Journal of Computers Vol. 29 No. 6, 2018, pp. 140-147
doi:10.3966/199115992018122906013

Efficient Least Squares Regression Algorithm for Autonomous Maneuvering UAV System

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Received 9 January 2018; Revised 11 January 2018; Accepted 22 January 2018

Abstract. In this paper, we propose an algorithm for minimizing the amount of iterative computation in a system in which a communication relay UAV autonomously maneuvers to an optimal relay location. Existing autonomous maneuvering systems use the classical time difference of arrival (TDOA) or time of arrival (TOA) localization technique. Fundamentally, these techniques have a problem of excessive regression calculations. We utilize the geometric features of the pseudorange information of the TOA and the minimax center to solve the problem of TOA computational complexity. Numerous simulations were performed with MATLAB for performance verification, and simulation results showed that the least squares regression of TOA could be reduced by half, while maintaining similar performance accuracy.

Keywords: iterative algorithms, minimax technique, time of arrival estimation (TOA), unmanned aerial vehicles (UAVs)

1 Introduction

Unmanned Aerial Vehicles (UAV), developed for military purposes, are experiencing a significant increase in demand worldwide owing to the rapid rise in technology levels and commercialization. The world market for UAVs continues to double in decade-long cycles, and their application is not limited to defense, but is increasingly expanding into a wide range of fields such as traffic control, communications, sports, and other fields [1].

The utilization of UAVs for positioning will be highly beneficial. In recent years, there have been increasing studies concerning position estimation using UAVs. The use of global navigation satellite systems (GNSS), used in current positioning techniques, is limited owing to the difficulty of constructing and maintaining high-cost systems, vulnerability by jamming, and military or political interference from countries owning the specific GNSS. UAVs, on the other hand, can be utilized as effective pseudo-satellites because of their simple system structure and relatively low construction and maintenance costs [2]. In particular, in the battlefield environment, UAVs, capable of rapid deployment and withdrawal, will play a key role in positioning.

A key characteristic of a UAV is that it is possible to estimate position using only one UAV, based on its rapid displacement. Positioning using these characteristics is mentioned in several articles. Kim proposed a passive localization method that measures the position of terrestrial terminals, by sequentially receiving a position signal from a moving UAV [3]. In this method, terrestrial terminals receive at least four position messages in chronological order. Each sequential message and arrival time is modeled by a time difference of arrival (TDOA) technique, and its position is estimated by a nonlinear least squares estimation. Simulations were performed by dividing the trajectory of the UAV into two types, circle and spiral, and each position (3D) dilution of precision (PDOP) was measured.

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Saputra proposed an Archimedean spiral trajectory for UAVs to cover a wider battlefield area [4]. Archimedean spiral path planning provided a lower localization error than conventional circular or spiral path planning, but an unrealistic simulation assumption was made with the UAV turning at a speed of 400 *km/h* with a radius of 150 *m*.

Jee proposed a scheme for autonomous maneuvering of UAVs as communication relays on battlefields [5]. The UAV uses itself as a reference point to calculate the position of each terrestrial terminal, and to find the minimax center of the terminals distribution.

All the above studies estimated the location of all terminals by using the TDOA of signals received by terrestrial terminals or the UAV. However, no mention was made of the number of regression analysis iterations of the nonlinear least squares method used.

The computational complexity of regression analysis has a direct effect on the energy consumption of the UAV, as energy consumption increases with increasing computation. Excessive energy consumption will reduce the operating time of the UAV. This is a critical issue as it is directly related to the available duration of command and control on battlefields. In this paper, we propose an algorithm to minimize the number of regression iterations of the least squares method. The characteristics of time of arrival (TOA) and minimax center are utilized to reduce computational complexity.

The remainder of this paper is organized as follows. In Section II, we present an overview of the autonomous maneuvering scheme Jee proposed in a previous paper [5], and the details of the algorithm proposed in this paper. Section III presents the simulation scenario and assumptions, and conclusions are presented in Section IV.

2 Proposed Scheme

2.1 Scenario and Scheme Overview

As shown in Fig. 1, the overall structure of the system used in this paper comprises a ground control station (GCS), UAVs, and terrestrial terminals [5]. In some studies, UAV networks are regarded as models similar to mobile ad hoc networks (MANET) or vehicular ad hoc networks (VANET) because of their frequent connecting and disconnecting. However, due to the inherent nature of UAV networks, classifying them as similar network models is not appropriate [6].

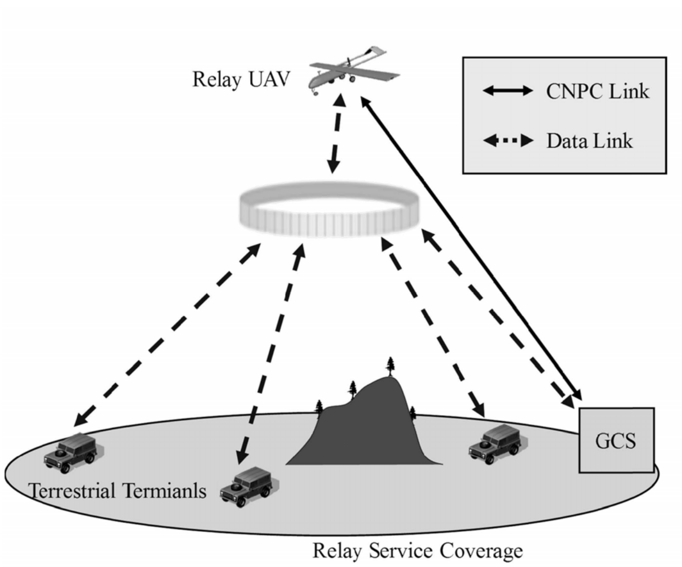


Fig. 1. Basic networking architecture of proposed algorithm

One of the salient features of a communication-relay UAV network is that a star network topology is formed, with the UAV as the central node. The UAV is directly connected to the GCS, and the connected link is divided into a control and non-payload communication (CNPC) link and a data link [7]. The CNPC link is an essential control channel between the GCS and the UAV, and supports the takeoff, landing, flight control, and route control of UAV. The data link is a communication link on which practical mission command and control is carried out, and various reports or instructions are periodically, or non-periodically, transmitted on the link. The CNPC link is considered unnecessary for autonomous maneuvering, except for initial flight. Command and control between terrestrial terminals and the UAV is communicated with time division multiple access (TDMA) over the data link. An efficient least squares regression algorithm will be proposed for the scenario described above.

In a previous paper, Jee proposed a scheme of simulating a terrestrial terminal by using the characteristic that one UAV moves rapidly with time [5]. As shown in Fig. 2, a UAV moves at a relatively low altitude and high speed compared to a satellite, therefore, one UAV has the same effect as several satellites transmitting signals. Each of the pseudoranges can be measured by determining the UAV positions at different times as reference points, and multiplying the propagation times of the received signals by the speed of light ($3\times10^8 m/s$). The position of the target in the TOA localization using pseudoranges, is determined by the intersection of the spheres produced by the pseudoranges from the reference points.

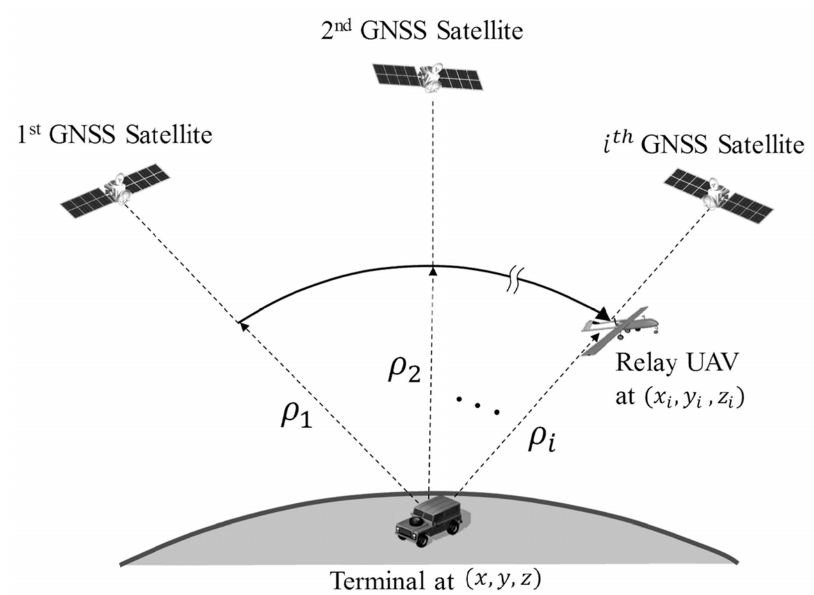


Fig. 2. Operating TOA for autonomous maneuvering UAV system

$$(x-x_i)^2+(y-y_i)^2+(z-z_i)^2=\rho_i (i=1,2,\cdots,n) \quad \textbf{(1)}$$

where (x, y, z) is the position of the terrestrial terminal on the spherical coordinate system, n is the sequential order in which the UAV maneuvers and receives the signal, (x_i, y_i, z_i) is the coordinate when the UAV that knows the position moves and receives the i-th signal, and ρ_i is the pseudorange measured at the UAV [8].

The measured pseudoranges have errors due to environmental and internal noise, and the intersection of all the spheres is not determined as a single point. Therefore, it is necessary to find a point that minimizes the error to estimate the closest target position. The solution is obtained using the well-known nonlinear least-squares method. It is also possible to track a moving target by properly controlling the window of the moving average.

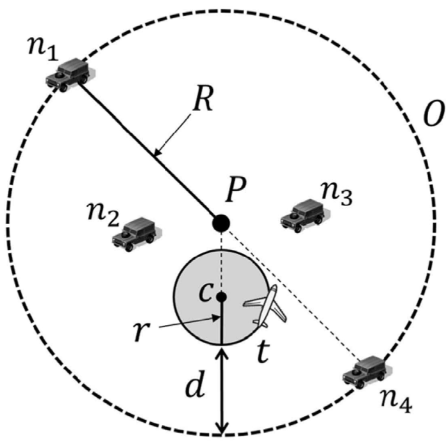
These estimated terminal distributions provide optimal coordinates for autonomous maneuvering of communication relay UAVs. The minimax center theory is used to support communication over the shortest distance, so as to minimize the output power of the UAV. By activating the UAV with the corresponding coordinates, the communication relay function can be supported with the maximum coverage and minimum power The paper size is A4. The printing margins are: 2cm for up and down margins and 2.5cm for left and right margins. The text should be justified to occupy the full line width, so that the right margin is not ragged, with words hyphenated as appropriate.

2.2 Proposed Algorithm

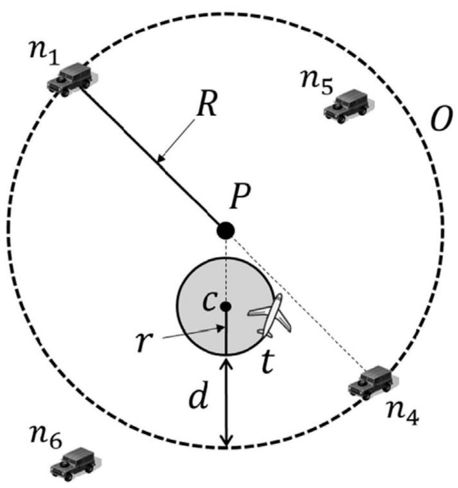
A general UAV-aided network can determine the optimal point by simplifying it to a two-dimensional (2D) coordinate space, assuming that the UAV is flying at the lowest altitude that guarantees line-of-sight with the terrestrial terminals.

In most cases at least two ground nodes are used to find the center of a 2D-space minimax location [9]. The method of minimizing the TOA regression is derived from the fact that it is not necessary to know the location of all the terrestrial terminals to find the minimax center. The basic concept of the proposed algorithm, Algorithm 1, is to determine whether regression calculations are necessary, based only on pseudoranges collected by the TOA. Therefore, if calculations are not required, the number of regression iterations will be reduced.

Fig. 3 shows the UAV and the terrestrial terminals projected onto the xy-plane, to explain the working of the proposed algorithm. The UAV, which takes off and estimates the positions of the terminals with the autonomous maneuvering scheme, turns around the initial minimax center, *c***.** Terminals on the ground move respectively to the UAV. In Fig. 3(a), n_1, n_2, n_3, and n_4 represent the shifted terrestrial terminals, and the outermost terminals forming the minimax center, n_1 and n_4, are defined as "*defining points*". The circle through the defining points is labeled *O,* and *P* is the minimax center of the terminals. The turning circle of the UAV is *t*, with *c* the center. In this case, d is defined as



(a) Case 1: n_2 and n_3 excluded from calculation (non-promising)



(b) Case 2: n_5 and : n_6 calculated (promising)

Fig. 3. Proposed algorithm

$$d = R - (\| P - c \| + r) \quad \textbf{(2)}$$

where *R* is the radius of *O*, $\| P - c \|$ is the Euclidean norm vector of *P* and *c*, and *r* is the turn radius of the UAV, that is, the radius of *t*.

As shown in Fig. 3(a), the UAV turns around *c*, receives the signals from the shifted nodes, and measures new pseudoranges. In this case, if the set $\mathbf{P}_i = \{\rho_1, \rho_{2,i}, \cdots, \rho_{m,i}\}$ of the *m* pseudoranges, collected from n_i, has at least one pseudorange less than *d*, node n_i can not be a minimax defining point, as it exists inside *O*. Therefore, it is not necessary to perform a nonlinear least squares regression calculation for position estimation, as it is classified as a non-promising defining point.

In Fig. 3(b) with nodes n_5 or n_6, all pseudorange components are larger than *d*. In this case, it is classified as a promising defining point, and the calculation is performed, and it can be determined immediately if it is a defining node.

Algorithm 1. *Minimization calculations algorithm for autonomous maneuvering UAV system*

```
Initialization
 Initial path of UAV, N ←the number of terminals, d ←0

for Terminal K acquires all pseudoranges do (0<K≤N : integer)
     Calculation pseudorange of received signal
end for

// case 1: Terminal K is promising defining point
if ∀ρ of terminal K >d
     Perform non-linear regression analysis for terminal K
     K ←promising terminal
// case 2: Terminal K is non-promising defining point
else
    K ←Non-promising terminal
end if

Find minimax center with promising point
Autonomous maneuvering to minimax center
Calculate d using Equation (2)
Go back to line #3
```

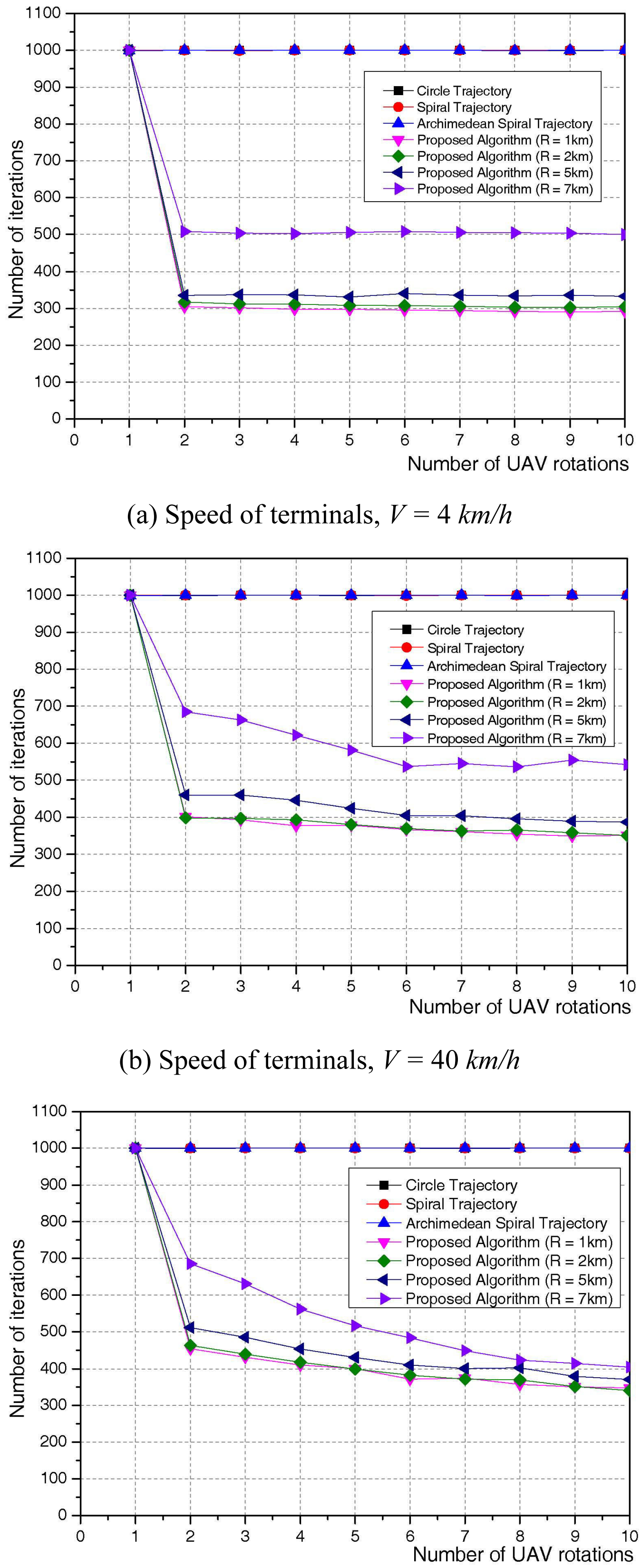
3 Simulation Results

To verify the feasibility, and to analyze the performance of the proposed algorithm, simulations were performed using a modified MATLAB GPS simulator. The parameters used in the simulation are presented in Table 1. Each simulation result was calculated as an average of over 10,000 values.

Table 1. Simulation parameters

Parameters	Value	Unit
Size of operational area	10×10	*km*
Speed of UAV	140	*km/h*
Altitude of UAV	1	*km*
Turning radii of UAV (*R*)	1, 2, 5, 7	*km*
Signal period	10	*s*
Max iteration of least squares	100	-
Number of terminals	5, 10, 15, 20	-
Speed of terminals (*V*)	4, 40, 100	*km/h*

Fig. 4 shows the results comparisons between the number of least squares regression iterations used to estimate the location of 10 terrestrial terminals at random positions. The x-axis is the number of UAV rotations at a radius $R = 1\,km$, and the y-axis the number of iterations. The terrestrial terminals moved in random directions at different speeds.



(a) Speed of terminals, $V = 4\ km/h$

(b) Speed of terminals, $V = 40\ km/h$

(c) Speed of terminals, $V = 100\ km/h$

Fig. 4. Least squares regression iterations to estimate location of 10 terrestrial terminals at random positions

As expected, if we use the proposed algorithm, we can confirm that the number of computation iterations performed to find the minimax center is significantly reduced as the UAV turns. In Fig. 4(a), when the speed of the terrestrial terminal is 4 *km/h*, which is slow compared to the speed of the UAV, the number of iterations is less than in the second turning flight. However, as shown in Fig. 4(b) and Fig. 4(c), when the terminal distribution changes frequently because of the high relative speed of the terminals, the number of iterations converged slowly, and was higher than the convergence iteration number in Fig. 4(a). A further important variable influencing the results is the turning radius *R*. It can be seen from Equation (2) that, the greater the UAV turning radius, the smaller the value of *d,* and, the smaller the value of *d*, the more difficult it is to satisfy the non-promising point condition, and more iterations are required for convergence. Therefore, in order to minimize the number of iterations, we can conclude that the UAV turning radius needs to be as small as possible.

We then compared how the proposed algorithm performs against existing techniques. The y-axis in Fig. 5 represents the three-dimensional root mean square deviation error (RMSE) between the xyz-coordinates of the minimax center calculated by each algorithm, and the actual minimax center coordinates. The x-axis is the number of terminals. Overall, the RMSE tends to increase with the number of terminals. Simulation results show that the accuracy of the proposed algorithm is similar to that of the circular path, as only the circular path-based minimax defining point was used. The Archimedean spiral path has the lowest error value, but is not mentioned as unrealistic simulation assumption was made, as described in Section 1.

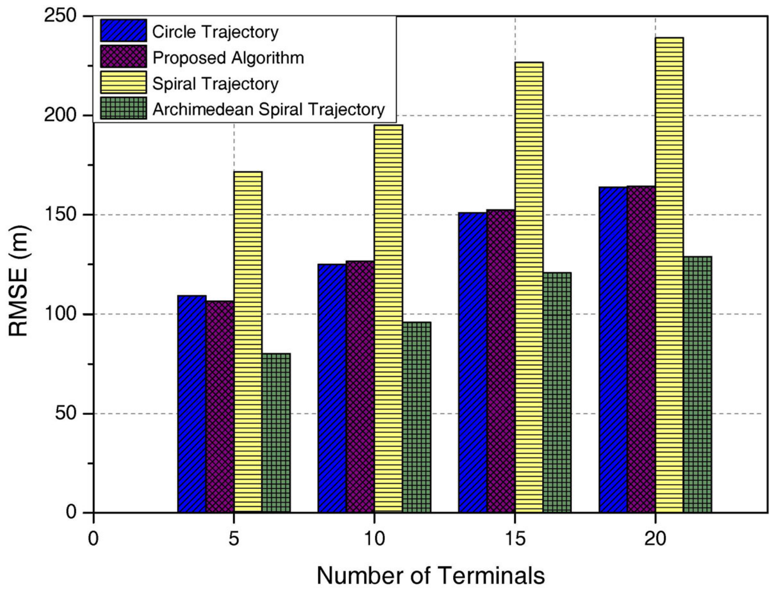


Fig. 5. Performance comparison between proposed algorithm and existing trajectory scheme

Table 2. RMSE between the minimax center calculated by each algorithm and the actual minimax center

Number of terminals	Circle trajectory	Proposed algorithm	Spiral trajectory	Archimedean spiral trajectory
5 nodes	109.1594 m	106.4382 m	171.6995 m	80.3286 m
10 nodes	125.0316 m	126.5753 m	195.2077 m	96.0882 m
15 nodes	151.0669 m	152.5573 m	226.6841 m	120.8331 m
20 nodes	163.9016 m	164.2635 m	239.0472 m	128.9588 m

4 Conclusions

In this paper, we proposed an algorithm to reduce the number of least squares regression iterations in the autonomous maneuvering UAV system presented in a previous paper. To reduce the number of iterations, the characteristics of the defining point of the minimax location theory and the TOA pseudorange information were used. Computation using terrestrial terminals not required for the minimax center was minimized. In order to verify the performance of the system, a MATLAB simulator was used, and the simulation results showed that the amount of iterations performed was significantly reduced. This reduction in computation will reduce the complexity of a UAV's onboard computer, and will minimize power consumption, that will contribute to the operating time and mission performance of a relay UAV.

However, the average RMSE of the proposed algorithm is over 100 m, which is relatively higher than other GNSS systems, as only one UAV operates as a reference point for positioning. In order to solve this problem, a study to overcome the geometrical limit by using several UAVs, will be conducted in the future.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2016R1A2A1A05005541).

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