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Compact docking station for sub-150g UAV indoor precise landing

Thomas Martin^{1,2*}, Jefferson Roman Blanco¹, Jean-Baptiste Mouret², Thibaut Raharijaona¹

Abstract—To be used at their full potential, sub-150g drones need to be integrated in a “foolproof” deployment system, from take-off to landing. In this paper, we introduce a compact (less than 15×15 cm) docking station that could fit in a suitcase. To achieve accurate drone localization, we evaluated various systems (OptiTrack Duo/Trio, Bitcraze’s radio-based system) and found that a vertically mounted lighthouse sensor from the HTC Vive system offers a few centimeters of accuracy while being significantly smaller than multi-camera systems. Our final docking station design incorporates this sensor, along with an actuated landing pad that retracts from the sensor’s field of view during landing. This novel landing system paves the way for the use of small indoor drones by professionals without the need for extensive drone training.

I. INTRODUCTION

Outdoor quadrotors have become ubiquitous and are routinely utilized across various scenarios, such as inspecting industrial buildings for leaks, capturing aerial footage for documentaries, and participating in search and rescue missions [1]. By contrast, indoor quadrotors are rarely used despite their potential to provide assistance in numerous contexts. For example, firefighters often need to locate “hot points” within expansive warehouses: one or several small autonomous UAVs would be ideal for this mission. In addition, sub-150g indoor UAVs do not require a drone pilot licence, which makes them ideal for many professionals.

The infrequent deployment of small indoor drones mainly comes from the need for a “foolproof” system that operates reliably and autonomously for untrained users. In an ideal scenario, users would open a suitcase containing both a UAV and a docking station, press a button, and watch as the small UAV takes off, collects data, and autonomously lands. Such a system would allow users to focus on other tasks without the need for manual UAV control or piloting skills. Outdoor UAVs are capable of doing such mission, because they rely on GPS for accurate positioning, but GPS is not available indoor.

This paper focuses on the last phase of an autonomous mission: autonomously landing on a docking station that is small enough to be carried in a suitcase. Precision landing is mainly a localization challenge, this is why our main question is how to precisely locate a sub-150g UAV with a sensor (or a set of sensors) that is straightforward to deploy.

Contributions: The main contributions of the present paper are:

- 1) a comparative analysis of four indoor positioning systems to evaluate their effectiveness for precise UAV landing/docking;
- 2) the design of a compact base station for precise indoor UAV docking (Fig. 3), based on a technology from virtual reality (HTC Vive lighthouse);
- 3) the integration with a 120g quadrotor (based on Bitcraze’s open-source quadrotor) (Fig. 1).

The supplementary video shows 3 successful landings with the Lighthouse-based docking station.



Fig. 1: A high-resolution, time-lapse shooting sequence capturing the autonomous landing of the Proxyflie drone (a.k.a. Proxydrone). The sequence is depicted in different stages: initial alignment with the docking station, followed by a gradual descent and approach with the landing gear extended towards the docking interface, culminating in the drone resting securely upon the docking station, signifying the completion of a successful landing. The supplementary video (<https://tinyurl.com/SpotreturnICUAS24>) shows 3 successful landings with the Lighthouse-based docking station.

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II. STATE OF THE ART

Precision docking on small surfaces in GPS-denied environment is one of the most significant challenges in the development of autonomous docking systems for quadrotors [2], [3]. Precision docking on small surfaces presents challenges, including:

- 1) Spatial constraints: Limited space demands high-precision navigation and control systems to ensure accurate docking without collisions [4]. The paper develops an algorithm for drones to perform vertical landings at designated points in urban areas, focusing on avoiding collisions with obstacles by using 3D LiDAR for real-time obstacle detection.
- 2) Sensor limitations: The effectiveness of sensors in detecting small surfaces from a distance and under various environmental conditions can impact docking accuracy [5]. The paper presents a system for autonomous UAV landing on moving platforms, integrating vision-based target detection, Extended Kalman Filter (EKF) for accurate target position estimation, and a Model Predictive Control (MPC) based control scheme.
- 3) Environmental variability: External factors such as wind, lighting conditions, and physical obstacles complicate the docking process [6]. The paper introduces a quadcopter system designed for precise landing on moving targets, incorporating a disturbance observer-based control algorithm and an autonomous landing planner in dynamic environments.

Several mechanical designs have been explored to address the precision docking challenges:

- 1) Inverted docking station: The design proposed in [7] of an docking station on the ceiling is a solution to precision docking that simplifies the UAV's alignment and connection process, relevant for small surface areas.
- 2) Docking platforms: Specific docking platform designs intended to facilitate precise UAV docking. For instance, the docking platform designed in [8] incorporate features aimed at enhancing docking accuracy on small surfaces.
- 3) Autonomous docking mechanisms: An autonomous docking mechanism with a static ring and actuated legs is constructed for precise positioning and successful docking in variable conditions in [9].

III. DOCKING SYSTEM

A. UAV

The research drone we developed, called "Proxyflie", is based on Bitcraze's control board Bolt 1.1, a versatile and open-source development platform for micro-drones or nano-drones. It has been chosen for its adaptability and extensive community support. This board allows the use of brushless motors which have better reliability and performance compared to brushed motors. We use the ROBO 1202.5

11500kv FPV motors associated with GEMFAN 3018 2-blade propellers from Flywoo. The XSD 7A ESC from Flash Hobby makes the bridge between the control board and the motors. The drone is powered by a single 18650 Li-ion battery from Sony Murata with a $\geq 30A$ discharge current and a capacity of $\geq 2600mAh$ held in a battery support from Keystone. The electronic hardware is fixed on a 2mm thick carbon fiber frame on which we can add 3D printed feet and a structure to add extension decks on top of it thanks to a homemade design ribbon cable. The drone weights about 114g and has a hovering autonomy of about 15min.

With this STM32F4-based control board, Bitcraze sells extension decks that connects to the control board to add sensors to the drone, as shown in Fig. 2 detailing the underside of the drone. An IMU and a barometer are already present on the control board. We have chosen 2 decks to demonstrate the system. The Flow deck, in the middle of the drone, adds an optical flow sensor and a Time of Flight (ToF) sensor to estimate its relative horizontal displacement and its altitude respectively. It is used as an example of a localization system used for exploration, far from the docking station.

The Lighthouse deck, below the Flow deck in Fig. 2 adds 4 IR light sensors that reads the information sent by the station's IR lasers. The decision to mount the lighthouse deck facing downward is for optimal visibility of the station. Putting it on the side of the drone creates interactions between the IR light and the propellers before reaching the sensors, hence reducing the field of view and inducing errors in reading the information. Also, the drone would have to turn around to have the deck facing the station. To estimate its position, the drone uses an algorithm called the "EKF Lighthouse Measurement model" implemented by Taffanel et al. [10] from Bitcraze. This model uses the Extended Kalman Filter (EKF), the estimated positions of the IR sensors and the data received on each IR sensor.

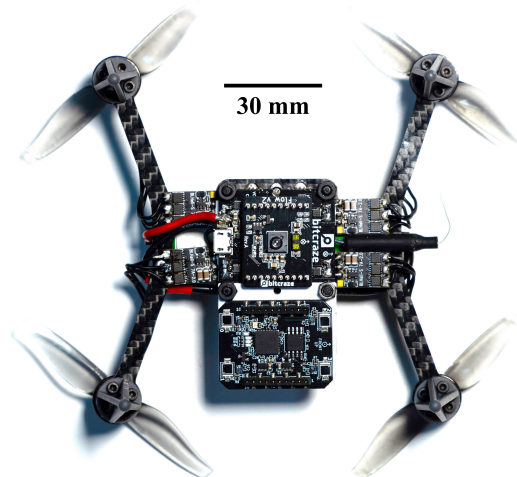


Fig. 2: Bottom view of the Proxyflie drone with the integrated stabilization and localization systems: Flow deck (center) and Lighthouse deck (sideways), respectively.

B. Docking station

The docking station is composed of a 3D printed box encasing a SteamVR Lighthouse V2 base station developed by Valve (see Fig. 3). This device features a rotating drum that emits infrared (IR) light sweeps across two planes positioned at different angles. These light sweeps, carrying the angle position of the drums, are detected by photodiode sensors on the Lighthouse positioning deck as previously explained. This compact system (80×74×63mm) has a wide and far emission range for indoor uses, extending from 0.4m (there is a dead zone under 0.4m) to more than 5m and with an emitting cone of 150° along the one side and 110° on the other side to it.

On the sides of the station, two landing supports are actuated by 2 MX28 Dynamixel motors operated by a computer. As seen in Fig. 1, these supports can be in open position, facing the left and right sides of the station, to not mask the emission of the IR light while the drone is returning for docking. In close position, facing the top of the station, the supports allow the drone to land on the arms supporting its motors.

The size of the full system is quite small being less than 15×15×15cm in close position and 25×15×15cm in open position. Although, it can be optimized to be even smaller.

C. Docking protocol

The docking protocol assumes the drone utilizes a localization system that allows it to return autonomously to the area covered by the signal of the station. Coming back from its mission the drone will detect the IR signal from the station with its landing supports in open position. The station is supposed to be placed on a flat, horizontal and still surface. At that moment, the drone stops its trajectory, hovering in place. It sends the data obtained by the Lighthouse deck to the computer operating the station. Then, the computer processes the data using Bitcraze’s cflib Python API to calculate the position and yaw of the drone relative to the station. These information are sent back to the drone to correct its position and yaw estimation. Then, the drone deactivates its current localization system and activates the Lighthouse positioning system in the EKF. Last but not least, the drone autonomously flies towards the station, stabilizing over it at about 0.5m to avoid the dead zone. It aligns its yaw with the station and stabilizes its position. Finally, the landing supports move to their close position and the drone lands in less than 1s on them helped by its IMU sensor.

IV. METHODS

A. Experimental setup

We aim to compare the Lighthouse system against the Loco positioning system from Bitcraze and OptiTrack’s Trio and Duo cameras to see if it is sufficiently accurate in dynamic motion. The benchmark for positional and rotation (yaw only) accuracy is derived from an 8-camera OptiTrack system deployed within our flight arena. We operate the reference motion capture system as well as the Trio and

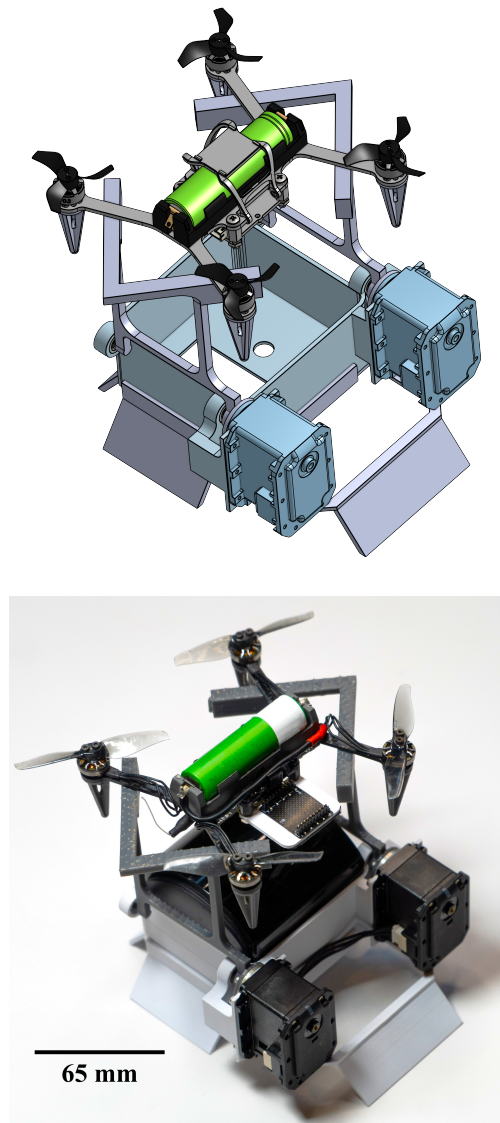


Fig. 3: The Proxyflie positioned on its custom-designed docking station, transitioning from the design phase (above) to the real prototype (below).

Duo cameras at 120Hz. The drone records its position and orientation on a local SD card at 500Hz.

OptiTrack’s Duo and Trio systems are not very reliable to track small IR reflective markers (<8mm in diameter) close to each other on a fast moving drone over distances >3m so we restrict the flight trajectory to a rectangle of 90×50cm in the horizontal plane close to both of these cameras. These cameras are mounted on tripods at a height of about 1.7m looking downwards where the center of the reference frame is at about 1.5m of them. Table I references the setpoints of the trajectory of the drone. We also increase the yaw by 45° at each setpoint of the rectangle as the Lighthouse deck can also calculate the yaw of the drone. We use the Hand Rigid Bodies Marker from OptiTrack as the support for 12.7mm reflective markers for better visibility by the reference cameras as well as the compared systems (see Fig.

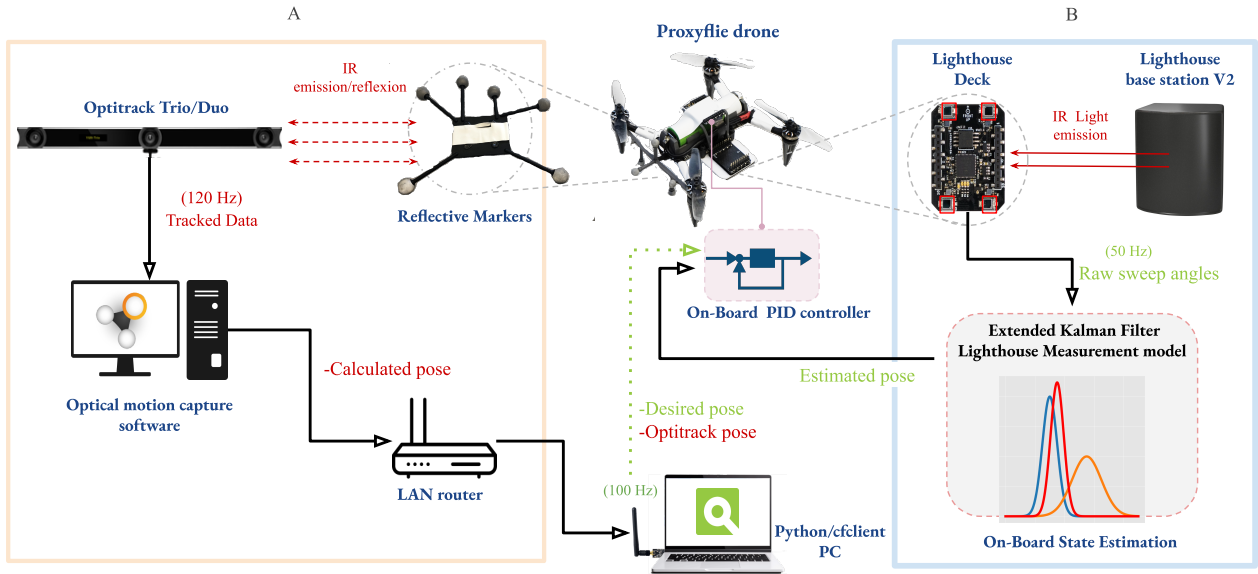


Fig. 4: Communication scheme between the Proxyflie drone and both of the IR light-based systems used for pose tracking. The OptiTrack cameras (A) necessitate a more intricate hardware configuration due to their dependency on a Windows computer for computation of the position and transmission. In contrast, the Lighthouse system (B) leverages the onboard computing capabilities of the drone and operates independently without direct communication with the control station.

4).

Before taking off, the drone is placed on the ground in the center of the rectangle trajectory and reference frame for all positioning systems but the station. For the station using the Lighthouse system, the drone starts from an elevated platform where the Lighthouse deck can detect the IR light signal of the station. The Flow deck is not present in these tests.

The flight altitude is 1.2m for the Loco, 1m for the Lighthouse and 0.34m for the Duo and Trio. For each flight, the drone has to fly this trajectory 3 times. Each time the drone has less time to reach the defined setpoint: 4s, 2s, 1s. So speed can vary between 0.225m/s to 0.9m/s. With 10 flights it makes a dataset of 700s for each positioning system.

X (cm)	Y (cm)	Yaw (°)
0	0	0
25	45	0
-25	45	45
-25	-45	90
25	-45	135
25	45	180
25	-45	-135
-25	-45	-90
25	45	-45
25	45	0
0	0	0

TABLE I: X,Y and Yaw setpoints the drone has to reach during the trajectory in chronological order

To synchronize the internal clock of the drone with the reference clock (OptiTrack system of the arena) we use the active marker deck from Bitcraze that has IR LEDs that turns on and off at the start and end of the flight respectively. That information is recorded on the SD card. When the

LEDs turns on and off, the rigid body associated to the deck respectively appears and disappears on the OptiTrack software, defining the starting and ending times.

In a second experimental setup, we want to test the overall docking system protocol. We use the 8-camera OptiTrack system as a reference to track the position of the drone during the whole process. The drone will be placed in 8 different positions on a square of 2×2m where station rests in the center. The drone will take off and stabilize at an altitude of 1.5m. Then, it should be receiving the IR light signal from the station, hence launching the docking protocol.

B. OptiTrack motion capture system

OptiTrack is a company that makes optical motion capture systems allowing real time, 6DoF precise tracking of objects in space. These systems are designed to work with passive or active markers that respectively reflect the IR light emitted by the cameras or emits it with IR LEDs. As shown in Fig.4 (A) each camera captures the data as 2D images, then transferred to an external computer where 2D positions are calculated, and the overlapping position data is compared to compute the 3D positions via triangulation with a proprietary specialized software called Motive:Tracker.

With an estimated accuracy of $< 0.1\text{mm}$, eight Prime 17W OptiTrack cameras are placed all over the flight arena (7×4.5×4m) acting as ground truth, whereas the compact V120:Duo (2-camera system) and V120:Trio (3-camera system) OptiTrack cameras are used as pose estimation systems to be compared with the proposed solution for docking. The tracked poses and orientation from these compact multi-camera system are then sent to the control board of the drone as positioning data to be integrated in its EKF.



Fig. 5: The composite image encapsulates different positioning estimation technologies approaches for precise docking compared during the landing tests. (A) exhibits the Proxyfly engaging with a lighthouse docking station to perform a precision landing. (B) depicts the Proxyfly in flight. Its movement is tracked by an OptiTrack Trio system. (C) displays the Proxyfly utilizing the Loco Positioning System that operates on UWB technology.

C. Loco Positioning System

The Loco Positioning System (LPS) from Bitcraze is an open source local positioning system based on DWM1000 Ultra Wide-Band (UWB) modules that are used to collect UWB TWR (Two Way Ranging Protocol) measurements in robotics applications [11]. In TWR mode, the tag placed on the drone sequentially communicates with the anchors placed on known positions. This allows it to measure the distance by sending short high frequency radio messages. To optimize accuracy, eight LPS anchors (see Fig. 5C) are fixed on the corners of the flying arena structure. The drone itself was outfitted with the a LPS deck (tag) to interface with this system. All requisite data and algorithms for position computation is contained within the LPS deck and the control board of the drone, facilitating onboard position estimation.

D. Hardware adaptation

To fly the drone using the Lighthouse alongside the reference positioning system we must only use active markers. Although the Lighthouse deck is upside down, the more intense IR light emitted by the OptiTrack cameras can still impact the Lighthouse system in some situations (eg. surfaces reflecting the IR light from the OptiTrack on the ground). One active marker deck would be enough to track the position, however because it was not designed to be used with the OptiTrack system and because of its symmetric design, the OptiTrack system cannot track the orientation. Thus, we removed the passive marker support to replace it with an active marker deck construction. The adaptation we made use 2 active marker decks on top of each other with the one above rotated in the horizontal plane and tilted so it is not longer parallel to the other deck. Both are connected by a ribbon cable and supported by a 3D printed structure (see

Fig. 6). With this modification, even if the 8 IR LEDs are grouped in a very small area ($<75 \times 75 \times 50\text{mm}$) relative to their distance to the reference cameras ($>3\text{m}$), the OptiTrack reference system can track the orientation almost as well as with the passive markers. The data shows a bit more spikes, corresponding to inversions of the Up axis, that are easily filtered out.

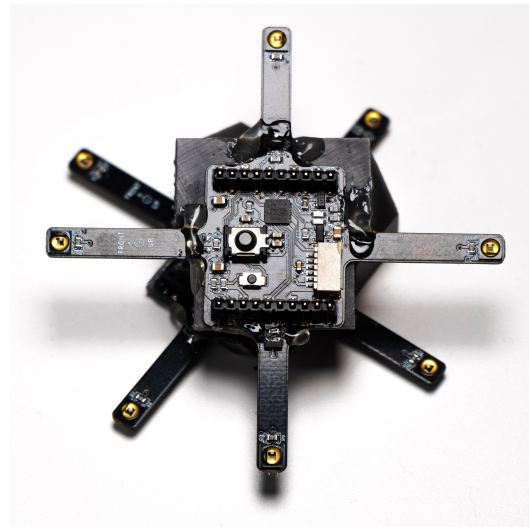


Fig. 6: 3D printed structure supporting 2 Active marker decks from Bitcraze used for recording the tests with the Lighthouse base station and the OptiTrack ground truth at the same time.

E. Comparison protocol

To compare the data from our positioning systems against our reference, we use the method proposed in Section IV of [10]. For the temporal alignment, we had the same difficulty

syncing both our signals because of the internal clock drift of the drone. We also had some random offset on when the IR LEDs were turned on and off. Thus, we use the LEDs as a first approximation of the dataset alignment. Then we minimize the euclidean distance between both positions moving the time when the LEDs are enabled and disabled in a $\pm 1.2s$ interval.

To compare the yaw accuracy, after aligning temporally the data with the method used previously, we pick an offset that minimize the sum of the absolute yaw errors. Then, we compute the yaw difference between the system to compare minus the reference system.

V. EXPERIMENTAL RESULTS

A. Position accuracy

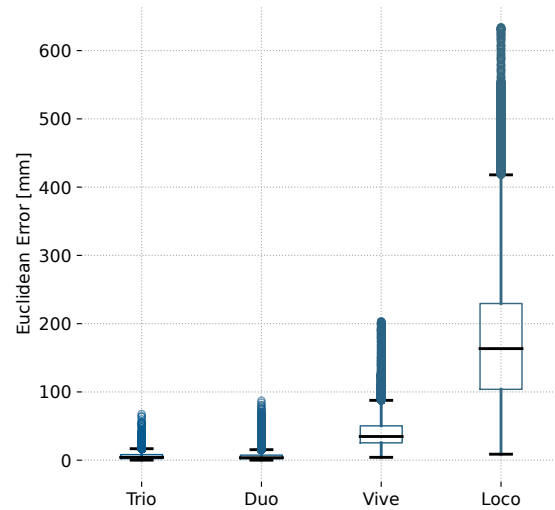
The results for position accuracy are presented in Figure 7. The following observations can be made:

- The Trio and Duo systems offers the best accuracy (consistently low error). Both have a very tight interquartile range, with the upper quartile under 1cm, indicating that these systems provide the best position accuracy to the drone.
- The Lighthouse Vive station exhibits increased variability and larger error magnitudes, characterized by an interquartile range between 2.5cm to 5cm surpassing those observed with Trio and Duo systems. However, the data found for this system correlates with the study by [10], which suggests a standard performance for this positioning device.
- In contrast to other systems, the Loco Positioning System demonstrates the broadest interquartile range and the highest median error, indicating the impossibility for achieving accurate docking at the base station. The Loco system is not fit for accurate positioning as the error recorded exceeds 10cm for the lower quartile. During the flights, we observed that the drone did not kept a stable altitude, moving up and down by more than 10cm around its target altitude.

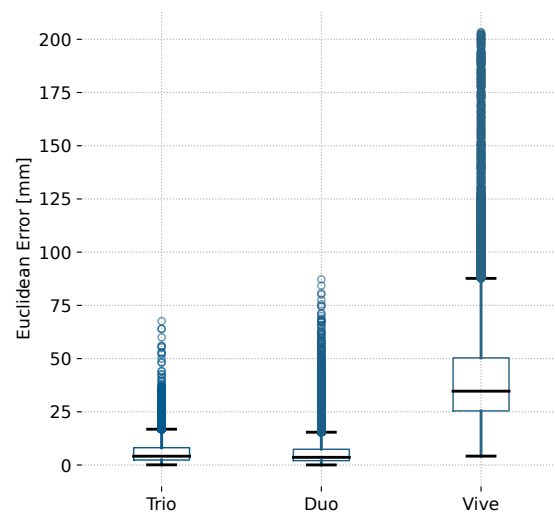
B. Yaw accuracy

The results for yaw accuracy are shown in Figure 8. The drone was placed in such a way that the position and rotation of the center of the reference positioning system frame is mostly aligned with the drone's. Consequently, the drone was able to maintain an accurate yaw rotation relative to the reference, courtesy of its internal gyroscope. The Loco positioning system is only used to estimate the position of the drone, not the rotation, which accounts for its larger interquartile range. The following observations can be made:

- The Trio and Duo still offers the best accuracy. Both have the tightest interquartile range under $\pm 0.2^\circ$.
- The Lighthouse station shows also a very good accuracy with the interquartile range under $\pm 0.5^\circ$.



(a)



(b)

Fig. 7: (a) Boxplots illustrating the accuracy of position estimation across the four systems evaluated (OptiTrack **Trio**, OptiTrack **Duo**, Lighthouse **Vive** Base Station, and **Loco** Positioning System) relative to the 8-camera system of the flight arena, serving as the ground truth. (b) For better comprehension, a zoomed-in view of the first three systems is provided. The outcomes obtained from the Vive system correspond with the reported results in [10]. In all the boxplots presented in this study, the box signifies the interquartile range, i.e., the 25th and 75th percentiles. The median is represented by a thick bar within the box. The whiskers, which extend from the box, are distanced by $1.5 \times IQR$

C. Landing success

A total of 100 take offs were conducted at various locations in the vicinity of the station to evaluate the station's ability to retrieve the drone and facilitate its docking. Figure

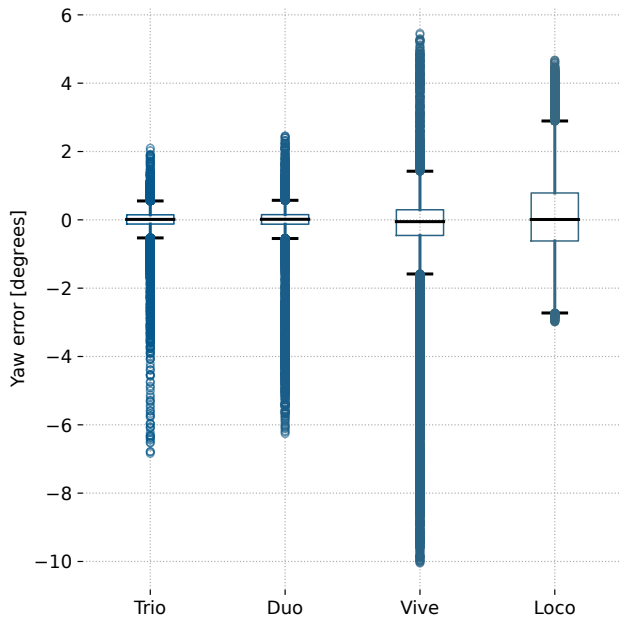


Fig. 8: Boxplot illustrating the accuracy of yaw estimation across the four systems evaluated (OptiTrack **Trio**, OptiTrack **Duo**, Lighthouse **Vive** Base Station, and **Loco** Positioning System) relative to the 8-camera system of the flight arena, serving as the ground truth.

9 illustrates the take off positions. Each flight involved the drone ascending to a height of 1.2m before starting the docking protocol. The station demonstrated a 100% success rate in retrieving the drone and to bring it back hovering 0.5m over the station. However, the success rate dropped to 89% when it came to docking the drone on the station. The drone must rely on its IMU sensor in the last phase of the landing. This adds inaccuracy, even if this lasts less than 1s. The drone sometimes lands 2 centimeters out of the “safe” landing surface which measures about $3 \times 3\text{cm}$. This failures could potentially be mitigated by redesigning the landing pads to provide a larger surface area for landing. Notably, the drone was also successfully landed from an initial distance of 6m and a height of 2m.

As depicted in Figure 10, the drone consistently achieves successful landings on the station from all initial positions. Some data from take off for starting positions at the corners of the square $(x,y) = (\pm 1\text{m}, \pm 1\text{m})$ are absent. This deficiency can be attributed to the limited camera coverage of our flight arena and the compact design of our custom active maker deck (seen in Fig. 6). Upon takeoff, the drone exhibits a tendency to relocate rather than maintain a stationary hover. This behavior is a consequence of the drone’s need to adjust its position and yaw to align with the Lighthouse base station’s frame. This adjustment can induce a displacement of approximately 10cm before the drone achieves stabilization and proceeds to the station as we have to manually input a new setpoint right after changing the drone pose. Otherwise, the drone will return to its original setpoint.

We tried to use the OptiTrack Duo and Trio but we had issues tracking the drone on such trajectories. The

reflective markers must entirely cover the drone and be big enough while not superposing on each other from a camera standpoint. This makes the drone a lot heavier and bigger than the original version.

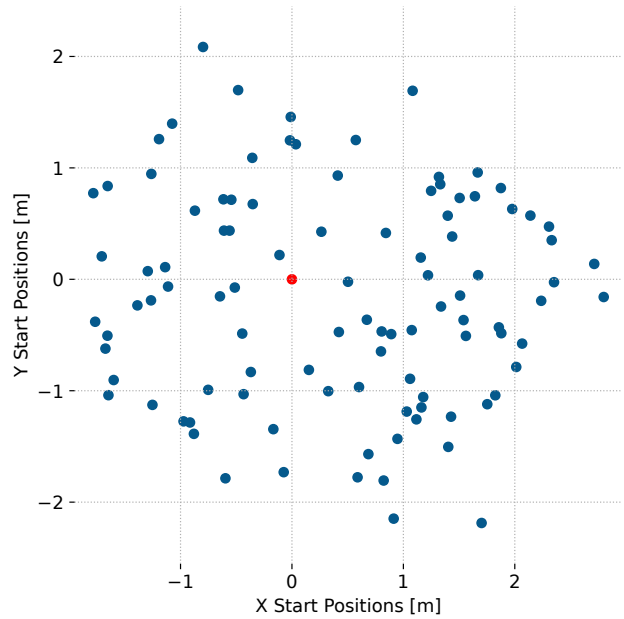


Fig. 9: Plot illustrating the take off positions of the 100 flights of the landing tests in blue. The red dot is the docking station.

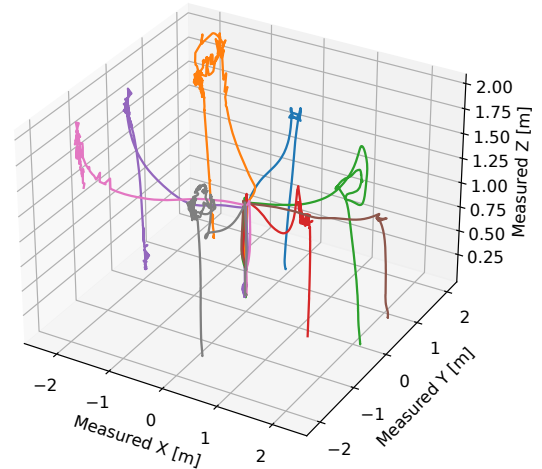


Fig. 10: 3D plot illustrating 8 trajectories of the drone starting from positions all around the docking station (located at $(x,y,z)=(0,0,0)$) from takeoff to landing. The position is recorded using the 8-camera system of the flight arena.

D. Performance to price and size comparison

The docking station’s solution emerges as the superior choice when considering factors such as accuracy, size, cost (refer to Table II). Although the accuracy and precision of the station is within the range of a few centimeters, it is sufficient for navigating towards the station and executing accurate landings. Particularly, all the positioning calculus is made on board. The Duo and Trio cameras, despite their superior accuracy and precision, lack the reliability required for tracking such a small drone. These cameras requires reflectors that must be placed all around the drone in an asymmetrical way and distant from each other to avoid them to superpose on the captured image. Furthermore, these cameras have a shallow and small field of view compared to the Lighthouse and needs a Windows based computer system to calculate the resource intensive image data flow and send the final position to the drone, thereby augmenting the overall dimensions and price of the docking solution. Ultimately, the compact design, range of action, cost-effectiveness of the Lighthouse Vive system and its centimeter precision is a very good compromise over the millimeter precision offered by Optitrack solutions for a tracking system that gets a 120g drone back to its station.

	Trio	Duo	Vive	LPS
MEE	4 mm	4 mm	35 mm	160 mm
Size	58 × 4 × 5cm	28 × 4 × 5cm	8 × 7 × 6cm	Volume > 8m ³
Price	€3,999	€2,999	€230	€1,450

TABLE II: Comparison of the benchmarked systems based on Median Euclidean Error (MEE), size, and price.

VI. CONCLUSION AND PERSPECTIVES

While take off for quadrotors is straightforward, navigating around obstacles remains a complex challenge. However, recent advancements suggest promising approaches to this issue [12]–[14].

The compact size of the Proxyflie, evident from the scale in Fig. 3 and Fig. 2, makes it suitable for precise docking operations within confined spaces. This feature is critical for applications that require high maneuverability and accuracy, such as detailed inspections in cluttered environments or autonomous indoor flight tasks.

We have developed a docking system for tiny drones that operates without GPS, ideal for indoor environments or areas where GPS is unreliable. This system, utilizing a single Lighthouse base station and advanced algorithms running on board to accurately guide the drone to dock. This addresses the challenges associated with the small size and maneuverability of tiny drones. The 3D-printed structure of the docking station highlights the design, allowing for rapid prototyping and customization to fit the specific requirements of the Proxyflie drone. The landing gears, powered by two Dynamixel motors, facilitate precise actuation of the landing support. This feature maintains the compactness of the docking system while providing a platform for stabilizing the drone upon docking when needed without obstructing

the IR signal of the beacon when the drone reaches the station, emphasizing the task of aligning and securing the drone without human intervention.

The Lighthouse Vive system was selected for precision docking due to its optimal balance between localization accuracy for docking operations, low cost acquisition, small size, and relatively low implementation complexity, including considerations of sensor compactness and computational resources, as depicted in Fig. 4B. Additionally, our work includes a comparison of our solution with alternatives like the OptiTrack motion capture and UWB technology.

This innovation aims to enhance the utility of tiny drones for tasks such as surveillance and exploration in GPS-denied areas and confined spaces, contributing to the ongoing evolution of drone technology.

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