Modern Warehouse and Delivery Object Monitoring – Safety, Precision, and Reliability in the Context of the Use the UWB Technology

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Abstract. This document assesses six technologies – including visual or radio methods – currently used to monitor shipments and traffic in warehouses and logistics centers. The work presents eight important aspects from the point of view of systems monitoring the location of people and loads in areas where logistic operations are carried out. Among them, you can distinguish factors such as the accuracy of determining the distance aimed at improving the positioning of objects in warehouse spaces, the frequency of acquiring items that affect the safety and management of human resources, and the effectiveness of the system in unfavorable conditions in the form of objects on the line of sight. The document's conclusion indicates the preferential technology and the proposed application possibilities within industry 4.0. At the same time, the analysis showed that the existence of a universal method is currently impossible. Still, the dissemination of radio technologies such as UWB is a new opening in the aspect of warehouse management.

Keywords: industry 4.0 · warehouse management · package tracking · logistics

1 Introduction

Transportation of goods, despite the crisis caused by COVID-19, continues to grow. Forecasts indicate a further increase in merchandise trade volume, and thus also in global and intercontinental shipping, as well as in last-mile transport. A big challenge in such transportation is constant supervision and detailed monitoring of individual batches of goods in the context of the increasingly frequent transport of general cargo. Monitoring more comprehensive and automated logistics centers is also a significant challenge, especially with rising energy prices. Also, ensuring the safety and optimization of employees' work, especially in the Western European market, where an employee's supply significantly shrinks, becomes a significant problem.

These and many other challenges make you check how you can monitor warehouse spaces and freight so that it is as precise and reliable as possible, not energy-consuming, and simultaneously qualitatively competitive with the currently used methods. These

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considerations lead to a comparison of several leading monitoring methods, both in the global frame of reference and confined spaces such as warehouses, production halls, the interior of container ships, etc. The analysis of technologies and methods that can be used to determine the location of people and objects in warehouse centers should begin with determining the factors based on which the optimal strategy will be selected.

At this stage, it should be noted that the set of 8 factors responsible for the technology division has a large impact on the target choice and should be made dependent on a specific application. Their detailed description in the context of the paper's topic is presented. The study considered six technologies (including vision and radio) that were analyzed in the context of their use in warehouses and distribution centers. A detailed description of the methods and their potential with the adopted coefficients is presented. Based on the analysis, it was decided to conduct a study of the UWB technology, which showed the most significant potential applicability in the context of low-energy monitoring of warehouse spaces.

1.1 Methods of Assessing the Quality of Positioning Systems

The proposed system for monitoring storage space can be characterized in the following areas:

- System application place (indoor/outdoor/mixed)
- Energy demand (AC/battery/computing power)
- Accuracy and precision
- Operating range (local, global, scalability)
- Price
- Required infrastructure
- Communication and other sensing possibilities
- Working conditions & ease of use

The selection of parameters is based on an analysis of the literature and a review of the most frequently raised weaknesses of the systems [1–3]. It was also decided to place a detailed description of the parameters near the tables they refer to in the next chapter.

1.2 Systems Included in the Analysis and Their Discussion

Based on the study of the systems currently used on the market and of potentially good solutions enabling the achievement of the set goals, six methods were selected, which were then analyzed based on the criteria presented above. The systems finally considered were:

- Vision recognition [4–7]
- Barcodes [8–10]
- GPS (Global Positioning System) [11–14]
- UWB (Ultra-Wideband) [3, 15–18]
- LoRaWAN (LoRa Wide Area Network) [19–21]
- RFID (Radio-frequency identification) [22–24]

To prepare the characteristics in the best possible way, the features of the systems are listed in eight tables, each table for one of the features. To simplify the description of each technology, an identifier is assigned in the first table, represented in the following.

The first area to be dealt with is the system application place. This parameter defines the capabilities of the system application. A modern system should enable tracking in the door-to-door system with the simultaneous possibility of interoperability within the warehouse space, sea freight process, road transport, etc. Assigning subsequent identifiers in this process, with the simultaneous change of monitoring systems, leads to errors resulting from the human factor. At the same time, monitoring both shipments and a fleet of specialized vehicles (forklifts, self-propelled warehouse vehicles, indoor cargo vehicles) is an essential aspect of security. For example, the ability to detect potential collisions among staff, monitor unforeseen events among employees and respond faster in case of a need for cooperation. A detailed comparison of systems in the context of this parameter is presented in Table 1.

Table 1. System application place.

System	Description
Vision systems (1)	The system characteristics largely assume a static infrastructure with known camera locations and a constant power supply. The ability to monitor objects within the range of the camera limits the operation to a relatively small area. Possible identification problems
Barcode analysis (2)	However, position information provided during scanning is limited to a specific item, e.g., a conveyor belt or a mobile scanner. Reliable identification is possible as long as the label is not broken
GPS (3)	Limited to open-air spaces or equipped with additional systems imitating the GPS signal. The necessity of communication and identification on the end tag side
UWB (4)	The exact position is only available if infrastructure exists in a given location. The ability to track the distance (point to point) using a mobile terminal anywhere
LoRaWAN (5)	The position determination accuracy depends on the network density in a given area, the operating environment, and the distance from the system nodes. There are currently around 88,000 system nodes scattered around the world, with a range of about 10–15 km. The determination of the position is possible when the marker has access to a minimum of 3 of them
RFID (6)	It is required to keep relatively short distances during scanning. It requires dense infrastructure (for passive tags) or a constant power supply to all system nodes

Another proposed parameter is energy demand – a factor gaining importance in the continuous increase in electricity prices. It makes it possible to determine whether the planned system can take the form of mobile devices in the form of wearable IoT or it will be an energy-consuming system, forcing a constant power supply from the mains. At the same time, attention should be paid to the frequency of charging devices and the risk of semi-portable infrastructure, i.e., one that formally works on battery power, but in the operation process, the battery life does not coincide with the employee's working time unit, so it is necessary to replace the cells or their recharging during work A comparison of the systems in this respect is shown in Table 2.

Table 2. Energy demand.

System	Description
(1)	The imaging device itself consumes a relatively large amount of energy (especially if it has an appropriate infrared or visible light illumination). In the case of the desire to transmit identification, automated decision-making, and storage of data provided by the system on the part of the shipping company/warehouse, it is also necessary to provide power for the infrastructure, as well as for computing power and data warehouses
(2)	The average energy consumption level includes, for example, a scanner on a belt feeder and a system for video processing of the data obtained in this way. A mobile scanner's consumption is lower and limited to the PDA device's battery power. The need to consider the energy required, e.g., printing labels
(3)	Depending on the application, relatively high GPS radio power consumption is required in continuous monitoring. The system consumes less energy if an item is delivered within a specific time interval (every 30 min, for example)
(4) (5)	Very low energy consumption on the side of the dimensioning infrastructure, the ability to work on battery power. The low complexity of the positioning algorithm also results in low energy consumption. Mobile dimensioning devices have the power consumption of a standard PDA
(6)	Possibility to use passive tags not equipped with batteries (supply via induction). Battery-powered active tags might also create the system. Mobile dimensioning devices have an energy consumption slightly higher than standard PDAs

Accuracy and precision are other parameters taken into account. These are two independent position measurement attributes that depend on the system used. The first one – accuracy – tells us about the overall quality of determining the position. The system with this feature can indicate the distance range from the tag to search for the located object. The second factor – precision, illustrates the certainty of finding a given object with the search area, e.g., on a heatmap. If both factors provide high quality, we can accurately indicate the desired object regarding its place and distance. Their comparison in the context of systems is presented in Table 3.

Operating range – this parameter is similar to the application place, but it expresses the possible location area in a broader context. We can distinguish direct systems requiring contact at a distance of a few cm, systems with a wider range of operations within one locating point, or global systems that allow us to determine the location regardless

Table 3. Accuracy and precision.

System	Description
(1)	Depends on the resolution of the camera and the monitored area. The precision depends on the object's size and the classification algorithm's quality. Typically, the accuracy in industrial systems is around one to several meters
(2)	Very high accuracy in determining the object's position in the case of scanners on conveyor belts (the precision depends on the object's size to the label). In the case of handheld scanners, the position is limited to, e.g., the area of operation of a given scanner or manual operator integration
(3)	Dependent on location and environmental conditions. Usually in the range from a few to several meters
(4)	Precision corresponds to the standard deviation of 20 cm. However, the accuracy of the position depends on the quality of the infrastructure calibration and the working environment
(5)	The position determination accuracy depends on the network density in a given area, the operating environment, and the distance from the system nodes. It can range from 20–200 m
(6)	It is a system heavily dependent on technology (active/passive) and the density of reference points. In one of the more favorable cases, the accuracy is at the level of 3 m [25], but the real cases allow for estimation in the range of 6–7 m [22]

of the infrastructure we manage. The operating range of the analyzed systems is shown in Table 4.

Table 4. Operating range.

System	Description
(1)	In local operation, a large number of cameras also necessitates the use of a local data processing center. Extending the system largely requires local infrastructure, cabling, and computing resources
(2)	It can work globally (e.g., a manual scanner) but does not provide the location. In another variant, it only works stationary. It is possible to precisely locate, for example, a package on a conveyor belt, but it is not allowed to do so at any time during storage or transport
(3)	Global coverage without the need to invest in additional infrastructure (not counting the required receiver). The range is limited inside buildings where GPS simulation systems can be used

(*continued*)

Table 4. (*continued*)

System	Description
(4)	The local range. However, relatively low energy consumption allows for quick adaptation to larger areas. Requires more than one reference point to obtain a position
(5)	The metropolitan range. The availability of areas with a higher density of LoRaWAN system transmitters limits the system. Requires more than one reference point to obtain a position
(6)	Local scope. The RTLS variant requires a high concentration of reference points and an active marker. Suppose it is only necessary to notify the presence. In that case, passive tags can be used to confirm their presence within the antenna range (e.g., presence information within several dozen meters), but it requires low interference and good access for waves

Another factor taken into account is price. It considers two components: the cost of implementation (including initial investments in infrastructure and hardware) and operating costs (related to consumables, licenses, software, and maintenance). The estimated list of prices, based on the analysis of available solutions, is presented in Table 5.

Table 5. Price (based on commercial systems)

System	Description
(1)	A single node (cam + wiring) is about \$100, but the entire system to the warehouse, including network stuff and computing servers, is around \$50–\$100 thousand. In this case, operating costs should also include electricity costs. We can omit server costs when we outsource video processing, but there will be extra cloud computing power to pay for
(2)	Depends on the type and class of the device. One personal scanner costs around \$100, while one scanner on a belt feeder can cost from several to several thousand dollars, depending on the quality and scanning (e.g., scanning individual codes in a designated area on one plane or a multi-scanner that allows you to handle multiple labels at once) on five or even six sides of the package)
(3)	A single device costs a dozen or so dollars. In addition, there is a position information transmission system (e.g., in the form of an industrial sim card). The cost of the server monitoring the position of shipments and the costs of the network infrastructure should be added to this, which depends on the number of devices and the scale of activity, but is cheaper than systems processing video images
(4)	A single device currently costs \$20–\$30. However, reference infrastructure is also required. Position information exchange may be based on communication between nodes (mesh) or another protocol (WLAN, industrial sim). Additionally, infrastructure for position monitoring and analysis should be included

(*continued*)

Table 5. (*continued*)

System	Description
(5)	Depending on the infrastructure model. If we use public infrastructure, the cost is for each module (currently around $10) and subscription, allowing the use of public infrastructure (from $3,000 to $50,000, depending on the level of support). Additionally, infrastructure for position monitoring and analysis should be included
(6)	The cost of the tag ranges from $0.10–$2 to $15–$20 depending on whether it is passive, sticker, sew-on component, or active with a small battery. The reader costs $200–$500 depending on the presence of the screen and other functions, e.g., the form of communication with the database or additional location based on different technologies

A factor that cannot be overlooked when implementing significant complex investments is the required infrastructure. Depending on the form of infrastructure (centralized or distributed), it may be necessary to purchase local modules (endpoints of the location system) that can be connected to cloud services. It may also be required to buy a central infrastructure in the form of computing and aggregating systems, decision-making systems, etc. Some systems require a similar or very similar infrastructure, which is included in Table 6.

Table 6. Required infrastructure.

System	Description
(1)	Technology prefers a centralized infrastructure, the main component of which is a server that performs video analysis. It often forms an extended star topology, where smaller units analyze data from a given sub-area and send information about events to the chief supervisor
(2) (6)	The infrastructure is limited to single points with a declared position (e.g., on a conveyor belt) or operating in a given area (e.g., a handheld scanner in a given section of a warehouse) that connect to a centralized database
(3) (4) (5)	Single devices, for example, use the Internet to connect to the server or cloud services, transmitting information about the position and status

Communication and other sensing possibilities verify whether there is computing capacity on the part of the located object and the possibility of feedback (in the form of a message, warning) or sensing the parameters of the positioned object (e.g., temperature measurement of transported goods, verification if the object is in motion, etc.). The description of the implementation (and its availability) of communication is presented in Table 7.

The last factor taken into account is working conditions & ease of use. It is information on what environmental conditions a given system can operate and the level of complexity of the service. For example, some solutions require direct contact, being in

Table 7. Communication and other sensing possibilities.

System	Description
(1)	The lack of communication possibilities, however, allows, for example, a visual assessment of the condition of the shipment and archiving its appearance
(2)	Unable to communicate
(3)	Unable to communicate. Possible communication is realized with different technology
(4)	Full two-way communication enables transmitting position information and additional data from possible sensors. It also allows the reception of messages to, for example, change the parameters of heating, tightness, etc.
(5)	In some variants, two-way communication is possible, but usually, communication is in the marker-reference point direction. The transmission speed is limited to 27 kbit/s
(6)	They offer both one-way and two-way communication, depending on the technology. Theoretically, performing two-way communication using passive RFID tags (such as saving the last transaction on a payment card) is possible. Still, active RFID tags are often used for this purpose due to the increased range of operation

sight, under the open sky, etc. At the same time, the level of complexity of service is essential in determining the cost of implementing a new employee or functional expansion of the proposed system. A summary of the capabilities of the proposed systems in relation to this parameter is presented in Table 8.

Table 8. Working conditions & ease of use.

System	Description
(1)	The system is practically maintenance-free, but its preparation is a tailor-made solution. It requires visibility conditions (LOS) and good lighting conditions (lighting of the halls, maneuvering areas, etc.). The service is limited to a system of notifications and alerts about the detection of individual objects, motion detection, etc. The risk is the possibility of the real-time video preview, which may reveal sensitive data in the event of a leak
(2)	Due to its limited capabilities, the system is straightforward, and its implementation and subsequent implementation of employees do not generate additional costs. It requires direct contact with the parcel or the appearance of the parcel in the scanning area
(3) (4) (5)	The system requires assigning an identifier to a particular tag and attaching it to the shipment (container, pallet). The tag itself must be pre-configured and, e.g., assigned to a cloud account of a given company

(*continued*)

Table 8. (*continued*)

System	Description
(3)	Additionally, it requires sky visibility for proper operation
(4) (5)	The system does not require visibility conditions (it works in NLOS). However, the very close proximity of metal objects to the antenna may disturb the transmission quality
(6)	Depending on the tag type, it requires its association with a given shipment (passive tag) or initial configuration (active tag)

2 Analysis of the Prepared Statement

From the analysis performed, it can be seen that there is a huge discrepancy between the positioning systems used in trade and logistics, and in particular, among the systems that can be used to track a shipment from the manufacturer of the goods through logistics hubs and centers up to "last mile" delivery. It is impossible to select an undisputed leader regarding the entire process. Still, it can be pointed out that its elements – are due to the constant development of wireless technologies and their advantage over solutions, e.g., video. The steps involved in covering long distances in the open air are indeed unrivaled regarding satellite navigation technologies (whether GPS or other commonly available technologies). However, in the context of logistics centers, warehouses, and their immediate vicinity, the matter is more complex due to the lack of GPS signal.

For retail customers, cheap solutions will most often be the leading one because monitoring parcels worth several or several dozen USD is challenging to implement with systems exceeding their value (even assuming that these systems will be returnable). However, if we consider small and medium-sized enterprises, the situation is no longer so obvious.

Both reducing errors in logistics, ensuring constant monitoring of transport conditions and quality, as well as precise step-by-step tracking of deliveries allow us to believe that the systems enabling two-way communication – such as UWB – will be the future of forwarding in this area. In addition, the UWB technology is the only one of the discussed technologies that allow for two-way communication while meeting the RTLS requirements, which also allows for implementation in the warehouse as an internal system of communication and warning about danger.

Based on these dependencies, it is proposed that the system under which logistics is carried out should be based on a layered model. In this case, on par with the currently used solution, it also uses the approach based on UWB technology. It can be used as a support or transition period, as presented in Fig. 1.

The advantage of the proposed solution is interoperability (e.g., within a ship whose position is determined using GPS, there is also the possibility of visualizing the position of containers and determining, e.g., the humidity prevailing in them). It can also increase safety (the forklift operator no longer has to be warned about a dangerous event) by the security guarding the video surveillance. Still, it can be done by a system that will automatically inform about a potential collision or even turn off the drive. Finally, there

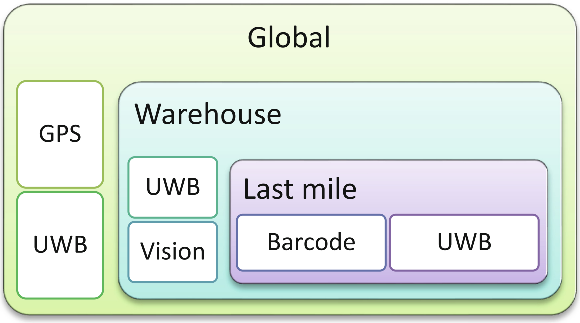

Fig. 1. Proposition of coexistence of a UWB-based system at various stages of storage and shipping.

is also a guarantee of delivery, where the courier, even if by mistake scans the wrong label, will be informed when leaving the parcel that the wrong one is the package was removed from the delivery truck.

The current expansion of UWB technology remains a question. It indicates two main trends – the development of mobile applications, the implementation of the latest flagship smartphones of brands such as Apple [26] or Google [27], and the trend focused on automotive technology. Of course, the interoperability of these two approaches is also possible. So, for example, Apple is considering cooperation with BMW [28], where cars are to be opened using virtual keys stored on the brand's phones and communicating with vehicles using UWB technology. None of these approaches fit in with market solutions aimed directly at industry and transport, but more and more companies are offering such solutions commercially on a smaller scale [29]. Moreover, the intensified development of this technology in the above-mentioned areas allowed for its gradual miniaturization and cost reduction.

3 Summary and Conclusions

The article presents several requirements and how the latest technologies used in warehouses and distribution centers deal with them. As has also been shown, no one-size-fits-all method can meet the requirements of large-scale shipment monitoring and security, and positioning within warehouses. Nevertheless, it has been shown that many warehouse requirements can be met with radio technologies, which allow for constant location monitoring, with simultaneous, two-way communication and low energy consumption. The technology that attracted particular attention is UWB, which both meets the requirements presented above and is currently strongly developed in the context of industry and consumer solutions. In addition, there are more and more commercial solutions on the market that introduce this technology for use within the discussed topic.

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