TDoA for In-Flight Relative Localization in UAV Swarm using Ultra-Wide Band

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Abstract

The development of wireless networks allowing precise time-stamping of emitted/received packets paves the way to precise localization, which can be used for communication and coordination inside a fleet of Unmanned Aerial Vehicles (UAV). In this paper, we present the limit of Ultra-Wide Band (UWB) to perform relative positioning and UAV navigation, and we propose an architecture based on Time Difference of Arrival (TDoA), which doesn't depend on deploying external equipment, as receivers will be embedded on the UAV itself. Results from simulation campaigns reveal that even if distance measurements lack precision to be useful, direction measurement on the other hand has enough precision, and this information allows us to reduce the number of packets exchanged to perform relative positioning.

Keywords

UAV, position measurement, UWB, TDoA

1. Introduction

Since the emergence of UAVs, especially rotor drones, many works have focused on flying fleet formation, with spectacular progress in the last years. However, most of the successful experiments rely on an external controller, either manual or programmed, that pilots each UAV in the fleet. In order to maintain an autonomous drone fleet in formation, whether the control is distributed or performed by a fleet leader, several challenges remain to be solved. One of them, and not the least, is measuring the locations of the drones relative to one another [1].

Localization, in general, has been widely addressed in the literature, whether it is in the context of UAVs or not. Many technologies are available on the shelf, but do not fit the specific constraints of in-flight localization for UAV swarm. The Global Navigation Satellite System (GNSS) is the most prominent technology available to end users. Although it relies on satellites, GNSS can be unavailable or inaccurate in some locations, because of local regulations or specific characteristics of the flight environment (e.g. indoor/underground) [2]. Besides, GNSS is also exploiting a ground infrastructure for improved accuracy that may not be possible to deploy or would limit the navigation area. Other prominent technologies in the context of UAVs are Light Detection and Ranging (LiDAR) and SLAM localization techniques. The wider field of view LiDAR are however expensive, bulky, and still limited to $180° \times 40°$ (such as the Wide

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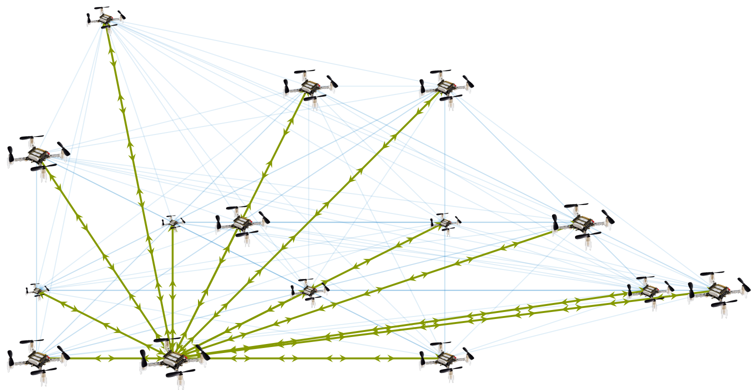


Figure 1: UAVs estimating each other's relative positions by exchanging UWB packets.

FoV LiDAR Scanner – CH64W at $ 4400), and would require several of them to cover the whole field of view.

Since most of recent devices are wirelessly connected, in particular in the rising Internet of Things, it is natural to try and leverage the communication devices to provide localization or, at least, ranging, that is estimating distances. As first order model of path loss is directly bound to the distance, it is tempting to use the received signal strength of communications to estimate the distance between the source of the transmission and the receiver. It was however experimentally and theoretically shown that the precision of such estimate is very low, even for static devices [3]. The measures are fast changing with the radio conditions, making these techniques even more inadequate for UAVs. In contrast, the propagation speed of a radio signal is less prone to uncertainty, in particular in Line of Sight conditions. Therefore, estimating the distance between two radio interfaces by measuring the time of flight (ToF) has been well investigated. The `802.11mc` amendment of WiFi measures the Round Trip Time (RTT) to provide a more reliable estimation. The resulting precision is however only of 1 to 2 m, which is too large for controlling a swarm of small UAVs [4].

The physical layer of WiFi is the main reason of the (comparatively) low precision of `802.11mc`. This explains the recent interest in Ultra-Wide Band (UWB) technology for ranging. It has been widely exploited for indoor localization [5][6]. It is indeed based on the emission of very short pulses (2 ns wide) spread on an ultra wide bandwidth. In contrast, WiFi is a more narrow band technology that splits the bandwidth into sub-channels to multiplex several transmissions, and each one lasts longer. Shorter pulses are more resilient to multi-path propagation [7]. In particular, it allows us to have a more precise measurement of the propagation time along the direct path. The consequent ranging precision is in the 10 cm range [8].

In this paper, we investigate how UWB communications can be exploited to compute relative positions in a swarm (Figure 1). Our contribution is threefold:

- we thoroughly describe the main factor of localization errors and the practical limits implied by the use of UWB communications
- we propose an architecture of UAV localization system based on Time Difference of

Arrival multilateration that does not require distributed clock synchronization between UAVs and uses a very low number of transmissions
- we evaluate in details the nature and geometry of localization errors, paving the way to an efficient control mechanism of UAVs.

The roadmap of the paper is as follows. In Sec. 2, we go into the specific and practical limitations imposed by the use of UWB in the settings of swarms. In particular, we show that clock synchronization issues introduce a trade-off between the size of the swarm, the frequency at which localization is updated, and the multilateration techniques that are used. We then propose in Sec. 3 a pure TDoA-based architecture that alleviates distributed clock synchronization requirements between UAVs and theoretically achieves relative positioning with a very low number of transmissions, hence making it possible to address large swarms. Finally, in Sec. 4, we evaluate the performances of this architecture through extensive simulations.

2. Limits of UAVs relative positioning using UWB

Working with a swarm of UAVs, fast and efficient computations of positions is a key challenge. In this section, we investigate the limits due to the Ultra-Wide Band technology in distance estimation used for multilateration.

Computing each UAV position needs at least four distance measurements. Several packets have to be exchanged, which may lead to collisions or network saturation. It is therefore crucial to investigate the trade-off between the limits on precision and those on the size of the swarm that can be achieved, which depends on the multilateration and measurement techniques.

Using a classic Time of Arrival (ToA) approach theoretically allows us to compute the position of a UAV with a single transmission received by at least four reference anchors. It however requires strong clock synchronization among all devices: as we are dealing with propagation time close to the speed of light, $1\,\mathrm{cm}$ of precision requires roughly $33\,\mathrm{ps}$ of synchronization. Clocks variations also affect distance measurement and positioning. An analysis of the induced error due to the clock drift on common positioning methods is described in [9]. Classic Time Difference of Arrival (TDoA) approaches relax the need for synchronization between the emitter and the receivers, but not among the receivers.

A widely studied way to compensate the lack of strong synchronization is to use algorithms of the Two-Way Ranging (TWR) family (e.g. SDS-TWR [10]). They however involve exchanging multiple packets between each pair of UAVs in order to compute their distance, which may take too long or use too much network bandwidth.

2.1. Limitations on frame rate

Despite data transfer rates up to $6.8\,\mathrm{Mbps}$ for the UWB, the transmission frame rate is not very high and constrains the scalability of the swarm for localization. An analysis for indoor localization [11] shows theoretical limits for an indoor anchor-tags system to be 254 tags for TWR+ALOHA or 5545 tags for TDOA+TDMA.

Indeed, a UWB configuration well-suited for distance measurement [12] with a reasonably small payload of 20 bytes and security enabled would take $\tau_{\text{frame}} = 137.4\,\mu\mathrm{s}$ to be transmitted, which means at most 7278 frames per second.

Depending on the underlying MAC protocol (ALOHA, TDMA, ...) the actual achievable frame rate will then be between 1338 (non slotted ALOHA) and 7278, which will limit the number of distance/localization measurement according to the selected method (TWR, TDoA, ToA, ...) as it could require more than one frame per measurement.

2.2. Swarm scalability

To control its flight, a UAV needs to acquire its position frequently enough. A $control\_frequency$ of the order of 10 Hz is considered the minimum requirement for a stable flight [13], higher speeds requiring higher sampling frequencies.

Computing each position requires performing one or more transmissions, their number being denoted $transmissions$ in the following. 3D positioning requires at least 4 distances, that can be obtained with 1 (ToA/TDoA) to 4 (SDS-TWR) transmissions each. In these examples $transmissions \in [4, 16]$.

Then the maximum achievable swarm size $\mathcal{S}$ is related to these quantities and the available $frame\_rate$ of the implemented UWB protocol is as follows:

$$\mathcal{S} \leq \frac{frame\_rate}{transmissions \cdot control\_frequency}$$

A 10Hz sampling using SDS-TWR with 4 reference anchors has been experimented using Crazyflie, STM32F405 on small scale systems [14]. Such a scenario would limit the swarm to $\mathcal{S} \in [8, 45]$ UAVs.

Using SS-TWR instead and taking into account the clock offset information available in the DW1000 chipset it is possible to have the same precision as with SDS-TWR [15]. It is also possible to decrease the number of transmissions by one packet for each distance by embedding the transmission timestamp in the transmitted packet itself (but tricky to implement). The same initial packet can also be used (broadcasted) to trigger replies from all the anchors. Leading to further optimization where $\mathcal{S} \in [26 - 145]$. This size could be pushed to $\mathcal{S} \in [33 - 181]$ by considering that one quantity is obtained by an external sensor (e.g. altitude given by a telemeter), hence reducing the number of needed references to 3.

TDoA and ToA approaches only require 1 transmission to get each position measured, which allows much larger swarm sizes, as summarized in table 1. Moreover, this number is decorrelated from the number of anchors, since the same transmission is used by all anchors.

2.3. Timestamping and clock error in DW1000 chip

All the distance and position measurements are performed by identifying the moment of the packet emission/reception, so it is important to have a precise and coherent timestamp of these moments. Besides clock synchronization issues, timestamping is also a source of loss of precision. In the following, we consider a system built on an NRF52840 micro-controller and the Decawave DW1000 chipset, which has a Cortex M4 running at 64MHz. The timestamping process runs a Leading Edge Detector algorithm, which is influenced by signal reception power (as well as voltage and temperature that can impact oscillators and antennas). This influence can

Method	Anchors	ALOHA	Max
SDS-TWR	4	8	45
SS-TWR with initial packet broadcasted	4	26	145
SS-TWR with initial packet broadcasted and with altimeter	3	33	181
TDoA	5	133	727
ToA	4	133	727

Table 1
Swarm size limits (UAV controlled by a $10\,\mathrm{Hz}$ frequency)

be partly mitigated using internal chip information (e.g. offset register and CIR register) [15]. There are nevertheless residual errors that will be aggregated in a timestamping error parameter.

3. TDoA-based architecture for relative positioning

Ideally, if all UAVs share a common clock, there wouldn't be any clock synchronization issues. Of course, that cannot be achieved for ToA localization without costly hardware. There is however a way to implement that with TDoA, which only requires synchronization among receivers while imposing no condition on the emitter. Another significant advantage of TDoA (and ToA) compared to TWR methods is its ability to estimate the position using a single packet, making it immune to UAV movements.

3.1. Architecture

The base idea is to reverse the classic TDoA approach and consider that all the receivers are embedded on the UAV that wants to localize an emitter. In such a setup, the receivers are close enough to each other to actually synchronize with the same physical clock (using wires).

Figure 2 depicts the theoretical set-up of UWB receivers on a UAV. They are distributed on a sphere $\mathcal{S}_R$, as a solution to the Thomson problem, the UAV being the center O of the sphere. The UAV computes the relative localization of an emitter E (which can be an anchor or another UAV).

The additional benefit of using TDoA is that localization can be done theoretically with only one transmission from the reference anchor. The movements of the UAVs are not degrading the distance estimation between successive transmissions. Moreover, unlike TWR, there is no information to transmit in the packets' payload which is available for other tasks. In particular, localization can be performed for each transmission useful to the application.

3.2. Localization challenges

From a mathematical aspect, with an infinite precision on time measurements, this architecture achieves the localization of our UAVs. However, the aforesaid errors in timing measurements are unavoidable. Consequently, the localization is an estimation provided by solving an optimization algorithm, such as the Nelder-Mead algorithm [16].

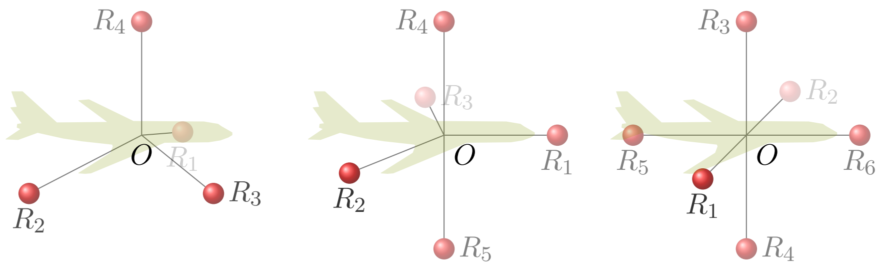


Figure 2: Radio receivers (anchors) attached on the UAV. Possible placements for 4, 5, or 6 receivers.

In the configuration yielded by our architectures, the emitter is outside of the convex hull formed by the receivers. This is the worst case scenario for solving TDoA localization.

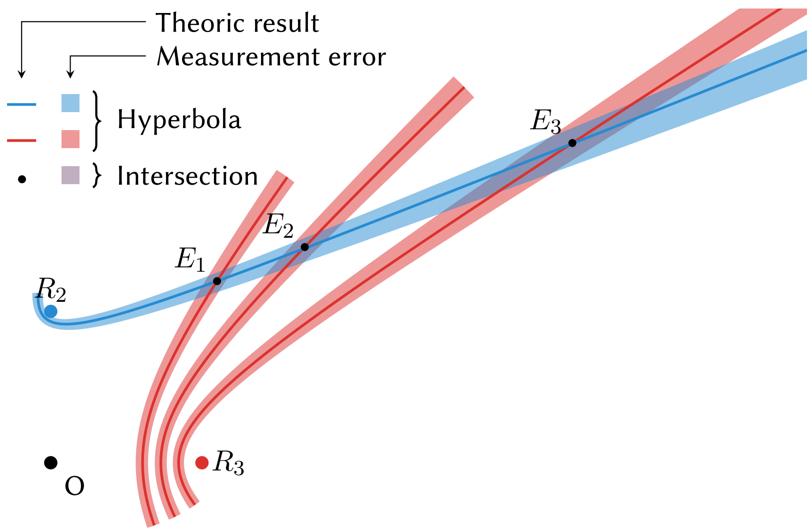


Figure 3: TDoA precision vs distance. The probable intersecting zone increases with distance.

The localization is indeed the intersection of hyperbolas, but when there are errors in the measurements, the estimation of localization is in the intersection of the shaded areas depicted in Figure 3. The size of this area is an upper bound on the localization error. Unfortunately, as the emitter gets further away from the convex hull formed by the receivers, the area increases in an oblong shape. This can lead to large errors in the estimation of the distance between the emitter and the UAV. The estimation of the angle is on the contrary more robust since the intersection is aligned with the vector between the emitter and the UAV as shown in Figure 4,

In the next section, we investigate the sensitivity of our architecture to a UWB chipset precision and error measurements.

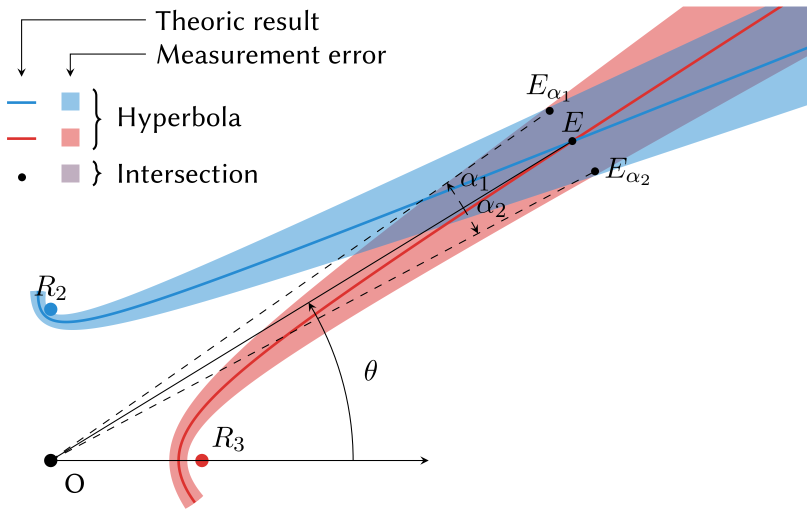


Figure 4: TDoA direction precision. The angle error is bounded.

4. Experimental validation

Suppose that a UAV A, carrying our TDoA architecture, estimates the position of a UAV B emitting a packet as depicted in Figure 5).

Figure 5: UAV A performing position estimation by listening for the single packet emitted by UAV B

Our simulation will only need to consider fixed UAVs as the position estimation using ToA/TDoA is done using a single packet, making the UAV movement negligible compared to the packet propagation speed.

Architecture parameters

We consider the DW1000 UWB chipset, where timestamps are 40-bit values at a nominal 64 GHz resolution. The timestamp precision is approximately 15 ps, denoted as *a tick*. Considering that radio signals travels at the speed of light, a tick represents about 5 mm of precision for distance estimation. Timestamping errors are measured as a number of ticks. They are intrinsic to the UWB chipset and hardware.

The receivers of our architecture are supposed to be installed at the extremities of the UAV, roughly at half the wingspan of the UAV to its center.

The following parameters describe a test configuration of the architecture, denoted aXsYsZ.

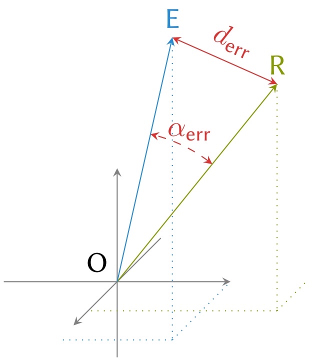
- a, the timestamping error (in ticks) occurring in the time stamping process.
- s, the number of receivers (4, 5, or 6) in the architecture.
- S, the distance of the receivers to the center of the UAV center.

The number of receivers and the wingspan describe the UAV characteristics, while timestamping errors represent an external source of errors. In this paper, unless stated otherwise, we will report the results of the four following configurations, which include different timestamping errors, number of receivers, and wingspans.

configuration	max error	receivers	wingspan
a0s5S25	*no error*	5	50 cm
a4s4S25	4 tick	4	50 cm
a2s6S25	2 tick	6	50 cm
a5s5S40	5 tick	5	80 cm

Measurement error

Two components of the position estimation errors are evaluated, the distance and the angle as depicted in Figure 6.



R = real position

E = estimated position

$$d_{\text{err}} = \|\overrightarrow{OE} - \overrightarrow{OR}\|$$

$$\alpha_{\text{err}} = \frac{\arccos(\overrightarrow{OE} \cdot \overrightarrow{OR})}{\|\overrightarrow{OE}\| \cdot \|\overrightarrow{OR}\|}$$

Figure 6: Measurement error decomposition

Average error

We consider indoor settings. UAV B is at a distance ranging from (almost) 0 to 10 m at all possible angles. We report in the following the average overall positions p_0 at distance $d \in]0, 10]$, of the errors in distance and angle estimations.

Maximum minimal achievable error

We also consider that UAV B is allowed to explore various positions p around a position p_0 within a small radius δ. $E(p)$ being the error for the position p, we define the *minimal achievable* *error* (for distance or angle) around p_0 as $E_{\min}(p_0, \delta) = \min_{\|p-p_0\|<\delta} E(p)$. It represents the most precise localization estimations a UAV could get by achieving small movements around its position. We report in the following the *maximum minimal achievable errors* (figure 7) within the 10 m radius sphere $\mathcal{B}$ around UAV A, with respect to δ. It represents the worst case a UAV will face.

$$E_{\min}(\delta) = \max_{p_0 \in \mathcal{B}} \left(\min_{p \in \mathcal{B}, \|p-p_0\|<\delta} E(p) \right)$$

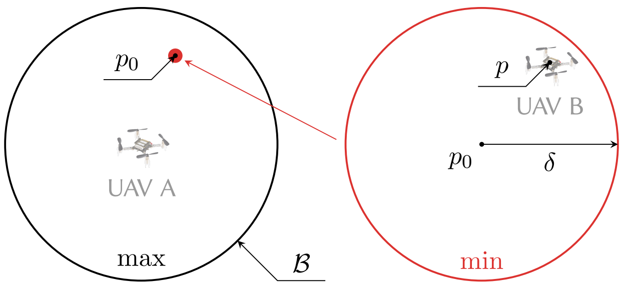
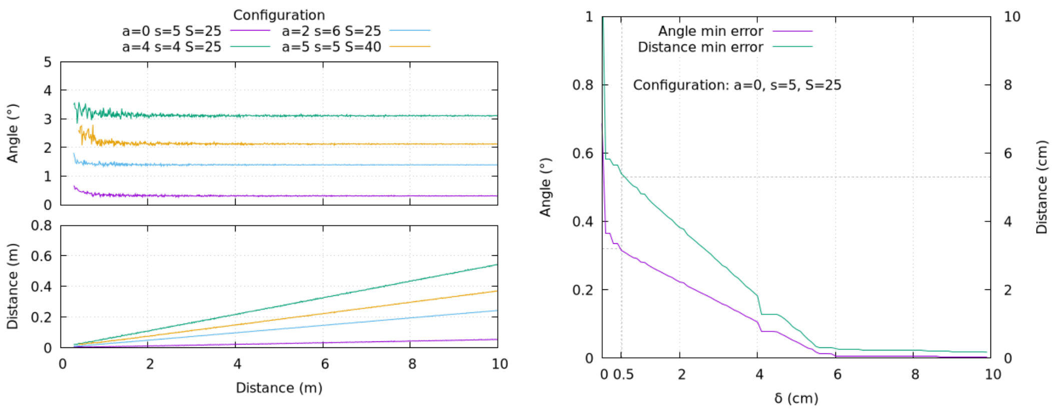


Figure 7: Maximum minimal achievable error for the space $\mathcal{B}$ around the UAV

ToA as a baseline

As a baseline, we first evaluate the performances of our architecture in the theoretical case where ToA is possible and report them in Figure 8. It would give very good performances, but requires that the emitter and the receivers are synchronized. This is technically achievable using chip scale atomic clock (such as Microchip CSAC-SA45S) calibrated to a known distance. It is however very expensive, between 2000 \$ and 5000 \$ per receiver and emitter.



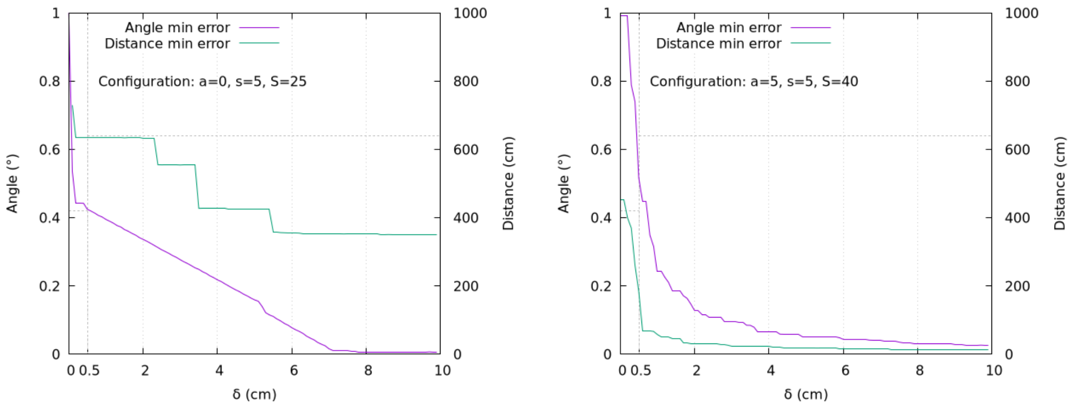
(a) Average angle and distance errors (b) maximum minimal achievable errors

Figure 8: Relative positioning errors between UAV A / UAV B using ToA (configuration a0s5S25)

For configuration a0s5S25, with no timestamping error, 5 receivers and 50 cm wingspan, the minimum achievable error is depicted in Figure 8b.

4.1. Analysis of TDoA

Figure 9a shows the minimum achievable errors obtained on configuration a0s5S25 with no timestamping error, 5 receivers and 50 cm wingspan. Even without comparing to ToA performances, one can see that the distance estimation is too approximate to be useful, in particular in indoor settings : the worst case exceeds 4 m even for $\delta = 10$ cm. As expected, however, the angle estimation is well constrained to 0.5°.



(a) a0s5S25 (b) a5s5S40

Figure 9: Maximum minimal achievable error for two different configurations using TDoA

As a matter of fact, it happens that the position estimation computed by the Nelder-Mead algorithm fails. It can diverge, and provide no values, or converge to absurd distance values while providing a correct angle value. These points are respectively reported as "non-converging" for both angle and distance, or for distance only.

Figure 10 depicts what happens in the sphere of radius δ around a non-converging position; a layered structure emerges. Yellow layers are the non-converging positions, while other layers are different level of errors. Therefore, if the UAV does small movements around its position, in the δ radius sphere, while repeating its measurements, it will always have a solution and be able to reach the minimum error, at least for the angle. As a matter of fact, this is naturally the case of a drone that tries to remain stationary. It will certainly undergo small random variations in its position.

Wider configuration

The distance between the receivers is a strong factor of sensitivity to errors in the TDoA estimation. Figure 9b shows the errors for configuration (a5s5S40) with a timestamping error of 5 ticks, a wingspan of 80 cm, and the same 5 receivers. For ToA, the timestamping errors degrades the precision compared to (a0s5S25). For TDoA however, the wider wingspan makes

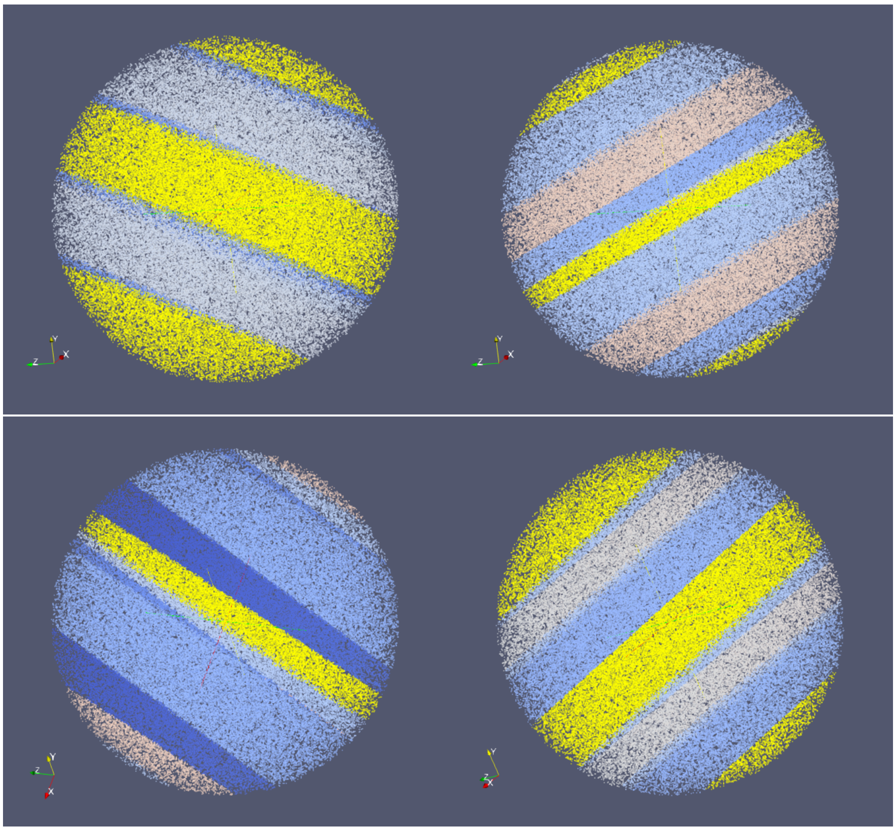


Figure 10: Convergence and angle precision around four non-converging points p_0 (configuration `a0s5S25`). Non-converging points p_0 are the center of the explored balls of radius $\delta = 0.5\,\mathrm{cm}$, . Yellow indicates non-convergence, and blue to red scale indicates level of errors. Graphics show that errors are distributed in layers.

the architecture more robust and the errors are much lower. The maximum minimal achievable error becomes practical when $\delta > 5\mathrm{cm}$.

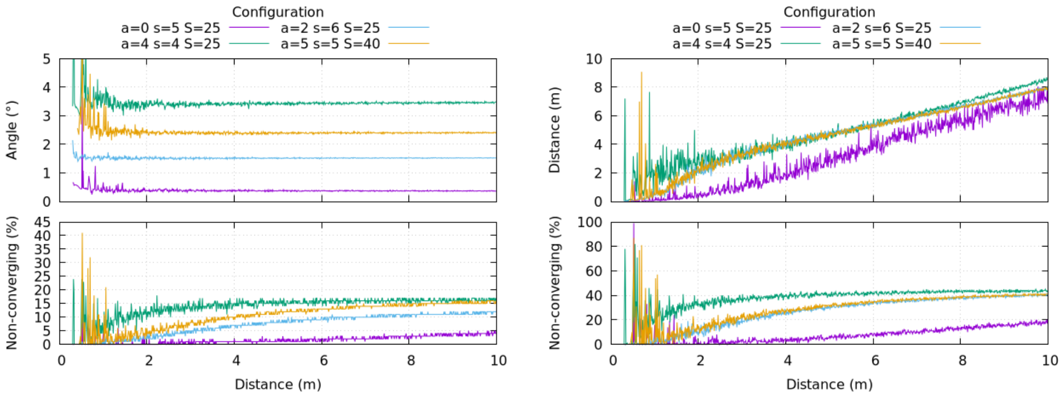
Average errors on all configurations

The average errors of all aforesaid configurations are summarized in Figure 11. Configuration (a4s4S25) with only 4 receivers is mathematically under determined and theoretically leads to two solutions. However, the initial search position of the Nelder-Mead algorithm chooses the most likely valid solution.

At close range, the impact of timestamping errors ((a4s4S25) and (a5s5S40) configurations) on both angle and distance error makes the architecture unsuitable even for preventing collisions.

On larger distances, the average angle error is reasonable: under $5\,^{\circ}$ with about $15\,\%$ of non-converging measurements.

The average distance error seems much less practical, with a linear growth as expected from the geometry of hyperbolas intersection. These average results even look contradictory with the maximum minimal achievable errors described in the previous section: the average distance errors of (a5s5S40) are worse than those of (a0s5S25). This can be explained by the larger proportion of non-converging positions, strongly impacted by the timestamping errors (the a parameter). The better results of the maximum minimal achievable errors show that the exploration over the small δ radius sphere around a position allow us to circumvent the non-convergence issue. Whatever the position of the UAV, it is close to a converging and low error position estimation.



(a) Angle

(b) Distance

Figure 11: Average errors and non-convergence percentage for different configurations using TDoA

5. Conclusion and future works

Our TDoA architecture which embeds receivers on the UAV is a promising way to build a cost-effective solution for relative localization within a large swarm using Ultra-Wide Band transmissions. Our simulations show that the precision of angle measurement is practical in all configurations, even when timestamping is prone to large errors. The average precision of distance measurement cannot however be exploited without further improvements because of the specific geometry of intersection of hyperbolas underlying TDoA errors. Local exploration seems to mitigate efficiently the TDoA distance problem. It however yields further issues to be investigated. First, it would require several transmissions. Even if the payload of the packets is still available for the application, the network load should be put compared to TWR-like protocols as it has been identified as a limitation of the size of the swarm. Then, being able to identify the minimal error in the exploration sphere is not trivial and should be carefully analyzed. Another interesting direction to explore is to fuse information from other sensors (telemeter, altimeter, relative speed, ...) to further increase the precision.

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