A Recovery System for SUAV Operations in GPS-Denied Environments Using Timing Advance Measurements

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ABSTRACT

This paper describes a recovery system for Small Unmanned Aerial Vehicles (SUAVs) operated in and around urban areas. The purpose of the system is to provide guidance to a SUAV allowing safe navigation to an area where it can be recovered in the event of a GPS outage using current technology and implement the solution within a one-year timeframe. The prototype SUAV system presented in this paper made use of a federated filtering approach to calculate position, velocity, and attitude in GPS-denied environments. An Attitude Heading Reference System computed attitude followed by an air-data based dead reckoning navigator to determine the velocity and position of the SUAV. This system was aided by position fixes derived from the onboard cell phone receiver. Coarsely discretized time-of-arrival (TOA) information from the receiver bounded the position error of the dead reckoning navigator. The short-term performance of the system was evaluated through flight testing incorporating 2-5 minute GPS outages. Hardware-in-the-loop (HIL) simulations were conducted to demonstrate the system performance during extended (30-minute) GPS outages. The average position error magnitude of an un-aided dead reckoning navigator at the end of 25 Monte Carlo HIL simulations was 5275 m. In spite of the coarse TOA data, the cell phone-aided system out-performed the un-aided solution and bounded the average error to 166 m.

INTRODUCTION

To date, Small Unmanned Aerial Vehicles (SUAVs) have been used extensively in military operations. However, many non-military uses for these vehicles exist including law enforcement and civilian applications. Additionally, the Federal Aviation Administration (FAA) Modernization and Reform Act of 2012 (HR658) requires the FAA to integrate routine unmanned aircraft operations into the national airspace system (NAS) as soon as practical. However despite

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the numerous benefits that SUAVs can provide, one major obstacle standing in the way of this integration into the NAS is the reliability of these vehicles and their high accident rate relative to manned aircraft. There are many causes for this including the fact that UAV technology is still relatively new and evolving. Additionally, a critical characteristic of SUAVs is their low-cost which encourages the use of commercial-off-the-shelf (COTS) components. The limited reliability of low-cost hardware corresponds to limited reliability of the system as a whole and increases failure probability. One method, proven in commercial aircraft applications, for improving reliability is increasing the hardware redundancy of the aircraft systems which are most susceptible to failures. However, this approach inevitably leads to higher cost and consequently reduces one of the most attractive characteristics of SUAVs. In this paper, we will focus on the reliability of a typical SUAV navigation system which depends on the Global Positioning System (GPS) for proper functioning. This dependence leads to GPS vulnerabilities translating into SUAV vulnerabilities, and hardware redundancy alone will not mitigate these hazards since, for example, radio-frequency interference (RFI) of one GPS receiver will affect all onboard GPS receivers. Therefore, this paper proposes a backup navigation system for the SUAV flight control system that will maintain the low-cost objective of SUAVs while improving reliability.

The typical SUAV navigation system is the GPS-aided Inertial Navigation System (INS). INSs determine the vehicle position, velocity, and attitude, or navigation state, using an Inertial Measurement Unit (IMU) to measure accelerations and rotation rates. SUAVs require components that have low Size, Power, and Weight (SWaP) requirements, and therefore, typically low-cost “automotive” grade Micro-Electro-Mechanical Systems (MEMS) IMUs are installed in these small aircraft. Despite their flexibility to operate in nearly any environment and low SWaP requirements, these IMUs cannot obtain the same level of accuracy as GPS sensors due to inherent errors in the measured accelerations and rotation rates which lead to drifting position and velocity solutions of approximately 100+ meters/minute. Therefore, it is imperative that this drift be corrected by “resetting” the INS with some other navigation sensor or external information. To accomplish this, practically all SUAV autopilots employ GPS-aiding. The GPS position and velocity information can be used to periodically reset the position and velocity estimates derived by the INS alone. Attitude can be determined by the INS, but by utilizing an extended Kalman filter (EKF), the GPS and INS sensors can be fused to indirectly correct errors in the navigation state estimation. Figure 1 displays the typical architecture of a GPS-aided INS.

As indicated by the architecture in Figure 1, the GPS position and velocity measurements are critical to arrest the error growth in the INS. However, there are a number of GPS vulnerabilities that exist and, if encountered, can cause intermittent loss of GPS signals or even complete GPS-denial. Thus, it is paramount that the SUAV is either capable of avoiding all GPS vulnerabilities or be equipped with a backup capable of bounding the errors of the INS during GPS disruptions. Several hazards that threaten GPS signals as well as potential mitigations are detailed in [1]. This paper will focus on a signal-of-opportunity navigation system that exploits cell phone signals to determine the position fixes necessary to aid the SUAV navigation system.

![Figure 1: Typical Architecture of a GPS-Aided INS in Most SUAV Autopilots (Reproduced from [1])]
marized. Additionally, the software of the cell phone-aided navigation filter will be discussed detailing the derivation of the range measurements extracted from cell phone signals. Third, the setup and results of flight tests will be illustrated. Due to the combined limitations of the system and available flight test area, hardware-in-the-loop (HIL) simulations will also be summarized including their validation and verification. Finally, we will address some of the limitations, mitigations, potential improvements, and future work related to the cell phone-aided navigation system.

CONCEPT OF OPERATIONS
The system developed is designed to provide a backup navigation solution to a SUAV flight control system when GPS is unavailable. The flight area is assumed to have cell phone tower coverage that allows for line-of-sight communications with at least two cell phone towers for at least 50% of the flight. In the event of a GPS outage, the system will safely navigate the aircraft to a location where GPS is available for auto-landing or for manual controlled landing by the SUAV pilot. Therefore, it is anticipated that the aircraft will be initialized and operating in its assigned area for some time with GPS available.

The horizontal errors of the proposed system will limit the aircraft’s ability to avoid obstacles such as trees, buildings, other aircraft, etc. that are at the same altitude as the SUAV. Therefore the proposed environment will be one whose flight plan would require the aircraft to fly at an altitude above and/or away from any obstacles or other aircraft within the mission area. Figure 2 depicts a nominal scenario where a SUAV is assisting in emergency response far from the base station, and GPS is available. At some point during the mission GPS services are interrupted by a jammer, as shown in Figure 3, and the backup system will take over navigating the aircraft and guide it back to the base station where a safe manual or automatic recovery of the aircraft can be accomplished.

SYSTEM ARCHITECTURE
The proposed system will use a GPS-aided INS for typical operations, but upon determining that GPS is no longer reliable, the SUAV flight control system will activate the proposed backup system. This system will use time-of-arrival data from the line-of-sight (LOS) communications between the on-board cell phone modem and the cell phone towers in view. This cell phone data will be fused with the information from other on-board sensors in an estimation filter to aid a dead reckoning navigator. This cell phone-aided dead reckoning navigator uses an Attitude Heading Reference System (AHRS) to determine the attitude. This attitude solution from the AHRS is fused with air data measurements to mechanize the dead reckoning system to estimate the position and velocity of the aircraft. Since an accurate estimation of attitude is crucial for safe control of the aircraft, this cascaded approach allows for an independent estimation of the attitude from the velocity and position. This separation of the navigation state estimates is in contrast to a traditional GPS-aided INS. Consequently, this cascaded-filter approach will prevent any position errors inherent in the cell phone-aiding from corrupting the attitude solution. This architecture, shown in Figure 4, makes use of two separate EKFs, one for the AHRS and one for the dead reckoning, and both will be detailed in the Software section.

Figure 3: Scenario when GPS Unavailable

HARDWARE
This backup system was integrated into the University of Minnesota UAV Research Group (UMN-URG) Goldy Flight Control System (FCS). An overview of
the hardware used in the standard Goldy FCS is given as well as the necessary additions made to support the cell phone modem used for this research. The modified Goldy FCS and prototype navigation system was flown on an UMN-URG research vehicle the Ultra Stick 25e, shown in Figure 5.

Figure 5: Ultra Stick 25e

The customized Goldy FCS is shown in Figure 6. It is equipped with a sensor suite that includes a cell phone receiver, IMU, magnetometer triad, GPS receiver, and two pressure sensors (for the pitot-static system). Table 1 gives a list of the individual components used to mechanize this backup navigation system. The air vehicle and each component of the FCS was chosen for capability while maintaining the low-cost COTS objective of SUAVs. Further details related to the Ultra Stick 25e, the Goldy FCS, and other UMN-URG infrastructure can be found in [2].

Figure 6: UMN-URG Goldy Flight Control System

<table>
<thead>
<tr>
<th>Aircraft Component</th>
<th>Manufacturer</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial Measurement Unit (IMU)</td>
<td>Analog Devices</td>
<td>ADIS 16405</td>
</tr>
<tr>
<td>GPS Receiver</td>
<td>Hemisphere Crescent</td>
<td>OEM Board</td>
</tr>
<tr>
<td>Datalink Radio</td>
<td>Freewave</td>
<td>MM2 900 MHz</td>
</tr>
<tr>
<td>Flight Computer</td>
<td>Phytel</td>
<td>MPC5200B Tiny</td>
</tr>
<tr>
<td>Pressure Transducers</td>
<td>AMSYS</td>
<td>AMS5812</td>
</tr>
<tr>
<td>Cell Phone Modem</td>
<td>Multi-Tech Systems</td>
<td>MT100EOCG-G2</td>
</tr>
</tbody>
</table>

Table 1: UMN-URG Goldy FCS Components

CELL PHONE MODEM OPERATION

The cell phone modem used for this research was made by Multi-Tech Systems [3]. The Open Communications Gateway - Embedded (OCG-E) product was chosen for its COTS availability as well as its low SWaP requirements. The MT100EOCG-G2 variant was chosen because of its unique capability to request the Cell Environment Description (+CCED) command from the main serving cell phone tower as well as up to six neighboring towers. This +CCED command is unique in that it supplies the modem with TOA information in the form of timing advances (TAs) for each of the towers in LOS organized by their Cell ID (CID). CID is a unique number used to identify each tower within a given cell phone provider’s network.

As described in [4], the TA is sent by a cell phone tower to the cell phone receiver. The TA is used by the receiver to compensate for propagation delay when communicating with the tower. The expected time delay from a signal being sent by a receiver to a tower is zero when the tower and the cell phone are collocated, and thus, the TA is zero. These TAs are measured in bit periods, rounded to the nearest whole bit period, and are accurate to ±1 bit period. A bit period is 48/13 µs. The TAs returned to the modem are a representation of the round trip time for a signal sent from a tower to the receiver and then sent back to the tower.

Because these TAs are rounded to the nearest bit period, this yields the following one-way range resolution for the cell phone modem range measurement given that the speed of light is 299 792 458 m/s and after dividing by 2 due to the TAs indicating round trip time:

\[
1 \text{ Bit Period} = \left( \frac{48}{13} \mu s \right) \left( \frac{299 792 458 \text{ m/s}}{2} \right) \left( \frac{1}{2} \right)
\]

\[
1 \text{ Bit Period} = 553.46 \text{ m}
\] (1)

Thus, one significant drawback is that the range measurement can be in error by as much as 553.46 m. This does not include additional noise or error sources on the TA data due to multi-path effects or RFI.

Figure 7 frames this issue in another way by showing the area around a tower that would return a TA of zero (red) to the receiver corresponding to a range anywhere from 0 m to 553.46 m from the tower. Similarly a TA of one (blue) corresponds to a range from 553.46 m to 1106.92 m. This large area where the TA will be one discrete range value will create relatively large position errors compared to a GPS-based fix. However in the absence of GPS, several minutes of un-aided dead reckoning can lead to kilometers of error. Thus range
estimates derived from TAs can bound the position errors on the navigation state and permit the aircraft to return within ±553.46 m, ideally, of its base station.

The difference between this acceleration experienced by the aircraft and gravity serves as the innovation for the measurement update used to determine \( \phi \) and \( \theta \). A second stage of the measurement update for \( \psi \) is calculated using magnetic field measurements from a magnetometer triad in the body frame. The difference between the measured magnetic field in the body frame (projected into the navigation frame) and the local magnetic field of the given flight area is the innovation. This local magnetic field is hard-coded into the algorithm prior to flight using the World Magnetic Model (WMM) 2010.

**DEAD RECKONING FILTER**

The dead reckoning EKF consists of the following 11 states:
1. Latitude (\( \hat{\lambda} \))
2. Longitude (\( \hat{\lambda} \))
3. Altitude (\( \hat{h} \))
4. North/South Wind Component (\( \hat{W}_{\text{North}} \))
5. East/West Wind Component (\( \hat{W}_{\text{East}} \))
6. Estimated Error on AHRS \( \hat{\psi} \)
7. Estimated Error on AHRS \( \hat{\theta} \)
8. Airspeed Error in X Component of Body Frame
9. Airspeed Error in Y Component of Body Frame
10. Airspeed Error in Z Component of Body Frame
11. Barometric Altitude Offset from \( \hat{h} \)

The 50 Hz time update of this filter was performed by projecting the body frame airspeed into the navigation frame, correcting for estimated wind, and calculating the latitude, longitude, and altitude rate equations shown in Equation 4.

\[
\begin{bmatrix}
\dot{\Lambda}_k \\
\dot{\lambda}_k \\
\dot{h}_k
\end{bmatrix} = \begin{bmatrix}
\dot{V}_{\text{North}} + \dot{W}_{\text{North}} \\
\dot{V}_{\text{East}} + \dot{W}_{\text{East}} \\
(R_{NS} + \dot{h}) \cdot \cos(\Lambda) \\
-\dot{V}_{\text{Down}}
\end{bmatrix}
\]

(4)

Where \( R_{NS} \) is the Earth’s radius of curvature in the North/South direction and \( R_{EW} \) the East/West direction. These rate equations were then used in Equation 5 to predict the 3-dimensional position of the aircraft at the next epoch. Additionally, a 50 Hz altitude-based measurement update was executed with innovation derived from the difference in the barometric altitude and the estimated altitude, \( \hat{h} \).

\[
\begin{bmatrix}
\dot{\Lambda}_{k+1} \\
\dot{\lambda}_{k+1} \\
\dot{h}_{k+1}
\end{bmatrix} = \begin{bmatrix}
\dot{\Lambda}_k \\
\dot{\lambda}_k \\
\dot{h}_k
\end{bmatrix} + \Delta t \begin{bmatrix}
\dot{\Lambda}_k \\
\dot{\lambda}_k \\
\dot{h}_k
\end{bmatrix}
\]

(5)

Aiding was provided by the cell phone TA based range measurements from each cell phone tower signal received. In an effort to simplify the problem, a library of CIDs and their locations in the flight area were

**SOFTWARE**

The software consists of two cascaded EKFs. The first filter is the AHRS, and the second is a dead reckoning EKF.

**AHRS FILTER**

The AHRS portion of the algorithm consists of a six state EKF. The states of the EKF includes the three Euler angles (roll angle, \( \phi \); pitch angle, \( \theta \); and heading angle, \( \psi \)) as well as three gyroscope bias values (\( \hat{p}_{\text{bias}} \), \( \hat{q}_{\text{bias}} \), and \( \hat{r}_{\text{bias}} \)) which correspond to the x, y, and z-axis rotation rate biases, respectively. The hat, \( \hat{\cdot} \), indicates an estimated quantity. This filter employs gyro-integration for a 50 Hz time update prediction step described in Equation 2 where the subscript \( k \) designates the current epoch and \( k+1 \) the next epoch. For ease of notation \( c \), \( s \), and \( t \) correspond to \( \cos \), \( \sin \), and \( \tan \) respectively.

\[
\begin{bmatrix}
\hat{\psi}_{k+1} \\
\hat{\theta}_{k+1} \\
\hat{\phi}_{k+1}
\end{bmatrix} = \begin{bmatrix}
\hat{\psi}_k \\
\hat{\theta}_k \\
\hat{\phi}_k
\end{bmatrix} + \Delta t \begin{bmatrix}
1 & s\hat{\phi}_k t\hat{\theta}_k & c\hat{\phi}_k t\hat{\theta}_k \\
0 & c\hat{\phi}_k & -s\hat{\phi}_k \\
0 & s\hat{\phi}_k & c\hat{\phi}_k
\end{bmatrix} \begin{bmatrix}
p \\
q \\
r
\end{bmatrix}
\]

(2)

The measurement update step occurs at a rate of 1 Hz and used to arrest the drift caused by gyro integration. The acceleration measured by the IMU in the body frame is corrected for centripetal acceleration and is projected into the navigation frame using the body to navigation coordinate frame transformation matrix given in Equation 3.

\[
R = \begin{bmatrix}
c\theta c\psi & c\theta s\psi & -s\theta \\
-s\phi s\psi - c\phi c\psi & s\phi s\psi + c\phi c\psi & s\phi c\psi \\
c\phi s\theta c\psi + s\phi s\theta s\psi & c\phi s\theta s\psi - s\phi c\psi & c\phi c\theta
\end{bmatrix}
\]

(3)

Figure 7: Ranges of Incremental Timing Advances
surveyed a priori. Although a method for estimating tower locations is feasible when GPS is available (using TA based ranges to towers to reverse the problem from locating the aircraft to locating the tower as described in [5]), the 553.46 m discretization combined with the relative ease with which the towers were physically located made this method expedient. Due to the large position errors inherent to the TA based ranges, an update rate of 0.2 Hz was chosen instead of a 1 Hz update used in the UMN URG GPS-aided INS.

These measurements were completed by first converting the coordinates of the cell phone towers into the North, East, and Down (NED) coordinates from a common reference origin chosen to be the initial location of the SUAV. When GPS becomes unavailable, the estimated location of the aircraft is converted into the NED frame. Next, the cell phone data is parsed to determine if any observed CID matches one from the library. In order to account for the uniform distribution of the discretized timing advance information, the measurements are determined using the most likely range, or least error range, which is assumed to be exactly halfway between the measured bit period and the next. Therefore we add 0.5 to the rounded bit period returned and calculate the range, $\rho$, as shown in Equation 6.

$$\rho = (\text{bit periods} + 0.5) \times (553.46\,\text{m}) \quad (6)$$

Viewed another way, it is assumed that a TA value of zero will signify a range of 276.73 m from the aircraft to the corresponding tower. Likewise a range of 830.19 m will be used for a TA of one, and consequently, the true range error will be ±276.73 m assuming there is no additional sources of error or noise. If an observed CID matches a library CID, the range is compared to the estimated range, $\hat{\rho}$, and the observation model matrix, $H$, is calculated by Equation 10.

$$\hat{x}_{SUAV} = \begin{bmatrix} \dot{N}_{SUAV} \\ \dot{E}_{SUAV} \\ \dot{D}_{SUAV} \end{bmatrix} \quad (7)$$

$$x_{CID} = \begin{bmatrix} N_{CID} \\ E_{CID} \\ D_{CID} \end{bmatrix} \quad (8)$$

$$\hat{\rho} = \|\hat{x}_{SUAV} - x_{CID}\| \quad (9)$$

$$H = \frac{1}{\hat{\rho}} [\hat{x}_{SUAV} - x_{CID}] \quad (10)$$

Thus, the cell phone-aiding innovation vector is given by Equation 11.

$$\text{TA innovation} = \rho - \hat{\rho} \quad (11)$$

One important note regarding the CID is that all CIDs observed in the flight area were 5 digit numbers where the first four digits corresponded to that unique cell phone tower. The fifth digit designated which sector the signal was being received by. Each CID observed consisted of three possible sectors located in an equilateral triangle around the tower or structure. This is illustrated in Figure 8 where a hypothetical cell phone tower 1234 is shown with sectors 1, 2, and 3. Therefore, TA data could be returned by each of the three sectors, two of the three, or just one. In the case of multiple TAs from the same tower, a measurement update would occur only on the shortest TA based range regardless of sector. Test data showed that the shortest TA range corresponded to the sector antenna that was most directly oriented at the receiver when the TA was requested.

Figure 8: Sector Arrangement for Hypothetical Cell Phone Tower 1234

Another important check prior to completing any range update was an inspection of the innovation compared to the expected innovation covariance. Figure 9 shows a subset of 160 TA based ranges and their true ranges (derived from GPS data).

Figure 9: Cell Phone TA Range vs. True Range

The TA based range compares as expected, ±553.46 m, to the true ranges from the towers except for a few “spikes” particularly evident on the left side of the figure. These spikes are believed to be due to multi-path effects because of an increased occurrence when the receiver was closer to the ground where the LOS could be obstructed. In order to prevent these faulty TA ranges from corrupting the solution, two logic checks were implemented. The first was an empirically determined altitude check to ensure the aircraft was at least
10 m above the ground as determined by the barometric altimeter. The second was a check of the standard deviation of the expected innovation, σ_innov, as defined in [6]. An empirically determined cutoff multiplication factor of 1.5, i.e. $1.5 \times \sigma_{\text{innov}}$, was used. This check was implemented by verifying each measured innovation was less than $1.5 \times \sigma_{\text{innov}}$ prior to completing any update.

The effectiveness of this method relies upon accurate statistical models for the process noise, $Q$, and measurement noise, $R$. Additionally, the state errors due to process noise must increase the state covariance, $P$, at a sufficiently slow pace to keep the innovation covariance small enough to expect relatively small innovations. Otherwise, large state covariances will cause the expected innovation covariances to be large as well, and that would make it difficult to differentiate the “bad” measurements from the “good” ones. Nevertheless the sensors used in this SUAV do allow for this method to be effective as indicated by Figure 10. Implementing this check and a measurement noise of $553.46^2 \, \text{m}^2$ allows for updates to completed on all the “good” measurements while rejecting the “bad” ones.

Figure 10: TA Range Innovation Cutoff

SYSTEM PERFORMANCE

Both flight testing and hardware-in-the-loop (HIL) simulations were performed to analyze the effectiveness of the cell phone-aided dead reckoning system. A reference GPS-aided INS filter determined the true navigation state of the aircraft. This reference system was run in the background of the flight-code uploaded to the Goldy FCS. It was supplied with a continuous and uncorrupted stream of 1 Hz GPS data for proper state estimation. This background system did not interact with neither the backup system being tested nor the guidance system and the control laws that autonomously fly the SUAV. As such, the guidance system and control laws were supplied with a navigation state determined by the backup system.

All flight testing was conducted at the University of Minnesota Outreach, Research and Education Park (UMore Park). The Multi-Tech Systems MT100EOCG-G2 was equipped with a commercial cell phone network carrier’s Subscriber Identity Module (SIM) card. To develop the “library” of CIDs, the authors gathered the position information on sixteen towers within that carrier’s network within LOS of the UMore Park flight area.

Figure 11 shows the UMore Park flight area, the pre-programmed route loaded into the SUAV flight-code prior to each flight the, and the boundaries of the FAA Certificate of Authorization (COA). This COA is a certification of operations which includes the ground station, airframe, and operating procedures, and it was obtained by the UMN-URG for the area designated by the green dashed circle. The ground station and airframe used in a flight test conducted on 31 July 2014 are shown in Figure 12.

Figure 11: Flight Test Area & Flight Path

Figure 12: Flight Test Setup

FLIGHT TEST RESULTS

As illustrated in Figure 11, the size of the COA boundaries only allow for a 1100 m radius centered at
44°43'32.71" N and 93°4'44.49" W. This fact coupled with the measurement noise on the TA based ranges makes it difficult to observe large corrections caused by the cell phone-aiding. Stated another way, the terms of the COA prevent test flights that include a long enough straight-line path to allow the drift from the dead reckoning time update to exceed the measurement noise. This fact is reflected in the flight test data shown in Figure 13.

Figure 13: Flight Test: Position Solution Comparison

This plot shows the results of one flight test with the position solutions for three filters. The reference (true aircraft location) is shown in green. An un-aided dead reckoning is displayed in red, and the cell phone-aided dead reckoning is in blue. By design, all three filters provide the same solution during the portion of the flight when GPS is available. Once way-point 8 is passed, a GPS outage is simulated. Subsequently, each dead-reckoning filter attempts to navigate the aircraft back home without GPS available. As indicated by the green true position, the aircraft is actually drifting to the north of the estimated path of both dead reckoning systems. Small adjustments can be seen in the cell phone-aided solution, and these adjustments pull the estimate closer (North) to the aircraft’s true position. This behavior is not seen in the un-aided dead reckoning filter due to the absence of any measurements to correct the drift. Figure 14 displays the 3-Dimensional position error magnitude against time starting at the moment GPS becomes unavailable.

Figure 14: Error Growth Comparison

It is clear from this plot that the errors on the cell phone-aided dead reckoning filter are less than those experienced by the un-aided dead reckoning filter due to the fusion of TA range estimates into the solution. Additionally as shown in Figure 15, both dead reckoning filters provide an altitude estimate with little error. This is due to the continued aiding of the vertical channel by the barometric measurement updates provided by the pitot-static system.

Figure 15: Flight Test: Altitude Solution Comparison

SIMULATION RESULTS

Due to the limited airspace available, the performance of the cell phone-aided dead reckoning system during a persistent GPS outage was not assessed by flight testing. However, 25 Monte Carlo HIL simulations were used analyze this performance. Figure 16 shows a schematic of the HIL depicting signal flows and modules.

Figure 16: Hardware-in-the-Loop Simulation Block Diagram

This HIL simulation created in MathWorks Simulink utilized a 6 degree-of-freedom (DOF) nonlinear model of the Ultra Stick 25e that included models for relevant SUAV subsystems such as the actuators, motor, propeller, and sensor noise characteristics. An environmental model was used to recreate Earth’s atmosphere, gravity, magnetic field, and wind. MathWork’s Real-Time Windows Target toolbox was used to ensure the simulation supplied the Goldy FCS flight computer with simulated sensor data at the required 50 Hz rate [7]. Figure 17 depicts the physical setup during a HIL simulation.
To ensure the HIL simulation results obtained are representative of those that would have been collected during real flight testing, accurate error models were developed for the TA data. The TAs were simulated by determining the true range, $\bar{\rho}$, from each of the sixteen cell phone towers to the aircraft given the cell phone tower locations and true aircraft position (determined by 6 DOF nonlinear Ultra Stick 25e model). The +CCED command returns the TAs for the serving cell phone tower and up to six neighboring cell phone towers depending upon whether those additional towers are within LOS communication. To replicate this behavior, the number of LOS cell phone towers available, $n$, at the measurement epoch was randomly chosen from a uniform discrete distribution between 1 and 7. The $n$ closest tower CIDs and corresponding true ranges were selected for the simulated sensor data. Finally, the true range to each tower was corrupted by noise and converted into a TA corresponding to the rounded bit period by Equation 12.

$$TA_{HIL\ Sim} = \text{round} \left[ \frac{\bar{\rho} \pm \text{noise}}{553.46 \text{ m}} \right] \text{ for } 1 \leq n \leq 7 \quad (12)$$

The noise value was chosen by randomly selecting a value based on a normal distribution with zero mean and a standard deviation of 350 m. This distribution was determined experimentally to replicate the probability density function (PDF) constructed from actual sensor data collected on the ground and in flight. This PDF is shown in Figure 18 where the x-axis the position error of the TA based range as defined by Equation 13.

$$Error = \bar{\rho} - (TA_{actual} + 0.5) \ast (553.46 \text{ m}) \quad (13)$$

The HIL simulated TA data error distribution is shown in Figure 19 where the x-axis the true position error of the HIL generated TA based range as defined by Equation 13 where $TA_{actual}$ is replaced with $TA_{HIL\ Sim}$.

As expected, Figure 18 exhibits the large outliers discussed earlier. However since the backup system employs a check on the expected innovation, the spikes were not simulated. Nevertheless, both plots depict similar behavior in the core of the PDF indicating that the simulation reasonably imitates the real-world TAs.

One more important factor addressed to ensure the simulation results reflect real flight testing was reasonable wind conditions. The environmental model winds were set to match the winds experienced during the flights that generated the plots shown in Figures 13 - 15. The winds on the day of flight testing were a sustained 5 kts from the South. This observation was reflected in the estimates of the north and east wind states in the dead reckoning filter which approximated that the steady wind varied from 1 kts to 8 kts with a turbulence of 0.5 m/s. The Low-Altitude Discrete Dryden Wind Turbulence Model from the MathWorks Aerospace Blockset was used in the HIL simulation, and the turbulence was set to 0.5 m/s on all three body axes. The steady wind was set to 1 kts and was ramped up to 8 kts during simulated flight.

With the simulation models set, the flight computer was loaded with the same software used during the flight tests and produced the results summarized in Figure 20 which compares very well to the flight test results plotted in Figure 13.
With the HIL simulation validated, 25 extended simulations requiring several miles of GPS-denied navigation were completed. A start point for this simulation was chosen at the western most edge of the known cell tower coverage area. Typical operations (i.e. GPS available) are being conducted near this point at the beginning of the simulation. The SUAV home base was chosen 14 miles East to allow for an eastbound flight path that would traverse the entirety of the tower coverage. When GPS services was disrupted, the SUAV attempted to navigate to this home base. This simulation was completed using the full library of sixteen cell phone towers within a 235.19 square mile area creating a cell phone tower density of 14.7 square miles/tower. Figure 21 shows the results generated during one extended simulation.

Figure 21 shows the desired flight path in green which designates the course each filter attempts to track. The red and blue line represent the true position of the SUAV when navigated by the un-aided filter and cell phone-aided filter, respectively. The un-aided solution causes the SUAV to drift to the south and east despite estimating the SUAV location to be on the green desired track. Conversely, the cell phone aided solution remains on track albeit with an oscillatory pattern. The average position error magnitude of all 25 Monte Carlo simulations vs. the elapsed time of simulation is shown in Figure 22. The position error magnitude statistics are also summarized in Table 2.

![Figure 20: HIL Simulation: Position Solution Comparison](image)

**CONCLUSIONS**

In this work, a SUAV equipped with an airspeed-based dead reckoning filter aided by cell phone signals was demonstrated. It was shown that this system can safely return the SUAV to its home base (or other unaffected region) when a GPS interruption occurs. This was accomplished while using COTS equipment that could provide range measurements in 553.46 m increments. However, this was sufficient to provide a measurement update capable of bounding the large drift errors inherent to un-aided dead reckoning navigators.

The multilateration technique requires knowledge of cell phone tower locations in the SUAV flight area before flight. Currently most cell phone network providers are reluctant to provide the precise coordinates of the towers. Consequently a library of relevant tower locations were encoded into the system. Although feasible for research purposes, this method may be too labor intensive and create memory issues for real-world applications. For these uses, cell phone tower locations may need to be determined by an additional estimation algorithm designed to determine tower positions while GPS is available. Alternatively,
perhaps a more accurate and computationally faster method would be to incentivize network providers to make their tower locations available to users. It can be reasonably assumed that the cell phone towers have position information available due to the fact that network timing is provided by GPS receivers [8].

This reliance upon GPS receivers for critical time information could create a liability for the cell phone-aided system (which is reliant upon network clocks to calculate TAs). However, as described in [8] network providers have recognized the vulnerabilities of GPS and are addressing the issue by working to improve the time synchronization protocols used in these networks and their robustness to GPS outages.

Despite this backup system proving the concept of using cell phone signals to aid an airspeed based dead reckoning filter, position errors on the order of hundreds of meters are very large, especially for SUAVs. One of the utilities of these small aircraft is to perform operations at lower altitudes and in tighter spaces, and although a backup system will not be as accurate as GPS, it is desired that the backup will allow the SUAV to exit any GPS-denied region safely including urban settings. This research proves a multilateration approach using cell phone signals can be implemented into a SUAV flight control system. However, further research designing and integrating a software defined cell phone modem may lead to improved system performance. In the short term, this migration away from COTS equipment may increase costs. However, evolving technology in the clock industry has allowed for the development of chip-scale atomic clocks with single unit quantities having comparable cost to other low-cost SUAV autopilot components. Consequently, an advanced cell phone modem equipped with a highly accurate atomic clock can still comply with the low-cost nature of SUAV components while providing a considerable improvement in signal TOA information and therefore position accuracy.

Additionally, Received Signal Strength Indication (RSSI) is commonly available in all cell phone receivers, and an intelligent integration of RSSI into an estimation filter may increase location accuracy. RSSI may serve as an indirect evaluation of range, or perhaps a more promising usage would be RF fingerprinting. A brief examination of RSSI was conducted during the course of this work, and patterns in RSSI were evident with stronger signals received when the SUAV was closer to the corresponding cell phone tower. However, RF fingerprinting for SUAV applications will require a careful use of multiple antennae due to the pitching and rolling dynamics of an aircraft causing signal blockage when only one antenna is used.

Finally, the effectiveness of using cell phone signals for localization needs to be evaluated for all the settings that SUAVs will be deployed in. For instance, an evaluation is needed for what role cell phone tower density has on the performance of these systems. This will be particularly relevant for rural settings like those encountered in border patrol operations or agricultural applications where tower coverage is more sparse than urban areas. Likewise a reduced tower coverage may be experienced during CONOPs that may require non-line-of-sight (NLOS) communications for cell phone modems.

References


