GUIDED EXPLORATION FOR COORDINATED AUTONOMOUS
SOARING FLIGHT

A Thesis in
Aerospace Engineering
by
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Abstract

An exploration strategy to effectively guide coordinated mapping of vertical wind speed in autonomous soaring flight is proposed. A map is discretized into a grid, and a scalar Kalman filter estimates vertical wind speed in each cell. Exploration is driven by uncertainty in the vertical wind speed estimate and by the relative likelihood of thermal triggering. This relative likelihood is computed based on solar incidence, which is in turn computed from digital elevation data (obtained from US Geological Survey) and the position of the sun. An exploration priority function is developed to drive mapping of vertical wind. This exploration strategy leads to a well-explored map in regions where the predicted maximum solar heating occurs. Regions having a low likelihood of thermal formation are avoided. Exploration resources are saved and utilized on regions where thermals are more likely to form.

Performance of the exploration strategy is verified using Monte Carlo simulations for various flock sizes at different geographic locations as well as different levels of altitude floors (which trigger energy exploitation). Results show that endurance is greatly improved when the prediction of thermal triggering is accurate. Performance gains decrease with rising altitude floor which reduces the exploration time. When thermal prediction provides minimal guidance, performance loss occurs for a small flock size. Larger flock size and lower altitude floor are necessary to provide excess exploration resources. This result suggests a heavier weight on the uncertainty in the wind estimate when exploration resources are restricted.

The feasibility of the exploration strategy is demonstrated in a high-fidelity soaring flight simulator, which contains more realistic thermal dynamics. This simulation setup is a stepping stone to the hardware implementation of the guided exploration algorithm. Finally, hardware implementation of the exploration strategy with a commercially available autopilot system and an SB-XC sailplane is provided. Results from hardware-in-loop simulation show that the current system is ready to perform guided exploration in autonomous flight.
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Dedication

I would like to dedicate this thesis to my beloved parents, Hoibun and Potai who have contributed everything to support my education. Their hard work and continuous support gave me an opportunity to go to college, and to become an aerospace engineer. I will always appreciate all that they have done.

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Chapter 1

Introduction

This research ultimately seeks to enable persistent surveillance with a flock of small unmanned air vehicles (SUAVs). Small aircraft have several advantages over their larger cousins: cost is typically lower, allowing riskier missions to be undertaken; they require smaller ground crews for operation (one operator vs. a team); and detectability (visual and aural) is lower. The lower detectability means that these aircraft can be flown at low altitudes (i.e. below clouds), so optical sensors can maintain visual contact with the ground. However, SUAVs have restricted fuel capacity (with a typical flight duration of approximately an hour). This research is motivated by the need to improve endurance for persistent surveillance missions. Advances in battery technology will enable longer duration missions but performance improvements can be gained immediately and with existing hardware by harvesting atmospheric energy.

This research focuses on harvesting energy from columns of vertical rising air (known as thermals) triggered by unevenly heating of the ground. Birds and human pilots routinely exploit this energy to achieve long distance flight. However, the presence of thermals is inherently non-deterministic [1]. Predictive tools are only available at resolutions of several kilometers [2, 3, 4], which are too coarse for soaring flight. Birds and human pilots often perform cooperative soaring (see Figure 1.1) to increase likelihood of encountering thermals. A flock of birds exploits energy from thermals can often be observed in nature. Human sailplane and hang glider pilots often search for cumulus clouds, which indicate high likelihood of updraft near those regions. However, thermal finding based on visual recognition
of cumulus clouds is not currently feasible for unmanned aircraft, and another approach is required. This thesis combines a coordinated approach to mapping by a flock of small, soaring-capable UAVs with predictions of likely thermal triggering based on the angle of solar incidence onto terrain.

Several factors are known to affect thermal formation: terrain albedo, soil moisture content, and solar incidence angle all play a role. Variation in terrain albedo and soil moisture content is on a relatively large scale, which is not suitable to guide aircraft exploration within a small region (several kilometers square). Solar incidence angle varies on a scale of tens of meters (resolution of 25 meters is used in this research). Additionally, maximum solar heating occurs while sun is perpendicular to the terrain surface. It implies that thermals are more likely to be found near those regions. Therefore, solar incidence angle suggests a possible exploration strategy.

This thesis presents an exploration strategy to drive aircraft exploration behavior so that mapping updrafts in the environment can be performed effectively. Aircraft carries a map of updraft onboard. The distribution of measurement allows knowledge of updrafts to be shared with remote aircraft. Since thermal formation is a stochastic, dynamic phenomenon, the map should contain a measure of uncertainty in thermal strength. The validity of updraft measurement decreases with time, which requires frequent measurements to be taken. As a result, an exploration strategy can be derived from a combination of solar incidence angle and uncertainty in measurement for autonomous soaring flight. A schematic of explo-
ration strategy is depicted in Figure 1.2.

![Figure 1.2. Overview of the guided exploration strategy](image)

A cartoon representing the behavior of a flock of aircraft in this research is shown. Thermals are more likely to be found while the sun is perpendicular to the terrain. Aircrafts search for regions with high likelihood of thermal triggering to obtain updraft measurements. Aircraft broadcasts its measurement while adopting the measurements from others so that knowledge is shared. While energy exploitation is necessary, aircrafts use the energy map to location thermal nearby.

The objective of this thesis is to:

- develop an exploration strategy that guides exploration behavior of a flock of aircraft in soaring flight to regions with a high likelihood of thermal triggering by incorporating solar irradiance, topography, and uncertainty in wind measurement.

- investigate the effectiveness of the exploration strategy through Monte Carlo simulation with multiple flock sizes at different geographic locations. Guided exploration in a high fidelity flight simulator is demonstrated because it provides a realistic dynamic thermal model, orographic lift, wind shear, and is capable of correctly modeling extreme flight maneuvers such as spins.
• demonstrate the feasibility of the exploration strategy in hardware-in-loop simulations with an autopilot system.

1.1 Motivation

UAVs are becoming more capable. Notably, the military use of UAVs has expanded into areas including surveillance, communications relays and even combat. High altitude, long endurance (HALE) and medium altitude long endurance (MALE) UAVs such as Global Hawk and Predator (see Figure 1.3) have been deployed to perform surveillance missions across the globe as a result of their ability to provide excellent remote sensing capability even at high altitude. The combination of a large fuel payload capacity and aerodynamic efficiency enables persistent surveillance with those aircraft; flight times of tens of hour have been reported for Predator and Global Hawk.

Flight at high altitudes can lead to loss of target visibility due to clouds. Flight below cloud base (in the atmospheric boundary layer) would allow continuous surveillance even on cloudy days, but large vehicles with relatively large wingspans (Predator’s wingspan is 15 meters, Global Hawk’s wingspan is 35 meters) become vulnerable to detection or destruction from ground-based threats. Additionally, each unit of a large UAV costs ten of millions for development and maintenance [5]. A possible low-cost solution is the use of small, and hand-launchable UAVs.

The use of SUAVs provides several advantages over their larger counterparts. The relative low cost associated with SUAVs implies that mission can be performed at higher risk. The small size of SUAVs (with wingspans ranging from 1 to 4 meters, see Figure 1.4) makes them less susceptible to detection, which would enable persistent surveillance from within the atmospheric boundary layer where visibility of target is improved.

However, range and endurance of SUAVs remains a problem: small payload size limits both the sensing payload and the ability to carry fuel or batteries, and the lower Reynolds numbers associated with SUAVs results in lower overall aerodynamic efficiency. Currently, flight times of only one to one and a half hours are possible with hand launchable aircraft, making persistent surveillance difficult. Future technology improvement in solar cells or battery will further improve flight
endurance. However, SUAVs are unlikely to achieve persistent surveillance flight while exclusively using with on-board energy sources. Significant improvement in endurance can only be sought by harvesting energy available from the atmosphere.

Large birds such as hawks and vultures (which are similar in size and aerodynamic performance to SUAVs) routinely employ soaring flight to traverse hundreds of kilometers over several hours without flapping wings, and human sailplane pilots (both full scale and radio-controlled) routinely soar. The capability to soar autonomously would similarly have a significant impact on the operational utility of small unmanned aircraft.

1.2 Problems of Guided Exploration

One approach to improving persistence of a flock of small soaring-capable UAVs is to cooperatively generate and maintain a map of vertical air motion. This map can then be used by each aircraft when it needs to soar to regain altitude. Such a map is described in Depenbusch [6]: the environment is divided into cells and a Kalman Filter maintains an estimate of vertical wind speed and the associated covariance in each cell. Efficient exploration of the environment (so that available resources are allocated towards search in areas that are likely to contain upwards air motion) must still be addressed. This thesis discusses: (1) non-deterministic
1.2.1 Non-deterministic Thermal Triggers

In a general sense, thermal formation is through uneven heating of the ground from solar radiation. The complexity of the actual thermal triggering makes prediction extremely difficult. Currently, predictive tools for thermal formation and locations are unavailable at an adequate resolution to guide soaring flight in the manner proposed in this thesis. Boundary Layer Information Prediction Maps (BLIPMAPS) [2, 3, 4] predict thermal activity with grid spacing of two kilometers, which is too coarse for this research application. A thermal predictive method...
on a tens of meters scale is proposed in this thesis by using solar incidence angle.

Solar incidence angle plays an important role in thermal triggering, with maximum heating of the ground occurring when solar incidence is perpendicular to the ground. Knowledge of solar incidence can thus be used as a guide to drive exploration towards regions where thermals are more likely to be found and away from regions where solar incidence is shallow or the ground is shaded.

1.2.2 Dynamics of a Thermal

Thermal strength, lifespan, and core radius can greatly vary between thermals. Differences in dynamics of a thermal between simulation and reality determine the validity of energy map. To include time-varying characteristic of a thermal, the uncertainty associated with the updraft measurement increases over time. A relatively higher exploration priority is assigned to a cell with a high level of uncertainty in updraft estimate. Simulation results from Silent Wings flight simulator with a realistic thermal model is to evaluate the performance of the exploration strategy proposed in this thesis.

1.2.3 Exploration Priority

With the ultimate goal of persistent surveillance, objective is to obtain a useful energy map. This means exploring regions that are likely to contain thermal lift as well as maintaining a current energy map. When energy exploitation is required, a nearby source of lift with adequate confidence can be located using the map. An exploration strategy can then be formulated as the weighted average function between solar incidence and uncertainty in wind measurement. However, heavy weight on solar incidence can lead to excess exploration on the same region without the presence of thermal. Conversely, heavy weight on uncertainty can lead to resource wasting by targeting regions where thermals are unlikely to be found. Therefore, the choice of weight factor influences the performance of the guided exploration approach, and the best is determined through simulations over a range of weight factors.
1.3 Overview of Guided Exploration

The architecture that allows coordinated mapping and exploration is depicted in Figure 1.5. A flock of aircraft performs cooperative mapping and exploration in an environment that contains atmospheric energy available for harvesting. The solar incidence angle is used as a priori information to contribute a portion to guide exploration. With the combination of vehicle states, updraft estimate as well as a priori information, the desired aircraft flight behavior including a decision between exploration and exploitation can be determined by the high-level decision controller. The flight control follows the commands derived from the decision controller, and provides input to the vehicles dynamics. The communication between aircrafts broadcasts the updraft estimate at current aircraft location and adopts the measurement from remote aircraft.

Throughout this thesis, this general architecture of exploration guidance is slightly modified for different purposes; Monte Carlo simulation, coordinated soaring in the flight simulator, and hardware-in-loop simulations of guided exploration all have a similar setup with small adjustments. The specific setup for each demonstration of guided exploration is described in Section 4.1.1, Section 4.2.2 and Section 5.2 respectively.

Figure 1.5. Architecture of Coordinated Mapping and Exploration
1.4 Review of Related Work

There has been a significant amount of research relating to autonomous soaring conducted over the past few years. Recent works including simulation results of thermal flight are reported by Allen (2005) [7] and corresponding flight test results are presented in Allen (2007) [8]. Autonomous thermal soaring has also been addressed by Edwards [9]. Research by Andersson and Kaminer has focused on flight control for thermal soaring[10, 11]. Soaring by manned sailplanes has also been studied extensively, with several authors addressing the optimal static soaring trajectory problem in the context of soaring competition. The MacCready problem [12, 13], the final glide problem [14], and “Dolphin” flight along regions of alternating lift and sink [15, 16, 17] all address optimal static soaring including optimal speed to fly between thermals of known strength. de Jong [18] describes a geometric approach to trajectory optimization. Most of this research is limited by known lift distribution (e.g. sinusoidally varying lift [19] or “square wave” lift [20]) and generally do not consider the effects of horizontal wind components.

Earlier research has demonstrated the feasibility and utility of autonomous soaring for improving range and endurance of SUAVs. Most autonomous soaring research has focused on exploiting thermals because of their relate static nature and the well developed methods for climbing in them. Since thermal formation is inherently non-deterministic, autonomous thermal soaring has typically relied on aircraft randomly finding a thermal to exploit (essentially counting on luck to extend endurance). Research by Depenbusch has shown that the availability of a map can greatly improve overall performance[6], and also showed that mapping is improved as flock size in increased. However, the mapping in that work was driven exclusively by uncertainty in the map: in essence, an aircraft explored regions where uncertainty in the map was high. This leads to a well-explored space, but can lead to cases where resources are wasted exploring regions where thermals are unlikely to be found. Note that energy can be harvested from predictable, deterministic phenomena such as ridge lift and wave[21] as well as in thermals, but the focus of this thesis is on improving performance in stochastic environments.
1.5 Summary of Contributions

• Thermal Hotspot Identification
  A method that incorporates the solar irradiation and topography of a region to determine likelihood of thermal formation for the discretized environment at resolution of an aircraft turn radius. Resources can then be focused on searching in regions where thermals are more likely to be found.

• Exploration Guidance for Coordinated Autonomous Soaring
  The application of an exploration priority function provides a coordinated exploration approach for a flock of SUAVs through the use of a priori information and confidence in wind estimation. This formulation determining exploration priority allows for easy modification to overall aircraft behavior according to the flock size and the confidence in thermal prediction.

• Performance Verification: Simulations
  A Monte Carlo simulation in MATLAB that includes of solar irradiance, topography models and a thermal updraft model is used to evaluate the performance of the exploration priority function with a range of weighting factors between a priori information and uncertainty in wind estimates. High fidelity flight simulation provides a more realistic atmospheric environment where the guided exploration strategy is demonstrated. Finally, results from hardware-in-loop simulations of guided exploration show that the system setup is ready to be tested in real flight.

1.6 Reader’s Guide

The remainder of this thesis is organized as follows:

Chapter 2: The Problem of Guided Exploration for Coordinated Soaring provides the equations and methods that are used in developing the results given in this thesis. The mapping algorithms used in thermal updraft estimation, vehicle dynamics, low-level control, and aircraft flight behavior are all included. Finally, the atmospheric environment consisting of sun irradiance, topography, and thermal
updrafts is provided in order to create an environment for performance validation of the exploration strategy in autonomous soaring flight.

Chapter 3: Implementing the Exploration Priority Function further describes the exploration guidance strategy developed in this thesis. Two exploration strategies are first introduced, and then combined into a single hybrid approach defined as the exploration priority function. The choice of weight factor used in the exploration priority function is investigated via the results of Monte Carlo simulation. This chapter concludes with the implementation of aircraft exploration behavior by incorporating the uncertainty in updraft estimates and solar incidence as a priori information.

Chapter 4: Simulation Results presents the results of Monte Carlo simulation of guided exploration as proposed in this thesis. The covariance driven approach developed in earlier work serves as baseline scenario to evaluate the performance gain from guided exploration. Further, simulation results from coordinated soaring flight using a priori information in a commercially available high-fidelity multiplayer soaring flight simulator are presented.

Chapter 5: Hardware Demonstration of Exploration Guidance describes the hardware setup and hardware-in-loop testing of the exploration strategy developed in this thesis.

Chapter 6: Conclusion summarizes the result of this thesis and provides recommendations for future research.
The Problem of Guided Exploration for Coordinated Soaring

This chapter is devoted to providing the necessary equations and methods used in developing the results that are given in this thesis. The problem of guided exploration and coordinated mapping for autonomous soaring flight is explained in Section 2.1. Next, the wind mapping algorithm used in thermal updraft estimation is presented in Section 2.2. The equations of motion for the aircraft model and the low-level controller are given in Section 2.3. The high-level decision controller that governs the aircraft flight behaviors according to a set of behavior switching criteria is detailed in Section 2.4. Note that the inclusion of a priori information in aircraft flight behavior is discussed in Chapter 3. The atmospheric environment including solar irradiance, topographic elevation model and thermal updrafts model is presented in Section 2.5.

2.1 Problem Statement

This research seeks an effective exploration strategy to search for atmospheric energy in order to enable persistent soaring flight with a flock of SUAVs. In earlier work a means of cooperatively mapping the environment for autonomous soaring flight using an approach derived from occupancy grid mapping by Depenbusch[6] showed significant improvement in a simulation environment with increased flock sizes. The objective of cooperative mapping and exploration is to obtain wind
measurements at locations where uncertainty (represented by a covariance) in wind estimates is high. This leads to a well-explored space, but can lead to cases where resources are wasted exploring regions where thermals are unlikely to be found.

Thermal triggering is a stochastic phenomenon in the convective boundary layer [22]. Typical updraft core radii is range from tens to hundred of meters. Thermals are affected by atmospheric phenomena such as lateral winds. Accurate thermal prediction at high resolution is extremely difficult, if not impossible. Weather prediction tools such as BLIPMAPS [2, 3, 4] (used to aid flight planning for sailplane and hang-glider pilots) provide information on a coarse grid (roughly kilometer-sized), which is too large for the SUAVs considered here. Moreover, sailplane and hang-glider pilots often look for cumulus clouds as a indication of thermal formation. However, observation of cumulus cloud formation is not yet feasible on small autonomous aircraft: this would require significant advances in computer vision and lots of processing power.

The problem at hand is to develop a means to guide exploration behavior to focus on areas that are more likely to contain thermals. Several factors are known to affect thermal formation: solar incidence angle, terrain albedo, vegetation, and soil moisture content all play a role, with solar incidence angle and albedo having the largest influence. Albedo defines the reflectivity of terrain surface from solar irradiance. As the most extreme scenario, thermals are more likely to be found on land covered by forest than snow; forest and snow have albedo ranging from 0.03 to 0.1 and 0.5 to 0.9 respectively. However, albedo is unable to provide guidance for soaring flight over the terrain associated similar albedo values. The effectiveness of terrain albedo to guide exploration depends on geographic location. Therefore, the primary focus of this thesis is on the solar incidence angle, which depends on the relative orientation between the sun and terrain surface. Variation in solar incidence angle has much smaller scale (elevation data at resolutions of 3 meters is publicly available from different sources). Atmospheric parameters such as lapse rate are important, but these typically vary over a larger scale than terrain-dependent parameters.

A high likelihood of thermal formation occurs while the position of the sun is perpendicular to the terrain surface, which leads to the maximum heat absorption by the ground. Conversely, thermals are unlikely to be found while the solar in-
cidence angle greater than $\frac{\pi}{2}$ implies that the terrain is shadowed. The autonomous soaring exploration strategy proposed here (recall from Section 1.2) utilizes the mapping algorithm developed earlier (and described in detail in Depenbusch[6]) with a priori information of regions where thermal formation is more likely to guide exploration. The exploration strategy is assisted by the development of an exploration priority function detailed in Chapter 3, which is a weighted average between the covariance of the updraft estimate and likelihood of thermal triggering across the map. The exploration priority associated with each location can then be computed.

It is expected that guided exploration is the most beneficial for small flock sizes and while thermal activity is weak. It is also reasonable to expect performance gains from cooperative exploration because multiple measurements are obtained at different locations increasing the information available to each vehicle.

### 2.2 Mapping Atmospheric Energy

The mapping algorithm used in updraft estimation is outlined in this section. The simulation environment is discretized into a grid of equally sized cells, with cell size determined by the coordinated turn diameter of the aircraft in typical thermalling flight conditions (roughly 25 meters for the RnR Products SB-XC radio-controlled sailplane). A smaller grid spacing provides a higher resolution energy map but it introduces a correspondingly higher level of correlation between cells in the updraft estimation. With the grid spacing of 25 meters, an aircraft is able to track waypoint in nearby cells and thermal without crossing into surrounding cells.

The mapping algorithm is implemented as an array of 1-D scalar Kalman filters. Each cell is associated with an estimate of vertical wind speed $\hat{w}_{z,ij}$ and error covariance of the estimated wind speed $P_{ij}$. The error covariance indicates the level of confidence in the wind estimate associated with each cell. Small values in error covariance indicate high confidence in the wind speed estimate. Conversely, high values of error covariance indicate high levels of uncertainty in the estimate wind speed, which may be estimated more accurate by more measurements.

The vertical wind speed in a cell is assumed to be independent of that in surrounding cells. This assumption greatly simplifies the high dimensional estimation
problem to a scalar estimation problem. Note that this assumption is not strictly accurate (since a thermal can be larger than a single grid cell) but ignoring correlation between cells is conservative.

The dynamics of vertical wind speed in a cell is assumed to be linear with zero-mean Gaussian noise:

\[ w_{z,ij,k+1} = aw_{z,ij,k} + w_k \]  
\[ w_k \sim N(0, Q) \]

where \( a \) is a scaling factor such that the thermal strength decays to 20% of its full strength at mean thermal lifespan \( \bar{T}_{\text{thermal}} \) (thermal parameters are given in Table 2.2 and are based on those in Section 2.5.2 by Allen [23]), \( Q \) is chosen so that it has standard deviation of 4 m/s after one mean thermal lifetime \( \bar{T}_{\text{thermal}} \) to correspond to the largest expected thermal strength. The map is initialized with no a priori information about vertical wind speed and maximum uncertainty in each cell. The time update step of the \( ij^{th} \) vertical wind estimate is given as

\[ \hat{w}_{z,ij,k|k-1} = a\hat{w}_{z,ij,k-1|k-1} \]  
\[ P_{ij,k|k-1} = a^2P_{ij,k-1|k-1} + Q \]

Wind measurement \( y_{ij} \) is obtained at aircraft location in \( ij^{th} \) cell, which is corrupted by measurement noise \( v_k \) with Gaussian distribution \( N(0, R) \), where \( R \) has standard deviation of 0.2 m/s. The measurement update of the \( ij^{th} \) cell is

\[ P_{ij,k|k} = (P_{ij,k|k-1}^{-1} + R^{-1})^{-1} \]  
\[ K_{ij,k} = P_{ij,k|k} R^{-1} \]  
\[ \hat{w}_{z,ij,k|k} = \hat{w}_{z,ij,k|k-1} + K_{ij,k}(y_{ij} + \hat{w}_{z,ij,k|k-1}) \]

In addition to updating the cell where the measurement is taken, a measurement update is performed on the surrounding cells because a thermal radius is typically larger than the width of a cell (and there actually is correlation among cells, although this is not assumed explicitly). However, this update on those cells is
done without direct measurements in that cell, and as a result the measurement noise covariance associated with the measurement update on those cells is increased linearly from $\sigma = 0.2 \ m/s$ to $\sigma = 4 \ m/s$ one mean thermal radius $\bar{R}$ away to ensure that those cells are visited to obtain measurement later (aircraft exploration behavior is presented in Chapter 3).

For a sailplane, the total specific energy $e_{tot}$ in gliding flight can be computed from altitude $h$ and airspeed $v_a$.

$$e_{tot} = h + \frac{1}{2g}v_a^2 \quad (2.8)$$

The atmospheric energy available to be harvested is only from thermal updrafts. The change in aircraft total specific energy $\dot{e}_{tot}$ is equivalent to the the vertical wind measurement at the aircraft location for the purpose of energy mapping.

$$\dot{e}_{tot} = \dot{h} + \frac{1}{g}\dot{v}_av_a \quad (2.9)$$

Measurements may be shared between aircraft to provide updates to the maps held onboard by remote aircraft. The map of cell covariance $P_{ij}$ from updraft estimation at a resolution of 25 meters is suitable to provide guidance for autonomous soaring flight. Time derivative of the change in total specific energy of aircraft $\ddot{e}_{tot}$ will be used in thermal centering controller presented in Section 2.3.

$$\ddot{e}_{tot} = \ddot{h} + \frac{1}{g}(\ddot{v}_av_a + \dot{v}_a^2) \quad (2.10)$$

### 2.3 Vehicle Dynamics and Low-level Control

The equations of motion for the aircraft model and the low-level controller designed to follow commands from the high-level decision controller (Section 2.4) are presented. An aircraft model representative of the RnR Products SB-XC radio-controlled sailplane is used in this research (parameters are given in Table A.1 in the appendix). The vehicle carried reference frame is represented in north-east-down coordinate system. The heading $\psi$ is defined from North axis, and the glidepath angle $\gamma$ is defined as the angle between the horizon and the airspeed vector $V_a$ as shown in Figure 2.1. The kinematics of the aircraft model with wind
\[ [w_N \ w_E \ w_D]^T \] at the aircraft location is

\[
\begin{bmatrix}
  v_N \\
  v_E \\
  v_D
\end{bmatrix} = \begin{bmatrix}
  \cos \gamma & 0 & -\sin \gamma \\
  0 & 1 & 0 \\
  \sin \gamma & 0 & \cos \gamma
\end{bmatrix} \begin{bmatrix}
  \cos \psi & \sin \psi & 0 \\
  -\sin \psi & \cos \psi & 0 \\
  0 & 0 & 1
\end{bmatrix}^T
\begin{bmatrix}
  v_a \\
  0 \\
  0
\end{bmatrix} + \begin{bmatrix}
  w_N \\
  w_E \\
  w_D
\end{bmatrix}
\]

(2.11)

Since controller design is not the focus of this research, it is assumed that the aircraft is equipped with an autopilot that can follow airspeed \( v_{a,cmd} \) and turn commands \( \dot{\psi}_{cmd} \) as well as maintain trimmed flight. The aircraft state vector \( x \) and control input \( u \) are

\[
x = [p_N \ p_E \ p_D \ v_a \ \psi \ \gamma]^T
\]

(2.12)

\[
u = [v_{a,cmd} \ \dot{\psi}_{cmd}]^T
\]

(2.13)

Later in this thesis, guided exploration is demonstrated in high-fidelity flight simulator (Section 4.2.3) and hardware-in-loop simulation (Section 5.4) by using an autopilot to follow low-level commands including bank angle, airspeed, and waypoint tracking.
Aircraft flight path angle is

\[ \gamma = \arctan \frac{C_D}{C_L} \]  

(2.14)

where the lift coefficient \( C_L \) is determined from airspeed in trimmed level flight, and \( C_D \) is a function of \( C_L \). The resulting aircraft system equations are

\[
\dot{p}_N = v_a \cos \psi \cos \gamma + w_N
\]

(2.15)

\[
\dot{p}_E = v_a \sin \psi \cos \gamma + w_E
\]

(2.16)

\[
\dot{p}_D = v_a \sin \gamma + w_D
\]

(2.17)

\[
\dot{v}_a = v_{a,cmd}
\]

(2.18)

\[
\dot{\psi} = \dot{\psi}_{cmd}
\]

(2.19)

\[
\dot{\gamma} = \gamma
\]

(2.20)

The system equations are propagated using fourth-order Runge-Kutta integration with a time step of 0.02 seconds.

Command inputs to the low-level controller are derived from the high-level behavior controller described in Section 2.4. A heading controller tracks a target waypoint by computing the difference between heading to the target waypoint and current heading. The maximum turn rate \( \dot{\psi}_{c,max} \) is limited so that the load factor is less than 2 for a given airspeed.

\[
\dot{\psi}_c = \psi_{wp} - \psi
\]

(2.21)

For energy exploitation in a thermal, the thermal centering controller presented by Andersson and Kaminer [10, 11] provides required turn rate for a steady turn radius \( r \) and airspeed \( v_a \) given as

\[
\dot{\psi}_c = \frac{1}{r} v_a - k \ddot{e}_{cv_a}
\]

(2.22)

where \( k \) is a scale factor to reflect importance of energy “acceleration” \( \ddot{e}_{cv_a} \). This controller centers a thermal by tuning turn rate so that the rate of change of total energy is maximized.

During exploration the aircraft flies at its best L/D speed (which maximizes
range). Assuming a second order polynomial relating sink rate to airspeed, the airspeed for best L/D is used by Reichmann [14].

\[
v_{L/D} = \sqrt{\frac{c + w_z}{a}}
\]  

(2.23)

where \( w_z \) is current vertical wind measurement, \( a \) and \( c \) are the coefficients of quadratic fit of the SB-XC aircraft sink-rate polar (Table A.1 of the Appendix). While thermalling, the airspeed to fly is at minimum sink in order to maximize the altitude gain in a thermal. The airspeed at minimum sink is 15.5 m/s for the SB-XC aircraft model.

### 2.4 Aircraft Flight Behaviors

This section describes the aircraft behaviors including local exploration, global exploration, cruise to thermal, and thermalling mode (the inclusion of \textit{a priori} information to guided exploration is discussed in Chapter 3). Behavior switching occurs at the end of a planning interval \( \Delta t_{plan} \) of 1 second, with mode selection occurring based on aircraft states and thresholds as defined in Table 2.1. The priority of aircraft behaviors is shown in ascending order. The behavior in a lower level can be overridden by an aircraft behavior on a higher level with the exception that global exploration cannot override local exploration unless the target waypoint is reached. It prevents the behavior switching while the aircraft encounters a well-explored region during the transit from one location to another. Local exploration mode is the default aircraft flight behavior.

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Exploration</td>
<td>default behavior</td>
</tr>
<tr>
<td>Global Exploration</td>
<td>mean(( \Sigma_{local} )) &lt; ( \Sigma_{thresh} )</td>
</tr>
<tr>
<td>Cruise to Thermal</td>
<td>( h &lt; h_{min} ), ( \hat{w}<em>{z,ij} &gt; v</em>{\text{MinSink}} ) and ( P_{ij} &lt; P_{\text{thresh}} )</td>
</tr>
<tr>
<td>Thermalling</td>
<td>( w_z &gt; v_{\text{MacCready}}(h) )</td>
</tr>
</tbody>
</table>

The objective of exploration is to search for updrafts at locations with a relatively high likelihood of thermal formation. The map of estimated wind speed is updated as measurements are taken. Local exploration leads the aircraft to search
in the region bounded by the index $\Delta i_{local}$ and $\Delta j_{local}$. The cell associated with highest priority is chosen for local exploration (exploration priority is explained in Chapter 3). If the covariance of the local wind estimate is smaller than the threshold (an indication of confidence in the wind estimate), the global exploration behavior is pursued such that a larger area may be explored. The region bounded by $\Delta i_{global}$ and $\Delta j_{global}$ is evenly divided into subregions. The center of a quadrant associated with highest priority is selected as the target waypoint.

The energy exploitation mode can override both local and global exploration modes if the aircraft’s altitude falls below a threshold or if a strong thermal is encountered. The MacCready value of a particular thermal indicates whether it is a “useful” thermal, and it depends on thermal strength and the current aircraft altitude[12, 14]. The MacCready value function developed by Cochrane [13] is applied to the SB-XC aircraft model: if an updraft greater than current MacCready value is encountered, thermalling mode will be activated immediately to override any current flight behavior because the ultimate goal of guided exploration is to extend endurance. With the approximated airspeed of 15.5 $m/s$ and thermal radius of 100 meters, thermalling mode is locked for an interval of 2 minutes in order to allow the thermalling centering controller to locating the core of the updraft.

If an aircraft’s altitude falls below an altitude floor $h_{min}$, the energy exploitation mode is immediately triggered, and the map of updraft estimates is used to locate thermals with adequate strength. If no suitable sources of lift can be identified on the map, the local or global exploration behavior is switched on. If a source of lift can subsequently be identified within gliding range of the aircraft, the previous behavior will be overridden, and the aircraft will be commended to take advantage of the lift. The altitude floor corresponds to the level of risk that aircraft is willing to take. Exploration with a lower altitude floor is risky, but it provides more time for exploration. Conversely, a higher altitude floor provides a safer exploration strategy in exchange for decreased exploration time. With the addition of topography, the importance of $h_{min}$ (as a height above the maximum terrain elevation) is investigated by simulation results from Monte Carlo simulation presented in Section 4.1.3.
2.5 Atmospheric Environment

This section details the key components of an atmospheric environment for soaring flight including solar irradiance, a topographic elevation model, and thermal updrafts. Some assumptions are made to simplify the atmospheric model such as negating the effects of land cover and lateral winds, but it still provides an adequate environment in which to evaluate the guided exploration approach described in Chapter 3. Knowledge of the solar incidence angle provides \textit{a priori} information on the likelihood of thermal formation to guide aircraft flight behavior. Modeled thermal updrafts provide sources of atmospheric energy in the simulation. Later in this thesis, the demonstration of the exploration approach is performed in a high fidelity flight simulator with more realistic thermal dynamics and atmospheric environment described in Section 4.2.3.

2.5.1 Sun Incidence

Solar heating of the ground is a function of the solar incidence angle, which is defined by the angle between the terrain normal vector and sun position vector. The rate of heat absorption is maximized when solar incidence is normal to the terrain. A map of the solar incidence angle indicates the likelihood of thermal triggering for the modeled world. The resolution of solar incidence map is chosen to match the grid size used in the map of updraft estimates which is in turn based on the turn radius of the SB-XC aircraft model.

The Solar Position Algorithm (SPA) \cite{24}, developed for solar radiation applications computes azimuth $\theta_{az}$ and zenith $\theta_{ze}$ angles of the sun given a geographic location and time. The SPA algorithm is accurate with uncertainties of $\pm 0.003$ degrees from the year $-2000$ to $6000$ and is chosen for this reason over other algorithms that have uncertainties greater than $0.01^\circ$, and are only valid for a certain number of years. The azimuth and zenith angles with respect to observer location can be obtained as shown in Figure 2.2.

In the persistent surveillance problem considered here, all aircraft stay within a region covering a few square kilometers. Over this scale the variation in solar azimuth and zenith due to curvature of the earth is small, hence it can be computed once for a single reference latitude and longitude defining the center of the grid.
The solar irradiance vector $\hat{r}_{\text{sun}}$ in east-north-up (ENU) coordinate system can be computed from the azimuth and zenith angles as

$$\hat{r}_{\text{sun}} = \begin{bmatrix} \sin \theta_{\text{az}} \sin \theta_{\text{ze}} \\ \cos \theta_{\text{az}} \sin \theta_{\text{ze}} \\ \cos \theta_{\text{ze}} \end{bmatrix}^T$$ \hspace{1cm} (2.24)

Computing solar incidence angle requires knowledge of the terrain normal vector. The National Elevation Dataset (NED) [25] of the United States Geological Survey (USGS) provides digital elevation data in orthometric height, which is the height above the geoid referenced to the North American Vertical Datum of 1988 (NAVD 88). Over the scale of the grid considered here the variation in geoid height between each grid spacing is small, which has negligible effect on the computation of terrain normal vector. Orthometric height can then be treated as ellipsoidal height.

In addition to terrain height, USGS provides terrain cover maps, which would allow more accurate computation of likelihood of thermal trigger with additional information on terrain heat capacity. However, the effectiveness in using terrain heat capacity depends on geographic location such as soaring over an area with similar type of terrain. Therefore, land cover is ignored here to focus on the solar incidence angle.

Elevation data at resolutions of 3 meters, 10 meters and 30 meters are publicly available from USGS. Resolution of 3 meters and 10 meters provides more
detailed topography but it significantly increases the computational cost. In addition, thermal updrafts have a much larger scale, which ranges from tens of meters to hundreds of meters in core radius. It is reasonable to assume that the variation of elevation at a smaller scale does not affect thermal formation. Therefore, elevation data at resolution of 30 meters provides adequate size for topographic model. The elevation data is interpolated to obtain the resolution of 25 meters used in energy map. Two topographic elevation models of 4 km by 4 km are obtained near State College, PA and Warm Springs, VA as shown in Figure 2.3. The topographic model in State College provides a geographic location with relatively small variation of elevation. The topographic model at Warm Springs provides much larger variation of elevation with ridges that have slopes facing east and west. These two different types of terrain allows the performance of guided exploration proposed in this thesis to be evaluated over a wide range of geographic locations.

The terrain normal vector $\hat{n}_{ij}$ for the $ij^{th}$ grid cell is computed from the cross product of the two vectors that define diagonals across the cell in Figure 2.4. It is then normalized so it has a magnitude of one.

The solar incidence angle $\theta_{\text{incidence},ij}$ of the $ij^{th}$ cell can now be computed from the dot product of the unit vector to the sun and the unit vector defining the terrain normal:

$$\theta_{\text{incidence},ij} = \arccos (\hat{r}_{\text{sun}} \cdot \hat{n}_{ij}) \quad (2.25)$$

Here $\theta_{\text{incidence},ij} = 0$ means that the sun is overhead and the vector to the sun is exactly perpendicular to terrain, in this case, solar heating will be maximized. When $\theta_{\text{incidence},ij} > \pi/2$, it is implied that the terrain is shadowed, and solar heating will be zero. A map of solar incidence angle at each grid cell for the region centered on State College, PA is shown in Figure 2.5.

### 2.5.2 Thermal Updraft Model

An accurate thermal model requires significant amount of information on the atmosphere environment, which is extremely difficult to model. Assumptions are made about the characteristics of thermals to simplify the model but that still provide reasonable thermal dynamics. Atmospheric energy available from spatial and temporal gradients are not modeled. Long duration lift from wave and wind deflected
Figure 2.3. Topographic elevation models

by the slope of mountains is not simulated so that the effectiveness of prediction of thermal formation based on incidence angle can be investigated. Thermal updrafts provide the only energy source for exploitation. Thermals are assumed to rise in a vertical column. Thermal strength, shape, and core radius are constant from the ground to the top of the convective boundary layer. Each thermal is simulated independently and cannot interact with nearby thermals.

As a thermal expands and rises, the vacated region of air is filled by the sur-
rounding air due to convection, which introduces an area of downward moving air around the core of thermal. A thermal updraft model proposed by Gedeon[26] is used here which captures this phenomenon:

$$w_z(x, y, t_0) = \omega_0 e^{-\left(\frac{\sqrt{(x-x_0)^2 + (y-y_0)^2}}{R}\right)^2 \left[1 - \left(\frac{\sqrt{(x-x_0)^2 + (y-y_0)^2}}{R}\right)^2\right]^2}$$

(2.26)

where $\omega_0$ is the maximum vertical wind speed, $x_0$ and $y_0$ are the coordinates of the thermal center, and $R$ is the core radius of thermal. This thermal model is shown in Figure 2.6(a).
Thermals are time-varying, with a typical lifespan of approximately 15 minutes. The time history of a thermal is modeled using sigmoid functions:

$$\frac{w_z(x, y, t)}{w_z(x, y, t_0)} = \left(\frac{1}{e^{\eta(t-(t_0+\frac{1}{2}T))}} + 1 + \frac{1}{e^{\eta(t-(t_0-\frac{1}{2}T))}} + 1 - 1\right)$$  \hspace{1cm} (2.27)

where $\eta$ is the scaling factor that determines rise time to full strength. Thus, the thermal model can be tuned to more accurately model the actual dynamics of a thermal by changing $\eta$. A time history of thermal strength variation is shown in Figure 2.6(b). Typical thermal characteristics are used for parameters such as thermal period, thermal radius, and core strength. It is assumed that these variables have Gaussian distribution, with parameters obtained from Allen [23] and given in Table 2.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Mean</th>
<th>$\sigma$</th>
<th>max/min</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>$T_{thermal}$</td>
<td>20</td>
<td>7.5</td>
<td>60 / 5</td>
<td>minutes</td>
</tr>
<tr>
<td>Radius</td>
<td>$R$</td>
<td>75</td>
<td>20</td>
<td>200 / 30</td>
<td>m</td>
</tr>
<tr>
<td>Core strength</td>
<td>$\omega_0$</td>
<td>-2.56</td>
<td>1.5</td>
<td>-7 / 1</td>
<td>m/s</td>
</tr>
</tbody>
</table>

For the Monte Carlo simulation results presented in Section 4.1.3, thermal
generation is partially dependent on incidence angle, with thermals triggering with higher probability where solar incidence is near perpendicular to terrain. To reflect low heat absorption at high incidence angle, thermals are not triggered at locations where incidence angle is greater than a certain $\theta_{\text{limit}}$, which depends on geographic location. The probability of thermal triggering is formulated as a function of solar incidence angle and noise with uniform distribution $\epsilon$ within $\pm 0.2$. The noise term introduces randomness to thermal generation:

$$
P_{\text{thermal}} = \begin{cases} 
1 - \left(\frac{\theta_{\text{incidence,ij}}}{\theta_{\text{limit}}}\right)^{1.5} + \epsilon & \text{if } \theta_{\text{incidence,ij}} \leq \theta_{\text{limit}} \\
0 & \text{if } \theta_{\text{incidence,ij}} > \theta_{\text{limit}} 
\end{cases}
$$

(2.28)

Constraints are imposed on the maximum number of thermals in the world, and the probability of thermal generation at each time step $\Delta t_{\text{gen}}$. This is done to provide a more realistic simulation environment so that all thermals are not generated and dissipated at once. The maximum number of thermals $N$ within an area $A$ given by Allen [23] allows far too many thermals for an realistic environment. The maximum number of thermals is scaled down by a factor $b = 3$ allowing for a maximum of 20 thermals in a 4 km by 4 km map given as

$$
N = \frac{0.6A}{bz_i \bar{R}}
$$

(2.29)

where $z_i$ is the boundary layer thickness, and $\bar{R}$ is mean thermal radius. The probability of generating a thermal $P_{\text{generate}}$ is inversely proportional to thermal generation interval $\Delta t_{\text{gen}}$ and number of active thermals $n$.

$$
P_{\text{generate}} = \min\left(\frac{\Delta t_{\text{gen}}N}{T}(N - n), 1\right)
$$

(2.30)

When the conditions on maximum number of thermals $N$ and the probability of generating a new thermal $P_{\text{generate}}$ are satisfied, a new thermal is triggered in a cell associated with the highest $P_{\text{thermal}}$, and its location is subject to the minimum separation distance between thermals, which is approximately four times the core radius of a thermal. Thermal activity is sensitive to the choice of $\theta_{\text{limit}}$, which depends on the topographic elevation model.
2.6 Summary

Section 2.1 reviewed the problem of guided exploration and cooperative mapping for autonomous soaring flight. The objective of guided exploration is to extend endurance for surveillance missions by targeting regions where thermals are most likely to be found. Resources are not wasted exploring regions where thermals are unlikely to exist. Current weather forecasting tools are unavailable to provide thermal prediction at high resolution to guide aircraft exploration. However, solar incidence angle is the most influential factor that affects thermal formation, and it can be computed from a topographic elevation model and sun position as a priori information. The variation in solar incidence angle has a much smaller scale, which can be used to guide exploration for SUAVs.

Section 2.2 described the mapping algorithm used in updraft estimation. The world is discretized into a grid with equal spacing of 25 meters, which is determined by the turn diameter of the SB-XC aircraft model. Negating the effect of the correlation between cells significantly reduces the dimensionality of the estimation problem. The mapping algorithm is implemented as an array of 1-D Kalman filters. (The updraft estimate is the change in total specific energy of the aircraft.) The measurement update is also applied to the immediate surrounding cell because a typical thermal radius is larger than the grid size. The covariance associated with those cells is increased because the update is done without direct measurement. The distribution of the energy map allows thermal information to be shared among aircrafts at remote locations.

Section 2.3 provided the system of equations of the SB-XC sailplane aircraft model in the presence of wind. An autopilot is assumed to be available to perform low level control that follows commands from high level controller. A heading controller is used for waypoint tracking and thermal centering. An airspeed controller maintains aircraft flying speed at minimum sink to maximize altitude gain for energy exploitation; alternatively airspeed is maintained at best L/D to maximize range for exploration.

Section 2.4 outlined the aircraft flight behaviors and behavior switching criteria based on the aircraft states and specified thresholds. Exploration mode selects a waypoint associated with first priority based on an exploration priority function.
detailed in Chapter 3. Energy exploitation is triggered by an aircraft altitude falling below the altitude floor or encountering a strong thermal by computing the MacCready value function at aircraft altitude.

Section 2.5 detailed the key components of an atmospheric environment for soaring flight including sun irradiance, topography, and the thermal updraft model. The map of solar incidence is computed by the dot product of the sun and the unit terrain normal vector presented in Section 2.5.1. In Section 2.5.2, a thermal updraft model by Gedeon[26] is used because it provides an area of sinking air surrounding the core of the updraft. The time-vary quality of thermal strength is modeled using a sigmoid function. Next, the method of thermal generation is presented. While the conditions for the maximum number of thermals, incidence angle limit, and the probability of generating a new thermal are satisfied, a new thermal is triggered at a cell associated with the minimum incidence angle, and its location is subject to the minimum separation distance between thermals, which is four times the core radius of a thermal.

The equations and methods presented here are used throughout this thesis. The development of a guided exploration strategy that utilizes covariance from updraft estimate with solar incidence as a priori information in aircraft flight behavior is detailed in Chapter 3. Performance validation of guided exploration approach and simulation of coordinated thermal mapping in a high fidelity flight simulator are provided in Chapter 4. Eventually, hardware implementation of guided exploration with an autopilot system is evaluated in hardware-in-loop simulations presented in Chapter 5.
Chapter 3

Implementing the Exploration Priority Function

This chapter details the methodology of the exploration priority function, which determines aircraft flight behaviors in cooperative autonomous soaring flight. The covariance driven exploration framework developed by Depenbusch [6] is extended with the inclusion of solar incidence as a priori information. This thesis expands that work by incorporating the topographic models and solar irradiance (presented in Section 2.5) to develop an exploration strategy. A brief background of the covariance driven and a priori information driven exploration strategies is described in Section 3.1. Both exploration approaches contain downsides, which can be eliminated by an hybrid approach. This leads to the formulation of the exploration priority function presented in Section 3.2. The choice of proper weight factor is investigated by conducting Monte Carlo simulations. Finally, aircraft flight behaviors, derived from the exploration priority function including local exploration, global exploration, and cruise to a thermal are explained in Section 3.3.

3.1 Review of Exploration Strategies

The earlier work demonstrated the utility of coordinated autonomous soaring for improving range and endurance for SUAS. The exploration priority was driven purely by uncertainty in the map of updraft estimates (outlined in Section 2.2). High exploration priority was assigned to regions where error covariance in the
vertical wind estimate was high. The objective of the exploration behavior was to maintain the accuracy of the map (thermals typically have lifespans of 15 minutes). When immediate energy exploitation was required, the energy map provided locations associated with strong thermal lift as well as high confidence in the updraft estimate within reachable distance. Simulation results with various flock sizes had shown that single aircraft can still benefit from the use of an energy map but this approach was essentially counting on luck to extend endurance [6]. For large flock sizes (six to eight aircraft) this approach performed very well, ensuring that the environment remained well-explored without any included model of thermal formation (thermals were generated randomly with constraints to provide a reasonable environment). With a flock size of eight aircraft, almost all aircraft remained aloft for the duration of the mission. However, this approach led to significant exploration of regions where thermals were unlikely to be found.

One could drive exploration solely by the likelihood of thermal triggering (here driven by solar incidence, presented in Section 2.5.1), which is more effective than counting on luck (using the covariance). Resources are not wasted on exploring shaded regions where thermal formation is unlikely. While this will lead to exploration of regions more likely to contain thermals, it is likely to result in “excessive exploration” of these areas, even when no thermals are present there. Aircraft might become trapped in the same region without the presence of actual thermals. Further, some terrain maps may have large flat regions where solar incidence is roughly uniform, providing little \textit{a priori} guidance for the search.

On the other hand, confidence in updraft estimates in the form of covariance driven exploration, prevents aircraft from flying to same location repeatedly within a short period of time. However, random searching for thermals is especially inefficient with small flock size and weak thermal activity. In order to eliminate downsides from each individual exploration methodology, an hybrid approach that combines the covariance in vertical wind estimates with \textit{a priori} information is presented in Section 3.2. Thus, this hybrid approach can be applied to geographic locations with various characteristic topographies and different levels of thermal activity.
3.2 Exploration Priority Function

A hybrid approach that computes an exploration priority based on some function of both vertical wind covariance and solar incidence angle is likely to provide a good solution to the problems presented in the previous section. The downsides of each individual approach can be eliminated using this hybrid approach. Vertical wind covariance prevents aircraft from flying to the same locations that have been visited recently, while \textit{a priori} information drives the aircraft to explore regions with a high likelihood of thermal formation. The concept of the exploration priority function is proposed to guide exploration for coordinated autonomous soaring flight, and defined as a weighted average between vertical wind covariance and solar incidence angle.

In this approach a cell that combines high covariance with near-perpendicular sun incidence will be assigned the highest priority for exploration, thus driving exploration to regions that are both relatively unexplored and likely to contain thermals. It is reasonable to expect a performance gain by eliminating the need to visit regions in which there is a high confidence in the wind estimate and a low probability of thermal formation as shown in Figure 3.1. (The regions associated with high likelihood of thermal formation and the surrounding are well explored.) Other regions where thermal formation is unlikely are completely avoided.

The exploration priority function is formulated by first computing the mean value of incidence angle $\bar{\theta}_{\text{incidence}}$ and the standard deviation of the incidence angle $\sigma_{\text{incidence}}$ in a cell. The contribution to the exploration priority value for the $ij$th cell due to the solar incidence angle is defined as

$$p_{\text{incidence,ij}} = \frac{\theta_{\text{incidence,ij}} - \bar{\theta}_{\text{incidence}}}{\sigma_{\text{incidence}}}$$  \hspace{1cm} (3.1)

The quantity $p_{\text{incidence,ij}}$ is thus a measure of the number of standard deviations away from the mean incidence angle.

Note that $\theta_{\text{incidence,ij}}$ varies from 0 to $\pi$, with $\theta_{\text{incidence,ij}} = 0$ corresponding to solar incidence perpendicular to terrain (leading to highest solar heating), and $\theta_{\text{incidence,ij}} > \frac{\pi}{2}$ implying terrain in shadow. Positive values of $p_{\text{incidence,ij}}$ will thus
be desirable for exploration. The net exploration priority $Z_{ij}$ for the $ij^{th}$ cell is

$$Z_{ij} = \alpha \sqrt{P_{ij}} + (1 - \alpha)p_{\text{incidence,ij}}$$

(3.2)

The weighting factor in the exploration priority function allows easy modification for overall exploration behavior of a flock of aircraft. The choice of $\alpha$ depends on variation in elevation and thermal activity for particular soaring conditions. The exploration priority function enables aircraft to rely more on covariance while soaring over regions with small variation in elevation (a priori information provides only minimal guidance). When thermal activity is weak or flock size is small (exploration resources are very limited), a priori information guided exploration is more likely to encounter thermals than covariance guidance. Therefore, selecting an adequate weighting factor according to the geographic location and atmospheric conditions is critical to the success of guided exploration.

The choice of weight factor is influential to the performance of the exploration priority function. Scaling differences in the expected standard deviation of the estimation error (which has unit in m/s) and the quantity $p_{\text{incidence,ij}}$ (which is
unitless) complicate the choice of weight. Monte Carlo simulation results for various flock sizes and a range of weight factor are conducted in order to determine a suitable weight factor. $\alpha = 0.05$ corresponds to exploration driven nearly entirely by solar incidence while $\alpha = 1$ corresponds to covariance driven exploration.

Simulation setup and conditions are outlined here (details are provided in Section 4.1.1). Monte Carlo simulations have 20 runs for each set of conditions. A 4 km by 4 km terrain model near Mifflin, PA is shown in Figure 3.2. This geographic location provides an average terrain model between State College, which has very gentle terrain and Warm Springs, which has large variations in elevation. Since the goal of exploration is thermal search, a minimum altitude floor of 200 meters (above the highest terrain feature) provides for the maximum exploration time to map thermals. This altitude floor provides just enough height for an aircraft to traverse the map for energy exploitation if necessary. The criteria for selecting the weight factor is that which results in the maximum number of thermal found for overall flock sizes.

![Figure 3.2](image)

(a) N 40.5°, W 77.5° near Mifflin, PA
(b) Aerial image of topography

**Figure 3.2.** Topographic elevation model for weight selection

For the single aircraft case in Figure 3.3(a), the maximum number of thermals occurs at $\alpha = 0.4$. However, results from two aircraft indicate similar performance for a range of weight factors from $\alpha = 0.4$ to $\alpha = 0.7$ in Figure 3.3(b). Results from both four and eight aircraft cases show that maximum number of thermals found occur at $\alpha = 0.5$ in Figure 3.4. Additionally, results from various flock sizes show a peak in the number of thermals within the range of $\alpha \in 0.4, 0.5, 0.6, 0.7$. 
It suggests that the proper choice of weight factor lies within this range. $\alpha = 0.5$ gives the best performance for overall flock sizes, which is chosen in developing the Monte Carlo simulation results presented in Chapter 4.

### 3.3 Combining Behaviors with Solar Incidence

The high-level behavior control developed in earlier work is expanded to incorporate *a priori* information in local exploration, global exploration, and cruise to thermal modes (the behavior switching criteria is explained in Section 2.4). Since the inclusion of *a priori* information does not affect the thermalling mode, it is not included in this chapter. The goal of exploration is to maintain the accuracy of the map of updrafts at locations where the likelihood of thermal formation highest.

#### 3.3.1 Local Exploration

The search range for local exploration is bounded by $\Delta i_{local}$ (up and down direction) and $\Delta j_{local}$ (left and right direction) about current aircraft location ($i_{cur}, j_{cur}$). Before waypoint is assigned, the search range of $\Delta i_{local} = 3$ and $\Delta j_{local} = 3$ is checked as shown in Figure 3.5, ensuring that aircraft explores within the map. Regions associated with the highest value of exploration priority function $Z_{ij}$ are targeted for exploration.

\[
Target_{local} = \max(Z_{ij}) \quad \text{for} \quad \begin{array}{l}
i \in [i_{cur} - \Delta i_{local,up}, i_{cur} + \Delta i_{local,down}] \\
j \in [j_{cur} - \Delta j_{local,left}, j_{cur} + \Delta j_{local,right}]
\end{array}
\]  

(3.3)

where $\Delta i_{local,up}$ and $\Delta i_{local,down} \leq \Delta i_{local}$, $\Delta j_{local,left}$ and $\Delta j_{local,right} \leq \Delta j_{local}$.

#### 3.3.2 Global Exploration

Global exploration searches for a much longer distance as shown in Figure 3.6. A larger region bounded by $\Delta i_{global} = 30$ and $\Delta j_{global} = 30$ is checked to ensure that aircraft stays within the map. This region is evenly divided into a number of subregions bounded by $\Delta i_{subregion}$ and $\Delta j_{subregion}$. 
\[ \Delta i_{\text{subregion}} = \frac{i_{\text{up}} + i_{\text{down}}}{k_i} \quad \text{for} \quad i_{\text{up}} \leq \Delta i_{\text{global}}, i_{\text{down}} \leq \Delta i_{\text{global}} \quad (3.4) \]

\[ \Delta j_{\text{subregion}} = \frac{j_{\text{left}} + j_{\text{right}}}{k_j} \quad \text{for} \quad j_{\text{left}} \leq \Delta j_{\text{global}}, j_{\text{right}} \leq \Delta j_{\text{global}} \quad (3.5) \]

where \( k_i \) and \( k_j \) are the factors that determine number of subregions.

The exploration priority function \( Z_{Q,ij} \) associated with subregion \( Q_{ij} \) is computed by the sum of exploration priority function for each cell. The aircraft targets the center of a subregion with the highest value of the exploration priority function.

\[ \text{Target}_{\text{global}} = \max(Z_{Q,ij}) \quad \text{for} \quad i = 1,...,k_i \text{ and } j = 1,...,k_j \quad (3.6) \]

\[ Q_{ij} = \begin{cases} i \in [i_{\text{cur}} - i_{\text{up}} + (i-1)\Delta i_{\text{subregion}}, i_{\text{cur}} - i_{\text{up}} + i\Delta i_{\text{subregion}}] \\ j \in [j_{\text{cur}} - j_{\text{left}} + (j-1)\Delta j_{\text{subregion}}, j_{\text{cur}} - j_{\text{left}} + j\Delta j_{\text{subregion}}] \end{cases} \quad (3.7) \]

### 3.3.3 Cruise to Thermal

When energy exploitation is required, gliding range \( \Delta i_{\text{search}} \) and \( \Delta j_{\text{search}} \) is computed at current aircraft altitude \( P_D \) with respect to the maximum terrain elevation \( h_{\text{terrain}} \). The boundary of map is again checked to ensure the aircraft stays within the map.

\[ \Delta i_{\text{search}} = \Delta j_{\text{search}} = \text{floor}\left(\frac{P_D - h_{\text{terrain}}}{c \tan \gamma}\right) \quad (3.8) \]

where \( c = 25 \text{ meters} \) is the grid spacing of the map.

The energy map provides locations of thermal and an indication of whether they are of adequate strength. If suitable updrafts are found within gliding range, the “attractiveness” \( A_{ij} \) associated with the \( ij^{th} \) cell is

\[ A_{ij} = \frac{w_{z,ij}}{d} \quad \text{for} \quad i \in [i_{\text{cur}} - \Delta i_{\text{search}}, i_{\text{cur}} + \Delta i_{\text{search}}] \\ j \in [j_{\text{cur}} - \Delta j_{\text{search}}, j_{\text{cur}} + \Delta j_{\text{search}}] \quad (3.9) \]

where \( d \) is the distance between the aircraft and the thermal location. The aircraft targets the most “attractive” cell.

If an updraft is not available within range, the aircraft continues to perform local or global exploration until an updraft is encountered or found by the flock.
3.4 Summary

Section 3.1 reviewed two exploration approaches; one that is purely driven by covariance and another driven by the likelihood of thermal triggering. Each individual approach has downsides; the covariance approach is ineffective for small flock sizes and weak thermal activity and the likelihood of thermal triggering approach might lead to excessive exploration of the same region, and may provide little guidance on gentle topographic locations. An hybrid approach eliminates the downsides by combining error covariance and solar incidence, and can be applied to geographic locations with small variation in terrain elevation and weak thermal activity.

Section 3.2 presented the exploration priority function as applied to the problem of guided exploration for coordinated mapping and autonomous soaring flight. The exploration priority function is a weighted average between covariance in wind estimates and the likelihood of thermal triggering. A cell that has high covariance with near-perpendicular sun incidence is assigned the highest exploration priority. Moreover, the weight factor enables easy modification of the flock behavior. Exploration priority can rely more on covariance while soaring over regions with minimal variation in elevation. Conversely, soaring on a weak thermal day can rely more on a priori information. The proper choice of $\alpha = 0.5$ is determined by conducting Monte Carlo simulation results, and is used in developing results presented in this thesis.

Section 3.3 described changes to aircraft behaviors due to incorporating a priori information. Local exploration searches for a small region. A destination is assigned to a region with the largest exploration priority. When a level of threshold confidence in local wind estimates is achieved, the aircraft is commended to explore a region further away. The search space is first divided into subregions, and a destination is assigned to the center of a subregion with the largest value of exploration priority function. The search range for energy exploitation is computed relative to the maximum terrain elevation. If updrafts are found, the “attractiveness” of these cells are computed to aid in the selection of a destination. If an updraft is unavailable, the aircraft continues exploration mode until an updraft is found.

Performance verification of the exploration strategy for different flock sizes at
two terrain models will be presented in Chapter 4. Additionally, the feasibility of the exploration guidance strategy will be demonstrated in a high fidelity soaring flight simulator with a realistic thermal model. Finally, hardware-in-loop simulations of the exploration guidance algorithm with an autopilot system and an SB-XC sailplane will be detailed in Chapter 5.
Figure 3.3. Number of thermals found versus weight factor
Figure 3.4. Number of thermals found versus weight factor
Figure 3.5. Local exploration for $\Delta i_{local} = \Delta j_{local} = 3$

Figure 3.6. Global exploration for $k_i = k_j = 2$
Chapter 4

Simulation Results

This chapter presents simulation results for the guided exploration method for coordinated mapping in autonomous soaring flight. Performance of the exploration priority function is evaluated by conducting Monte Carlo simulations. Covariance driven exploration in the earlier work serves as baseline scenario for comparisons. The effect that the altitude floor (immediate energy exploitation threshold) has on the performance of guided exploration is investigated for various flock sizes.

Finally, the feasibility of guided exploration in cooperative soaring flight (single and two aircraft) is demonstrated in a high fidelity flight simulator, which provides a more realistic atmospheric environment that is not modeled in Monte Carlo simulation. The setup used in demonstrating guided exploration in the simulator is modified for the hardware implementation of exploration guidance as detailed in Chapter 5.

4.1 MATLAB Simulation

4.1.1 Simulation Setup

Recall from Section 1.3 the general structure of exploration guidance (also shown in Figure 4.1). Aircraft kinematics and the low-level controller provided in Section 2.3 are used for vehicle dynamics and flight control systems. Since current research focuses on exploration guidance, it is assumed that the aircraft is equipped with an autopilot to follow airspeed and heading commands as well as maintain trimmed
flight conditions. The mapping algorithm (Section 2.2), behavior determination (Section 2.4), and aircraft flight behavior (Section 3.3) are deployed in developing simulation results. The map of wind speed estimates which is built by the team of aircraft is assumed to be available at all times to all aircraft. The simulation environment (Section 2.5) contains the thermal model to provide energy sources to power soaring flight. A screenshot from a representative run of a Monte Carlo simulation and a barogram are depicted in Figure 4.2 and Figure 4.3.

4.1.2 Simulation Conditions

Simulation results are conducted with flock sizes of 1, 4 and 8 aircraft for two terrain models: State College, PA and Warm Springs, VA. A weight factor $\alpha = 0.5$ in the exploration priority function is used. Performance verification of guided exploration is performed by using covariance driven exploration as a baseline scenario.

Three levels for the altitude floor (the level at which an immediate mode switch to energy exploitation is triggered) are used: $h_{\text{min}} = 200$ m, 500 m, and 800 m above the maximum terrain elevation in each terrain model. The lowest altitude floor of 200 meters above the maximum terrain elevation provides aircraft just enough height to traverse the map at best L/D speed and allows for maximum exploration time. Touch down is defined when altitude drops below terrain elevation.

Figure 4.1. MATLAB simulation setup
Eight SB-XC sailplanes exploit energy and map the environment over State College, PA. A contour plot of the energy map is shown on bottom with updraft estimate denoted as circles. Terrain model colored by the incidence angle denotes high likelihood of thermal formation in red. The actual locations of thermal updrafts are denoted as columns.

Thermal activity starts in late morning, and it is expected to become weaker at sunset. Thus, simulations start at 11 a.m. on June 6, 2012 and last six hours. Thermals are not generated at locations where solar incidence angle $\theta_{\text{limit}}$ is greater than $\frac{\pi}{4}$.

Each simulation case uses the same set of random number sequences in order to provide identical atmospheric environments. Monte Carlo simulation of 70 runs use different seeds of random number, which generate thermals at different locations and various parameters; core radius, strength, and lifespan are gaussian random variables by Allen [23]. Aircrafts are initialized at center of the map with different headings and altitude of 1500 meters above the maximum terrain height. Aircraft start at the ceiling altitude of 2000 meters and 2800 meters over the State College and Warm Springs terrain respectively. The height of the convective boundary layer in reality is often higher than these starting altitude. Communication between aircraft is available at all times, such that wind measurements may be shared at intervals of 3 seconds.

Now that the simulation setup and conditions are described, simulation results
Figure 4.3. Barogram of the representative run

Aircraft altitude is colored according to flight behavior. Local exploration is blue. Global exploration is black. Cruise to thermal is green. Thermalling is red. Touch down is denoted as $\oplus$.

of guided exploration can be shown.

4.1.3 Monte Carlo Simulation Results

Monte Carlo simulation results are shown as boxplots in Figure 4.4, 4.5 and 4.6. For each boxplot, the central line is the median; the edges of the box are defined by the interquartile range (IQR); whiskers extend to datapoints in the range $q_1 - 1.5(q_1 - q_3)$ to $q_3 + 1.5(q_1 - q_3)$; outliers “+” are plotted individually.

Results summarizing the Monte Carlo simulations for a single aircraft are shown in Figure 4.4. For the State College terrain in Figure 4.4(a), guided exploration outperforms covariance driven exploration at all levels of altitude floor. However,
the performance gain decreases at higher altitude floors. This makes sense because lower altitude floors allows more time for exploration, and exploration time decreases with rising altitude floors.

Results from the Warm Springs terrain tells a different story as shown in Figure 4.4(b). Guided exploration is completely outperformed by covariance driven exploration. Where guided exploration allows an aircraft to avoid regions where the likelihood of thermal triggering is weak, a performance gain is expected. This contradictory and unexpected result is examined after the Monte Carlo results of four and eight aircraft are shown.

At Warm Springs terrain, the maximum performance loss occurs at the lowest altitude floor of 1500 meters, and the minimum loss occurs at the highest altitude floor. Long duration flight is not achievable with a single aircraft given the atmospheric condition in this thesis. Flight experience by other researchers (Allen[8], Edwards[9], and Andersson[11]) suggests that in practice significantly longer flight times are achievable.

With an increase of flock size to four aircraft for State College terrain, Figure 4.5(a) shows that guided exploration provides larger performance gain over the baseline at altitude floor of 600 meters than does the single aircraft case. Again, guided exploration at a lower altitude floor provides better performance but performance gain decreases at a higher altitude floor.

For Warm Springs terrain, Figure 4.5(b) shows a similar trend as is present in the single aircraft case. The exploration priority function results in even worse performance with an altitude floor of 1500 meters. An increase of altitude floor reduces the gap between the performance of the covariance and the exploration priority function.

For the eight aircraft case, guided exploration provides a dramatic improvement for State College terrain as shown in Figure 4.6(a). A relatively smaller improvement occurs at the altitude floor of 1200 meters. All results from State College terrain clearly show that the performance of guided exploration depends on the altitude floor.

On the other hand, a performance gain can be achieved over the Warm Springs terrain with a flock size of eight aircraft as shown in Figure 4.6(b). However, the altitude floor of 2100 meters does not lead to performance gain, implying
Figure 4.4. Endurance versus altitude floors for single aircraft
Figure 4.5. Endurance versus altitude floors for four aircraft
that a certain amount of exploration time is necessary. All results from Warm Springs terrain concludes that large flock size and low altitude floor are required for improved endurance. Next, the poor performance of guided exploration by using single and four aircraft is explained.

Two instances of the solar incidence angle map for the different are shown in Figure 4.7 for comparison. The Warm Springs terrain contains much larger areas of low solar incidence where the likelihood of thermal triggering is high throughout simulation. Therefore, a large flock size and low altitude floor is necessary in order to provide enough agents and exploration time to visit this large area with enough frequency to detect and map transient thermal lift. The results from Warm Spring also suggest that a heavier weight on error covariance in the updraft estimate would be benefited because solar incidence provides very little exploration guidance.

Simulation results from the State College terrain indicate absolute performance gains from the use of the exploration priority function as summarized in Table 4.1. The maximum improvement often occurs at the lowest altitude floor because it provides the most exploration time. The smallest performance gain always occurs at the highest altitude floor. Long-duration flight is achievable with a flock size of eight aircraft. In almost two third of the simulation runs the flock survives for 90% of simulation duration by using eight aircraft and altitude floor of 900 meters.

<table>
<thead>
<tr>
<th># aircraft</th>
<th>$h_{\text{min}}$</th>
<th>$t_{\text{median, cov}}$</th>
<th>$t_{\text{median, exp}}$</th>
<th>% gain</th>
<th>$t_{90%, \text{cov}}$</th>
<th>$t_{90%, \text{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>600 m</td>
<td>0.82 h</td>
<td>1.07 h</td>
<td>30.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>900 m</td>
<td>0.89 h</td>
<td>1.02 h</td>
<td>14.9</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1200 m</td>
<td>0.88 h</td>
<td>0.95 h</td>
<td>7.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>600 m</td>
<td>1.46 h</td>
<td>2.64 h</td>
<td>81.6</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>900 m</td>
<td>1.72 h</td>
<td>2.10 h</td>
<td>22.0</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>1200 m</td>
<td>1.44 h</td>
<td>1.81 h</td>
<td>25.7</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>600 m</td>
<td>2.68 h</td>
<td>5.79 h</td>
<td>116.1</td>
<td>4</td>
<td>44</td>
</tr>
<tr>
<td>8</td>
<td>900 m</td>
<td>2.41 h</td>
<td>5.86 h</td>
<td>143.3</td>
<td>21</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>1200 m</td>
<td>2.57 h</td>
<td>3.57 h</td>
<td>39.0</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

On the other hand, results from the Warm Springs terrain are summarized in Table 4.2. Guided exploration is outperformed by covariance in most cases. Performance gain is not achievable with single and four aircraft flocks. While solar incidence provides little guidance, the lowest altitude floor results in the
Figure 4.6. Endurance versus altitude floors for eight aircraft
Figure 4.7. Comparison of thermal triggering between terrain models

Contour plots of thermal trigger probability based on incidence angle at noon on June 6, 2012. Region in red represents high likelihood of thermal formation.

(a) 4 km x 4 km region in State College, PA  
(b) 4 km x 4 km region in Warm Springs, VA

worst performance. This result confirms that a higher altitude floor should be set for regions with unknown thermal distributions. Overall, the number of runs that survived 90% of simulation duration indicate similar performance between the covariance and the exploration priority function driven exploration. A weight factor \( \alpha > 0.5 \) (heavier weight on covariance) should be used, confirming previous results.

In general, Monte Carlo simulation results suggest that an altitude floor of 800 meters provides the safest exploration approach when operating without knowledge of thermal distribution. When thermal prediction is accurate, small performance gain can be obtained. Conversely, while thermal prediction provides little guidance, there is only slightly performance loss.
Table 4.2. Monte Carlo result for Warm Springs terrain

<table>
<thead>
<tr>
<th># aircraft</th>
<th>$h_{min}$</th>
<th>$t_{median,cov}$</th>
<th>$t_{median,exp}$</th>
<th>% gain</th>
<th>$t_{90% ,cov}$</th>
<th>$t_{90% ,exp}$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1500 m</td>
<td>1.45 h</td>
<td>1.26 h</td>
<td>-13.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1800 m</td>
<td>1.26 h</td>
<td>1.23 h</td>
<td>-3.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2100 m</td>
<td>1.10 h</td>
<td>1.06 h</td>
<td>-3.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1500 m</td>
<td>2.79 h</td>
<td>2.18 h</td>
<td>-22.0</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>1800 m</td>
<td>2.70 h</td>
<td>2.26 h</td>
<td>-16.2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>2100 m</td>
<td>2.27 h</td>
<td>2.16 h</td>
<td>-4.6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1500 m</td>
<td>3.38 h</td>
<td>3.78 h</td>
<td>11.7</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>1800 m</td>
<td>4.03 h</td>
<td>4.76 h</td>
<td>18.3</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>2100 m</td>
<td>3.57 h</td>
<td>3.44 h</td>
<td>-3.4</td>
<td>25</td>
<td>24</td>
</tr>
</tbody>
</table>

4.2 Simulation in Flight Simulator

4.2.1 Silent Wings

Silent Wings is a commercially available multi-player soaring simulator\(^1\), which contains a dynamic thermal model, orographic lift, wind shear, and is capable of correctly modeling extreme flight maneuvers such as spins. Silent Wings provides a more realistic atmospheric environment to demonstrate the feasibility of the exploration guidance strategy. Additionally, Silent Wings serves as a testing platform for the development of the guided exploration strategy. The platform developed for Silent Wings simulations is adopted for hardware implementation of guided exploration presented in Chapter 5.

4.2.2 Simulation Setup and Conditions

The simulation setup for coordinated mapping with two aircraft is depicted in Figure 4.8. Vehicle dynamics are modeled by a linear aerodynamic model of SB-XC sailplane. Low-level control is implemented on an Arduino Mega 2560, which hosts an autopilot to track heading and airspeed commands (Section 2.3). The autopilot is equipped with an Arduino Ethernet Shield to receive state information from Silent Wings and sends commands to Silent Wings via UDP. The autopilot communicates with the exploration guidance algorithm running on a separate laptop computer in Simulink via a serial port.

\(^1\)http://www.silentwings.no/
Exploration guidance consists of a mapping algorithm (Section 2.2), a behavior determination controller (Section 2.4), aircraft flight behavior (Section 3.3), and a priori information (Section 2.5.1), which are implemented in Simulink as C-Mex S-function blocks, and run on a laptop computer. Sharing of updraft measurements among aircraft is performed via UDP at at 3 second intervals.

Note that this setup for Silent Wings simulations is a stepping stone to hardware demonstration of guided exploration in real flight. The Arduino autopilot can be replaced by a commercially available autopilot system and the Silent Wings simulator replaced by an SB-XC sailplane. The exploration guidance algorithm remains unchanged except that the communication between the autopilot and the guidance algorithm running in Simulink is modified. Therefore, the overall structure is very similar, and Silent Wings simulations are used to evaluate the exploration guidance algorithm thoroughly without risking the hardware.

A 4 km x 4 km topographic elevation model is generated in Silent Wings as a scenery, which is centered at N 37.1972°, W 80.5814° near Blacksburg, VA. Simulation starts at 11 a.m. on June 6, 2012. Thermal activity, strength and size are set to medium in the simulator setup. A snapshot of actual thermal locations is shown in Figure 4.9.

Simulation setup and conditions have been provided. Now guided exploration with a single and with two aircraft in Silent Wings can be shown.

### 4.2.3 Demonstration of Thermal Mapping

Results of a single aircraft in flight are summarized in Figure 4.10. The feasibility of exploration guidance by incorporating mapping algorithm and solar incidence is demonstrated. Flight paths in Figure 4.10(a) and Figure 4.10(c) indicate favorable regions on the lower left and upper right of the map where the likelihood of thermal triggering is high. In fact, actual thermals are generated nearby these regions by the simulator, and no thermals are generated in the middle of the map as shown in Figure 4.9. Exploration in the middle of the map is effectively avoided.

For the simulation run in Figure 4.10(b), the aircraft encounters a thermal that is stronger than the minimum thermal strength computed from MacCready function. Exploitation mode is triggered even though aircraft altitude is above
Silent Wings simulation setup for coordinated mapping

Silent Wings provides the simulation environment. A linear SB-XC sailplane model is used as vehicle dynamics. An Arduino-based autopilot follows airspeed and heading commands. Exploration guidance is implemented as S-function block in Simulink. Updraft measurements are shared via UDP.

Figure 4.8. Silent Wings simulation setup for coordinated mapping

altitude floor of 800 meters. For the second run in Figure 4.10(d), the aggressive exploration approach allows the aircraft to locate a thermal at the threshold altitude. At the point when the thermal strength is weaker than minimum thermal strength specified by the MacCready value (a function of altitude), the aircraft exits the thermal and continues to explore the map. A visualization of this behavior switching is depicted in Figure 4.11.

Cooperative behaviors in autonomous soaring flight are summarized in Figure 4.12. Two aircrafts are started at center of the map. Initially, the aircraft perform local exploration for nearby cells until confidence in the wind speed estimates is above a threshold. The two aircraft spread out to explore larger regions as shown in Figure 4.12(a) and Figure 4.12(b). When immediate energy gain is required, the aircraft searches for updrafts within a distance reachable from the current altitude. If updrafts are available within the glide range, the aircraft cruises to the location of updraft with adequate strength. The availability of an energy
map allows updraft locations and strengths to be shared with the other aircraft some distance away as shown in Figure 4.12(c) and Figure 4.12(d). When aircraft in the lower portion of the map locates a thermal, its location and strength are available to the top aircraft to inform energy exploitation behavior. If an updraft is not available, the aircraft would continue to explore the surroundings. Effective guided exploration can be seen by comparing the actual thermal locations and history of the aircraft flight paths as shown in the Figure 4.9(b) and Figure 4.12(c). Aircraft only explore regions nearby actual thermals while regions without thermal are avoided.

4.3 Summary

This chapter presented simulation results for guided exploration which incorporating error covariance in updraft estimates and solar incidence to drive aircraft mapping behavior. Aircraft visited areas where both a high likelihood of thermal triggering and a high uncertainty in vertical wind estimates was presented. However, long duration flight requires at least eight aircraft given the atmospheric
Figure 4.10. Guided exploration with a single aircraft
Altitude floor of 200 meters provides maximum exploration time. Since “thermal cheat” is turned on for visualization, a portion of the flight path (c) and altitude plot (barogram) (d) is shown in red.

Simulation results confirmed that the altitude floor was influential to performance of guided exploration. While prediction of thermal triggering was accurate, dramatic performance gain was achieved with eight aircraft and the lowest altitude floor, which provided significant amount of resources for exploration. Higher altitude floors led to a decrease in performance gain because it reduced exploration time.

Conversely, results from the Warm Spring terrain suggested that a heavier weight on covariance is necessary because solar incidence provided very little ex-
Figure 4.11. Aircraft flight behavior switching

Thermalling mode is triggered for energy exploitation. When enough energy is acquired, the aircraft switches back to local exploration mode.

exploration guidance. Large flock size and low altitude floor were required to provide enough resources for exploration. Without enough exploration resources, an aggressive exploration approach resulted the maximum performance loss.

Overall, simulation results suggests an altitude floor of 800 meters without knowledge of thermal distribution. It leads to less performance gain when prediction is good, and less performance loss when solar incidence has little guidance.

Simulation results from the Silent Wings flight simulator demonstrated guided exploration in coordinated soaring flight. The exploration priority function allowed avoidance of areas where the likelihood of thermal formation was small. Both single aircraft runs were able to locate two thermals out of 12 total during an hour simulation. Finally, the Silent Wings simulation setup can then be modified for hardware implementation of guided exploration presented in Chapter 5.
(a) Switch from local to global exploration
(b) Spread out with confidence in wind estimate
(c) Share thermal location
(d) Harvest energy in a thermal

Figure 4.12. Cooperative behaviors in autonomous soaring flight
Chapter 5

Hardware Demonstration of Exploration Guidance

This chapter presents the hardware implementation of the guided exploration strategy for autonomous soaring flight. Instead of the Arduino autopilot used to direct behavior in Silent Wings simulation (Section 4.2.3), a dedicated commercially available autopilot system follows vehicle state commands and maintains trimmed flight conditions. The SB-XC sailplane and the autopilot system are first introduced in Section 5.1. Next, the overall structure of exploration guidance is described in Section 5.2. The simulation setup and flight plan are reviewed in Section 5.3. Finally, hardware-in-loop simulation of guided exploration is presented in Section 5.4. Concluding remarks for this research and recommendations for future work are provided in Chapter 6.

5.1 Description of Hardwares

This research uses an SB-XC radio-controlled sailplane with a wingspan of 4.1 meters manufactured by RnR Products\(^1\). A sophisticated autopilot system including an autopilot and a ground station from Cloud Cap Technology\(^2\) is utilized as shown in Figure 5.1. The Piccolo SL autopilot is well-equipped with an inertial measurement unit (IMU), global positioning system (GPS), and air pressure

\(^1\)http://www.rnrproducts.com/
\(^2\)http://www.cloudcaptech.com/
sensors to provide measurements for vehicle state estimation by using an extended Kalman filter. The Piccolo SL autopilot can interface with an external magnetometer via a serial communication link to improve the heading estimate. Two operational modes are available; manual mode is primarily used for launching and landing here; autopilot mode can take over to perform autonomous flight while certain altitude is reached. The wireless link with the ground station is made from the MHX-910 frequency hopping radio from Microhard Systems Inc\(^3\). The Radio communication is at 900 MHz Unlicensed ISM with a maximum 1 Watt output power. The hardware is integrated to the SB-XC sailplane as shown in Figure 5.2.

![Piccolo SL autopilot](image1.png) ![Portable ground station](image2.png)

(a) Piccolo SL autopilot  (b) Portable ground station

**Figure 5.1.** Piccolo autopilot system

### 5.2 Structure of Hardware Implementation

A schematic of the setup for hardware implementation of the developed control scheme is depicted in Figure 5.3. Most components are adopted from the Silent Wings simulation (presented in Section 4.2.2). Now, the high-level decision controller running in Simulink sends vehicle state commands to the ground station via a serial connection, which is then sent to autopilot via radio communication. The telemetry of vehicle states is downlinked to the ground station at 25 Hz, which is

\(^3\)http://www.microhardcorp.com/
then passed back to the Simulink model for updraft estimate mapping and behavior determination in real time. The Piccolo Command Center (PCC) provides a graphical user interface mainly for monitoring purpose only.

Note that communication delay from ground station is observed about 0.6 seconds. This amount of delay is unacceptable if vehicle states must be commanded from the ground while the aircraft is thermalling. Implementation of high-level control on an embedded computer onboard the aircraft is necessary to send state commands at higher rate. The delay is negligible for guided exploration, however, which requires only waypoint tracking.
The Piccolo Command Center (PCC) is a graphical user interface, which provides a convenient environment to communicate with the autopilot. However, PCC is only for monitoring purpose here. The Simulink model is able to send state commands directly to the autopilot via the ground station, and to receive telemetry from the autopilot without running the PCC.

5.3 Simulation Setup

Hardware-in-loop simulation is performed prior to actual flight test, ensuring that each component performs normally in a lab environment without risking the hardware in real flight. The goal is to demonstrate the ability to guide exploration in autonomous flight with the current setup. Afterwards, hardware demonstration of guided exploration in real flight can proceed.

For hardware-in-loop simulation, the AVL\(^4\) aircraft model is given to the Piccolo Simulator, which creates an environment and provides vehicle dynamics to the autopilot. The controllers in the autopilot are validated in simulations.

The simulation setup is shown in Figure 5.4. The flight test site is located at Centre Airpark in Centre Hall, PA. This site provides a small area, which suffices to evaluate the exploration guidance algorithm running in Simulink. An airspace restricts the aircraft to fly within this boundary. When the aircraft exceeds this

\(^4\)http://web.mit.edu/drela/Public/web/avl/
area, flight termination can be activated immediately. A simple flight plan consists of four waypoints (from waypoint 50 to waypoint 53). The waypoint 50 is designated as the lost communication waypoint. The aircraft follows these waypoints in an ascending order until the highest waypoint is reached. The aircraft then tracks back to the smallest waypoint (waypoint 50). The four interest points defined an area where the aircraft performs exploration and mapping. These interest points form a 15 by 7 grid at an resolution of 25 meters. Waypoints are only assigned within this map.

![Diagram of flight path and interest points](image)

**Figure 5.4.** Beginning of hardware-in-loop simulation

*An airspace is bounded by the blue region. The aircraft initially tracks to a simple flight path starting at waypoint 52.*

This flight plan has two phases. First, the aircraft takes off and tracks to the first waypoint. The flight controls are confirmed to work properly by following the simple flight plan. Afterward, the guided exploration algorithm is activated to send waypoints to the autopilot.

Note that, a pilot is responsible for take off and landing in real flight. If any unexpected aircraft behavior is observed, the pilot takes full control of the aircraft. Thus, the flight plan forms a closed loop within a line of sight of the pilot.
The simulation setup is presented. Next, results from hardware-in-loop demonstration of guided exploration can be shown.

## 5.4 Hardware-in-loop Simulation

Recall from Section 5.3 the beginning phase of simulation shown in Figure 5.4. The mapping algorithm is running but waypoints are not sent until controllers are confirmed. The aircraft is in autopilot mode throughout the mission (take off and landing are in manual mode in real flight). The aircraft follows the simple flight path starting at waypoint 52, ensuring that the controllers are working properly.

The exploration guidance algorithm is engaged to send a waypoint to the aircraft from Simulink as shown in Figure 5.5. The first waypoint (waypoint 36) is assigned to the center of the map in default. Due to the turn diameter of 25 meters for the SB-XC sailplane, the next waypoint is assigned when a distance smaller than 30 meters between the aircraft and the waypoint projected on the ground.

Since the aircraft first explores the top of the map while following the simple flight plan, the error covariance in wind estimates is relatively higher at the top of the map. Thus, the top region is targeted for exploration as shown in Figure 5.6. When the top of the map is well explored, the aircraft explores the lower region of the map as shown in Figure 5.7.

The hardware implementation of the guided exploration algorithm with the Piccolo autopilot system is demonstrated in simulation. Results show that the current setup works as expected by incorporating the wind map and solar incidence angle as *a priori* information. The exploration priority function drives the aircraft to explore regions with high uncertainty and high likelihood of thermal triggering. Next step is to demonstrate guided exploration in real flight.

## 5.5 Summary

This chapter presented a brief description of the hardware involved in this research including the SB-XC sailplane and the Piccolo autopilot system. The Piccolo SL autopilot is capable to follow state commands. The ability to track waypoint was solely used to perform guided exploration in this thesis.
Figure 5.5. Follow the flight path

The flight plan is denoted in green, and starting from waypoint 50 to waypoint 53. Waypoint 35 is the aircraft location when a waypoint command is sent to the autopilot. Waypoint 36 is the destination. The aircraft flight path history is denoted as the blue bread crumb trail.

The structure of the hardware implementation was developed by adopting the Silent Wings simulation setup with minor changes. The communication between the guided exploration algorithm in Simulink and the autopilot was established in order to receive telemetry of vehicle states from the autopilot and send waypoints to the autopilot. Delay from ground station suggested the implementation of a embedded computer onboard to send state commands (bank angle and airspeed) at higher rate while the aircraft is thermalling.

The simulation took place in Centre Airpark in Center Hall, PA where the environment was discretized into a 15 by 7 grid at resolution of 25 meters according to the SB-XC turn diameter. The aircraft initially followed a flight plan making sure that the aircraft behaved as expected. Afterward, waypoints were sent from the guided exploration algorithm. The aircraft explored the top of the map on regions where uncertainty in updraft estimates was higher. When enough confidence in estimates was gained, the aircraft explored the bottom portion of the map.
Figure 5.6. Exploration at the top of the map

Figure 5.7. Exploration at the bottom of the map
Finally, the results demonstrated the feasibility of guided exploration in a more realistic environment. The current system is ready to be tested in real flight.
Chapter 6

Conclusion

The first flight of Global Hawk and Predator widely used in surveillance missions today was 15 and 19 years ago respectively. Since then, advanced technology has been added to these platforms to expand their capabilities with only minor airframe modifications. Numerous persistent surveillance missions have been demonstrated with these vehicles given their large payload capacity and aerodynamic efficiency. However, large UAVs are vulnerable to detection by radar and are unsuitable to fly low altitude missions. Reconnaissance at high altitude can also be obscured by clouds. Critical life threatening mission requires surveillance of target at all time. Persistent surveillance within the atmospheric boundary layer becomes necessary for these missions. The small size of hand-launchable SUASS provides an alternate approach.

The lack of endurance of SUASS motivates the current research, which remains a barrier to long-duration surveillance missions using these vehicles. Immediate improvements in endurance can be achieved by harvesting thermal updrafts (stable energy sources that exist on a time scale of sufficient size to be utilized by small aircraft). This research envisions persistent surveillance mission that can be performed by a flock of soaring capable SUASS. One agent maintains visibility of ground target while others are free to exploit energy and map the updraft at every locations. This research develops an exploration strategy to guide the mapping of vertical winds in the environment effectively. Birds and human pilots often exploit thermal lifts to fly long distance. Therefore, persistent surveillance is feasible and will likely be made easier with an effective method of cooperatively mapping the
environment.

Earlier work has demonstrated the utility of coordinated mapping to improve endurance. However, no strategy for seeking thermals was developed, rather thermals were encountered by luck only. An effective exploration approach is proposed here by combining the mapping framework with the inclusion of solar incidence as a priori information to drive exploration behavior. The terrain elevation is available at resolution as high as a 3 meters grid, which allows thermal prediction at a much smaller scale than current thermal forecasting tools which have resolutions on the order of kilometers. This approach allows exploring aircraft to take measurements only at location where thermals are likely to be formed. The ability to avoid region that are not strongly illuminated by the sun enables savings of significant exploration resources.

While other factors also affect thermal triggering such as land cover and lapse rate, this research focus on exploration guidance from solar incidence, which provides the source of energy to create a thermal as the most important factor among the others. The contributions of this thesis are summarized in Section 6.1. Persistence flight with coordinated mapping has been shown in simulation and hardware-in-loop testing. Hardware demonstration of guided exploration remain as a future work. Continuous research is necessary to enable persistent surveillance, and is detailed in Section 6.2.

6.1 Summary of Contributions

6.1.1 Framework for Exploration Guidance

An exploration approach that guides coordinated mapping of atmospheric energy has been developed. Aircraft cooperatively explored regions associated with both a high likelihood of thermal trigger and a high uncertainty in vertical wind estimates. The solar incidence could be pre-computed and easily combined with the updrafts estimate in real-time to provide exploration guidance. The choice of weight factor enabled the overall exploration behavior to be modified according to atmospheric conditions and flock size. Additional factors that affect thermal triggering can easily be added such as terrain albedo. The weight factor $\alpha = 0.5$
provided an reasonable weight to balance the contribution between likelihood of thermal triggering and updraft estimate.

6.1.2 Performance Validation: MATLAB Simulation

Results from Monte Carlo simulations showed the performance gains from the exploration priority function compared to the covariance approach especially for the State College terrain. A flock size of eight aircraft and an altitude floor of 500 meters above ground level resulted in a dramatic improvement of 143% over the covariance only method. Almost two third of simulation runs survived 90% of mission duration. The performance of guided exploration was verified with multiple flock sizes and altitude floors at two different types of terrain. Given the atmospheric condition in this thesis, persistent surveillance is feasible with a flock size of eight aircraft.

The effects of altitude floor on the performance of guided exploration were evaluated. Results from the State College terrain with multiple flock sizes showed an identical result. The maximum improvement occurred at the lowest altitude floor, and improvement started to decrease at higher altitude floor. This result makes sense because a smaller altitude floor allows more exploration resources to search for thermals. However, contradictory results were obtained from the Warm Spring terrain. The guided exploration strategy was outperformed for a single and four aircraft cases. The maximum performance loss occurred at the lowest altitude floor, and was reduced with rising altitude floor. Therefore, this unexpected result was investigated by the use of solar incidence angle maps in thermal prediction.

The choice of altitude floor relative to the amount which a priori information was able to inform thermal prediction was investigated. Results from the State College terrain showed significant performance gains for all simulation cases but the Warm Springs terrain failed to show the same improvement beyond the baseline. The incidence angle map for the State College terrain gave an clear indication of locations with high likelihood of thermal triggering. Conversely, high likelihood of thermal triggering was found over a wider areas in Warm Springs terrain where solar incidence provided minimal exploration guidance. This result suggests a higher altitude floor and a heavier weight on the uncertainty in updraft estimate
when uncertainty in thermal prediction is high.

Nevertheless, results from Warm Spring terrain with eight aircraft confirmed that performance gains were achievable even \textit{a priori} information provided little guidance. But excess exploration resources were required (eight vehicles and an altitude floor of 200 meters above ground level) to frequently visit this large area to obtain updraft measurements.

### 6.1.3 Demonstration of Guided Exploration

Result from simulation in the Silent Wings simulator demonstrated the feasibility of coordinated soaring flight in a more realistic atmospheric environment. The exploration priority function effectively avoided the regions associated with a low likelihood of thermal formation. Although the actual number of thermals ranged from 5 to 7 in a 4 km by 4 km map, the aircraft, guided by the exploration priority function, could still harvest energy from the atmosphere.

More importantly, the platform used in Silent Wings simulation can be easily adopted for hardware implementation of guided exploration in real flight. Results from hardware-in-loop simulations were conducted to ensure that the current system worked properly prior to flight testing. Hardware demonstration of guided exploration in real flight can be proceeded.

### 6.2 Recommendations for Future Research

#### 6.2.1 Inclusion of Land Cover as \textit{a priori} Information

In addition to solar incidence, terrain albedo plays a role in thermal formation. Albedo is a small scale (scale depends on geographic location), terrain-dependent parameter, which can be incorporated in the exploration priority function. Using the terrain albedo, the performance of the exploration strategy in Warm Springs terrain might be improved. Land cover data is publicly available from USGS at resolution of 30 meters at no cost. The resolution is the same as the elevation data used in the topographic model. Thus, it should suffice for the purpose of exploration guidance.
6.2.2 Tuning of Thermal Estimator

The thermal mapping algorithm approximates thermal parameters from Allen [23] such as maximum thermal strength, decay rate, and period. However, the characteristics of any individual thermal may greatly vary in real world. The difference between the parameters in the model and a thermal in real life has an impact on the accuracy of the energy map. A better thermal model would allow for a more accurate map of lift and would therefore improve the performance of guided exploration. Tuning of the thermal estimator is necessary but will likely require a significant amount of flight testing.

6.2.3 Demonstration of Cooperative Mapping in Flight

Cooperative mapping of energy has shown promising results in simulation, leading to significant performance gains. However, hardware demonstration has not been preformed. Communication dropout often occurs in real flight due to interference or lost of line of sight between aircraft. The effect of communication drop outs on the energy map might lead to map divergence, which needs to be addressed. The ability to share wind measurements accurately among aircraft is vital to the success of a persistent surveillance mission using SUASS.

6.2.4 Implementing on-board High-Level Controller

The current hardware setup requires commands to be sent from operator’s computer via the ground station to the onboard autopilot, and vice versa. Delay in this data link has been observed. The amount of delay is acceptable for an aircraft in exploration mode. However, certain commands need to be sent at a much higher rate, such as bank angle commands for the thermal centering controller. It is often necessary to perform a tight bank to immediately center a thermal. Since the high level decision and mapping algorithms are written in C and C++ as Simulink S-function block, it can be implemented on a PC104, an embedded computer. The delay from transmitting command packet between autopilot and operator’s computer via the ground station would then be eliminated.
A.1 Vehicle Properties

Simulation results are based on the RnR products SB-XC radio control glider. Note that a fourth order polynomial is used to relate $C_D$ to $C_L$: this provided a better fit to the computed data over the full speed range.

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Table A.2. Summary of parameters used in behavior determination

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Figure A.1. SB-XC aircraft model
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