ORIGINAL ARTICLE

A Performance Analysis on Swarm Drone Loco Positioning System for Two-Way Ranging Protocol

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Abstract: An important factor that should be taken note in swarm application is the localization of each aerial drone for accurate implementation of a specific task. Indoor localization techniques, such as vision systems and radio systems, are developed to answer the mentioned problem. This paper presents a performance analysis of loco positioning system through varying configurations for swarm drone applications. Loco Positioning System is a radio localization technique in which processes two ranging protocols such as the Two-Way Ranging and Time Difference of Arrival. Cases are divided into 2 parameters, namely the number of anchors used, and the distances between anchors. These two parameters are set since they are important factors for constraints in costs and working space. Data showed that increasing the number of anchors from 3 to 6 decreases the error from 25.96% to 8.45%; in addition, results also showed that decreasing the distance between anchors 0.6m to 1m would give minimal increase in error. This paper is able to provide a performance report based on accuracy for each case on the specified parameters. These data may be utilized by users in determining their ideal setup based on their constraints through the two mentioned parameters.

Keywords: Swarm Drone; Loco Positioning System; Radio Localization; Two-Way Ranging

Introduction

UAV technology is rapidly evolving and is being utilized for various applications such as terrain scouting, package delivery, swarming, and more [1]. UAV swarming is a concept where two or more UAV or aerial drones operate simultaneously whether autonomously or remotely operated by one controller. The drones in the mentioned application are able to communicate with each other and respond to situations autonomously while executing a specified task [2]. UAV swarming is one of the popular as it is able to resolve some of the limitations of the current aerial drone technology, specifically the issue on short operational period [3]. One important aspect in the 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 pin-point its location represented through XYZ coordinates, or through longitudes and latitudes. Satellites uses a Global Positioning System (GPS) which would return longitudes, latitudes, and may also return elevation parameters; however, this system poses limitations as it becomes inaccurate when the aerial drone operates indoors, or also known as GPS denied environments. To answer this limitation, indoor localization techniques utilizing various vision cameras were developed [4]. 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.

J. Priess et al, were able to conduct a swarm experiment with 49 units of Crazyflies and termed their system as the Crazyswarm. The researchers mainly utilized motion capture technology, specifically the Vicon Tracker, as their localization client. The Vicon Tracker would require a reflective marker to be placed on each aerial drone to obtain the raw position data. 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 position, consequently capturing the position of a placed marker each second. Each successive image is being compared to one another for the whole duration of the experiment to obtain position data. In addition, the researchers also utilized a configuration wherein an individual drone will be able to detect its proximity with respect to other aerial drone with the placed markers and autonomously move to avoid collision [5].

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 mounted on the aerial drone. The anchors are set as reference points and actively communicate with the tag through radio signals, 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 for aerial drone application are still limited as of the present as it is still a newly developed application.

Researchers from University of California, Berkley also conducted researches on localization utilizing ultra-wideband (UWB) radios. One approach focused on developing a general extended Kalman filter (EKF) that integrates the data between the on-board IMU and data obtained from UWB radios. The study was validated by a series of flight experiments such as hovering and executing a circular trajectory of a single drone. In addition, a motion capture system is used to obtain data, which is utilized as basis, for comparison. The experiment utilized 5 UWB beacons and the drone is set to execute the two mentioned tasks. After the experimentation, it was found that the position tracking error was relatively large [6].

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 which increases the accuracy of 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 translates a system's dynamics to a designated set of trajectories, was compared to the accuracy of the PID controller; and, the SMC produced more accurate readings for roll, pitch, and yaw compared to the designated PID controller [7].

The same proponents from University of California also developed an EKF estimator that allows the utilization of a mobile anchor concept. This was primarily achieved by minimizing the determinant of the covariance matrix. The experiment setup possessed static anchors around the test area; however, the researchers added dynamic anchor into the setup. Similar experiments such as hovering and trajectory tracking was done in this experiment and if showed an improvement of 14% in the obtained results [8].

Researchers from Bitcraze developed an aerial drone called the Crazyflie, as shown in figure 1. The 4 inches by 7 inches, 27 grams aerial drone is equipped with the bare minimum for flight operation in order to minimize the costs. In addition to the Crazyflie, expansion systems that are mountable to the aerial drone, were also developed for additional applications; with this in mind, one of mountable systems is the Loco Positioning System or LPS for short. The Loco Positioning 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 further explained in the next section. Current studies on radio localization do not offer much performance data on the Loco Positioning System with different anchor setup and space applicability. The paper presents a performance analysis of loco positioning systems with TWR protocol. It will determine the ideal setup based on the accuracy, the number of anchors in the setup and the space variations between anchors. The study presents various considerations and present 5 setup cases and conduct an experiment for each case. The study presents an accuracy performance of different configurations for radio localization operating on the Two-Way Ranging Protocol. This will aid users of the loco positioning system to determine the optimal operating setup with the consideration of parameters such as desired accuracy, size of available flight space, and number of anchors.

Figure 1. Crazyflie. Source retrieved from [9]

Loco Positioning System (LPS)

The Loco Positioning System is one of the localization techniques which uses radio signals. The system comprises mainly of two components, namely the Loco Positioning Deck and the Loco Positioning Anchor. The Loco Positioning Deck, or deck for short, is mounted on the Crazyflie to serve as a tag in the system. A tag is the object of interest in the system wherein its location is determined through radio communication between anchor and tag. On the other hand, the Loco Positioning Anchor is a separate component, not mounted to the Crazyflie, which is utilized to set the boundary space for the tag to be located. A system would usually utilize at least 3 or 4 anchors at a specified location and distance from each other depending on the application. The system's software is equipped with algorithms, such as the Kalman filter, in order to integrate relevant data, between the on-board IMU and the readings from the LPS, and produce an accurate reading on the localization. The anchor and decks are equipped with UWB radios that are based on the Decawave DWM 1000 module; additionally, communication is done in 2 protocols, specifically the Two-Way Ranging (TWR) and Time Difference of Arrival (TDoA) [10]. This research focuses its experimentations to the Two-Way Ranging protocol only.

Two-Way Ranging (TWR) Protocol

The TWR protocol is one of the 2 available protocols in the Loco Positioning System developed by Bitcraze. The protocol requires a tag deck that will be mounted on the Crazyflie and multiple anchors to serve as the reference points and to set the flight space. Both the tag and the anchor are in active communication with each other by sending and replying data packets in sequence. Figure 2, TWR for 2 Message Packets, shows a diagram on the communication process for 2 messages and can be expressed numerically in equation 1, with t_f as the time of flight. However, the TWR protocol requires 4 messages, to ensure a reply, confirmation, and a delivered report. Figure 3 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, establishing 1 exchange. Another exchange is made to remove or minimize the clock drift error and to produce a report. Equation 2 shows how the time of flight is calculated through the whole process and this data will be used to establish the position coordinates of the tag which is mounted on the Crazyflie [11].

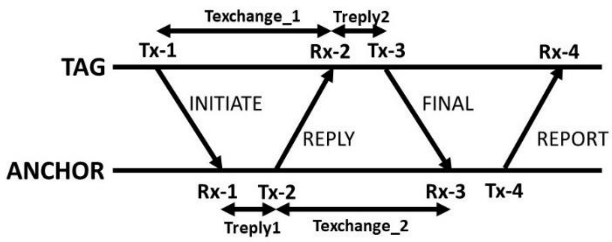

Figure 2. TWR for 2 Message Packets

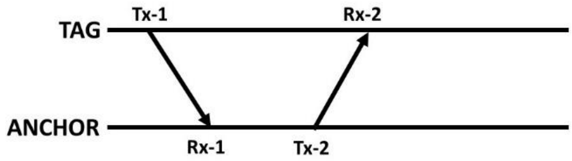

Figure 3. TWR Protocol

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

$$t_f = \frac{T_{exchange_1} * T_{exchange_2} - T_{Reply\ 1} * T_{Reply\ 2}}{T_{exchange_1} * T_{exchange_2} + T_{Reply\ 1} * T_{Reply\ 2}} \quad (2)$$

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 a reply is sent 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 [12].

$$Distance = C * \frac{(t_{Rx} - t_{Tx}) - t_{Reply}}{2} \quad (3)$$

where C = speed of light, 299792458 m/s
t_{Rx} = reception time
t_{Tx} = transmission time
t_{reply} = time delay of reply

Methodology

Figure 4 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.Design/Define Different Cases

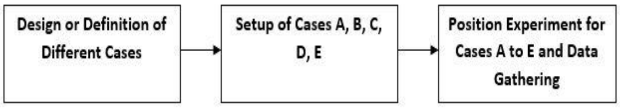

Figure 4. Methodology Flowchart

Various Cases are setup and tested out to determine the behavior and the accuracy of the Loco Positioning System. The experiment setups will be based on two parameters, namely, the number of anchors, and the space between anchors in the setup of 6 anchors. The prior aims to determine the optimal number of anchors required, while the latter setup aims to determine the optimal distance between anchors. Relative errors are retrieved from both parameters to offer a performance data of the different setups. Each parameter would offer a study on 3 different setups for comparison. A grid system with 0.3m increments, unless specified otherwise, is also used and applied to the experiment setup to serve as the true data and reference to where the Crazyflie, mounted with the TAG, is positioned to obtain data. Data is obtained through the Crazyflie PC Client as it is the official software for the Crazyflie drone and it has the LPS functionality and can return X, Y, and Z coordinates as the aerial drone is moved from one position to the other position. Though the experiment is done in a 2D space, similar behavior should be observed as well when applying in a 3D setup; consequently, 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 relative errors will be obtained from these setups to determine the performance of each case setup.

Case A

Case A utilizes 6 anchors, which is the recommended number of anchors to be used by the developers, with a distance of 1 meter from each other forming a rectangular space. Figure 5, 6 Anchor Setup, offers a visualization on the setup of the 6 anchors.

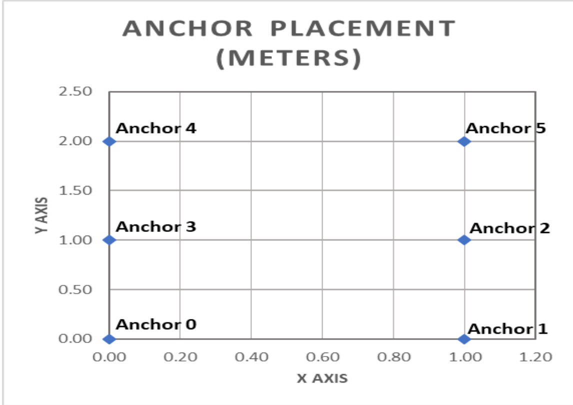

Figure 5. 6 Anchor Setup

Case B

Case B, as shown in figure 6, 4 Anchor Setup, utilizes 4 anchors with a distance of 1 meter from each other forming a square space. The objective of this setup is to validate the functionality of the TWR protocol operating on the minimum required number of anchors.

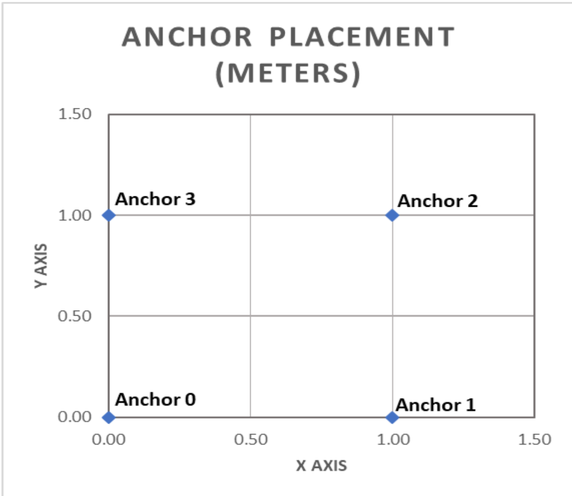

Figure 6. 4 Anchor Setup

Case C

Case B utilizes 3 anchors forming a triangular space as shown in figure 7, 3 Anchor Setup, to observe the behavior of the data when there is one less anchor from the required setup.

Case Setup Based on Distance Between Anchors

Another set of 3 cases, utilizing 6 anchors, are presented in this section. However, the distances between anchors varies for each case. The same parameter of average relative errors will be obtained from these setups to determine the performance of each configuration.

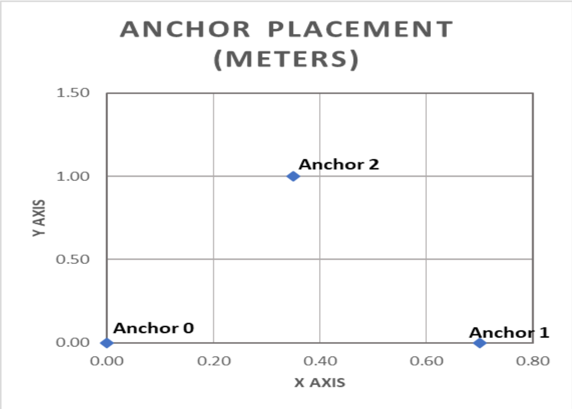

Figure 7. 3 Anchor Setup

Case D

Case D utilizes 6 anchors, as recommended by the developers, forming a rectangular shape as shown in figure 8, 6 Anchors (2m apart). The setup aims to present the behavior of and accuracy of the data in a big workspace. Case A will also be utilized in this portion as it also meets the criteria this set.

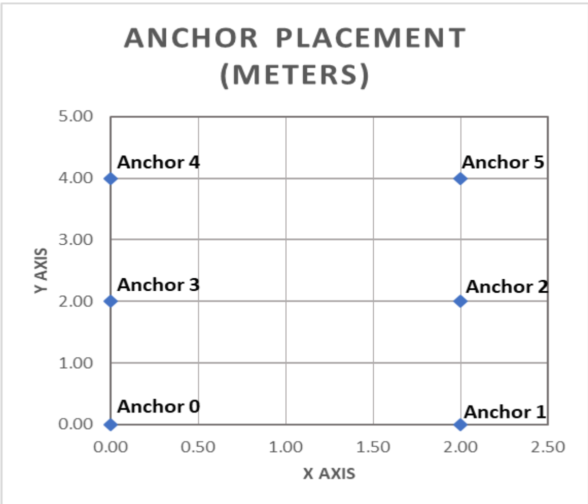

Figure 8. 6 Anchor (2m apart)

Case E

Experiments will also be conducted on a tight space, visualized in figure 9, 6 Anchors (0.6m apart), to observe how a small space can affect the accuracy of the setup, given that the space between anchors are 0.6m.

Setup for Each Case

The anchors are labeled from 0 to 5 and corresponding anchors will be used as per case requirements. Coordinates in meters will be written and saved to the anchors with the use of the PC Crazyflie client. Anchor 0 serves as the reference point with coordinates 0, 0, 0. The anchors are then set into the specified configuration of the case and are powered up by power banks. To ensure that the active protocol of the anchor is TWR, LED indicators, particularly *power* and *mode* must be turned on. The Crazyflie then is powered on facing towards the positive X axis to calibrate its on-board inertial measurement unit (IMU) and within the boundary set by the anchors. The setup is verified in the PC Crazyflie client when both the anchors and tag are detected and movements are reflected on the graphs in the client.

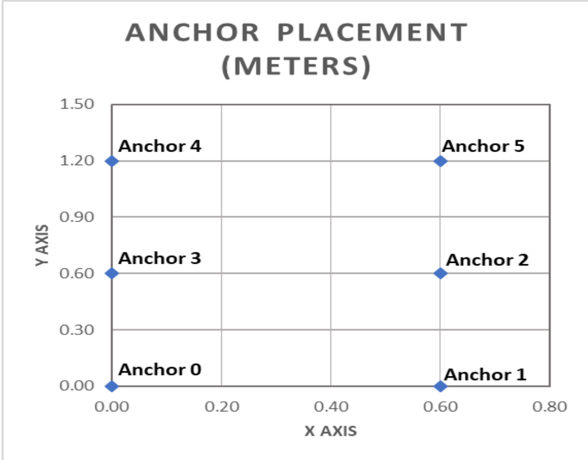

Figure 9. 6 Anchors (0.6m apart)

Position Experiment for Each Case

Experimentation will involve manually positioning the aerial drone in various positions along the 2D grid and the x and y coordinates are recorded. The z-axis data is omitted since the research focuses on 2D experimentation. This process will be repeated around 3 to 5 times to obtain an average data. Figure 10, Position Experiment Setup, below offers a visual representation on how the experiments are conducted. The data that is obtained from the experiment will then be analyzed and evaluated. The data gathered should provide similar data or minimal variance as compared to the true values of the data.

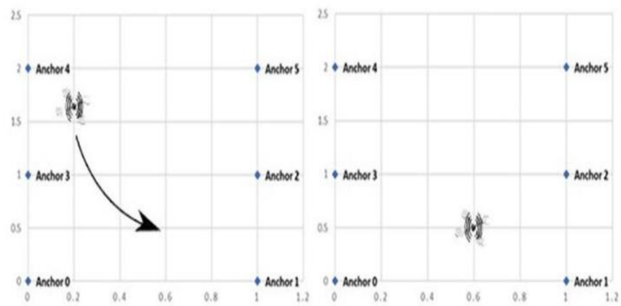

Figure 10. Position Experiment Setup

Results

Each case presents a figure showing different colored shapes in a 2D graph. The green diamond denotes the anchor location, blue squares as the specified positions or true value positions, and yellow triangles represent the position of the Crazyflie estimated by the loco positioning setup. Additionally, labels such as set 1, set 2, set 3, set 4, and set 5 are placed beside the yellow triangles to reference which estimated point corresponds to which specified point, allowing for easier comparison. Set 1 refers to the column of blue squares (specified coordinates) closes to the reference point, eg. Case A Set 1 refers to the set of points on X = 0.0 m. Succeeding sets corresponds to the succeeding columns on the right after the first set.

Case Setup Based on Number of Anchors

This portion shows the results obtained for the case setups based on the number of anchors.

Case A

Experimentation on case A, as shown in figure 11, Case A Results, showed that the values along the border and some sets do not offer a clear pattern. It is also observed that 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. The average relative error obtained in this setup has the average relative error obtained is 8.45%.

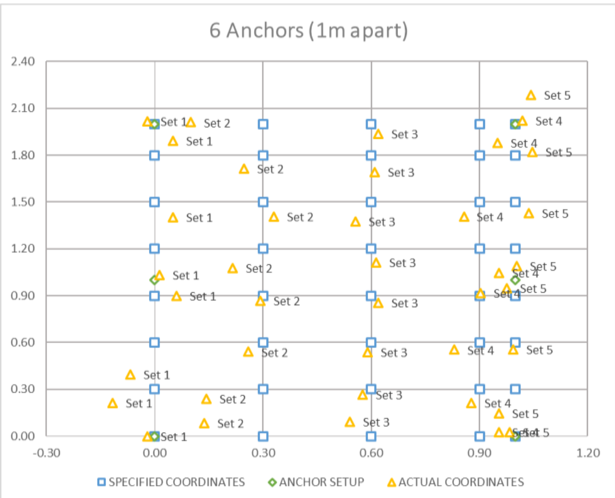

Figure 11. Case A Results

Case B

The setup of Case B is based on 4 anchors with 1 m distance from each other is shown in figure 12, Case B Results. The objective of this case is to validate the minimum requirements of the TWR protocol of the Loco Positioning System. The study gave a maximum error variance of 22cm at set 4 while most points remained within a 10cm variance. Given this setup and space configuration, an average relative error of 12.27% is obtained.

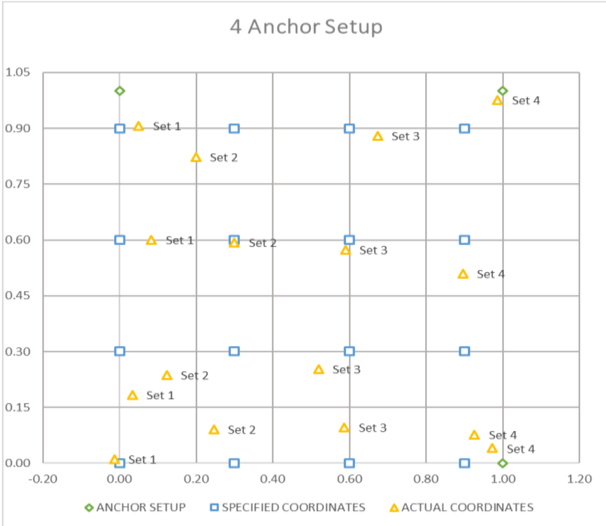

Figure 12. Case B Results

Case C

The setup of case C utilizes 3 anchors forming a triangular shape is shows in figure 13, Case C Results. The objective of this experiment is to determine the behavior of the data when the minimum required anchors is not met. Set points are also present beyond the boundary to determine whether the tag can be read beyond the set boundary. This setup along with the specified points outside the set boundary gave an average relative error of 28.42%. However, analyzing the data of the points within the boundary would give an average relative error of 25.96%

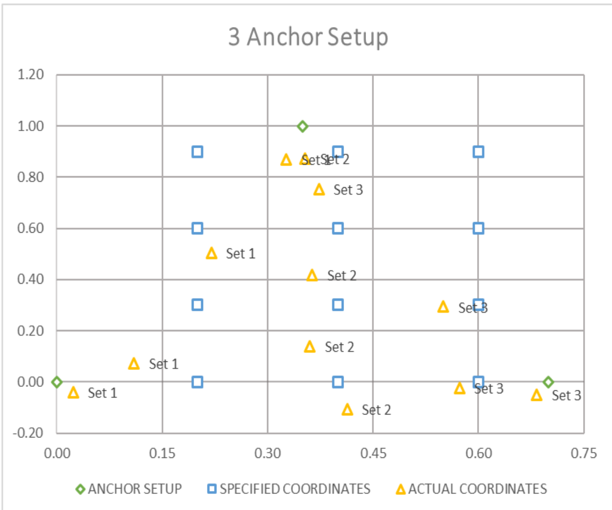

Figure 13. Case C Results

Case Setup Based on Distance Between Anchors

This portion shows the results obtained for the case setups based on the number of anchors.

Case D

Case D utilized 6 anchors placed 2m apart from each other and the specified positions are set to have increments of 60cm from each other. The setup serves as the ideal setup as the estimated points are close to the specified points as shown in figure 14, Case D results. However, data on set 1 had points with variances of 14 cm while most of the remaining points possess a less than 6cm variance. Set 1 data are not as accurate as compared to the other points since these records are taken along the boundary of the setup. Experiments in this setup bore an average relative error of 3.60%.

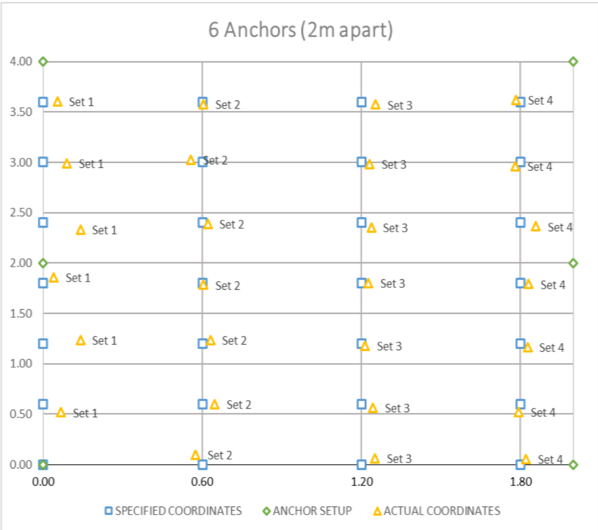

Figure 14. Case D Results

Case E

Case E utilized 6 anchors placed 0.6m or 60cm apart from each other and the specified positions have increments of 0.15m or 15cm from each other. The objective of this case Is to determine the accuracy and behavior of the average data with a small setup. 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 other sets however, do not give a clear pattern on the values it returns. It is also observed that the points are inside the boundary. Experimenting in this setup will provide an average relative error of 8.68%.

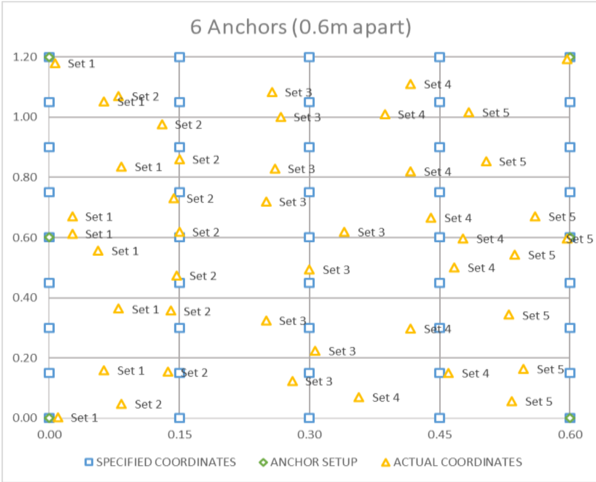

Figure 15. Case F Results

Evaluation

Results from case A generally gave an average relative error of 8.45%. It showed that the estimated points along set 3 are observed to near to the specified points offering an average relative error of 4.74% while the other sets are observed to be scattered; additionally, these sets give average relative errors from 6% to 7%. It can be inferred in this setup that 60 cm displacement between anchors and specified coordinates would present relatively accurate data.

Case B operating with 4 Anchors can still function as designed, however, an average relative error obtained is around 12.27%, around 4% more error compared with Case A.

Case C is still capable of functioning even with 1 less anchor from the required returning a relative average error of 28.42%. As the Crazyflie equipped with the Tag component moves to the specified points, denoted by blue squares, it can be observed that the estimated data, denoted in yellow triangles, follows the shape established by the positioned anchors. This observation suggests that the Crazyflie should operate within the set boundary established by the anchors. Specified points beyond the boundary will give inaccurate estimates on the position as it will follow the shape set by the anchors. Further experimentation was conducted with 2 anchors set along the x-axis. The estimate data observed formed a linear pattern, regardless of the presence of y-axis values. between the two anchors. It should be noted that operating within the set boundary would give out an average relative error of 25.96%.

From cases A to C it was observed that there should be a minimum of 3 anchors for the operation of the loco positioning. The average relative error is inversely proportional with the number of anchors present; therefore, the more anchors utilized, the average relative error is decreases. Table 1, summary of results for cases based on number of anchors, show the cases, the number of anchors used per case, and its corresponding average relative error to aid users in determining which setup is ideal for their use based on their allowable error.

Table 1. Summary of Results for Cases Based on Number of Anchors

Case Configuration	# of Anchors	Average Relative Error
Case A	6	8.45%
Case B	4	12.27%
Case C	3	25.96%

Case D is the ideal setup since it offered an average relative error of 3.6%. However, this setup requires a large space and 6 anchors. Data retrieved along the borders may be unreliable since the estimated point tends to stay inside the boundary. This case experiment also confirms the claim that 60 cm displacement between anchors and specified points would offer accurate readings.

Case F, which possessed smaller distances from each other still offered an average error of 8.68%, around 0.23% more than the previous case. Though the increase in error may be small or negligible, an increase is still observed. This suggests that the average relative error is also inversely proportional to the distance between the anchors even though the difference in error is small. Table 2, summary of results for cases based on distance between anchors, should aid users in deciding how much space they should utilized based on their allowable error.

Table 2. Summary of Results for Cases Based on Distance Between Anchors

Case Configuration	Distance	Average Relative Error
Case D	2 meters	3.85%
Case A	1 meter	8.45%
Case E	0.6 meters	8.68%

Conclusions and Recommendations

The research presented 3 setups for each specified parameter, namely the number of anchors, and the distance between anchors. 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 accuracy of the system increases as the number of anchors increases from 3 to 6, giving average relative errors from 25.96% to 8.45%. For the cases based on distance between anchors, it was observed that there is an increase in error as distance decreases as shown in cases D to F. The paper was able to present cases base on the two parameters and offered accuracy results for each case in the set parameter.

Users may utilize 4 anchors with 1-meter distance between anchors for 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 parameter in swarm application. It is hypothesized that additional anchors beyond 6 offer more redundancy but will not significantly offer more accurate results; experiments can be conducted to validate this claim. Since it was observed that the estimated data follows the boundary or shape set by the positioned anchors, further experiments can be done with different shape configuration of the anchors while observing the behavior and accuracy for each configuration for specialized applications.

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