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Reviewers:

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Heorhii Kuchuk – Dr. Sc. (Engineering), Professor, Professor of the Department of Computer Engineering and Programming, National Technical University «Kharkiv Polytechnic Institute».

Authors: Anishchenko A., Badaniuk I., Bezkorovainyi V., Bezuhla H., Bondrenko A., Bulavin D., Bushuiev K., Bushuiev M., Chumachenko I., Danshyna S., Davydenko O., Dotsenko N., Druzhinin A., Druzhinin E., Farionova T., Fedorovich, O., Fonarova T., Galkin A., Husieva Y., Kharytonov Yu., Khomiuk N., Khrustalev K., Khrustalova S., Klymenko O., Klymenko O., Korkhina I,, Kosenko, V., Kovalchuk O.,Kuchuk H., Lutai, L., Maksymova S., Matkivska H., Medvedieva O., Molokanova V., Morozova A., Nevliudov I., Nevliudova V., Nikitin D., Novoselov S., Obukhova N., Padalko H., Pavlikha N., Petrenko V., Petrova R., Prokhorov, O., Pronchakov, Y., Rach V., Razumov-Frizyuk E., Rossoshanska O., Slobodian S., Strelets R., Sychova O., Timofeyev V., Trunova A., Vorona M., Vzhesnievskyi M., Yakushyk I., Yevsieiev V., Zachko O.

The monograph presents the achievements of Ukrainian scientists in the field of business management, use of economic and mathematical modeling, information technologies, management technologies and technical means in the field of functioning, development, and project management at enterprises.

The publication is recommended for professionals in the fields of economics, information technology, project and program management - for undergraduate and graduate students, as well as academics and teachers of higher education.

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FEATURES OF WAVE ALGORITHM APPLICATION IN WAREHOUSE LOGISTICS TRANSPORT SYSTEMS

Nevliudov I., Yevsieiev V., Maksymova S., Klymenko O., Vzhesnievskyi M.

The relevance of research in the field of storage organization using automated transportation systems, including pallet transport technology using Radio Shuttle as part of Warehouse 4.0, is due to the rapid development of modern industry [1–3]. With the emergence of Warehouse 4.0 concept, warehouse systems have become an integral part of enterprises digital transformation within the framework of Industry 4.0 concept [4–6]. Automated transportation systems make it possible to significantly improve the productivity and efficiency of warehouse operations. This made it possible to improve the technologies of pallet storage and transportation moved to a new level became more flexible and adaptable thanks to Warehouse 4.0. This allows enterprises to cope with the growing volume of goods, meet the needs of customers and reduce costs. Robotic transportation systems using Radio Shuttle not only ensure pallets uninterrupted movement, but also integrate with other technologies, such as data analytics, artificial intelligence and the Internet of Things, enriching the warehouse system with valuable information data [7]. In addition, in the context of sustainable development, automated transportation systems based on Radio Shuttle allow to reduce energy consumption and reduce the impact on the environment, which corresponds to modern standards of responsible production and allows companies to implement environmentally sustainable practices.

But despite all the positive aspects of the implementation of automated transportation systems based on Radio Shuttle as part of Warehouse 4.0, these systems have a number of significant disadvantages. One of them is the limited flexibility when using the Radio Shuttle system, which refers to limitations in the ability to change or reorganize warehouse space without serious technical changes [8–10]. Here are some aspects that make the system less flexible:

– Radio Shuttle works inside certain rails and specially designed racks. These structural elements are specially designed to work together with the system. Because of this, it is impossible to simply change the configuration of the warehouse, move racks or rails. Changing the warehouse structure will require a complete restructuring of the system, which is difficult and expensive;

– due to fixed rails and racks, storage options are limited. The system does not allow quick adaptation to new types of goods or changes in demand. New products may not meet the system parameters, this creates difficulties in their effective storage and use;

– because the system works within a limited space, products that require turning or flipping for optimal storage can cause complications. In some cases, this can lead to inefficient use of warehouse space;

the storage of old goods due to fixed rails and racks. Such restrictions can make it difficult to optimize warehouse space and manage the movement of goods;

– difficulties in managing access to goods: If the system uses the LIFO method and the latest goods are stored closer to the exit, this may create restrictions on access to old goods, especially if there is a need for manual access to them. Similarly, in the case of FIFO, it is more difficult to organize quick access to new goods, since old goods may take up more accessible space within the system;

– optimizing space usage: Disadvantages in storage methods can increase the challenges of optimizing space usage within Radio Shuttle structures. Difficulties in efficient space using may arise due to the system's inability to adapt to different sizes and goods characteristics that require storage using certain methods (LIFO or FIFO);

– difficulties in configuration changes: If LIFO and FIFO methods require changes in goods distribution, this may require major changes in the configuration of the Radio Shuttle system. This, in turn, can be a labor-intensive and costly process, which creates difficulties in System control [16].

Thus, the disadvantages of LIFO and FIFO storage methods may exacerbate limitations and weaknesses in Radio Shuttle design, creating additional challenges in optimizing and cotrolling warehouse operations. The optimal solution in this situation requires a careful analysis of warehouse requirements and selection of a storage method that best meets the characteristics of the goods and warehouse operations[17, 18]. The main types of Radio Shuttle that are used within Warehouse 4.0 are presented in Figure 1 [19].

a) b) c) d)

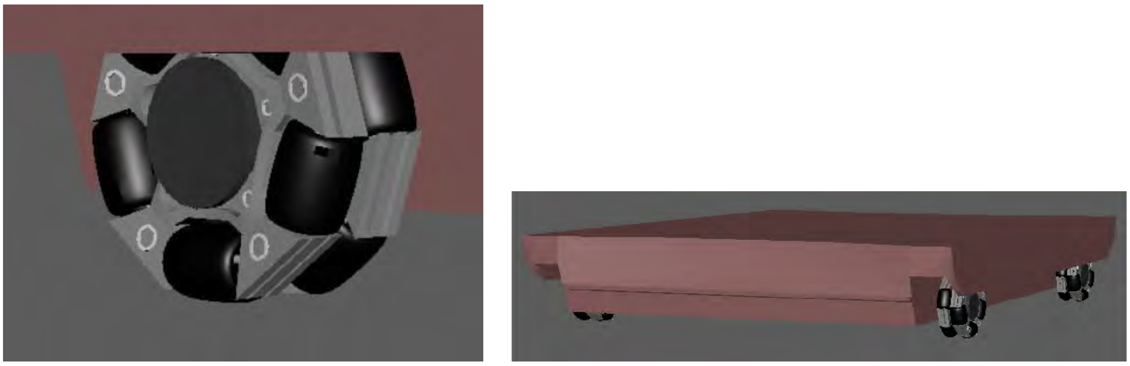
Fig. 1. Main Radio Shuttle Types That Are Used within Warehouse 4.0
a) Radio Shuttle; b) Multi-deck Shuttle carrier;
c) Four-way Shuttle system; d) Shuttle Carrier

Based on the design features of the above Radio Shuttle, we will conduct a study and compare the permissible movement trajectories, which are presented in Table 2.

From the presented table it can be seen that each of the systems has its own advantages and limitations regarding permissible movement trajectories. The use of Mecanum wheels can significantly improve the efficiency and flexibility of these designs.

and adaptable to different working conditions in the warehouse. These advantages justify the decision to improve systems using Mecanum wheels [20].

Using 3D modeling, let us design a Radio Shuttle robotic platform with built-in Mecanum wheels; an example of implementation is shown in Figure 2.



a) b)

Fig. 2. Mecanum Wheels 3D Model on 3D Radio Shuttle Robotic Platform
a) Mecanum Wheels 3D Model;
b) Radio Shuttle Robotic Platform 3D Model General View

So, it is necessary to improve the supporting structure of the racks in order to realize the benefits of Mecanum wheels on the Radio Shuttle platform. A 3D model of rack structure and a schematic representation of permissible movement trajectories are presented in Figure 3.

Let's improve the wave algorithm in accordance with the schematic representation of the permissible trajectories of Radio Shuttle movement when using Mecanum wheels.

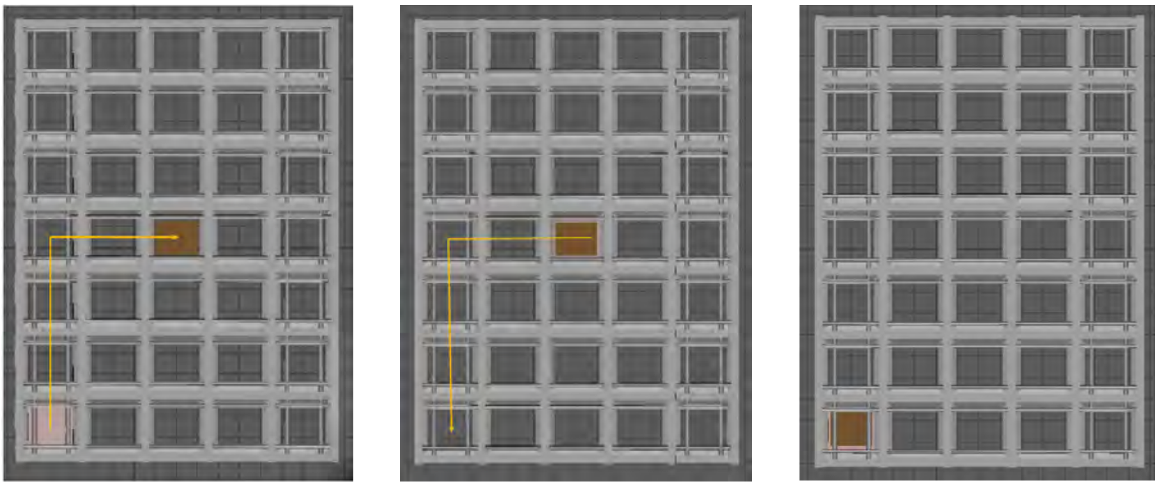
Let W – wavefront matrix of size $M \times N$, where M – number of lines, N – number of columns. We denote the initial position of the robot by (x_{start}, y_{start}), since the route is arranged in two-dimensional space, therefore the final position where the robot should deliver/pick up the cargo will be denoted by (x_{end}, y_{end}). Let us fill in the wavefront matrix $M \times N$ by values -1. This will indicate that a given cell in the matrix W, Radio Shuttle was not visited. Let us set $W(x_{start}, y_{start}) = 0$, this entry will make it possible to indicate that Radio Shuttle is in this position. Now we can move on to a description of wave propagation. Wave propagation is a key step in the wave propagation algorithm. In this step, the wave propagates from the starting position of the Radio Shuttle to the remaining cells in the work area. In each iteration of this step, the wave propagates one cell further from the starting position. The robot uses this wave to determine the shortest path to each cell in the warehouse. Based on this, we can wave does not propagate to cells that have already been visited. Thus, it is determined how to update the value of the wavefront during wave propagation, taking into account the current value of the wavefront in the cells (x, y) and neighboring cell (x', y') state.

The next step in finding the shortest path in the wave propagation algorithm occurs after the wave has been successfully propagated from the initial position to all other cells in the working area. The process of finding the shortest path consists of going back from the final position to the starting position, choosing a path through cells with decreasing wavefront values. This process ensures that the path found using wave propagation is the shortest path as it follows cells of decreasing wavefront values from the final position to the starting position. Let's describe it like this: let (x, y) be the current position, we look for neighboring cells (x', y') that satisfy the following condition

$$W(x', y') = W(x', y') - 1 . \tag{3}$$

In expression 3, $W(x, y)$ is the value of the wavefront in the cell (x, y). After finding such a cell, we add it to the path and set $(x, y) = (x', y')$. The process is repeated until we reach the starting position. The resulting path will be the shortest path from the end position to the start position.

To check the correctness of decision-making, let us conduct several experiments to simulate the movements of the Radio Shuttle. Let the Radio Shuttle be in the lower left part of the storage system, and the cargo that needs to be retrieved be in the center of the storage system. Using the improved wave algorithm (1–3), we will simulate route construction in the developed 3D model of the storage system. The simulation results are presented in Figure 4.



a) b) c)

Fig. 4. Results of the First Experiment in Modeling the Route Construction of an Improved Radio Shuttle: a) starting point (with a constructed route); b) end point (route back); c) Radio Shuttle delivered the cargo

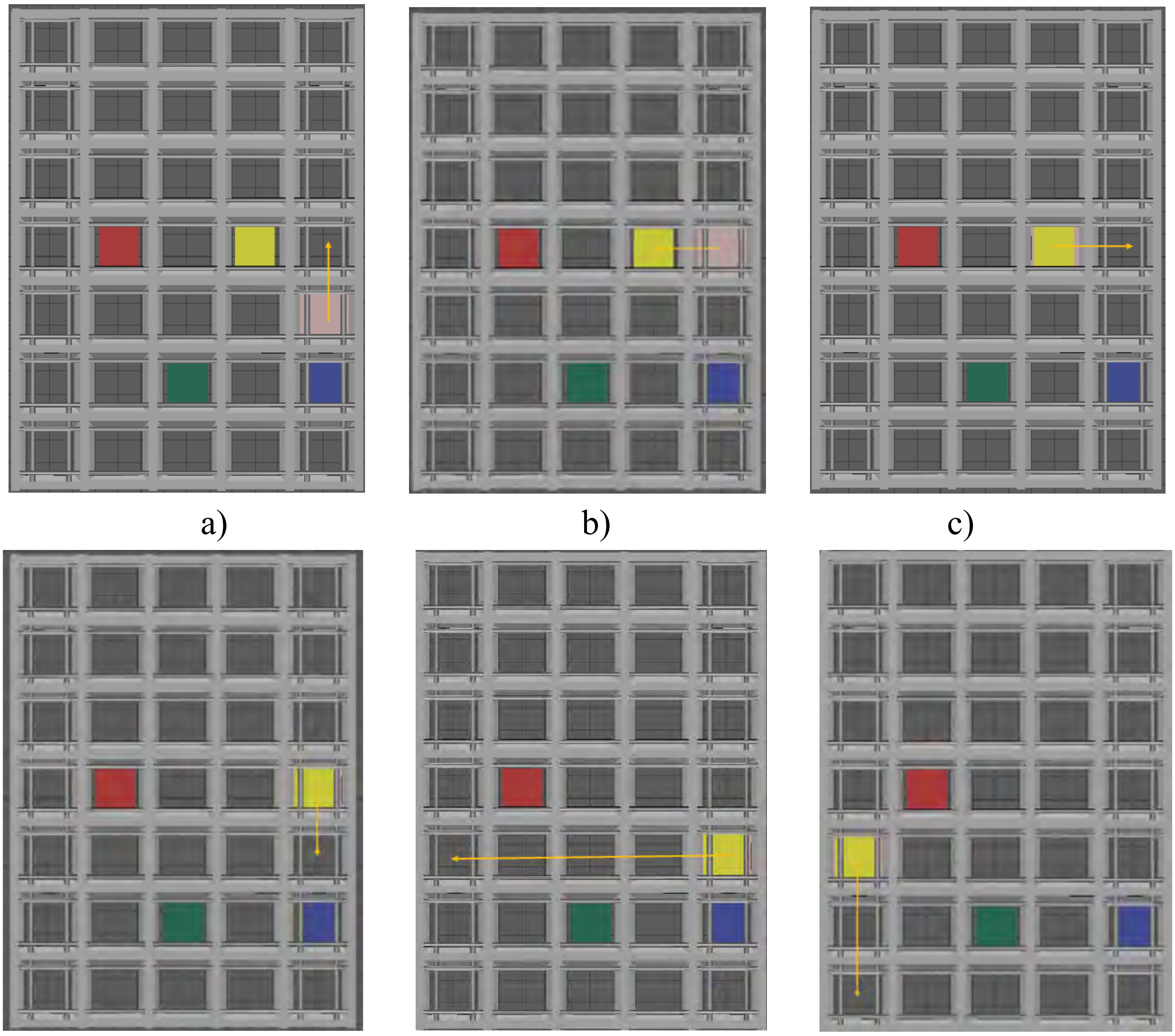


Fig. 6. Results of the Third Experiment
in Modeling the Route Construction of an Improved Radio Shuttle

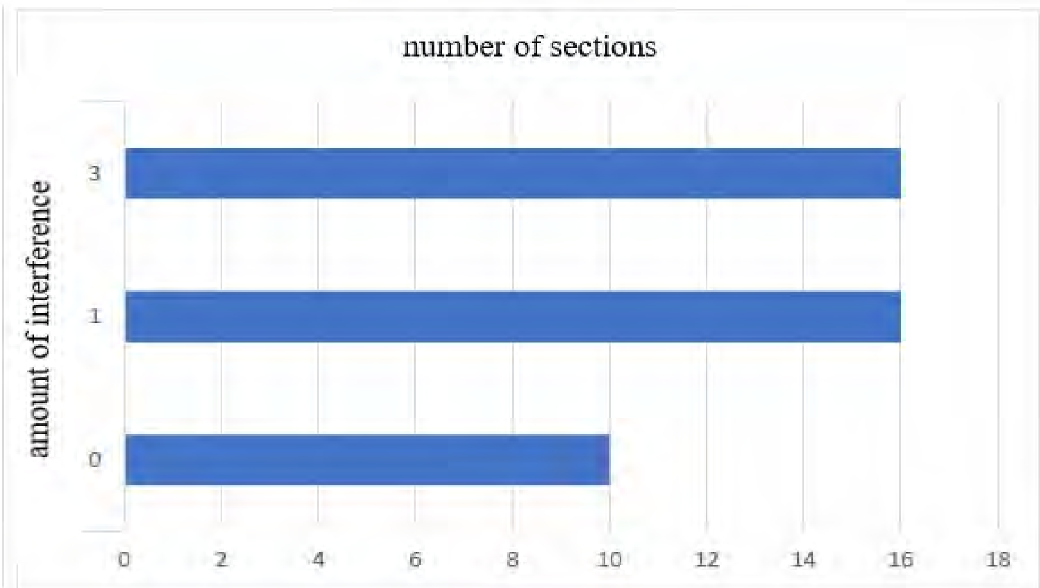


Fig. 7. Graph of the Number of Sections Passed Versus the Amount of Interference

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