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Engineering Notes

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Algorithms for Geolocation of an Ad Hoc Network of Unmanned Systems

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I. Introduction

UNMANNED systems have been successfully utilized for numerous applications, many of which require the system to determine its position in the world for navigation. Although the global positioning system (GPS) has proven to be an integral part of modern navigation, there are some instances when GPS signals become degraded either by the environment or by jamming. Some environments that degrade GPS accuracy include under tree canopies, inside cities between skyscrapers, indoors, and in heavily mountainous terrains. The problem with each of these areas is that GPS signals from some satellites can become blocked, thus reducing the number of available satellites from which to multilaterate the position. All of these environments are potential areas where unmanned systems could be used for reconnaissance or surveillance. In addition to degradation caused by environmental effects, there are also methods of jamming GPS signals, which can result in GPS being unavailable, thus potentially preventing a GPS-dependent unmanned system from accomplishing its mission.

Because of these problems with GPS, current research is focusing on a method to potentially serve as a complement to the GPS system, particularly for unmanned ground vehicles and unmanned aerial vehicles (UAV). Although there are algorithms for combining inertial inputs with GPS information,[1] inertial sensors that are accurate enough to be used for an extended period in the absence of GPS can be an expensive addition to an otherwise low-cost UAV. The proposed method would utilize localized rf-based or other means of ranging between unmanned vehicles to multilaterate an unknown vehicle position. Whereas most similar techniques typically utilize fixed nodes that act as ranging nodes from which the positions for receiver nodes are determined, this method would allow each unmanned vehicle, or node, to serve as either a ranging or a receiver node. Specifically, the idea is to form a mobile, ad hoc network of vehicles that are used as ranging or receiving nodes depending upon each node's confidence in its position, whether the position is obtained from GPS or calculated using this technique. When available, GPS information would be combined with the ranging information to obtain the best location solution. A Kalman filter is used to help determine the best solution given the combined data of ranges and GPS. Simulations have been performed to help determine the feasibility of this type approach to unmanned systems, particularly in the case of a swarm of UAVs flying into a city and then randomly moving about over the city for surveillance purposes. Results from these simulations are summarized throughout this document.

II. Mobile Ad Hoc Geolocation Network

A. Concept

The mobile ad hoc geolocation network (MAGNET), as this method of geolocation has been named, consists of a simplified mobile ad hoc network (MANET) of nodes, each with integrated ranging capability. A MANET is a network in which nodes are allowed to come and go at will, and no fixed-location nodes are required. In this case, each node would have a GPS receiver, which would allow the node to locate itself accurately when GPS is available. Each node would also contain the required hardware to obtain ranges to other nodes in the network. These ranges to other nodes would then be used to multilaterate the node's position if GPS were unavailable or degraded. Multilateration requires at least four input nodes to completely constrain the problem, but there are often more input nodes available. In this case, the problem becomes overconstrained, and an error minimization technique must be used in an effort to obtain the optimal solution to the problem.

One important feature of this approach is that any node in the network can act as a ranging node, whether or not that node has GPS available. This enables the ranging technique to reach further into an area that does not have GPS. However, this does require nodes to perform a reasonable estimation of the expected error associated with the position calculation. This error, known as the estimated position error (EPE), is broadcast to surrounding nodes along with the calculated position. This allows receiving nodes to use both the position and EPE of surrounding nodes to determine the best nodes to use as ranging nodes. The reason it is necessary for GPS to be used when available is that this method of geolocation needs some way of fixing the location of the network. If no reference points were available, then the nodes could be located relative to one another, but there would be no way of locating the network in the world. Because of this dependency upon GPS or other means of obtaining reference points, the ad hoc ranging network does not by itself serve as a replacement for GPS. However, it does act as a complement to provide coverage in areas where GPS is degraded or unavailable either because of environmental surroundings or intentional jamming. The algorithms being developed are not dependent upon a particular ranging technique.

B. Kalman Filter

Any algorithm or set of algorithms for calculating the position using the multilateration technique described necessitates the solving of multiple equations containing error. This can be accomplished numerous ways, but the Kalman filter is often used because of its efficiency and accuracy. Because our input of range has a nonlinear relationship to position, we chose to use the extended Kalman filter.

For each node the filter chooses to use for its multilateration, the filter receives that node's second-order solution and estimated error as well as the measured range to that node and the error on that measurement. Currently the range measurements fed to the

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filter are already synchronized in time, but the time difference could also be an added state to the filter. The filter can operate at varying frequency, but this Note assumes the output frequency is the same as GPS or at a 1-Hz update rate. Because at each 1-Hz update the filter decides which nodes to use for multilateration, if a node were to leave communication as is common in ad hoc networks, it would pose no impact on the calculating node. If a node were to leave the network midway through node selection, the data that were not received from that node would be entered into the filter with a high error. This would effectively tell the filter to ignore the measurement providing only minimal impact on the solution. However, with proper node selection methods, the occurrence of this happening can be greatly reduced.

III. Simulation Results

A. Simulation Software Description

Previously documented results for this approach utilized MATLAB® simulations that focused on issues such as node selection techniques, number of input nodes, and error propagation.[2] To more accurately model the system, however, it was necessary to expand the simulation such that all of the nodes in the network were using the same set of algorithms for position determination. To facilitate the simulation of these algorithms, an application was developed in C++ that allows playback of scenarios with scripted entity paths that follow a spline through predefined waypoints. To simulate areas of degraded GPS and various ranging errors, the simulation software was designed to allow the creation of both rectangular degraded regions, which can be rotated as desired, and circular jammed regions. These error regions can be placed as desired in a scenario to simulate various degraded environments through which entities must navigate.

Degraded regions can be defined as either low-, low-to-medium-, medium-to-high-, or high-error regions. For the purposes of the simulation, low-error areas are signified by the color green, low-to-medium errors are signified by the color yellow, medium-to-high errors are signified by the color orange, and high errors are signified by the color red. Areas where there are no degraded or jammed regions are considered low error or green areas. Table 1 summarizes the different errors for each area along with the maximum range distances. These values are all changeable using the simulation application user interface.

The circular jammed regions have three radii, each of which defines a different error region. Inside the inner radius is defined to be a high-error or red area, from the inner to the middle radius is a medium-to-high-error or orange area, and from the middle to the outer radius is a low to medium error or yellow area. Each of these three portions of the jammer can be enabled or disabled. Also, the radius for each area can be modified.

To simulate a potential use of UAV swarms, a scenario was generated that contained 20 UAVs flying in a swarm into a city and then randomly flying around over the city. This could simulate a reconnaissance or surveillance mission. To test the capabilities of the MAGNET approach, different simulations were generated to represent various causes of GPS degradation. Some of these simulations and the corresponding results and analysis are provided in the remainder of this Note.

B. Simulation of Simplified Real-World Environments

The simulation that was generated to represent a potential real-world environment simply used a red degraded region that covered the city. As the UAVs flew over the city, they moved in and out of this degraded region; therefore, there were many times when they were actually able to obtain a good GPS reading. Then, when the UAVs flew through the red region, the ranges to surrounding nodes were used to calculate their position. Figure 1 shows a screenshot of this simulation scenario.

Table 1 Error types and associated colors

Error type	Color	GPS error	Range error, %	Range distance, m
Low	Green	2–6 m	0.5–1	550
Low to medium	Yellow	10–25 m	1–2	500
Medium to high	Orange	30–50 m	2–4	450
High	Red	No lock	4–6	400

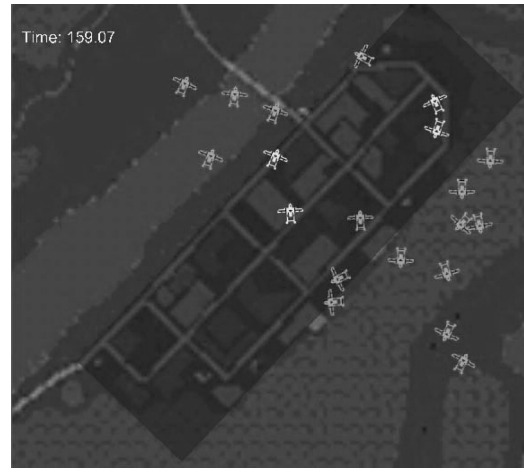

Fig. 1 Red degraded city simulation.

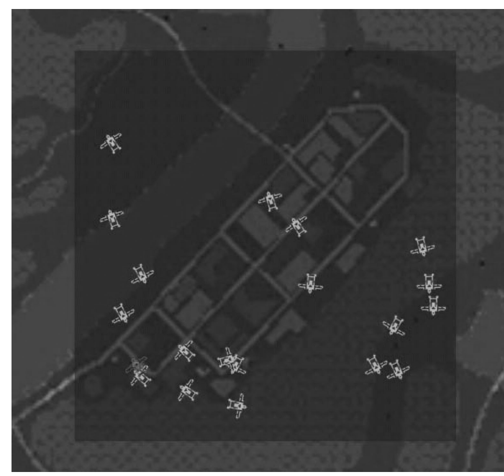

Fig. 2 Large degraded area simulation.

C. Simulations of Entire Network in Unusable GPS Areas

Although the previously described simulation was perhaps more realistic, there was also a need to consider the possibility that all of the nodes in a particular network could move into a red region and stay in that region for a fairly long period of time. In general, this scenario is actually worse than what would be a typical scenario. This is because the assumption is that all of the nodes move into a red region and stay there, whereas in a typical real-world environment there would often be members of the network that were outside of the degraded areas. This would usually mean that there were nodes on the network that could obtain a good GPS reading and therefore could serve as good ranging nodes to those nodes that were in degraded areas. However, despite the fact that this would not be the most typical environment, there was much to be learned from this simulation, and the possibility exists that such an environment could be encountered. Figure 2 shows a screenshot of this simulation scenario.

Although the algorithms can operate without the addition of any other measurements, such a harsh environment as just described will sometimes require extra inputs to track well. With only range measurements, each nodes error will drift over time. However, with the addition of other measurements it could become possible to either prevent this drift from happening or minimize its effects. One such possibility is the addition of velocity and altimeter readings. The navigation algorithms that guide UAVs will almost certainly have a reading on speed, heading, and altitude. One simulation focused on how adding these measurements into the Kalman filter might affect its results. Because these algorithms are envisioned to be a cheap complement to GPS, these measurements were simulated as relatively inexpensive parts one might add to a cheap UAV. As such, these measurements are useless at tracking on their own, but might be useful when combined with ranging in the Kalman filter.

D. Results/Analysis

To properly analyze the output data, there needs to be truth data to compare. Therefore with each simulation, the actual position was printed in an output file along with the calculated position and EPE. To analyze the EPE, the distance between the calculated and actual position was also determined and added to the output file. Although the results were analyzed on a single node basis, similar performance applies to the entire swarm because all of the nodes experience comparable errors throughout the simulation.

The first scenario we will analyze is the city where GPS is degraded (Fig. 1). Figure 3 shows the calculated position and the analyzed position.

As can be seen from the figure, the Kalman filter appears to be able to correctly track the UAV as it flies in and out of the city. To verify this hypothesis, examine Fig. 4. The filter is able to track consistently with an accuracy of less than 3 m. EPE is also consistently less than 18 m. As expected, the distance accuracy decreases as the UAV flies through the degraded city. This is even more noticeable in EPE. The filter's confidence in its position decreases, as noted by the three peaks, as the UAV flies into and out of the city. However, the filter is able to continue correctly tracking the UAV as the error distance stays below 20 m and is consistently below EPE.

Now let us consider the situation where perhaps the entire swarm or network of UAVs is in an area where GPS is unavailable. This differs from the previous simulations in that those nodes were allowed to leave and reenter the degraded area. In the following simulations, once the UAV enters the degraded area it does not leave for the duration of the simulation, with a few exceptions. One would expect the error to increase as the UAV stays in the area longer, but it is interesting and important to know how that error will propagate.

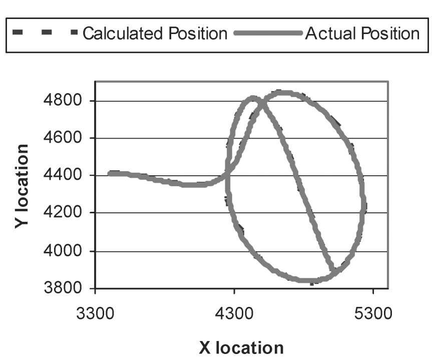

Fig. 3 UAV track in degraded city with no sensors.

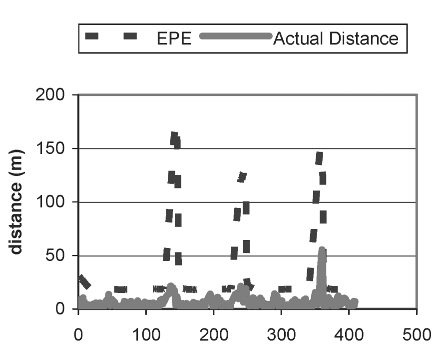

Fig. 4 EPE and actual distance in degraded city with no sensors.

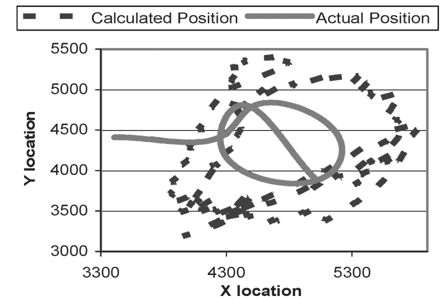

Fig. 5 UAV track in degraded area with no sensors.

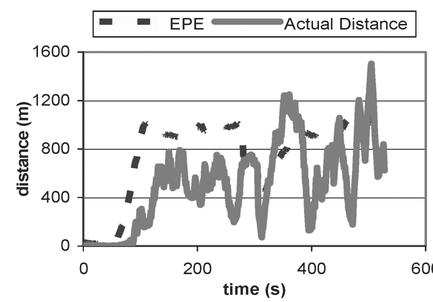

Fig. 6 EPE and actual distance in degraded area with no sensors.

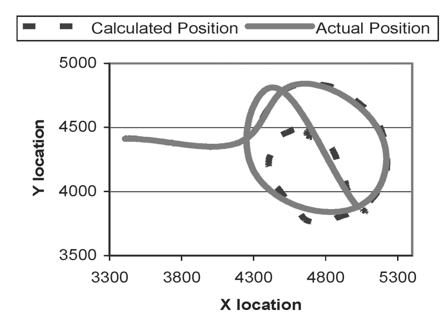

Fig. 7 UAV track in degraded area with velocity and altitude.

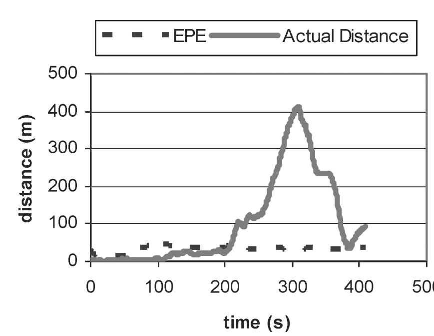

Fig. 8 EPE and actual distance in degraded area with velocity and altitude.

It is easy to see from Figs. 5 and 6 that the filter becomes inaccurate fairly soon after the UAV enters the degraded region. However, the filter does not lose the track. The EPE is still consistently above the calculated distance, which means the filter is still tracking and its output is technically correct. Simply put, the filter output is bad, and it knows it. Let us now see if velocity and altitude measurements will help increase our accuracy.

Looking at Fig. 7, the filter indeed now appears to be tracking more accurately. One would conclude simply by looking at this graph that our results are better. However, looking at Fig. 8, the EPE becomes invalid halfway through the simulation. That means the filter loses track halfway through. How can adding more measurements make us lose track? To understand this phenomenon,

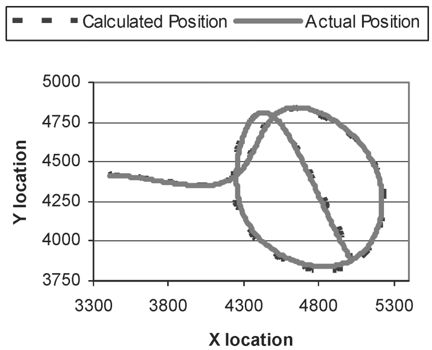

Fig. 9 UAV track in degraded area with velocity, altitude, and increased range.

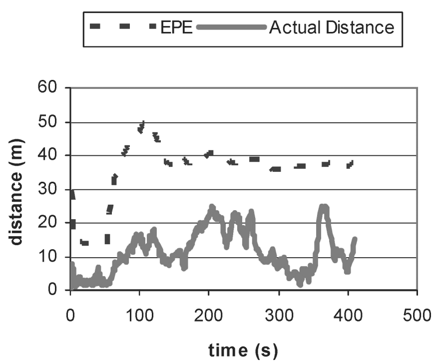

Fig. 10 EPE and actual distance in degraded area with velocity, altitude, and increased range.

we must look internally at the Kalman filter. After the halfway point, there are many times when the filter does not have the seven nodes within range it is trying to get. Therefore, it basically ignores the range measurements and begins calculating almost solely with the velocity and altitude measurements. It is unaware that these measurements have caused it to drift horribly off course.

To verify these suspicions, we will assume we have a better ranging radio for this next simulation and it can range 600 m within the degraded area instead of just 450 m. We can quickly see from Fig. 9 that it does appear to correctly track. The calculated position is able to follow the actual position throughout the simulation. But let us check EPE to be sure the filter knows it is tracking well. From Fig. 10 we see that the filter not only is tracking again, but is tracking quite well. With just the addition of two cheap sensors, the distance error is now below 20 m, and the EPE is now below 40 m. Furthermore, it appears that the network has reached equilibrium. In other words, all of the nodes have drifted as far as they will. With the exception of dilution of precision, there are no more errors the filter will see that it has not already filtered as well as it can. That is clearly noted by the leveling off of EPE and distance error.

IV. Conclusions

The method of geolocation described in this Note would provide a way for unmanned systems to navigate in areas where GPS is not available because of jamming or environmental degradation. Although the multilateration technique described is not by itself a sufficient positioning system, it can be used along with GPS to provide reasonably accurate geolocation for a network of nodes, even when some of the nodes are unable to receive accurate GPS readings. As described, addition of inexpensive inertial sensors can greatly increase the accuracy of the location determination when used in conjunction with the described ranging technique. Although there are numerous issues that must still be studied before fielding a system such as the one described, simulations have thus far shown that this technique could be a viable solution to the problem of geolocation of unmanned systems in areas where GPS is unavailable.

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