A PRELIMINARY CONTROLLER DESIGN FOR DRONE CARRIED DIRECTIONAL COMMUNICATION SYSTEM

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In this thesis, we conduct a preliminary study on the controller design for directional antenna devices carried by drones. The goal of the control system is to ensure the best alignment between two directional antennas so as to enhance the performance of air-to-air communication between the drones. The control system at the current stage relies on the information received from GPS devices. The control system includes two loops: velocity loop and position loop to suppress wind disturbances and to assure the alignment of two directional antennae. The simulation and animation of directional antennae alignment control for two-randomly moving drones was developed using SIMULINK. To facilitate RSSI-based antenna alignment control to be conducted in the future work, a study on initial scanning techniques is also included at the end of this thesis.
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TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapters</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>COPYRIGHT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. Problem Formulation</td>
<td>2</td>
</tr>
<tr>
<td>1.2. Overview of Thesis</td>
<td>2</td>
</tr>
<tr>
<td>2. THE CONTROL SYSTEM DESIGN</td>
<td>4</td>
</tr>
<tr>
<td>2.1. Control System Performance</td>
<td>4</td>
</tr>
<tr>
<td>2.2. Typical closed-loop controllers</td>
<td>6</td>
</tr>
<tr>
<td>2.2.1. PID controller and their variants</td>
<td>6</td>
</tr>
<tr>
<td>2.2.2. Fractional Order PID Controller</td>
<td>7</td>
</tr>
<tr>
<td>2.2.3. Fuzzy Logic controllers</td>
<td>8</td>
</tr>
<tr>
<td>2.2.4. Linear Quadratic Regulator (LQR) Controller</td>
<td>9</td>
</tr>
<tr>
<td>2.3. The Control System Components</td>
<td>10</td>
</tr>
<tr>
<td>2.3.1. The Drive Model</td>
<td>10</td>
</tr>
<tr>
<td>2.3.2. The wind disturbance</td>
<td>12</td>
</tr>
<tr>
<td>2.3.3. Antenna-velocity loop</td>
<td>13</td>
</tr>
</tbody>
</table>
2.3.4. Antenna-Position loop…………………………………………15

2.4. Simulation using MATLAB …………………………………………16

2.5. Digitization and PID library in Arduino Microcontroller…………..18

3. SIMULATION RESULTS …………………………………………………20

3.1. Simulation of Two Drones: one Fixed Drone and the Other Moving on a Pre-set Trajectory ……………………………………………………………………………………………………….20

3.2. Acquisition of GPS Data …………………………………………..21

3.3. The Control System with GPS Data as the Input Signal……………22

3.4. Simulation of Two Drones: One Fixed Drone and The Other Moving on a Random Track…………………………………………………………………………………………………24

3.5. Simulation of Two Drones Moving along Random Trajectories ……26

4. RSSI SCANNING ……………………………………………………………27

4.1. RSSI Initial Conical Scanning………………………………………27

4.2. RSSI Initial Scanning Using the Pattern-Based Search Algorithm……33

5. CONCLUSION AND FUTURE WORK……………………………………..36

REFERENCES…………………………………………………………………………37
LIST OF FIGURES

1.1 The GPS-based controller framework involves two components: the acquisition of GPS locations, and 2) the directional antenna control system ........................................1

2.1 An illustration of settling time and overshoot of a step response [1]......................................5

2.2 An illustration of steady-state error [1].................................................................................5

2.3 The performance of a PID and fractional PID controllers are compared [8].........................7

2.4 Fuzzy Proportional Controller [9]........................................................................................8

2.5 A comparison of time responses between PID and LQR controllers [10].........................9

2.6 The drive model including the motor and the gearbox [1]..................................................11

2.7 Antenna configurations versus the wind..............................................................................13

2.8 The velocity loop (the inner loop) are used to suppress the wind disturbance.............14

2.9 The Antenna-position loop including the PID controller $K(s)$.......................................16

2.10 A MATLAB© SIMULINK model for the control system ...............................................17

2.11 Response of the controlled torque in the existence of wind disturbances (random signal marked in green), the desired angular pulse is marked in red and the output angular signal is marked in blue...........................................................................................................18

3.1 The Animation of two drones: one is moving according to a pre-set trajectory (marked in red), and the other (marked by the blue circle) is fixed. The antenna (marked by the blue *) carried by the fixed drone tracking the moving drone...............................................21

3.2 The control system with GPS position data as the input signal..........................................22

3.3 Modified SIMULINK model that includes the GPS information at the input ports.........23
3.4 Generated MATLAB© Waves for the desired angular signal marked in red, the output angular signal marked in blue with the existence of wind disturbances (random signal marked in green).........................................................................................................................24

3.5 The animation of two drones: one drone is randomly moving (with the trajectory marked in red) and the other one is fixed (marked by a blue *). The antenna (marked by a blue circle) of the fixed drone is tracking the randomly moving drone........................................................................................................25

3.6 The animation of drone-carried directional antenna alignment for two randomly moving drones. The antenna of the first drone (marked by red **) is tracking the antenna of the second drone (marked by green **)...................................................................................................................26

4.1 The power measurements taken at the antenna of the receiver side during the scan...........32

4.2 Flow chart of the Pattern-Based Search Algorithm [12].......................................................35
CHAPTER 1
INTRODUCTION

In this thesis we design a preliminary control system for directional antenna devices carried by drones. The goal of the control system is to ensure the best alignment between two directional antennas so as to enhance the performance of communication, e.g., the throughput. The control system at the current stage relies on the information received from GPS devices. In the future, we will explore the use of received signal strength indication (RSSI) to improve the controller performance. The framework of this project involves two components (as shown in Figure 1.1): 1) the acquisition of GPS locations, and 2) the direction control based on GPS locations. In particular, the GPS locations of two drones provide relative directions that the drone-carried directional antennas should point towards, and then the directional antennae are controlled in closed-loop to align in those directions. To facilitate the further controller development using RSSI, we also study in this thesis an initial scanning technique based on RSSI to find the best initial alignment between the two drones.

Figure 1.1 The GPS-based controller framework involves two components: the acquisition of GPS locations, and 2) the directional antenna control system.
1.1 Problem Formulation

We first describe the assumptions made in developing the directional antenna control system framework. The assumptions are concerned with the antenna axes of rotation and the processing of wind disturbance.

We assume that the drones operate at the same height. With this assumption, the directional antennae move in a horizontal plane, and require a single control system because we have a single degree of freedom. The control systems for the two antennas are the same. In general, the first antenna has information about the position of the second antenna because we are using the GPS device; and then the desired angular rotation is translated to the amount of needed torque. In the future, we will allow drones to operate at different heights and study directional antenna control in three dimensions. In that case, we will need to design two independent control systems: one for the elevation degree of freedom, and the other for the cross elevation degree of freedom.

The wind disturbance affecting the antenna beam is assumed to be random. In our simulations using SIMULINK and MATLAB, we consider wind disturbance as a random signal to investigate the performance of the designed control system. In the future, we will explore the uncertainty of wind disturbance and predict desired torques for that, so as to enhance the performance of directional antenna control.

1.2 Overview of Thesis

This thesis focuses on the design of a control system for drone-carried directional antenna. The direction control is aimed to have little error, produce fast response and be capable of suppressing huge amount of disturbance generated by the wind. In Chapter 2, a general
background on control theory is discussed, supported by an example to be considered as the basis for our control system design. Chapter 3 presents an animation of directional antenna control with two drones following random trajectories. The results are based on the simulations using MATLAB. In Chapter 4, a RSSI algorithm for initial scanning is presented for RSSI-based tracking system to be developed in the future. A conclusion and discussion of future work is presented in Chapter 5.
In Chapter 2, we first provide a general background on the control systems theory and principles and a variety of different types of commonly used controllers. We then discuss in detail our control system design. In the end, the implementation using SIMULINK is discussed with performance analyzed.

2.1. Control System Performance

The controller performance is typically measured using the following criteria [1]:

- **Settling time of a step response**, which is defined as the time at which the output (e.g., antenna output position in our study) remains within ±2% threshold of the nominal value of the step response (see Figure 2.1). In our study, the settling time is an indication of the speed of the antenna response to reach the desired output level. We aim to achieve a very short settling time.

- **Overshoot**, which is defined as the relative difference between the generated output signal and the desired set point value divided by the desired set point value. For example, an overshoot of 5% is observed in Figure 2.1.

- **Steady-state error**, which is defined as the difference between the set point and the output of a system in the limit as time goes to infinity (as shown in Figure 2.2). It depends on the type of the input signal and the disturbance signal.

- **Rise time of a step response**, which is the time required for the output level to rise from 10% to 90% of its steady state value.
- **Bandwidth**, which is the frequency at which the magnitude of the closed loop transfer function representing the control system drops 3 dB or to 70.7% below zero dB level.

Figure 2.1 An illustration of settling time and overshoot of a step response [1].

Figure 2.2 An illustration of steady-state error [1].
2.2. Typical closed-loop controllers

In this section, we provide a brief background on the different types of controllers that can be used for closed-loop control, including Proportional-Integral-Derivative controller (PID), fractional PID, fuzzy PID, and Linear Quadratic Regulator (LQR).

2.2.1. PID controller and their variants

PID controllers are widely used in control system design. A regular PID controller has the following transfer function:

\[ \frac{K_p + K_i s^{-1} + K_d s}{s} \quad (2.1) \]

where \( K_p \) is the proportional part coefficient, \( K_i \) is the integral part coefficient, \( k_d \) is the differential part coefficient and \( s \) is the Laplace operator.

If \( k_d \) is zero, the PID controller is considered a PI controller. Tuning methods can be used to find the coefficients. For instances, the tuning of a PI controller can be summarized in two steps [1]:

- Tune the proportional gain by increasing the gain until the limits are reached at 70% of its maximum values.
- Tune the integral gain by increasing the gain until oscillations and undershoot appear and assign it 70% of that reached value.

We observed from the properties of PI controller that the settling time decreases with the increase of the proportional gain and vice versa. Similarly, the steady-state error decreases with
the increase of the proportional gain, while the bandwidth increases linearly with respect to both the proportional and integral gains.

2.2.2. Fractional PID Controller

A fractional PID controller has a transfer function as follows [8]:

\[
K_p + Ki s^{-\lambda} + Kd s^{\delta}
\]  

(2.2)

where \(\lambda\) and \(\delta\) are the power coefficients in the integration and differentiation terms respectively.

![Figure 2.3 The performance of a PID and fractional PID controllers are compared [8].](image)

A fractional controller improves the performance of PID in terms of the peak overshoot and rise time specifications (see Figure 2.3). In this case the extra parameters are the powers of \(s\) for the integral and derivative terms, \(\lambda\) and \(\delta\) respectively.

An algorithm called the Particle Swarm optimization (PSO) can be used to find the \(\lambda\) and \(\delta\) parameters. The algorithm uses an iterative process to configure the location of a pole-point in
the solution space, and eventually it converges to a single minimum error solution. For more details see reference [8].

2.2.3. Fuzzy Logic controllers

Fuzzy control is a mathematical logic tool for dealing with uncertainty. The PID controller can be replaced by a linear fuzzy controller, which is similar in the form of summation [9].

For a fuzzy proportional controller, a function $f(GE \ast e)$ determines the input-output map of fuzzy control where $GE$ is the gain of the fuzzy error with respect to the original one and $e$ is the input (see Figure 2.4).

The rule base determines the approximation of the output ($U$) based on the fuzzy error signal ($E$). The controller output is found as the following:

$$U = GE \ast e \ast GU \quad (2.3)$$

where GU is the output gain.

The gain factor is equivalent to the proportional gain as the following:

$$Kp = GE \ast GU \quad (2.4)$$

![Figure 2.4 Structure of a Fuzzy Proportional Controller][9]
The same rule should apply to fuzzy PID controller. Please see reference [9] for more details.

2.2.4. Linear Quadratic Regulator (LQR) Controller

The LQR requires designing a state feedback controller $K$ such that the objective function $J$ is minimized [10]. In this method, a feedback gain matrix is designed to minimize the objective function and to achieve a compromise between the error and the speed of response while guaranteeing a stable system (see Figure 2.5).

![Figure 2.5 A comparison of time responses between PID and LQR controllers [10].](image)

An LTI system in the state space representation is:

$$\dot{x} = Ax + Bu$$  \hspace{1cm} (2.5)

where $x \in R^{n \times 1}$ is the state vector, $A \in R^{n \times n}$ is the state matrix, $B \in R^{n \times m}$ is the input matrix and $u \in R^{m \times 1}$ is the input vector.

The objective function $J$ is found as the following [10]:

$$J = \int (x^TQx + u^TRu)\,dt$$  \hspace{1cm} (2.6)
where $Q \in \mathbb{R}^{m \times n}$ is a positive semi-definite weight matrix and $R \in \mathbb{R}^{m \times m}$ is positive matrix.

The feedback control law that minimizes the value of the cost is found according to the following equation:

$$u = -Kx$$  \hspace{1cm} (2.7)

where $K \in \mathbb{R}^{m \times n}$ is given by:

$$K = R^T B^T P$$  \hspace{1cm} (2.8)

and $P \in \mathbb{R}^{n \times n}$ can be found by solving the Riccati equation [10]:

$$A^TP + PA - PB R^{-1} B^T P + Q = 0$$  \hspace{1cm} (2.9)

2.3. The Control System Components

In this section, we introduce the main elements to control the antenna to desired directions despite the existence of wind disturbances. The plant of this control system is the motor that drives the antenna and the antenna itself. We first describe models for the drive motor and wind disturbance. We then describe the control system that includes two components; the inner loop is called the velocity loop and the outer loop is the position loop.

2.3.1. The Drive Model

The drive model represents a connection between the control system of the antenna device and the DC motor which is used to provide the required torque. The drive model includes the motor dynamics and the gearbox (as shown in Figure 2.6) where the net torque affecting the antenna is produced.

A series DC motor is considered in this case. By applying Kirchhoff’s Voltage Law (KVL) around the armature circuit, we obtain the following equation [1]:

\hspace{1cm}
Figure 2.6 The drive model including the motor and the gearbox [1].

\[ Va = La \frac{di_o}{dt} + R_a i_o + k_a \omega_m \]  \hspace{1cm} (2.10)

where \( Va \) is the armature voltage, \( R_a \) is motor resistance, \( La \) is motor inductance and \( k_a \) is the armature constant.

The motor angular position \( \theta_m \) is controlled by the armature voltage (\( Va \)), and the motor torque (\( \tau_m \)) is proportional to the motor current (\( i_o \)) as the following:

\[ \tau_0 = k_m i_o \]  \hspace{1cm} (2.11)

where \( k_m \) is the torque constant for the motor and \( \tau_0 \) is the equilibrium torque acting on the rotor that is found according to the following equation:

\[ \tau_0 = J_m \ddot{\theta}_m + \tau_m \]  \hspace{1cm} (2.12)

where \( J_m \) is the motor moment of inertia.
Using Laplace transform after we rearrange the equations, the electrical current and the angular velocity formulas are written as:

\[ i_o = \frac{V_a - k_a \omega_m}{L_a s + R_a} \quad (2.13) \]

\[ \omega_m = \frac{\tau_o - \tau_m}{J_m s} \quad (2.14) \]

At the drive shaft, the speed is changed in response to the gear ratio \( N \) as shown in the following equation [1]:

\[ \frac{\theta_m}{\theta_g} = N \quad (2.15) \]

2.3.2. Wind disturbance

Wind disturbance has a major impact on the stability of the antenna direction. In this section the nature of the wind disturbance is explained and the amount of torque produced from the wind is formulated.

The wind induces a torque that affects the antenna drive, and this torque in general is dependent on both the dimensions of the antenna device and the wind dynamic pressure according to the following equation [13]:

\[ T_n = pAD C_t \quad (2.16) \]

where \( p \) is the wind dynamic pressure \((N/m^2)\), \( C_t \) is the torque coefficient determined after testing the wind-tunnel, \( AD \) are the dimensions of the affected antenna (see Figure 2.7). The wind dynamic pressure is related to the wind velocity as the following:

\[ p = \alpha_p v_m^2 \quad (2.17) \]
where \( v_m \) is the wind velocity.

The wind disturbance in reality is random. The following approximation can be achieved by combining the two previous equations [13]:

\[
T_n = C_t \alpha_p AD v_m^2
\]  

(2.18)

where \( \alpha_p \) is the static air density which is normally given as 0.6126 Ns\(^2\)/m\(^4\), \( C_t \) is a constant that fluctuates between -0.05 and 0.5.

In Section 2.4, the wind disturbance is considered as a random signal in our simulation, in order to investigate the robustness of the designed control system to wind disturbances.

### 2.3.3. Antenna-velocity loop

The role of the antenna-velocity loop is to suppress the wind disturbance and to control the antenna beam (see Figure 2.8).
Figure 2.8 The velocity loop (the inner loop) are used to suppress the wind disturbance.

The dynamics of the antenna device is described by the second law of Newton’s inertia as the following [1]:

$$J\omega = \tau$$ \hfill (2.19)

where $J$ represents the moment of inertia for the antenna body, $\dot{\omega}$ is the angular acceleration and $\tau$ is the output torque.

Applying Laplace transform to both sides of the equation, we are able to obtain the transfer function of a rigid antenna as the following:

$$A(s) = \frac{\omega(s)}{\tau(s)} = \frac{1}{Js}$$ \hfill (2.20)

where $\omega(s)$ is the angular velocity.
The velocity loop is considered as a proportional controller used in the open loop function before the negative feedback is also added. The equivalent closed loop transfer function of the velocity loop is written as the following:

\[ G(s) = \frac{K_0 A(s)}{1 + K_0 A(s)} \]  \hspace{1cm} (2.21)

where \( G(s) \) is the total closed loop transfer function and \( K_0 \) represents the gain of the proportional controller used in the velocity loop.

2.3.4 Antenna-Position loop

The position loop represents the outer loop of the dynamics of the directional antenna and the controller used in this loop is generally PID. If \( K(s) \) is considered as the transfer function of PI or PID controller (see Equation 2.1). Note that an integrator block is added to the velocity signal in order to obtain the angular position signal as shown in Figure 2.9. The closed loop transfer function of the whole system represented by the position loop is written as the following:

\[ G_{cl} = \frac{\theta(s)}{r(s)} = \frac{K(s)G(s)/s}{1+K(s)G(s)/s} = \frac{K_0(K_dS^2 + KpS + Ki)}{Js^3 + K_0(1 + K_d)S^2 + K_0KpS + K_0Ki} \]  \hspace{1cm} (2.22)

The transfer function of \( G_{cl} \) represents the relationship in the s-domain between the angular position and the torque applied by the drive. Here in order for the position loop to be stable, the following condition should be satisfied: \( Kp > \frac{J}{K_0} Ki \) [1].

Although the wind disturbance is mainly suppressed by the velocity loop, the position loop also suppresses the disturbance using the PID controller, which provides more stability to the system. The antenna-position loop is shown in Figure 2.9.
2.4. Simulation using MATLAB

In this simulation example, the control system is designed using both the velocity and position loops. The velocity loop includes the antenna dynamics and a proportional controller used to suppress the wind disturbance. The position loop provides more stability and decreases the overshoot. In Figure 2.10, the SIMULINK model shows the control system that includes the velocity and position loops. We assume that the $K_p$-controller of the velocity loop has a value of 15, the PI controller for the position loop is of values $K_p=2.2$ and $K_i=1.4$, and the antenna’s inertia equals to $1 \text{ N.m.s}^2/\text{Rad}$. 

Figure 2.9 The Antenna-position loop including the PID controller $K(s)$. 

-16-
From the results seen in Figure 2.11 the settling time is approximately 3.5 sec and the achieved overshoot is 20%. Also we can notice that the effect of the wind disturbance is suppressed by the velocity loop and the output angle is almost close to the step signal applied at the set point. In the future work, we will optimize the parameters to achieve the best performance.
Figure 2.11 Response of the controlled torque in the existence of wind disturbances. Wind disturbances are marked in green. The desired angular pulse is marked in red and the output angular signal is marked in blue.

2.5. Digitization and PID library in Arduino Microcontroller

In order to implement using a microcontroller, the control system in the analog continuous-time domain should be discretized using the digital-control rules. Before doing the transformations, we need to determine the sampling frequency \( \omega \) from the Bode diagram. A simple rule for the transformation is the Tustin’s rule which is derived from the trapezoidal integration [11]. The mapping function of Tustin’s rule is:

\[
S = \frac{2z-1}{Tz+1}
\]  

(2.23)
where $T$ is the sampling period and the transfer function is transformed to the $z$-domain.

MATLAB implements this conversion using the Function “sysd”.

The Arduino platform provides a PID library. The Library contains eight functions and the PID code-function is self-contained and very easy to use and understand.
CHAPTER 3
SIMULATION RESULTS

In this chapter, we present simulation results of the drone-carried directional antenna control. We first consider the case that the location of one drone is fixed and the other is moving on a pre-set trajectory. We then include the acquisition of Global Positioning Systems (GPS) locations into the simulation environment, and present simulation results for two cases: 1) one drone is fixed and the other is moving on a random track, and 2) both drones are moving on random tracks. We adopt random mobility models developed in the lab’s previous studies to simulate the random movement of drones [7]. In the future, we will develop RSSI-based control schemes to find the best initial alignment between the two drones.

3.1 Simulation of Two Drones: one Fixed Drone and the Other Moving on a Pre-set Trajectory

In this study, the MATLAB and SIMULINK are used to simulate a virtual drone moving along a pre-set track trajectory when the second drone is fixed. The antenna of the fixed drone moves to stay aligned with the antenna of the moving drone.

As the trajectory of the moving drone is planned beforehand, the antenna carried by the fixed drone changes its direction based on the known trajectory information. Figure 3.1 shows the simulation result.
Figure 3.1 The animation of two drones: one is moving according to a pre-set trajectory (marked in red), and the other (marked by the blue circle) is fixed. The antenna (marked by the blue *) carried by the fixed drone tracks the moving drone.

3.2 Acquisition of GPS Data

GPS operates at a pair of frequencies in the L-Band: L1 (1575.42 MHz) and L2 (1227.6 MHz). L1 is the only frequency range that can be used for civilian purposes. GPS may not be fast enough to be used in very accurate positioning appliances. A chipping code or the Gold codes are used to cut the received message from GPS into chips at a rate of 1.023 MHz. The receiver knows all the Gold codes and it is capable to run the message through several parallel correlations [14].
GPS receivers are capable to find their position almost anywhere on the globe with an accuracy of ±10 m. However several factors affect the strength of GPS signals such as environmental changes over the communication channel like fading and multipath reflections, the drifts in satellite orbits, and the errors in the clocks of the satellites.

3.3 The Control System with GPS Data as the Input Signal

In this section the control system diagram is updated by using the information received from the GPS device as the input signal. Figure 3.2 shows the acquisition of GPS locations added to the control system diagram. This process leads to the desired angular position in the embedded system. The GPS receiver calculates the distance from the signals sent from the GPS satellites by multiplying the velocity of the transmitted signal by the time it takes the signal to reach the receiver [15], and then GPS receiver should be able to calculate its approximation for the latitude and longitude coordinates. If the current position of the drone \((x_0, y_0)\) in two dimensions is assumed to be the origin point and the new position of the drone is \((x_1, y_1)\) when it is moving on a two-dimensional trajectory, the angular displacement can be found using the tangent formula as the following:

\[
\theta = \tan^{-1}\left(\frac{x_1-x_0}{y_1-y_0}\right)
\]  

(3.1)

Figure 3.2 The control system with GPS position data as the input signal.
The SIMULINK model (in Figure 3.3) shows the addition of the GPS information at the input side to the control diagram we shown in Chapter 2.

Figure 3.3 Modified SIMULINK model that includes the GPS information at the input ports.

We now reconsider the case studied in Chapter 3.1, with the assumption that the location information is not known beforehand. Instead, GPS locations are constantly fed to the system for directional antenna control. The generated output waves from the control system are shown in Figure 3.4. The angular positions are periodic pulses represented by the difference of two steps, in the future a continuous signal block can be used to replace the step signals in the SIMULINK diagram.
3.4 Simulation of Two Drones: One Fixed Drone and The Other Moving on a Random Track

In this part, the trajectory of the moving drone is random, unlike the one in Chapter 3.1. The fixed antenna still uses the GPS information to find the location of the other antenna. In Figure 3.5, an animation of a fixed antenna tracking the other antenna carried by a randomly moving drone is shown.
The MATLAB code we adopted in this part uses the random mobility model. The mobility model captures the tendency of airborne vehicles toward making smooth trajectories by randomly choosing a turning radius. Please see reference [7] for more details.

Figure 3.5 The animation of two drones: one drone is randomly moving (with the trajectory marked in red) and the other one is fixed (marked by a blue *). The antenna of the fixed drone (marked by a blue circle) is tracking the randomly moving drone.
3.5 Simulation of Two Drones Moving along Random Trajectories

In this section, an animation is shown for two drones moving along two random trajectories. The directional antennae carried by both drones track each other to stay aligned using the GPS information (see Figure 3.6).

Figure 3.6 The animation of drone-carried directional antenna alignment for two randomly moving drones. The antenna of the first drone (marked by red **) is tracking the antenna of the second drone (marked by green **).
In this chapter, the goal is to design an initial scanning technique based on RSSI and use it to determine the position of the next drone to find the best initial alignment between the two drones. The RSSI initial conical scanning is presented in Chapter 4.1, and the pattern-based search algorithm of the RSSI initial scanning is explained in Chapter 4.2.

4.1. RSSI Initial Conical Scanning

Based upon the power level of signals sent by the directional antenna of the other drone, the estimation of the next position of the antenna at the fixed drone can be completed using different types of scanning techniques. One scanning technique is called “Conical Scanning” [1]. This scanning technique is achieved by a continuous rotating motion of the antenna at the fixed side. The next position is calculated after completing a full-scanning cycle.

The scanning has a frequency of $\omega_s$ rad/s. The period of conical scanning ($T$) is recommended to be between 5 and 120 seconds [1]. The loss of the signal power during the scanning is around 0.1 dB, and the loss depends on the frequency of the received signal, the radius of the scanning angle and the sampling rate of the scan. The sampling frequency ($n$) should be at least twice as the scanning frequency to follow the Nyquist rate. It is calculated as the average number of samples obtained in one cycle.
Antenna position error $e_i$ is used to estimate the next position of the antenna carried by the fixed drone so that the best alignment between the two antennas is achieved. The antenna position error is related to the carrier power with a Gaussian function as a random function. The position error $e_i$ is given by [1]:

$$e_i = s - a_i$$  \hspace{1cm} (4.1)

where $a_i$ is the angular position of the antenna during the scan and $s$ is the value we intend to obtain eventually as the next angular position. The angular position during the scan $a_i$ is given by:

$$a_i = r \cos(\omega_s t_i)$$  \hspace{1cm} (4.2)

where $t_i$ is the time at which each sample is obtained:

$$t_i = i \Delta t$$  \hspace{1cm} (4.3)

and $\Delta t$ is the period of the scanning divided by the sampling rate as the following:

$$T = n \Delta t$$  \hspace{1cm} (4.4)

For example, if $T$ the period of scan equals to 5 seconds, and the scanning frequency is found as: $\omega_s = \frac{2\pi}{T} = \frac{6.28}{5}$ rad, and using a sampling frequency of $n = 200$ samples/cycles then $\Delta t$ is 6.28 ms.

The absolute value of the position error is found according to the following equation:

$$e_i = \sqrt{(s - a_i)^2}$$  \hspace{1cm} (4.5)
The Carrier power $P_l$ is a function of $e_i$ as a Gaussian approximation as mentioned above as the following [1]:

$$P_l = P_{oi} e^{\frac{-\mu}{h^2} e_i^2} + v_l \quad (4.6)$$

where $P_{oi}$ is the maximum carrier power and is assumed constant, $v_l$ is the signal noise, $h$ is the half-power beam width (17 mdeg for KA-band), and $\mu = 4 \ln(2) = 2.7726$.

Using the approximation $e^x \approx 1 + x$, Equation 4.6 becomes as the following:

$$P_l = P_0 \left(1 - \frac{\mu}{h^2} e_i^2\right) + v_l \quad (4.7)$$

and from Equation 4.5 $P_l$ becomes:

$$P_l = P_0 \left(1 - \frac{\mu}{h^2} |s - a_i|^2\right) + v_l \quad (4.8)$$

If we substitute Equation 4.2 in Equation 4.8, $P_l$ becomes:

$$P_l = P_0 \left(1 - \frac{\mu}{h^2} (r^2 \cos(\omega_s t_i)^2 + s^2) + \frac{2P_{o\mu r}}{h^2} \cos(\omega_s t_i)s\right) + v_l \quad (4.9)$$

Rearranging the previous equation we obtain:

$$P_l = p_m + \frac{2P_{o\mu r}}{h^2} \cos(\omega_s t_i)s + v_l \quad (4.10)$$

where $p_m$ is ignored because the function is non-linear.

Here we introduce a new term $dp_l$ as:

$$dp_l = \frac{2P_{o\mu r}}{h^2} \cos(\omega_s t_i)s + v_l \quad (4.11)$$

$$dp_l = g \cos(\omega_s t_i)s + v_l \quad (4.12)$$
where

\[ g = \frac{2P_\text{ref}}{h^2} \]  

(4.13)

Assuming noise \( v_i \approx 0 \), the least-square method can be used to solve the following equation:

\[ dp_i = K_i s \]  

(4.14)

where

\[ K_i = g \cos(\omega_s t_i) \]  

(4.15)

Using linear algebra:

\[ dK = \begin{bmatrix} dp_1 \\ dp_2 \\ \vdots \\ dp_n \end{bmatrix} \]  

(4.16)

\[ k = \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_n \end{bmatrix} \]  

(4.17)

and

\[ s = [s_1] \]  

(4.18)

The final solution to Equation 4.15 is:

\[ s = (K^TK)^{-1}K^Tdp \]  

(4.19)
Both matrices $K$ and $dp$ have the same size of $n \times 1$ where $n$ is the sampling rate. The value $s$ obtained after solving Equation 4.20 using the least-square method represents the next position of the antenna carried by the fixed drone.

To demonstrate an example that explains the previous Equations, we assume the period of scan $T$ is 5 seconds so the scanning frequency $\omega_s = \frac{2\pi}{T} = \frac{6.28}{5} = 1.26$ rad, and the sampling frequency $n = 5$ samples/cycles.

From Equation 4.3 and Equation 4.4 $\Delta t = \frac{T}{n} = 1$ sec, and $t_i = i\Delta t = i = i$ sec so that $t_1 = 1$ sec, $t_2 = 2$ sec, etc. If we choose $r=1$ deg, $a_i = r \cos(\omega_s t_i) = \cos(\omega_s t_i)$, then $a_1 = \cos(1.26 \cdot 1) = 0.31, a_2 = \cos(1.26 \cdot 2) = -0.81, a_3 = \cos(1.26 \cdot 3) = -0.8, a_4 = \cos(1.26 \cdot 4) = 0.32$ and $a_5 = \cos(1.26 \cdot 5) = 1.$

Before Equation 4.12 ($dp_i = g \cos(\omega_s t_i) s$) is applied the value of $g$ is found as the following:

$$g = \frac{2P_o \mu r}{h^2} = \frac{2 \times 1 \times 10^{-3} \times 2.7726 + 1}{(17 \times 10^{-3})^2} = 1.6 \times 10^{-6},$$

where the maximum carrier power $P_o$ is given as 1 mW and the other parameters in the Equation were previously defined.

From Equation 4.15 $K_i = g \cos(\omega_s t_i) = 1.6 \times 10^{-6} \cdot a_i$, and the $k$ matrix from Equation 4.17 can be found as:

$$k = \begin{bmatrix}
1.6 \times 10^{-6} \cdot 0.31 \\
1.6 \times 10^{-6} \cdot -0.81 \\
1.6 \times 10^{-6} \cdot -0.8 \\
1.6 \times 10^{-6} \cdot 0.32 \\
1.6 \times 10^{-6} \cdot 1
\end{bmatrix}
= \begin{bmatrix}
0.5 \times 10^{-6} \\
-1.3 \times 10^{-6} \\
-1.28 \times 10^{-6} \\
0.51 \times 10^{-6} \\
1.6 \times 10^{-6}
\end{bmatrix}.$$
The values of the received power samples during the scan should be provided by the taken measurements and given the following matrix of the power measures at the five sampling points as shown in Figure 4.1 as the following:

\[ dp = \begin{bmatrix} 1.5 \text{ mW} \\ 1.4 \text{ mW} \\ 1.1 \text{ mW} \\ 0.8 \text{ mW} \\ 1.1 \text{ mW} \end{bmatrix} \]

Finally, the least-square method of Equation 4.19 is applied to find the value of the next position \( s \) in degrees as the following:

\[ s = (K^T K)^{-1} K^T dp \]
\[
\begin{pmatrix}
0.5 \times 10^{-6} & -1.3 \times 10^{-6} & -1.28 \times 10^{-6} & 0.51 \times 10^{-6} & 1.6 \times 10^{-6} \\
0.5 \times 10^{-6} & -1.3 \times 10^{-6} & -1.28 \times 10^{-6} & 0.51 \times 10^{-6} & 1.6 \times 10^{-6}
\end{pmatrix}
\]

\[
\begin{pmatrix}
1.5 \times 10^{-3} \\
1.4 \times 10^{-3} \\
1.1 \times 10^{-3} \\
0.8 \times 10^{-3} \\
1.1 \times 10^{-3}
\end{pmatrix}
\]

\[
= (6.3985 \times 10^{-12})^{-1} \times -3.1 \times 10^{-10} = -48.45 \text{ deg}.
\]

4.2. RSSI Initial Scanning Using the Pattern-Based Search Algorithm

In this section, the pattern-based search algorithm is explained to find the orientation of the antennas that enables them to receive the best alignment. The pattern-based search algorithm is the most popular optimization technique for the self-orientation of directional antennas in long point-to-point broadband and wireless networks [12]. This algorithm does not require prior knowledge of the objective function gradient but requires sampling points in the search domain to help finding the global minimum.

The sensing model is denoted by 2-tuple \((P_i, O_i)\) where \(P_i\) is the location \((x,y)\) of the directional antenna in 2D plane, and \(O_i\) is the sensing orientation which includes the horizontal offset angle \((\theta)\) from the origin of the antenna. Using Friis equation we can formulate the relationship between the received and transmitted power between the two antennas [12]:

\[
\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi r}\right)^2 G_t G_r \overrightarrow{Ot} \overrightarrow{Or}
\]
where $\lambda$ is a wavelength, $r$ is a distance between the two antennas, $G_t$ and $G_r$ are the antennas gains and $\vec{Or}$ is the direction in which the receiver sees the transmitter.

The best orientation is obtained when the receiver gets the maximized signal strength, and one antenna is configured as the fixed transmitter and the other as the rotatable receiver. The problem in this section can be stated as that we need to find the orientation angle $\theta$ by minimizing the $f(\theta)$ subjected to some criterion such as: $\theta_L \leq \theta \leq \theta_U$; where the objective function $f(\theta)$ produces a current RSSI measures at the angle $\theta$. The antennas have no information about the location of the other drone and the objective function becomes hard to predict in this case.

The algorithm performs a pattern move until the minimum is found or the maximum number of evaluations is reached. Please refer to Figure 4.2 for a flowchart of the algorithm. In this algorithm, the initial points of $\theta$ should be carefully chosen. It is recommended to take 4 points at the beginning $f(\theta_0), f(\theta_1), f(\theta_2)$ and $f(\theta_3)$ and then dismiss the lowest ones. A termination criterion is the following:

$$\frac{f(\theta_h) - f(\theta_l)}{1 + |f(\theta_l)|} \leq \varepsilon \ [12].$$
Figure 4.2 Flow chart of the Pattern-Based Search Algorithm [12].
CHAPTER 5
CONCLUSION AND FUTURE WORK

In this thesis, a preliminary design of control system for drone-carried directional antenna alignment is introduced based on the information received from the GPS devices measurement. The control system includes two loops: velocity loop and position loop to assure the alignment of two directional antennae. The simulation and animation of directional antennae alignment control for two-randomly moving drones was developed using SIMULINK. To facilitate RSSI-based antenna alignment, initial scanning techniques are also studied. In the future work, multiple improvements will be conducted. First, the step function reference signals used in the SIMULINK diagrams will be replaced by more realistic continuous signals and the parameters in the control system will be carefully designed to achieve the optimal performance. Second, the control system for three-dimensional antenna movement will be designed, by including a second control system for the other degree of freedom. Third, a predictive tracking technique that explores uncertain drone mobility will be developed to enhance the robustness of antenna alignment. Finally, a RSSI-based directional antenna alignment algorithm will be developed to remove GPS location errors.
REFERENCES


