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A PERFORMANCE ANALYSIS ON DRONE LOCO POSITIONING SYSTEM FOR TWO-WAY RANGING PROTOCOL

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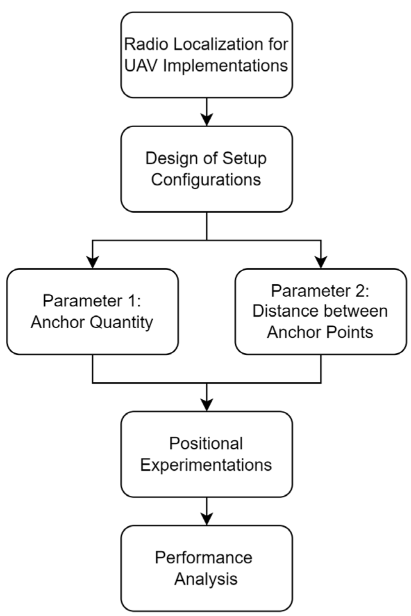
Graphical abstract



Abstract

Localization is vital in UAV operation as it monitors the position of each drone in a workspace. Existing localization techniques such as GPS are limited for outdoor implementations and cannot be implemented inside closed spaces or GPS denied areas. To address this concern localization techniques, such as vision systems and radio systems, are developed. The drawback of vision systems is the cost of implementation as the system usually requires multiple cameras strategically positioned around the experimental space to monitor the aerial drone's position and orientation. Radio localization, on the other hand, is a cheaper alternative for indoor localization as it requires only a set of anchor and tags that communicates through a certain radio frequency; however, experimental setups and materials on this localization technique is limited at this time. This paper offers an analysis of the performance of the loco positioning system, a form of radio localization, through varying configurations for swarm drone applications. The Loco Positioning System possesses two protocols; and this paper focuses on the Two-Way Ranging protocol. The study presents different setup configurations governed by 2 parameters; *number of anchors used, and the distance set between anchors*, and their corresponding performances. Data showed that an increase in anchor count from 3 to 6 decreases error from 25.96% to 8.45%, and that decreasing the distance between anchors 0.6 m to 1 m would give a minimal increase in error. Users may use these performance reports to determine their ideal setup based on the mentioned parameters.

Keywords: Loco Positioning System, Radio Localization, Swarm Drone, Two-Way Ranging, Unmanned Aerial Vehicles

1.0 INTRODUCTION

Unmanned Aerial Vehicles (UAV) technology is a rapidly evolving field of study and is being utilized for various applications such as 3D map generation [1], transport and logistics [2], swarming [3-4], and more [5]. UAV swarming is a concept where two or more UAV or aerial drones would simultaneously fly around given a control implementation. The drones in the mentioned application can communicate with each other and respond to situations autonomously while executing a specified task [6]. UAV swarming is one of the popular applications as it can resolve some of the limitations of the current aerial drone technology, specifically the issue in a short operational period [7]. One important aspect of swarm technology is the localization of each aerial drone. *Localization* is when an external component, such as satellites, vision cameras, or radio components, is utilized to detect the aerial drone and pinpoint its location represented through XYZ coordinates, or longitudes and latitudes. Satellites use a *Global Positioning System (GPS)* which would return longitudes, latitudes, and may also return elevation parameters. Generally this localization technique is used for outdoor activities such as utility post inspection or traffic monitoring [8]. However, this system poses limitations as it becomes inaccurate when the aerial drone operates indoors, also known as GPS denied environments. To address this limitation, indoor localization techniques utilizing various vision cameras were developed [9]. *Vision Localization* usually utilizes multiple cameras positioned to capture different angles of the aerial drone during operation and accurately return the position data of each drone, which can be used for various applications.

Another indoor localization technique is using radio signals, this technique is called Radio Localization; wherein, the concept utilizes several anchors that are placed into different points to set up a flight environment and a tag that is normally equipped on the aerial drone. The anchors are set as points of reference and both components are in active communication with each other with radio packets, and the position of the aerial drone is calculated through the exchange of signal packets between the anchor and tag. However, studies regarding radio localization targeted towards UAVs are currently limited as of the present as it is still a recently developed application.

The paper offers a set of setup configurations, utilizing the radio localization technique, and its corresponding performance analysis; readers can refer to when developing an ideal operating configuration setup with the consideration of parameters such as desired accuracy, availability of space, and the number of anchors. It will determine practical setup configurations based on a trade-off between the desired accuracy, the number of anchors in the setup, and the space variations between anchors. The paper focuses on the Loco Positioning System implementation, specifically the Two-Way Ranging protocol, which will be discussed under the Theoretical Considerations.

Previous Works

J. Priess et al were able to conduct a swarm experiment with 49 units of Crazyflies and called it the Crazyswarm. They mainly utilized motion capture systems, particularly the Vicon Tracker, as their localization client. The Vicon Tracker would require a reflective marker to be placed on each aerial drone for raw data acquisition in terms of position. With the data obtained from the motion capture technology, the researchers introduced the *Iterative Closest Point (ICP)* algorithm to record the position for each marker within the total flight space. The ICP is capable of recording the position of the placed marker on a frame-by-frame basis, consequently capturing the position of a placed marker each second. Each successive image is being compared with the other during the whole process to obtain position data. In addition, the proponents of this study also utilized a configuration where an individual drone will be able to detect its proximity with respect to another aerial drone with the placed markers and autonomously move to avoid collision [10].

At the University of California, Berkley, the proponents of the study researched localization utilizing *ultra-wideband (UWB)* radios. One approach zeroed into the development of an *Extended Kalman Filter (EKF)* that integrates the data between the onboard IMU and data obtained from UWB radio components. The study was validated by a series of flight experiments. A single drone was tasked to hover and move along a circular trajectory. Also, a motion capture system is used to obtain data, which is utilized as a basis, for comparison. The experiment utilized 5 UWB beacons and the drone is set to execute the two mentioned tasks. Results from the experimentation suggested that there was a relatively large error in the position tracking [11].

Since one important parameter in localization is a system's accuracy, various studies were made with methods such as introducing a new control unit or algorithms that aim to decrease errors in the system. A study was made in De La Salle University-Manila, where the researchers introduced a modified *Sliding Mode Control (SMC)* method to the quadrotor. This nonlinear control method, which takes dynamics of the system and translates it to a corresponding set of trajectories, was assessed together with the PID controller application to determine which is more accurate; and it was found that the SMC produced better accuracy results for roll, pitch, and yaw than the utilized PID controller [12].

Researchers from [10] extended their research and were able to further develop an EKF estimator that allows the utilization of a mobile anchor concept. The main approach of the method is through the minimization of the determinant obtained from the covariance matrix. The experiment setup possessed static anchors around the test area, together with a moving anchor implementation to the system setup. Similar experiments such as hovering and trajectory tracking was done in this experiment and an improvement of 14% was observed in the obtained results [13].

Researchers from Bitcraze developed another indoor localization technique called the *Loco Positioning System (LPS)*. The system utilizes the concept of radio localization and focuses on the use of ultra-wideband (UWB) radio. One of the protocols utilized in the system is the Two-Way Ranging protocol which will be explained in detail in the succeeding sections of this paper. Current studies on radio localization do not offer much performance data on the Loco Positioning System with different anchor setup and space applicability.

A summary of these research works is collated in Table 1, highlighting the localization techniques used in the study, the contribution, and the limitations mentioned in the study.

Table 1. Summary of Contributions of Related Works

Localization Technique	Contribution	Limitation
GPS Localization [12]	A novel control algorithm, SMC, capable of performing comparably with PID controllers while adapting to unforeseen circumstances	Experimentations were limited to GPS Localization. Further research can be done for indoor implementation
Visual Localization [10]	Reliable localization technique that obtained a mean position error of < 2 cm using video localization	System used 24 cameras and high computational resources, making this an expensive implementation
Radio Localization [10, 13]	A comparative study showing that Radio Localization can perform as good as Vision Localization	Research can expanded to explore various setup configurations and offer performance analyses

2.0 THEORETICAL CONSIDERATIONS

Loco Positioning System

The Loco Positioning System (LPS) is a localization technique that uses radio signals. The system comprises mainly of two components based on UWB radio architecture, the Loco Positioning Deck and the Loco Positioning Node. The Loco Positioning Deck is attached to the Crazyflie to serve as a tag in the system. A tag is the object of interest in the system wherein its position is determined through radio communication between anchor and tag. The Loco Positioning Node is a separate component that functions as the anchor and is utilized to set the boundary space for the tag to be located. A system would usually utilize a minimum of 3 to 4 anchors strategically positioned depending on the application. Filter algorithms, like the Kalman filter, are used to integrate data from the onboard IMU and readings from the LPS to produce an estimate of the tag's position within the experiment space. The LPS operates under 2 protocols, the *Two-Way Ranging (TWR)* and *Time Difference of Arrival (TDoA)* [15]. This research focuses its experimentations on the Two-Way Ranging protocol only.

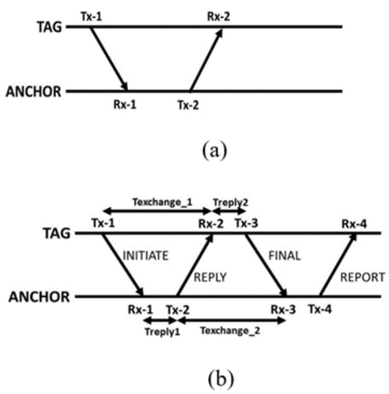


Figure 1 (a) TWR for 2 Message Packets (b) TWR Protocol

Two-Way Ranging (TWR) Protocol

This protocol requires the tag and the anchor to be engaged in active communication by sending and replying to data packets in a sequence at fixed intervals. Figure 1(a) shows a diagram of the communication process for two messages and can be expressed mathematically in equation 1, with t_f as the time of flight. However, the TWR protocol requires four messages, to ensure a reply, confirmation, and a delivered report. Figure 1(b) shows the whole process of the TWR protocol. It begins with the tag transmitting a message that will be received by the anchor. The anchor then sends back a message to the tag for a complete exchange. An additional exchange is made to minimize the clock drift error and to produce a report. Equation 2 mathematically expresses how t_f is computed with the additional exchange of data packets [16].

$$t_f = \frac{(t_{Rx-2} - t_{Tx-1}) - (t_{Tx-2} - t_{Rx-1})}{2} \quad (1)$$

$$t_f = \frac{T_{exchange\_1} * T_{exchange\_2} - T_{Reply\,1} * T_{Reply\,2}}{T_{exchange\_1} * T_{exchange\_2} + T_{Reply\,1} * T_{Reply\,2}} \quad (2)$$

Generally, equations 1 and 2 take the average time of the information exchanges less the time of reply. An exchange, $T_{exchange\_n}$, is defined as the time the tag receives a reply from the anchor, t_{Rx-n+1}, less the time it initially transmitted information, t_{Tx-n}, where n is the number of exchanges. A reply, $T_{Reply\ n}$, is defined as the amount of time the anchor takes to send a message from the time it receives the initial message. This means that a reply is a difference in the time when the message is sent from the anchor to the tag, t_{Tx-n+1}, less the time the anchor received a piece of information from the tag, t_{Rx-1}, where again n is the number of replies done. Once t_f is calculated, the distance between the anchor and tag can be computed through the section below.

Time of Flight (ToF)

The Time of Flight or TOF is a supplementary concept of the TWR protocol of operation. It functions by sending a signal from ANCHOR to TAG and vice-versa after a certain time delay. This allows the ANCHOR to calculate the total roundtrip time. When multiplied with the speed of light, C, to get the round-trip distance traveled. The distance between an ANCHOR and TAG is determined when the obtained value is halved as shown in equation 3 below [17].

$$Distance = C \times t_f \quad (3)$$

where C = speed of light at 299792458 m/s
t_f = time of flight, obtained through TWR protocol

Once the distances between all anchors are calculated, the values are collated to determine the position of the aerial drone. Figure 2 below shows a sample of how the position of an aerial drone is obtained with three anchors, where CF represents the aerial drone and A0, A1, and A3 represents the anchors.

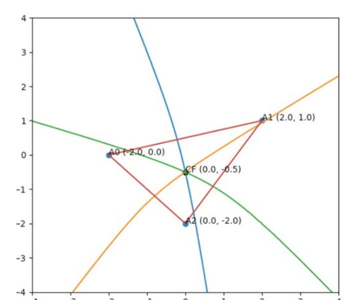


Figure 2 Aerial Drone Estimation with 3 Anchors, adapted from [18]

3.0 METHODOLOGY

Figure 3 shows the necessary steps conducted in this research. It is mainly divided into 3 parts, the Design or Definition of Different Cases, Setup of the Cases, and Position Experiment for the specified cases.

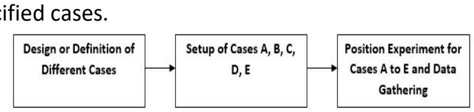


Figure 3 Methodology Flowchart

Design/Define Different Cases

Experimental setups are designed and tested to determine the behavior and the accuracy of the Loco Positioning System in the TWR protocol. The experiment setups vary mainly on two parameters, the number of anchors used, and the distance of the anchors from each other in a six-anchor setup configuration. The prior aims to discover what would be the ideal quantity of anchors required for a particular use-case, while the latter setup aims to discover the ideal distance between anchors. Percent errors are retrieved from both parameters to offer performance data of the different configurations. Each parameter would offer a study on 3 different configurations; and, a grid system having increments of 0.3 m is also used and applied to the experimental setup to function as the testing points where the Crazyflie, mounted with the TAG, should be positioned to obtain data. Estimate position values of the LPS system as the drone is moved from one position to the other is obtained through the Crazyflie PC Client. The scope of this experiment is evaluated using a 2D workspace, however, similar observations can be expected in a 3D setup application; thus, data along the z-axis is not put into the consideration of this experiment.

Case Setup Based on Number of Anchors

Three setups will be presented which are based on the criteria of the number of anchors in this study. Average percent error will serve as the performance parameter for these setups to evaluate the performance of each case setup.

- <u>Case A</u> utilizes 6 anchors, which is recommended by the developers of the LPS system, together with a 1 m distance in between each anchor forming a rectangular space. Figure 4, 6 Anchor Setup, offers a visualization of the setup of the 6 anchors.
- <u>Case B</u>, as shown in Figure 5, 4 Anchor Setup, utilizes 4 anchors with a distance of 1 meter from each other forming a boxes space. The objective of this setup is to validate the functionality of the TWR protocol operating on the minimum required number of anchors.
- <u>Case C</u> utilizes 3 anchors forming a triangular space as shown in Figure 6, 3 Anchor Setup, this aims to observe the behavior of the tag when there is one less anchor from the recommended number.

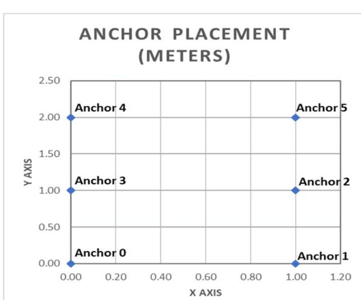


Figure 4 6 Anchor Setup [Case A]

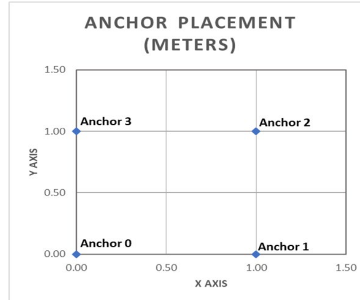


Figure 5 4 Anchor Setup [Case B]

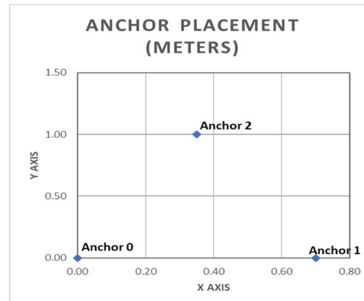
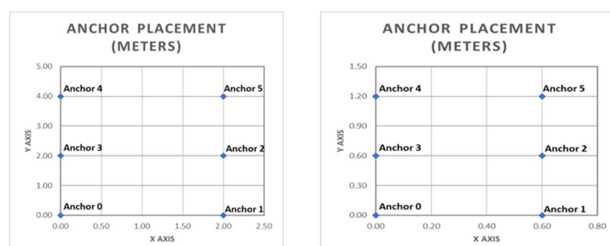


Figure 6 3 Anchor Setup [Case C]

Case Setup Based on Distance Between Anchors

This set of configurations utilize 6 anchors with varying distance between anchors. Similarly, in the previous section, the average percent error serves as the performance parameter.

- <u>Case D</u> utilizes 6 anchors forming a rectangular shape as shown in Figure 7(a), 6 Anchors (2m apart).
- <u>Case A</u> is also considered under this parameter as the setup utilizes 6 anchors and has a 1 m anchor distance.
- <u>Case E</u> is visualized in Figure 7(b) where 6 Anchors are spaced 0.6 m apart. This allows the proponents to observe how a small space can affect the accuracy of the setup.



(a) (b)

Figure 7 (a) 6 Anchors (2m apart), (b) 6 Anchors (0.6m apart)

Setup for Each Case

Each anchor is given a unique identification number from 0 to 5 and is positioned on the experimental space according to the configuration to be tested. Position vectors are programmed to each anchor corresponding to the desired configuration. Anchor 0 functions as the point of origin, serving as a reference for the succeeding anchors. The Crazyflie is powered on facing towards the positive X-axis and within the boundary space formed by the anchors to calibrate its onboard inertial measurement unit (IMU). The setup is verified in the PC Crazyflie client when both the anchors and tag are detected, the actual configuration setup reflects on the PC Client, and the movements are tracked on the PC Client.

In the experimental setup, vertical and horizontal lines are drawn from the origin up to the boundary set by the anchors, thus forming a 2D grid system. For the first parameter, the distance between these lines is 0.3 m, while for the second parameter, the distance between these lines is 0.6 m for Case D, 0.3 m for Case A, and 0.15 m for Case E. The intersection of these vertical and horizontal lines shall serve as the testing points for the Position Experiment. The testing points indicate where the researcher should position the aerial drone and shall also serve at the true value which will be used to evaluate the accuracy of different configurations.

Position Experiment for Each Case

The experiment process involved manually placing and relocating the aerial drone on the testing points along the 2D grid and then recording the obtained readings from the PC Client; this process was repeated five times. Figure 8, offers a visual of how experiments were conducted. After completing the test, the recorded data was compared to the true values to obtain the variance between the true values and the estimated values, indicating the performance of a particular configuration setup.

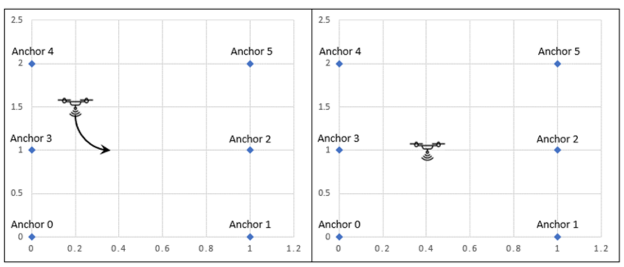


Figure 8 Experimental Process

Percent Error

Percent Error is used to evaluate the accuracy of the configuration setup as true values are known in this experiment. A percentage comparison between the estimated value and true values for the x and y axes are expressed in equation 4. Upon obtaining all percentage errors for each point, the average of these values was calculated to obtain an average percent error, expressed in equation 5.

$$Percent\ Error = \frac{|v - v_a|}{v} \times 100 \tag{4}$$

$$Average\ Percent\ Error = \frac{Percent\ Error}{n} \tag{5}$$

where v = true value; v_a = approximate value; n = number of samples in the setup

Materials

The research utilized the Crazyflie drone mounted with a Loco Positioning Deck shown in Figure 9(a). Multiple Loco Positioning Nodes, in Figure 9(b), are also used and function as the anchors of the system; in addition, the nodes also set the boundary of the experiment space.

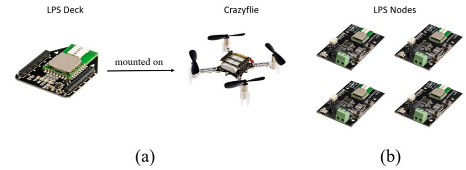


Figure 9 (a) Loco Positioning Deck to be mounted on Crazyflie, (b) Loco Positioning Nodes, images adapted from [14,19-20]

4.0 RESULTS AND DISCUSSION

This section is divided into two subsections, *Case Setup Based on Number of Anchors* and *Case Setup Based on Distance Between Anchors*. Each subsection presents the results of different case scenarios through a figure, together with an interpretation of the results. The figure is a 2D graph with 3 colored shapes; the green diamond represents the position of the anchors, the blue squares represent the testing points, and the yellow triangles represent the position estimated through the LPS system. In addition, set labels, set 1 to set 5, are placed beside the yellow triangles to track which estimated point refers to which testing point. Set 1 refers to the column of testing points along the origin; set 2 refers to the column of testing points to the right of the previous set, and so on. An evaluation is presented at the end of both subsections to determine how the mentioned parameter affects the performance of a given setup. The results were collated and presented in a summary table at the end of this section.

Case Setup Based on Number of Anchors

Case A

Experimentation on case A generally obtained an average percent error of 8.45%, as shown in Figure 10, Case A Results. It can be observed in set 3, 60 cm along the x from the reference point, returned values that are near to the true values, with a maximum variance of 13 cm. However, the values obtained in the other sets did not present a clear pattern, showing some variances up to 20.67 cm while most variances are below 10 cm, and are as low as 0 cm.

Case B

The overall results in case B returned an average percent error of 12.27%, shown in Figure 11(a), Case B Results. The study gave a maximum error variance of 22.33 cm at set 4 while most points exhibited variance values below 10 cm. The minimum variance obtained in this case is 0 cm. This case aims to offer validation on the minimum requirements for the TWR protocol.

Case C

Results obtained from case C experimentation. Presented in Figure 11(b), showed an average percent error of 28.42%. This setup possessed a maximum variance of 32.33 cm and a minimum of 1.33 cm. It should be noted that most of the data are beyond 10 cm variance, resulting in an 11.39 cm mean-variance. The objective of this experiment is to determine the behavior of the data when the minimum required anchors are not met. Set points are also present beyond the boundary to determine whether the tag can be read beyond the set boundary. Reanalyzing the data to zoom in to points within the boundary resulted in an average percent error of 25.96%.

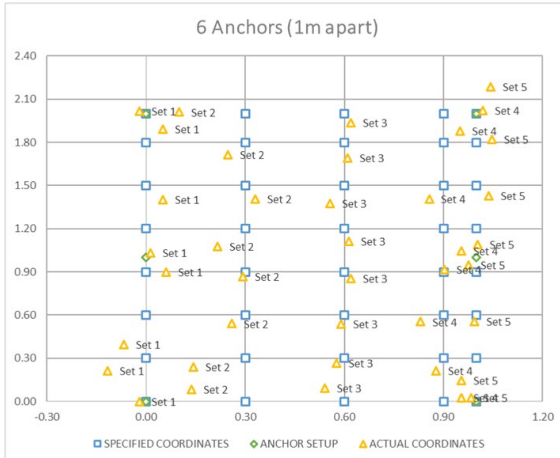
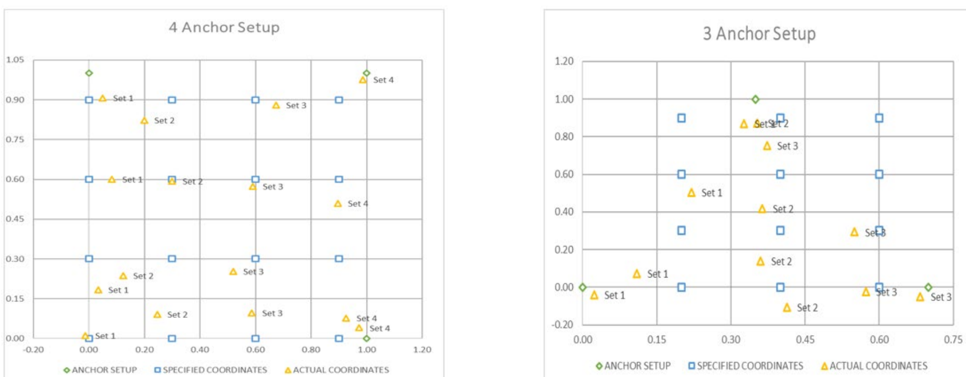


Figure 10 Case A Results



(a) (b)

Figure 11 (a) Case B Results, (b) Case C Results

Evaluation

Results from this parameter, shown in Table 2, showed that a system needed at least three anchors to track the Crazyflie within the XY plane. However, the three-anchor setup created a triangular boundary limiting the LPS estimations within that boundary despite the actual position being outside of the boundary. The average percent error of Case C, limiting calculations to the points inside the boundary, was 25.96%. This phenomenon showed that operations must be within the boundary set by the anchors. Adding one more anchor into the system, as presented in Case B, significantly improved the performance of the setup configuration, dropping the average percent error from 25.96% to 12.27%. Adding two more anchors into the system, as presented in Case A, further dropped the average percent error to 8.45%. This observation suggested that when more anchors are used in the system the accuracy of estimating the Crazyflie's position increases.

Table 2. Result Summary for Cases Based on Number of Anchors

Case Configuration	No. of Anchors	Average Percent Error
Case A	6	8.45%
Case B	4	12.27%
Case C	3	25.96%

Case Setup Based on Distance Between Anchors

Case D

Results for case D are shown in Figure 12, Case D results, obtained an average percent error of 3.60%. The data showed 2 points with a maximum variance of 14 cm and most of the points exhibited variances below 6 cm, with a minimum of 0 cm variance and a mean of 3.86 cm variance. Data in Set 1 are not as accurate as compared to the other points since these records are taken along the boundary of the setup. The setup serves as the ideal setup as the estimated points are close to the specified points shown in sets 2 and 3.

Case E

Results from the experiment on case E setup, shown in Figure 13, Case E Results, showed an average percent error of 8.68%.

Set 2 and set 3 are the only sets that are able to return values close to the actual or with a maximum variance of 13 cm and 12 cm displacement respectively. The mean-variance observed in this setup is 4.27 cm, with a minimum of 0 cm. The other sets do not give a clear pattern on the values it returns. It is also observed that the points are inside the boundary.

Evaluation

Results from this parameter, presented in Table 3, showed that increasing the distances between anchors decreases the average percent errors. Case E obtained an average percent error of 8.68%, while Case A and Case E obtained average percent errors of 8.45% and 3.60% respectively. It was also observed that Case E was a viable configuration as it showed similar performance with Case A. A consistent observation for all setup configurations was that positioning the Crazyflie along the boundary has returned inaccurate estimations. This observation further suggested that aerial drone operation must strictly be within the set boundary. The configuration presented in Case E would suffer the most given this constraint as it does not offer many allowances for error in aerial drone operations.

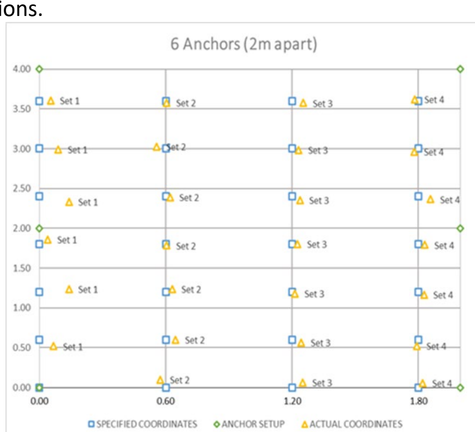


Figure 12 Case D Results

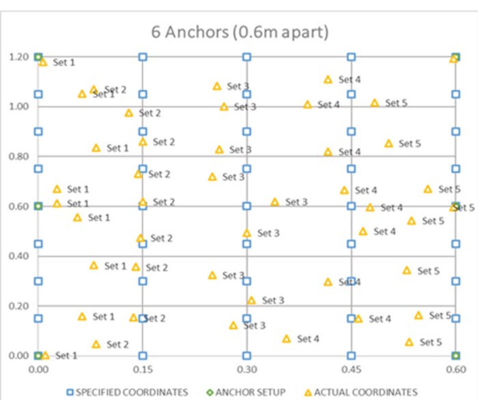


Figure 13 Case E Results

Table 3. Result Summary for Cases Based on Distance Between Anchors

Case Configuration	Distance	Average Percent Error
Case A	2 meters	3.85%
Case B	1 meter	8.45%
Case C	0.6 meters	8.68%

Summary

Table 4, a summary of variance per case, shows the results for each case provides information on the minimum, maximum, mean, and standard deviation on the variance values obtained for each case.

Table 3. Summary of Variances per Case

Case	Minimum Variance (cm)	Maximum Variance (cm)	Mean (cm)	Standard Deviation (cm)
Case A	0.00	20.67	6.24	4.96
Case B	0.00	22.33	5.83	5.13
Case C	1.33	32.33	11.39	8.79
Case D	0.00	14.00	3.86	3.01
Case E	0.00	13.00	4.27	3.32

Generally, the configuration in case D serves as the ideal setup for testing and experimentations as it holds the least average error. However, this configuration would require six anchors and a large space, around 2x4 meters. In scenarios where a large room is not available, it is possible to downscale the distances of anchors as low as 0.6 m. Maintaining at least a 1 m distance between anchors would be an ideal setup to allow some degree of errors during operation since it was observed that estimations along the boundary are most likely inaccurate. Though the minimum number of anchors for the operation was found to be three, it is recommended to have six anchors in a setup to maximize the accuracy of the estimations by the LPS system, especially when expanding the setup configuration into a three-dimensional workspace.

5.0 CONCLUSION

The research presented 3 setups for each specified parameter, namely the number of anchors in the system, and the anchor-anchor distance. Experimentation was executed manually by positioning the Crazyflie installed with a Tag and recording data through the PC client. It was observed that the loco positioning requires at least 3 anchors for operation but the accuracy of the system increases as the number of anchors increases from 3 to 6, resulting in a decrease in average percent errors from 25.96% down to 8.45%. For the cases based on the distance between anchors, it was observed that there is an increase in error as distance decreases as shown in cases D to E. The paper was able to present setup configurations and their corresponding performance reports in terms of accuracy based on the two parameters. In addition, the mean position error obtained for case D is 3.86 cm which is close to the performance of the vision system presented in [10].

Users may utilize 4 anchors with a 1-meter anchor distance for applications on single drone operation and familiarization. However, in swarm application, 6 anchors would be required with distances in between anchors around 1-meter or more, as positioning accuracy is a very important factor in swarm application. It is hypothesized that additional anchors beyond 6 offer more redundancy but will not significantly offer more accurate results. Additional experiments, such as swarm implementation will be conducted in the future to validate the performance and the viability of these configurations in swarm operations. Since it was observed that the estimated data follows the boundary or shape set by the positioned anchors, further experiments can be done with various anchor configurations following different shapes while observing the behavior and accuracy for each configuration.

Acknowledgement

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