Optimizing UAV-Based Inventory Detection and Quantification in Industrial Warehouses: A LiDAR-Driven Approach

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Abstract: The advancement of technology has brought about a revolution in industrial operations, where specialized tools play a crucial role in enhancing efficiency. This study delves into the significant impact of the logistics department in global industries and proposes an innovative solution for inventory detection and recognition using unmanned aerial vehicles (UAVs) equipped with LiDAR technology. Unlike existing research that often involves intricate hardware systems and algorithms leading to increased costs and computational demands, our research focuses on streamlining the inventory detection process by utilizing a LiDAR data and an algorithmic approach that minimizes the time of extensive counting process into the warehouse to quantify the pallets existing. The proposed methodology entails a custom-made quadcopter equipped with a single-beam and high-frequency LiDAR range finder. Operating autonomously along a predetermined flight plan, the drone captures high-frequency range data of warehouse inventory. The paper comprehensively outlines the UAV control procedures, warehouse scanning using LiDAR, and the inventory detection and quantification of pallets algorithmic process. The proposed method processes LiDAR data in a post-process way, estimating the number of pallets and, consequently, producing a map of each stack within the warehouse denoting the quantities of pallets. The research results showcase the successful implementation of the proposed approach in a model warehouse, achieving an impressive 100% evaluation accuracy. Future research endeavors aim to extend this methodology to warehouses with dynamic product placements, emphasizing real-time monitoring for comprehensive inventory detection. This innovative approach stands out as a cost-effective and efficient solution for industries seeking accurate and timely inventory information.

Key-Words: LiDAR, UAVs, Inventory Detection, Warehouse Measurement

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1 Introduction

The evolution of technology in our days has brought significant progress and improvement in every sector of the industry area. Specialized and constantly evolving technological tools are being incorporated daily into industrial units to facilitate the implementation of industrial production, organize a set of tasks necessary to be carried out within the operations framework of an industrial unit, optimize the development and marketing departments of the industries, and achieve the most immediate and effective ”digital” connection between different departments of an industry unit or among units within a global industry (communication between branches on a global scale). As a result, the continuous integration of new technologies into industrial units is critical and obsolete this is administered through new high-end hardware implementation or new and improved software integration in each department of any structured industry.

Unmanned aerial vehicles (UAVs), commonly referred to as drones, have garnered considerable attention and found widespread commercial applications across various domains, [1], [2]. UAVs, with their distinctive characteristics, offer specific advantages tailored to focused tasks or activities. In recent years, several studies have introduced innovative initiatives to foster the adoption and implementation of drones in warehouse management. Notably, these initiatives encompass the integration of Unmanned Aerial Vehicles (UAVs) with technologies such as barcodes, computer vision (CV), and machine learning (ML), [3]. These integrations are designed to automate various warehouse operations, including tasks like barcode detection and decoding, [4], [5]. Simultaneously, studies, such as [6], have explored enhancing self-positioning UAVs and automatic identification and data capture (AIDC) by integrating drones with light detection and ranging (LiDAR) devices and radio-frequency identification (RFID).

Despite the growing interest in adopting drones for warehouse management tasks, the existing body of research has primarily focused on diverse domains like construction, humanitarian efforts, and agriculture. Studies centered on UAV-based warehouse management exist and are linked with supply chain management (SCM) and logistics management, [2]. Thus our research and proposed methodology is essential for driving UAV adoption in this domain.

The logistics department of industry plays a significant role in the global economy today. It is a vital department of an industry that requires immediate updates (live- updates) and precision in inventory monitoring. By succeeding in this, industries would stay up-to-date and have full knowledge of the products' sufficiency at any given moment and in a global status. Industries today rely on their logistics, which provides constant and reliable inventory information, to improve their economic value. Therefore, the automation of the inventory detection and recognition mechanism is considered necessary to give the real inventory status of products available to the industry as quickly as possible and without any human error, which may occur due to the ”human factor”. By this, selling goals are succeeded, profit is increased, and production costs are minimized because ”no unnecessary products” are produced.

Using unmanned aerial vehicles (UAVs), commonly known as ”Drones,” is believed to improve this area significantly. Currently, the constant development of drones' vision positioning and GPS integrations are capable of being operated indoors and outdoors autonomously, without any human intervention, only by giving a flight route plan. It is, therefore, crucial to find suitable software that, utilizing the data provided by the unmanned aircraft, can accurately complete a full inventory scanning by being able to live record the quantities of products in each warehouse - branch in any industry's premises. The discovery of such an algorithm depends on the chosen technologies a drone will be equipped with. Depending on the technologies mentioned above, different approaches emerge to implementing an efficient algorithm that will complete the above process in the best possible way. Therefore, careful examination and selection of technological utilities are required, which, in combination with the algorithm, will produce results with accuracy and at the lowest implementation cost.

Regarding the existing research conducted in the product inventory detection and recognition Field, [7], the authors focus on developing and evaluating an aerial robotic system (UAV) for intelligent inventorying of accumulated materials within a warehouse. The LIDAR system collects data points (using PCL technology). Subsequently, with appropriate post-processing, the algorithm creates a three-dimensional model of the environment (the warehouse and storage points) from which material measurements are taken. Through detailed processing, the researchers managed to estimate the quantities of bulk materials in each stack.

In [8], an approximate counting of accumulated materials (specifically, recyclable waste) located in an open area is attempted using the process of ”Photogrammetric Surveying.” This process relies on data processing collected through the photography of the materials to be measured using an unmanned aerial vehicle (UAV or Drone).

Furthermore, in [9], research focuses on automating inventory management in a large product warehouse. Specifically, they attempt to detect and identify various products in stock using UAV (Drone) technology and QRCode technology (Quick Response Code).

In [10], the authors propose the use of a high-resolution portable radio frequency identification (RFID) reader in a UAV (Drone) for conducting inventory surveys in industrial product warehouses. Their work aims to find the optimal algorithm for designing the 3D trajectories of unmanned aerial vehicles (UAVs) in complex industrial warehouses, primarily due to the complexity of the UAV process for the complete detection and reading of all RFID labels on products within the warehouse proposing the use of the hybrid fitness-based differential evolution algorithm (PSO-DE).

In [11], the authors propose an approach based on the use of unmanned aerial vehicles for scanning warehouse inventories and a convolutional neural network-based deep learning method (R-CNN - Deep Learning) for autonomous surveying activities.

The research mentioned above cases approach the problem with relative accuracy and efficiency. However, there are several disadvantages to implementing each algorithm. These disadvantages are related to complex hardware systems (RFID Readers, QR-Code Readers, and Lidar Scanners), which increase the implementation cost and affect the flight autonomy of drones due to increased total weight. The above-mentioned research is based on the use of complex algorithms that have a high computational cost, as well as the use of complex data that are difficult to manage. As a result, data post-processing is mandatory so that the algorithm can complete the process of recognizing the inventory of the warehouse.

This research aims to find the optimal algorithm for detecting and recognizing inventory in a warehouse using an unmanned aerial vehicle (UAV - Drone), which will capture stereoscopic data using a LiDAR Scanner. Furthermore, this study tries to identify the best algorithm that effectively and directly utilizes the LiDAR Scanner's stereoscopic data, unlike the complex data used in existing research. This allows for completing the inventory detection and recognition process on the fly without further data processing. This approach minimizes the cost and time required for implementing the process, as described below.

2 Methodology

In this section, a proposed solution to the above problem is described. Fig. 1 depicts the basic steps of the product inventory detection and measurement process.

Figure 1: Implementation Steps (Diagram)

2.1 UAV Control and Navigation System

In favor of the best solution to the research, a custom-made drone constructed from lightweight materials (carbon fiber frame) was chosen. This drone should be equipped with all navigation control systems (mainboard, GPS navigation system) and a high-performance lidar scanner without exceeding its maximum payload capacity while maintaining the maximum possible flight autonomy. This ensures that the drone can complete the scanning process without further interventions. Initially, the drone operator creates a flight plan by mapping out the predetermined path the drone will follow using specially designed software. The software used, "Mission Planner", [12], utilizes point-to-point navigation technology. On a map (embedded in the software), the flight's starting point, route, and endpoint are visually marked. Each selected point corresponds to specific GPS coordinates. Subsequently, the flight plan is loaded into the drone's system, which successfully executes it through its GPS navigation system. Throughout the entire process, the operator does not intervene, except in cases where there is a safety concern for the surrounding environment.

In Fig. 2, the actual state of an inventory warehouse is shown (using a warehouse model for research purposes).

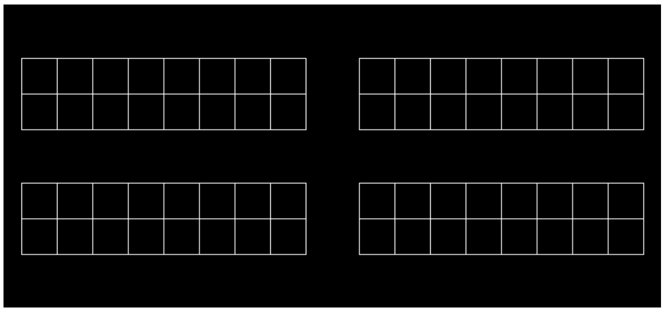

Figure 2: The representation of an empty warehouse

After receiving the flight plan data through the process mentioned above, the drone carries out the flight mission over the warehouse. Specifically, the drone navigates over the inventory according to the operator's pre-defined position points. The operator predetermines the flight altitude through the program and is a critical element for the subsequent operation of the detection algorithm.

2.2 Warehouse Scanning Using LiDAR Technology

LiDAR technology is utilized for the implementation of warehouse inventory detection. Specifically, the drone is equipped with a LiDAR sensor that captures elevation data. To execute this process, specific system parameters must be defined in advance. Initially, the drone flies directly above the products. The products are originally placed on pallets of exact known dimensions (length and width of the pallet). Additionally, each pallet has a specific maximum load height, meaning that each pallet carries a predetermined number of products. The pallets with products can be stacked (one pallet on top of another, as this is common in industrial warehouses) with a specified maximum stack height. This parameter is crucial to the solution given because it determines the flight altitude of the drone. The stacked pallets are placed in predefined sections of the warehouse (each section is divided into predefined columns and rows – specific areas) to ensure that the products on the pallets are sorted by type and can be detected.

Fig. 3 shows a model of an empty section of a warehouse. Each section has predefined columns and rows where the workers place stacked pallets. Each "box" represents a pallet or a stack of pallets.

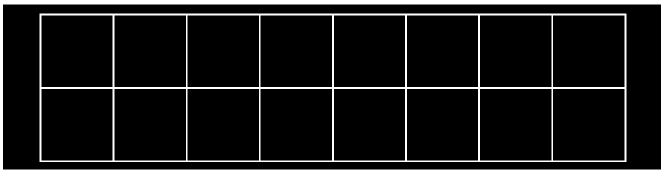

Figure 3: The representation of an empty section of the warehouse

In Fig. 4, the model represents the exact position of the drone above every stacked pallet in each predetermined area of the warehouse.

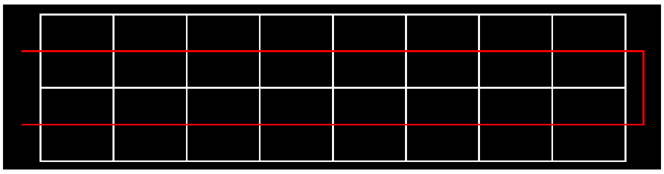

Figure 4: The navigation protocol the drone produces above each section

During the drone's flight, the LiDAR scanner captures the distance between the initial lidar position and the stacked pallets below the drone at regular intervals, which are determined by the software. This distance represents the metric difference between the stack's distance from the drone's predetermined flight altitude. The same procedure is applied to each area of the warehouse until the scanning of all sections of the warehouse is completed.

2.3 Inventory detection and scanning algorithm

The data obtained from the LiDAR scanner is extracted from the drone and is input into the software. Subsequently, the algorithm provides an estimation of the number of counted products (in stacks) in the warehouse. Along with the LiDAR scanner's recorded data values, specific parameters necessary for the algorithm's correct operation are defined into the program. Specifically, the program incorporates the drone's flight altitude, the LiDAR sampling resolution, the predetermined length and width of each pallet, as well as the specified height that each pallet can be loaded. In Fig. 5 and Fig. 6, each diagram illustrates the distance measurements obtained by the LiDAR scanner in relation to the sampling frequency. To accurately represent the real state of the warehouse, the algorithm includes a flight margin compensation to reduce instances of incorrect measurements of product stacks.

The flight margin compensation in our algorithm plays a crucial role in mitigating inaccuracies in the measurement of product stacks during UAV flights. This compensation accounts for variations in flight conditions, such as changes in altitude, wind speed, and other environmental factors, which could impact the precision of LiDAR measurements. In practical terms, the algorithm incorporates a margin of adjustment during the flight, allowing for real-time adaptations based on the dynamic conditions encountered. By doing so, we aim to enhance the accuracy of measurements, ensuring that the LiDAR data collected aligns more closely with the actual state of the warehouse at any given moment. This adaptive approach minimizes the likelihood of errors in the determination of product stack dimensions, contributing to a more accurate representation of the warehouse environment.

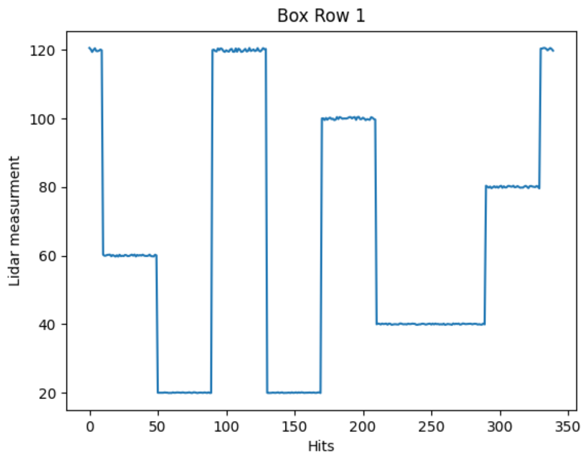

Figure 5: Diagram representing the Lidar's distance calculations in Row 1

The above measured distances are converted into stack height values through a process used by the algorithm to estimate the number of pallets in every stack of each section in the warehouse.

In Fig. 7, the model represents the results of the scanning and identification procedure by the algorithm.

To achieve optimal results, the algorithm groups the values obtained from the LiDAR scanner into values of the same or similar height, considering the predefined error margin. Each subsequent value is included within the existing value group if it falls within the bounds of the mean value of the current value group, based on the specified error margin. Each value group corresponds to the width of each stack of pallets located on the same line in each warehouse area, only in case they have the same value as the mean of the current value group. In cases where val-

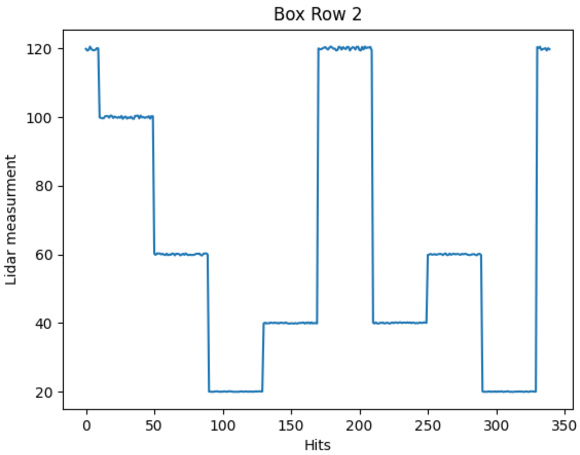

Figure 6: Diagram representing the Lidar's distance calculations in Row 2

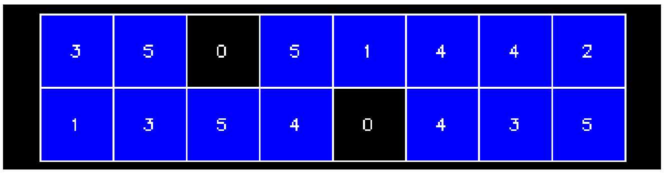

Figure 7: Results of the inventory scanning procedure

ues differ from the mean, a new stack is created. The differentiation of consecutive stacks of pallets of the same height is achieved by comparing the number of values in the group (along with the error margin) with the predetermined width of each pallet. The LiDAR sampling resolution is also taken into account as a parameter. This process ensures that the algorithm will group lidar measurements and recognize each consecutive stack of pallets without the risk of incorrect estimation, due to the fact that some stacks of pallets may have the same height in each measuring line.

3 Results ans Discussion

The above procedure was tested and evaluated using random given data in a model. The results were evaluated at 100%. The same process is used to fully scan and estimate the exact inventory of each section in a warehouse. The same navigation protocol is used, specifically modified for more sections in the warehouse. In Fig. 8, the navigation process is being represented.

In Fig. 9 and Fig. 10, each diagram illustrates the distance measurements obtained by the LiDAR scanner in relation to the sampling frequency.

Obtained data from the drone are inserted into the program. The results of the algorithm are evaluated at 100%. In Fig. 11, we represent the evaluation results of a total warehouse scanning.

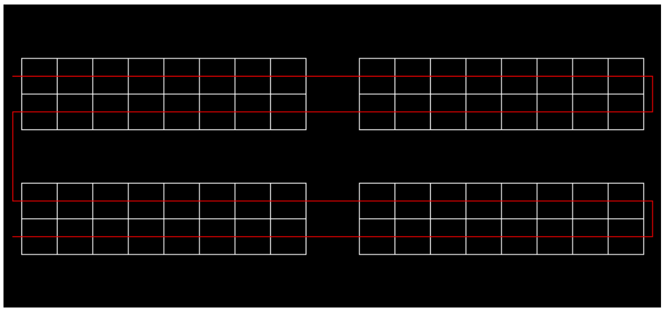

Figure 8: Navigation guidance through every section of a warehouse

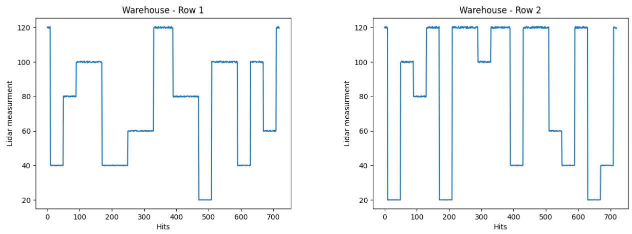

Figure 9: Scanning Procedure for Rows 1 and 2

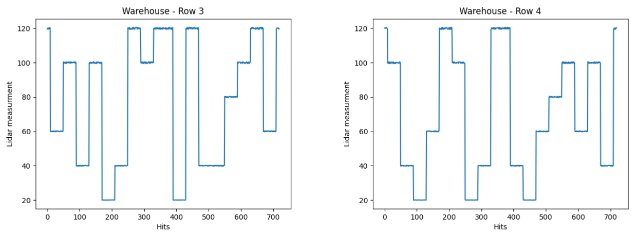

Figure 10: Scanning Procedure for Rows 3 and 4

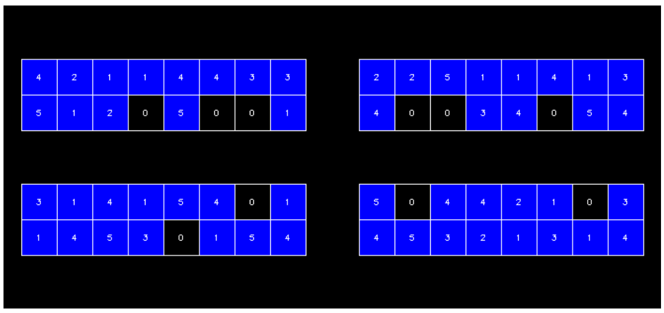

Figure 11: Results of Warehouse Inventory estimation

Unmanned Aerial Vehicles (UAVs) have emerged as game-changers in the realm of industrial inventory management. Leveraging state-of-the-art technology, UAVs equipped with LiDAR sensors provide an innovative solution for the detection and quantification of inventory in large-scale warehouses. This approach reduces reliance on traditional manual methods, enhancing efficiency and accuracy in assessing stock levels. The integration of UAVs introduces a dynamic and adaptable system that autonomously navigates warehouse spaces, capturing detailed LiDAR data to precisely quantify inventory items. This transformative technology holds the promise of revolutionizing how industrial warehouses manage and optimize their inventory processes.

In the pursuit of advancing warehouse logistics, the implementation of UAV-based inventory detection offers a paradigm shift. This approach not only streamlines the traditional inventory management process but also introduces a cost-effective and time-efficient solution for industries grappling with the challenges of large-scale warehouse operations. As industries increasingly recognize the potential of UAVs in this domain, the integration of LiDAR technology for accurate and real-time inventory assessments becomes a pivotal advancement, marking a significant step toward the future of smart and automated warehouse management systems.

4 Conclusion

In subsequent stages, the Goal is to implement the detection of inventory within a warehouse with pallets and products placed in unspecified positions. This hypothesis represents the primary objective of the research, as in all industrial warehouses, predetermined product placement positions cannot exist, because every section is continuously modified to serve various types of product placement. Furthermore, the future aim of this research is to complete the entire inventory detection and inventory scanning process, using the existing resources and achieving on-the-fly detection. We are encouraged to complete the above whole process using special hardware and software attached to the drone, as to achieve real-time monitoring of an industrial warehouse.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflicts of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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