ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20250408125740

Preliminary communication
Received: 2025-04-08, Accepted: 2025-04-30

Sustainability in Drone Technology – Tracking Using Drone

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Abstract: Sustainability and Industry 4.0 technologies are increasingly integrated into modern production. Among these, drones represent a newer autonomous device with potential beyond aerial photography. This paper introduces a novel industrial application of drones: inventory checks and tracking of Autonomous Mobile Robots (AMRs). At the University of Miskolc's Logistics 4.0 Laboratory in Hungary, a roller conveyor system transports unit loads, supported by one larger AGV (Automated Guided Vehicle) and two smaller AMRs. While these ground-based devices navigate independently, their sensing is limited to ground level. The proposed drone solution enhances this system by performing horizontal photographic inventory checks and tracking the movement of mobile robots from above. This dual-purpose use of a single drone improves motion accuracy and reduces the need for multiple tracking systems. The paper outlines the system's design and presents the results of implementing this drone-supported approach.

Keywords: Autonomous Mobile Robot (AMR); drone; inventory check; logistics; sustainability; tracking

1 INTRODUCTION

Nowadays, sustainability and Industry 4.0 technologies are widely referred to in production and management of technology. One of the Industry 4.0 technologies is autonomous devices, and among them, drones represent one of the newest advancements, alongside older robotic technologies. Drones are commonly used in everyday life for aerial photography; however, in industry, this capability can be utilized in various ways.

This paper proposes a new approach to the industrial application of drones. The idea is to use a drone for inventory check and also tracking an AGV (Automated Guided Vehicle) or AMR (Autonomous Mobile Robot). At the University of Miskolc in Hungary, within the Laboratory of Logistics 4.0, a roller conveyor system is in place that can transport unit loads along different routes. For performing storage, an automated shelving system was implemented into the laboratory. Substituting manual transport, the system incorporates one larger AGV and two smaller AMRs. The AGV carries unit loads, while the AMRs assist in predicting and optimizing the AGV's route. Although these devices utilize their own navigation systems, they are limited to sensing objects at ground level. By employing a drone to track these units from an overhead photographic perspective, motion accuracy can be improved, and a single device is sufficient for this purpose. From other perspectives, with the front photography view the same drone can be used also for inventory check and scanning.

This paper presents the background of this function and explores different results. Chapter 2 discusses the literature background of this topic. Chapter 3 introduces the background for inventory check, while Chapter 4 presents the steps taken in its development so far. Chapter 5 highlights the practical implementation of inventory check and tracking mobile devices. Finally, Chapter 6 summarizes the paper and shortly enhances future possibilities.

2 LITERATURE BACKGROUND

The integration of Industry 4.0 technologies in manufacturing and logistics has been widely researched in recent years. Sustainability and automation are central themes, with autonomous systems such as drones playing a crucial role in industrial applications.

A key aspect of Industry 4.0 is the improvement of logistics operations through automation and digitalization. According to Zhong et al. [1], smart manufacturing uses autonomous devices to optimize efficiency and reduce human operation. Drones, as a part of these technologies, have gained attention for their potential in logistics. Researchers such as Otto et al. [2] highlight their role in inventory monitoring and real-time data collection.

In warehouse management, drones have been increasingly used for automated inventory tracking, as reported by Kim and Lee [3]. Their study demonstrates how aerial imagery and machine learning algorithms can improve stock accuracy and reduce operational downtime. Furthermore, drones have been proposed as a solution for supporting Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs). According to Bogue [4], AGVs and AMRs rely primarily on ground-based navigation sensors, which limit their awareness of overhead obstacles and global positioning accuracy.

Recent studies suggest that drones can complement AGVs and AMRs by providing aerial tracking and guidance. Eski and Tjahjono [5] argue that integrating drones with existing robotic systems improves operational flexibility and safety. This is coincidence with experimental implementations at the University of Miskolc's Logistics 4.0 laboratory, where a drone is tested for improving AGV/AMR path accuracy and collision avoidance.

Additionally, the role of artificial intelligence (AI) in drone navigation has gained interest. Advanced AI-driven systems allow drones to adapt to dynamic environments, improving their tracking and decision-making capabilities. Researchers such as Smith and Brown [6] suggest that integrating AI with drone navigation can significantly enhance performance by enabling real-time adjustments based on environmental factors. This is particularly important in industrial settings where obstacles and workflow variations occur frequently.

Another important area of research is the communication and data exchange between drones and AGVs/AMRs. Wireless sensor networks have been explored to create smooth communication, as written by Chang et al. [7]. Their study highlights how reliable data transmission between aerial and ground-based autonomous devices can improve coordination and reduce errors in logistics operations.

Further advancements in sensor technology, including LiDAR and thermal imaging, have also been explored to enhance drone-assisted tracking. Johnson et al. [8] investigated how combining multiple sensors can improve localization accuracy and overall efficiency in industrial environments.

The current framework of research highlights the potential of drone-robot integration in industrial automation. Future studies should explore advanced sensor fusion techniques and artificial intelligence applications to maximize efficiency and reliability. Moreover, energy efficiency remains a challenge in drone-based tracking, as highlighted by Wang et al. [9]. Addressing battery life and optimizing energy consumption are crucial for long-term industrial deployment.

3 BACKGROUND OF INVENTORY MANAGEMENT WITH DRONE TECHNOLOGY

Inventory management plays a crucial role in a company's operations, as it is essential to accurately track the quantity and location of all materials in the warehouse. Proper inventory records are necessary for forecasting, which is essential for order management. Orders must be executed based on inventory levels to prevent supply chain disruptions.

Figure 1 Drone in a warehouse [10]

In larger warehouses, the inventory inspection process can be time-consuming and may also lead to higher costs. Therefore, drone-assisted inspection is compared with traditional methods, as time savings are one of the most important factors in achieving efficient operations.

An example of using drones in a warehouse is illustrated in Fig. 1. In this case there was a bigger and older drone available, which can be controlled basically manually or semi-automatically, the fully automated movement can be performed only in a limited way. Hence at the background of picture a drone operator can be seen with a controller and a mounted smartphone for checking the movement of drone.

3.1 Conditions

The use of drones in inventory management offers several advantages, such as enabling full automation of the process, thereby minimizing inventory discrepancies caused by human error. However, certain essential conditions must be met to ensure the smooth and efficient implementation of this process.

3.1.1 Essential Requirements for Drone Implementation

First and foremost, it is necessary to acquire a drone that can be equipped with various sensors or cameras to read barcodes, QR codes, or RFID tags. Precise navigation is crucial, as even a few millimeters can determine whether a collision occurs or is successfully avoided.

Additionally, the drone must be capable of highly accurate maneuvering since it needs to be navigated between shelves. If it lacks sufficient precision, it would be unable to travel effectively from one shelf to another, making it essential to ensure that the selected drone possesses exceptional maneuverability and control. Therefore cost-effective, toy-like drones are not proper for this purpose.

3.1.2 Navigation

Indoor navigation can be challenging when using GPS, as its functionality may be compromised in enclosed spaces. To ensure effective navigation in such environments, an appropriate localization system must be implemented. GPS-based localization has several weaknesses. Since it relies on radio signals, it is susceptible to interference from various sources. In certain environments, such as areas surrounded by tall buildings, GPS signals may be unavailable, rendering these locations GPS-deprived zones. Even when a drone has a direct line of sight to GPS satellites, its signal information can be manipulated by malicious attackers. As a result, GPS-based navigation can accumulate positioning errors, leading to inaccurate navigation in many cases.

In study, Emimi et. al. [11] proposed a system for autonomous path following that utilizes visual information captured by a monocular camera mounted on the drone. The advantage of this approach is that the information is immediately available, does not depend on external signals, and is less vulnerable to spoofing attacks. The proposed system builds a combined database using simulator-generated data as well as data collected from manually controlled or GPS-based navigation paths. This database is then used to train a Convolutional Neural Network, which generates drone control commands based on detected images, thereby enabling autonomous drone navigation.

3.1.3 Data Processing

Also, data processing software is a key factor that can process drone-scanned 1D ID codes, QR codes and RFID tags in real time and link this data to the warehouse's inventory management system. In order to communicate with the company's inventory management system, the drone requires wireless connectivity and device compatibility.

3.1.4 Safety

Safety measures must be observed to minimize both personal injury and material damage. When using a drone, the drone must be given adequate space to avoid accidents and therefore be safe. Designating flight zones and communicating them to workers can make it easier to ensure that the drone's path is not crossed by humans. Regular, professional maintenance of the drone can prevent malfunctions and resulting accidents.

3.1.5 Warehouse Design

The warehouse must be arranged and designed in such a way that the drone has easy access to the labels identifying the products on the shelves. This also means that the rows between shelves must have sufficient width to allow maneuvering, including that the labels on the products or materials on the shelves are in a position that can be read by the drone's camera or code reader. Therefore, the label must be facing the right direction, and its visibility is also important, which can be ensured by the lighting in the warehouse or by an auxiliary light source mounted on the drone.

3.1.6 Identification System

The company needs to implement and use an identification system that can interpret and manage separate tags such as barcodes or QR codes. The absence of such an identification system and the inadequate handling of drone-read codes would limit the transparency of the stock control system.

3.1.7 Operator

To ensure that everything runs smoothly, the drone operator needs to have the right knowledge to operate the drone and to use the software, which may require training, and for bigger drone, also a so-called drone license. Maintenance is also important in a case like this, as a drone malfunction can mean a big loss of time, especially if the maintenance worker is unable to correct the fault after the malfunction has occurred due to lack of knowledge, or even if he or she makes the situation worse, like making an accident, especially critically to humans.

3.1.8 Costs

Costs should be calculated at every step of the system's implementation, sometimes more, sometimes less. Setting up a warehouse or converting an existing warehouse, purchasing a drone, purchasing software for identification, all involve significant costs. Attention must also be paid to ensuring data security and protection, as the information collected by the drone must be handled with care, so security systems may need to be put in place. Furthermore, there are costs associated with the purchase of maintenance equipment or spare parts, which are necessary for regular use, as wear and tear and possible failure are inevitable. What can increase expenditure even further is the amounts spent on employee training.

3.2 Example for Inventory Management with a Drone

There are companies where it is possible to register stocks by drone. In [12], Tubis et al. tested a drone-based inventory tracking system at a logistics service provider's decentralized center in Poland was investigated. The drone used included a proximity sensor, gyroscope, camera and GPS receiver. In this case, it was not possible to control the drone via GPS positioning, as there was no GPS signal in the warehouse under investigation. Therefore, positioning was only possible by tracking the drone's movements. The unit loads placed on the shelves of the shelving system used had a QR code identifier, which is identified and interpreted by the system. It is solved by stopping the drone after finding it and generating the streamed image stream that can be interpreted by the scanner software of the handling device.

3.3 QR Code and Barcode

When building a new system, it is necessary to decide whether to use a barcode or another code, such as a QR code. However, if a modification of an existing system is the goal, it is needed to consider whether to use the existing one or introduce a different code type, as both have their advantages and disadvantages.

3.3.1 Barcode

This type of ID code can store up to 20 characters of data, taking up more space than a QR code. If a barcode becomes corrupted it can no longer be scanned, and the position of the barcode is also phonetic, cannot be any, as by the QR-code.

3.3.2 QR Code

A QR code can store up to 7100 characters of data in both vertical and horizontal directions. If a QR code is damaged, it can recover about 30-35% of the data. Its position is less important because it can be scanned in multiple orientation, it is not as bound in this space as a barcode, and it stores the same amount of data in a tenth of the area [13].

4 PRACTICAL IMPLEMENTATION OF INVENTORY CHECK

The next measurement was carried out at the University of Miskolc, in the Laboratory of Logistics 4.0 in the Institute of Logistics. The purpose of the measurement was to compare, through a practical example, the inventory check is more efficient either with a drone or with a traditional manual barcode scanner. The drone was controlled manually, so a more inaccurate result will be presented.

4.1 Used Tools for Practical Measurement

The instruments used during the measurement process are firstly described in this subchapter, especially the drone, the handheld barcode scanner, and the shelving system under evaluation. Additionally, during manual barcoding, an elevation aid was required to access the upper shelves, since the top shelf is positioned at a considerable height. In this case, a simple chair was used for this purpose.

4.1.1 Drone

The drone used was from brand DJI and type Mini 4 Pro, as shown in Fig. 2a. The DJI Mini 4 Pro is a drone that weighs less than 249 grams and is easy to carry due to its small size. This drone is C0 certified, which means it has a maximum take-off weight of 0.25 kg, a maximum flight speed of 19 m/s and a flight altitude limited to 120 m. Its camera is capable of 4K resolution, HDR (High Dynamic Range) vertical recording and video transmission in Full HD quality up to a distance of 20 km. It is equipped with omnidirectional obstacle detection, which makes it easier to handle, as using it means that it avoids hitting obstacles on its own. In active use, the manufacturer's battery life is 34 minutes [14, 15].

(a) DJI Mini 4 Pro (b) Zebra TC20 with handle part

Figure 2 Drone and Scanning device (self-made photo)

4.1.2 Manual Barcode Scanner

The hand-held barcode scanner consists of two separate parts, a mobile data collector and a corresponding gun barcode scanner. Type of data collector Zebra TC20, as shown in Fig. 2b.

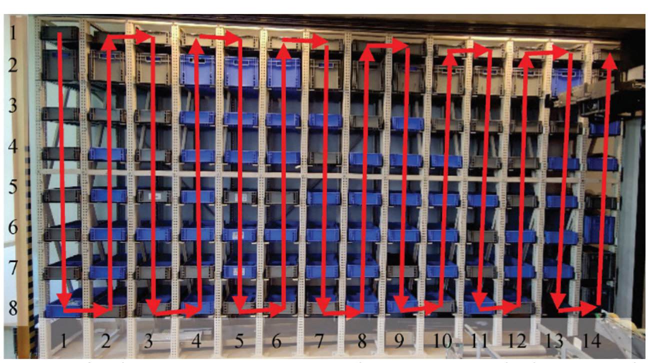

Figure 3 Shelf system with movement route for measurements (self-made photo)

4.1.3 Automated Shelving System

The shelving system consists of 14 columns and 8 rows (see Fig. 3), but as the load machine could not approach the highest and lowest rows due to the proximity of the ceiling and floor, hence the measurement was only performed technically along 6 rows.

4.2 Measurement Procedure

The measurement was started by using the drone. The first problem that arose was that the load machine in the lab was covering two poles in front of the drone, so it could not approach them. This reduced the possibility of going through the shelves row by row, as this would have required the drone to avoid the loading machine in each row, which is time consuming. Therefore, the column-by-column movement was chosen. Then the fact occurred that it would be more ideal if the drone started not on the columns from one direction, but first from the top to down, and then always start on the next column from where we ended on the previous column. The route of movement is illustrated on the Figure 3. However, this method is still issued due to the presence of the load machine. This problem was solved by moving the loader during the inspection, i.e., the drone was moved away from the shelf by the fifth column and then moving the load machine to the first column, so it was no longer in the way. The operation of inventory check then continued as drone approached the sixth column.

The next step involved the use of the traditional inventory control method. For this, the barcode scanner and the chair were required to access the higher shelves. To ensure a more accurate comparison, the shelving system was examined in the same sequence as before with the drone. However, it is important to note that the load machine also had to be repositioned in this process. The chair was first placed in front of the second column, and the first three columns were examined. It was then moved to the fifth column to inspect the next three columns. Following this, the load machine was relocated to the first column, and the process continued in groups of three columns until the final two columns were reached.

4.3 Comparison of Inventory Check Methods

The most important point of comparison is the time difference between the two methods of implementation.

4.3.1 Drone Method

From the very beginning of the measurement, it became clear that the drone could not be flown as close to the ground as would be necessary to read the bottom line. If this method is to be implemented in an existing warehouse, it is essential to consider that the shelving system may not always be optimally designed. In such cases, either a reconfiguration of the layout or the integration of multiple methods may be required, depending on the most cost-effective solution. However, if the goal is to utilize the drone in a newly constructed warehouse rather than replacing an existing system, the design must ensure that the drone can maintain a safe distance from surrounding objects during flight, with no obstacles obstructing takeoff or landing. Additionally, a dedicated charging station is necessary, as the drone will require periodic recharging, which must be factored into the warehouse layout. Pathways between the shelves and the charging station should also be planned to enable efficient automation.

Before implementation, it is crucial to thoroughly examine the drone's specifications, including its sensors, cameras, and compatibility with the warehouse's internal structure. If the drone is operated manually rather than autonomously, human control will be required, though this approach is less efficient than full automation. Regardless of the mode of operation, a maintenance technician will be necessary to repair potential failures, along with the appropriate tools and replacement parts.

The following section outlines the methodology used to estimate the duration of automated operation. In the measurement process, the entire operation—from takeoff to landing—took 398 seconds under manual control. However, automation would significantly reduce this duration by eliminating the need for manual corrections caused by imprecise control inputs. Since the time required to travel between the charging station and the shelving system depends on the station's location, only the duration from the approach to the shelving system until the final barcode was scanned was considered, which amounted to 349 seconds.

The positioning times were categorized into horizontal and vertical movements, with the shortest recorded times for each category used in the calculations. The barcode reading time was assumed to be 0,5 seconds per scan. Throughout the experiment, the drone executed 70 vertical and 14 horizontal movements. The shortest and average time for a vertical adjustment was recorded at 0,89 and 1,735 seconds, respectively, while the shortest and average time for a horizontal movement was 1,67 and 3,0 seconds, respectively. However, one of the 14 horizontal movements required the drone to move away from the shelves to accommodate load machine repositioning, which took 50,89 seconds. For the remaining 13 horizontal movements, the shortest recorded time was used.

With these calculations, the total time required for 70 vertical adjustments incl. shortest time of 0,89 seconds, 13 standard horizontal movements incl. shortest time of 1,67 seconds, one extended horizontal repositioning, and 84 barcode scans amounted to 151,455 seconds. If, instead of the shortest times, the average movement durations were used — 1,735 seconds for vertical movements and 3,0 seconds for horizontal movements — the total estimated duration would be 202,53 seconds. Using shortest time has risks, such as necessity for drone movement correction, not exact location of barcodes.

4.3.2 Traditional Method

With this method, the same problem did not occur as in the other case of not being able to reach certain shelves because of the proximity to the ground, so access to the barcodes is easier in crowded places. However, moving the load machine was still necessary to reach all the barcodes. It took a total of 230 seconds to check the entire shelving system.

4.4 Comparing the Results

This subchapter discusses the limitations of the approaches used. From the times written above and summarized in Tab. 1, it can be seen that the drone method is only profitable if it is automated, since it takes more time with manual control than with the traditional inspection, based on these results. If the drone is automated, the inventory record time is significantly reduced, compared to when an operator controls the drone, which is also confirmed by the fact that the 349 seconds measured with manual control are less than two-thirds of the 202,53 seconds calculated with average values. The method is also depends on the storage system, because in a warehouse where the barcode of every product stored there can be read from the ground, the use of a drone is probably not significantly faster. The traditional method is slower for the higher the shelving system under examination, since the most time is required for the operator performing the inspection to move the ladder and stand on it, so the higher he has to go, the slower the operation will be. However, it must be also taken into account that every drone has a period of time after which it can no longer operate, so if it has to move over such a large area that it cannot do so without charging, it will mean a significant loss of time. Therefore, choosing the drone is also a key task in such a case. Choosing an inventory management method is a multifunctional task that requires careful and thorough research, as it depends on the quantity of products to be recorded, the design of the warehouse, the variety of type and size of products. The labor intensity is for manual control is continuously 1 person, for the automated drone control is 1 person, but only for setup. The drone should work off-hours.

Table 1 Comparing results

Testing method	Time (s)
Drone – measured manual control	398
Drone – calculated automated control	203
Traditional handheld control – measured	230

5 EXAMPLES FOR OTHER TRACKING FORM WITH A DRONE

This chapter shortly introduces two further examples.

5.1 Tracking a Unit Load with Drone

The first method is following a unit load from overhead photographic way. The unit load in this case moves onto the conveyor system, and the drone can follow its movement. The example is illustrated in the Fig. 4.

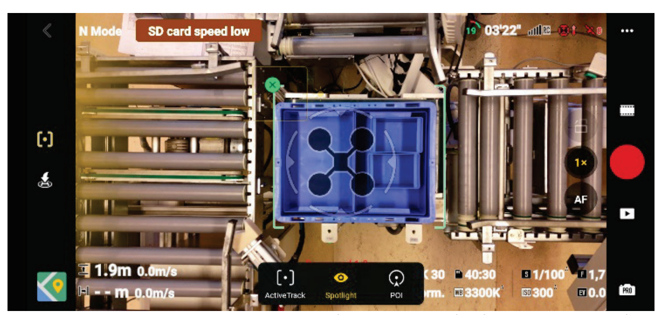

Figure 4 Tracking a unit load by drone from overhead (self-made screenshot)

5.2 Tracking an AMR with Drone

The other method is tracking movement of an AMR. This AMR is a Festo Robotino, which can be controlled either manually or automatically. In this way the drone determines the position of AMR using a vision system. Then the drone can send this data across the laboratory control to the AMR to correct its position. An example from the viewpoint of drone can be seen in Fig. 5.

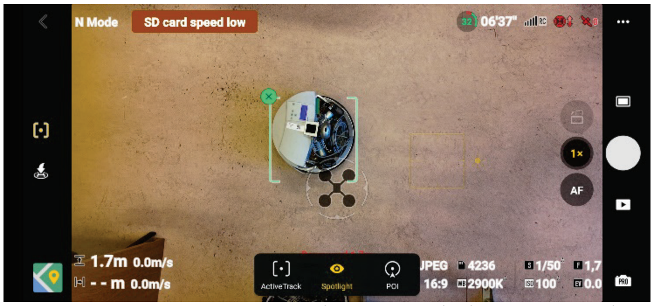

Figure 5 Tracking an AMR by drone from overhead (self-made screenshot)

6 SUMMARY

The paper dealt with different tracking methods using drone. After introduction, the background of tracking with drone technology was detailed. In the next part, practical implementation was written. The first goal was an inventory check, where the traditional handheld and the novel drone method was compared. It can be stated that a drone can be significantly faster, however it needs fully automatic operation and good located barcodes for improving sustainability factor. Two other examples for tracking with drone technology were shortly introduced due to lack of space. Here tracking of a unit load moving on conveyor system and tracking of an AMR were illustrated. Regarding future research directions, the tracking solutions can be improved including further enhancements in drone tracking accuracy, integration with AI-based predictive analytics, and the potential for multi-drone cooperation to optimize industrial automation processes.

Funding

Project No. 2023-1.2.4-TÉT-2023-00027 has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, and was financed under the 2023-1.2.4-TÉT funding scheme.

Supported by the University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund (Egyetemi Kutatói Ösztöndíj Program (EKÖP)).

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