Adverse Event Analysis in the Application of Drones Supporting Safety and Identification of Products in Warehouse Storage Operations

Agnieszka A. Tubis
Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, 27 Wyspianskiego St., 50-370 Wroclaw, Poland.
E-mail : agnieszka.tubis@pwr.edu.pl

Arkadiusz Żurek
Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, 27 Wyspianskiego St., 50-370 Wroclaw, Poland.
E-mail : arkaudiosz.zurek@pwr.edu.pl

The currently observed development of the Industry 4.0 concept causes the development of new technologies that support not only production processes in the smart factor, but also logistics processes including safety during warehouse inventories. For this reason, Logistics 4.0 systems use automatic data identification (barcodes, RFID) and autonomous vehicles. In the article, particular attention was paid to the use of unmanned aerial vehicles in logistic processes and thanks using them much higher level of safety during warehouse storage operations. They are used in particular for repetitive or hazardous operations where the human factor should be limited. The research area is the use of drones to support warehouse operations that are related to stock-taking. The aim of the article is to identify possible adverse events that may occur during the implementation of the drone mission and to classify them according to the selected classification criteria. The article presents the identified key adverse events and their causes. Then, they were classified based on the effects they generate for each stage of the measurement process. As part of the discussion, control measures and good practices were proposed that may reduce or even eliminate the occurrence of identified adverse events in the future. All the work was summarized in the final conclusions.

Keywords: Unmanned Aerial Systems – UAS, the drones, Logistics 4.0, adverse events, product identification, inventory audit

1. Introduction
Companies attach increasing importance to attributes such as flexibility, adaptability, proactivity, safety and self-organization. Wang (2016) emphasizes that these attributes can be achieved today by integration of new intelligent technologies. For this reason, we observe the growing popularity of the Industry 4.0 concept and development trends that accompany it also in non-production processes. One of such trends is the development of the Logistics 4.0 strategy. According to Wang (2016), it allows to achieve goals such as: complete transparency form supplier to customer, networked processes, decentralized management, effective small batch manufacturing and high numbers of variants.

Most of the innovations in the area of Logistics 4.0 concern processes related to warehouse services (Wawrla et al. 2019). One of the tools that allows you to automate selected warehouse operations is Unmanned Aerial Systems (drones). These devices are used primarily in work involving the risk of loss of life or health of employees, but also in routine and time-consuming processes. One of such time-consuming operations is stock-taking. This is an activity that in some warehouses is carried out periodically with low frequency (1-2 times a year). However, there are distribution / logistics centers that require regular inventory of inventory. In their case, this measurement is carried out even with the frequency of 1 day. The use of autonomous vehicles in this case is primarily aimed at eliminating errors caused by human mistakes, reducing the costs of these routine operations, but also reducing the time of their execution. However, the use of Unmanned Aerial Systems in warehouse operations generates the occurrence of other adverse events, that should be subject to risk analysis related to the implementation of this solution.

The authors of the article participated in many missions, that were carried out by drones in various types of warehouses. On this basis, it is possible to reliably determine the most frequent disturbances, that prevent the achievement of a satisfactory level of implementation of the assumed measurement results. Therefore, the aim of the article is to identify possible adverse events, that may occur during the implementation of the drone mission and to classify them according to the selected classification criteria. The structure of the article includes 5 points. A literature review on logistics 4.0 and the use of drones in warehouse operations will be presented in point 2. In point 3, we will present the research area and research methodology. The research results will be discussed in section 4. Based on the results obtained, the scope of control activities and good practices were proposed. Their implementation may reduce the frequency of occurrence of the identified adverse events. This is discussed in section 5.
The whole article will be summarized in the form of final conclusions presented in section 6.

2. Literature review

For several years, we have been observing the development of the Industry 4.0 concept. Its constant development is possible, among others, thanks to (Gotz 2017): (1) worldwide access to the Internet, (2) drastic reduction of data storage costs, (3) development of mobile devices and intelligent sensor technology, and (4) data mining. Grzybowska and Łupicka (2017) also note, that this dynamic development is a result of several worldwide social and technological processes as internationalization, information technology development, and hyper global competition. This concept is a complex solution created at the interface between engineering, computer science and management sciences. The key technological innovations include (Gajdzik et al. 2021): (1) a new communication system connecting the digital and real world; (2) intelligent sensors with built-in systems of individual identification, data processing and communication; (3) simulation techniques for the operation of real objects in their virtual representations, based on data provided and processed in real time, allowing to test and optimize the configuration of production processes before introducing physical changes. For this reason, an important feature of the fourth revolution is the intelligent networks based on cyber-physical systems, Barreto et al. (2017).

The Industry 4.0 concept is gradually implemented in enterprises through investment projects implemented in selected areas of activity, Lee et al. (2015). One of such areas is logistics. Industry 4.0 change and improve traditional logistics, transforming it into Logistics 4.0. Wang (2016) defines logistics 4.0 as a collective term for technologies and concepts of value chain organization. In line with Wang (2016) approach, cyber-physical systems monitor the processes of physical material flow, create a virtual copy of the physical world and make decentralized decisions. Szymańska et al. (2017) note that the concept Logistics 4.0 combines two aspects: processual (supply chain processes are a subject of the Logistics 4.0 actions) and technical (tools and technologies that support internal processes in the supply chains). An important element of this concept is also the application of advance Big Data analytics. The use of Big Data in supply chain management can improve decision making in all logistics processes, in particular in inventory tasks, Wang et al. (2016). Wawrla et al. (2019) note that the fourth industrial revolution applies in particular to warehouses. It is in the storage process that new technologies related to automatic data identification (bar codes, QR codes, radio frequency identification - RFID) and autonomous mobile robots and unmanned aerial vehicles - drones are increasingly appearing. The development of autonomous vehicles is particularly important today. These devices are to support the implementation of logistic processes and limit the participation of the human factor. However, their use in warehouse operations results primarily from the economic benefits associated with their implementation (Bechtis & Tsolakis 2018):

- the capability to function on a 24/7 basis;
- the minimization of labor cost;
- the low maintenance cost,
- the enhanced accuracy in daily activities, and
- the improved safety at industrial facilities.

The use of drones in the Industry 4.0 and Logistics 4.0 concepts is noteworthy. According to Fernandez-Carames et al. (2019) unmanned aerial vehicles are considered a key technology in smart factories. This is due to the possibility of their use in repetitive and dangerous tasks in which human participation should be limited. For this reason, in recent years, a wide use of drones in the fields like remote sensing (e.g., mining), real-time monitoring, disaster management, border and crowd surveillance, military applications, delivery of goods, precision agriculture, infrastructure inspection or media and entertainment can be observed (Shakhatreh et al. 2018; Hassanalian & Abdelkefi 2017). Wawrla et al. (2019) note that drones are also playing an increasingly important role in automating warehouse operations. According to Kostrzewski et al. (2020), the use of unmanned aerial vehicles in Logistics 4.0 will represent future trends in the next 5 years. The growing popularity of drones is due to their ability to fly and hover autonomously, avoid obstacles in different warehouse layouts, navigate indoor, and land precisely, Wawrla (2019). Unlike any ground machine the movement of drone is not limited to ground, but it extends to all the three dimensions, Deepak (2015).

Currently drones perform tasks that constitute one of the foundations of Industry 4.0: to collect as much data as possible from multiple locations dynamically. However, as noted by Fernandez-Carames et al. (2019) UAVs not only collect data, but are also able to store, process and exchange information with suppliers or with devices deployed in factories. Barreto et al. (2017) also states that the use of drones in the warehouse to improve the availability of information in real time can increase the efficiency of decisions made. According to the research of Wawr et al. (2019), the greatest potential for the use of drones in warehouses concerns the three processes shown in Figure 1.

According to Kostrzewski et al. (2020) drones can also monitor autonomous warehouse especially in its areas where employees are not allowed to enter for reasons of potential danger of health and life.
In recent years, scientific research and press publications have provided descriptions of projects regarding the use of drones in warehouse operations. An example is the project described by Deepak (2015). The aim of this project was to develop an automated system which can perform routine warehouse inventory process without any human interference. Also noteworthy is the joint initiative of two companies, Geodis and Delta Drone (2018), which developed a fully automatic drone warehouse inventory solution as part of cooperation. The creators of this solution indicate that its implementation brings certain benefits: the productivity gains generated by the realization of the inventories outside the hours of activity of the warehouse, the reinforcement of the safety at work for the collaborators of the site which no longer have to perform this tedious task and sometimes risky, and reliable inventory management. Also noteworthy is the project implemented by the Ware start-up, which develop a warehouse inventory automation platform that uses drones, the Skydio 2 to be specific (www.nanalyze.com 2021). To prove that using a drone for inventory is economically beneficial, Ware deployed their solution in several warehouses belonging to two top-twenty third-party logistics providers. The following key metrics were monitored in the research: accuracy, number of full inventory counts, lost inventory, headcount (the number of humans you need on your inventory team). The most important effect was to prove, that a team of humans, on average, covers 13 bins per hour and each Ware drone can cover 75 bins per hour (www.nanalyze.com 2021). Many of the described solutions are based on the automatic identification of data using barcodes, including (DroneScan 2021; Geodis and Delta Drone (2018). However, there are more and more publications on the use of drones in warehouse operations using RFID technology, for example (Beul et al. 2018; Fernandez-Carames et al. 2019).

However, the use of drones in the area of Industry 4.0 also generates specific challenges. Maghazet & Netland (2020) identified in their research five generic categories of challenges and drawbacks related to the use of drones: (1) technological challenges; (2) operational challenges; (3) organizational challenges; (4) legislative challenges; (5) societal and mental challenges. According to these researchers, the major challenges to the industrial application of drones are related to technological limitations, the most frequently mentioned of which related to constraints in current battery technologies. The organizational challenge related to the use of drones is also no less important. As noted by Pagell et al. (2000) workers’ knowledge and technical experience, training and involvement in planning are key determinants for the success of technology adoption.

3. Research area and methodology

The conducted research concerns the use of drones in a confined space to support warehouse processes in accordance with the concept of Logistics 4.0. The research presented in the article focuses on the use of drones to support operations related to the identification of goods in the warehouse for the purposes of the inventory audit.

The general goal of the research work is to develop an autonomous system for precise modeling and monitoring of spatial systems in logistics centers. The proposed system is an integral part of the automated airborne measurement platform and is the response of NeuroSpace company to the growing interest in this type of solutions. The analyzed system is still in the development phase and the conducted measurement works are part of the tests aimed at its improvement. Technical parameters of the tested Unmanned Aerial System are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>400x400x150 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>1,1 kg</td>
</tr>
<tr>
<td>Type of engine</td>
<td>electric</td>
</tr>
<tr>
<td>Maximum flight time</td>
<td>18 minutes</td>
</tr>
<tr>
<td>Charging time from 0 to 100%</td>
<td>1:30 h</td>
</tr>
<tr>
<td>Ascent / descent speed</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Flight speed</td>
<td>2 m/s</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>From -10°C to 50°C</td>
</tr>
<tr>
<td>Ambient humidity</td>
<td>Max. 90%</td>
</tr>
<tr>
<td>Maximum flight altitude</td>
<td>200 m</td>
</tr>
</tbody>
</table>

This drone is also equipped with the following devices:
- a stereoscopic camera for indoor navigation;
- 8 Mpix navigation cameras to determine the position of the drone in relation to the reference markers;
- measurement cameras operating in the visible spectrum.

The innovative nature of the proposed solution concerns the precise spatial mapping of elements within the monitored system in real time (SLAM - Simultaneous
Localization and Mapping), which enables the autonomous movement of the platform (avoiding collisions) and the autonomous implementation of measurements (analysis of the completeness and correctness of the collected measurement data). Thanks to this, the drone can move at any low altitude and between the infrastructure elements of the monitored area, carrying out inspection tasks. Algorithms based on neural networks (deep learning) were used to analyze data from a multi-sensor measurement system. The following neural networks were used:

- **OCR network**: The input to the network is a clipping of a picture containing a piece of alphanumeric text. This picture is processed by many convolutional layers - these are the so-called network filters - the aim of which is to extract features of an increasingly higher order from the sets of individual pixels in the picture.

- **Barcode filtering network**: The low light level of the photo combined with a short exposure time causes that the photo does not meet the required level of quality. Even for high-resolution photos, the quality of the barcodes visible in the photo is often poor - individual bars in the barcode are less than 2 pixels wide. The filtering network classifies individual pixels individually in and around the barcode, thus determining where a single black bar in the code begins and ends.

Algorithms for calculating and managing point clouds, such as RANSAC (RANdom SAmple Consensus), SFM (Structure From Motion), SIFT (Scale Invariant Feature Transform), were also used.

In order to take into account the various conditions of the research environment, the analyzed missions were carried out in the warehouses of various logistics operators and producers. However, in order to be able to compare the obtained results and formulate general conclusions, missions were included in the analysis, which were carried out in facilities with similar parameters. Information on the tests performed is presented in Figure 2.

![Fig. 2. Information about the conducted research](image)

Fig. 2. Information about the conducted research

![Fig. 3. Stages of mission implementation.](image)

Fig. 3. Stages of mission implementation.
The research was carried out using the direct accompanying observation method. Each adverse event was recorded by the observer in a customized measurement form. Each event was also assessed in terms of its impact on the success of the mission. Then the effects of the recorded events were assigned to the distinguished stages of the mission, which are shown in Figure 3.

The reasons for the occurrence of registered adverse events were also analyzed. This made it possible to group the identified adverse events and to develop guidelines for the implementation of the mission in the tested operating conditions.

4. Results

Based on the missions carried out in selected warehouses, the 10 most important adverse events were identified. These events are presented in Table 2.

Table 2. Identified adverse events.

<table>
<thead>
<tr>
<th>Event symbol</th>
<th>Description of the adverse event</th>
<th>Number of occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODE1</td>
<td>Lack of GCS connectivity (Ground Control Station)</td>
<td>9</td>
</tr>
<tr>
<td>ODE2</td>
<td>Limited bandwidth on various communication interfaces</td>
<td>12</td>
</tr>
<tr>
<td>ODE3</td>
<td>Insufficient photo exposure</td>
<td>38</td>
</tr>
<tr>
<td>ODE4</td>
<td>Loss of position by the location system</td>
<td>29</td>
</tr>
<tr>
<td>ODE5</td>
<td>Reflections on location markers</td>
<td>21</td>
</tr>
<tr>
<td>SDE1</td>
<td>Lack of communication with on-board cameras</td>
<td>18</td>
</tr>
<tr>
<td>SDE2</td>
<td>Lack of connection between on-board computer and autopilot</td>
<td>10</td>
</tr>
<tr>
<td>SDE3</td>
<td>Errors in the on-board computer software</td>
<td>33</td>
</tr>
<tr>
<td>SDE4</td>
<td>No connection to the RC (Radio controller) device</td>
<td>4</td>
</tr>
<tr>
<td>SDE5</td>
<td>Vibration isolation problems (vibrations)</td>
<td>31</td>
</tr>
</tbody>
</table>

The adverse event is divided into two groups: systemic events (marked with the SDE symbol) and operational events (marked with ODE). Systemic adverse events refer to disruptions resulting from the operation of technical elements and their occurrence is independent of the type of warehouse and the implemented mission. Operational events are related to the implementation of a specific mission in specific warehouse conditions.

The highest frequency occurs in the case of an event related to insufficient photo exposure (ODE3) - this event covers over 18% of all recorded disturbances during measurements. A high frequency of errors in the on-board computer software (SDE3) and problems with vibration isolation (SDE5) in the initial tests of the tested device were also recorded. The total number of occurrences of both of these events is 64 and covers over 31% of all adverse events.

Their limitation became a priority for the company, as both of these events were systemic in nature, which meant that their occurrence was highly repeated in subsequent missions. The detailed percentage of individual adverse events is presented in the figure 4.

![Fig. 4. The percentage share of adverse events in all registered disturbances](image)

For each of the adverse events, the causes of their occurrence were determined on the basis of the control documentation prepared at the end of each mission. The obtained results are presented in the table 3.

Table 3. Reasons for identified adverse events

<table>
<thead>
<tr>
<th>Event symbol</th>
<th>Reasons for the occurrence of the adverse event</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODE1</td>
<td>Local network problems</td>
</tr>
<tr>
<td>ODE2</td>
<td>Hardware management errors / too low (limited) hardware performance</td>
</tr>
<tr>
<td>ODE3</td>
<td>Incorrect illumination of the label when taking a photo with a camera</td>
</tr>
<tr>
<td>ODE4</td>
<td>Light reflections, vibrations, software errors, loss of communication between the on-board computer and the pilot, errors in the placement of aruko location markers</td>
</tr>
<tr>
<td>ODE5</td>
<td>Technology of making location markers (aruko)</td>
</tr>
<tr>
<td>SDE1</td>
<td>Problems with the electrical connection / mechanical damage to the camera / improper focus in the cameras</td>
</tr>
<tr>
<td>SDE2</td>
<td>Electrical connection problems</td>
</tr>
<tr>
<td>SDE3</td>
<td>Insufficient number of simulation tests, programming errors</td>
</tr>
<tr>
<td>SDE4</td>
<td>Damaged antenna, interference, broken electrical connection with the autopilot</td>
</tr>
<tr>
<td>SDE5</td>
<td>Incorrect vibration isolation of the mechanical structure</td>
</tr>
</tbody>
</table>

Analysis of the effects of the occurrence of each adverse event allowed to identify 3 types of potential consequences of their occurrence: (E1) the inability to start the mission; (E2) lack of the expected mission effects (in terms of the quality and completeness of the measurements made); (E3) crash or permanent damage to the drone. The
effects of groups (E1) and (E3) result in a complete failure to achieve the assumed goal for a given mission. In the case of the effects of events from group (E2), the achievement of the goal is partial. However, in the case of an efficiently operating system of assessment / verification of the obtained effects, it is possible to immediately start a mission supplementing the quantity or quality of measurements. The attribution of the effects of individual events to each of the groups is shown in the figure 5.

Fig. 5. Ordering the effects of adverse events in accordance with the adopted classification.

It is noteworthy that the SDE5 event may result in incorrect mission performance (blurred photo), but also may cause instability of the location system and crash the drone. The scope of effects in this case depends on the achieved scale of vibrations caused by incorrect / insufficient vibration isolation of the mechanical structure.

5. Discussion
The analytical procedure made it possible to distinguish two groups of adverse events that were identified as part of the conducted measurements - systemic and operational events. The division of adverse events into two groups allows to define the scope and nature of the actions taken to improve the measurement process. Systemic adverse events require immediate reaction and introduction of changes to prevent their repetition in the implementation of subsequent missions. These changes may include improvements / modifications in the following areas: (a) technical equipment of the drone, (b) software used, (c) electrical connections.

In the case of operational adverse events, preventive actions should primarily concern the environment in which the mission is carried out. These activities should focus on the development of control procedures that should cover both pre-mission (ex-ante control) and post-mission (ex-post control) activities. The purpose of ex-ante controls is to assess the correctness of the conditions under which the mission will be carried out. It will mainly relate to the assessment of: lighting conditions, temperature measurement, the functioning of the local network, technology of making location markers and possible airways. Prior verification of the labels used by the company is also important, in particular what data should be obtained from them by drone cameras. Therefore, it is necessary to conduct an on-site visit in advance at the client's premises. Its purpose is also to check if there are any disturbances in the functioning of the local network or contraindications to the technology of the location markers used. On the other hand, ex-post control will focus primarily on the assessment of the quality of the measurements performed. The control will cover the completeness of the collected data, identification of the so-called "Measurement holes", the quality of the taken identification photos. Adequate ex-post control carried out immediately after the end of the mission allows for the identification of any deficiencies and allows for quick supplementary measurements or re-execution of the full measurement sequence.

The most important area of improvements is the elimination of events that may lead to damage to the drone - group E3. They are associated with high costs related to its reconstruction / repair, but also potential losses in the customer's facility (damage to the product, warehouse infrastructure) and related penalties. Their occurrence is therefore associated with high effects. At the same time, these are the events which in the analyzed period were characterized by a high frequency of occurrences - a total of 81 occurrences were registered, which constitutes almost 40% of all registered disturbances. Both of these factors mean that these events have a high risk index that is not acceptable to the company's management.

Adverse events classified as group E1 constitute approximately 27% of all occurring disturbances. Their occurrence makes it impossible to carry out the mission at its initial stage. As a result, the measurement is impossible, but at least the drone is not damaged (compared to group E3). These incidents can be largely eliminated by introducing appropriate inspection procedures before the start of the mission. Currently, such procedures have been introduced in the performed measurements, which allowed to limit the number of events in this group to a minimum (occasional random occurrence). Their elimination is important from the cost point of view (operational costs related to the preparation for the mission in a given location, and then failure to carry it out), but also from the image point of view (despite the preparation of the entire system, the measurement is not performed).

Events included in the E2 group do not generate large financial losses, however, from the point of view of lean management, it is a classic waste (performing the same operation again). The measurement system and environment should be prepared in such a way that the mission can be performed once while achieving the full assumed final effect.

6. Conclusion
The analyzes presented in the article are an introduction to further research on the reliability of the use of drones in the improvement of warehouse processes as part of logistics 4.0. The conducted research is aimed at identifying and analyzing possible disruptions in the drone's work process, but also at the quality and completeness of the measurement
missions performed. The use of drones to support selected warehouse operations is justified primarily in a situation where their implementation will eliminate the occurrence of measurement errors and shorten the implementation time of the indicated operations. However, it is achievable when the system is operating efficiently and the identified adverse events are eliminated or minimized.

The results presented in the article are a preliminary stage for further research. The proposed classification is general and is intended to define the direction for further required measurements and analyzes. The next step in the research procedure will be to carry out a detailed risk analysis using quantitative and qualitative methods, allowing for a wider identification of occurring adverse events (not only of a technical but also organizational nature) and the assessment and evaluation of the associated risk.

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