Enhanced Drone Swarm Localization Using GPS and Trilateration Based on RF Propagation Model

Paula Kokić, Boris Tomaš
Faculty of Organization and Informatics
Pavlinska 2, 42000 Varaždin
{paukokic, btomas}@foi.hr

Abstract. *GPS system can provide information about location of any device that has embedded GPS receiver. However, when using swarm of drones, that information may not be enough for precise tasks. Using given GPS location error values, trilateration technique and radio frequency propagation model, an algorithm is developed, trying to minimize provided GPS location of an individual drone inside a swarm. Every drone in a swarm is observed as GPS referent node, receiving the data from RF visible nodes and forwarding data to other nodes via communication channels. Simulation results have shown that given algorithm can lower the location error of each node in a swarm, giving more precise location of a node.*

Keywords. IoT, drone, trilateration, localization.

1 Introduction

Drones combine achievements in electronics and aeronautics. Precise positioning is of the essence if drones should be used in a simple scenarios like delivery or complex scenarios like search and rescue missions. GPS and alternatives, do provide positioning solution; however, precision varies from several decimetres to several meters. Use of existing technologies like radio communication for distance measurements is widely used in space exploration, making its use interesting for researchers.

This research combines GPS and RF technologies in drone swarm to generate information valuable for each drone in the swarm.

2 State of the Art

2.1 Global Positioning System (GPS)

GPS is American space-based system which provides localization, navigation and time services in all weather conditions, anywhere on the Earth.

The system is divided into three work segments: space segment, control segment and user segment. Space segment consists of 24-31 satellites that circle around the Earth and transmit the signal. Control segment consists of global network that monitors GPS satellites, exchanges data and does analysis. User segment consists of GPS receivers in any form, whether it is a stand-alone receiver or receiver embedded in other device, like smartphones or watches ("Official U.S. Government information about the Global Positioning System (GPS) and related topics", 2016). GPS uses two types of error: by design and natural. First one is employed as different service level, where most precise service is reserved for military purpose. Second error type is caused by environmental conditions and EM fluctuations.

2.2 Radio Frequency (RF) propagation

Radio frequency is defined as any frequency of electromagnetic (EM) field that lies in range extending from 3 kHz and 300 GHz, including those used for communication or radar signals ("Dictionary – Radio Frequency", 2016). Wi-Fi signal, which is transmitted by drones, uses frequencies of 2.4 GHz and 5 GHz.

RF propagation is a term used to describe a way of spreading radio waves between two points in space and on the Earth. Because of physical properties of radio waves, signal propagation can be used to determine the distance between those two nodes. Node transmitting signal is called "signal sender" and node receiving signal is called "signal receiver". Every signal sent from a node is transmitted with a defined level of power ratio (measured in decibel-milliwats, dBm), which is weakened as it propagates through the EM field. The signal would never stop its propagation, but signal receivers can measure only defined level of power, that reaches down to -90 dBm ("Industry standard for minimum Wifi signal strength?", 2013). Therefore, if the signal at some location is higher than -90 dBm, "signal sender" is visible to the "signal receiver", which can receive signal and decode all the data that is send though that signal. (Hogg, 1993)

Distance between "signal sender" and "signal receiver" can be calculated using the value of power level which is measured by "signal receiver", through *free-space path loss* formula, as shown in (1)

$$r = 10^{\frac{\ln(10)\times(T-R-K-20\log(f))}{10n}} \quad (1)$$

where:

- R – receive power level, measured with appropriate equipment (dBm),
- T – transmit signal power level, equals 17 dBm (or individually set by each drone),
- K – path loss constant, equals -147.55,
- f – the WiFi frequency, equals 2450 MHz,
- n – the path loss exponent, equals 2, because drones are flying in a free space.
- r – distance between two nodes (result in meters, m) (Tomaš, 2013) (Dasarathan et al, 2007).

2.3 Unmanned Aerial Vehicle (UAV)

Unmanned aerial vehicle (or drone) represents an aircraft without its aircrew, i.e. its on-board pilot. The UAV can be monitored and navigated remotely. It is usually equipped with a lot of sensors, cameras, transmitters and receivers (e.g. a GPS receiver or RF antenna), depending of their purpose ("The UAV – Unmanned Aerial Vechile", 2016)

2.4 Crowdsourcing

Crowdsourcing represents a way of gathering needed services, ideas or data from undefined group of people (Frančula, 2015). Crowdsourcing systems are systems consisting of many units that exchange data independently. (Yuan et al, 2009)

In this research, crowdsourcing is employed on a drone system (swarm), where every drone is a GPS referent node for other drones. Drones are exchanging their data over WiFi network, including information about their GPS location.

3 Problem Definition

Every GPS receiver (including those embedded in drones) from GPS satellite receives lot of data. The most important data is information about location of a node. Location is given as two properties: latitude and longitude, both measured in geographic degrees, minutes and seconds. Aside location, GPS location error is received from GPS receiver in a receiving data stream. This error represents possible deviation from given location, consists of longitude error and latitude error and is measured in meters ("Official U.S. Government information about the Global Positioning System (GPS) and related topics", 2016).

GPS location error may vary up to 30 meters ("Navstar GPS User Equipment Introduction", 1996). That could be a problem if drones are located much closer to each other in a swarm so that navigating could be difficult. Lack of precision in location may cause drone to accidently collide with an object, harming either that object or itself, crashing to the ground and failing given mission.

The hypothesis of the research is:

Using RF propagation model GPS location error in crowdsourced systems can be minimized.

Aim of the research:

- simulate moving drone swarm in open space,
- using RF propagation model calculate distances between drones,
- develop an algorithm for minimizing GPS location error of drones in swarm,
- get more precise location of each drone in the swarm.

4 Solution

4.1 Drone model

Every drone in the swarm represents individual node as GPS referent beacon. Therefore, each node is simultaneously "signal sender" and "signal receiver". Each node can move in 2-dimensional space (3rd dimension is not considered in this research) and has same properties: ID, name, location (longitude and latitude) and location error (by longitude and by latitude). Each node is equipped with GPS receiver and RF antenna which allows to exchange data over WiFi network.

4.2 Algorithm

As a solution for the given problem, an algorithm for minimizing GPS location error is developed.

Input parameters of algorithm are:

- GPS location of a node (x,y) – x representing latitude and y representing longitude, measured in geographical degrees,
- GPS location error of a node (e_x, e_y) – e_x representing latitude error and e_y representing longitude error, both measured in meters,
- data (GPS location, GPS location error and received power level) of each node in the swarm that is visible by observed node.

As mentioned before, GPS location, along with its error, is received by GPS system using GPS receiver device on each node. For the purposes of simulation, GPS location and error will be generated, as described in Section 5.

Output parameter of an algorithm is specific region, i.e. surface of a geometric shape, representing the surface where observed node could be located.

Purpose of the algorithm is to return specific surface that would be smaller than the surface of an ellipse that is made using initial information about GPS location error from the input parameter.

Pseudocode of the algorithm is described through following steps:

1. Read WiFi signal power levels and determine visible nodes.
2. Calculate the surface of initial error ellipse. Initial error ellipse is created for data received from GPS component, i.e. location (x, y) and location error (e_x, e_y). Error ellipse is constructed around the location point of an observed node, on a distance that equals latitude location error (e_x) in a horizontal line and on a distance

that equals longitude location error (e_y) in a vertical line. Surface of the error ellipse represents the space where actual node is probably located. This surface would be compared to the surface calculated by the algorithm, to measure improvement of actual location precision. Figure 1. shows initial error ellipse.

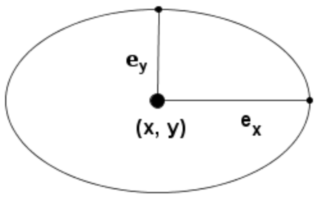

Figure 1. Initial location error elipse of observed node

3. Calculate elliptical crown around each visible node - for each visible node to the observed node, do the following:

3.a Read data of visible node: location (x, y), location error (e_x, e_y) and receive power level (R) – based on received values, determine the distance between observed node and visible node using the *free-space path loss* formula (mentioned in paragraph II).

3.b Calculate the *inner ellipse* based on calculated distance (from step 3.a) and location error of visible node. Two radiuses are determined. First radius is horizontal and is calculated by subtracting visible node's latitude location error value (e_x) from calculated distance value (r), as follows (2):

$$r_{x1} = r - e_x \tag{2}$$

Second radius is vertical, and calculated by subtracting visible node's longitude error value (e_y) from calculated distance value (r), as follows (3):

$$r_{y1} = r - e_y \tag{3}$$

These two radiuses are used to construct *inner ellipse* around the visible node.

3.c Calculate the *outer ellipse* based on calculated distance (from step 3.a) and location error of a visible node – following the same logic as in step 3.b. Two radiuses are determined: first radius is horizontal and is calculated by adding visible node's latitude location error value (e_x) to the calculated distance value (r), as follows (4):

$$r_{x2} = r + e_x \tag{4}$$

Second radius is vertical, and calculated by adding visible node's longitude error value (e_y) to the calculated distance value (r), as follows (5):

$$r_{y2} = r + e_y \tag{5}$$

These two radiuses are used to construct *outer ellipse* around the visible node.

3.d Determine elliptical crown based on an *inner ellipse* (from step 3.b) and *outer ellipse* (from step 3.d). Surfaces of those two ellipses can be recognized as two sets of points.

Set of points A and B are declared as: A is declared as surface of *outer ellipse* and B as surface of *inner ellipse*, standard difference (or exclusion) operation can be performed on those two sets. Excluding set B from set A will result in a set of point that represent surface of elliptical crown around the visible node. Figure 2. shows way of calculating elliptical crown of a visible node, using following labels:

- e_x – latitude location error of visible node
- e_y – longitude location error of visible node
- D_1 (x_1,y_1) – location of observed node D_1 (represented by blue colour)
- D_2 (x_2,y_2) – location of visible node D_2 (represented by green colour)
- *r* – calculated distance between two nodes

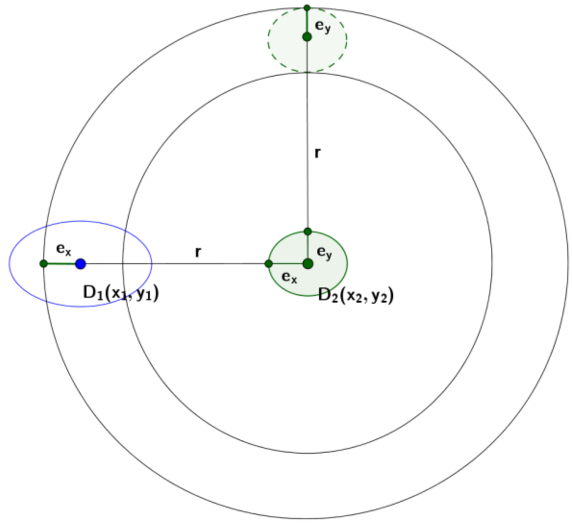

Figure 2. Eliptical crown of visible node

4. Calculate the correction surface. Correction surface is final, output value of algorithm. It is calculated through the operation of intersection between initial location error surface of observed node (from step 1) and surface of elliptical crown of each visible node (from step 3.). Formula can be presented as (6)

$$A' = A \cap C_1 \cap C_2 \cap \ldots \cap C_n, \tag{6}$$

where:

- *A'* – new set, representing location correction surface (result of algorithm)
- *A* – initial set, representing initial surface of possible observed node location
- C_1, C_2, ... C_n – set of elliptical crowns surfaces', calculated in step 3, from the data of all visible nodes, where n represents number of visible nodes.

Figure 3. shows scenario with three nodes, where drone D_1 is the observed drone, and D_2 and D_3 are its visible drones, i.e. its referent beacons which affect correction

of its location. Final minimized location surface of observed drone is blue shaded.

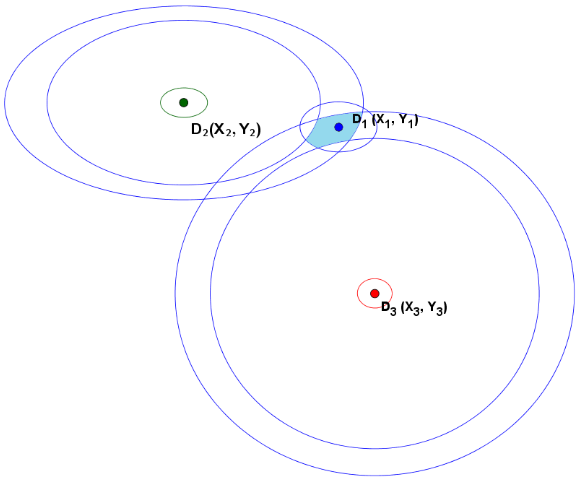

Figure 3. Blue shaded surface of observed node minimized location

4.3 Application

To test algorithm, a simple application is developed, using C# and Microsoft .NET technology. Application is used to simulate moving drones, generating location and location errors for each drone and then using, previously defined algorithm to calculate correction of drone location.

Application input parameters is data about each drone (name/ID, initial location, velocity and direction of moving). GPS location error simulation is implemented using invisible map in the background: window surface is divided by several unequal regions, and every region has different value of location error, thus making GPS error not uniformly distributed in the field. When drone enters specific region, it receives that region's location error. Receive power level (R) for each drone is simulated using the same *free-space path loss* formula, including the actual value of distance between two nodes.

For each drone transmit power is set to 17 dBm, in actual scenarios this value might vary but it is known. Application allows user to save results of simulation in .csv format. Each loop of algorithm is recorded and results are saved.

Results include: drone ID, drone name, current location (x,y), surface of GPS location error, surface of error correction, and percent of improvement.

5 Simulation

In simulations, metric used id percentage of improvement, it is a value that describes how much (in percent) new error correction surface is smaller than initial GPS correction error surface. It is calculated using (7)

$$p = \left(1 - \frac{S_{current}}{S_{initial}}\right) \times 100\,, \qquad (7)$$

where:

- p – percent of improvement, result in %,
- $S_{current}$ – current error correction surface
- $S_{initial}$ – initial GPS location error surface

To monitoring simulation results, the same properties will be used throughout all scenario definitions, which include:

- Total – total number of information records (algorithm calls)
- Minimum – the minimum value of correction improvement percent
- Maximum – the maximum value of correction improvement percent
- Zero percent – number of improvements with value of 0%
  - Twenty percent – number of improvements with value more than 20%
  - Fifty percent – number of improvements with value more than 50%
  - Average – average improvement percent, result of sum of all improvements divided by total number of records

For the rows “Zero percent”, “Twenty percent” and “Fifty percent”, another column will be added: “Percent in total” – this describes the percent of that value in number of total records.

5.1 Scenario definition

Three scenarios are defined.

In the first scenario, number of nodes is two, which is minimal possible for algorithm to work. In the second scenario, number of nodes is increased to four (the setup for first two nodes remains the same, and second two nodes are added). In third scenario, number of nodes is increased to eight, i.e. four new nodes are added.

Every simulation lasts 30 seconds.

5.2 Results

After simulations results are shown on Table 1 for the first scenario simulation with two nodes.

Table 1. Result analysis of first scenario

Property	Result	Percent (%)
Total	1848	-
Minimum	0%	-
Maximum	63,6475%	-
Zero percent	675	36,53%
Twenty percent	470	25,43%
Fifty percent	77	4,17%
Average	11,55%	-

Table 2. shows results analysis for the second scenario simulation with four nodes.

Table 2. Result analysis of second scenario

Property	Result	Percent (%)
Total	3860	-
Minimum	0%	-
Maximum	78,7964%	-
Zero percent	583	15,10%
Twenty percent	1500	38,86%
Fifty percent	501	12,98%
Average	18,87%	-

Table 3. shows results analysis for the third scenario simulation with eight nodes.

Table 3. Result analysis of third scenario

Property	Result	Percent (%)
Total	2552	-
Minimum	0%	-
Maximum	99,1818%	-
Zero percent	167	6,54%
Twenty percent	1500	61,91%
Fifty percent	501	26,68%
Average	32,34%	-

As expected, from the given tables can be read that maximum value of improvement is increasing with the number of nodes. Furthermore, values greater than twenty and fifty percent are also increasing with the number of nodes. Average improvement percent is also increased from 11,55% in the first scenario to 32,34% in the third scenario.

Results show that using algorithm single pass improves node location by at least 11,55% in the worst-case scenario (first scenario with two nodes). Such results have confirmed hypothesis given in problem definition.

6 Conclusion

This research pointed out a problem regarding precise localization of nodes that use GPS system. The location error given by the GPS system could be very high, therefore not offering enough precise information about the location of the node. This paper observed a possible way of minimizing GPS location error in swarms of UAV nodes. According to the aim of the research, an algorithm is developed that uses trilateration theory and RF propagation model. After implementation of the algorithm, a simulation of drones moving in 2-dimensional space with same parameters but different number of nodes is run. Results of simulation have shown that algorithm gives better results when there are more drones in a swarm. Finally, it can be concluded that hypothesis given in problem definition has been confirmed, because the average improvement of node location surface in minimum swarm setup is 11,55%.

According to the simulation results, it can be concluded that algorithm satisfies given parameters and goals. However, there are areas that should be improved and researched further:

- Multiple algorithm passes, where the input would be output surfaces from this algorithm. This may or may not generate even more precise crowns and intersections and therefore more precise location of given nodes.
- 3rd dimension should be used; current research and implementation only uses 2D Cartesian coordinate system. Also, geographic coordinate system should be used instead of cartesian coordinate system.
- Ellipse was used as location estimation representation; however, actual location is not that uniformly distributed. Concept like fuzzy logic, fuzzy ellipse should be used with non-uniform location probability distribution.
- Particle filtering theory could be used, giving the algorithm different aspect of processing data from a probabilistic not geometry approach.
- Crowdsource using another source of data like sound, light, fingerprinting, landmarks, etc.
- The same principle can be applied to any group that require precise localization, for example: people or vehicle.

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