating Frequency</td>
<td>17</td>
</tr>
<tr>
<td>Table 3.2. Radar Design Specifications</td>
<td>33</td>
</tr>
<tr>
<td>Table 5.1. UAV General Characteristics</td>
<td>49</td>
</tr>
<tr>
<td>Table 5.2. UAV Performance Characteristics</td>
<td>49</td>
</tr>
<tr>
<td>Table 5.3. UAV Payload Characteristics</td>
<td>50</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Demonstration of the A* algorithm</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>The A* algorithm</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Demonstration of the Geometric Vector Algorithm</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Two UAVs Headed for a Collision</td>
<td>13</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Collision Avoidance System Overview</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Block Diagram of Radar System</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Signal-to-Noise Ratio (SNR)</td>
<td>20</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Characteristics of a Pulse Radar</td>
<td>21</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Radar Range Measurements</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Relationship between Bandwidth and Range Resolution</td>
<td>22</td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>Detection of Signals in Noise</td>
<td>23</td>
</tr>
<tr>
<td>Figure 3.7</td>
<td>Coherent Integration</td>
<td>23</td>
</tr>
<tr>
<td>Figure 3.8</td>
<td>Non-Coherent Integration</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3.9</td>
<td>Matched Filter Concept</td>
<td>25</td>
</tr>
<tr>
<td>Figure 3.10</td>
<td>Matched Filter Implementation</td>
<td>26</td>
</tr>
<tr>
<td>Figure 3.11</td>
<td>Matched Filter Convolution Process</td>
<td>26</td>
</tr>
<tr>
<td>Figure 3.12</td>
<td>Isotropic Antenna</td>
<td>27</td>
</tr>
<tr>
<td>Figure 3.13</td>
<td>Directional Antenna</td>
<td>27</td>
</tr>
<tr>
<td>Figure 3.14</td>
<td>Antenna Gain Pattern</td>
<td>28</td>
</tr>
<tr>
<td>Figure 3.15</td>
<td>Phased Array Antennas</td>
<td>29</td>
</tr>
<tr>
<td>Figure 3.16</td>
<td>Data Collection for Doppler Processing</td>
<td>31</td>
</tr>
<tr>
<td>Figure 3.17</td>
<td>Doppler Filter Bank</td>
<td>32</td>
</tr>
<tr>
<td>Figure 3.18</td>
<td>High-level Radar Systems Design Model</td>
<td>33</td>
</tr>
<tr>
<td>Figure 3.19</td>
<td>Radar Signal Synthesis</td>
<td>36</td>
</tr>
<tr>
<td>Figure 3.20</td>
<td>Received Signal Synthesis</td>
<td>39</td>
</tr>
</tbody>
</table>
Figure 4.1. Linear Frequency Modulated (LFM) Waveform. ..........................................................40
Figure 4.2. Transmitted Signal, Received Signal & Match Filtered Signal. ........................................41
Figure 4.3. Gain-adjusted Signal for 10 Pulses..................................................................................42
Figure 4.4. A Single Pulse Rectangular Waveform............................................................................43
Figure 4.5. 3-D Response of a 30-by-30 Uniform Rectangular Array. ..............................................44
Figure 4.6. Antenna Gain Pattern of a 30-by-30 Uniform Rectangular Array. .......................................44
Figure 4.7. Phased Array Scan Map. ..................................................................................................45
Figure 4.8. Transmitted Pulse, Received Echo without/with Match Filtering............................................46
Figure 5.1. Target Trajectory of a UAV. ...............................................................................................50
Figure 5.2. Radar Estimate of the Target Position and Velocity. ..........................................................51
Figure 5.3. Displacement of the Maneuvering UAV..............................................................................54
Figure 5.4. TCAS II Advisories............................................................................................................55
Figure 5.5. Flow Chart of the Collision Avoidance Algorithm...............................................................56
Figure 5.6. Trajectory of Target 1 and Target 2 at T = 1 sec...............................................................57
Figure 5.7. Trajectory of Target 1 and Target 2 at T = 4 sec...............................................................57
Figure 5.8. Trajectory of Target 1 and Target 2 at T = 23 sec.............................................................58
Figure 5.9. Trajectory of Target 1 and Target 2 at T = 28 sec.............................................................58
Figure 5.10. Trajectory of Target 1 and Target 2 at T = 29 sec...........................................................59
Figure 5.11. Trajectory of Target 1 and Target 2 at T = 30 sec...........................................................59
Figure 5.12. Trajectory of Target 1 and Target 2 at T = 43 sec...........................................................60
Figure 5.13. Trajectory of Target 1 and Target 2 at T = 46 sec...........................................................60
Figure 5.14. Trajectory of Target 1 and Target 2 at T = 120 sec..........................................................61
CHAPTER 1

INTRODUCTION

Whenever the terminology unmanned aerial vehicle (UAV) is used, people often think of a remotely operated aircraft equipped with video sensors for retrieving data. Data retrieved by a UAV can be used for surveillance, search and rescue, oil exploration, filmmaking, journalism and law enforcement. Within the general American public, UAVs are commonly known for their specific military uses; however, over the last decade, a growing number of Unmanned Aerial Systems (UAS) vendors have catered to clients in each of the aforementioned industries [1].

In 2014, Fortune Magazine described the economic potential for commercial UAVs as follows:

The global market for commercial unmanned aircraft has already ballooned into a $2.5 billion industry, one that is growing 15% to 20% annually, and that is under the current law. One of the biggest potential markets for commercial drones—the U.S.—is not even open for business yet. While the use of unmanned aerial vehicles (UAVs) for commercial purposes is soaring in countries like Japan, Australia, France, and the U.K., the U.S. Federal Aviation Administration (FAA) has yet to institute regulations governing the operation of commercial unmanned aircraft, and in the meantime has issued a blanket ban prohibiting their use in nearly all endeavors. Despite the ban prohibiting the use of commercial unmanned aircraft, everyone from Fortune 500 companies to venture capitalist to startups is pouring vast amounts of money into the commercial unmanned aircraft technology. Amazon, Google, and German shipping giant DHL have made headlines by experimenting with drones for deliveries. Facebook says it is developing a drone the size of a 747 that could fly for months at a time, beaming down wireless signals. [2:134]

1.1 PROBLEM STATEMENT

In spite of the growing demand and promising business prospects for commercial unmanned aircraft, the FAA is not ready to allow commercial UAVs access to the National Airspace System (NAS) mainly because most commercial UAVs do not have the ability to detect and avoid other aircraft (manned or unmanned). UAVs that are not equipped with any
type of active communications device like a radar or a transponder—a device that transmits aircraft altitude, speed and location for target tracking—have no means of alerting or avoiding a potential mid-air collision, posing serious threats to air safety. This is the underlying problem that this thesis will attempt to solve.

1.2 DEVELOPING A SENSE-AND-AVOID ALGORITHM

One major challenge in attempting to solve this problem is that there is no way to predict the number of UAVs that are headed for a mid-air collision. Developing a sense and avoid algorithm for ten UAVs headed for a collision is a far more complex problem than developing a sense and avoid algorithm for two UAVs headed for collision. The development of a sense and avoid algorithm for every combination of UAVs headed for a mid-air collision is beyond the scope of this thesis. This thesis will focus instead on the design and implementation of a sense and avoid algorithm for two UAVs headed for a mid-air collision, with the expectation that this solution can eventually be customized for mid-air collisions involving multiple UAVs.

If a certifiable collision avoidance solution that works for all types of UAVs can be designed, tested and implemented, the FAA will have the assurance that allowing UAVs access to the NAS will not endanger air travel safety. Also, a successful solution could lead to a variety of new investments in commercial UAV technology. There are however, a number of constraints that need to be either minimized or overcome prior to realizing a certifiable product.

1.3 CONSTRAINTS TO COLLISION AVOIDANCE SOLUTIONS

The first constraint pertains to rules and regulations that each UAV must comply with. These rules and regulations are still in development by the FAA. In order to minimize any potential issues with prospective regulations, this thesis will utilize Right-of-way rules established in 14 CFR 91.113 as the primary guidelines for designing a collision and avoidance system. These rules will be discussed in a later chapter.

The second constraint pertains to the different UAV performance and payload capabilities that must be considered prior to developing a collision and avoidance solution. Table 1.1 lists three general classes of commercial unmanned aircraft.
Table 1.1. Characteristics of the Three General Classes of Commercial UAVs

<table>
<thead>
<tr>
<th></th>
<th>Low-end</th>
<th>Midrange</th>
<th>High-end</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Price</strong></td>
<td>Below $30</td>
<td>$30 to $5000</td>
<td>More than $5,000</td>
</tr>
<tr>
<td><strong>Classification</strong></td>
<td>Toy or R/C product</td>
<td>Low-speed UAV</td>
<td>Military or other functional UAV</td>
</tr>
<tr>
<td><strong>Engine Type</strong></td>
<td>Electronic motor</td>
<td>Electronic motor</td>
<td>Internal combustion or solar-powered engine</td>
</tr>
<tr>
<td><strong>Battery Life</strong></td>
<td>3 to 10 minutes</td>
<td>8 to 60 minutes</td>
<td>30 minutes to 30 days or more</td>
</tr>
<tr>
<td><strong>Payload Capacity</strong></td>
<td>0kg</td>
<td>0.5 to 9kg</td>
<td>More than 9kg</td>
</tr>
<tr>
<td><strong>Interaction</strong></td>
<td>Eye contact</td>
<td>Real-time view</td>
<td>Real-time view, satellite</td>
</tr>
<tr>
<td><strong>Function</strong></td>
<td>Flight</td>
<td>Aerial, security, self-sense, data collection</td>
<td>Survey and mapping, agriculture, tourism, communication</td>
</tr>
<tr>
<td><strong>Sensors</strong></td>
<td>None</td>
<td>Pressure sensors, ultrasonic altimeter, accelerometers, gyroscope, GPS</td>
<td>All sensors in midrange drones, thermal sensors, humidity sensors, radar, light detectors, obstacle sensors</td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>Low</td>
<td>Normal</td>
<td>High</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Remote Control</td>
<td>Remote control with signal sender and receiver</td>
<td>Professional control station</td>
</tr>
<tr>
<td><strong>Signal Transmission</strong></td>
<td>PWM</td>
<td>IR ray, Wi-Fi</td>
<td>IR ray, satellite signal</td>
</tr>
<tr>
<td><strong>Effective working range</strong></td>
<td>Less than 15m</td>
<td>Less than 1km</td>
<td>Less than 30km</td>
</tr>
<tr>
<td><strong>Working Height</strong></td>
<td>Less than 5m</td>
<td>Less than 1km</td>
<td>Less than 3 to 5km</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>1 to 3m/s</td>
<td>10 to 30m/s</td>
<td>30 to 400m/s</td>
</tr>
</tbody>
</table>

Source: [3]

The third constraint pertains to current state-of-the-art sense-and-avoid technologies: “The problem with an airborne sense and avoid system is that it requires size, weight and power on the air vehicle … and those are all in very short supply on smaller and Midrange UAS. Attaching any type of transponder to an air vehicle could quickly eat up precious power” [4:28].

1.4 Thesis Objective

Based on the above constraints, the main objective of this thesis is to design a sense-and-avoid solution, which is expected to take full control of a UAV and guide it past other aircraft (manned or unmanned) within the NAS. The scope of this solution is limited to high-end commercial unmanned aircraft, with the hope that a viable solution can ultimately be adapted for both Low-end and Midrange commercial unmanned aircraft based on this research.
CHAPTER 2
LITERATURE REVIEW OF COLLISION AVOIDANCE SYSTEMS

This chapter reviews prior research completed on the subject of unmanned aircraft and their ability to detect a target. First, state-of-the-art technology on a number of different aircraft sensors is examined, including discussion of the pros and cons of each sensor. There is also a discussion on the criteria that was used in selecting the desired sensor for the sense-and-avoid solution.

2.1 SENSOR TECHNOLOGIES

This section surveys available sensor technologies and their potential to be used in the development of a sense-and-avoid solution.

2.1.1 Optical Camera

An optical camera is a type of sensor technology that can be used to passively acquire information about a target based on reflected light. An optical camera is considered a non-cooperative type of sensor because it does not have the ability to broadcast information such as aircraft altitude, speed and location to another target. Compared to radar, an optical camera generally achieves accurate detection based on azimuth and elevation. An optical camera however, cannot operate at night or in inclement weather (rain, fog, etc.). An optical camera by itself cannot be used for range detection. Since optical cameras acquire target information passively, optical cameras have lower power consumption compared to radar or transponder devices. Unlike a transponder, which generally has the ability to provide the trajectory of a target to an aircraft, an optical camera derives the trajectory of a target of interest. A sense-and-avoid solution whose primary sensor is an optical camera has range limitations. An optical camera cannot detect moving targets, and can only be relied upon during the day or in good weather conditions [5].
2.1.2 Acoustics

Acoustics are a type of sensor technology that can be used to actively acquire information about a target based on listening. Similar to an optical camera, an acoustic sensor is considered a non-cooperative type of sensor: it does not have capacity to broadcast logistical information to another target [5].

Even though an acoustic sensor has the ability to provide accurate range detection, it can only detect a target as far as 100 ft. Research has shown that acoustic sensors provide “a spherical instantaneous coverage area, allowing the detection of air traffic approaching from any angle rather than from only a limited frontal sector” [6]. An acoustic sensor will allow target detection via a bearing of 360 degrees, both in azimuth and elevation. Acoustic sensors typically interface with a UAV flight control system in a Ground Control Station (GCS) to gather location and additional aircraft information in order to derive the trajectory of a target, and can be relied upon to detect moving targets. The drawback with using an acoustic sensor is that it relies on input from a pilot in a GCS [5]. The sense-and-avoid solution is expected to detect a target and autonomously avoid a collision without any type of input from a pilot.

2.1.3 Laser/LIDAR

Laser is a type of sensor technology that uses light from a timed semiconductor to actively detect information about a target. Similar to an acoustic sensor, laser is also considered a non-cooperative type of sensor. A laser range finder generally requires more power for operation mainly because it is an active sensor. Lasers typically provide more accurate target range information. However, lasers are limited in range up to 1000 ft. Laser can be relied upon to detect moving targets. Lasers generally provide narrow angular resolutions in terms of azimuth and elevation. Unlike a transponder, which generally has the ability to provide the trajectory of a target to an aircraft, laser derives the trajectory of a target of interest [5, 7].

2.1.4 Transponders

A transponder is a type of sensor technology that transmits aircraft altitude, speed and location for target tracking. Because of its ability to broadcast information to a target of interest, a transponder is considered a cooperative sensor. A transponder can be relied upon for accurate range detection and can detect a target as far as tens of miles. A transponder
calculates bearings (azimuth and elevation) based on pressure altitude. A transponder has the ability to provide the trajectory of a target to an aircraft. However, a transponder “does not permit sensing of non-transponding targets, so non-cooperative unmanned aircraft must be identified through other means” [5:4].

2.1.5 Thermal Sensors

A thermal sensor is a type of sensor technology that can be used to passively acquire information about a target based on temperature. A thermal sensor is considered a non-cooperative type of sensor because it does not have the ability to broadcast information to another target. Compared to radar, a thermal sensor generally achieves accurate detection based on azimuth and elevation. A thermal sensor by itself cannot be used for range detection. Since a thermal sensor acquires information about a target passively, it has lower power consumption compared with a radar or a transponder. Unlike a transponder, which generally has the ability to provide the trajectory of a target to an aircraft, a thermal sensor derives the trajectory of a target of interest [5].

2.1.6 Radar

Radar is a type of sensor technology that actively detects information about a target such as position, motion, speed and direction. Radar is considered a non-cooperative type of sensor because it does not have the ability to broadcast logistical information to another target. Radar can be relied upon for accurate range detection, and can detect a target as far as a mile. Radar can search for a target with 360° azimuth coverage and 360° elevation coverage. Radar can see through obstacles and operates in spite of severe weather conditions. Images captured by radar, however, have lower detection quality compared to images captured by an optical camera. Unlike a transponder, which generally has the ability to provide the trajectory of a target to an aircraft, a radar system derives the trajectory of a target of interest [5].

Each sensor comes with its own advantages and disadvantages, however, the best sensor technology for the design of a sense-and-avoid system is expected to meet the following capabilities:

- Actively detect a target
- Detect non-transponding targets
- Detect moving targets at any range (short or long)
• Scan with 360° azimuth coverage
• Scan with 360° elevation coverage
• Detect smaller targets and larger targets
• Operate in all-weather conditions
• Work day and night
• Detect targets in 3D-space
• Derive the trajectory of a target of interest

Out of all of the sensors discussed, radar is the sensor that meets the most of the stated requirements. The limitations of radar do not affect this research.

2.2 Collision Avoidance Methods

This section of the thesis is a presentation on different collision avoidance methods and a criteria that was used to select a collision avoidance method.

2.2.1 Astar (A*) Algorithm

Peter Hart, Nils Nilsson and Bertram Raphael of Stanford Research Institute (now SRI International) first described the A* algorithm in 1968. The A* algorithm is an extension of Edsger Dijkstra’s 1959 algorithm and it includes a heuristics function. The A* algorithm is a discrete path finding algorithm, which can be customized for collision avoidance by searching among all possible paths in a grid that a moving object needs to travel prior to reaching its intended destination [8, 9]. The A* algorithm fulfils its goal based on a path that incurs the smallest cost (least distance travelled or shortest time), and among these paths it first considers the ones that appear to lead most quickly to a designated end point [8, 9].

Figure 2.1 and 2.2 are demonstrations of how the A* algorithm works. Figure 2.1 shows a grid of nodes, the white nodes represent the areas in the grid that a moving target can access. The red nodes represent the obstacles, which in real life could be a building, a mountain or another aircraft in space. The objective of the A* algorithm is to find the shortest path from node A to node B. Figure 2.2 is an illustration of the path determined by the A* algorithm that leads a moving target most quickly to a designated end point.
Based on a published research paper by Eivind Hope Sørbo, A* determines a path that leads most quickly to a designated end point based on an estimate of the cost (total weight) still to go to the end node [8, 9]. Specifically, A* selects the path that minimizes the function $f(n)$

$$f(n) = g(n) + h(n)$$
Where:

\( n \) is the end node on the path

\( g(n) \) is the cost of the path from the start node to \( n \)

\( h(n) \) is the heuristic function that estimates the cost of the cheapest path from \( n \) to the goal.

The heuristic function is problem-specific. For the algorithm to find the actual shortest path, the heuristic function must be allowable, meaning that it never overestimates the actual cost to get to the nearest node [8, 9].

The limitations with the A* algorithm is that it requires a lot of computing time if the search includes many nodes, making this algorithm computationally intensive [8, 9]. Also, considering the fact that the A* algorithm is a discrete path finding algorithm, it finds an optimal path only in a discrete grid, which may not be applicable when an optimal path needs to be determined in a continuous grid [8, 9].

2.2.2 Geometric Vector Algorithm

The Geometric Vector Algorithm is a method of collision avoidance that relies on using geometry to alter the pre-planned path of aircraft headed for a collision. If two UAVs are on course for a head-on collision, they can both be considered point masses travelling at a constant velocity. The general assumption here is that a collision between two UAVs can be avoided:

- if the location of each target can be estimated in space and time
- if the heading or bearing of a target can be determined

Figure 2.3 is a demonstration of the Geometric Vector Algorithm. As illustrated in Figure 2.3, UAV1 and UAV2 are on course for a head-on collision. The horizontal distance between P1 and P4 represents the minimum distance of separation between the two UAVs. Using Pythagoras Theorem, UAV1 undergoes both a vertical and horizontal displacement based on a bank angle in order to transition from P1 to P2. This same concept is applicable when UAV1 transitions from P2 to P3.
The Geometric Vector Algorithm is generally considered a simple concept in terms of its complexity and it is easily visualized in 2-D. The main objective of this algorithm is minimizing the time that it takes for a UAV to avoid a collision. The calculations involved in this algorithm are based on trigonometry and Pythagoras Theorem and can easily be programmed in MATLAB. The Geometric Vector Algorithm is not as computationally intensive as the A* algorithm, however, calculations can easily become complex for situations that involves multiple UAVs with known or unknown velocities and positions. Also, the Geometric Vector Algorithm is based on a fixed set of predefined rules without performing any additional computation in the event that a UAV discovers a new obstacle.

2.2.3 Protocol Based Decentralized Collision Avoidance

Baraa Albaker and Nasrudin Abd Rahim in a published research paper have presented a way of solving the collision avoidance problem using a protocol based decentralized approach. A description of this methods is as follows:

This method offers a very elegant solution to conflict free navigation for a team of agents, where each agent represents an aircraft. Inter-agent communication includes sharing position, velocities, waypoints and heading. Agents make decisions based on a common set of rules decided based on theoretical deduction rather than empirical observation. This method is decentralized, highly scalable and guarantees safety. However, the tradeoff is that unnecessary long trajectories can be generated during long missions. [10:5]
2.2.4 Optimization Algorithm

Eivind Hope Sørbo in a published research paper presents optimization as a method to solve the collision avoidance problem. The optimization problem can be expressed as

\[
\min_{x} F(x) \tag{2.1}
\]

Subject to:

\[
g(x) = 0, i = 1, \ldots, n \tag{2.2}
\]

\[
h(x) = 0, i = 1, \ldots, n \tag{2.3}
\]

Where:

- \( F(x) \) is the object function, which is minimized
- \( g(x) \) and \( h(x) \) are the constraints.

The object function can be optimized with respect to path length, fuel consumption, weather condition, time or speed, depending on the type of UAV. This optimization problem can be solved using Mixed Integer Linear Programming [8]. One challenge when solving an optimization problem is that it requires a lot of computation time. This is normally not a problem for off-line path planning before the mission has started. However, in a collision avoidance approach with unknown obstacles, the use of optimization can be very challenging [8]. Each time the vehicle discovers a new obstacle it needs to redo the optimization problem, which takes time [8].

2.2.5 Autonomous UAV Path Planning and Estimation

John Tisdale and J. Karl Hedrick in the published research paper “Autonomous UAV Path Planning and Estimation.” conducted research using a team of UAVs to search for and localize a stationary target using an optical camera as the primary method of sensing. Frames received from the team of UAVs were processed by an algorithm to form likelihood functions, which were subsequently combined with a Bayesian function in order to estimate the position of the target. Likelihood functions are passed between vehicles in order to cooperatively search for a target. Cooperative planning according to this research was accomplished by exchanging predicted sensing actions between vehicles. Data for
cooperative sensing and planning is exchanged among UAVs over a wireless ad-hoc network [11].

2.2.6 Airborne Collision Avoidance System X (ACAS X)

Another example of research pertaining to a UAV collision avoidance algorithm includes research completed by Mykel J. Kochenderfer, Jessica E. Holland, and James P. Chryssanthacopoulos [12]. This research involves:

The development of an Airborne Collision Avoidance System X (ACAS X), which is a major enhancement to the current state-of-the-art technologies on surveillance and traffic advisory logic such as Traffic Collision Avoidance System (TCAS). ACAS X represents a move from the beacon-only surveillance of TCAS to a plug-and-play surveillance architecture which supports surveillance based on global positioning system (GPS) data and accommodates new sensor modalities, including radar and electro-optical sensors, which are especially important for unmanned platforms. The logic optimization process behind ACAS X uses a probabilistic dynamic model and a multi-objective utility model as input. The probabilistic dynamic model is a statistical representation of where the aircraft will be in the future, and the multi-objective utility model represents the safety and operational objectives of the system. Next, an optimization process called dynamic programming is used to produce a numeric lookup table. The ACAS X system receives sensor measurements every second. On the basis of these sensor measurements, the system infers the distribution over the aircraft’s current status. This status, or state estimation, takes into account the probabilistic dynamic model and the probabilistic sensor model. This state distribution determines where to look in the numeric logic table to determine the best action to take—that is, whether to issue an advisory and if so, what vertical rate to use. This processing chain is repeated once per second with every new sensor measurement. Two important concepts are critical to understanding the logic optimization process. The first is a Markov decision process, which is essentially the probabilistic dynamic model combined with the utility model. The second is dynamic programming, which is the iterative computational process used to optimize the logic. [12:22]

2.2.7 Summary

This section of the thesis presented an overview of different collision avoidance methods that are applicable for the design of a sense-and-avoid solution. Even though research shows that the Autonomous UAV Path Planning and Estimation method in 2.2.5 has actually been used in a real-world test with UAVs, this method is not a viable sense-and-avoid solution because of its method of sensing, which is based on optics. A sense-and-avoid
solution based on optics can only be relied upon during the day but not at night or in inclement weather. The optimization method although useful is generally used in conjunction with the other collision avoidance methods. The Protocol Based Decentralized Collision Avoidance and ACAS X methods involve a lot of advanced complexity. These two methods are candidates of future research work. The Geometric Vector Algorithm on the other hand was selected as the algorithm for this thesis mainly because it is simple in terms of complexity and it can easily be realized in a computer program such as MATLAB.

2.3 POTENTIAL SOLUTION

This section presents a potential solution to the problem statement discussed in the introduction. The airborne collision avoidance solution can be broken down into two main parts: (1) a radar system for detecting a target, and (2) a collision avoidance algorithm that changes the pre-planned path of a UAV, so that a mid-air collision is avoided. This solution is limited in scope to two UAVs which are headed for a mid-air collision as shown in Figure 2.4.

![Figure 2.4. Two UAVs Headed for a Collision.](image-url)
Figure 2.5 is a high-level system overview of the collision avoidance system. The collision avoidance system consists of the following units: a sensor, an estimator, collision detector and the collision avoidance algorithm.

a. Sensor: for this thesis, the general assumption is that the potential collision avoidance solution receives position and velocity data from a radar system for all targets within a certain distance from an aircraft.

b. Estimator: After a radar system identifies a target within range from a UAV, an estimator based on an Euler equation is used to estimate a target's velocity and bearing using positional data from a radar simulation.

c. Collision Detection: Once the all relevant data has been received by the collision avoidance system, the system determines if the distance between two UAVs approaching a head-on collision is equal to or less than the minimum distance of separation. If the aforementioned condition is true the collision avoidance algorithm is activated.

d. Collision Avoidance: Once the collision avoidance algorithm is activated, the Geometric Vector Algorithm described in section 2.2.2 is executed, with the expectation that this algorithm will provide guidance to an aircraft so that a mid-air collision can be avoided.

The two-part collision avoidance solution is specified below:

a. Design a Non-Coherent-Pulse Doppler radar in MATLAB to fulfill a Search and Detection mission. The threat consists of a single UAV. The radar frequency band is X-band. The radar has a range resolution of 150 m, an operating frequency of 10 GHz, an RF bandwidth of 3 MHz, a pulse width of 0.3 microseconds, a PRF of 18750 Hz and the number of pulses of integration is 10. Assume a noise figure $F = 6$ dB, and total receiver loss $L = 8$ dB. Assume that 13 dB signal-to-noise ratio (SNR) is a reasonable detection threshold. Finally, assume a flat earth.

b. Design a collision avoidance algorithm based on the Geometric Vector approach in MATLAB that will be implemented in conjunction with the radar system described above. This algorithm is expected to function autonomously of any kind of ground equipment. If the risk of collision is imminent, the radar is expected to detect and alert an unmanned aircraft about the possibility of a mid-air collision. The algorithm, on the other hand, is expected to determine a new trajectory for an aircraft so that a collision can be avoided.
The next two chapters will describe the research methodology used in the design of the radar system and the collision avoidance algorithm. Other issues pertaining to the proposed solution will also be discussed.
CHAPTER 3

RESEARCH METHODOLOGY

The research methodology used to design the airborne radar system was derived from an online Introduction to Radar Systems lecture course presented by Dr. Robert M. O’Donnell, a recently retired senior staff member at MIT Lincoln Laboratory [13]. This course consisted of ten lectures developed to provide a basic working knowledge and understanding of radar systems concepts and technologies. Upon gaining an understanding of key radar concepts and technologies, I performed additional research on Mathworks.com, and found tools such as the Phased Array System Toolbox that can be used to design and simulate an End-to-End Radar System. The design and simulation of a radar system for this thesis is based on a MathWorks model using the MATLAB programming language. Fundamental radar concepts associated with the proposed solution will be summarized herein prior to addressing the radar system design.

3.1 What is Radar?

The word radar is an abbreviation for Radio Detection and Ranging. Bassem R. Mahafza, Ph.D. and Atef Z. Elsherbeni, authors of the textbook Simulations for Radar Systems Design define radar as follows:

Radar systems use modulated waveforms and directive antennas to transmit electromagnetic energy into a specific volume of space to search for targets. A target within a search volume will reflect portions of this energy back to the radar. The returning echoes are then processed by the radar’s receiver to extract target information such as range, velocity, azimuth, elevation, and size. Radars are useful for commercial and military purposes, specifically, in the areas of surveillance, target identification or discrimination, target tracking, fire control, ground surveillance, reconnaissance, ground mapping, moving target detection and air traffic control. [14:19]
3.2 Radar Classifications

Radar is generally classified based on characteristics, such as frequency band of operation. Table 3.1 shows radar classifications based on operating frequency. The information in Table 3.1 shows the portions of the electromagnetic spectrum that are allocated for use by radar systems. The International Telecommunications Union (ITU) makes these allocations so that radar systems do not interfere with one another in the usage of specific frequency bands [14].

Table 3.1. Radar Classifications Based on Operating Frequency

<table>
<thead>
<tr>
<th>Letter designation</th>
<th>Frequency (GHz)</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>0.003 – 0.03</td>
<td>High Frequency (HF) radars utilize the electromagnetic waves reflection off the ionosphere to detect targets beyond the horizon</td>
</tr>
<tr>
<td>VHF</td>
<td>0.03 – 0.3</td>
<td>Very High Frequency (VHF) and Ultra High Frequency (UHF) bands are used in very long range Early Warning Radars (EWR)</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3 – 1.0</td>
<td>Radars in the L-band are primarily ground-based and ship based systems that are used in long range military and air traffic control search operations</td>
</tr>
<tr>
<td>L-band</td>
<td>1.0 – 2.0</td>
<td>Radars in the L-band are primarily ground-based and ship based systems that are used in long range military and air traffic control search operations</td>
</tr>
<tr>
<td>S-band</td>
<td>2.0 – 4.0</td>
<td>Most ground and ship based medium range radars operate in the S-band</td>
</tr>
<tr>
<td>C-band</td>
<td>4.0 – 8.0</td>
<td>Most weather detection radar systems are C-band radars. Medium range search and fire control military radars and metric instrumentation radars are also C-band</td>
</tr>
<tr>
<td>X-band</td>
<td>8.0 – 12.5</td>
<td>The X-band is used for radar systems where the size of the antenna constitutes a physical limitation; this includes most military multimode airborne</td>
</tr>
<tr>
<td>Ku-band</td>
<td>12.5 – 18.0</td>
<td>The higher frequency bands (Ku, K, and Ka) suffer severe weather and atmospheric attenuation. Therefore, radars utilizing these frequency bands are limited to short range applications, such as police traffic radar, short range terrain avoidance, and terrain following radar</td>
</tr>
<tr>
<td>K-band</td>
<td>18.0 – 26.5</td>
<td>The higher frequency bands (Ku, K, and Ka) suffer severe weather and atmospheric attenuation. Therefore, radars utilizing these frequency bands are limited to short range applications, such as police traffic radar, short range terrain avoidance, and terrain following radar</td>
</tr>
<tr>
<td>Ka-band</td>
<td>26.5 – 40.0</td>
<td>The higher frequency bands (Ku, K, and Ka) suffer severe weather and atmospheric attenuation. Therefore, radars utilizing these frequency bands are limited to short range applications, such as police traffic radar, short range terrain avoidance, and terrain following radar</td>
</tr>
<tr>
<td>W-Band</td>
<td>40 – 100+</td>
<td>W-band are mainly limited to missile seekers</td>
</tr>
</tbody>
</table>

Source: [14]

3.3 Radar System Composition

Figure 3.1 shows a block diagram of a radar system. Each component within the diagram is a radar subsystem and will be described separately.
3.3.1 Waveform Generator

The Waveform Generator controls the frequency, phase, bandwidth, range resolution and the modulation characteristics of the transmitted electromagnetic (EM) wave [15].

3.3.2 Transmitter/Modulator

The transmitter is responsible for amplifying the signal generated by the Waveform Generator and produces a short-duration, high-power radio frequency (RF) pulse of energy that is radiated into space by an antenna via a switch [15].

3.3.3 Switch

The amplified signal by the transmitter goes into a switch, where the microwave energy is sent to an antenna with none of the microwave energy leaking into the receiver [15].

3.3.4 Antenna/Antenna Controller

The antenna is responsible for directing the energy in the microwave pulse to the area and space where a target needs to be illuminated. The antenna also intercepts and captures the received echoes from a target of interest [15].

3.3.5 Propagation Medium

The electromagnetic (EM) wave is transmitted into a propagation medium (air/atmosphere); when it hits a target, some of the energy will be reflected off the target [15].
3.3.6 Receiver

Once an electromagnetic (EM) wave is transmitted into space to hit a target, the switch is turned off and the receiver listens for a returning echo. The receiver is responsible for amplifying, filtering, translating and demodulating the radio wave captured by the antenna [15].

3.3.7 Analog to Digital Converter

The received echo is transformed from an analog signal to a digital signal by the Analog to Digital Converter via a process called sampling [15].

3.3.8 Digital Signal Processor

The Digital Signal Processor processes the target echo in order to:

- Attain the best resolution of the received echo through a process called Pulse Compression [15].
- Determine if the frequency of the received echo has been shifted. If the frequency has been shifted, a process called Doppler Processing can be used to determine the radial velocity of the moving target [15].
- Establish a target detection threshold limit in order to determine if a detected target is larger than the defined threshold. If a detected target exceeds a detected threshold limit, the target is classified as a true target. If a detected target falls below the threshold limit, the target will be classified as a false alarm [15].
- Determine the location of a target in space and time from one pulse to another through a process called Pulse Integration. The parameters derived through target tracking and parameter estimation include range, direction, elevation, azimuth and accuracy [15].

3.3.9 Timing and Control Elements

The timing and control elements are responsible for maintaining synchronization between all of the aforementioned radar subsystems [15].

3.4 Radar Terminology and Concepts

The terminology and concepts necessary to a fundamental understanding of radar systems is described below.
3.4.1 Signal-to-Noise Ratio (SNR)

The signal-to-noise ratio is a measure of signal strength in the presence of noise. The SNR can also be described as a measure of a radar receiver’s sensitivity to noise. The best method for measuring SNR is by comparing the power in the signal of interest to the power in the noise. A radar receiver generally has better receiver sensitivity if the desired signal power level is significantly greater than the noise level as shown in Figure 3.2 [16].

Figure 3.2. Signal-to-Noise Ratio (SNR). Source: [16].

I. SNR can be expressed as a fraction:

II. $\text{SNR} = \frac{\text{Power of the Wanted Signal (Psignal)}}{\text{Power of the Noise (Pnoise)}}$

III. $\text{SNR}_{\text{dB}} = 10\log_{10}\left(\frac{\text{Psignal}}{\text{Pnoise}}\right)$

IV. The relative value of two things, measured on a logarithmic scale, is often expressed in deciBel’s (dB)

V. $\text{SNR}_{\text{dB}} = \text{Psignal}_{\text{dB}} - \text{Pnoise}_{\text{dB}}$

3.4.2 Pulse Radar Concepts

The characteristics of pulse radar such as peak power, duty cycle, average power, pulse repetition frequency and pulse repetition interval are all defined and illustrated in Figure 3.3 [13].
I. Duty cycle = \( \frac{\text{Pulse Length (T)}}{\text{Pulse repetition interval (PRI)}} \)

II. Average power = Peak power (Pt) * Duty cycle

III. Pulse repetition frequency (PRF) = 1/(PRI)

IV. For a continuous wave (CW) radar: Duty cycle = 100% (always on)

V. Bandwidth = 1/(Pulse Length)

VI. \( T_c = M \cdot PRI \), where \( T_c \) is the Coherent processing Interval (CPI) and \( M \) is the number of pulses in the CPI. \( M = 2, 3 \), or sometimes 4 for MTI. \( M \) is usually much greater for Pulse Doppler [13].

### 3.4.3 Radar Range Measurement

Based on Figure 3.4, a pulse is transmitted to hit a target at the speed of light. The radar’s receiver receives the reflected pulse after a round trip duration \( \tau \). The target range \( R \) is be computed as follows [13]:

\[
R = \frac{c \cdot \tau u}{2}
\]

Where \( c = \) speed of light = 3*10^8 meters per second

\( \tau \) = round trip time (in seconds)

\( R = \) slant range (in meters)
3.4.4 Radar Bandwidth

Bandwidth (BW) is the difference between the upper and lower cut-off (3-dB) frequencies of a radar receiver measured in hertz. The wider the bandwidth of the radar receiver, the greater the degree of noise that will be input into the receiver. Since noise exits at all frequencies, the broader the frequency range to which the receiver bandpass filters are tuned, the higher the intensity levels of the noise and the lower the signal-to-noise ratio. Figure 3.5 illustrates how a higher bandwidth leads to a low range resolution and vice versa. Shorter pulses have higher bandwidth and better resolution [13].

3.4.5 Detection of Signals in Noise

A detection threshold is established in Figure 3.6 to determine if a detected target is larger than the detection threshold in the presence of random noise [13].

a. If the power in the detected target exceeds the detection threshold, the target is classified as a true target [13].

b. If the power level of the random noise signal exceeds the detection threshold, the random noise signal is classified as a False Alarm [13].

c. If a detected target’s power level falls below the detection threshold, the target will be classified as a missed target [13].
3.4.6 Pulse Integration

Pulse Integration is a technique used to improve a radar receiver’s sensitivity. This is accomplished by inserting an integrator in the receiving path of a radar. The pulse integrator adds radar echoes from different successive pulse periods. The location of the integrator in the radar-receiving path usually determines the type of pulse integrator [17].

3.4.6.1 COHERENT INTEGRATION

With coherent integration, a coherent integrator is inserted between a matched filter and an amplitude detector as illustrated in Figure 3.7. The coherent integrator samples the returns from each transmit pulse at a spacing equivalent to the range resolution of the radar and adds the returns from N pulses. After it accumulates the N pulse summation, it performs the amplitude detection and threshold check. SNR is increased by a factor of N. Coherent Integration results in radar keeping track of a target’s amplitude and phase. Fast Fourier Transformations (FFTs) in a digital signal processor can be used to perform coherent integration [13].
3.4.6.2 NON-COHERENT INTEGRATION

With Non-Coherent integration, a Non-Coherent integrator is inserted between an amplitude detector and Threshold Device as illustrated in Figure 3.8. For a Non-Coherent integrator, since the signal has undergone amplitude detection, the phase information is lost. A non-coherent integrator operates in the same fashion as the coherent integrator in that it sums the returns from N pulses before performing the threshold check. SNR is increased by N. Non-Coherent Integration results in radar keeping track of a target’s amplitude and not the phase. In older radars, low-pass filters are used to implement them. In newer radars, a non-coherent integrator is implemented in special purpose hardware or radar computer as digital summers [13].

Figure 3.8. Non-Coherent Integration. Source: [13].

3.4.7 Target Radar Cross Section

Robert M. O’Donnell in the MIT Radar lectures defines the Target Radar Cross Section as follows: “Radar cross section is the area intercepting that amount of power, which if radiated isotropically, produces the same received power in the radar” [13]. Target radar cross section is represented by a single term, σ, known as the radar cross-section, which has units of m². This unit shows that the radar cross section is an area. Factors that determine radar cross-section include: target size, target shape, material of the target orientation, and the direction of the illuminating radar [13].

3.4.7.1 CALCULATION OF RADAR CROSS SECTION

Radar cross section σ is defined as:

\[
\sigma = \frac{4\pi r^2 \cdot Sr}{St}
\]
Where:
\[ \sigma = \text{a measure of the target’s ability to reflect radar signals in the direction of the radar receiver, in } [\text{m}^2] \]
\[ S_t = \text{the power density that is intercepted by the target, in } [\text{W/m}^2] \]
\[ S_r = \text{the scattered power density in the range } r, \text{ in } [\text{W/m}^2] \]

3.4.8 The Concept of a Matched Filter

For a simple continuous wave (CW) pulse, the pulse energy is a product of power and the duration of the pulse. The match filter in Figure 3.9 is responsible for maximizing the peak signal-to-mean noise ratio. The frequency response of the continuous wave pulse has its peak energy concentrated at one center frequency. The phase increases linearly. For a rectangular CW pulse signal, the matched filter is a simple bandpass filter, which exhibits the same shape and power spectrum as the transmitted pulse. It also has the same frequency spectrum characteristics as the transmitted pulse [13].

Figure 3.9. Matched Filter Concept. Source: [13].

3.4.8.1 IMPLEMENTATION OF THE MATCHED FILTER

The matched filter is implemented by “convolving” the reflected echo with the “time reversed” transmit pulse as illustrated in Figure 3.10.
3.4.8.2 MATCH FILTER CONVOLUTION PROCESS

a. Move digitized pulses by each other, in steps

b. When data overlaps, multiply samples and then sum them

3.4.9 Antennas: What is an Antenna?

An antenna is a means for radiating or receiving radio waves or a transitional structure between a transmitter and free space. A radiated electromagnetic wave consists of electric and magnetic fields, which jointly satisfy Maxwell’s equations [13].

3.4.9.1 CHARACTERISTICS OF AN ANTENNA

- An antenna focuses the energy in a transmitter into a focused beam in order to direct a large amount of energy density towards a target [13].
- When listening following signal transmission, the antenna should listen selectively at an angle to where the returning echo is coming from [13].
- The antenna will typically measure the angle (azimuth and elevation) where the target is coming from, thus allowing the user to resolve targets [13].
3.4.9.2 ISOTROPIC ANTENNA

An isotropic antenna typically radiates the same intensity of radiation in all directions. It has no preferred direction of radiation. It radiates uniformly in all directions over a sphere, centered on the source [13].

![Figure 3.12. Isotropic Antenna. Source: [13].](image)

3.4.9.3 DIRECTIONAL ANTENNA

A directional antenna is an antenna which radiates or receives greater power in specific directions, allowing for increased performance and reduced interferences from unwanted sources [13].

![Figure 3.13. Directional Antenna. Source: [13].](image)
3.4.10 Characteristics of an Antenna Pattern

Figure 3.14 is an antenna gain pattern for a parabolic reflector antenna with an aperture diameter of 5m, a frequency of 300 MHz and a wavelength of 1 meter [13]. The figure plot below shows the following [13]:

- An antenna gain of 24 dBi (decibel over isotropic)
- Isotropic side lobe level of 6 dBi
- Side lobe level of 18 dBi
- Half-power (3-dB) Beamwidth: 12 degrees

![Antenna Gain Pattern](image)

Figure 3.14. Antenna Gain Pattern. Source: [13].

3.4.11 Phased Array Antennas

A phased array antenna is composed of many radiating elements, each with a phase shifter. Beams are formed by shifting the phase of the signal emitted from each radiating element, in order to provide constructive/destructive interference to steer the beams in the desired direction. Figure 3.15 shows the gain patterns for different antennas. The following concepts are critical to understanding the design and construction of an airborne radar system [13]:

a. The gain pattern for an isotropic element is uniform across [13].

b. If an array of elements is combined, the amplitudes and phases constructively and destructively interfere with each other. A gain pattern that is a maximum response at the center is obtained [13].
c. If more elements are added, the main beam gets narrower and the gain increases; directivity is increased and the side lobes are reduced [13].

d. By adjusting the phase of the array elements, the direction can be changed in milliseconds or microseconds. The main beam will be pointing in a different direction [13].

![Diagram of Isotropic Element, Array, and Phased Array](image)

Figure 3.15. Phased Array Antennas. Source: [13].

### 3.4.12 Moving Target Indicator (MTI) Techniques

MTI techniques are used to separate moving targets from the clutter using High Pass Filtering techniques, where low Doppler frequencies are rejected. The High Pass Filter passes a moving target using short waveforms, typically two or three pulses. Conversely, Pulse Doppler (PD) techniques separate the targets into different velocity regimes and cancel clutter. PD techniques provide a good estimate of the target radial velocity using long waveforms, which are typically tens to thousands of pulses [13].

#### 3.4.12.1 Relationship between Doppler Frequency and Radial Velocity

The Doppler frequency and radial velocity are both related via the below equation:

\[ F_d = \frac{2V}{\lambda} \]
Where:

\( F_d \) = the Doppler frequency (in Hertz)

\( V \) = the radial velocity (in meters per second)

\( \lambda \) = the wavelength (in meters)

### 3.4.12.2 Data Collection for Doppler Processing

The returning echoes received by the radar are analog signals, which need to be converted into digital signals for processing. An analog-to-digital converter is used to sample the analog signals one at a time and then convert them into digital signals. The returning echo is a vector with both amplitude and phase, this vector is characterized by real (in-phase) and imaginary parts (quadrature) [13].

The data collection for Doppler processing is as follows:

A radar pulse is transmitted, and the returning echo is observed and recorded in order to compute the range. The range is computed based on the speed of light multiplied by the sampling time of the returning echo, then divided by 2. Figure 17, below, demonstrates how to use the sample time of returning echoes to determine the distance of the target from the radar receiver. For Pulse 1, the 12\(^{th}\) sample is 8.3 km away from the radar receiver. For Pulse 1, two different matrixes—the real and imaginary—were filled for a returning echo. In dealing with MTI, the value of M usually equals 2, 3 or 4. [13]
3.4.12.3 PULSE DOPPLER PROCESSING

The returning echoes received from M-transmitted pulses are received at the radar receiver. They are initially stored in a matrix for a given range gate and processed through different filters in parallel. The filter setup for processing the M pulses below is called a Doppler Filter Bank. Each of the complex returns are multiplied by a set of weights with specific Doppler characteristics, as shown in the curve below. Filter 1 will pass a set of Doppler velocities; the same applies to each subsequent filter. These curves are logarithmic in shape. The goal is to determine if the target is moving. A set of Doppler filters are used to show how fast the target is moving. Through the process of generating the output of the linear filter, the integration all of the pulses in the coherent processing interval may be seen. This Doppler processing technique is used to reject clutter. It is also used to resolve targets into different velocity segments, while allowing for fine grain target radial velocity estimation [13].

Figure 3.16. Data Collection for Doppler Processing. Source: [13].
3.5 Design and Analysis of the Radar System

The early part of this thesis focused on concepts fundamental to radar system design. The remainder of this section will involve a discussion on the methodology that was used to design and simulate an End-to-End radar system using the MATLAB Phased Array Toolbox.

a. A simple ground-based radar model configured with an isotropic antenna is designed and simulated in MATLAB.

b. This ground-based radar model is then customized whereby the isotropic antenna is replaced with a phased array antenna.

3.5.1 Design of an End-to-End Radar System (Isotropic Antenna)

The goal of this section is to design a ground-based radar system to detect three non-fluctuating targets, which are all in line of sight of the radar. The radar system to be designed is equipped with an isotropic antenna. The three targets have the following RCS, locations and velocities:

a. Target 1: RCS of 2.2, location in 3-D space: [2500;0;0], velocity: [0;0;0]

b. Target 2: RCS of 1.1, location in 3-D space: [4800;0;0], velocity: [300;0;0]

c. Target 3: RCS of 1.05, location in 3-D space: [6200;0;0], velocity: [-300;0;0]

The radar is designed to meet the specifications in Table 3.2.
Table 3.2. Radar Design Specifications

<table>
<thead>
<tr>
<th>Radar Design Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar Type</td>
</tr>
<tr>
<td>Radar Frequency Band</td>
</tr>
<tr>
<td>Radar Operating Frequency</td>
</tr>
<tr>
<td>RF bandwidth (instantaneous)</td>
</tr>
<tr>
<td>Pulse width</td>
</tr>
<tr>
<td>PRF (variable)</td>
</tr>
<tr>
<td>Range Resolution</td>
</tr>
<tr>
<td>Number of Pulses to Integrate by</td>
</tr>
</tbody>
</table>

Source: [18]

A high-level radar system model consists of the following sub-systems illustrated in Figure 3.18: a waveform generator, a transmitter, transmit and receive array, an environment, targets, propagation effects models, a receiver and a signal processor.

Figure 3.18. High-level Radar Systems Design Model.

3.5.2 Configuration Process

The following steps were followed in order to configure each radar subsystems discussed above:

3.5.2.1 GENERATE A WAVEFORM

Using the radar specifications in Table 3.2, a Linear Frequency Modulated (LFM) Waveform was generated.
3.5.2.2 **Configure the Transmitter**

The radar transmitter was configured with a peak power of 2240 Watts and a gain of 20 dB.

3.5.2.3 **Configure the Antenna**

The isotropic radar antenna was configured to operate at the radar operating frequency of 10 GHz. Pulses were propagated from this antenna at a speed of 3e8 m/s.

3.5.2.4 **Configure the Receiver**

The radar receiver was configured with the following parameters: Gain: 20 dB, Loss Factor: 0, Noise Method: ‘Noise temperature’, Noise Figure: 0, Reference Temperature: 290K and Sample Rate: 6000000.

3.5.2.5 **Define the Targets**

To test the radar system’s ability to detect targets, the target RCS, location in 3-D and velocity were defined as follows:

a. Target 1: RCS of 2.2, location in 3-D space: [2500;0;0], velocity: [0;0;0]

b. Target 2: RCS of 1.1, location in 3-D space: [4800; 0; 0], velocity: [300; 0; 0]

c. Target 3: RCS of 1.05, location in 3-D space: [6200; 0; 0], velocity: [-300; 0; 0]

For simulation purposes a propagation channel between the radar system and each of the three targets was defined. Since this radar system design is monostatic, the channels were set to simulate two-way propagation delays.

3.5.2.6 **Setup of Matched Filter**

Each of the received pulses from the target were first passed through a matched filter to improve the SNR prior to pulse integration.

3.5.2.7 **Range and Reference Losses**

After the matched filter stage, the SNR is generally expected to be improved. However, because the received signal power is range dependent, the return of a close target will be much stronger than the return of a target farther away. To ensure that the threshold is fair to all the targets within the detectable range, a time-varying gain was used to compensate for the range dependent loss in the received echo.
3.5.2.8 **Detection Threshold**

The detector compares the signal power in each of the received echoes to a given threshold. The noise is assumed to be white Gaussian and the detection is non-coherent. For this simulation, the detector at the receiver had a threshold of 4e-11.

3.5.3 **System Simulation**

Following the configuration of all of the sub-systems, the pulse generated by the radar was synthesized based on the flow chart in Figure 3.19, which is a flow chart that runs a system simulation for 100 pulses.

3.6 **Design of an End-to-End Radar (Phased Array Antenna)**

The isotropic antenna discussed in Section 3.5 typically transmits the same amount of power in all directions, very similar to a light bulb. A light bulb that is turned on transmits the same amount of brightness in all directions; in the case of a UAV antenna, this is not what is desired. An end-to-end radar system requires a laser pointer or an antenna that has a narrow beam of electromagnetic wave that can point in any direction.

In designing a radar system, the main objective is to send out an electromagnetic wave which will bounce of a target and return to the radar system. The echo returning from the target is used to determine the distance of the target to the radar. If the same amount of electromagnetic waves is sent in all directions, it is not possible to tell if a target is an aircraft that is approaching the radar or a bird that is moving away from the radar system. This clearly defeats the purpose of radar. Therefore, a radar antenna must send out a narrow beam of electromagnetic waves that will allow the radar to determine the distance and the precise direction of the target object being detected.
Figure 3.19. Radar Signal Synthesis.
Phased Array Antennas are a group of antennas very similar to the light bulb antennas described previously. These antennas are placed next to each other either in a rectangular grid or in a straight line. When each of the antennas sends out the same signal, a very interesting result occurs. As the sinusoidal waves that the antennas transmit travel outward, they constructively and destructively interfere with each other. If the phased array antenna has been designed correctly, the waves will all add up to form a narrow beam in one specific direction, but then cancel each other out in all other directions. If the same exact signal is sent from each of the antennas, the signals add up to form a narrow beam that is perpendicular to the antennas [19].

If a small time delay is added to each of the signals that is propagated out of each antenna, the direction of the narrow beam formed by the antennas changes. This new direction depends on how much time delay is added into the system. Time delay is easy to implement in digital processing [19].

3.6.1 Problem Statement

Design a Scan Radar using a uniform rectangular array to fulfil the following mission: Search and Detection. This problem statement builds upon the problem statement defined in section 2.1. It simulates a phased array radar that periodically scans a predefined surveillance region. A 900-element rectangular array was used in this monostatic radar simulation.

3.6.1.1 WAVEFORM GENERATION (RECTANGULAR WAVEFORM)

A single pulse rectangular waveform was generated to meet the following requirements: sample rate = 5995849.16; pulse width = 3.33564095198152e-07; PRF = 29979.2458; Output Format: Pulses; Number of Pulses = 1.

3.6.1.2 CONFIGURE THE TRANSMITTER

The radar transmitter was configured to have a peak power of 5226 Watts and a gain of 20 dB.
3.6.1.3 **Configure the Antenna**

The isotropic radar antenna was configured to operate through the radar operating frequencies 5 GHz – 15 GHz. Pulses were propagated from this antenna at a speed of 3e8 m/s.

3.6.1.4 **Configure the Receiver**

The radar receiver was configured with the following parameters: Gain: 20 dB; Loss Factor: 0; Noise Method: Noise temperature; Noise Figure: 0; Reference Temperature: 290K; Sample Rate: 5995849.16.

3.6.1.5 **Phased Array Antenna Design**

A 30-by-30 uniform rectangular array with an element spacing lambda/2 was designed.

3.6.1.6 **Creation of a Scanning Schedule**

A scanning schedule was created for the phased array antenna. The phased array antenna was required to search in the azimuth dimension. The radar was required to search from +45 degrees to -45 degrees in azimuth. According to this schedule, the revisit time should be less than 1 second, meaning that the radar should revisit the same azimuth angle within 1 second.

3.6.2 **Target Location**

The two non-fluctuating targets had the below-stated mean RCS, initial positions and velocities respectively:

a. Target 1: MeanRCS, 1.6, Initial Position, [3532.63; 800; 0], Velocity, [-100; 50; 0]

b. Target 2: MeanRCS, 1.2, Initial Position, [2000.66; 0; 0], Velocity, [60; 80; 0]

3.6.3 **Received Pulse Synthesis**

Once all subsystems have been defined, the received signals may be simulated. The total simulation time corresponds to one pass through the surveillance region. Because the reflected signals are received by an array, a beam-former pointing to the steering direction
was used to obtain the combined signal. Figure 3.20 shows a flow chart of a system simulation for that runs for 150 cycles.

Figure 3.20. Received Signal Synthesis.
CHAPTER 4

RESULTS AND CONCLUSIONS

The previous chapter discussed the fundamental concepts necessary to design a radar system. These radar concepts were used to design a simple ground-based radar system. The ground-based radar system was later customized to a radar design that was more applicable for airborne applications. This chapter discusses the results of the radar system designed using an isotropic antenna and the radar system designed using a phased array antenna.

4.1 RESULTS OF RADAR SYSTEM DESIGN (ISOTROPIC ANTENNA)

The results of the end-to-end radar system design are stated below.

4.1.1 Waveform Generator

A plot of the LFM waveform is illustrated in Figure 4.1.

![Linear Frequency Modulated (LFM) Waveform](image)

Figure 4.1. Linear Frequency Modulated (LFM) Waveform.
The scope plot in Figure 4.1 shows the following:

- An increasing LFM waveform with a sweep bandwidth of 3MHz
- The pulse width of the LFM waveform is 6.67 microseconds
- A pulse repetition interval of the LFM waveform is 0.53 microseconds
- The LFM waveform has a 12.5% \((6.67\times10^{-6}/0.53\times10^{-6})\) duty cycle.

### 4.1.2 System Simulation

A MATLAB simulation of the transmitted signal, the received signal, and the Match-filtered signal is shown in Figure 4.2.

*Figure 4.2. Transmitted Signal, Received Signal & Match Filtered Signal.*
4.2 RESULTS DATA

The scope plots in Figures 4.2 and 4.3 show simulation results of a radar system designed to detect three non-fluctuating targets. A system simulation of the end-to-end radar system in the two plots above shows four time-scopes, which are used to observe the radar pulse at different stages of the radar signal processing chain. In Figure 4.2, the first three scopes display the transmitted signal, received signal, and the post-matched-filter and a gain-adjusted signal for 10 pulses.

a. Figure 4.2 shows a high-power pulse train in scope 1. However, scope 2 demonstrates a much weaker received signal due to propagation losses that occur when an electromagnetic wave initially illuminates a target and a radar receiver receives the returning echo.

b. In scope 3 of Figure 4.2, only the first target can be detected above the detection threshold. The two other targets cannot be detected using the preset detection threshold.

c. In Figure 4.3, even after matched-filtering and subsequent pulse integration by a factor of 10, all three targets are not easily detected.

4.2.1 Results Radar System Design
(Phased Array Antenna)

4.2.1.1 WAVEFORM GENERATOR

A plot of the LFM waveform is illustrated in Figure 4.4.
The single pulse rectangular waveform in Figure 4.4 has a pulse width of 0.3 microseconds. Dividing this value by the pulse repetition interval of (1/30000) obtains a single pulse rectangular waveform with a 1% duty cycle.

4.2.1.2 **Uniform Rectangular Array**

A 3-D and an array gain pattern of a 30-by-30 uniform rectangular array with an element spacing lambda/2 is shown in Figure 4.5 and Figure 4.6 respectively. Figure 4.5 shows a main lobe along the X-axis in addition a number of side lobes.
Figure 4.5. 3-D Response of a 30-by-30 Uniform Rectangular Array. Source: [18].

Figure 4.6. Antenna Gain Pattern of a 30-by-30 Uniform Rectangular Array. Source: [18].
The Figure 4.6 plot shows the following:

- An antenna gain of 0 dBi (decibel over isotropic)
- Side lobe level of 13 dBi below the main lobe

4.2.1.3 **THE PHASED ARRAY SCAN**

The scan map in Figure 4.7 shows two peaks. The target closest to the radar is detected at about 0 degrees in azimuth, the other target is detected at about 12 degrees in azimuth.

![Phased Array Scan Map](image)

**Figure 4.7. Phased Array Scan Map. Source: [18].**

4.3 **SUMMARY OF RESULTS**

This section demonstrated how to simulate a phased array radar to scan a predefined surveillance region for two targets, one target is located in space at [2000.66; 0; 0] and moving at a Velocity [60; 80; 0] and a second target located in space at [3532.63; 800; 0] and moving at a Velocity [-100; 50; 0]. There are three scope plots in Figure 4.8.
a. The first scope plot shows a rectangular waveform generated with a 1% duty cycle.

b. The second scope plot shows a detected target located at approximately 3.53 km from a radar receiver. As shown by the plot, the received echo is highly attenuated.

c. The third scope plot shows how a matched filter was used to improve the signal-to-noise ratio by a factor of 10.

4.4 CONCLUSIONS (RADAR SYSTEM DESIGN)

This section of this thesis highlights the main points of the research associated with the design of the radar system:

a. Peak Power Optimization

In the design of the radar system, the original transmit power, calculated based on a single antenna isotropic antenna, was about 5.3 kilowatts. With the design that included the 900-element phased array antenna, the power required for each element was re-calculated using the radar range equation to be about 65 Milliwatts. A phased array antenna provides a significant reduction in power compared to an isotropic antenna.
b. Scanning Schedule
The phased array antenna for this radar system was designed to search from +45 degrees to -45 degrees in azimuth for each transmitted pulse. A pre-calculated scan step of -6 degrees and a search volume from +45 degree to -45 degree (90 degrees total) resulted in a total number of 15 steps for the entire surveillance region of 90 degrees. The number of pulse integrations specified in the radar requirements were 10, which results in 150 values for all 10 pulses.

c. Processing the Received Echoes in a Data Matrix
The early review of radar systems contained herein discussed the fact that the returning echo is a vector with both amplitude and phase; this vector is characterized by real (in-phase) and imaginary parts (quadrature). The vector is stored in a data matrix, with the fast time (time within each pulse) along each row, and the slow time (time between pulses for each scan) along each column. The fast time was computed by dividing the total number of samples (6000000 samples/second) by the pulse repetition frequency (18,750 Hertz) for a value of 320. The data matrix is a 320 by 150 matrix.

d. Data Collection for Doppler Processing
The early review of radar systems contained herein discussed the fact that, when a radar pulse is transmitted, the returning echo is listened to and sampled in order to then compute the range. The range is computed based on the speed of light multiplied by the sampling time of the returning echo all divided by a value of two. The sample times pertaining to the returning echoes are used to determine how far a target is away from a radar before and after match filtering the returning echo.

e. Pulse Integration
The signal-to-noise ratio in each returning echo in the data matrix was improved by non-coherently integrating the received pulses. The non-coherent integrator adds radar returns from different successive pulse periods in the 320 by 150 data cube. The non-coherent integrator summed the returns from 10 pulses before performing the threshold check. SNR is increased by 10.

f. Range Detection
Threshold detection was performed on all of the integrated pulses in the 320 by 150 data cube. The detection scheme identifies the peaks and then translates their positions into the corresponding ranges of the targets [18]. In estimating the range of the two targets, two peaks were visible above the detection threshold, corresponding to the two targets defined earlier [18]. These two peaks were used to find the locations and estimate the range and angle of each target [18].

g. Doppler Estimation
Upon successfully estimating the ranges of the targets, the Doppler information was estimated for each target. Doppler estimation is essentially a spectrum estimation process. The first step in Doppler processing is to generate the Doppler spectrum from the received signal. The received signal after the matched filter is a matrix with columns that correspond to the receive pulses. Unlike range estimation, Doppler processing processes the data across the pulses (slow time),
which is along the columns of the data matrix. Because there is one sample from each pulse, the sampling frequency for the Doppler samples is the pulse repetition frequency (PRF). Since 10 pulses for 15 scan steps were transmitted, there were 150 samples available for Doppler processing [18].
CHAPTER 5

METHODOLOGY

5.1 COLLISION AVOIDANCE ALGORITHM

Having spent a significant amount of discussion on the design of a radar system, this chapter will focus on the collision avoidance algorithm. The two UAVs discussed earlier in the potential solution section of this thesis, both satisfy general, performance, and payload characteristics as defined in Tables 5.1, 5.2, and 5.3.

Table 5.1. UAV General Characteristics

<table>
<thead>
<tr>
<th>RPA General Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>16 feet 5 in (5.00 m)</td>
</tr>
<tr>
<td>Wingspan</td>
<td>35 feet 4 in (10.75 m)</td>
</tr>
<tr>
<td>Height</td>
<td>2 feet 4.5 in (0.75 m)</td>
</tr>
<tr>
<td>Empty weight</td>
<td>560 lbs. (250 kg)</td>
</tr>
<tr>
<td>Gross weight</td>
<td>1,140 lbs. (520 kg)</td>
</tr>
<tr>
<td>Powerplant</td>
<td>1 × Rotax 582, 65 horse power (48 kW)</td>
</tr>
</tbody>
</table>

Source: [20]

Table 5.2. UAV Performance Characteristics

<table>
<thead>
<tr>
<th>UAV Performance Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed</td>
<td>120 mph (192 km/h)</td>
</tr>
<tr>
<td>Endurance</td>
<td>28 hours</td>
</tr>
<tr>
<td>Service ceiling</td>
<td>25,000 feet (7,600 m)</td>
</tr>
</tbody>
</table>

Source: [20]
Table 5.3. UAV Payload Characteristics

<table>
<thead>
<tr>
<th>UAV Radar Weight and Power Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar</td>
</tr>
<tr>
<td>Transmitter</td>
</tr>
<tr>
<td>Receiver &amp; Exciter</td>
</tr>
<tr>
<td>Processor</td>
</tr>
<tr>
<td>Antenna system</td>
</tr>
<tr>
<td>Cables and connectors</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

Source: [20]

5.2 GENERAL PRINCIPLES AND CONCEPTS

The UAV target trajectory assumed here is shown in Figure 5.1.

![Target Trajectory of a UAV](image)

**Figure 5.1. Target Trajectory of a UAV.**

The location of the Target is assumed at the following points in space and time:

i. At $t = 1$, assume the target is actually located at point M

ii. At $t = 2$, assume the target is actually located at point N

iii. At $t = 3$, assume the target is actually located at point O

a. If the radar processes the initial target position M at $t = 1$, the estimated target position is $M'$

b. At $t = 2$, the estimated target position $N'$ is computed based on Euler’s equation:

$$X(t + 1) = X(t) + dt * V(t)$$

where:

* $X(t + 1)$ is the estimated target position at $t + 1$
* $X(t)$ Initial position of the target at $t = 1$ second
* $dt$ is the rate at which we update the information read by the radar
* $V(t)$ is the velocity of the target at a specific moment in time

$$N' = \text{Velocity of the target} \times \text{time} + M$$

c. At $t = 3$, the estimated target position $O'$ is: Velocity of the target*time + N
The above radar system design was used to estimate the location of each target’s position and velocity, as shown in Figure 5.2.

Figure 5.2. Radar Estimate of the Target Position and Velocity.

a. At t = 1 second, the actual position M of the target can be represented by

\[
\begin{bmatrix}
dx_1 \\
dy_1 \\
dz_1 
\end{bmatrix}
\]

represented in space by the 3-D matrix:

\[
\begin{bmatrix}
dx_1 \\
dy_1 \\
dz_1 
\end{bmatrix}
\]

b. If the radar processes the actual position of the target, the estimated position of the target M’, can be represented by the matrix:

\[
\begin{bmatrix}
dx_1 \\
dy_1 \\
dz_1 
\end{bmatrix}
\rightarrow [Radar \ function] \rightarrow \begin{bmatrix}
dx_1' \\
dy_1' \\
dz_1' 
\end{bmatrix}
\]

(5.1)

c. At t = 2 seconds, the estimated target position N’ can be represented by the matrix:

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z 
\end{bmatrix} \* \text{dt} + \begin{bmatrix}
dx_1 \\
dy_1 \\
dz_1 
\end{bmatrix} = \begin{bmatrix}
dx_2' \\
dy_2' \\
dz_2' 
\end{bmatrix}
\]

(5.2)

Where the 3-D matrix \[
\begin{bmatrix}
V_x \\
V_y \\
V_z 
\end{bmatrix}
\]
represents the velocity of the target.

d. At t = 3 seconds, the estimated target position P’ can be represented by the matrix:

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z 
\end{bmatrix} \* \text{dt} + \begin{bmatrix}
dx_2 \\
dy_2 \\
dz_2 
\end{bmatrix} = \begin{bmatrix}
dx_3' \\
dy_3' \\
dz_3' 
\end{bmatrix}
\]

(5.3)

Where the 3-D matrix \[
\begin{bmatrix}
dx_2 \\
dy_2 \\
dz_2 
\end{bmatrix}
\]
represents the actual position of the target at t = 2 seconds.
5.3 Right-of-Way Rules

Having already discussed the constraints pertaining to the lack thereof regulations for unmanned aircraft operating in the national airspace, this thesis will adopt 14 CFR 91.113 Right-of-way rules, as the primary guidelines for designing a collision and avoidance system. The Right-of-way rules are as follows:

a. Inapplicability. This section does not apply to the operation of an aircraft on water [21].

b. General. When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft to see and avoid other aircraft. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear [21].

c. In distress. An aircraft in distress has the right-of-way over all other air traffic [21].

d. Converging. When aircraft of the same category are converging at approximately the same altitude (except head-on, or nearly so), the aircraft to the other’s right has the right-of-way. If the aircraft are of different categories—
   1. A balloon has the right-of-way over any other category of aircraft; [21]
   2. A glider has the right-of-way over an airship, powered parachute, weight-shift-control aircraft, airplane, or rotorcraft [21].
   3. An airship has the right-of-way over a powered parachute, weight-shift-control aircraft, airplane, or rotorcraft [21].
      However, an aircraft towing or refueling other aircraft has the right-of-way over all other engine-driven aircraft [21].

e. Approaching head-on. When aircraft are approaching each other head-on, or nearly so, each pilot of each aircraft shall alter course to the right [21].

f. Overtaking. Each aircraft that is being overtaken has the right-of-way and each pilot of an overtaking aircraft shall alter course to the right to pass well clear [21].

g. Landing. Aircraft, while on final approach to land or while landing, have the right-of-way over other aircraft in flight or operating on the surface, except that they shall not take advantage of this rule to force an aircraft off the runway surface, which has already landed and is attempting to make way for an aircraft on final approach. When two or more aircraft are approaching an airport for landing, the aircraft at the lower altitude has the right-of-way, but it shall not take advantage of this rule to cut in front of another, which is on final approach to land, or to overtake that aircraft [21].
5.4 General Concepts and Assumptions

Each UAV will not change its speed instantaneously. The air traffic by default will not maneuver, which is to say that a UAV will only avoid a collision if it avoids the point of collision by a specific distance in meters or more. The primary factor in displacing an UAV is the bank angle. For a given bank angle, the time required to displace an RPA by a specified distance in meters is relatively independent of the aircraft velocity [22]. For a typical head-on collision (+/-60 degrees), this can be shown through the application of the turn radius and the turn rate equations:

\[ r = \frac{v^2}{g \tan \theta} \]

Where:
- \( r \) = turn radius of the RPA (in meters)
- \( v \) = True speed of the RPA (meters per second)
- \( g \) = acceleration due to gravity (meters per second squared)
- \( \theta \) = bank angle

\[ \omega = \frac{g \tan(\theta) \times 360}{v \times 2 \times \pi} \]

Where:
- \( \omega \) = turn rate, degrees/second

The UAVs used in simulating the collision avoidance algorithm are both on the same elevation. A worst case scenario of a head-on collision between the two UAVs is assumed. The flight path of the aircraft will be visualized in MATLAB in standard Cartesian coordinates. The location of the non-maneuvering aircraft in space at any point in time position \((y) = \text{velocity} (v) \times \text{time} (t)\). The maneuvering aircraft will however be displaced in space horizontally and vertically. The goal of the maneuver is to be \(Y\) meters away from the non-maneuvering position at the point of collision.

An aircrew will be allowed to input specific variables for airspeed and bank angle for the maneuver and determine the amount of time needed to remain “well clear” of the collision. Using this value of \( t \), one can calculate the range needed to detect a traffic conflict by computing the relative velocities of the two aircraft involved in the collision. If the two
aircraft are involved in a head-on collision, the velocity of the maneuvering aircraft $V_{uav1}$ (m/s) and the velocity of the non-maneuvering aircraft will be $-V_{uav2}$ (m/s). The relative velocities between the two aircraft will be $V_{uav1}$ (m/s) – ($-V_{uav2}$ (m/s), which results in $V_{uav1}$ (m/s) + $V_{uav2}$ (m/s). The range needed to detect a traffic conflict: $R = t[V_{uav1}$ (m/s) + $V_{uav2}$ (m/s)]

5.4.1 Displacement of Maneuvering UAV

Section E of 14 CFR 91.113 Right-of-way rules states that the following: “When aircraft are approaching each other head-on, or nearly so, each pilot of each aircraft shall alter course to the right” [21]. Here, the maneuvering UAV will be displaced vertically and horizontally as shown in Figure 5.3.

![Figure 5.3. Displacement of the Maneuvering UAV.](image)

a. P1 in the above diagram represents the location of the maneuvering UAV at the time it has received notification about a Mid-air collision and needs to make a turn.

b. When the maneuvering UAV moves from P1 to P2, it undergoes a horizontal displacement of X1’ and a vertical displacement of Y1’ as shown in the Figure 32.

c. The primary factor in displacing an air vehicle is the bank angle theta.
d. The distance between the origin O and point P1 or P2 is called the radius R of the arc. Using trigonometry, the horizontal displacement of the maneuvering UAV at a specific time (t) was determined as follows:

\[
\sin(\theta) = \frac{X1'}{R}
\]

\[
X1' = R\sin(\theta \cdot t)
\]

e. The vertical displacement of the maneuvering UAV at a specific time (t) was determined as follows:

\[
Y1' = R - R \cdot \cos(\theta \cdot t)
\]

5.4.2 TCAS II Advisories

Pursuant to TCAS II, the FAA issues the following types of oral advisories: Traffic advisories (TA) and Resolution advisories (RA) [23]. When a TA is issued, pilots are instructed to initiate a visual search for the traffic causing the TA. If the traffic is visually acquired, pilots are instructed to maintain visual separation from the traffic. When an RA is issued, pilots are expected to respond immediately to the RA, unless doing so would jeopardize the safe operation of the flight. The collision avoidance algorithm stated herein utilized the traffic advisory time of 48 seconds. The TCAS II advisories are illustrated in Figure 5.4.

Figure 5.4. TCAS II Advisories.

5.5 Methodology

The collision avoidance algorithm is based on the flow chart shown in Figure 5.5. In order to maximize space, Figure 5.5 is illustrated on the following page.
Create 2-D Matrix to store Actual Position and Velocity of Target 1

Create 2-D Matrix to store the Estimates Position and Velocity of Target 1

Create 2-D Matrix to store Actual Position and Velocity of Target 2

Create 2-D Matrix to store the Estimates Position and Velocity of Target 2

Assign an initial position and velocity for both Target 1 and Target 2

Set Flag = 0

Using the radar function, estimate the position and velocity of Target 2

Plot the Actual position of Target 1 in Cartesian Coordinates

Plot the Estimated position of Target 2 in Cartesian Coordinates

Compute the distance between Actual position of Target 1 and the Estimated position of Target 2

Compute the relative velocities between Target 1 and Target 2

Define a traffic advisory time for warning an aircraft about an upcoming collision

Compute detection Range

Distance from Target 2 < range_of_detection

Set Flag = 1

Distance from Target 2 > range_of_detection

Set Flag = 0

Target 1 make a circular motion (compute vertical and horizontal displacements)

Target 2 stays on its original track

Distance from Target 2 < range_of_detection

Exit Loop

Loop Counter <= 120

Calculate the actual position and velocity of Target one for future advancements in time

Calculate the actual position and velocity of Target two for future advancements in time

Figure 5.5. Flow Chart of the Collision Avoidance Algorithm.
5.6 Collision Avoidance Results

Figure 5.6. Trajectory of Target 1 and Target 2 at T = 1 sec.

Figure 5.7. Trajectory of Target 1 and Target 2 at T = 4 sec.
Figure 5.8. Trajectory of Target 1 and Target 2 at T = 23 sec.

Figure 5.9. Trajectory of Target 1 and Target 2 at T = 28 sec.
Figure 5.10. Trajectory of Target 1 and Target 2 at T = 29 sec.

Figure 5.11. Trajectory of Target 1 and Target 2 at T = 30 sec.
Figure 5.12. Trajectory of Target 1 and Target 2 at $T = 43$ sec.

Figure 5.13. Trajectory of Target 1 and Target 2 at $T = 46$ sec.
5.6.1 Summary of Collision Avoidance Results

From the MATLAB plots above, UAV\textsubscript{1} at \( t = 1 \) sec. has an initial position of \([0; 2500; 0]\); and an initial velocity of \([80; 0; 0]\); UAV\textsubscript{2} at \( t = 1 \) sec. has an initial position of \([12000; 2500; 0]\); and an initial velocity of \([-80; 0; 0]\). Based on a plot of the trajectory of the two aircraft, it is clear that the two aircraft are approaching a head-on collision. The maneuvering aircraft is UAV\textsubscript{1}; UAV\textsubscript{2} is the non-maneuvering aircraft. If UAV\textsubscript{1} is moving at a speed of \(80\text{m/s}\) and UAV\textsubscript{2} is moving at a speed of \(-80\text{m/s}\), then the relative velocity between the two aircraft is \(160\text{m/s}\). This simulation, used a TCAS II Traffic Advisory time of 48 seconds. The range needed to detect a traffic conflict was calculated as \(48\text{seconds} \times 160\text{m/s} = 7680\text{ meters}\). At \( t = 28 \) seconds, the collision avoidance algorithm determines that the distance between the UAV\textsubscript{1} and UAV\textsubscript{2} is 7,680 meters. UAV\textsubscript{1} begins a circular motion based on a previously computed turn radius and turn rate, whereas UAV\textsubscript{2} stays its course with motion in a straight line. UAV\textsubscript{1} continues the circular motion until the distance between UAV\textsubscript{1} and UAV\textsubscript{2} is greater than the minimum distance of separation (7,680 meters). Once this condition becomes true, UAV\textsubscript{1} continues a straight-line motion.
5.7 Final Conclusions

The collision avoidance algorithm described in the Potential Solution section of this thesis is expected to determine a new trajectory for an aircraft so that a collision can be avoided. The MATLAB simulation results shown in Figure 5.6 through Figure 5.14 show two UAVs approaching a head-on collision. Each UAV is configured with a phased array antenna radar, which receives sensor measurements every second. The sensor measurements are used to determine a new trajectory for the maneuvering UAV. The maneuvering UAV, represented by the red dotted lines avoids a head-on collision by making a turn to the left based on a bank angle of 5 degrees. The aforementioned algorithm can be adapted for multiple UAVs converging at approximately the same altitude or multiple UAVs approaching each other on different altitudes.

5.8 Future Research

A significant portion of this research includes a study of different collision avoidance methods in addition to a simulation of a sense-and-avoid solution that consists of a radar and a Geometric Vector Algorithm in MATLAB. An important element missing from this research is that it does not have any simulation data for the A* algorithm, the Protocol Based Decentralized algorithm, ACAS X, or the Optimization algorithms for a comparison of simulation results. This thesis can further be enhanced in the future if additional research can be completed to determine the inputs, outputs and a transfer function for each of the aforementioned collision avoidance methods. The transfer function for each collision avoidance method can be modeled as an adaptive filter whose performance can be evaluated based on the response time for an aircraft converging to a target, steady state error, and stability.
REFERENCES


