

A UWB Positioning Network Enabling Unmanned Aircraft Systems Auto Land

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Abstract—Although Unmanned Aircraft Systems (UAS) have become popular, the auto land of a fixed wing UAS has still remained as a significant challenge. This paper presents a UAS auto landing system based on a Ultra Wide Band (UWB) positioning network. The geometry of the UWB anchors in the network is optimized to provide precise positioning accuracy during the course of UAS landing. The notable performance characteristics of the system is that the positioning of the UAS becomes more accurate as it approaches to the runway more closely. At the point of a landing flare, the landing system is expected to provide vertical positioning accuracy better than 20 cm in 95 percent of time. The paper discusses the methodology of designing the proposed UWB positioning network architecture and the positioning performance analysis through simulations.

Index Terms—Unmanned Aerial Vehicles, Ultra Wide Band technology, Aircraft Navigation, Global Positioning System

I. INTRODUCTION

THE Unmanned Aircraft Systems (UAS) have become widely popular and their applications are not only limited to military operations but also include various civil applications such as crop monitoring, aerial mapping, and aerial photos [1]–[3]. It is also expected that the UAS will be an important part of future air transportation systems [4]. However, one of the biggest challenges to the widespread of the UAS in the National Airspace System (NAS) is safety. Particularly, the autonomous landing of a fixed wing UAS is still problematic and its safety must be ensured before the introduction of the UAS into the NAS.

For manned aircraft, the Instrument Landing System (ILS) has been used as a primary landing system in the world [5]. More recently, the Ground Based Augmentation System (GBAS) of Global Positioning System (GPS) is being introduced and expected to replace ILS [6], [7]. These two systems have not been seriously considered as the auto landing system for a small fixed wing UAS. The primary reasons could be significant costs associated with the ground equipment and avionics. In addition, their positioning accuracy, particularly in vertical, does not seem to be sufficient. A reported vertical positioning accuracy of the state-of-the-art GBAS system is around 1 meter in 95 percents of time [8]. For a relatively larger aircraft such as commercial manned jets, the GBAS positioning accuracy should be satisfactory. However, the smaller fixed wing UAS whose height is less than 1 meter or so, a reliable auto landing would not be ensured even when the GBAS properly operates.

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Therefore, previous approaches for a fixed wing UAS auto landing typically use alternative systems for a better vertical guidance. Reference [9] used a differential GPS with barometric altimeters. Reference [10] integrated a differential GPS with precision tracking radar to augment vertical guidance. Reference [11] uses a gimbaled camera and an inertial measurement units (IMU) with image processing algorithms. Reference [12] also uses a camera integrated with IMU for the UAS to find a ship, generate landing paths, and finish the final landing procedure.

This paper introduces a novel fixed wing UAS landing system that uses a passive Ultra Wide Band (UWB) positioning network. The conceptual operation of the UWB positioning during a landing is depicted in Fig. 1. In this proposed landing system, the passive UWB positioning network listens to the UWB signals emitted from the UAS. In this way, the UWB positioning network minimizes required UWB communications and does not interrupt Radio Frequency (RF) environment in an airport. The position of the UAS is computed on the ground by using the received UWB signals at the anchors and is sent back to the UAS through a protected aviation communication channel. Compared to the prior arts, the onboard hardware requirements and computational complexity are expected to be minimal because the UAS position is computed on the ground. In addition, the vertical positioning accuracy would be superior to the prior arts by taking advantage of centimeter-level of the UWB ranging capability and the optimized anchor network geometry for a landing.

This paper first overviews the principles of UWB positioning and positioning uncertainty in Section II. Section III discusses modeled landing path configurations and the associated vertical positioning accuracy during the course of landing. Section IV introduces the methods used to search for the optimal geometry of the UWB positioning network. Section V presents the resultant optimal UWB network that enables a UAS auto land and its performance analysis before we conclude in Section VI.

II. OVERVIEW OF UWB POSITIONING NETWORK

A. Overview of Ultra Wide Band

The Ultra Wide Band (UWB) for ranging operates in the frequency bands from 3.1 to 10.6 GHz. This wide band frequency allows extremely sharp pulse widths from a few hundred pico seconds to nano seconds [13], [14]. Using the sharp UWB pulses, it is possible to obtain precise ranging measurements within centimeter-level of accuracy. Because of the precise ranging accuracy and the wall penetration

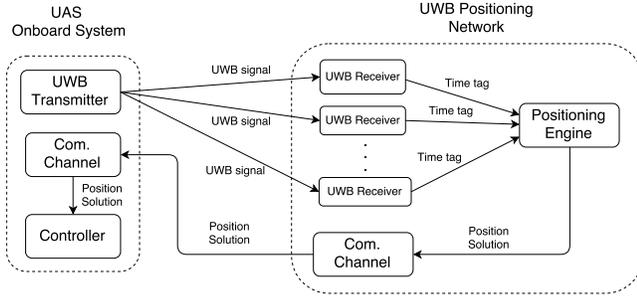


Fig. 1. Interaction between the UAS onboard system and the UWB positioning network

capability of the UWB, the UWB is increasingly popular for navigation and tracking in indoor and outdoor.

A UWB positioning system consists of a user tag and several anchors fixed at known coordinates. In a passive or tracking mode, the anchors are time-synchronized and one of the anchors or a master station gathers the time stamps of the received signals from other anchors. The master station formulates time difference of arrival (TDOA) measurements to compute the user position and sends back the computed position to the user. Note the time duration from the computation of the position solution to the delivery of the solution to the user must be minimal for a high dynamic user. In this passive mode, the time synchronization accuracy among the anchors is critical in the tracking mode. In a wired network using an optical fiber and a dedicated FPGA, the time synchronization can be maintained under 100 picoseconds [15], [16], whose impact to a positioning accuracy is insignificant in most applications. A time synchronization in a wireless network is much more challenging, where the achievable precision of the time synchronization used to be about $10\mu s$ [17]. However, recent research has reported a few nano seconds time synchronization performance by taking advantage of recent hardware advancements [18].

In an active positioning mode, on the other hand, the distance between a tag and an anchor is measured through a two-way communication. The coordinates of the anchors are usually embedded in communication messages. When the user receives range measurements from more than 2 or 3 anchors, it computes its positing through Time of Arrival (TOA) formulation. Note that the time synchronization error is eliminated in this approach, but the two-way communications require the hardwares of the tag and anchors to be more sophisticated than the tracking mode.

The UWB positioning approach employed in this paper is the passive tracking mode. The main motivation in using the passive mode is to reduce UWB communications between a tag (aircraft) and anchors such that any interference effects on other aviation navigation instruments can be minimized in an airport environment. However, the active positioning can also be used if the environmental limitation is not a concern.

B. TDOA Positioning Uncertainty Analysis

This section briefly discusses the TDOA positioning uncertainty analysis in the passive navigation mode.

Let us assume that there are m anchors in a UWB positioning network and the time synchronization between anchors are maintained under sub-nano (wired) or a few nano (wireless) seconds as discussed before. The coordinate of the i^{th} anchor is denoted as $\mathbf{a}_i = (a_{i,x}, a_{i,y}, a_{i,z})$. Taking \mathbf{a}_1 as the reference node, a user location, \mathbf{x}_u , can be computed from

$$\delta \hat{\mathbf{x}}_u = (\mathbf{H}^T \mathbf{W} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{W} \quad (1)$$

where \mathbf{W} is a weighting matrix and \mathbf{H} matrix is [19]

$$\mathbf{H} = \begin{bmatrix} \frac{\mathbf{x}_u - \mathbf{a}_2}{\|\mathbf{x}_u - \mathbf{a}_2\|} - \frac{\mathbf{x}_u - \mathbf{a}_1}{\|\mathbf{x}_u - \mathbf{a}_1\|} \\ \frac{\mathbf{x}_u - \mathbf{a}_3}{\|\mathbf{x}_u - \mathbf{a}_3\|} - \frac{\mathbf{x}_u - \mathbf{a}_1}{\|\mathbf{x}_u - \mathbf{a}_1\|} \\ \vdots \\ \frac{\mathbf{x}_u - \mathbf{a}_m}{\|\mathbf{x}_u - \mathbf{a}_m\|} - \frac{\mathbf{x}_u - \mathbf{a}_1}{\|\mathbf{x}_u - \mathbf{a}_1\|} \end{bmatrix}. \quad (2)$$

It is assumed that the range measurement error at i^{th} receiver follows a Gaussian distribution with zero mean and the standard deviation of σ_{ϵ_i} . Then, the position error standard deviation as σ_p has the following forms

$$\sigma_p = \sqrt{\text{trace}(\mathbf{H}^T \mathbf{W} \mathbf{H})^{-1}} \quad (3)$$

where the weighting matrix \mathbf{W} is

$$\mathbf{W} = \begin{bmatrix} \sigma_{\epsilon_1}^2 + \sigma_{\epsilon_2}^2 & \sigma_{\epsilon_1}^2 & \cdots & \sigma_{\epsilon_1}^2 \\ \sigma_{\epsilon_1}^2 & \sigma_{\epsilon_1}^2 + \sigma_{\epsilon_3}^2 & \cdots & \sigma_{\epsilon_1}^2 \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{\epsilon_1}^2 & \sigma_{\epsilon_1}^2 & \cdots & \sigma_{\epsilon_1}^2 + \sigma_{\epsilon_m}^2 \end{bmatrix}^{-1} \quad (4)$$

The positioning accuracy of a user in the UWB positioning network will be evaluated by using Eq. (3).

III. PARAMETERS FOR THE DESIGN OF A UAS AUTO LAND SYSTEM

A. Runway Configuration and Landing Path

Fig. 2 depicts the runway configuration taken in this paper. From the origin of the local cartesian coordinate on the runway, the aircraft glideslope begins at the range of R and at the height of $h1$. At the height of $h2$ above the origin, the nose of aircraft is raised and the landing flare begins. Then the touchdown and roll-out phases are followed. L is the length from the front end of the runway to the origin. T is the total length of the runway and W is the width. We use $L = 50$ m, $T = 2000$ m, and $W = 30$ m that are typical configurations of small municipal airports.

The range of today's UWB device can extend to around 350 m without any blockages. For this reason, R is set to 300 m. The height of the flare point, $h2$, is set to 50 cm in this paper because most UAS are expected to successfully finish a landing from this height by just gliding. It is possible that many UAS may need to take different glideslopes during a landing, depending on their form factor and maneuverability.

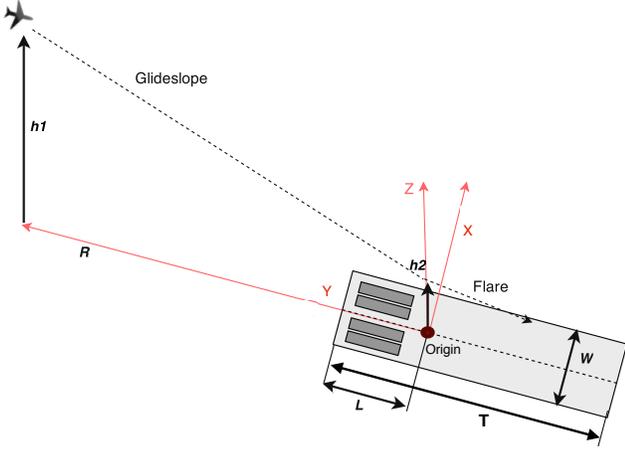


Fig. 2. A modeled runway configuration and landing path.

Considering the landing capability of various UAS and UWB Radio Frequency (RF) coverage, the range of glideslopes is set to between 5 degrees and 15 degrees, which will yield in $h1$ up to 69.5 m. Note that the runway geometry and the glideslopes may change depending on an airport environment and the coverage of UWB devices.

B. Required Positioning Accuracy

Assuming that no large objects are present along the course of a landing path, the usual threat during a landing is the collision to the ground. Thus, the vertical positioning accuracy of an aircraft landing system is particularly important. Therefore, the key parameter in determining the required positioning accuracy is the ratio between an aircraft altitude Above Ground Level (AGL) and a vertical positioning accuracy (VPA, 1σ), which is defined as Vertical Protection Ratio (VPR). Then, the VPR can be formulated as follows,

$$\begin{aligned} VPR(y, GS) &= \frac{AGL}{VPA} \\ &= \frac{h2 + y/\cos(GS)}{VPA} \end{aligned} \quad (5)$$

where y is the distance in the Y axis and GS is a glideslope angle. Note that the VPR must be large enough in all y values that the probability of hitting the ground before the flare point is kept very small. In this paper, we set the VPR as 5.2 such that the probability of having a position error beyond 5.2σ away from the true position is less than 10^{-7} , assuming that the vertical positioning error can be modeled as a zero mean Gaussian distribution. In other words, the probability that the aircraft hits the ground before the flare point is less than 10^{-7} .

Fig. (3) shows the proposed VPA requirement (1σ) with respect to the aircraft AGL during the descent. Note that, the required VPA is as high as 9.6 cm at the height of $h2$ and is truncated to 2 m when the AGL is larger than 10.3 meters to avoid large vertical positioning errors.

Note that the horizontal positioning accuracies in the x and y axes are also important. But, it was found that the horizontal

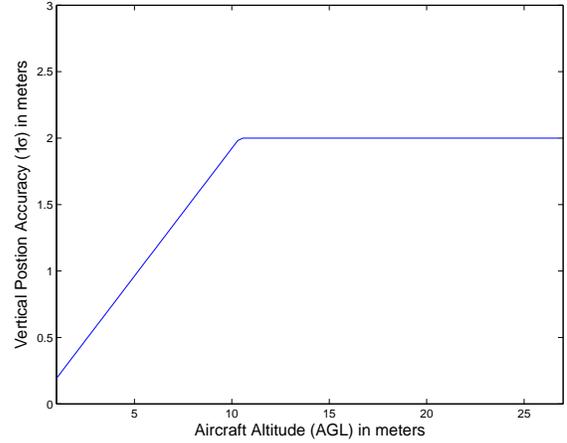


Fig. 3. Required vertical positioning accuracy during the modeled UAS Landing.

accuracy is usually sufficient when the a UWB positioning network meets the VPR. Therefore, the horizontal positioning accuracy does not play an important role in designing a positioning network.

In this paper, we assume that the UWB range error characteristics has a standard deviation of 5 cm with a Gaussian distribution [13], [20]. The range error includes the error source of time synchronization, thermal noise, multipath, and surveyed anchor coordinates.

IV. UWB POSITIONING NETWORK ARCHITECTURES

For the development of the UWB positioning network, the locations of the anchor nodes must be determined. The factors in determining the anchor nodes are the required UAS positioning accuracy along landing paths, RF range of UWB devices, terrain conditions, and runway configurations. This section first overviews the ranging source optimization algorithm and shows our approaches to design the UWB anchor node geometry.

A. Overview of Optimal Ranging Source Location Algorithm

The algorithms presented in this paper search for the set of anchor node geometries meeting the required positioning accuracy with the minimum number of anchors. The baseline search engine for the network is Binary Integer Linear Programming (BILP) [21]. To avoid an exhaustive search, the BILP also uses various heuristics such as distances between anchors, the number of difference of the anchors on the ground and in the air, and the symmetry of anchor locations with respect to the runway.

The BILP can be formulated as below and searches for an optimal UWB anchor placement through iterations.

$$\begin{aligned}
 \text{minimize } Z &= \sum_{i=1}^N w_i p_i = \mathbf{w}^\top \mathbf{p} \\
 \text{subject to: } \mathbf{V}\mathbf{p} &\geq \mathbf{v} \\
 \mathbf{D}\mathbf{p} &\leq \mathbf{d} \\
 \mathbf{A}\mathbf{p} &\leq \mathbf{a} \\
 \mathbf{S}\mathbf{p} &\leq \mathbf{s} \\
 (\mathbf{t} - \mathbf{b})^\top \mathbf{p} &\leq k \\
 \mathbf{w}^\top \mathbf{p} &\leq Z_{min} \\
 \mathbf{1}^\top \mathbf{p} &\leq N_{min} \\
 p_i &\in \{0, 1\}
 \end{aligned} \tag{6}$$

where Z is the cost function to be minimized and \mathbf{p} is the grid index column vector of the candidate anchor locations. \mathbf{p} takes the binary value of either 0 or 1. When $p_i = 1$, it contains an anchor at the i^{th} anchor location. Otherwise, $p_i = 0$. The vector \mathbf{w} is a weighting factor on \mathbf{p} that assigns preference of an anchor location to another.

The matrix \mathbf{V} in Eq. (6) is a visibility matrix. The i^{th} row of \mathbf{V} corresponds to a grid index of a user location and the j^{th} column to an anchor location. The elements of the matrix \mathbf{V} also take on the value of either 0 or 1. If a user at the i^{th} row location has a line of sight to the anchor at the j^{th} column location, V_{ij} is equal to 1. Otherwise, V_{ij} is equal to 0. The vector \mathbf{v} is the required minimum number of visible anchors at the corresponding user location and is set to 5 in this paper.

The matrix \mathbf{D} and the vector \mathbf{d} set the limit on the separation between anchors. If the distance between i and j anchors is less than the minimum separation, D_{ij} is equal to 1. Otherwise, D_{ij} is equal to 0. The vector \mathbf{d} is a vector of 1s that does not allow any anchors within the minimum separation distance. The minimum separation distance ranges from 5 meters to 10 meters in this paper.

The matrix \mathbf{A} contains the previous solution sets denoted as \mathbf{p}_s at each row, and the vector $\mathbf{a} = (\mathbf{p}_s^\top \mathbf{1} - u)\mathbf{1}$ forces the BILP formulation to yield a unique solution during the iterative search. u is a non zero positive integer number and is set to 2 in this paper.

The matrix \mathbf{S} is a symmetric matrix. S_{ii} is equal to 1 and S_{ij} is set to -1 if i^{th} and j^{th} anchors are symmetrically located with respect to the runway coordinates. The vector \mathbf{s} is zero vectors. This constraint enforces a symmetric positioning accuracy in the user positioning spaces.

The vectors \mathbf{t} and \mathbf{b} indicate whether an anchor is located on or above the ground. If t_i is equal to 1, the i^{th} anchor is located above the ground. Otherwise, t_i is equal to zero. Likewise, if b_i is equal to 1, the i^{th} anchor is located on the ground. Otherwise, b_i is equal to zero. k is the difference between the number of anchors located on the air and on the ground and is set to 0 in this paper.

Z_{min} is the minimum cost among the valid solution sets found through previous iterations. Similarly, N_{min} is the minimum number of anchors among the valid solution sets found through previous iterations. Note that Eq. (6) does not have the accuracy requirement as a constraint. Instead, the

resultant user accuracy is evaluated when a valid solution from Eq. (6) is obtained. Therefore, Z_{min} and N_{min} can be initially set to a large number. Whenever, a valid anchor network geometry is found, Z_{min} and N_{min} are updated to the lowest values found during the iteration. When Eq. (6) indicates no solutions in tens of iterations, a (local) optimal solution is considered to be found and the execution of Eq. (6) is terminated. Eq. (6) is solved by using an open source GNU Linear Programming Kit [22].

B. Candidate Anchor Locations and Positioning Service Area

Fig. 4 shows the array of candidate anchor locations around the runway. There are two anchor locations separated by 7.5 meters in the lateral directions at each side of the runway. In the longitudinal direction, there are 20 anchors separated by 3 meter. In the vertical direction, the anchors are either located on the ground or at 10 meters height antennas. Therefore, there are a total of 240 possible anchor locations.

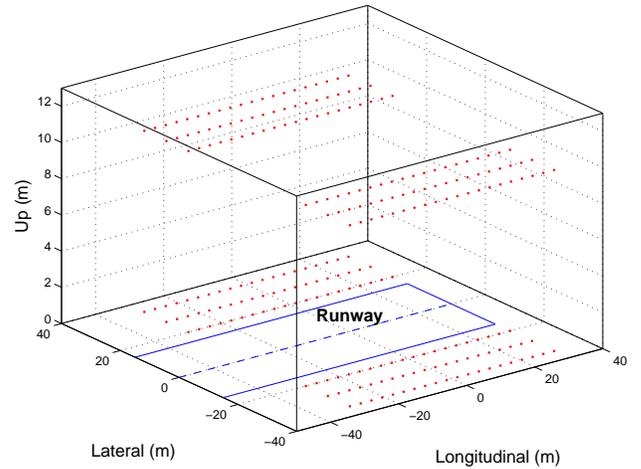


Fig. 4. Candidate anchor locations to support UAS landing.

Fig. 5 shows the UAS positioning service area during the landing operation. The lateral span of the positioning service area is 30 meters that is the width of the runway. The longitudinal range is up to 300 meters from the origin of the local runway coordinates. The maximum and the minimum slopes of the user positioning service area correspond to the supported glideslopes of 5 and 15 degrees. Note that the RF coverage of the UWB positioning network is much larger and positioning would be possible in the RF coverage where a UAS may have line of sights to multiple anchors. However, only the user positioning area guarantees the required VPR.

V. RESULTANT OPTIMIZED UWB POSITIONING NETWORK

This section presents the resultant anchor locations based on the candidate anchor locations and user positioning area. The positioning performance of the anchor network is also analyzed.

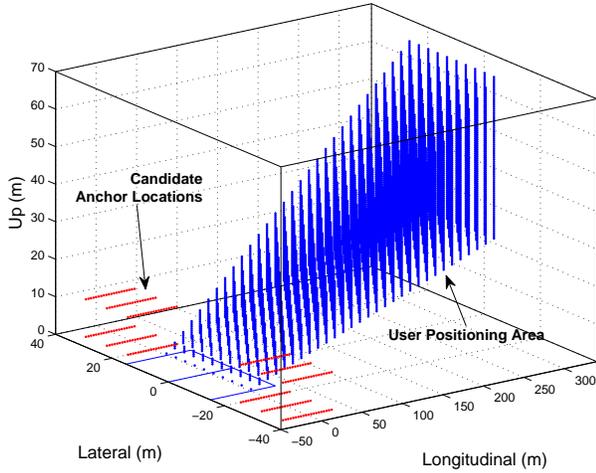


Fig. 5. Positioning service area to support UAS Landing.

A. Resultant baseline anchor locations

Fig. 6 shows the resultant optimal anchor geometry from iteratively solving Eq. (6). Six of the anchors are located in 10 meter height antennas and the rest of them are placed on the ground. As shown in Fig. 6, the anchor geometry is symmetric with respect to the runway. In the anchor location

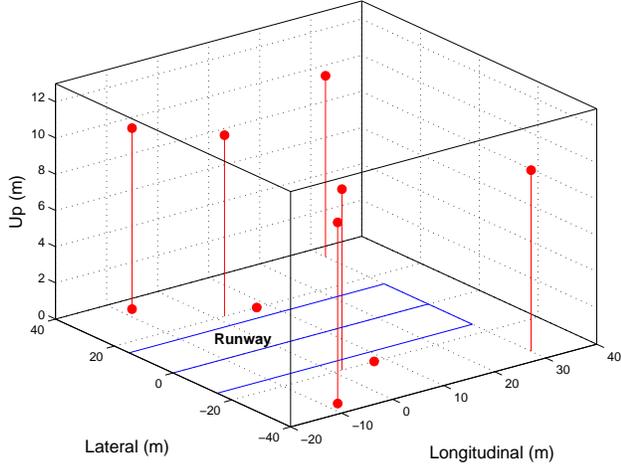


Fig. 6. Resultant ten anchor locations (red circles) from the optimal anchor location algorithms.

search algorithms, the VPR is required to be larger than 5.22. Fig 7 shows that the resultant VPR is overall much larger than 5.22 and the minimum VPR of 5.22 exists at the flare or origin point.

Fig. 8, 9, and 10 show the superimposed theoretical positioning accuracy (1σ) of the landing paths in the maximum and the minimum glideslopes. Because the resultant anchor geometry is symmetric, the positioning accuracy during the landing is also symmetric. In Fig. 10, the lateral positioning accuracy is better than 40 cm (1σ). Note that the lateral accuracy does not significantly vary with respect to glideslope changes. In Fig.

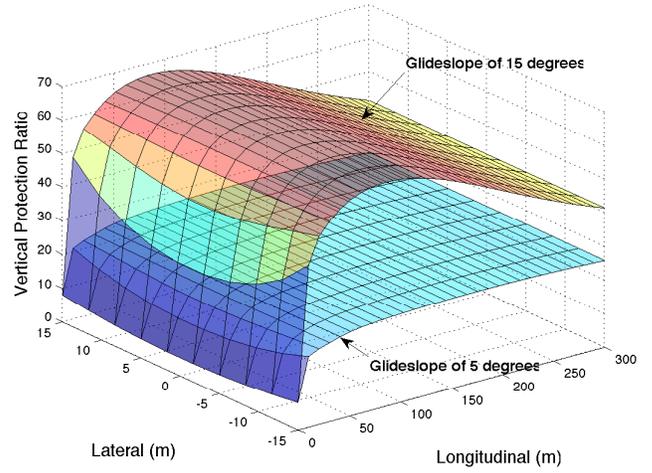


Fig. 7. The ration of aircraft altitude (AGL) to vertical positioning error

9, the vertical accuracy is as good as 9 cm (1σ) at the flare point and degrades as the longitudinal range increases from 0 to 300 m. The glideslope of 5 degrees provides a slightly better vertical positioning accuracy than the glideslope of 15 degrees. And, the vertical positioning accuracy of the landing paths between those glideslopes locates inside the two extremes. Therefore, the UAS landing with the glideslopes from 5 to 15 degrees is well supported in the lateral and vertical directions.

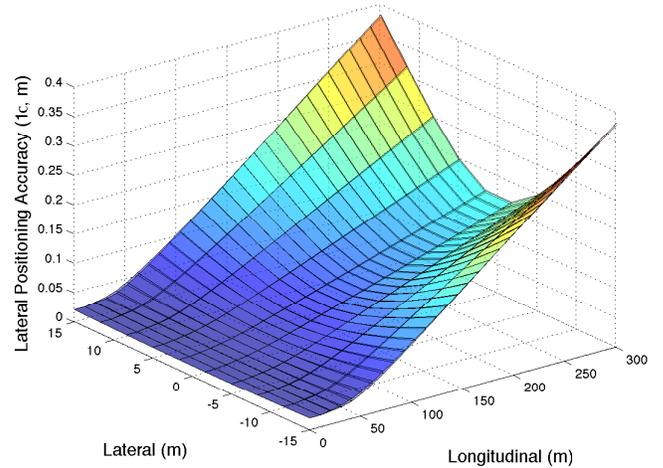


Fig. 8. Theoretical positioning accuracy (1σ) in the lateral direction.

The longitudinal positioning accuracy shown in Fig. 10 also overall seems to be sufficient to support an auto landing. However, the longitudinal positioning accuracy is somewhat poor where the longitudinal range is larger than 200 m. The reason is that the anchors are clustered in one direction at the UAS point of view, therefore the Dilution of Precision of the anchor geometry is particularly bad in the region. If a UAS can use other onboard sensors such as Inertial measurement units (IMU) for the longitudinal velocity, then a simple Kalman filter would enhance the longitudinal positioning accuracy. AI-

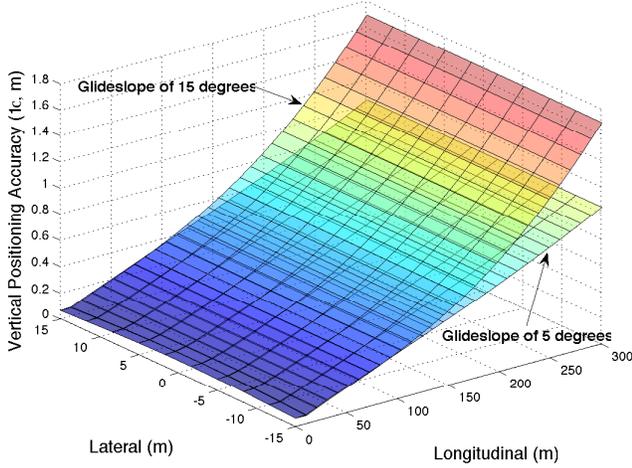


Fig. 9. Theoretical positioning accuracy (1σ) in the vertical direction.

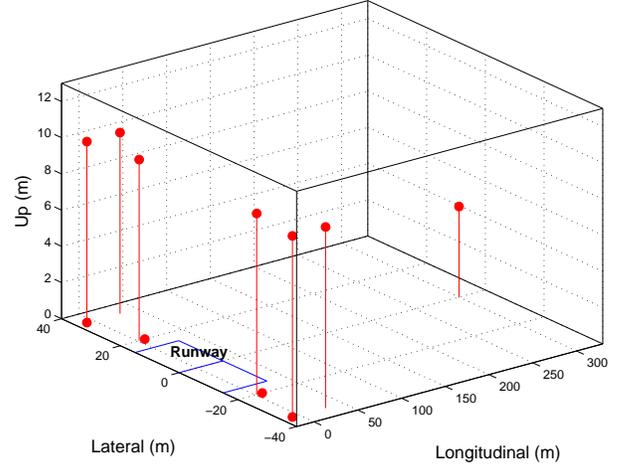


Fig. 11. Augmented anchors to improve positioning accuracy in the longitudinal direction.

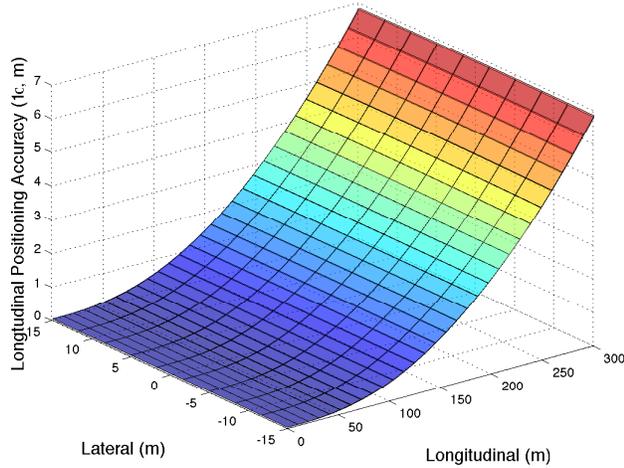


Fig. 10. Theoretical positioning accuracy (1σ) in the longitudinal direction.

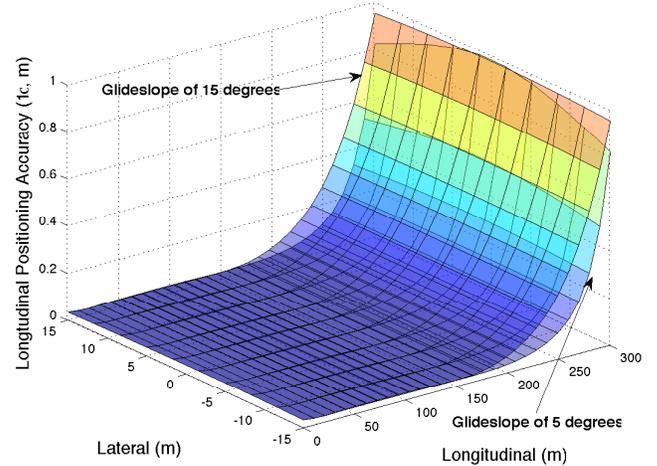


Fig. 12. Improved longitudinal positioning accuracy from using the augmented UWB anchor network

ternatively, additional anchors could be placed to improve the longitudinal positioning accuracy, which is further discussed in the next subsection.

B. Augmented anchor geometry for the longitudinal direction

The longitudinal positioning accuracy can be greatly improved when one additional anchor is placed below the initial descending point of the landing path. In Fig 11, one additional anchor was placed at (300, 0, 5) meters with respect to the runway coordinates. Fig. 12 shows the greatly improved longitudinal positioning accuracy from 3 cm at the flare point to 1 m at the initial descending point.

VI. CONCLUSIONS

The paper presented a novel UWB positioning network for an autonomous UAS landing. The UAS positioning during a landing is passive such that UWB signals is emitted from an UAS. And, the UAS position is computed on the ground

and is sent back to the UAS through a protected aviation communication channel. We discussed the anchor network geometry search algorithms based on Binary Integer Linear Programming. The algorithms were applied to a modeled runway and landing paths having glideslopes between 5 to 15 degrees in a relatively small local municipal airport. The resultant optimal network consisted of a total 10 anchors: 6 anchors in the 10 meter height antennas and 4 anchors on the ground.

We also presented lateral, longitudinal, and vertical positioning accuracies in the presumed landing paths. Overall, the positioning network provides excellent lateral and vertical positioning accuracy for a landing operation. The lateral positioning accuracy was better than 40 cm (1σ) in all of the user spaces, and the vertical accuracy is as good as 9 cm (1σ) at the flare point, which is the most critical point in a landing. The longitudinal positioning accuracy was relatively

poorer when an UAS is beyond 200 m from the flare point. This can be improved by placing another anchor around the initial decent point. We expect that the proposed UWB anchor network would be a viable solution for a fixed wing UAS auto landing with the lower cost and higher positioning accuracy compared to current manned aircraft auto landing systems such as ILS or GBAS.

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