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Unmanned Aerial Vehicle Landing Based on Ultra-Wideband Localization System and Optimal Strategy for Searching Optimal Landing Point

Meng Wu

***Abstract*—**Unmanned aerial vehicle (UAV) landing technology is a common task that is required to be fulfilled by fly robots. In this paper, the Crazyflie 2.0 is located by ultra-wideband (UWB) localization system that contains four UWB anchors. Another UWB anchor is introduced and installed on a stationary platform. One cost function is designed to find the minimum distance between Crazyflie 2.0 and the anchor installed on the stationary platform. The coordinates of the anchor are unknown in advance, and the goal of the cost function is to define the location of the anchor, which can be considered as an optimal landing point. When the cost function reaches the minimum value, the corresponding coordinates of the UWB anchor fixed on the stationary platform can be calculated and defined as the landing point. The simulation shows the effectiveness of the method in this paper.

***Keywords*—**Unmanned aerial vehicle landing, ultra-wideband localization system, ultra-wideband anchor, cost function, stationary platform.

I. Introduction

UAV landing and obstacle avoidance safely are two related areas of research with broad commercial and military applications. How to do indoor UAV landing and obstacle avoidance effectively is still a major challenge in small size UAV nowadays.

Compared with other kinds of indoor localization methods, UWB localization systems are becoming increasingly available and relatively affordable with localization accuracy ranging from several centimeters to several dozen centimeters depending on measurement conditions and particular system [1]-[6]. Position estimation provided by UWB system makes use of similar techniques as GPS systems, where so called anchors (antennas) are analogous to satellites and UWB tags are similar to GPS receivers. UWB localization systems can be used both indoors and outdoors, and are based on time-of-light measurements, in [7], authors used UWB system, accelerometer and gyroscope to estimate accurate indoor position. In [8], UWB signals are applied to realize indoor moving objects detection and range estimation.

Multi Class Support Vector Machine (MC-SVM) architecture is employed in [9] to both localize targets and identify them. In [10], Improved UKF algorithm is applied to achieve UWB localization estimation in NLOS (Non-Line of sight) environment. In [11] and [12], a dynamically adapting covariance Kalman filter based on sensor fusion of UWB localization and inertial measurements is employed in a medical room. In [13] and [14], a self- localization system is reported based on one-way communication with fixed-position UWB modules.

In [15], a high-precision UAV localization system for interconnection between unmanned ground robot (UGR) and UAV is presented and a fusion of 2D Lidar sensors, camera and ultrasonic system is to achieve robust UAV landing on the moving UGR. In [16], the application of infrared beacons for fixed-wing UAV landing is presented. In [17], the authors propose a system based on visual tag tracking and the ground robot position prediction system is used in this paper. In [18], authors proposed an implementation of a landing system for AR Drone 2.0 quadrotor and ROS packages are applied to realize camera calibration, marker recognition, drone control and a PID Controller is implemented to control the drone's velocity to realize hovering and landing stably. In [19], a visual camera is applied to realize precise landing on a static platform. In [20], bottom-facing and front-facing cameras are combined with inertial sensor to navigate and land AR.Drone 2.0 quadrotor in a visual landmark described as ArUco marker. In [21], a sonar sensor is applied to land a fleet of quadcopters on an unknown terrain.

Considering a fact that expensive and high-resolution cameras are not widely used in mini quadcopters such as Crazyflie 2.0, which is a light-weight quadcopter and it is not feasible for it to carry a big camera on it. In addition, several FPV (First-Person View) cameras are not high-resolution cameras. Particularly, in weak illumination environment, it is difficult for the FPV cameras to do visual ArUco marker detection to find an accurate landing point on a stationary platform. So, based on the considerations, only UWB localization system is applied in this paper to realize Drone landing in a small-scale indoor environment. Four UWB anchors are used to locate the Crazyflie 2.0, another UWB anchor is installed on a stationary platform and the anchor's position is considered as an ideal landing point, when the cost function reaches the minimum values, it means that the Crazyflie 2.0 obtains minimum distance between itself and the ideal landing point indicated by the anchor installed on the stationary platform.

This paper is organized as follows. In Section II, system architecture of this platform is introduced, In Section III, Landing Algorithm is introduced and analyzed. In Section IV, simulation results are discussed. Conclusions are summarized in Section V.

Meng Wu is with Chinacoal PingShuo Group Company in Shanxi Province, P.R.China (e-mail: wumenghust@163.com).

II. System Overview

The general system architecture of the proposed motion planning strategy is shown in Fig. 1. In this paper, a single UWB anchor and UWB localization system which contains four UWB static anchors are combined to realize UAV landing. The proposed algorithm in this paper can find an optimal landing point on the stationary platform to land the Crazyflie 2.0 at the point safely. The flow chart is shown in Fig. 1.

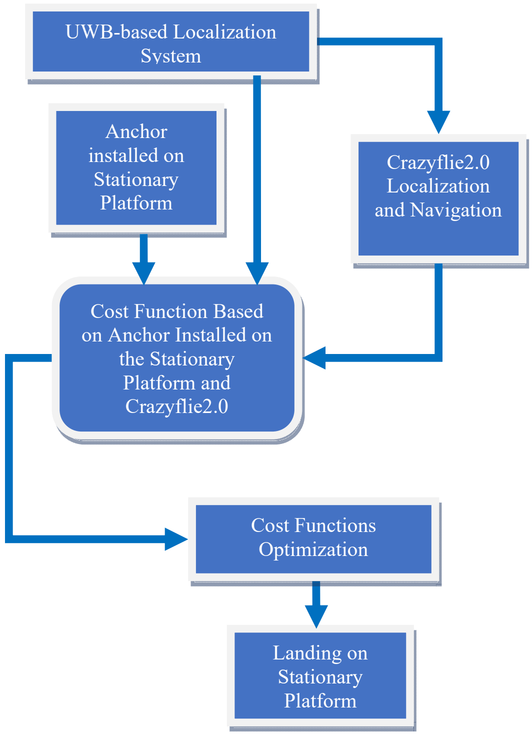

Fig. 1 Flow-Chart of Crazyflie 2.0 Landing Algorithm

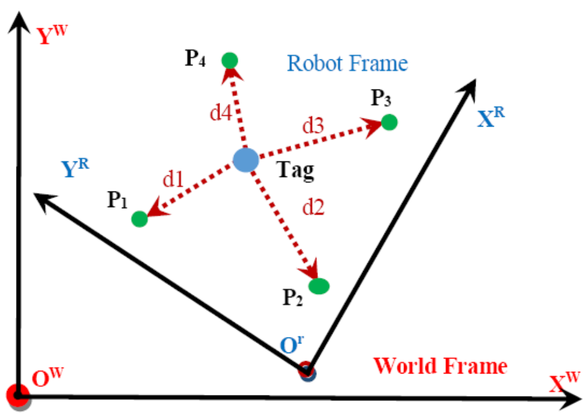

Fig. 2 Graphic Illustration of UWB Localization Theory

The general system architecture of the proposed UAV landing strategy is shown in Fig. 1. The DWM1000 chip installed on the Crazyflie 2.0 can detect UWB signals from different anchors, then, TOA (Time of Arrival) signals are to calculate the position of Crazyflie 2.0. A single UWB anchor which coordinates are unknown in advance is installed on a stationary platform and a cost function is configured to search for an optimal landing point which is indicated by the coordinates of single UWB anchor on the platform. The coordinates of UWB anchor which are response to minimum value of cost function can be considered as optimal landing point on the stationary platform.

A. Introduction of UWB Localization System

In general, UWB localization algorithm includes two steps. In the first step, four distances between the transmitter (the tag radio sensor) and four receivers (the four anchor radio sensors) are calculated, it is shown in Fig. 2, the four distances can be calculated by Time of Flight (TOF) which is shown as Fig. 3.

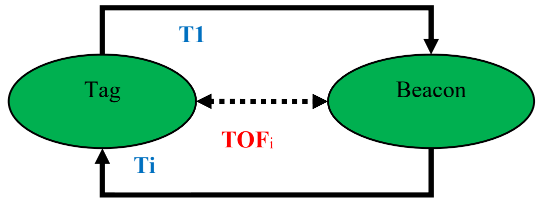

Fig. 3 Time of Arrival Propagation Diagram

Fig. 3 shows the time of arrival propagation diagram, where T1 is the time difference between the time when the tag radio sensor sent the signal to each of the anchors and the time when the Tag radio sensor received the signal from each of the anchors, and TOFi is the time difference between the time when each of the anchors received the signal from Tag radio sensor and the time when it is ready to send the signal back to the Tag radio sensor. Using the received TOFi from each of the anchors, the Tag radio sensor can then compute the corresponding distance between Tag and anchors.

$$\begin{cases} TOF_i = \dfrac{T_1 - T_i}{2} \\ i = 1 \cdots 4 \\ d_i = c \bullet TOF_i \\ c = 3\times 10^8 \left(m/s\right) \end{cases} \quad (1)$$

In the second step, the coordinate of the mobile Tag installed on the robot is calculated based on its distance to other stationary anchors using trilateration. Given four reference points P1(x1,y1), P2(x2,y2), P3(x3,y3), P4(x4,y4) in world frame, the position P(x, y) of the robot in world frame is equivalent to find the solutions in (2):

$$\begin{cases} (x - x_1)^2 + (y - y_1)^2 = d_1^2 \\ (x - x_2)^2 + (y - y_1)^2 = d_2^2 \\ (x - x_3)^2 + (y - y_3)^2 = d_3^2 \\ (x - x_4)^2 + (y - y_4)^2 = d_4^2 \end{cases} \quad (2)$$

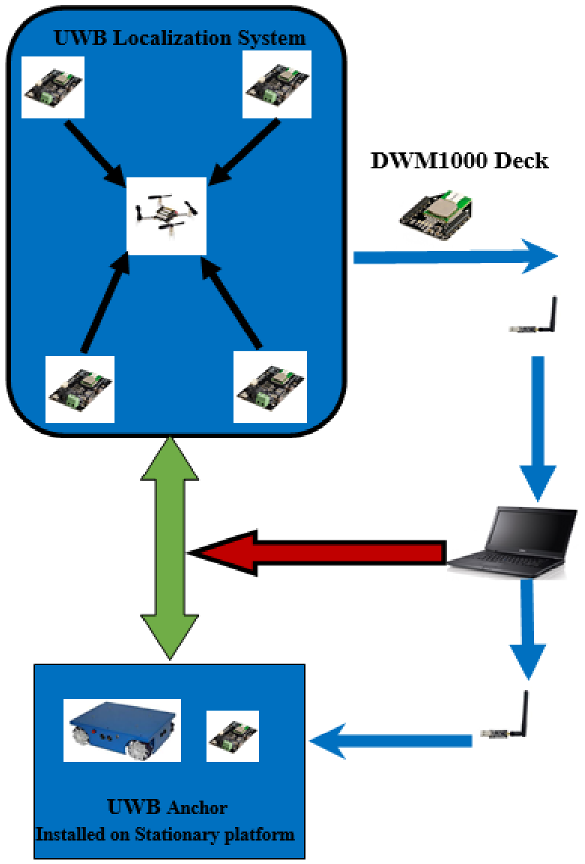

Fig. 4 Flow Chart of UAV Landing Based on UWB Localization System

Equation (2) can be written as follows:

$$\begin{bmatrix} 1 & -2x_1 & -2y_1 \\ 1 & -2x_2 & -2y_2 \\ 1 & -2x_3 & -2y_3 \\ 1 & -2x_4 & -2y_4 \end{bmatrix} \begin{bmatrix} x^2+y^2 \\ x \\ y \end{bmatrix} = \begin{bmatrix} d_1^2-x_1^2-y_1^2 \\ d_2^2-x_2^2-y_2^2 \\ d_3^2-x_3^2-y_3^2 \\ d_4^2-x_4^2-y_4^2 \end{bmatrix} \quad (3)$$

Using four computed ranges di, the mobile tag's position can be determined based on trilateration method or least-square method. In this paper, an UWB localization system is employed to do Crazyflie 2.0 localization.

B. System Architecture of Landing Algorithm

In Fig. 4, four UWB anchors are configured to calculate the Crazyflie 2.0's localization based on TOF. DWM1000 chip is installed on the crazyflie to send and receive TOF signals from each anchor. Another UWB anchor is installed on a stationary platform and its coordinates are considered as ideal landing point. Crazyradio PA is connected to Laptop by USB port to communicate data between UWB Localization System and ROS package. In ROS package, a cost function is built based on the relative distance between the Crazyflie 2.0 and UWB anchor installed on the stationary platform, when the cost function reaches the minimum value, the corresponding coordinates of UWB anchor on the stationary platform can be defined as optimal landing coordinates on the stationary platform.

III. Description of Proposed Algorithm

In this paper, the coordinates of landing point are defined as the coordinates of an UWB anchor installed on a stationary platform, the cost function is based on the relative distance between the Crazyflie 2.0 and the anchor. Cost function in this paper is defined as:

$$\begin{cases} \left\| X_{Landing} - X_{UAV} \right\| = \sqrt{(x_{Landing}-x_{UAV})^2+(y_{Landing}-y_{UAV})^2+(z_{Landing}-z_{UAV})^2} \\ f_{Landing}\left(X_{Landing}\right) = \left\| X_{Landing} - X_{UAV} \right\| \end{cases} \quad (4)$$

In (4): $x_{Landing}$, $y_{Landing}$ and $z_{Landing}$ = The Landing Coordinates which can be defined by the minimum value of $f_{Landing}\left(X_{Landing}\right)$ and it can be defined by the coordinates of an UWB anchor which is installed on a stationary platform. x_{UAV} , y_{UAV} and z_{UAV} = The coordinates of Crazyflie 2.0 which can calculated by UWB Localization System.

$$\begin{cases} f\left(x_{Landing}, y_{Landing}, z_{Landing}\right) = \left\| X_{Landing} - X_{UAV} \right\| \\ \dfrac{\partial f\left(x_{Landing}, y_{Landing}, z_{Landing}\right)}{\partial X_{Landing}\left(x_{Landing}, y_{Landing}, z_{Landing}\right)} = \begin{cases} \dfrac{d\left\| X_{Landing} - X_{UAV} \right\|}{dx} \\ \dfrac{d\left\| X_{Landing} - X_{UAV} \right\|}{dy} \\ \dfrac{d\left\| X_{Landing} - X_{UAV} \right\|}{dz} \end{cases} \\ \min\left(f\left(x_{Landing}, y_{Landing}, z_{Landing}\right)\right) \Rightarrow \left(x_{landing}, y_{landing}, z_{landing}\right) \end{cases} \quad (5)$$

When $\left\|X_{Landing}-X_{UAV}\right\|$ meets (5), the derivative of $\left\|X_{Landing}-X_{UAV}\right\|$ is a good solution to find optimal coordinates of the cost function $f\left(x_{Landing}, y_{Landing}, z_{Landing}\right)$.

After obtaining the minimum value of $f\left(x_{Landing}, y_{Landing}, z_{Landing}\right)$, the corresponding coordinates $\left(x_{landing}, y_{landing}, z_{landing}\right)$ can be defined as the landing point.

IV. Simulation and Results

In this paper, an UWB anchor is installed on a landing platform. Four UWB anchors are installed on the four top corners of the tent. When the Crazyflie 2.0 is flying inside the tent, its position is easily obtained by four UWB anchors based on the theory from Section II *A*. An optimal landing point which is illustrated by the coordinates of UWB anchor on the stationary platform can be obtained, when the cost function in (5) obtains a minimum value.

The experiment is implemented inside a tent with sizes Length: 2 m; Width: 2 m; Height: 2 m. A ROS node in PC is to realize the cost functions. Experiment configurations are shown as Fig. 5, Tables I and II.

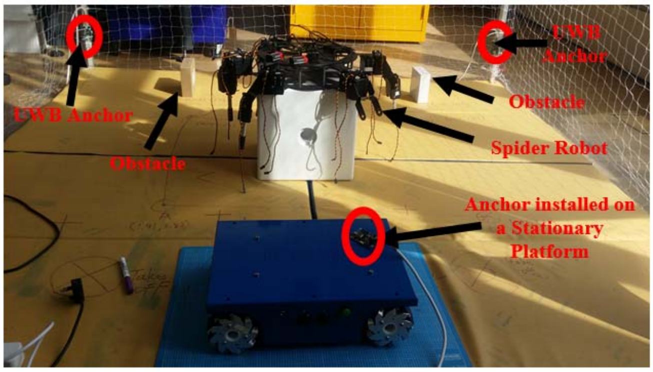

Fig. 5 Experimental Configuration in Indoor Tent

In Fig. 5, a Spider robot and several boxes are configured as obstacles in this experiment, an anchor is fixed on a platform. The Crazyflie 2.0 can navigate itself and landing on the platform based on UWB localization System and the cost functions defined in (4) and (5). The Parameters configuration of UWB localization system and Obstacle avoidance Setting in this experiment are shown in Tables I and II.

TABLE I
CONFIGURATION AND COORDINATES OF EACH ANCHOR IN UWB LOCALIZATION SYSTEM

Anchor ID	X (m)	Y (m)	Z (m)
1	0	0	0.16
2	0	1.95	0
3	0.75	1.10	0
4	1.95	0	1.63

TABLE II
CONFIGURATION AND COORDINATES OF EACH OBSTACLE

Obstacle ID	X (m)	Y (m)	Z (m)
Spider Robot	1.40	1.33	0.52
Grey-Box	0.45	0.51	0.34
White-Box	0.47	1.40	0.35

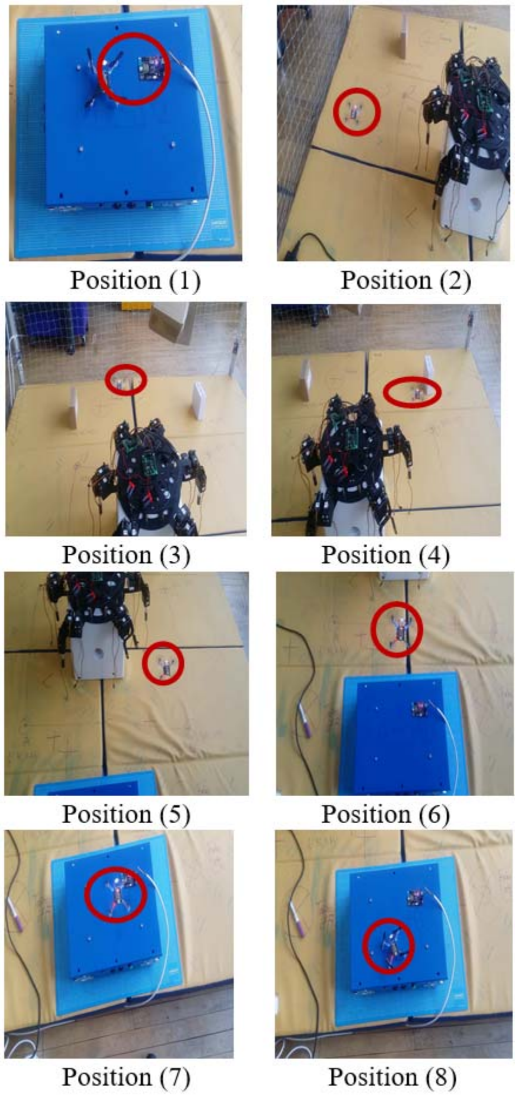

Fig. 6 Obstacle Avoidance and Landing Test Based on UWB Localization System and Optimal Coordinates Search Strategy

In Fig. 6, When the Crazyflie2.0 began to fly from the initial position which was (1.74 m, 0.94 m, 0.26 m), cost function described in (5) can be applied to calculate an optimal landing point when it reached to a minimum value. In this paper, an UWB anchor is installed on the stationary platform and its coordinates are unknown in advance and they can be considered as an ideal landing point. Crazyflie 2.0 is controlled by ROS package to take off from a stationary platform and still land on the stationary platform, the cost function described as (5) can help the Crazyflie 2.0 to find an optimal position to land safely.

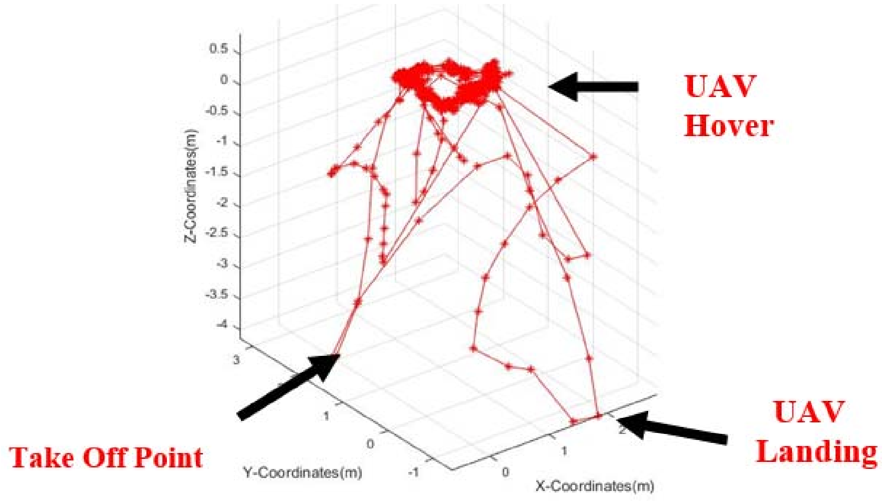

Fig. 7 UAV Landing Trajectory Based on UWB Localization System

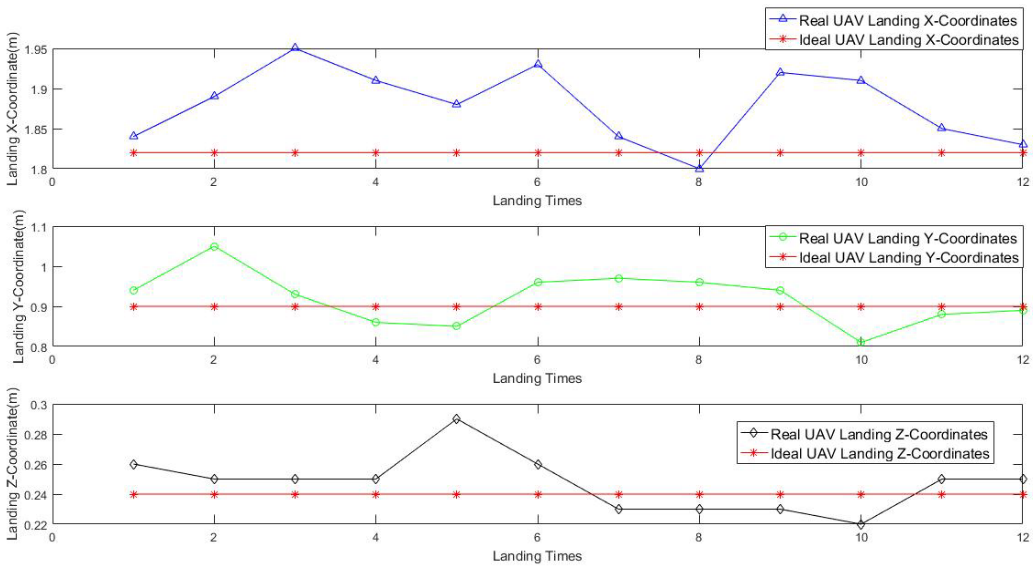

Fig. 8 Landing Points Comparison Between Real UAV Landing Points and Ideal Landing Points

In Fig. 7, it shows 3D trajectory of the Crazyflie 2.0 in the experimental scene, cost functions defined in (5) can help the Crazyflie 2.0 to find an optimal landing point on the platform. The coordinates of UWB anchor installed on the stationary platform can be calculated in (5) and the coordinates are considered as optimal landing point.

From Fig. 8, the landing points are compared between real landing points and ideal landing point (1.82 m, 0.90 m, 0.24 m) which is denoted by the initial position of UWB anchor on the stationary platform in this experimental. The fluctuation of comparison plots describes several landing disturbances from measurement outliers.

In Fig. 9, the landing errors between real landing positions and ideal landing point (1.82 m, 0.90 m, 0.24 m) indicate that some measurement outliers arise from electromagnetic disturbances and ultra-wideband (UWB) signal transmission errors in Indoor environment. When the Crazyflie 2.0 is flying in a fixed experiment area, TOF calculation errors and several signal delays between Crazyflie 2.0 PA radio and PC Host Computer also cause some calculation errors in cost functions described in this paper.

V. Conclusion

This paper proposed a landing approach for small size UAV named Crazyflie 2.0 using UWB localization system and optimal distance between the Crazyflie 2.0 and a UWB anchor installed on a stationary platform. Specifically, a cost function is configured based on relative distances between the Crazyflie 2.0 and a UWB anchor installed on a stationary platform. The derivation of cost function is applied to find minimum value of the cost function. The correspond optimal coordinates can be considered as landing point of Crazyflie 2.0 on a stationary platform.

In the future, landing Crazyflie 2.0 on a mobile robot is a good approach and better path planning methods should be proposed to improve the ideas in this paper.

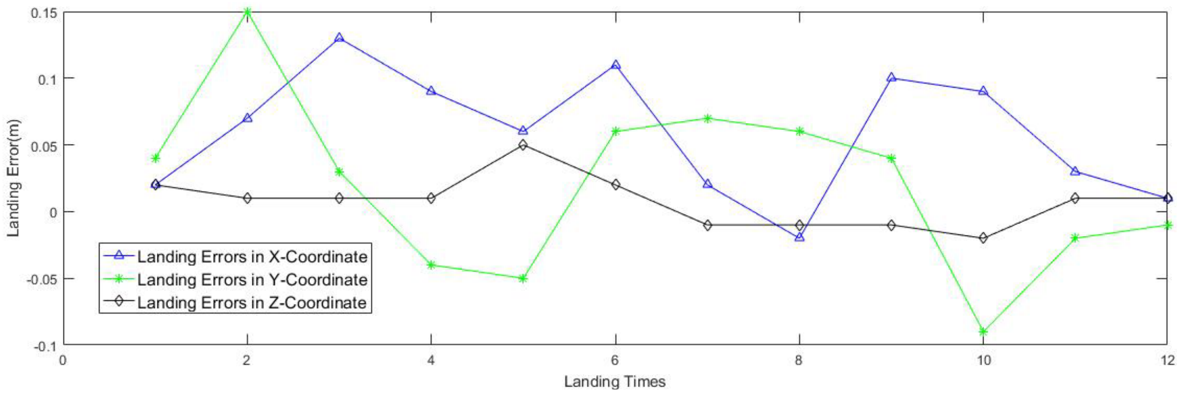

Fig. 9 Landing Error Comparisons in X, Y, Z coordinates

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