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Autonomous Aerial Radio Frequency Source Geolocation

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Abstract: The United States strives to develop cutting edge technology and minimize deficiencies. Because of GPS's limitations, the Department of Defense is working with the Department of Energy to develop independent geolocation assets. To meet this need, two search path algorithms were developed to locate the source signal in a simulation. The two methods used for the algorithms were a gradient search method and an interdisciplinary method based on glider thermalling techniques. Ground tests showed the viability of the algorithms being able to geolocate the source in a real environment. Flight tests showed the reality of the entire system working in conjunction to autonomously geolocate the source of a radio frequency.

Keywords: Geolocation, Gradient Search, Thermalling, Drone, UAS, asset location, autonomous and navigation

1. Introduction

The United States Air Force and Department of Defense (DOD) pride themselves in developing and implementing innovative technology in order to be the most advanced military in the world. Currently remote tracking and geolocation capabilities are reliant on global positioning system (GPS) assets. GPS is a critical technology used for asset location and navigation, but can be limited by human error, enemy jamming, and environmental obstacles. The DOD, in conjunction with the Department of Energy (DOE), is investigating nonlinear optimization and a "new combinations of known methods of asset location and navigation" (AFOSR: Engineering and Complex Systems, 2015). For this reason, the DOD is seeking to "achieve GPS-quality positioning in situations where GPS by itself is not sufficient" (AFOSR: Engineering and Complex Systems, 2015). This project creates an asset which can overcome the limitations of GPS to provide an effective alternative.

1.1 Client Background

This research is conducted in partnership with Sandia National Laboratories to use Unmanned Aerial Systems (UAS) to locate a radio frequency source independent of GPS. Sandia National Laboratories is operated and managed by Sandia Corporation, a subsidiary of Lockheed Martin Corporation, and is a Federally Funded Research and Development Center (FFRDC) (About Sandia, n.d.). Sandia was originally founded to work on nuclear weapons as part of the Manhattan Project (About Sandia, n.d.). Sandia Corporation was officially established in 1949 and headquartered in Albuquerque, New Mexico. As a contractor for numerous federal, state, and local government groups, Sandia supports U.S. national security through innovative research and development (About Sandia, n.d.). Over the years Sandia has expanded its mission to include defense systems and assessments, energy and climate research, international and homeland security, and nuclear security. Sandia conducts research for the government and, in this case, will be working on providing an alternative to GPS location through an autonomous UAS.

1.2 Problem Statement

Geolocation is essential to many military missions. The U.S. military is heavily reliant on GPS and signal triangulation for geolocation. Environmental and human factors can limit the accuracy and effectiveness of GPS systems. Sandia has proposed a new method for geolocating the source of a radio transmission using a radio receiver hosted on a UAS.

The UAS will actively sample the signal and autonomously direct its flight path dependent on changes in the detected radio signal over the course of the flight in order to locate the signal source. The focus of this project is to create an algorithm which allows a UAS to locate and fly to a radio frequency source in the shortest amount of time in a complex environment.

1.3 Related Work

Geolocation without GPS is a relatively new field of study. There have been numerous studies conducted pertaining to the autonomous navigation of robots and aircraft using various algorithms and methods. SRI International research institute has performed research on a gradient method for real time robot control. Their method used a "navigation function to generate a gradient field that represents the optimal (lowest-cost) path to the goal at every point in the workspace" (Konolige, 2000, p. 1). This article provides an example of a gradient search algorithm which could be applied to other navigation methods.

In a different application, Gersten (2005) documents the method glider pilots use to find the source of a thermal core and optimize their climb. Since gliders do not have an engine, they rely on rising columns of air, called thermals, to increase altitude. To find these thermals, pilots monitor the vertical velocity indicator in their cockpit to determine if the aircraft is rising or sinking. While the instrument indicates a decrease in vertical velocity the pilot turns until there is an increase in vertical velocity, and continues on this path until there is no longer an increase, at which point the pilot iterates at begins turning again. This method eventually will bring the pilot to the core of the thermal where the maximum amount of lift is found (Figure 1). This technique can be applied in the development of a radio frequency source location method because of the similarities between the thermal core and a source signal. Just as a glider pilot monitors vertical velocity, the UAS can monitor the signal strength and autonomously direct its flight path accordingly.

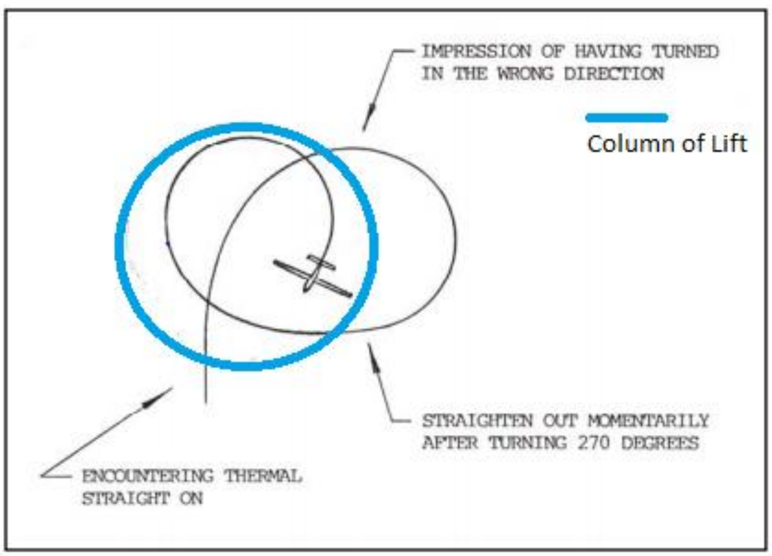

Figure 1. Centering and Optimizing the Climb (Gertsen, 2005)

Lastly, Dressel and Kochenderfer (2015) describe an approach to locate the source of signal jammers using small UAS. They implemented a partially observable Markov decision process to make decisions in a stochastic environment. The team used 5 different approaches to locate the signal source: QMDP, Fast Informed Bound, SARSOP, augmented MDP, and a baseline heuristic approach. They found varying success with different algorithms. The largest barrier was the computational time difference while the performance (time to target) between the algorithms was relatively the same. This study brings forward the idea of testing and comparing algorithms based on computational time which can be used in this geolocation problem.

1.4 Project Goals

The overall goal of this project is to develop and implement an algorithm that determines minimum time UAS routing to a radio signal source in an environment with no terrain or obstructions in the way. In order to reach this overall goal, two milestones have been set. The first milestone of the project focuses on the research and development of several search algorithms. The first objective set for the project was to perform extensive research into the radio frequency (RF) seeking process. To accomplish this, the project team searched for literature explaining different search algorithms and methods of optimizing the search path (Section 1.3 Related Work). The next step was to use the information gleaned from research to create prototype algorithms in order to minimize the search path and the time it takes for the algorithm to find a single RF source. These algorithms were built with the assumption of no signal interference from obstacles and a uniform degradation of the signal as distance from the source increases. Following the development of prototypes for several algorithms, simulation software was then created to generate data on each algorithm. This data was used to analyze the most efficient and effective algorithm by comparing the time to target for each algorithm and distance traveled.

The second part of the project focused on implementing the algorithm in a UAS operation. We were able to construct a payload that measured signal strength from the emitter, which was then applied within the algorithm to determine where the UAS should travel. The goal of this section was to prove that the proposed algorithm would be viable in the real world. We designed the experiment to have no obstructions between the emitter and UAS. However, our original assumption of uniform signal strength degradation could not be met. We expected to have to change the algorithm in order to accomplish this goal.

1.5 Organization

The remainder of this article is organized as follows. In Section 2, we describe our methodology. In Section 3, we show the results of our algorithm. We conclude with Section 4 with recommendations and suggestions for future work.

2. Methodology

We implemented two algorithms both separately and in cooperation in a hybrid algorithm in the simulated environment in order to test the feasibility of the project. After the algorithms were implemented in simulation with a perfectly propagated and measured signal, we conducted ground tests to assess the viability of the algorithms in a real environment. The variation and error in real signal propagation and measurement introduced complications in the implementation of our algorithms. This introduced increased complexity into our algorithm. As a result of this complexity and our available resources we were only able to implement the thermalling algorithm onboard a UAS for flight testing. A complex cloud network was created to interface the payload which measured signal strength with the algorithm and ground station which operated the UAS autonomously.

2.1 Routing Algorithms

The gradient method (see Algorithm 1) was developed using a gradient search function. This function is based on measuring the strength of the surrounding signal at the UAS's current location. When an increase in signal strength is found, the UAS will fly along an orthogonal path in the direction of the stronger signal strength. The UAS then moves a predetermined distance and repeats the process until it reaches the source signal.

Algorithm 1. Gradient method

```
While target not located
      Measure signal strength in a full circle surrounding UAS
      Fly orthogonal vector at heading with maximum signal strength.
End
```

The thermalling method (see Algorithm 2) was designed to search for the signal source similar to the way a glider pilot finds a thermal core (Gersten, 2005). This method stores the signal strength at each location and compares it to the maximum signal strength of the source. If the current signal strength is less than the maximum signal strength, the UAS flies in the direction of increasing signal strength and straightens the flight. If the signal strength from the last location decreases, the UAS turns until the signal strength increases. Once strength increases, the UAS will once again fly straight. Note that the UAS must always turn in the same direction during a single geolocation flight in order for the algorithm to work.

Algorithm 2. Thermalling method

```
While target not located
      If the current signal > than previous signal
            fly in the current direction
      Else
            turn
            fly in new direction
      End
End
```

Both algorithms 1 and 2 were implemented in simulation. After conducting ground tests, we determined that the algorithms needed to be refined in order to account for the imperfect signal propagation of the radio and measurement error of the payload. Because of the noise in the data, the algorithm had to be made more robust by adding a linear ordinary least squares (OLS) regression element. The data included in this regression are all the data collected between the previous iteration of algorithm and current iteration. The model used for the regression is:

$$\text{signal strength} = \beta_0 + \beta_1 \text{sequence number}$$

In the pseudocode β_1 is referred to as the slope.

Algorithm 3. Applied/UAS Thermalling Method

```
While target not located
      regress signal strength on sequence number*
      If slope > 0
            fly in the current direction
      Else
            turn
            fly in new direction
      End
End
```

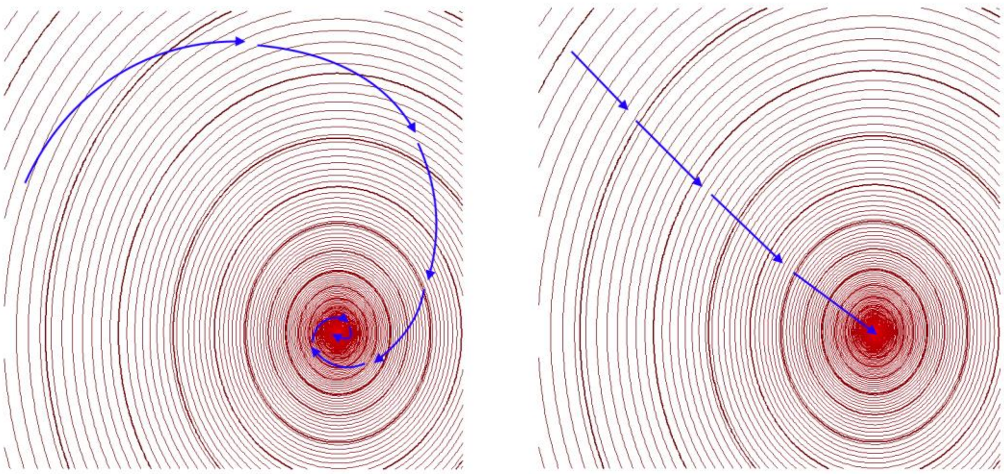

Figure 2. Graphic representations of the thermalling (left) and gradient method (right) search path algorithms

The hybrid method runs a single iteration of the gradient method, and then runs the thermalling algorithm.

2.2 Assumptions

For the first two algorithms, two major assumptions were applied that affect the performance. The first is that the emitter gives off a radio frequency which degrades perfectly with the inverse of the square of the distance from the emitter. This assumption underpins a simulation where the signal's strength always increases as the UAS approaches the emitter. Assuming this property of the signal provided a way to create a stopping procedure based on the fact that the signal will not decrease as the UAS approaches the emitter. A second assumption made was that there are no obstacles which interfere with signal propagation. Buildings or other obstacles could either create dead zones where there is no signal, or result in confusing signal reflections. This phenomenon is known as multipath. This assumption was made for our initial simulation in order to keep the algorithms manageable and ensure that the algorithms perform properly. This assumption was removed for algorithm 3 to account for imperfect signal propagation from the emitter.

2.3 Implementation

Comparative analysis of simulation results showed that the gradient method was the most efficient, and pinpointed the target within 10 meters. The thermalling method was more accurate at pin pointing the target, with the exception of several outliers, but took considerably longer. The hybrid method took the best of both worlds, but was still slower than the gradient method.

End distance to target (meters)	Thermalling Method	Gradient Method	Hybrid Method
Mean	54.237	7.0436	4.7621
95th percentile	6.5199	9.7275	7.7509

Time to target (minutes)	Thermalling Method	Gradient Method	Hybrid Method
Mean	6.4002	1.706	3.4504
Median	5.8750	1.5667	3.1550
95th percentile	12.9850	3.2000	6.5550

Table 1. Results of comparative analysis of algorithms

As a result of this complexity and our available resources we opted to implement the thermalling algorithm onboard a UAS for flight testing. Although the thermalling method showed some weaknesses in simulation, we were able to best configure the algorithm to handle the uncertainty of the environment (algorithm 3). The autonomous control was implemented through a network between the payload and ground control software. The payload measured the signal strength, uploaded it to the server which was then accessed by the ground control software, which iterated the algorithm and sent a flight command to the drone (figure 3).

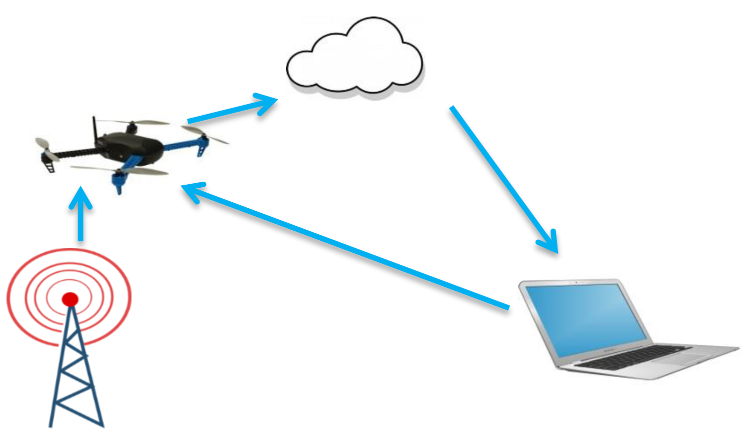

Figure 3. Network for UAS operations and communication

3. Results and Analysis

Although initial ground tests showed considerable variability in the measured signal strength, interpreting the necessary information from the data was not impossible. In one ground test we placed an emitter at the middle of a square with a length of 144 ft. and measured the signal in 2 ft. increments covering the entire square. Smoothing curves show that there is a signal within the noise, as there is a local maximum at the center of both the latitudinal cross section and the longitudinal cross section (figure 4).

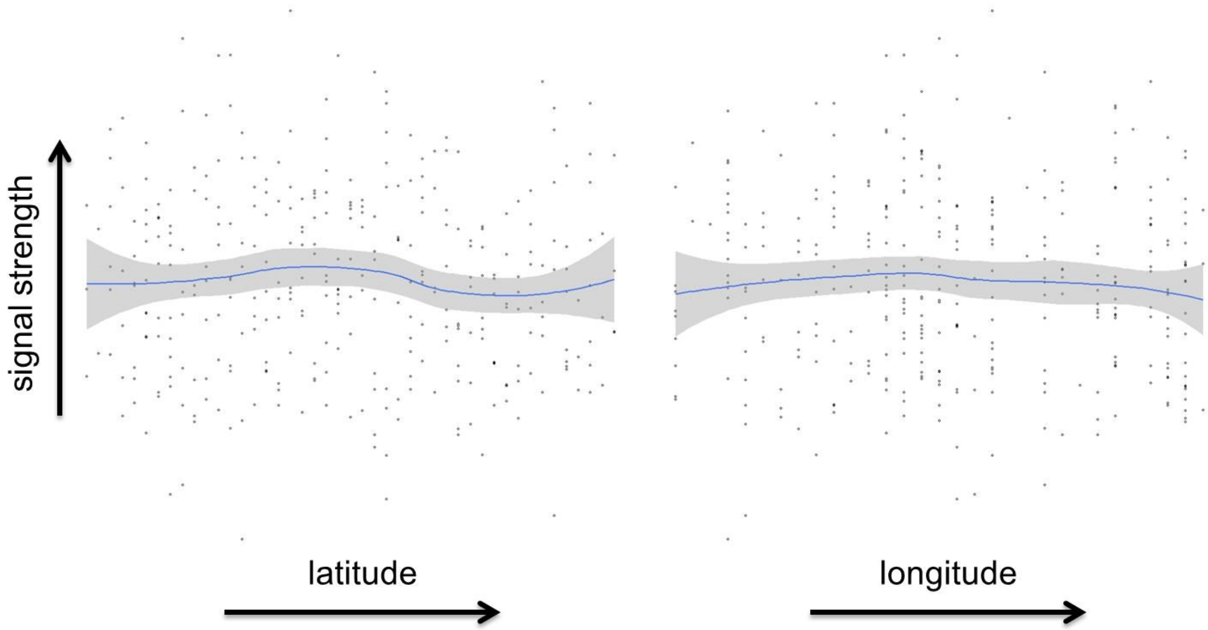

Figure 4. Latitudinal and longitudinal cross sections of signal strength in ground test

We further investigated this data to show that algorithm 3 would function in a real world environment. Choosing random simulated flight paths in the data showed that the regression consistently correctly predicted that whether the path was leading either towards the emitter or away (figure 5).

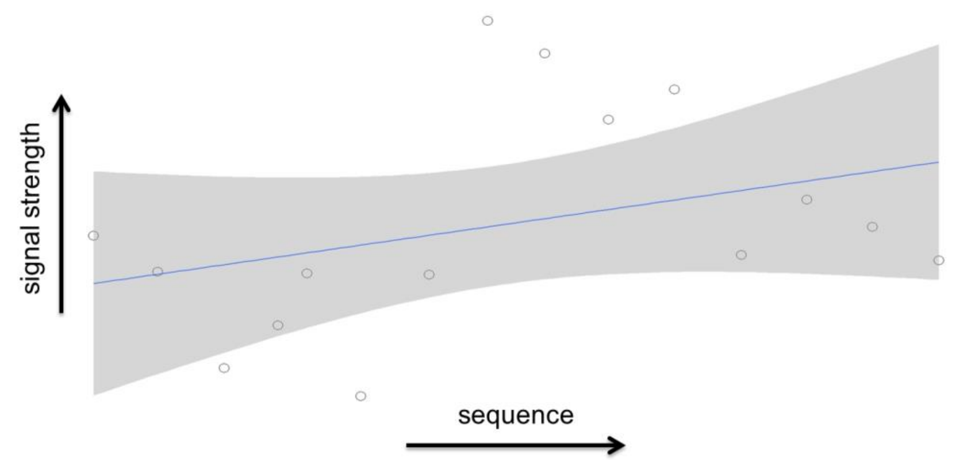

Figure 5. Example regression on a simulated flight path from ground testing data

Flight tests showed that real time operation of data measurement, acquisition and algorithm operation were well integrated and the system was capable of autonomously directing the UAS to the radio frequency source.

4. Conclusions and Future Research

Although flight tests were limited and hampered by high winds and communications issues, the research conclusively proves the reality of autonomous aerial radio frequency source geolocation. We successfully developed a geolocation alternative to GPS.

The horizon of future work is extensive. The areas that we feel are most important to investigate are 1. improvement of the system integration in entirety, preferably implementing the algorithm entirely on an onboard computer, 2. implementation of the gradient method on board a UAS, and 3. further development of algorithms to allow the system to operate in multipath environments, or to allow multiple UAS to work in conjunction with each other.

5. Acknowledgements

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7. Documentation

Major Pietz and Dr. Wilck reviewed a draft of this document and provided feedback on the content, format, and structure.