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CONTROL IN THE AUTOMATED CONTAINERS STORAGE SYSTEM BASED ON ROBOTIC MOBILE PLATFORMS

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Abstract. The development of effective means of automation of warehouse operations provides the possibility of their wide and successful implementation. One of the promising directions, in our opinion, is the creation of an automated container storage system (ACSS), based on the distribution of the functions of moving and storing containers between its components. The proposed ACSS in which the movement of containers in the vertical plane between several levels of racks is carried out by elevators, and the movement in the horizontal plane (for each level) is provided by a robotic mobile platform (RMP), in contrast to the currently popular systems in which the main operations for moving containers are performed by RMPs equipped with manipulators. This paper presents the control system of the ACSS, which provides control of four elevators and four RMPs (one for each level of racks) in the process of containers moving. Two components of the control system are considered: the technical one, which provides control of the technical means of the ACSS (elevators and RMPs) and the organizational one, which determines the order of placing containers in the cells of the racks and their retrieving.

Keywords: automated containers storage system, prototype of robotic mobile platform, control system, planning of placing and moving containers.

Introduction

Warehouse activities occupy an important place in industry, trade, logistics and agriculture. Performing warehouse operations manually is a laborious, but technically simple task. This necessitates the automation of warehouse operations. In order to unify the storage and movement of various cargoes weighing up to 20–30 kg, it is advisable to use containers of the same type. The maximum weight of a container, if it is supposed to be carried manually by one person, is limited by regulatory documents and is 30 kg. Therefore, the creation of specialized RMPs with low cost, which are focused on performing simple warehouse operations, is an urgent task. These RMPs are one of the important components of ACSS. The need to develop a control system for ACSS based on RMP determines the relevance of this work.

Review of Modern Information Sources on the Subject of the Paper

To perform warehouse operations, modern robotic systems based on intelligent robots and robotic mobile platforms (RMP) today are widely used [1]. One of the factors that hinder the mass implementation of automation means in warehouses is their high cost and insufficient consideration of the specifics of warehouse operations. Economic factors play an important role in the implementation of automation means. According to Work.ua [2], the average salary of a loader in Ukraine as of April 2025 is UAH 21,000. The average hourly wage of a loader in the USA is from $15 to $20 [3]. In Europe, the hourly wage of a loader is from EUR 12 to EUR 26 [4]. The cost of an RMP with a load capacity of 20–40 kg depends on the model and purpose and varies from EUR 11,000 to EUR 80,000 [5].

Based on the theoretical and practical studies [6–8], an experimental model of a specialized RMP for an automated container storage system (ACSS) was developed [9, 10]. The studies of this model showed the feasibility of developing a full-scale prototype of the RMP, taking into account the identified shortcomings. The design features of the created prototype of the RMP are presented in another paper.

In most of the works, the technical issues of RMP creation are mainly considered [11]. However, the organizational aspects of their effective application are considered much less often [12]. ACSS is a complex organizational and technical system that requires comprehensive development taking into account its technical and organizational components. This article is devoted to the development of a control system for the ACSS and for the created prototype of the RMP.

Problem Statement

The aim of the work is to develop a control system for an automated containers storage system based on the created prototype of a robotic mobile platform. To achieve this goal, the following tasks are solved in the work:

– development of the technical component of the ACSS control system;
– development of the organizational component of the ACSS control system;
– creation of a software system for planning of placing and moving containers.

Main Material Presentation

The organization of the ACSS is described in detail in [9]. The technical component of the control system is directly related to the mechanical construction of the RMP and the elevator of ACSS.

The construction of the developed RMP prototype is presented in Fig. 1 and consists of three main units: a drive unit for horizontal movement of the platform along the guides along the racks; unit for a container holding during its movement; a shifting unit for moving the container to the right or left of the longitudinal movement axis to load it into the rack cell or remove it from the cell onto the RMP load-bearing surface. The implementation of these units in the developed RMP prototype differs significantly from the previously proposed solutions in the experimental model [9, 10]. A detailed description of the construction and features of the developed RMP prototype is presented in another work.

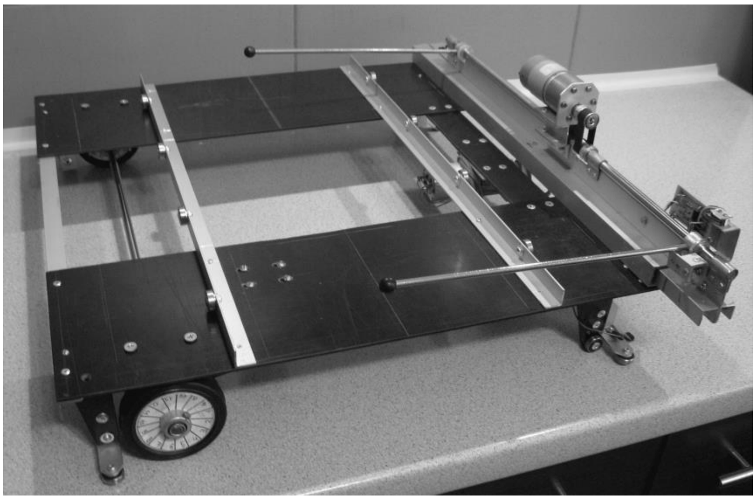

Fig. 1. The construction of the developed RMP prototype

Containers are stored in the cells (3) of two four-level racks (1) (Fig. 2). The containers (4) are moved vertically to the required level by elevators (7), and the container is moved horizontally along the racks at each level by the RMP (6). Placement of four stationary elevators at the beginning and end of each rack eliminates the need to equip the RMP with a manipulator for vertical movement and positioning of the container. The use of four separate RMPs for each level eliminates conflicts between them during simultaneous movement and increases system performance.

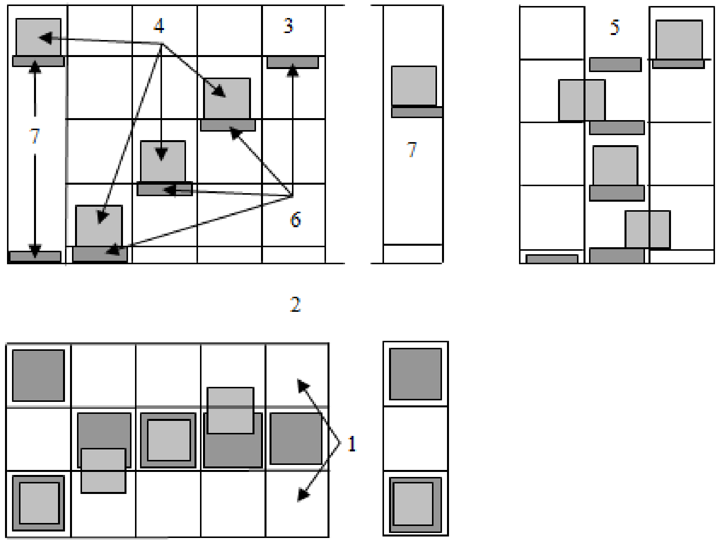

Fig. 2. Organization of the functioning of ACSS technical facilities

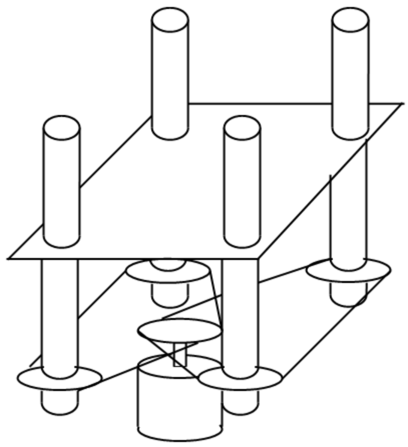

Fig. 3. Kinematic scheme of the elevator

The elevator consists of four rods (screws) two meters long with M10 threads cut on them, which are fixed in bearings in the corners of the initial and final vertical modules of the rack (Fig. 3). The supporting platform of the elevator is equipped with four nuts located at its corners. With the synchronous rotation of the screws, these nuts ensure vertical movement of the platform. Synchronous rotation of the screws is provided by two toothed belts and pulleys, fixed on the lower ends of the screws and on the shaft of the drive motor gearbox. The precise positioning of the elevator platform at the required level is ensured by limit switches. To reduce the force of horizontal movement of the container, two rows of bearings are installed on the elevator platform, the supporting surface of the RMP and the rack cells, and two angle guides are mounted on the bottom of the container.

The integration of the technical and organizational components of the ACSS control system is provided by a personal computer (PC) program. The personal computer operator, based on the customer's request for the issuance of one or more containers, uses a specialized program to generate a command file for the microcontroller (MCU) of one of the four RMPs.

Each container has a unique code that determines its contents. To place a container in a rack cell, its address is set, which contains the level number and the cell number at the specified level. Each level of the right and left racks is served by an individual RMP and one elevator attached to it, which in pairs ensures the fulfillment of the customer's request. In order to unify the commands, as an address for elevators and cells of each level, through numbering is used. In this case, the cells and elevator of the left rack have odd numbers, and the right rack has even numbers. If the total number of cells in a block of two racks is 200, and one level is 50, the address N for the left elevator will be N=1, and the right one N=2. Accordingly, for each level, the address of the last cell of the left rack will be N=51, and for the last cell of the right rack N=52. Since two elevators (out of four) are located at the end of the racks, the numbering for their levels is carried out in reverse order. Placing the elevator platform on the second level ensures its use as a terminal for issuing containers to the customer, or replenishment of ACSS with new containers.

The structural diagram of the ACSS control system is presented in Fig. 4.

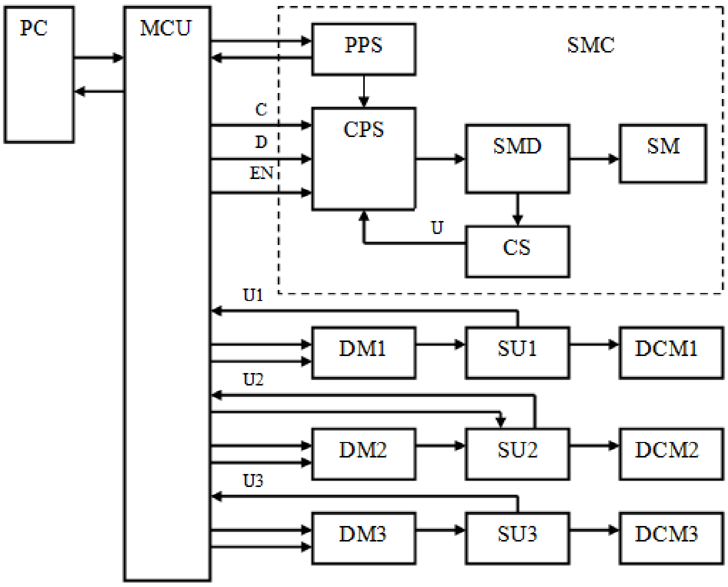

Fig. 4. Structural diagram of the ACSS control system

The command file contains one or more commands that are interpreted by the microcontroller program. Each command contains two addresses for moving the container. The first address determines the initial location of the container, and the second – the final location. During command processing, the microcontroller determines the necessary number of the stepper motor steps to move the RMP to the cell with the required container. In this case, changing the frequency of the synchronization pulses C ensures smooth acceleration of the RMP at the beginning of the movement, then movement at the nominal speed and smooth deceleration of the platform at the final section of the movement. A smooth change in the movement speed reduces the probability of skipping steps of the stepper motor and provides the possibility of precise positioning of the platform. Approximate positioning of the RMP is provided by counting the number of steps. For precise positioning of the RMP opposite the middle of the cell at the stage of platform deceleration, a precise positioning sensor (PPS) equipped with a limit switch and a mechanical catcher is used. At the same time, an information feedback signal is transmitted to the microcontroller. The control pulses for the driver SMD of the stepper motor SM are generated by the shaper (CPS). The input signal D from the controller determines the direction of movement of the RMP, and the signal EN stops the stepper motor in the specified position RMP. To limit the current of the stepper motor, a pulse-width regulator using a resistive current sensor CS (signal U) is implemented in the CPS.

The control of the DC motors (DCM1, DCM2, DCM3) for the container holding device, the shift device and the elevator is carried out by the driver modules DM based on the L298N chip and switching units (SU). The switching units process the limit switch signals and form information feedback signals. Based on the control signals I1 and I2 supplied from the controller, the voltage of the required polarity is supplied via the switching unit SU1 to the DC motor DCM1 via the H-bridge of the driver module DM1 to hold and release the container. The supply of voltage of different polarity (in accordance with the control signals I3 and I4) from the H-bridge of the driver module DM2 via the switching unit SU2 to the DC motor DCM2 ensures, based on the proposed kinematic scheme, the removal of the container from the rack cell to the working surface of the RMP, or its loading into the cell from the working surface of the RMP. The elevator motor DCM3 is controlled similarly to the DCM1 motor control using the driver module DM3 and the switching unit SU3.

In the considered control system, some of the functions are implemented in hardware, based on the proposed circuit solutions, and some – in software using the microcontroller. This contributes to the formation of functionally complete components of the control system and a reduction in the number of necessary interface signals for communication with the microcontroller. At the same time, it ensures a reduction in the number of used MCU pins and the use of its computing resources when implementing control functions. The electrical scheme of the stepper motor control unit is presented in Fig. 5.

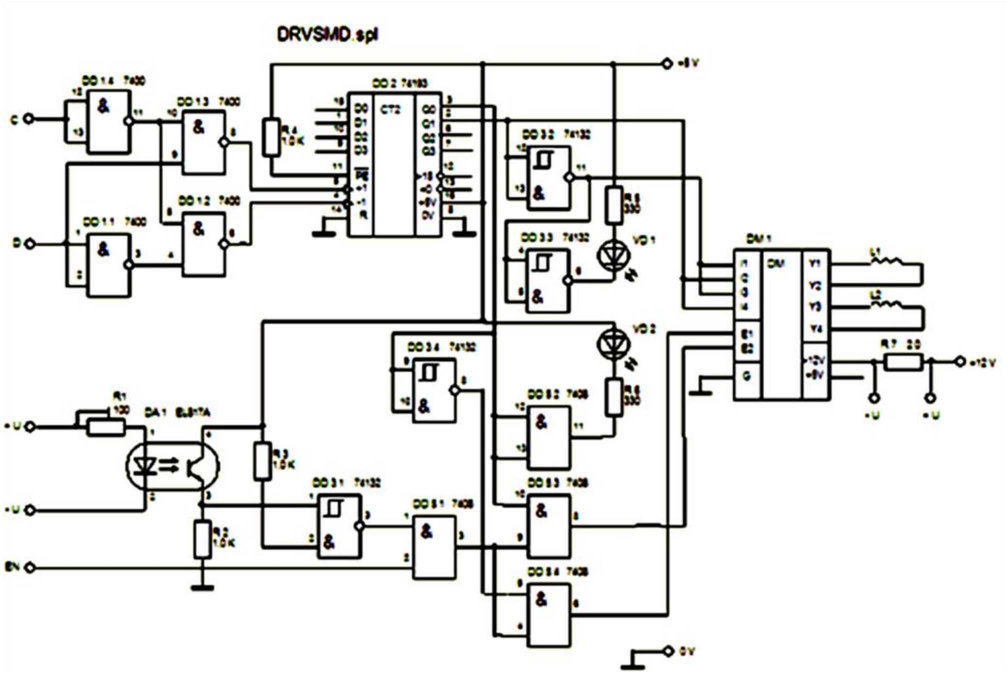

Fig. 5. The electrical scheme of the stepper motor control unit

The electrical scheme of the control unit for holding and shifting the container is shown in Fig. 6.

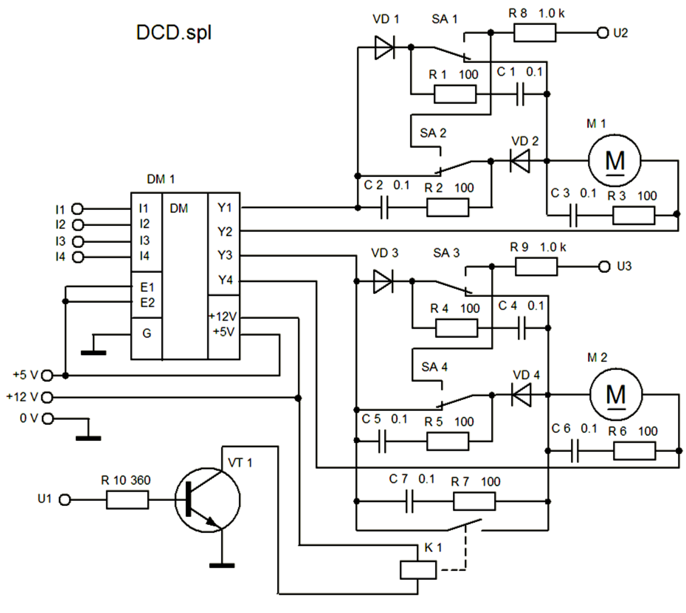

Fig. 6. The electrical scheme of the control unit for holding and shifting the container

Organizational component of the ACSS control system

The operational characteristics and parameters of the ACSS depend not only on the effective functioning of its technical devices, but also on the organization of the process of storing and moving containers.

The organizational component of the ACSS solves the following tasks:

– determining the order of rational placement of containers in the rack cells and fixing it in the system information database;

– determining the order of removing containers from the rack cells and moving them to the terminal for issuance to the customer;

– forming a command file for transfer to the RMP microcontroller to remove the necessary containers from the cells when fulfilling the customer's request;

– collecting and processing statistical data on the codes and number of containers issued based on customer requests;

– generating notifications about the need for timely replenishment of vacated rack cells with containers with the determination, based on the collected statistical data, of their codes and number.

A typical trajectory of a container's movement when it is loaded from a terminal into a rack cell or when it is removed from a cell and moved into the terminal is shown in Fig. 7.

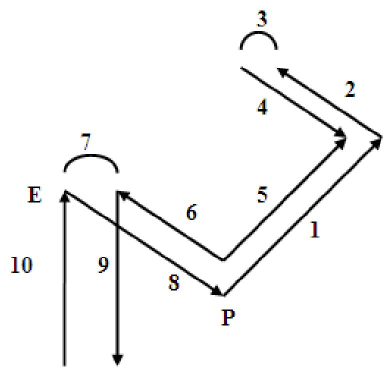

Fig. 7. A typical trajectory of a container's movement

The initial location of the elevator platform is at point E (at the level of the RMP assigned to it), and the RMP is at point P (opposite the elevator). When removing the required container for issuing it to the customer, the specified trajectory consists of the following segments: moving the RMP from the initial point P to the required cell, given by its number (1); shifting the RMP carriage into the cell of the rack to capture the container (2); capturing and holding the container (3); extending the carriage with the container from the cell (4); moving the RMP to the elevator (5); moving the container to the elevator platform (6); releasing the container on the elevator platform (7); extending the carriage to the initial position on the RMP (8); lowering the elevator platform to level 2 (terminal level) (9); raising the elevator platform to the initial point E (RMP level) (10).

Operations to move the container from the cell to the terminal and vice versa are technically carried out in the same way using the elevator and RMP. However, they require different times depending on the rack level and cell number.

The total estimated time T of the container movement is determined as

$$T = 2 \times t_m + 4 \times t_s + 2 \times t_z + 2 \times t_h, \quad (1)$$

where t_m – time of RMP movement from the elevator to the required cell or from the cell to the elevator; t_s – time of RMP carriage displacement into the cell / elevator or carriage extension from the cell / elevator to the initial position on the RMP (t_s = 6 s); t_z – time of container capture/release (t_z = 1 s); t_h – time of elevator platform lifting / lowering from the RMP level (L = 1, 4) to the terminal level (L = 2) or from the terminal level to the RMP level.

The value of t_m depends on the cell number and is determined by the following formula

$$t_m = t_v + 2 \times t_a = (\mathrm{INT}((N + 1) / 2) - 1) \times v + 2 \times t_a, \quad (2)$$

where N – cell number; t_v – RMP travel time with nominal speed v = 0.5 m/s; t_a – RMP acceleration/deceleration time (t_a = 1 s at acceleration a = 0.5 m/s^2).

With a distance between rack levels of 0.5 m, a speed of lifting / lowering the elevator platform of 0.03 m/s and the RMP level number L, the value of t_h is determined by the following formula

$$t_h = (0.5 \times |L - 2|) / 0.03). \quad (3)$$

The obtained formulas allow to calculate the total time of container movement for all ACSS cells and to store it in the control system to reduce the time spent in solving the problem of rational container placement.

The request for the issuance of one or several containers is determined by the needs of the customer. At the same time, the number of required containers and the codes that determine their contents are indicated. In the general case, each request is random in nature from the point of view of ACSS. However, statistical analysis of requests from many customers allows identifying certain patterns that affect the organization of ACSS functioning. In particular, taking into account these patterns provides a solution to the problem of rational placement of containers with different codes in the cells of ACSS racks to reduce the time of order fulfillment. It should be noted that the random nature of requests that change over time eliminates the possibility of classical formulation and solution of the problem of optimal placement of containers in ACSS cells.

In ACSS, it is assumed that the issuance of all necessary containers specified in a specific request by the customer is carried out only from one terminal defined by the control system. In accordance with formula (3), the time of moving the elevator platform for the terminal level (L = 2) is zero. For levels 1 and 3, the time of moving the elevator platform is 17 s and for level 4 – is 34 s. This allows the system to use the terminal of the first elevator (as the fastest due to the absence of the need to move the elevator platform) to serve priority customers with a large number of containers. The second elevator serves the fourth level with the longest time of moving the elevator platform to the terminal – 34 s. The terminal of this elevator is used for orders with a small number of rarely used containers. The third and fourth elevator terminals, which serve the first and third levels, respectively, with an elevator platform travel time of 17 s, are used to service requests with an average number of containers.

The following adaptive method of rational placement of containers in ACSS cells is proposed in the paper. The task of rational placement of containers in cells is solved separately for each level. In this case, statistical data on the issuance of containers for this level for a certain period of time are used.

The essence of the adaptive method for rational placement of containers in cells of a certain level is as follows.

In the zero cycle, primary statistical information is collected on the number of issued containers (frequency) $N_0(K)$ for each code K for a certain period of time (without using a control system). The total number of issued containers N_{0s} is determined by summing the frequency $N_0(K)$ for all codes. For each code K, the relative frequency $N_0(K)/N_{0s}$ is determined, which approximately corresponds to the probability of requesting a container of the corresponding code $P_0(K)$. The number of codes with a zero frequency K_{00} is determined. A frequency array $M_1(K)$ is formed to determine the required number of containers of each code to fill the cells of this level. For codes with a zero probability, the initial frequency value is set to 2. For the remaining codes, the value of the elements of the array $M_1(K)$ is determined as $\mathrm{INT}((50 - K_{00})\times P_0(K))$. Free cells of the level (starting from the smallest addresses) are filled with containers with codes for which the elements of the $M_1(K)$ array have the greatest value. Free cells with larger addresses will gradually be filled with containers with codes for which the values of the elements of the array $M_1(K)$ will decrease.

In the first cycle, the control system determines the frequency $N_1(K)$ for each code for a new period of time. The remaining containers of each code $Z_1(K) = M_1(K) - N_1(K)$ are determined. $N_1(K)$ is summed and the total number of issued containers N_{1s} is determined. The relative frequency $N_1(K) / N_{1s}$ is determined, which corresponds to the probability $P_1(K)$. The number of codes with a zero frequency K_{10} is determined. A frequency array $M_2(K) = (50 - K_{10}) \times P_1(K)$ is formed. Starting from the smallest addresses, the cells are filled with containers with codes that have the largest value $M_2(K)$. The values of the elements of the array $M_2(K)$ are adjusted taking into account the remaining containers $Z_1(K)$ to determine the real number of containers with the corresponding codes $M_2^*(K) = M_2(K) + Z_1(K)$. The determined values of the frequencies of the array $M_2(K)$ are recommended by the system for filling the cells taking into account the issued containers. Changing the array $M_2(K)$ by the system operator allows changing the number of containers with certain codes.

Results and Discussion

Subsequent cycles are performed similarly to the first cycle. The method is applied to the remaining levels of ACSS. The results of the application of the method for the test example are presented in Table.

The following new theoretical and practical results were obtained in the work:

1. The technical and organizational components were isolated and their functional interaction was ensured in the process of comprehensive development of the control system.

2. The system structure for controlling the main ACSS units was proposed.

Results of using the method for the test example

K	$N_0(K)$	$P_0(K)$	$M_1(k)$	$N_1(K)$	$Z_1(K)$	$P_1(K)$	$M_2(K)$	$M_2^*(K)$
1	1	0.067	3	2	1	0.046	2	3
2	3	0.200	9	9	0	0.216	9	9
3	2	0.134	6	5	1	0.120	5	6
4	5	0.335	15	13	2	0.312	13	15
5	4	0.268	12	11	1	0.264	11	12
6	0	0.0	2	0	2	0.0	0	2
7	0	0.0	2	1	1	0.024	1	2
	15	1.00	49	41	8	0.982	41	49

3. Original circuit solutions for functionally complete control units for the RMP and the elevator were proposed, which minimize the number of interface signals and the load on the microcontroller.
4. In-depth control by the microcontroller over the functioning of the control units was proposed and implemented based on the use of information feedback and the estimated time of operations execution.
5. Formulas were obtained for determining the time spent when performing container movement operations.
6. A method for rational placement of containers in rack cells at different levels was proposed in order to reduce customer service time.
7. The specifics of the proposed method of placing containers for further improvement of the organizational component of the control system are determined on the test example.

Conclusions

The proposed distribution of functions between the technical components of the ACSS provides structuring of the control system presented in the work into functionally complete blocks and simplifies and reduces the cost of its technical and software implementation. It is planned to continue the work in order to conduct research to increase the reliability and efficiency of the system.

References

[1] M. Shneier and R. Bostelman (2015). “Literature review of mobile robots for manufacturing”, NISTIR 8022. https://doi/org/10.6028/ NIST.IR.8022.

[2] E-resource: https://www.work.ua/jobs-rivne-logistic-supply-chain/?advs=1

[3] E-resource: https://www.ziprecruiter.com/

[4] E-resource: https://www.salaryexpert.com/

[5] E-resource: https://www.kuka.com/en-de/products/amr-autonomous-mobile-robotics/mobile-robots/kmr-iiwa

[6] V. V. Mazur and S. T. Panchak (2021). “Experimental model of a mobile platform for moving on orthogonal routes”, CAD in Machinery Design: Implementation and Educational Issues (CADMD 2020), IOP Conf. Series: Materials Science and Engineering, 1016 (2021), 012011. https://doi/org/10.1088/1757-899X/1016/1/012011, https://iopscience.iop.org/ article/10.1088/1757-899X/1016/1/012011/pdf

[7] V. V. Mazur (2021). “Robotic mobile platform for container transportation”, IEEE 16th International Conference on Experience of Designing and Application of CAD System (CADSM 2021), pp. 10–13. https://doi/org/10.1109/CADSM52681.2021.9385212, https://ieeexplore.ieee.org/document/9385212

[8] V. Mazur and S. Panchak (2023). “Improvement of the construction and control system of the robotic mobile platform”, IEEE XXVIII International Seminar/Workshop on Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory (DIPED), IEEE, pp. 242–246. https://doi/org/10.1109/DIPED59408.2023, https://ieeexplore.ieee.org/xpl/conhome/10269335/proceeding.

[9] V. Mazur and R. Panchak (2024). Robotic mobile platform for containers storage system, *Computer design systems. Theory and practice,* Vol. 6, No. 3, pp. 24–30.

[10] V. Mazur and R. Panchak (2025). “Robotic mobile platform for containers storage system”, Proc. of the XXXII Int. Polish-Ukrainian Conf. CAD in Machinery Design: Implementation and Educational Issues (CADMD 2024), Ukrainian, Lviv, p. 27.

[11] G. Cook and F. Zhang (2020). "Mobile robots: navigation, control and sensing, surface robots and AUVs", 2nd ed.,Wiley-IEEE Press,.

[12] M. A. Khan (2020). "Design and control of a robotic system based on mobile robots and manipulator arms for picking in logistics warehouses", Automatic, Normandie Université, English, NNT : 2020NORMLH31.

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КЕРУВАННЯ В АВТОМАТИЗОВАНІЙ СИСТЕМІ ЗБЕРІГАННЯ КОНТЕЙНЕРІВ НА БАЗІ РОБОТИЗОВАНИХ МОБІЛЬНИХ ПЛАТФОРМ

Отримано: Серпень 12, 2025 / Переглянуто: Серпень 25, 2025 / Прийнято: Вересень 2025

Анотація. Розроблення ефективних засобів автоматизації складських робіт забезпечує можливість їх широкого і успішного впровадження. Одним із перспективних, на наш погляд, напрямів є створення автоматизованої системи зберігання контейнерів (АСЗК), основаної на розподілі функцій переміщення та зберігання контейнерів між її складовими. Запропонована АСЗК, в якій переміщення контейнерів у вертикальній площині між кількома рівнями стелажів здійснюється ліфтами. Переміщення у горизонтальній площині (для кожного рівня) забезпечує роботизована мобільна платформа (РМП), на відміну від популярних нині систем, в яких основні операції із переміщення контейнерів виконують РМП, оснащені маніпуляторами. В роботі описано керуючу систему АСЗК, яка забезпечує керування чотирма ліфтами і чотирма РМП (по одній для кожного рівня стелажів) під час переміщення контейнерів. Розглянуті дві складові керуючої системи: технічна, яка забезпечує керування технічними засобами АСЗК (ліфтами та РМП), та організаційна, яка визначає послідовність завантаження контейнерів у комірки стелажів та виймання їх звідти.

Ключові слова: автоматизована система зберігання контейнерів, прототип роботизованої мобільної платформи, система керування, планування розміщення та виймання контейнерів.

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