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TOWARDS UAV TELEOPERATION BY MEANS OF VIRTUAL REALITY

TESIS

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PRESENTA
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Y para que así conste firmo la presente a los **20** días del mes de **agosto** delaño dos mil **veinticuatro**.

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Towards UAV teleoperation by means of virtual reality

Abstract

This study presents the development of virtual environments as control centers for remote teleoperation tasks of unmanned aerial vehicles (UAVs). Initially, our focus lies on reconstructing outdoor and indoor environments using a ZED mini stereo camera and reconstructing them through point cloud techniques; in this project, RTAB-Map is implemented for this purpose.

The virtual environment is hosted in Unity, a widely recognized platform for designing virtual reality (VR) video games. Within this environment, a digital twin UAV is embedded, tasked with replicating the real positions and orientations of the vehicle.To ensure accurate replication, both PID and PD control schemes are proposed for managing the positions and rotations of the virtual vehicle, allowing it to precisely follow the actual position of the UAV. This control strategy is pivotal in maintaining the fidelity of the virtual representation to its physical counterpart, ensuring that the teleoperation is both realistic and responsive.

Extensive testing was conducted to assess the effectiveness of these controls. A series of experiments were carried out in both outdoor and indoor settings to validate the functionality of this approach. These tests not only demonstrated the accuracy of the vehicle's position and orientation replication but also explored the system's operational limits and potential failure points. The results are promising, showcasing the system's capability to perform under various environmental conditions and its potential for broader applications in UAV-based operations.

Further, the study delves into the implications of this technology for real-world applications, including surveillance, inspection, and disaster response, where accurate and efficient remote operation of UAVs is critical. By integrating advanced control systems and realistic virtual simulations, this approach offers a significant advancement in the field of UAV teleoperation, potentially transforming how these vehicles are used in complex and hazardous environments.

Dedication

To all the people who contributed to this work in one way or another,
especially to my family.

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Publications

Conference papers

- Real-time mapping for teleoperation systems in VR of unmanned aerial vehicles. **Germán Ramírez**, Rodolfo Isaac Verdín, Gerardo Flores. ICUAS, 2023 International Conference on Unmanned Aircraft Systems. Chania, Crete, Greece on June 4-7, 2024. **Published**
- 3D maps of vegetation indices generated onboard a precision agriculture UAV. **Germán Ramírez**, Andrés Montes de Oca, Gerardo Flores. ICUAS, 2023 International Conference on Unmanned Aircraft Systems. June 6-9, 2023 | Lazarski University, Warsaw, Poland. **Published**
- Teleoperated aerial manipulator and its avatar. Communication, system's interconnection, and virtual world. **Germán Ramírez**, Thibaut Raharijaona, Gerardo Flores. SAGIP Marseille 2023, Société d'Automaqtique, de Génie Industriel & de Productique. June 7, 2023 | Marseille, France. **Published**

- Teleoperated aerial manipulator and its avatar. Communication, system's interconnection, and virtual world. Rodolfo Verdín, **Germán Ramírez**, Carlos Rivera, Gerardo Flores. 2021 International Conference on Unmanned Aircraft Systems (ICUAS). 15-18, 2021 | Athens, Greece. **Published**

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CHAPTER 1

Introduction

As unmanned aerial vehicles (UAVs) have become increasingly integral to a variety of sectors, their control systems have evolved to offer greater robustness and maneuverability. This evolution has facilitated their seamless integration into daily life and various professional domains. Concurrent advancements in artificial intelligence (AI), simultaneous localization and mapping (SLAM), and robotics have expanded the potential applications of UAVs, not just in traditional fields such as agriculture and industry, but also in areas that impact societal welfare directly.

While UAVs are now commonly used for tasks that range from precision agriculture to emergency response, their operation typically requires interaction with a remote operator. This interaction has been enhanced by significant technological advancements, yet challenges persist, particularly in real-time data transmission and accurate environment mapping, which are crucial for tasks requiring high precision and reliability. The advent of sophisticated First Person View (FPV) systems and other remote operation technologies has addressed some of these challenges but also highlighted new limitations in terms of depth perception and operational accessibility due to the high skill level required.

This thesis builds upon existing technologies and integrates advancements in virtual reality (VR) to address these challenges. VR technologies, which have matured significantly since their inception, now offer robust solutions that can significantly enhance the teleoperation of UAVs. By employing VR, this project not only aims to improve the operational efficacy of UAVs but also seeks to transform their application in complex and hazardous environments, making them more accessible and effective.

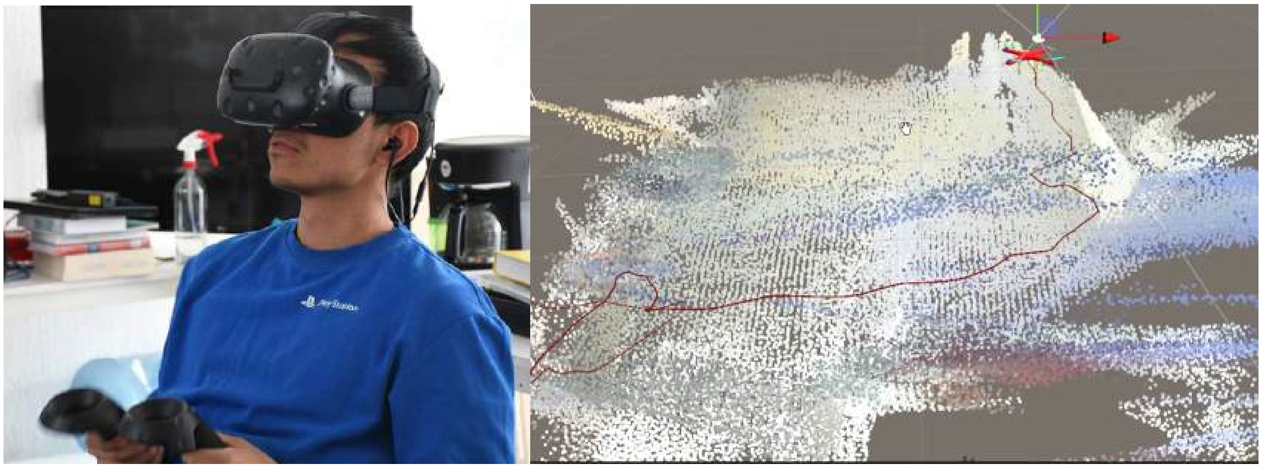
The overarching purpose of this work differs from the specific objectives of the research in that it seeks to fundamentally redefine the interaction between UAV operators and their remote environments. Unlike traditional research objectives focused on incremental technology improvements, this project aims to leverage VR to create a comprehensive, intuitive, and realistic control environment. This will facilitate a deeper, more natural interaction with UAVs, thereby enhancing the operator's ability to perform complex tasks remotely.

This introduction sets the stage for a detailed exploration of how integrated VR and UAV technology can not only overcome existing limitations but also open up new possibilities for their use in critical applications such as search and rescue, large-area surveillance, and disaster management. Combining hardware advancements and sophisticated software solutions, this project aims to demonstrate a significant leap in the capabilities of UAV teleoperation systems.

1.1 Background

Unmanned Aerial Vehicles (UAVs) have found widespread use, particularly in scenarios requiring interaction with a remote operator [1]. Examples include farm inspection [2–4], photovoltaic plant inspections [5], the film industry, hazardous area inspections, and topography [6–8]. The demand for efficient and secure task execution has driven the development of advanced outdoor robotic solutions, often used in environments that are dangerous or difficult for humans to access.

Despite these advancements, significant challenges remain, particularly with First Person View (FPV) systems, which transmit real-time video from the UAV's perspective [9]. These systems are limited in their ability to provide a complete understanding of environmental depth, and their performance is constrained by the efficiency of the transmission



(a) Virtual reality immersion.

(b) Virtual reality environment.

Figure 1.1: Virtual reality setup: (a) user experiences a virtual world through the HTC Vive; (b) this virtual world is a digital twin that replicates the real world, copying the position and orientation of the actual quadrotor, with the ZED mini mapping the world.

equipment. Furthermore, conventional teleoperation requires substantial training and experience, making it less accessible to a broader audience. While efforts have been made to improve visualization through the use of stereo cameras, this solution still focuses primarily on image transmission, failing to address more critical challenges like enhancing situational awareness, improving user interaction, and reducing cognitive load for operators.

Virtual Reality (VR) is an integrated information technology that emerged at the end of the 20th century. It seamlessly combines various branches of information technology, including digital image processing, computer graphics, multimedia technology, and sensor technology. [10,11] These technologies have reached a level of maturity that enables them to provide an immersive experience with minimal delays in motion tracking. This capability is the primary driving force for integrating VR into physical simulations like Gazebo [12,13]. This work constitutes the second part of an ongoing project [14] focused on the remote teleoperation of aerial manipulators, treating them as a virtual twin technology designed to address the challenge of the virtual-real interaction problem. Digital twins comprise virtual space, physical space, and the connection between the two spaces. The digital model created in the virtual space is dynamically mapped to the physical entity, accurately capturing the trajectory of the UAV throughout its entire flight. This allows for safe teleoperation of the UAV from a remote location, as illustrated in Figures 2.1a and 2.1b. In future phases, the intention is to teleoperate the aerial manipulator using the equipment and approaches developed in this research.

In response to these challenges, this work proposes an innovative solution by introducing real-time mapping of the environment, along with the transmission of positions and orientations to a digital twin. This information is channeled to a control center where the pilot, equipped with virtual reality, can visualize the vehicle from different angles and explore a detailed 3D map of the environment in real time. This approach not only overcomes the limitations of traditional visual perception but also opens up new possibilities for future applications, such as search and rescue missions, large-area surveillance, and space exploration.

1.2 Problem Definition

Within the context of emerging UAV technology combined with Virtual Reality systems, several key challenges have been identified that compromise the effectiveness and viability of these applications in fields as diverse as extensive area surveillance and rescue missions. Despite technological advances in simulation and teleoperation through virtual environments, significant limitations persist that need to be addressed:

1. **Latency and Interaction:** Low-latency communication between the physical drone and its virtual twin is crucial to enable real-time interaction, directly affecting the user experience and the effectiveness of the control system.

2. **Mapping Accuracy:** Achieving precise mapping of the physical environment and faithful replication in the virtual realm is essential to prevent disorientation and enhance system usability.

3. **Positional Data Synchronization:** Maintaining precise synchronization between the real-world drone position and its virtual representation is challenging, with discrepancies arising from sensor inaccuracies leading to misalignment.

4. **Control Algorithm Complexity:** Implementing control algorithms that smoothly translate user inputs into realistic movements poses a significant challenge, requiring stability and responsiveness in the UAV's behavior within the virtual environment.

1.3 Justification

The development of combined Unmanned Aerial Vehicles (UAV) and Virtual Reality (VR) technologies represents a significant advancement in the fields of robotics and remote sensing. This study is essential for several reasons:

1. **Contribution to Society:** The integration of UAVs and VR has the potential to benefit society at large. Advanced UAV systems can be used in search and rescue operations, offering quicker and more effective responses in emergencies. Additionally, they can contribute to disaster management and environmental monitoring.

2. **Technological Innovation:** This study promotes technological innovation by addressing and overcoming current technical challenges, such as communication latency, mapping accuracy, and positional data synchronization. Solving these issues will not only improve the operation of UAVs but also expand the applications of Virtual Reality, solidifying its use as a practical tool rather than merely a conceptual one.

3. **Study Beneficiaries:** The results of this study will benefit multiple stakeholders, including academics, technology developers, and professionals in security, inspection, and surveillance industries, as well as governmental agencies responsible for land management and emergency response. Furthermore, improvements in the accessibility and operability of UAVs in complex scenarios will facilitate new research and developments in related fields.

This work introduces a groundbreaking system that seamlessly integrates hardware and software, advancing real-time mapping and interaction between physical and virtual environments. Utilizing the ZED mini stereo camera as the mapping sensor, paired with the Jetson Xavier for computation, enhances point cloud generation's accuracy and efficiency, enabling detailed mapping of physical spaces. Integrating ROS Melodic and PX4 firmware establishes a robust communication framework and precise drone control, facilitating accurate extraction and transmission of positional data. Our approach utilizes Unity for virtual environment development, creating a realistic digital twin that mirrors the physical environment, enabling real-time interaction and visualization. The system's versatility is showcased by its applicability in remote teleoperation through virtual reality systems, extending its utility beyond mapping to remote control scenarios.

1.4 Objectives

The objectives defined here aim not only to overcome the identified technical obstacles but also to maximize the impact and utility of UAVs in both real and virtual environments. Below are the specific objectives of this research.

1.4.1 General Objective

- Develop a digital twin that accurately replicates the real-time movements and environmental perspective of the UAV, enabling teleoperation within a virtual environment.

1.4.2 Specific Objectives

- Design and implement control algorithms that allow the digital twin to accurately replicate the movements of the UAV in real-time.
- Develop communication protocols between the virtual environment and the drone to enable seamless interaction and data exchange during teleoperation.
- Validate and verify the accuracy and reliability of the digital twin through testing and comparisons with the physical UAV in different flight scenarios.

1.4.3 Particular Objectives

- Design and implement a bidirectional communication protocol that allows the drone to send telemetry data to the virtual environment and receive control commands in real-time.

- Develop control software on the drone that translates commands received from the virtual environment into physical actions, such as changes in speed and flight direction.
- Publish the results and lessons learned in specialized journals or congress and present them to contribute to advancing UAV teleoperation systems and the application of VR.

1.5 Hypothesis

The successful development and implementation of a bidirectional communication system between a drone and a virtual environment, along with the design of appropriate control software, will enable effective real-time teleoperation of the drone within the virtual environment, thereby improving the efficiency and precision of flight operations.

CHAPTER 2

State of the Art and Theoretical Framework

2.1 Literature Review

The integration of real-time mapping techniques with teleoperation systems for aerial manipulators in VR environments represents a growing field of research examining significant contributions and related works. Several studies have explored mapping techniques for teleoperation systems. [15] proposed a method using LiDAR sensors for real-time mapping of complex environments, albeit with a primary focus on ground-based robots. The application of UAVs in VR scenarios was not explicitly addressed.

Teleoperation systems incorporating VR for UAVs have gained attention. [16–18] presented a VR-based teleoperation framework for drones, emphasizing immersive control experiences. While the work enhances user interaction, its limitation lies in the absence of real-time mapping, restricting its applicability to scenarios requiring dynamic environmental awareness. Nelson et.al [19] describes a system architecture that merges virtual reality (VR) with drones, allowing inexperienced drone pilots to build and execute three-dimensional flight trajectories. It consists of two modules: a VR module to design the trajectories by interacting with the virtual environment, and a Control module that monitors the execution using a smartphone connected to the drone. In the integration of mapping and teleoperation, few studies have successfully merged these techniques in [20] demonstrated a method utilizing visual SLAM for mapping and teleoperation control. However, their research primarily focused on ground-based robots, leaving the transition to aerial manipulators in VR unexplored.

Smith and Rodriguez [21] explored the use of multiple sensors, including RGB-D cameras, for comprehensive mapping and teleoperation of drones. Their work highlights the importance of sensor diversity in enhancing the accuracy of environmental mapping. In summary, the evolving landscape of real-time mapping and teleoperation in VR for aerial manipulators incorporates diverse approaches, from sensor fusion to interactive control, providing valuable insights and paving the way for future advancements in this field. Works such as [22], where the humanoid can be controlled by a remote operator, effectively achieving a Suspended Aerial Manipulation Avatar. It is an example of where the proposed system can be used.

2.2 Teleoperation Systems

Teleoperation systems play a crucial role in enabling remote control and manipulation of drones from a distance. This encompasses a wide range of tasks and applications, from surveillance and reconnaissance to infrastructure inspection and environmental monitoring. The ability of these systems to operate in complex environments and carry out various tasks has spurred significant research and development efforts in the field of robot teleoperation [23, 24].

One of the major problems for teleoperated systems, especially for mobile robots, is the human pilot's visual limited range [25, 26]. Operators often rely on onboard cameras or sensors to perceive the robot's surroundings, which can restrict their situational awareness and task performance.

Performing a given task with a teleoperated aerial manipulator through the scene captured from mounted cameras could become a negative factor due to the visual limitations [27]. In such scenarios, operators may struggle to perceive depth, spatial relationships, and obstacles accurately. However, the integration of virtual reality (VR) technologies offers a promising solution to overcome these limitations since you can have a virtual model replicating the robot movements [28]. Finally, the operator can visualize and control the robot with more information.

In this work, the aim is to address the challenge of human-robot interaction by providing operators with an extended visual range through the use of digital twins by using VR.

2.3 Virtual Reality and Virtual Twins

Digital twins are virtual replicas of real-world objects or environments, created through data integration and simulation techniques. By bringing real-world elements into a virtual environment, operators can gain a broader perspective of the robot's surroundings and manipulate it more effectively.

In the context of UAV systems, digital twins offer significant advantages for various applications. For example, a digital-twin (DT)-assisted task assignment approach has been proposed to enhance the resource utilization and efficiency of deep reinforcement learning (DRL) in multi-UAV systems [29]. This approach leverages digital twins to optimize task assignments, leading to more efficient use of resources and improved performance of UAV operations.

Digital twins are also employed to solve the problem of precise UAV landing. By integrating sensor data, a digital twin can optimize motion planning and enhance the accuracy of landing procedures [30]. This methodology provides a promising way to design, test, and improve UAV precision landing systems, ensuring safer and more reliable operations.

Another application involves using UAVs to collect global images of forests and then utilizing digital twins for real-time monitoring and simulation [31]. This approach enables continuous observation and analysis, facilitating better decision-making and management of forest environments.

Overall, digital twin technology is proving to be a powerful tool in enhancing the capabilities of UAV systems, offering new opportunities for improved performance, precision, and monitoring in various applications.

Several applications have been developed to work with virtual environments (VE) using an intuitive human-robot interface for manipulating tasks. Certain applications include flying UAV systems [32] and simulations where the 3D world is reconstructed and gives dimensional feedback [33]. In [34] a monitoring system for old buildings is created through VR to detect possible structural damage using a UAV. On the other hand, in [35] vision-based navigation algorithms for UAVs are developed to monitor people through a VE.

Tasks involving manipulation are presented in [36] for maintenance or repairing industrial robots in a VE using an HTC Vive device. Also in [37] for complex manipulating tasks they use VR sets. For high-risk tasks in [38] intuitive and effective control methods based on VR are proposed to teleoperate an underwater robotic arm. Regarding aerial manipulation, in reference [39] a virtual simulator is implemented for collaborative tasks of autonomous and teleoperated navigation. Haptic and Virtual Reality-Based Shared Control for MAV is presented in [40] including an interface that allows a safer operation. A combined feedback system for an aerial manipulator is presented in [28] using VR trackers set in the user's arm and tracking gloves. In [25] the authors propose a new interaction paradigm that provides adaptive views for improving drone teleoperation. However, in [25] the authors only focus their efforts on 3D reconstruction and virtual navigation with the human. Furthermore, motivated by the growing trend of virtual reality systems, together with teleoperation, this project proposes to integrate an immersive environment created in a real-time map reconstruction.

2.4 Real-time Mapping

As previously mentioned, numerous studies have focused on mapping techniques, particularly within the field of Simultaneous Localization And Mapping (SLAM). This area of research is dedicated to tracking and mapping and has seen substantial advancements with a variety of proposed SLAM systems. These systems incorporate diverse sensors, optimization techniques, and map descriptions [41]. SLAM algorithms are vital for enabling robots to autonomously perceive their environment and navigate within it. They utilize sensors such as cameras and lasers to empower robots with the ability to map their surroundings and navigate independently. This capability significantly enhances robot autonomy and adaptability, making them invaluable in a wide range of applications.

Visual-based SLAM algorithms are particularly appealing due to their straightforward sensor configuration, miniaturized size, and cost-effectiveness [42]. These approaches can be categorized into three main types: monocular, stereo, and RGB-D. Each type is further subdivided into two primary methodologies: feature-based, which involves matching visual features across multiple frames, and optical flow techniques, which rely on the intensity changes of all pixels or specific regions in sequential images [43].

Several SLAM libraries have been instrumental in recent research. One notable example is ORB-SLAM, a highly successful SLAM system that utilizes sparse features and is designed for real-time camera tracking [44]. Another significant library is RTAB-Map, which supports RGB-D, stereo, and Lidar inputs. This approach is based on an incremental appearance-based loop closure detection method, catering to the demands of large-scale and long-term online operations [45]. This library was chosen for this project due to its prominent strengths, particularly its compatibility with the Robot Operating System (ROS), making it an excellent choice for robotics applications where communication between the quadrotor's IMU and the developed simulation is crucial. During the mapping phase, RTAB-Map is capable of generating various types of maps—dense, occupancy, and sparse—tailored to the specific needs and goals of the application.

Moreover, RTAB-Map includes a dedicated component for efficient memory management, which assumes paramount importance in scenarios involving large-scale environments. This memory management module effectively handles the growth of the graph structure and optimized computation time, contributing to the algorithm's scalability and robustness.

In [46] a comparative evaluation of three RGB-D SLAM algorithms (RTAB-Map, ORB-SLAM3, and OpenVSLAM) were conducted as shown Fig.2.1. In this study, the Absolute Trajectory Error was calculated where it was observed, that ORBSLAM3 demonstrated superior performance in terms of localization accuracy (0.1073m), followed by RTAB-Map (0.1641m). A notable challenge faced by feature-based SLAM algorithms arises in environments characterized by a scarcity of distinct visual features. During the experiments in a specific segment, the robot encountered a white wall with limited features. In this

(a) (b) (c)

Figure 2.1: Output maps of investigated methods (a) Dense map of RTAB-Map algorithm (b) Sparse map of OpenVSLAM algorithm (c) Sparse map of ORB-SLAM3 algorithm.

particular scenario, only RTAB-Map managed to maintain odometry, while the other two algorithms experienced difficulties and lost their position. RTAB-Map is capable of generating a dense map of the robot's environment in real-time crucial to achieving real-time teleoperation of the quadrotor proposed in this project.

Several studies have explored map reconstruction for robot teleoperation, implementing SLAM to enhance operational capabilities. Allenspach et al. [47] present a teleoperation system with force feedback that combines graphic and haptic inputs for improved telepresence. Their innovative approach has been applied to an electric power live line working robot system, which utilizes mixed reality to create a robust sense of telepresence. In contrast, our project is designed specifically for urban search and rescue operations, which require a system that is not only reliable but also capable of performing in highly unstructured environments.

Similar research initiatives have been undertaken in various other fields, demonstrating the versatility and applicability of these technologies. For instance, advancements in agriculture [48], industry [49], and medicine [50, 51] have all benefited from tailored SLAM implementations that address unique challenges within each sector.

CHAPTER 3

Methodology

This section outlines the procedures undertaken to carry out this project, structured into several subsections for clarity and coherence. The first subsection details the physical environment, including the specifications and characteristics of the drone, camera, and computers used for the experiments. Following this, the virtual environment is described, focusing on the software utilized for simulating the digital twin and reconstructing the environment. The subsequent subsection covers the control mechanisms employed for both the physical and virtual drones. Finally, the communication protocols and techniques used to synchronize and integrate the physical and virtual environments are discussed, ensuring seamless operation of the simulation.

3.1 Physical Space

3.1.1 Aerial Platform

The aerial platform utilized in this project features a quadrotor arranged in an X configuration, equipped with a standard set of sensors, actuators, and communication devices (see Figure 3.1). Table 3.1 provides detailed information about these components. The

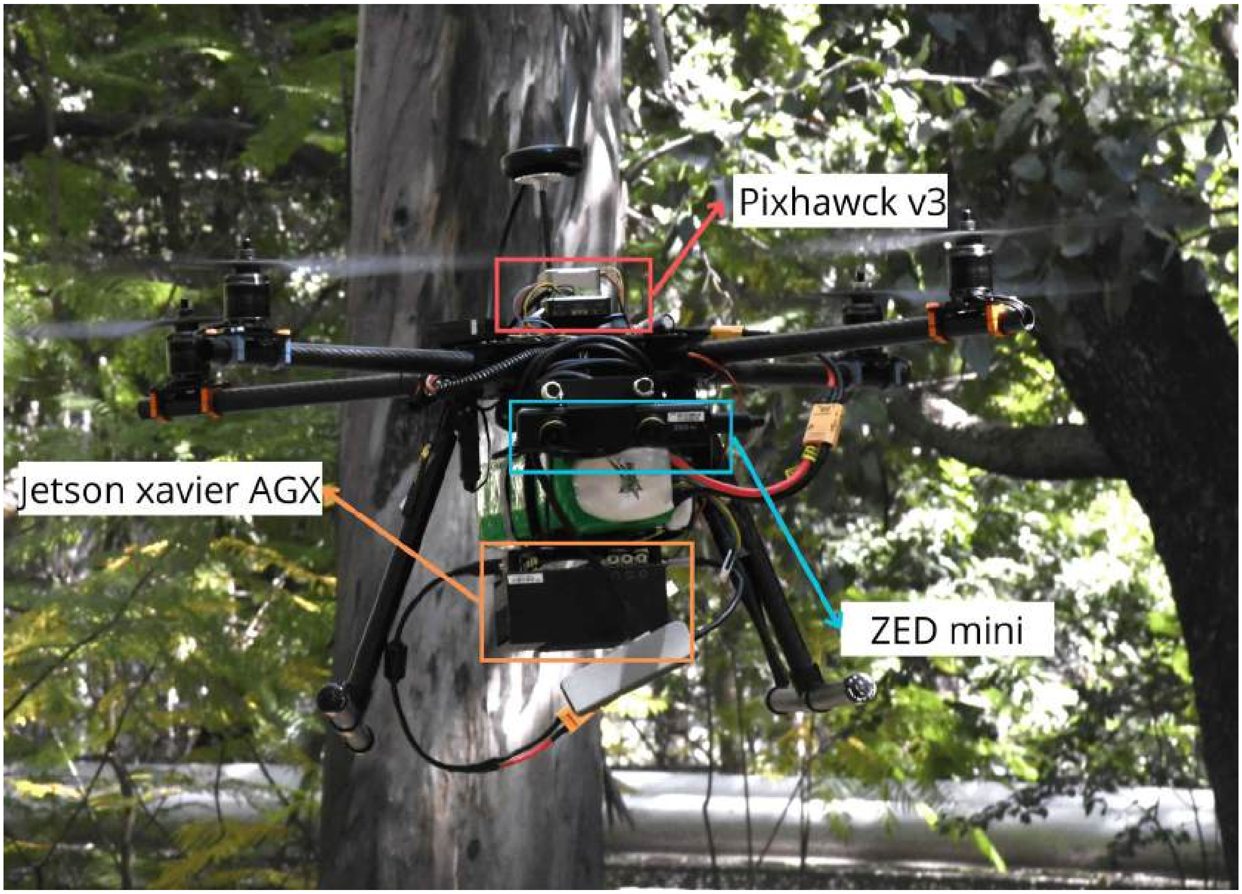


Figure 3.1: Employed quadrotor with specific components

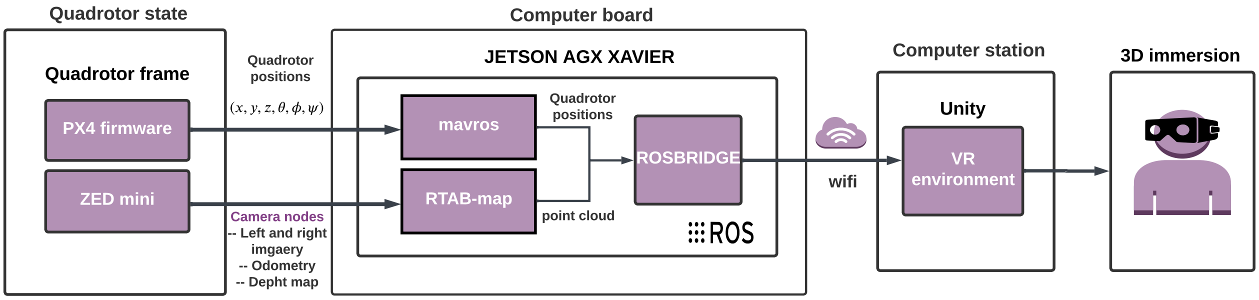


Figure 3.2: This diagram illustrates each subsystem that comprises this project. Starting with the quadrotor, whose information is gathered from the PX4 controller, it sends positions and orientations. From the ZED Mini, we run three nodes, which provide us with the depth map, stereo view, and odometry. This information is sent to the JETSON AGX Xavier mini computer. We use ROS Melodic for communication via MAVROS to process the positions. With RTAB-Map, we generate the point cloud. Through Rosbridge, we send this information via WiFi to Unity, where the virtual environment creates the 3D map and displays the positions.

quadrotor is controlled by a Pixhack V5 autopilot running PX4 firmware. In addition to the quadrotor's components, the UAV's payload includes a microcomputer and a stereo vision system, detailed in the following subsections.

Parameter	Description
Motor	Tarot MT4008 330 kv $(\times 4)$
Propeller size	15×5.5 in $(\times 4)$
Battery capacity	12 Ah Li-Po at 6 cells
GPS	UBLOX NEO-M8N
Telemetry	CUAV PW-LINK Wi-Fi
On-board computer	Jetson AGX Xavier
Stereo camera	ZED Mini
Weight (without payload)	3.0 kg

Table 3.1: The proposed UAV specifications.

3.1.2 Vision System

The vision system selected for this project is the ZED Mini stereo camera from Stereo Labs. This camera is chosen for its ability to capture stereo imagery essential for generating dense point clouds used in mapping. The ZED Mini offers several advantages over other

ZED cameras, including its smaller size and weight and its capability to provide inertial odometry information.

Stereo imagery enables the computation of depth maps from image pairs. These depth maps assign depth data to the detected points in the image pairs, allowing for the generation of a detailed point cloud of the environment targeted for 3D reconstruction. Table 3.2 provides the main specifications of the ZED Mini camera.

Parameter	Description
Field of view	$90° \times 60°$
Image resolution	4416×1242 pixels at 15 fps
Size	$124.5 \times 26.5 \times 30.5$ mm
Odometry	Internal IMU sensor
Weight	62.9 g
Baseline	65 mm.
Depth range	15 cm to 12 m.

Table 3.2: ZED Mini main specifications.

Given the computationally intensive nature of processing stereo imagery to generate a dense point cloud, it is crucial to utilize a high-performance embedded microcomputer for visual data processing. The objective is to conduct online dense point cloud reconstruction, necessitating an embedded microcomputer with sufficient processing power, compact size, and suitable design. The NVIDIA Jetson AGX Xavier is selected for this purpose, offering high computational capabilities while being lightweight and compact enough to be carried as a UAV payload. Table 3.3 outlines the specifications of the Jetson AGX Xavier microcomputer.

The Jetson AGX Xavier provides the necessary processing power to handle the computational demands of real-time dense point cloud reconstruction. Its integration into the UAV system enhances the overall capability of the platform, enabling advanced data processing directly on-board the drone.

3.1.3 Camera Location

In the proposed design, the onboard stereo camera is not positioned directly in front of the UAV with its optical axis parallel to the horizon. Such a placement would result in the front propellers appearing in every frame captured by the camera, potentially interfering with the reconstruction process. To address this issue, the camera is angled at a fixed angle of θ = 30° relative to the horizon. This adjustment ensures that the input imagery no longer contains the propellers, resulting in a cleaner reconstruction. Tests were conducted to confirm that the propellers were not captured within the stereoscopic view. However, due to this configuration, only objects within a 30° field of view below the horizontal plane can be reconstructed. If mapping of objects located above the drone is required, the UAV must be repositioned directly above the target point at a higher altitude.

This strategic placement and angling of the camera help in avoiding obstructions from the propellers, ensuring that the captured imagery is suitable for high-quality 3D reconstruction. The careful consideration of camera placement underscores the importance of optimizing the UAV design for effective data capture and processing.

Parameter	Description
GPU	512 cores with Tensor Cores
CPU	8-core ARM v8.2 64-bits
RAM	32 GB LPDDR4x
Weight	1.548 Kg
Size	$105 \times 105 \times 65$ mm
Operative System	Ubuntu 18.04

Table 3.3: Jetson AGX Xavier specifications.

3.2 Virtual space

The software core of the UI is built using Unity 3D software, a famous game engine used to build high-fidelity scenes, and a SteamVR asset, which provides a minimum set of tools to quickly build basic VR environments and control the HTC VIVE VR system. Based on Unity 3D software, the UAV model and environment reconstruction scene are built to simulate physical UAVs and physical scenes online. The essence of this digital twin is to map objects in physical space to virtual space through digital methods. In the virtual space, the digital models of physical objects are built, and the operation law of their life cycle is revealed through the sensors (ZED mini and PX4) according to the location and orientation of the UAV.

3.2.1 Environment Reconstruction

The process of environment reconstruction involves seamless imagery collection and dense point cloud computation executed in real-time during flight operations. This is achieved using the Real-Time Appearance-Based Mapping (RTAB-Map) algorithm, which generates the node $/rtabmap/cloud\_map$, a 3D point cloud saved in $PointCloud2$ format. This advanced algorithm facilitates the creation of a detailed PointCloud map, which is subsequently transmitted via a ROS web socket to Unity using ROS#.

ROS# is a set of open-source software libraries and tools in C# designed for communication with ROS from .NET applications, particularly Unity, where the point cloud is visualized in a virtual reality (VR) environment.

Positional data is obtained from the PX4 and ZED mini sensors via MAVROS and RTAB-Map, respectively, to replicate the UAV's movements within the virtual environment. The positional data from the PX4 is acquired using $PoseStamped$ format through a reliable wired connection via MAVROS. These positional data sets are then relayed to Unity, providing the foundation for accurately simulating the UAV's movements.

A PID controller is implemented to enhance the user's visualization experience within the Unity environment. This controller is crucial for accurately tracking positional data, ensuring seamless integration between real-world movements and their virtual representation. The PID controller adjusts the UAV's position in the virtual space to match its physical counterpart, providing a realistic and immersive experience.

3.3 Controllers

In this section the employed controllers are outlined, featuring a position control for the physical UAV and also for its digital twin.

3.3.1 Quadrotor Position Control

It is possible to operate the drone manually and autonomously; for the second case, we used part of the PX4 firmware position and attitude control units to implement a PID controller [52, 53]. With this control approach, we can ensure good flight stabilization in small perturbed environments and obtain a fast prototyping system. This way, position control is defined as,

$$f_B = m\left(-gu_z - K_p e_p - K_i \int e_p - K_d e_v + \ddot{x}_d\right) R^{-1} \tag{3.1}$$

where K_p, K_i, $K_d \in \mathbb{R}^{3\times 3}$ are positive diagonal gain matrices, $R \in \mathrm{SO}(3)$ is the rotational matrix. The position and velocity errors are defined as

$$e_p = p - p_d,\ e_v = v - v_d. \tag{3.2}$$

Again, we can see that the required force to reach a desired position depends on the drone position, velocity, and actual attitude error states.

Now, for attitude control, we also propose the PID control giving the following control law,

$$\tau_B = J\left(-K_R e_R - K_{Ri} \int e_R - K_\Omega e_\Omega + \ddot{\Omega}_d\right) + (\Omega \times J\Omega) \tag{3.3}$$

where the K_R, K_{Ri}, $K_\Omega \in \mathbb{R}^{3\times 3}$ being positive diagonal matrices, and the errors are given by

$$e_R = \frac{1}{2}\left(R_d^{\intercal}R - R^{\intercal}R_d\right)^{\vee} \in \mathbb{R}^3,\ e_{\Omega} = \Omega - R^{\intercal}R_d\Omega_d \in \mathbb{R}^3. \tag{3.4}$$

where $R_d \in \mathrm{SO}(3)$ is the desired rotational matrix computed by the position controller using the conventional inner-outer loop [54, 55]. The desired angular position is computed using the quadrotor-dynamic equation of the attitude; for details, please refer to [56].

3.3.2 VR-UAV Position Control

The drone's positions and velocities are continuously sensed and relayed to its digital twin via MAVROS where the positions are sent with the node $mavros/local\_position/pose$ at 30Hz. In real-time, the digital twin employs a PID controller to track the positions and orientations derived from the onboard sensors within discrete time intervals.

Position Control: The position error $e_i(k) \in \mathbb{R}$ in any direction i (where i can represent x, y, or z) is the difference between the real position p_i and the virtual drone position v_i:

$$e_i[k] = p_i[k] - v_i[k], \tag{3.5}$$

Calculates the proportional control signal $P_i(k)$ by applying a proportional term (k_p) to the position error:

$$P_i[k] = k_p e_i[k], \tag{3.6}$$

Calculates the integral term contribution $I_i(k)$ by accumulating the error over time and multiplying it by the integral coefficient (k_i):

$$I_i[k] = I_i[k-1] + k_i e_i[k]\Delta t, \tag{3.7}$$

Calculates the change in error over time ($\Delta e_i(t)$) by subtracting the current error from the previous error:

$$\Delta e_i[k] = e_i[k] - e_i[k-1]. \tag{3.8}$$

The derivative gain is determined as follows:

$$D_i[k] = k_d \frac{\Delta e_i[k]}{\Delta t}. \tag{3.9}$$

For movement along the [x, y, z] axes (U), a discrete PID linear controller is applied:

$$U_i[k] = P_i[k] + I_i[k] + D_i[k]. \tag{3.10}$$

where k_p, k_i, and $k_z \in \mathbb{R}$ are the scalar position gains in each (z, y, z) axis.
Rotation Control: The rotation velocity $U_R i\psi[k] \in \mathbb{R}$ is determined using Proportional (P) and Derivative (D) components:

$$U_R\psi[k] = k_p e_\psi[t] + k_d \frac{\Delta e_\psi[k]}{\Delta t}, \tag{3.11}$$

where k_p and $k_d \in \mathbb{R}$ and are the scalar rotation control gains, $\frac{\Delta e_\psi[k]}{\Delta t}$ is the change in error over time. The updated z axis rotation of the drone R_ψ is obtained by adding the rotation velocity to the virtual drone's position Rv_ψ:

$$Rv_\psi = U_R\psi[k] + Rv_\psi(k-1). \tag{3.12}$$

3.4 Communication

The drone transmits crucial positional and orientation data to the PX4 controller. This information is sent via a wired connection from the PX4 to the Jetson board, where it is read and processed using MAVROS, a ROS node for MAVLink communication. Simultaneously, the ZED Mini stereo camera captures key data streams such as a depth map, stereo images, and odometry. These data streams are processed by the Jetson AGX

Xavier mini-computer, where the RTAB-Map algorithm is applied to generate a detailed point cloud representation.

To facilitate seamless information exchange between the real and virtual environments, the processed data is transmitted via WiFi using Rosbridge to Unity, where it is interpreted by the ROS# library. Within Unity, a dynamic 3D map is constructed, allowing for precise visualization of positions in real time. This WiFi connection acts as the bridge between the physical and digital worlds, ensuring smooth integration and synchronization. For a visual representation of this process, refer to Fig. 3.2.

CHAPTER 4

Results

4.1 Initial Findings From Point Cloud Experiments

During the point cloud analysis experiments, specific studies were conducted in wooded areas as Figure 4.1b shows to calculate the Normalized Difference Vegetation Index (NDVI). The findings of these experiments were detailed in a recent article titled ”3D maps of vegetation indices generated onboard a precision agriculture UAV.” In this article, a Unmanned Aerial System (UAS) capable of providing indices for low-height vegetation in a dense point cloud format was proposed. The system features an onboard NVIDIA Jetson AGX Xavier computer and a ZED Mini stereo imaging sensor. Given that the ZED Mini captures RGB imagery in the visible spectrum, focus was placed on computing two visible-based vegetation indices: the Green Normalized Difference Vegetation Index and the Visible-band Difference Vegetation Index. Results from two experimental flights were presented to demonstrate the system’s functionality. During these flights, online reconstruction was performed using the RTAB-Map algorithm. After obtaining dense point clouds of the vegetation regions, the system processed the data to generate 3D maps of the vegetation indices as show Figure 4.2a and 4.2b.

(a) Vegetation area. (b) Dense point cloud.

Figure 4.1: These figures display the dense point cloud of the vegetation area, visualized using MeshLab to render the .ply file.

(a) Dense point clouds of the vegetation indices GNDVI experiment (b) Dense point clouds of the vegetation indices VDVI experiment

Figure 4.2: These figures display the postproces to calculate the GNDVI and VDVI

Additionally, a straightforward quantitative analysis was presented, which could be utilized for vegetation segmentation applications.

4.2 Experiments and Simulation Results

This section showcases the results of two flight plans and their respective reconstructions. The objectives of these experiments are to address the following aspects:

- Ensuring accurate replication by the digital twin of the positions and orientations of the physical quadrotor.
- Investigating and correcting any delay present between these two systems.
- Verifying that the reconstruction accurately reflects the measurements of the physical environment.

To commence, Figure 4.3 depicts the environment where the flight tests were conducted.

4.2.1 Position Results

This section presents the results obtained from the flight tests conducted in the environment illustrated in Figure 4.3 are presented. The primary objectives were to map as many points as possible and minimize the discrepancy between real and virtual positions. Figure 4.4 displays the linear positions during the 450-second flight test, where a random trajectory was followed to cover all potential points. The PID and PD gain parameters for VR-UAV position control are shown in Table 4.1.

Table 4.1: VR-UAV position control parameters

Controller	Gains
Discrete PID Position	k_p = 35, k_i= 0.24, k_d = 510
Discrete PD rotations	k_p = 0.094, k_d = 0.031

As depicted in Figure 4.4, the simulation commenced before the physical drone, which was already in operation and controlled using a radio controller. Subsequently, the quadrotor

Figure 4.3: The figure below shows the flight test site.

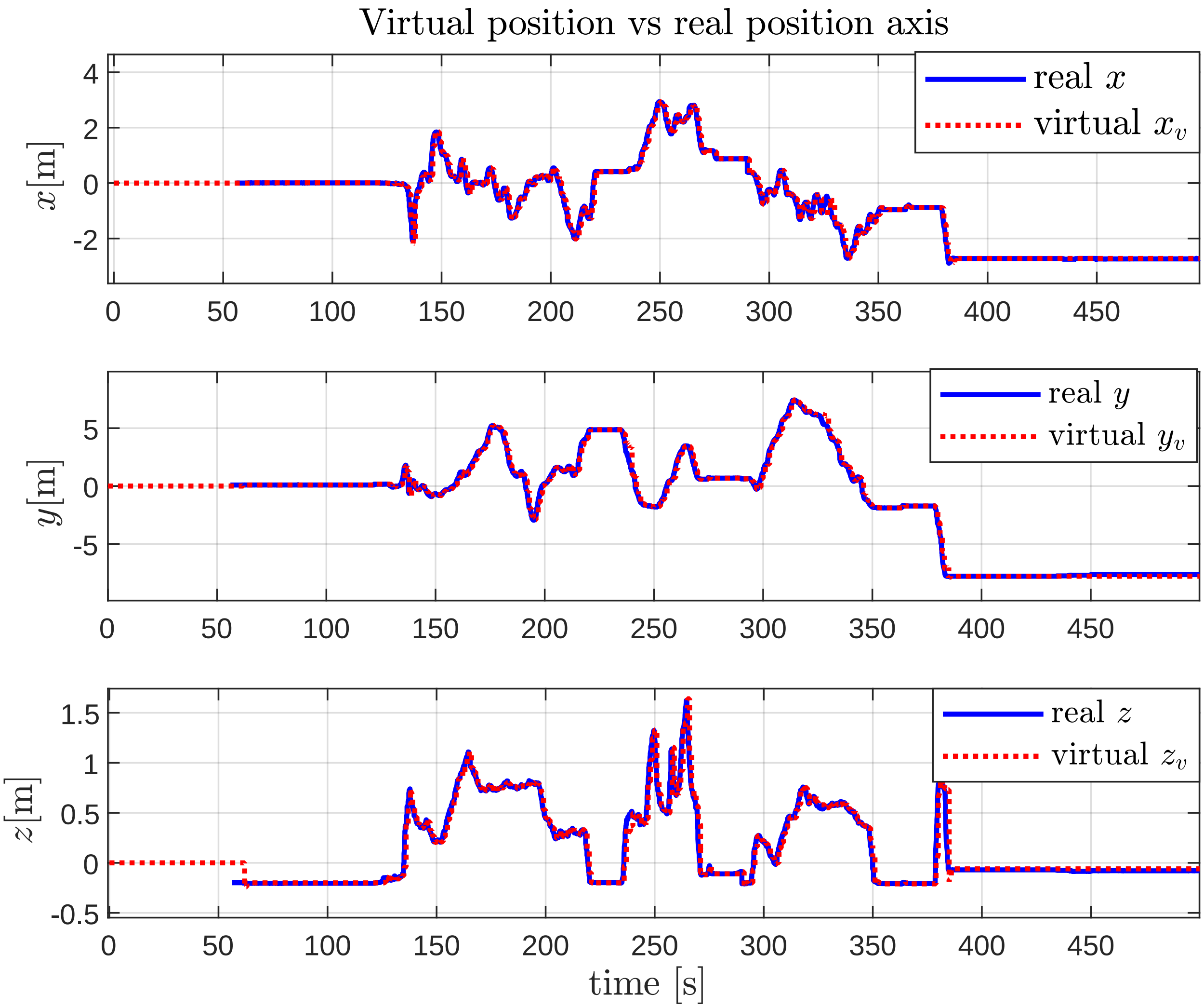


Figure 4.4: Quadrotor position states were obtained during the experiment. Note that the positions are similar in both cases and the delay is minimal.

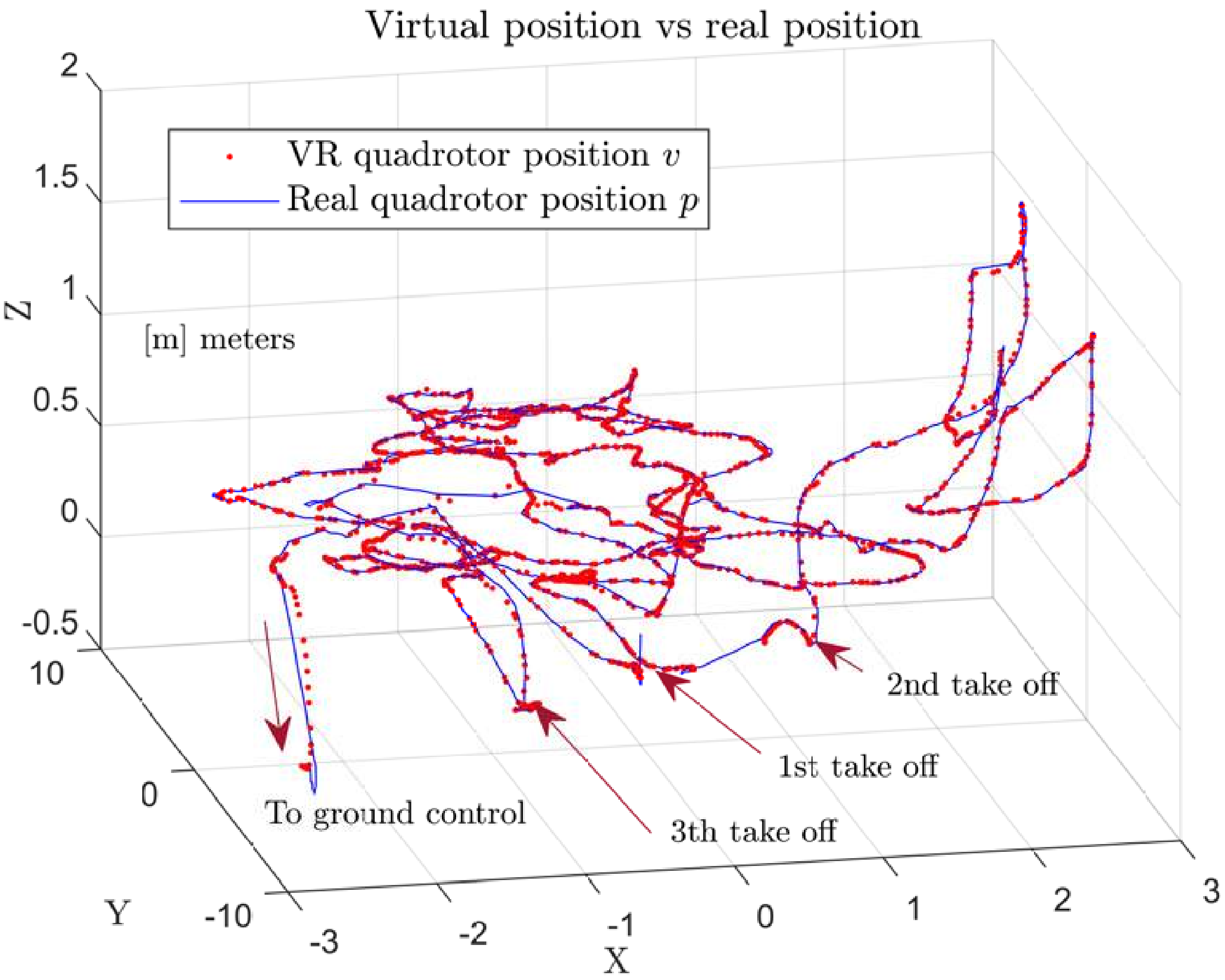


Figure 4.5: The quadrotor position states were obtained during the experiment. The red arrows indicate the different instances when the UAV ascended to perform the trajectory. In this simulation, the drone maintains several rotations around the z axis were performed. The dotted red lines represent the virtual trajectory, while the blue lines depict the real trajectory.

was assembled and lifted, undergoing three takeoffs to achieve optimal mapping. In total, the vehicle take off three times before being directed to the control center. Notably, the virtual vehicle exhibited behavior closely resembling the real vehicle, with minimal differences and a negligible delay.

Figure 4.5 provides valuable information, showing the complete trajectory of the vehicle and highlighting certain moments where the error between the virtual and real positions is minimal. The virtual positions, marked with red dotted lines, demonstrate consistency despite occasional signal drops. These drops, indicated by fewer points, did not significantly affect the overall accuracy.

A second trajectory, featuring a more planned rectangular shape, was conducted. Figure 4.6 shows the trajectory followed by the vehicle, illustrating that the virtual positions closely matched the real ones.

4.2.2 Point Cloud Results

This section presents the reconstruction of the point cloud in the virtual environment hosted in Unity, based on the experiment that includes the position test trajectory shown in Figure 4.5. The reconstruction was carried out in three takeoffs to cover the maximum number of points possible. RTAB-Map was utilized to send the point cloud data to Unity via Rosbridge. During this experiment, it was observed that before takeoff, the drone mapped a significant area. However, as the reconstruction area expanded, the process duration increased. Additionally, moments of reduced WiFi speed were noted, which resulted in the transmission of fewer points. Despite these challenges, the system demonstrated robust performance in generating a real-time point cloud reconstruction.

In Figure 4.8, the final result of the reconstruction is presented. Since the process is in real-time, there is a certain level of noise is present in the point cloud, which could be reduced through post-processing after the flight has concluded. Nevertheless, the contours and depths are distinguishable. Additionally, it is worth noting that the dimensions of the environment, the drone, and its location in space are identical to those in the real environment. These results indicate that the system is capable of producing accurate reconstructions, providing a foundation for ongoing improvements aimed at achieving more precise results

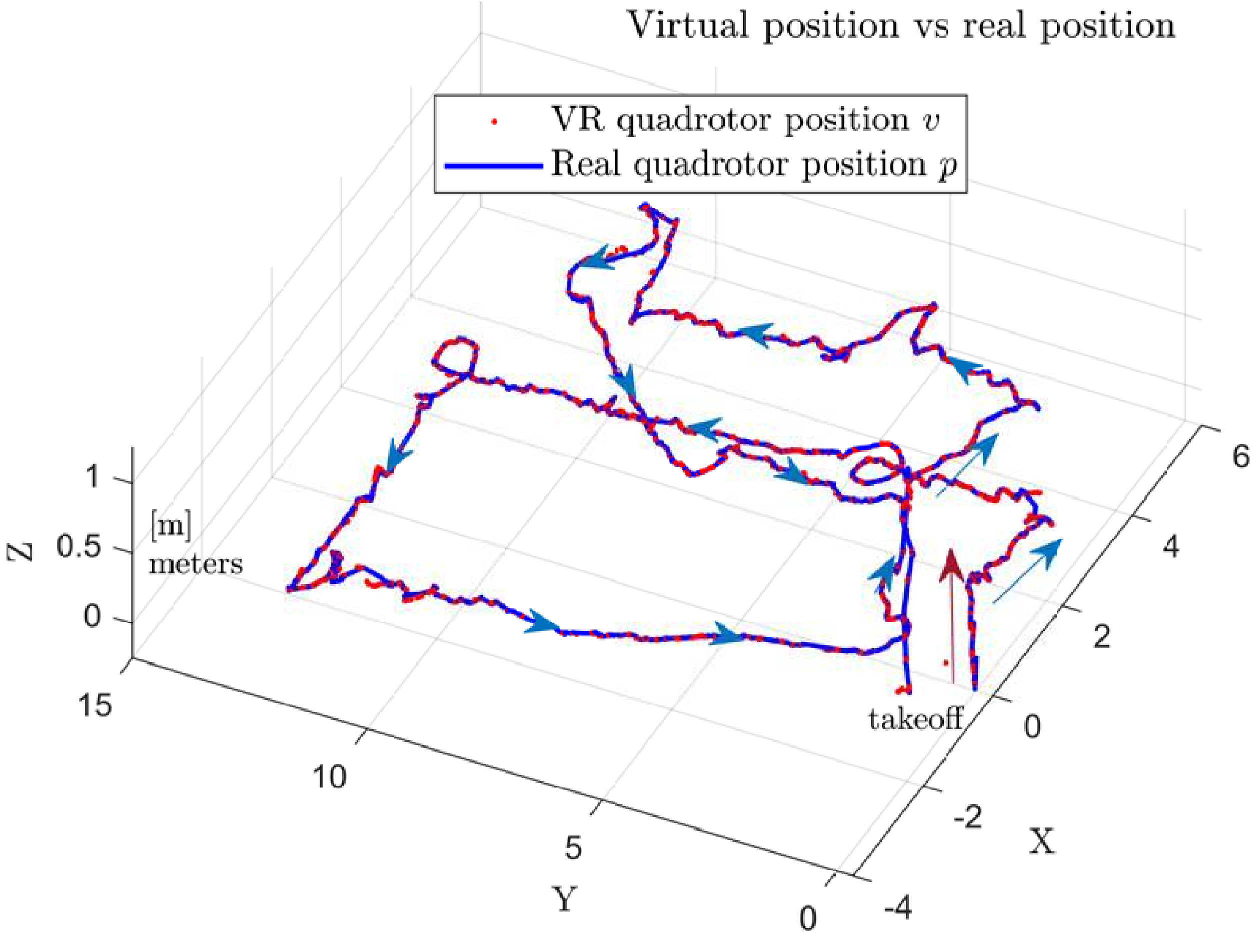


Figure 4.6: The quadrotor position states were obtained during the 2nd experiment. The red arrows indicate the different instances when the UAV ascended to perform the trajectory. In this simulation, the drone maintains several rotations around the z axis were performed. The dotted red lines represent the virtual trajectory, while the blue lines depict the real trajectory.

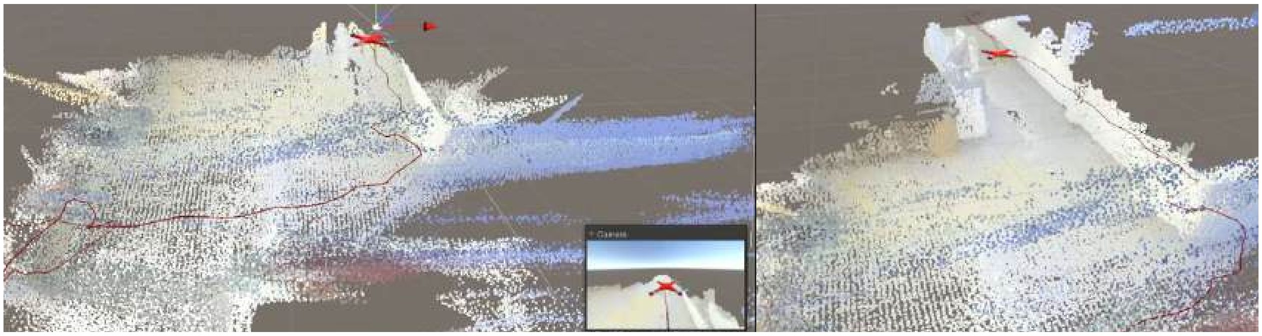


Figure 4.7: This figure shows the tests in an indoor environment, the experiments were performed with motors off. This display showcases the viewpoint observed by the pilot through the VR goggles. The goggles offer the flexibility to switch between perspectives, allowing users to seamlessly transition between third-person and first-person views.

in the future.

The second trajectory, as show in Figure 4.9, is represented in the point cloud depicted in the same figure. The results are similar, and the geometry of the space can be better appreciated in this second point cloud visualization.

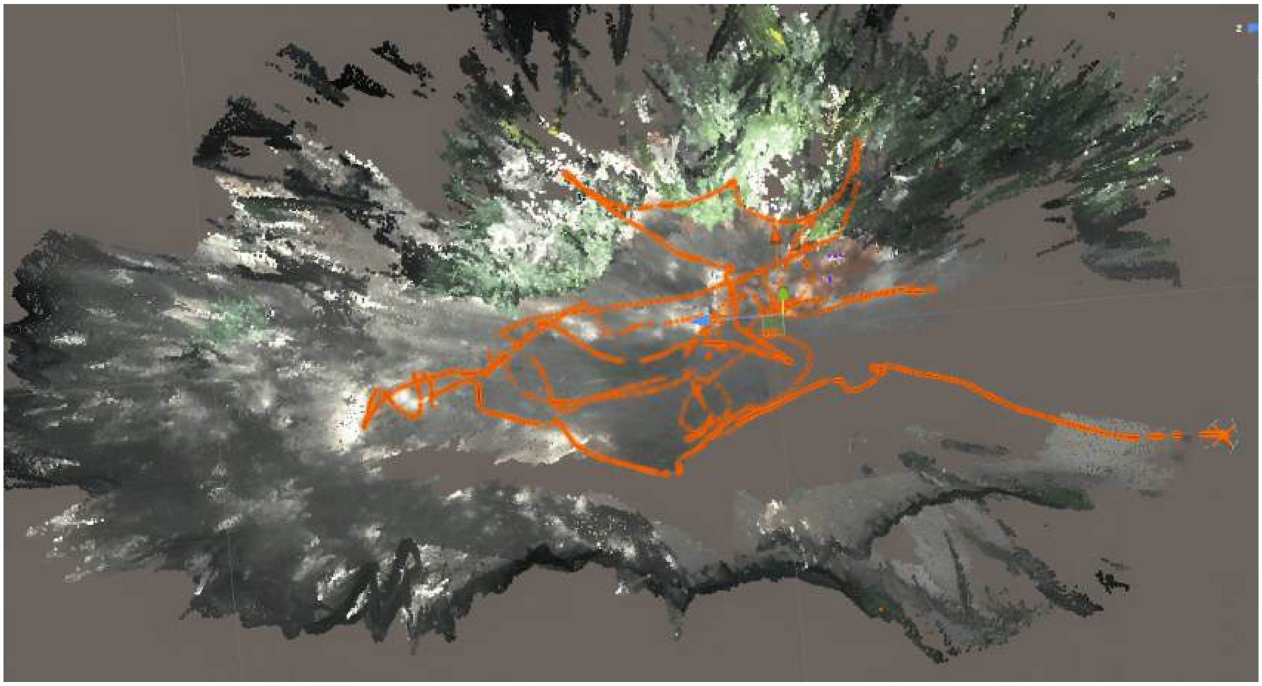


Figure 4.8: Point cloud of the test site from the first experiment, as visualized in the VR Unity environment.

These visualizations highlight the system's effectiveness in capturing and reconstructing the physical environment in a virtual space. The ability to map the environment accurately and in real-time is crucial for various applications, including navigation, surveillance, and virtual reality simulations. The consistency between the real and virtual representations, despite occasional slowdowns in data transmission, underscores the robustness of the approach.

4.2.3 VR Interaction

Based on the results presented in 4.2.2, it was evident that the point cloud exhibited significant noise and lacked the requisite density for effective visualization within the virtual reality setting. Instead, testing was conducted in an indoor environment featuring walls.

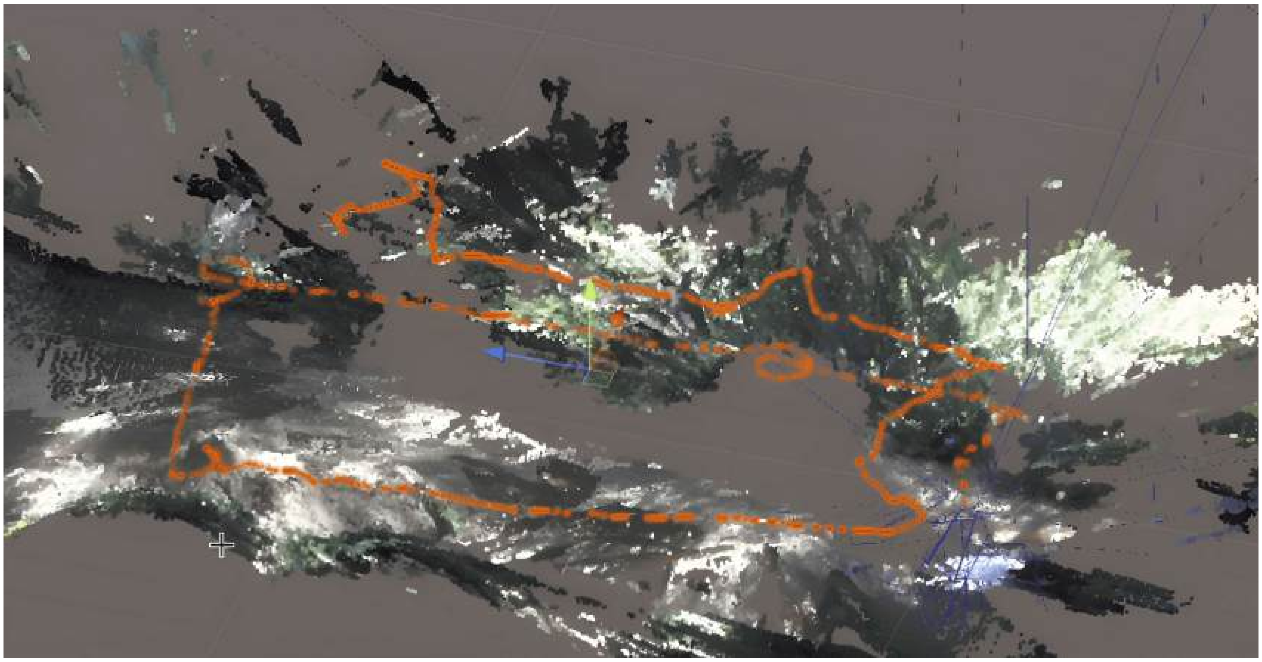


Figure 4.9: Point cloud from the second test, visualizing the same test site in the VR Unity environment.

Despite the persistent noise, its impact was somewhat mitigated due to the environmental conditions.

For visualization through VR goggles, the HTC Vive was utilized, along with the integration of the SteamVR plugin within Unity. During testing, interactions with the VR goggles and reconstruction procedures were conducted in an indoor setting with the drone's engines deactivated. As a safety precaution, the propellers were removed from the drone, allowing for manual displacement of the vehicle during the experiments.

Figure 4.7 provides a visual representation of the VR environment and the vehicle's perspective as seen through the goggles. This setup demonstrated how the VR system could be used to visualize and interact with the reconstructed environment in real-time, despite the presence of noise in the point cloud data.

The indoor environment provided a stable platform for testing the VR interaction capabilities of the system. The HTC Vive goggles, coupled with SteamVR, allowed for an immersive experience, enabling users to navigate and interact with the reconstructed environment effectively. The ability to switch between third-person and first-person perspectives within the VR environment provided flexibility and enhanced the user's spatial awareness and interaction experience.

Overall, these tests highlighted the potential of VR technology to enhance the visualization and interaction with real-time reconstructed environments, even in the presence of data noise.

CHAPTER 5

Conclusion

During the flight test, we observed ideal performance in the controls, especially in the VR control. Throughout the test, the digital twin managed to replicate the movements of the real drone almost exactly, which is highly favorable given the minimal delay. This aspect is crucial to avoid potential collisions due to a poor perception on the part of the pilot.

In contrast, concerning the reconstruction of the point cloud, the process was carried out in a reasonable time, although the results were somewhat blurry. Nevertheless, the obtained dimensions are accurate compared to reality. However, there is work to be done to enhance real-time environment reconstruction, particularly considering that most of the time this process is conducted online and with more powerful hardware. These improvements are necessary due to the limitations of the Jetson, which has certain restrictions in terms of processing capacity and compatibility.

5.1 Recommendations

In future work, the goal is to further enhance point cloud reconstruction, either by refining the current algorithm or exploring alternatives such as ORB-SLAM, despite hardware limitations. Additionally, plans include adding a secondary camera positioned at a 0-degree angle to improve data capture and optimizing data transmission. Another objective is to integrate a manipulator arm, a direction previously investigated in [18]. Furthermore, efforts will be focused on teleoperation tasks to expand the system's capabilities and potential applications. These advancements will contribute to the continued development and improvement of the project.

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