Alternatives to GPS Navigation in Controlling Drone Flight

Auburn REU on SMART UAVs 2018

Austin Kreulach
University of Arkansas
apkreula@uark.edu

Harrison Welch
Austin Peay State University
hwelch1@my.apsu.edu

June 19, 2018

Abstract

As technology continues to advance, electronics become cheaper and batteries smaller. This has led to cheaper and larger drones taking on new and more complex roles beyond their traditional place as either military hardware or hobbyist toy. As drones increase in both size and importance, we have to look more carefully at safety. Most drones, when guided autonomously, depend on our GPS network to function. GPS depends on relatively weak signals and is exceptionally easy to jam or render inoperable. This project aims to provide a passive and reliable method of Unmanned Aerial System astronavigation using careful calculations of the stars around the observing aircraft(s) to determine precise position, while utilizing inertial dead-reckoning system for correcting the celestial computations.

1 Literature Review

An Unmanned Aerial Vehicle (UAV) is a device intended to fly without a pilot. These devices can be autonomous, semi-autonomous, or radio-controlled. Ultimately a UAV can still be piloted by a human, the main stipulation is that no control staff be physically aboard the craft. Historically, aviation has depended greatly on the skills of the pilot. This increased distance between pilot and craft had led to new challenges in introducing UAVs into civil airspace. While prior FAA regulations required the pilot to simply 'see and avoid' other aircraft so as to allow flight without modern instruments, UAVs cannot 'see' in any legal sense. Thus, they must 'sense and avoid.' The primary focus of UAV research is, then, collision avoidance and navigation. The primary navigational method is GPS, due to it's exceptional coverage, precision, affordability, low weight, and compact size. However, GPS can frequently be unreliable. In both the civil and military airspace, GPS is often jammed, spoofed, or otherwise tampered with [3] to the point of being an unacceptable point of failure. Despite this problem, GPS does remain the gold standard of navigational aids. Many methods have been proposed, tested, and implemented as solutions to the problem of non-GPS navigation.

The first and most obvious solution is to use exceptionally accurate and precise tools to measure the forces on a craft and use that to calculate the current location using a previous known location. This is known as dead reckoning. As the name implies it is usually met with little success. However, some recent papers [6] have shown careful use of math and new technology can present decent results even with this method. The dead reckoning system, or inertial navigation system (INS) was deployed on a person's ankle and used to determine their position after a walk. The potential applications of this sort of method to aerial vehicles is more suspect due to the potential for unpredictable wind and other complex forces on the aircraft.

Another approach to this problem is LiDAR, which originated as a portmanteau of light and RADAR but eventually grew into a backronym. More to the point, LiDAR depends on a series of pulsed light emissions being measured at emission and receipt, then using the minute differences to calculate range. That is, LiDAR is a large bundle of laser range-finders being used in conjunction to create a 3D map of an area.

The primary draw of LiDAR is it's ability to penetrate thin surfaces, allowing the device to map the areas below thin cover. This is largely used in forestry surveys [5] due to the exceptional performance with leaves. The system does not offer much promise as a primary drone navigational technique, however, due to the active nature. As an active system, LiDAR sends out pulses which can be easily interfered with or detected. This poses a challenge in hostile environments.

A slightly less popular but nonetheless fascinating method is navigation by infrasound. This is believed to be the navigation method used by homing pigeons [1] and as a result shows great promise as a potential navigational solution usable from almost anywhere on earth. The concern is precision, however. As the cited paper shows, infrasound is difficult to measure precisely and it is further difficult to discern significant infrasound signals from meaningless noise. Thus far there has been no significant success using infrasound to navigate, at least none that this team has managed to find.

Another option investigated largely for it's unique and fascinating qualities is optical flow. Optical flow is a subset of computer vision where two images are taken at a specific time step apart and then analyzed to determine differences in color, pixel density, and other properties to show change over time. This is used mainly to determine if an object in the image has moved closer to the perspective or further away. What makes optical flow interesting is how easy it is to program autonomous routines using this information. Take for example a region of the image is moving closer at a rate faster than other parts of the image. If the goal is collision avoidance, then simply turn away from that side of the camera. If the goal is pursuit of a target, then turn toward that region to keep it in focus. If the goal is avoiding pursuit, then turn toward the area of motion and drive backward. [10]It's incredible how simple and diverse the uses of this information is. However, ease of coding is not the highest priority in drone navigation, and as such the other problems with this technique including high computational requirements tend to leave it as a poor choice.

Another entry in the series of navigational methods chosen for interesting properties is navigation by signals of opportunity. The method is fundamentally answering the problem of lacking a GPS signal by asking what other signals are available. A signals of opportunity navigation system is composed of a great many receivers for various signals such as radio or television broadcasts, and then using known signal emitters such as towers or stations to triangulate position. This is relatively expensive and bulky [12], however, and is further limited to urbanized areas that have a sufficiently high density of stray signals. It is thus unfit for use on the ocean rural areas of undeveloped countries.

A modern way of tackling the issue of non-GPS navigation would be the use of Machine Learning or Fingerprint navigation. This generally involves two phases of action: Training and Comparison. The training phase generally consists of running the flying instrument through environments akin to the actual area of action the UAS will actually be flying through. Fingerprints are the data the UAS uses to navigate and over time running many training flights the collection of fingerprints grows and so does the accuracy. These fingerprints can be gathered in a multitude of ways from received signal strength indicators (RSSI), computer vision, and/or magnetometry among other things [11] [9]. Once the training phase is complete/sufficient then the comparison or implementation phase begins. This again can be implemented many ways such as a nearest neighbor algorithm to find the truest position based off the current assumed/probable location of the candidate signal. [11] utilizes this nearest neighbor approach under an indoor situation detecting active wifi and cell phone signals. Other strategies of the comparison phase could be the neural network approach. Neural Networks make probabilistic decisions based off of a database of trained data in groups. Similarly the navigator or UAS would use its trained data to analyze groups of passively detected points to come to the best made decision. All said, fingerprint navigation implementations offer an interesting way for a UAS to travel.

The United States Air Force Institute of Technology in Ohio has preformed a study of how Magnetometry can be used to navigate [2]. They used a previously produced magnetic anomaly map of about 35 square kilometers from 2012 to fly a turbine Geo-survey plane. From the map, the plane was able to simply match the magnetic readings of the map to the ones the plane was passively detecting from the outside. One issue the authors mentioned was that the plane must fly fairly close to the ground for the best accuracy. While the paper didn't speak exactly how low, the authors expressed low altitudes are better many times in the text. Another issue is the weather can change magnetic signals picked up by the sensors. This will need to be compensated for either by attaching the required sensors to the flying instrument or by actively sending them up to the flying instrument from the ground, both options of which add to the weight and cost of the overall system. Speaking of cost, the sensors used by the Air Force are called "optically pumped scalar magnetometers" which costs in the range of $15,000 to $25,000 putting it far outside the range of the normal civilian's pocketbook. Cost and low altitude aside the method yields excellent results with only 13 meter errors in true location.

An interesting study out of the University of Alabama Huntsville uses the Panoramic annular lens attitude determination system or PALAD [8]. Implemented on a high altitude satellite, this system utilizes a special lens that reflects and refracts light to create an 360 degree photo or panorama of the satellite's surroundings at about 45 degrees in angle height-wise. This system enables the camera (with the lens attached) to see all the way around its current position. The paper this uses this panorama to determine the attitude in the satellite by calculating the position of the earth in the photograph. We are looking at this lens style approach given the altitude requirement isn't too high in the air.

The concept of filtering came up in many papers we have found throughout the literature survey process. Filtering, when used for navigation purposes, removes any unwanted data and provides a better estimation of the user's position. According to [11], there are at least three major types of filtering utilized for navigation: Kalman, Exponential Weighted Moving Average (EWMA), and Linear Weighted Moving Average (LWMA). Kalman filters use matrix multiplication to remove any unwanted noise, minor or major, from a data set over time. EWMA serves the same purpose as the Kalman filter, which is to remove unwanted noise, but this method saves some computing time at the cost of some accuracy. If applied in the right context EWMA may out-preform the Kalman filter if the accuracy is lesser needed. Simliar to the previous two methods, LWMA again serves to filter out noise from a data set while saving time computation-wise. [11] uses LWMA to remove any errors when measuring the wifi signal strengths surrounding the navigating UAS, and [7] uses a form of Kalman filter called "Memory fading unscented Kalman filter" where they put more weight on recent data estimations and less weight on older estimations.

Our method of attacking GPS-denied environment navigation problem is utilizing the algorithms and code from Astrometry.net to analyze photos coupled with PyEphem, a python library for analyzing the position of stars based on a given location coupled with inertial navigation system (INS) tools such as an altimeter and gyroscope. Astrometry.net is a resource for finding the area of the night sky you are looking at and outputs all the stars that can be seen in the image and a frame of reference to the edges of the photograph [4]. The hope with this resource is that we can use the known attitude (flight angle) of the UAS compiled with the output from Astrometry.net's library of code to give a rough estimate of our position on the globe. Then reverse engineer PyEphem's code base to find our position based on the observed star positions to then remove any errors from Astronomy.net's output. Then we aim to use the INS to provide further removal of errors from the gathered data set.

References Cited

[1] Riley Bauer, Shannon Nolet, and Saad Biaz. *A Novel Approach to Non-GPS Navigation Using Ultrasound*. 1998.

[2] A Canciani and J. Raquet. *Airborne Magnetic Anomaly Navigation*. 2017.

[3] Kashir Hill. *Jamming GPS Signals Is Illegal, Dangerous, Cheap, and Easy*. 2017.

[4] Dustin Lang, David W. Hogg, Keir Mierle, Michael Blanton, and Sam Roweis. *Astrometry.net: Blind astrometric calibration of arbitrary astronomical images*. 2009.

[5] R. Li, J. Liu, L. Zhang, and Y. Hang. *LIDAR/MEME IMU integrated navigation (SLAM) method for a small UAV in indoor environments*. 2014.

[6] Lauro Ojeda and Johann Borenstein. *Non-GPS Navigation with the personal dead-reckoning system*. 2007.

[7] F. Si, Y. Zhao, and X. Zhang. *Memory fading unscented Kalman filter and its application in navigation by stellar refraction*. 2017.

[8] Mark A. Stiedham and Partha R. Banerjee. *Panoramic annular lens attitude determination system*. 1995.

[9] Zain Bin Tariq, Dost Muhammad Cheema, Muhammad Zahir Kamran, and Ijaz Haider Naqvi. *Non-GPS Positioning Systems: A Survey*. 2017.

[10] Selim Timizer. *Optical Flow Based Robot Navigation*. 2001.

[11] X. Wang, J. Qui, S. Ye, and G. Dai. *An advanced fingerprint-based indoor localization scheme for WSNs*. 2014.

[12] Chunpeng Yan and H. Howard Fan. *Asynchronous differential TDOA for non-GPS navigation using signals of opportunity*. 2008.