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THE METHOD DEVELOPMENT FOR CONTROLLING THE MOBILE PLATFORM WITH FOUR STEERING WHEELS

The **subject matter** is a method for determining the robot trajectory with four steering wheels to reach a given point on a terrain map. **The research goal** is to develop a method for determining the orientation of the wheels depending on the trajectory of the mobile platform to increase the maneuverability of an autonomous robotic vehicle in a limited production space. **Tasks to be solved**: to analyze similar solutions, describe the proposed design of the steering unit mechanism for a mobile robotic cart, describe the kinematics of a mobile robot with four steerable wheels, develop an algorithm for the steering unit control module, propose a method for controlling a mobile platform with four steerable wheels, and perform experimental studies on the application of the proposed method. Scientific novelty: a method for determining the orientation of the wheels to reach a given point on the terrain plan has been proposed. An algorithm for performing calculations using a software tool has been developed. A mathematical justification for the method of controlling individual wheel blocks of a mobile platform has been provided. **Methods of the study**: modeling methods and automatic control theory, methods for describing linear dynamic systems, analytical modeling methods, computer modeling in the Matlab/Simulink environment. **Results and conclusions**: The mobile platform movement principle using four independent steering wheels is considered. A method for determining the orientation of the steering wheels depending on the trajectory of movement is proposed, which is based on the geometric analysis of the position of the platform and the target point, which allows calculating the angle of rotation of each wheel in such a way as to ensure movement to a given point without lateral slippage. A mathematical model of the control system is built, a structural and functional diagram is developed, an algorithm for processing commands, calculating the angles of rotation is described, and a three-level control system is implemented: linear speed, wheel orientation angle and angular speed of the entire platform. The developed mock-up sample of the mechatronic steering wheel assembly is described. The simulation conducted in the Simulink environment confirmed the operability of the proposed system.

Keywords: mobile robot; AGV; intelligent manufacturing; control method; automated system.

Introduction

In modern manufacturing environments, automated guided vehicles (AGVs) play a key role in intra-shop logistics, cargo transportation, and production line maintenance. However, the effective use of AGVs is often complicated by the specifics of the premises: limited space, narrow aisles, a large number of obstacles, and the need to perform precise maneuvers. Mobile transport robots operating in confined spaces, such as warehouses and factory floors, have strict requirements for omnidirectional mobility. Currently, various drive units have been developed that can move in all directions [1–5]. The two most common technologies that solve the problem of omnidirectional movement can be distinguished: omnidirectional Wheels [6] and rotary steering wheels [7].

The technology of using four steering wheels (4WS) opens up new opportunities for improving the maneuverability and precision of control of mobile platforms. The basic idea of 4WS is that each of the four wheels is not only driven by a separate motor, but can also change its angle of rotation independently of the others. This allows the AGV to perform complex maneuvers, including:

– circular movement with a minimum turning radius;

– "crab movement" (lateral movement of the entire platform);

– U-turn on the spot;

– precise positioning in the loading or service area.

In production facilities with narrow aisles, this allows you to reduce the area required for maneuvering, which, in turn, increases the density of equipment placement and optimizes logistics routes. In addition, by reducing the number of reverse movements, the load on the drive mechanisms is reduced, energy efficiency is increased and wear on the platform elements is reduced.

Intelligent control systems used for AGVs with four steering wheels are able to process sensor data, analyze trajectories and make decisions in real time. This ensures safe navigation in a dynamic environment, collision avoidance, and adaptation to environmental changes. This technology is especially effective for robots working in warehouse complexes, in electronics or pharmaceutical production, where space constraints are tight and movement accuracy is critical.

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This study is relevant because mobile platforms with four steering wheels have increased maneuverability in a confined space compared to traditional wheeled and even tracked types of control. However, such platforms are not yet very widespread due to the complexity of their control methods. The complexity of the control methods is due to the peculiarities of the kinematic scheme of the mobile platform, in which each wheel turns a certain angle independently of each other.

The goal of the work is to develop a method for determining the orientation of the wheels depending on the trajectory of the mobile platform to increase the maneuverability of an autonomous robotic vehicle in a limited production space. The object of the study is an automated system for controlling the movement of a mobile platform. The subject of the study is a method for determining the trajectory of a robot with four steering wheels to reach a given point on the terrain map.

Research task statement: to achieve the goal, it is necessary to analyze similar solutions, describe the proposed design of the mechanism of the steering wheel block for a mobile robotic cart, describe the kinematics of a mobile robot with four steering wheels, describe the developed algorithm for the operation of the steering wheel block control module, describe the proposed method for controlling a mobile platform with four steering wheels, and perform experimental studies on the application of the proposed method.

Analysis of last achievements and publications

A wheeled platform with independent drives and steering capabilities has several key advantages that make it particularly effective for mobile robots in various applications. Independent control of each wheel allows the robot to perform complex maneuvers, such as turning on the spot or moving in a tight space. This is especially important for tasks where space is limited, such as in production and warehouse facilities with narrow aisles. Thanks to the independent wheel drive, the platform can easily adapt to different surface conditions and provide reliable traction with it. This reduces the risk of slipping, allowing precise control of movement even on uneven or slippery surfaces. Steering of each wheel allows you to configure different movement modes, such as parallel control to reduce the turning radius or crab movement, where all wheels turn at the same angle for lateral movement. This significantly expands the possibilities of using a mobile autonomous robot in various scenarios of its use.

In works [8-10] a comparative analysis of different types of kinematic schemes of mobile robots is presented (Fig. 1). Scheme 1 shows an example of the implementation of a three-wheeled mobile robot with a motorized rear wheel drive and a neutral steering front wheel, with which the direction of movement is controlled. Scheme 3 shows an example of the implementation of a three-wheeled mobile robot, in which a front drive steering wheel with a motor is used. The rear wheels in this scheme are neutral without motors.

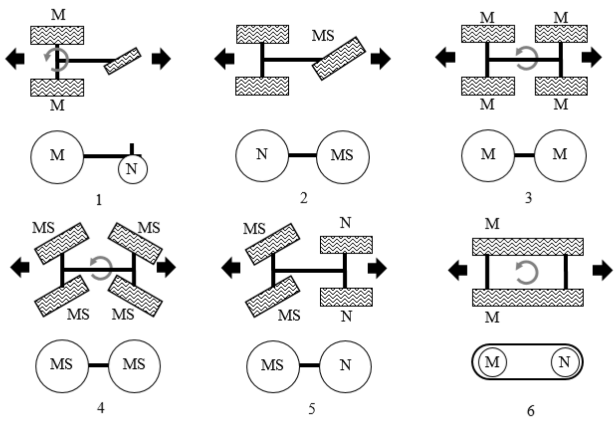

Fig. 1. The mobile robots main kinematic schemes classification:
M – Motor wheel; N – Neutral wheel;
MS – Motor and Steering wheel

Scheme 3 is a classic implementation of a mechanism with differential control (Differential Drive) [11]. In such a scheme, each wheel has its own separate drive (motor), but the direction of movement and turns of the robot are achieved due to the different speeds of rotation of the left and right wheels, without turning the wheels themselves. The advantage is a simple design, high maneuverability, the ability to turn in place, but the disadvantage is the complexity of control on uneven surfaces.

Scheme 4 uses four independent wheels, each of which can rotate. This is the so-called four-wheel scheme with independent wheel control (Four-Wheel Independent Steering and Drive) [12]. Each wheel has its own drive and can be independently controlled. This allows you to control the direction of movement of the robot without having to turn the entire platform. The advantage is high maneuverability, the ability to move sideways (crab movement), the ability to turn in place, but the

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disadvantage is the complex design and the need for complex control.

In scheme 5, steering is achieved using Ackermann Steering [13]. This scheme is used in cars and has motorized front wheels that turn and rear wheels that move straight. Turning is achieved by changing the angle of the front wheels. The advantages are stability at high speeds, effective steering over large areas. The disadvantages include poor maneuverability in confined spaces and the inability to turn on the spot.

Scheme 6 is a tracked platform where tracks are used instead of wheels, which allows the robot to move over complex and uneven surfaces (Tracked Drive) [14]. Tracks can be controlled using the differential control principle. The advantage is high cross-country ability and ability to overcome obstacles. The disadvantages of such an implementation are limited maneuverability compared to wheeled platforms, high friction.

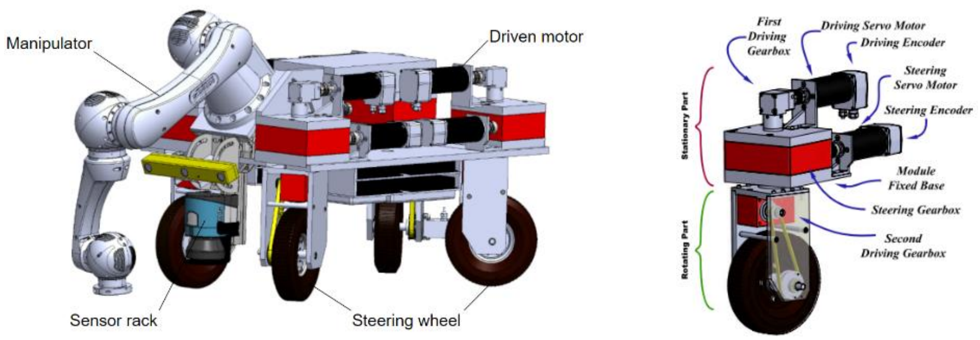
The studies conducted in [8] showed the effectiveness of a wheeled platform with independent drives and the ability to steer.

The article [15] discusses the development of a new control strategy for a four-wheeled mobile robot, which allows it to accurately follow the route in off-road conditions, while maintaining the desired orientation and avoiding lateral slippage. The main goal of the study is to develop a method that will not only provide the robot with the ability to follow the trajectory, but also help maintain the desired orientation of the robot, compensating for the effect of slippage, which is typical for off-road conditions. Also in this work a new approach to control the angles of rotation of the front and rear wheels using the strategy of "parallel control" is proposed. To increase the accuracy of control in sliding conditions, it was proposed to independently control the angles of rotation of the front and rear wheels. The rear wheels are responsible for the correction of lateral deviation, while the front ones control the orientation of the robot relative to the trajectory. To implement this strategy, two control laws are used, based on the backstepping method, which allows to achieve both the required trajectory and the desired orientation.

A feature of the proposed solution is the use of an observer to estimate the side slip angles. This allows to increase the control accuracy, taking into account the adhesion conditions with the surface and adjusting the algorithms based on the current slip conditions. The application of the developed strategy is promising, in particular, for solving tasks where mobile robots must perform tasks in confined spaces or on rough terrain. The results of the simulations confirm that the combination of the observer with the control laws based on the backward search method allows the robot to perform complex maneuvers with high accuracy.

In [16], the design of a mechatronic system of a four-wheeled robot with independent control of each wheel and a mechanism of fault-tolerant feedback by odometry is described. To perform tasks in a confined environment, the authors decided to use a platform with independent control of each wheel (4WS), which provides high maneuverability and efficiency of movement. One of the key design tasks was to synchronize eight electric drives to provide independent control of the movement and rotation of each wheel. This allows the robot to perform complex maneuvers in confined spaces. To implement these tasks, an embedded controller based on an embedded PC is used to provide the necessary computing power.

The article presents a 3D model and kinematic diagram of the mobile platform, and provides a description of the rotary unit for four independent wheels (Fig. 2).



a) b)

Fig. 2. Proposed design of a mobile robot with four independent swivel wheels [14]:
a) 3D model of the mobile robot; b) design of the swivel wheel mechanism

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The kinematic models presented in the article are used both for calculating motion control signals and for estimating the robot speed. Special attention is paid to solving problems with odometry and fault-tolerant estimation of the robot speed and position. The authors note that the developed system provides high maneuverability and reliability in difficult conditions. Fault tolerance is achieved due to special kinematics estimation algorithms that allow ignoring incorrect sensor data and maintaining operability even in the event of partial equipment failures.

In [17], a motion control algorithm for a four-wheel autonomous steering system (4WS) is presented, which independently controls the steering angles of the front and rear wheels. This capability allows the use of three different driving modes: forward steering mode, crab steering mode, and symmetrical steering mode. The proposed algorithm effectively uses these modes to achieve precise maneuverability, facilitating accurate navigation to the target location. The authors conducted a kinematic analysis of a four-wheel steered vehicle, focusing on its motion characteristics.

A separate task should be to plan the trajectory of a mobile autonomous robot with four independent swivel wheels. In [18], a description of the trajectory planner method based on the adaptive control strategy for a four-wheel steering autonomous vehicle (4WS) is presented. The article describes two control strategies for following the trajectory of a mobile robot with four steering wheels based on the feedback control method. In [19], a method for controlling a four-wheeled vehicle with steering wheels is proposed based on the calculus of variations, and the corresponding optimal path is selected according to a predefined objective function. In [20], a new approach to local path planning for an independent mobile base with four wheels (I4WS) is presented. The proposed method adaptively steers and rotates the platform, continuing to follow the given path and avoiding obstacles. The implemented predictive control model (MPC) generates optimized trajectories to avoid collisions up to several meters ahead, taking into account a set of data on a predefined trajectory, using the method of laser reading of the surrounding space.

Method for determining the orientation of the wheels depending on the trajectory of the mobile platform

In the process of moving a mobile platform, the tasks of changing the rectilinear direction of movement arise. For this purpose, various principles of constructing steering mechanisms are used. In our work, the principle of control with four independent swivel wheels is considered. Fig. 3 shows a kinematic model of a mobile platform with four wheels that can change the angle of rotation.

This kinematic model is characterized by the fact that the perpendicular lines to each wheel meet at a single point, which is the center of rotation of the mobile platform. This condition guarantees a rotation without the effect of slipping. The intersection point $C(x, y)$ is the center of rotation or the instantaneous center of rotation of the robotic vehicle. It can change during the movement – for rectilinear movement, the radius from $C(x, y)$ to each wheel has an infinite length, while for motion in place it is equal to the distance from the center of the wheel mounting to the center of the platform $M(x_0, y_0)$.

The center of mass of the robotic vehicle $M(x_0, y_0)$ rotates along a circular trajectory with a radius R, as well as a linear velocity V and an angular velocity ω. The distance between the front and rear axles is the wheelbase l, the distance between the wheels of one axle is the track d. Each wheel has a linear velocity vector V_i and a rotation angle δ_i, which is measured between the longitudinal direction of the robotic vehicle and the direction of the steering wheel.

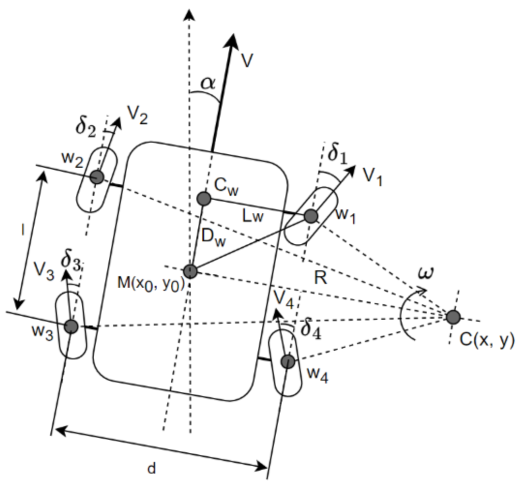

Fig. 3. Kinematic model of a moving platform with four wheels that can change the angle of rotation

The problem being solved has the following initial requirements. For a platform located at point $M(x_0, y_0)$, and currently having a velocity vector v (Fig. 4), it is

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necessary to determine such a rotation angle for each wheel so that it reaches point $T(x_1, y_1)$.

The following method is proposed to solve the problem.

On the map of the area, the coordinates of the location of the mobile platform and the desired point to which it is necessary to move this platform are determined.

If the target point is not on the axis of the velocity vector v, then it is necessary to find such a position of each steering wheel to ensure smooth rotation of the platform during movement to this point.

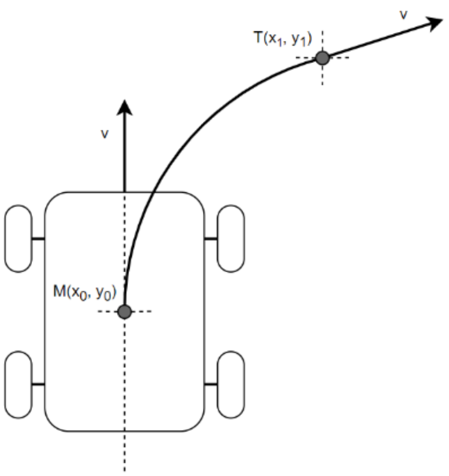

Fig. 4. Mobile platform movement trajectory

At the next stage, it is necessary to find the coordinates of the center of the circle $C(x, y)$, on which the trajectory of the platform movement lies (Fig. 5).

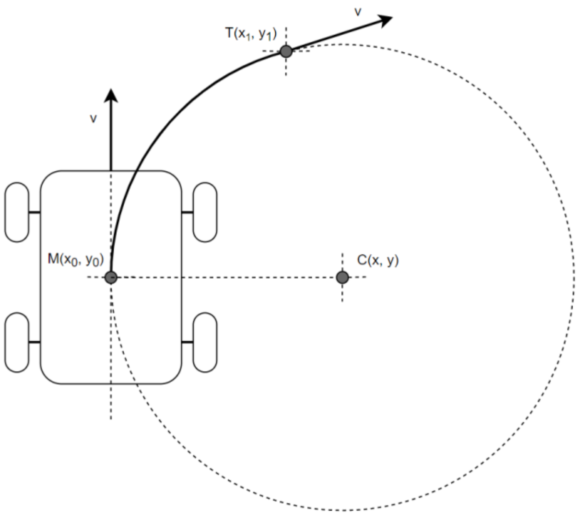

Fig. 5. Coordinates of the center of the circle $C(x, y)$, on which the trajectory of the platform movement lies

When determining the center of the circle, it is taken into account that its center is always located on the axis emanating from the geometric center of the platform (Fig. 5), perpendicular to the velocity vector v.

To calculate the value of the radius R, it is necessary to determine the angle of inclination of the trajectory of motion α (segment MT in Fig. 6).

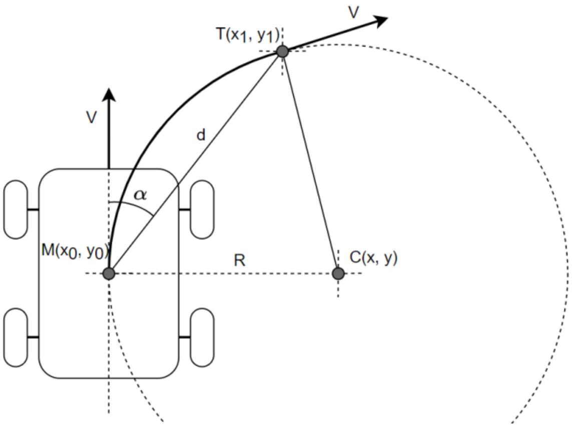

Fig. 6. Radius R calculation

By the law of cosines we get:

$$d^2 = 2R^2\left(1-\cos\left(2\alpha\right)\right), \tag{1}$$

where d is distance between the center of the mobile platform and the target point, R is the radius of the circle on the boundary of which points M and T lie; α is the angle between the velocity vector v and the line d.

Let us rewrite (1) as follows:

$$d^2 = 2R^2\left(1-\cos\left(2\alpha\right)\right) = 4R^2\sin^2\alpha, \tag{2}$$

Now from (2) we find R:

$$R = \frac{d}{2\sin\alpha}. \tag{3}$$

In order for the platform to reach point T, knowing the radius of the circle that is the trajectory of its movement, it is necessary to determine the angle of rotation of each wheel.

Let us consider the procedure for determining the angle of rotation of each wheel. To do this, we will build a geometric model that describes the behavior of the wheel during its rotation. Such a model for one wheel is shown in Fig. 7.

The main task in this case is to find the coordinates of the center of the wheel W_1 relative to the coordinates of the center of the mobile platform M. When we know this coordinate, we can draw a segment W_1C from the center of the circle of the platform's trajectory.

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The direction of rotation of the wheel will be normal to the segment W_1C.

In the general case, the platform will be in an arbitrary position relative to the central axis, which is the base for the terrain map and parallel to one of the x or y axes in the coordinate system. In this case, it is necessary to take into account the angle of rotation of the entire platform α (Fig. 7).

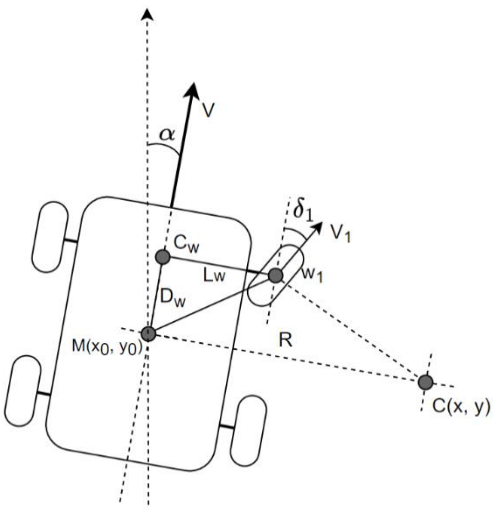

Fig. 7. Geometric model describing the behavior of the wheel

In Fig. 7 D_W is the distance from the center of the platform M to the line connecting the centers of the front wheels. L_W is the distance between the central axis C_W of the platform and the center of the wheel W_1.

The x coordinate of the point C_W, which is the center of the segment connecting the centers of wheels W_1 and W_2 (Fig. 3), is calculated by the formula:

$$C_{W,x} = C_x - D_W \cos\alpha , \tag{4}$$

where α is the angle of rotation of the mobile platform relative to the base axis; D_W is the distance from the center of platform M to the line connecting the centers of the front wheels.

The y coordinate of point C_W is calculated similarly, but instead of cosine we use sine:

$$C_{W,y} = C_y - D_W \sin\alpha . \tag{5}$$

Finally, the coordinate of the wheel center $W_{1,x}$ can be found using the:

$$W_{1,x} = C_x - L_W \cos(\alpha - 90) , \tag{6}$$

where L_W is the distance between the central axis C_W of the platform and the center of the wheel W_1.

The coordinate of the wheel center $W_{1,y}$ is found by the formula:

$$W_{1,y} = C_y - L_W \sin(\alpha - 90) , \tag{7}$$

The angle of rotation of the wheel is found as the normal to the radius extending from the center of the wheel $W_{1,(x,y)}$ to the center of the circle $C_{x,y}$.

To find the normal, we need to know the diameter of the wheel. Fig. 8 shows a schematic diagram of the main parameters of the mobile platform for calculating the angle of rotation of the wheel.

The coordinates of points D_{Wa} and D_{Wb} are calculated using the formulas:

$$D_{Wa} = W_{1,x} - D_W \frac{C_y - W_{1,y}}{\sqrt{(C_x - W_{1,x})^2 + (C_y - W_{1,y})^2}} , \tag{8}$$

$$D_{Wb} = W_{1,y} - D_W \frac{C_x - W_{1,x}}{\sqrt{(C_x - W_{1,x})^2 + (C_y - W_{1,y})^2}} , \tag{9}$$

where D_W is the wheel diameter; $W_{1,x}$ is x coordinate of the wheel center; $W_{1,y}$ is y coordinate of the wheel center; C_x is x coordinate of the trajectory circle center; C_y is y coordinate of the trajectory circle center.

The wheel rotation angle δ_1 is calculated as the angle between the central axis of the mobile platform, which is represented by points P_f and P_b, and the vector V_1 connecting points D_{Wa} and D_{Wb}.

$$\theta_1 = tg^{-1}\left(D_{Wa,y} - D_{Wb,y}, D_{Wa,x} - D_{Wb,x}\right) , \tag{10}$$

$$\theta_2 = tg^{-1}\left(P_{f.y} - P_{b,y}, P_{f.x} - P_{b,x}\right) , \tag{11}$$

where D_{Wa} and D_{Wb} are the points that define the diameter of the wheel; $P_{f.y}$ and $P_{f.x}$ are the points that define the length of the platform along the main axis.

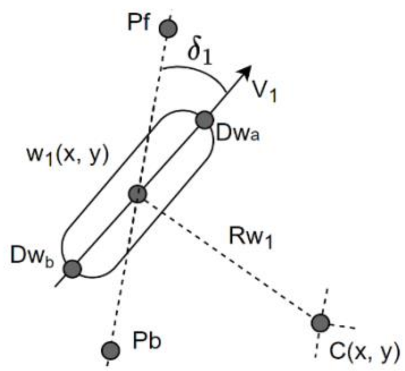

Fig. 8. Calculation of the wheel rotation angle

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The modulus of the difference between the values of θ_1 and θ_2 is calculated by the formula:

$$d_\theta = |\theta_1 - \theta_2|, \tag{12}$$

The wheel rotation angle δ_1 is calculated by the formula:

$$\delta_1 = \min\{d_\theta, |180 - d_\theta|\}. \tag{13}$$

Design of the swivel wheel unit mechanism

To build our own mechanism for the swivel unit, existing designs of similar solutions were analyzed. The MK4 Swerve Module [21] is an example of an SDS Swerve drive. The MK4 is equipped with a 1.5-inch wide swivel wheel. The MK4 uses a set of SDS 2nd generation bevel gears to drive the swivel wheel (Fig. 9). The MK4 uses a centrally located steering encoder to directly measure the angle of rotation without the use of gears. This eliminates encoder backlash and reduces the complexity of the design.

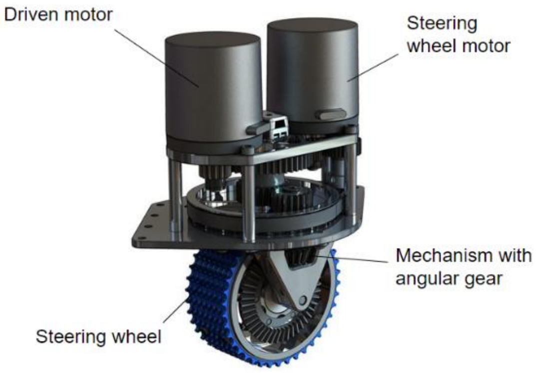

Fig. 9. SDS swivel wheel design

The compactness of the design is achieved by the vertical arrangement of the wheel drive motors and the rotation of the entire mechanism relative to the platform.

Fig. 10 shows an example of the implementation of the swivel wheel mechanism using the differential construction principle [22].

This configuration of the drive motors allows for a reduced height of the mechanism, which is suitable for the implementation of autonomous mobile robotic platforms for warehouse purposes. Such mechanisms can be located in the corners of the platform. The MK4i module inverts the motors on the MK4 module to a lower position, where they do not interfere with other components of the system. Thus, the overall height and center of gravity are lower. The MK4i module also moves the wheel further into the corner of the chassis for a wider wheelbase, which provides more stable operation of the mobile robot. Since the wheel is moved to the area usually occupied by the frame, the MK4i includes an auxiliary plate for proper placement in the chassis.

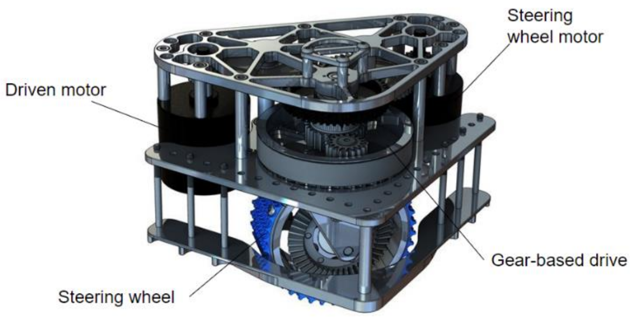

Fig. 10. Differential drive of the swivel wheels

Thus, the considered examples of the implementation of swivel wheel mechanisms showed that each design has its own advantages for a certain sector of application and can be changed depending on the purpose of the end device. This work proposes a universal design of a mechatronic module that uses the advantages of a parallel arrangement of motors to simplify the implementation of the wheel drive, and a differential one, which is characterized by a lower height.

Fig. 11 shows the proposed design of the swivel wheel unit.

This design uses a gear mechanism to rotate the wheel relative to the chassis (Fig. 11, a). Using a mounting plate, the wheel rotation unit is attached to the chassis with four screws. Thanks to the drive gear, which is mounted on the axis of the stepper motor, rotation is carried out to a given angle. The gear of the rotation angle sensor (Fig. 11, b) rotates synchronously with the drive gear, through the main gear. The rotation angle sensor is built on the basis of a multi-turn variable resistor. The rotating wheel is driven by its own motor. A belt drive is used to connect the wheel with the motor.

The entire mechanical part of the rotating wheel unit is mounted on a base plate (Fig. 11, a, b), which rotates relative to the axis on which the main gear is mounted, which is rigidly attached to the chassis of the mobile robot. An electronic control unit based on a microcontroller is also mounted on the base plate. This unit receives commands from the central control unit via the RS-485 interface and Modbus protocol.

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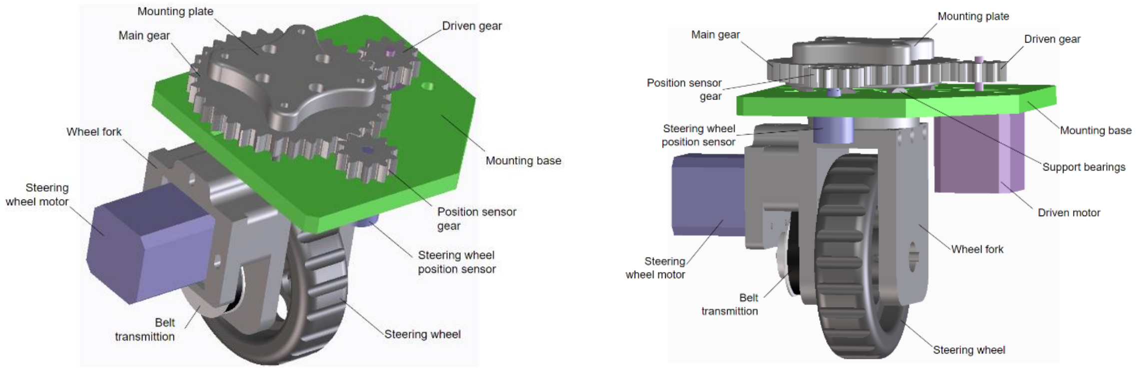

a) b)

Fig. 11. Proposed design of the swivel wheel unit:
a) view of the gear mechanism for rotating the wheel; b) view of the location of the motors and the rotation sensor

Description of the operating principle of the automated system for controlling the position of the steering wheel unit

Fig. 12 shows a block diagram of the motion control system of a mobile transport robot with swivel wheels.

The central control unit performs the function of collecting information from the local navigation subsystem and transmitting commands to the executive modules. It coordinates the operation of the turning wheel units, based on commands from the remote control or the autonomous navigation subsystem. At each step, depending on the current location coordinate on the map of the production facility, the angle of rotation of each wheel is calculated. The obtained parameters are transmitted using the RS-485 interface and the Modbus protocol to each individual turning wheel unit.

The autonomous navigation unit is responsible for the automatic movement of the robot according to the programmed route or built-in navigation algorithms (for example, using GPS, lidar, ultrasonic sensors, etc.). It can determine the current trajectory of movement and the position of the robot in space and transmits this information to the central control unit for further processing.

Independent turning wheel control units directly control the drives of each wheel. They receive commands from the central control unit and autonomously regulate the rotation speed and angle of rotation of the wheels. Thanks to this architecture, each wheel can move independently, which allows the robot to perform complex maneuvers, such as turning on the spot or crab movement (sideways movement).

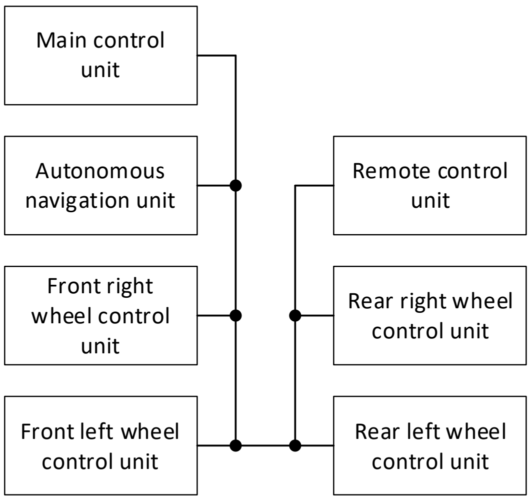

Fig. 12. Block diagram of the motion control system of a mobile transport robot with swivel wheels

Fig. 13 shows a diagram of the control algorithm for the rotary wheel module. At the beginning of the work, the wheel is set to the initial position. The initial position is considered to be the position when the limit sensor installed on the base is triggered. All other positions of the wheel are counted from this position.

After finding the initial position, the wheel is moved to the middle position. The middle position is considered to be the position in which the wheel is oriented clearly parallel to the direction of movement of the mobile platform.

When the module completes the calibration stage, the module controlling its operation goes into the waiting mode for commands from the main controller. Upon receipt of a command from the controller, it is processed and the specified angle of rotation of the wheel is determined.

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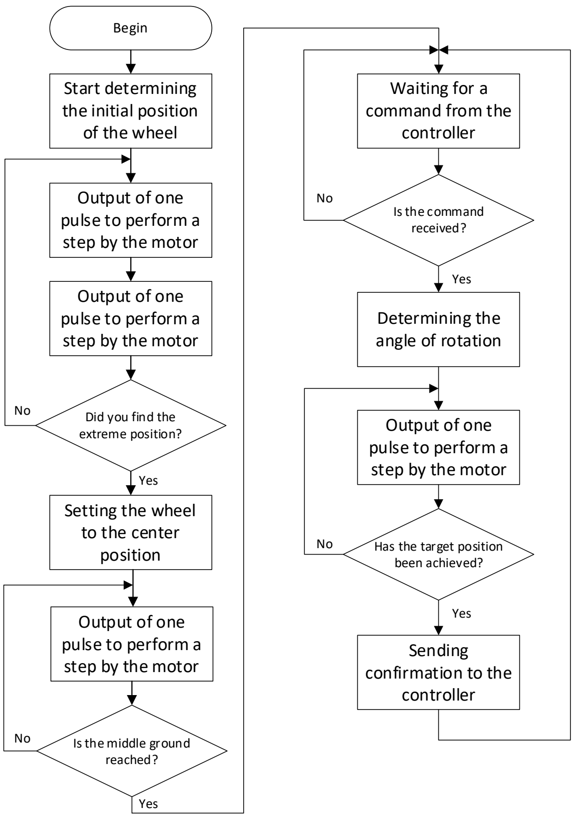

Fig. 13. Swivel wheel module control algorithm

In case of receiving a specified angle, the process of rotating the wheel to the specified position is started. This position is determined by the number of pulses to the stepper motor from the control module, and is also controlled by data from the rotation angle sensor. After reaching the specified position, the stepper motor stops and holds the wheel in the specified position, and the control module transmits a data packet to the main controller to confirm the operation of performing the wheel orientation.

Fig. 14 shows a diagram of the algorithm for synchronous control of the complex of rotating wheel modules.

At the beginning of operation, the initial position of the wheels is initialized. For this, a corresponding command is issued, which is recognized by each individual rotation module. Each module, independently of each other, executes the initialization command and reports this to the main module at its request.

The main module sequentially polls each rotation module and checks whether it has reached the initial position. Only after taking the specified position, the program proceeds to the stage of directly controlling the movement of the mobile platform. The determination of a certain angle of rotation of each wheel is based on data from the main control unit, which is responsible for laying the path. Typically, such a module is implemented on the basis of a Raspberry PI mini-computer.

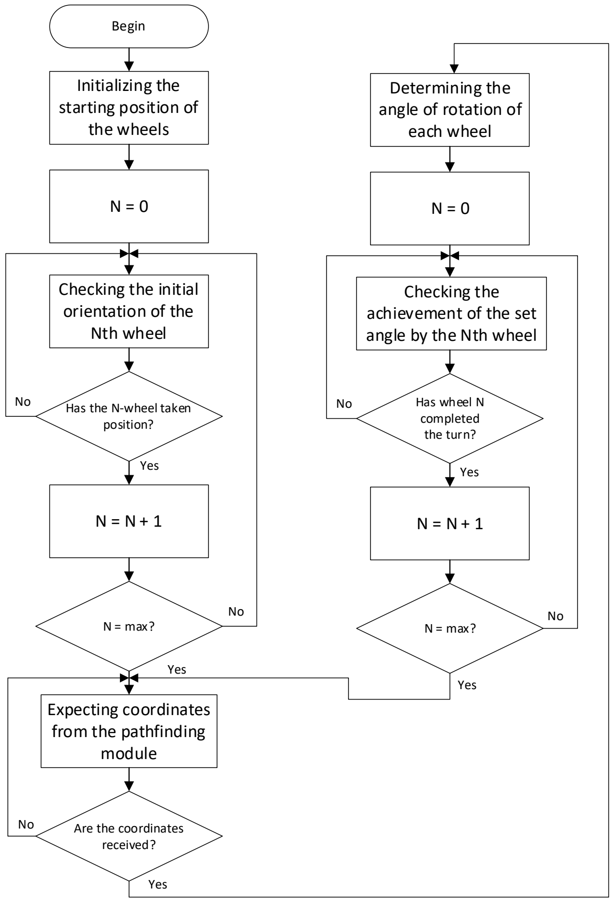

Fig. 14. Algorithm diagram for synchronous control of a complex of rotary wheel modules

Based on the received target coordinate and the current point in space, the method proposed in this work determines the angle of rotation of each wheel. Before starting the movement, the main controller sends a command to each control module with the corresponding data and monitors the completion of the process of acquiring the wheels of the given orientation. After completing the operation of turning the wheels, the module goes into the waiting mode for new coordinates.

Synthesis of the automatic control system block diagram

Fig. 15 shows a block diagram of the system for automatically adjusting the steering wheel angle to a given angle and linear speed of movement.

In this scheme, three loops can be distinguished. The first loop is responsible for regulating the linear speed and providing the setpoint V_{target} using

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a PID controller. The speed of movement is controlled by an encoder mounted on the wheel axis. A speed sensor is included in the feedback loop. The difference between the current and desired speeds $e_{\omega,i}$ is used to control the motor, which provides the necessary acceleration or deceleration. The encoder provides feedback and measures the actual speed V_i, which allows the controller to adjust the motor operation to achieve the desired speed value V_{target}.

The second loop is responsible for controlling the rotation of each controlled wheel to the desired angle δ_{target}. An angle sensor – a multi-turn potentiometer – is used as a sensor to measure the current angle of rotation of the wheel. The error $e_{\delta,i}$ between the actual angle δ_{out} and the specified angle of rotation $\delta_{target,i}$ is processed by a PID controller that regulates the motor, which ensures smooth and accurate positioning of the wheel mechanism. The angle of rotation is monitored by a sensor based on a multi-turn resistor. The model takes into account a reducer based on a gear transmission to provide the required ratio.

The third loop regulates the angular velocity ω_i of the mobile robotic platform. Each wheel has its own angular velocity, which is determined by the radius of rotation for the i-th wheel R_i and the linear velocity of the i-th wheel V_i. Angular velocity

$$\omega_i = V_i / R_i , \tag{14}$$

is determined by the turning radius, which is calculated by the formula

$$R_i = \frac{l}{tg\left(\delta_{\omega,i}\right)} , \tag{15}$$

where $\delta_{\omega,i}$ is the angle of the wheel rotation; l is the distance between the front and rear axles.

The error between the actual angular velocity ω_i and the average angular velocity ω_{avg} determined by the other steered wheels is fed to the PID controller to correct the steering angle of the wheels.

The lateral component of the velocity for each wheel is defined as:

$$V_{y,i} = V_i \sin\left(\delta_i\right). \tag{16}$$

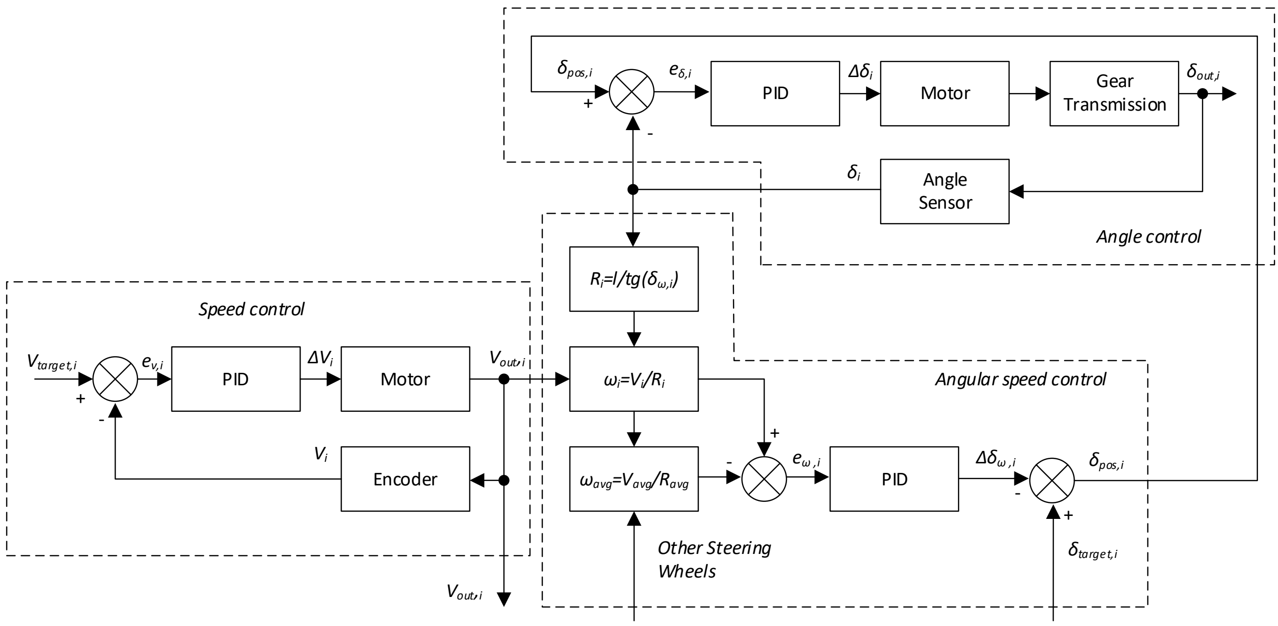

Fig. 15. Block diagram of the system for automatic adjustment of the steering wheel angle to a given angle and movement linear speed

The lateral component of velocity is the component of the velocity vector that determines the speed of an object in a direction perpendicular to the main direction of its movement. This speed is directed across the axis of motion of the vehicle or robot. The lateral component of velocity takes into account lateral displacements that occur during turns or other maneuvers.

The circuits work in conjunction to ensure smooth movement of the mobile robot. The first circuit controls the speed of the platform, the second is responsible for precise control of the angle of rotation of the wheels,

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and the third ensures uniform execution of the turn by all wheels of the platform.

The total angular velocity of the mobile robot ω_{avg} is determined based on the average turning radius and the average linear velocity. The average turning radius R_{avg} will be calculated taking into account all four wheels, taking into account their individual radii R_i and linear velocities V_i:

$$R_{avg} = \sum_{i=1}^{4} R_i V_i \Big/ \sum_{i=1}^{4} V_i \,, \qquad (17)$$

Then the angular velocity ω_{avg} of the robot can be calculated as:

$$\omega_{avg} = V_{avg} / R_{avg} \,, \qquad (18)$$

where R_{avg} is the average turning radius, taking into account the different turning angles for each wheel; V_{avg} is the average linear velocity, calculated by the formula:

$$V_{avg} = \frac{1}{4}\sum_{i=1}^{4} V_i \,, \qquad (19)$$

Given the independent control of each wheel and their different angles of rotation, the formula for angular velocity will look like this:

$$\omega_{avg} = \frac{1}{4}\left(\sum_{i=1}^{4} V_i\right)^2 \Big/ \sum_{i=1}^{4} \frac{lV_i}{tg(\delta_i)} \,. \qquad (20)$$

Formula (20) takes into account the individual angles of rotation and speed of each wheel of the mobile robotic platform, which allows the robot to adapt to complex trajectories and turns with different angles for each steering wheel.

Thus, the proposed model allows you to control the movement of a mobile platform with independent control of each wheel, to ensure high maneuverability in difficult operating conditions.

Description of the research results

Let us consider separately the circuit responsible for precise control of the wheel rotation angle (Fig. 16).

This diagram corresponds to the manufactured mock-up sample of the swivel wheel module, which is shown in Fig. 17.

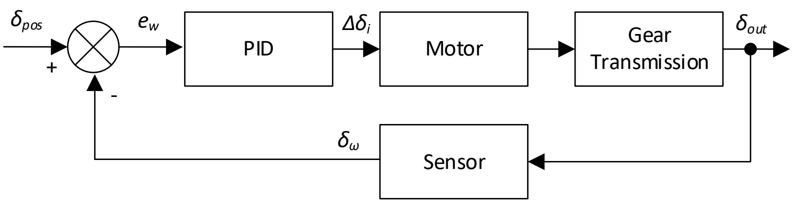

Fig. 16. Block diagram of the wheel steering angle control circuit

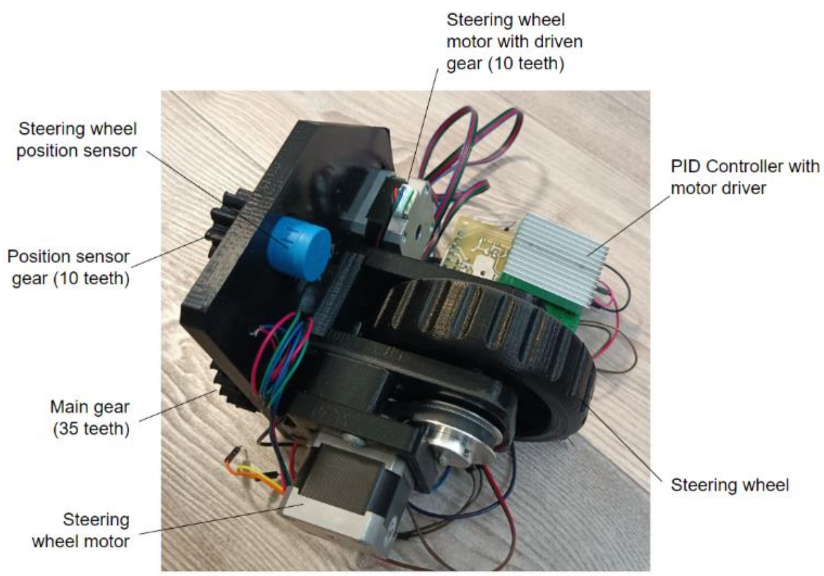

Fig. 17. Appearance of the mock-up sample of the swivel wheel module

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The parameters of the components of the layout are as follows:

– number of teeth of the main gear – 35 pcs.;

– number of teeth of the driven gear – 10 pcs.;

– gain of the positioning sensor based on a variable resistor – 5;

– type of stepper motor – NEMA17;

– rated current of the stepper motor – 2 A;

– torque – 40 N·cm.

Let us describe each component of the structural diagram separately. The PID controller has three main components:

– proportional component (P) provides a proportional response to the error;

– integral component (I) provides correction of the constant error by integrating the error over time;

– differential component (D) takes into account the rate of change of the error, which allows to increase the stability of the system.

The transfer function of the PID controller is written as:

$$W_{PID}(s) = K_p + \frac{K_i}{s} + K_d s\,, \qquad (21)$$

where K_p is the proportional component coefficient; K_i is the the integral component coefficient; K_d is the differential component coefficient; s is the Laplace operator.

The transfer function of a stepper motor driving a rotary mechanism is written in the following form:

$$W_{motor}(s) = \frac{K_m}{T_m s + 1}, \qquad (22)$$

where K_m is the motor gain, which characterizes the conversion of electrical pulses into angular motion; T_m is the motor time constant, which determines the inertia of the system.

The design of the swivel wheel mechanism uses a transmission system in the form of two gears with a number of teeth of 35 and 10 – this determines the ratio between the angles of rotation of the stepper motor and the swivel wheel mechanism. If N_1 is the number of teeth on the driving gear (10 teeth), and N_2 is the number of teeth on the driven gear (35 teeth), then the gear ratio:

$$N_2/N_1 = 35/10 = 3.5\,.$$

Thus, the transfer function of the transmission mechanism will be:

$$W_{gears}(s) = 1/3.5\,, \qquad (23)$$

A variable resistor is used to measure the angle of rotation through feedback. In this case, the transfer function of the sensor can be approximated by a linear relationship that converts the angle signal into an electrical voltage:

$$W_{sensor}(s) = K_{sensor}\,, \qquad (24)$$

where K_{sensor} is the coefficient of conversion of the angle of rotation into voltage, determined by the characteristics of the variable resistor. This coefficient is usually a constant value.

Let us substitute the determined transfer characteristics into the corresponding components of the steering wheel angle control system (Fig. 18).

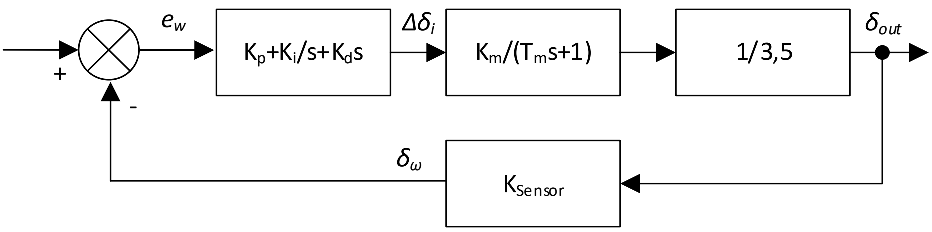

Fig. 18. Block diagram of the circuit for automatic steering angle adjustment with defined transfer functions

To synthesize the overall transfer function of the system, we need to combine the transfer functions of each element. The overall transfer function will look like this:

$$W_{sw}(s) = W_{PID}(s) + W_{motor}(s) + W_{gears}(s) + W_{sensor}(s)\,. \quad (25)$$

We substitute the transfer functions of each element:

$$W_{sw}(s) = \left(K_p + \frac{K_i}{s} + K_d s\right)\cdot\frac{K_m}{T_m s + 1}\cdot\frac{1}{3.5}K_{sensor}\,. \qquad (26)$$

Simplifying this equation, we get:

$$W_{sw}(s) = \frac{K_m K_{sensor}\left(K_p s + K_i + K_d s^2\right)}{3.5s\left(T_m s + 1\right)}\,. \qquad (27)$$

Let's simulate the developed automatic steering angle adjustment circuit using the Mathlab Simulink tool.

Let's define the coefficients of the transfer characteristics. For a stepper motor, the gain K_m depends

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on the torque M developed by the motor at the rated current $I_0 = 2A$:

$$K_m = \frac{M}{I_0} = \frac{40}{2} = 20\left(\frac{N \cdot cm}{A}\right). \qquad (28)$$

The system time constant T_m is determined by the inductance characteristics of the motor windings and can be calculated by the formula:

$$T_m = L/R\,, \qquad (29)$$

where L is the winding inductance (for the selected motor type, 5 mH); R this is the winding resistance (for the selected motor type, 2 Ohms).

Thus, for the selected type of Nema 17 motor with an inductance of 5 mH and a resistance of 2 Ohms:

$$T_m = \frac{5 \cdot 10^{-3}}{2} = 0.0025(s).$$

Thus, after substituting the coefficients in (22), we obtain:

$$W_{motor}(s) = \frac{20}{0.0025s + 1}.$$

Fig. 19 shows a circuit diagram of the automatic steering angle adjustment built in Simulink.

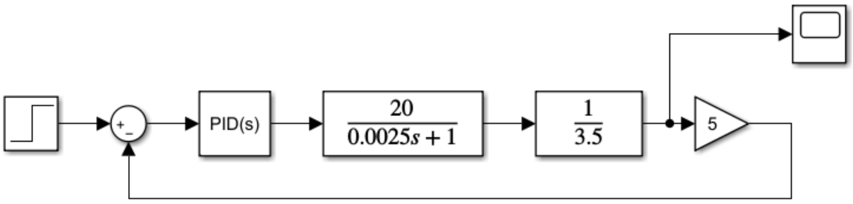

Fig. 19. Modeled circuit diagram of the automatic steering wheel angle adjustment

The PID controller parameters are as follows:

– proportional component coefficient $K_p = 2.5$;

– integral component coefficient $K_i = 25$;

– differential component coefficient $K_d = 0.0125$.

A graph of the transition process was constructed for the selected coefficients (Fig. 20).

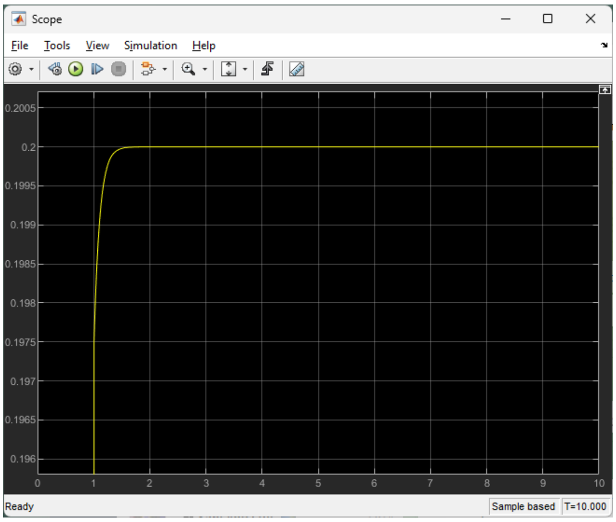

Fig. 20. Transient process graph for the modeled system

As can be seen from the graph above, the system reaches a stable state quite quickly, approximately 1–1.5 seconds after the start of the simulation. The value of the output parameter stabilizes at 0.2, which corresponds to a change in the wheel orientation by 1 degree. The gain coefficient of the rotation angle sensor is 5. It can also be seen that there is no significant excess of the set parameter, and the system quickly becomes stable. The output variable increases rapidly at the beginning of the simulation, which indicates that the system has good stability and fast response

Conclusions

This work studies a current topic related to solving the problem of increasing the degree of mobility of a mobile autonomous robot in a confined space. The principle of turning a mobile platform using four independent steering wheels is considered. A method for determining the orientation of the steering wheels depending on the trajectory of movement is proposed, which is based on the geometric analysis of the position of the platform and the target point, which allows calculating the angle of rotation of each wheel in such a way as to ensure movement to a given point without lateral slippage. A mathematical model of the control system was built, a structural and functional diagram was developed, an algorithm for processing commands, calculating the angles of rotation was described, and a three-level control system was implemented - linear speed, wheel orientation angle and angular velocity of the entire platform. The work also describes the hardware implementation of the steering wheel module, which uses a stepper motor, gear transmission and a position sensor based on a variable resistor. The developed prototype of the mechatronic assembly of the steering wheels is described. The simulation conducted in the Simulink environment confirmed the operability of the proposed system: the system quickly reaches a stable state, demonstrates the absence of readjustments and high positioning accuracy. Thus, the developed control method provides high maneuverability and accurate tracking of the trajectory of the platform with four independently steered wheels, which is an important step towards the development of autonomous robotics.

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РОЗРОБЛЕННЯ МЕТОДУ УПРАВЛІННЯ МОБІЛЬНОЮ ПЛАТФОРМОЮ З ЧОТИРМА КЕРОВАНИМИ КОЛЕСАМИ

Предметом вивчення є метод визначення траєкторії руху робота з чотирма керованими колесами для досягнення заданої точки на карті місцевості. **Мета дослідження** – розробити метод визначення орієнтації коліс відповідно до траєкторії руху мобільної платформи для підвищення маневреності автономного роботизованого транспортного засобу в обмеженому виробничому просторі. **Завдання**, які необхідно виконати: проаналізувати аналогічні рішення;

описати запропоновану конструкцію механізму рульового керування мобільного роботизованого візка; подати кінематику мобільного робота з чотирма керованими колесами; розробити алгоритм модуля управління рульовим керуванням; запропонувати метод управління мобільною платформою з чотирма керованими колесами; експериментально дослідити ефективність запропонованого методу. **Наукова новизна**: запропоновано метод визначення орієнтації коліс для досягнення заданої точки на плані місцевості; розроблено алгоритм розрахунків за допомогою програмного засобу; математично обґрунтовано метод керування окремими колісними блоками мобільної платформи. **Методи дослідження**: моделювання й теорія автоматичного керування, опис лінійних динамічних систем, аналітичні методи моделювання, комп'ютерне моделювання в середовищі *Matlab*/*Simulink*. **Досягнуті результати й висновки**. Розглянуто принцип руху мобільної платформи за допомогою чотирьох незалежних керованих коліс. Запропоновано метод визначення орієнтації керованих коліс відповідно до траєкторії руху, основаного на геометричному аналізі положення платформи й цільової точки, що дає змогу розрахувати кут повороту кожного колеса таким чином, щоб забезпечити рух до заданої точки без бокового прослизання. Побудовано математичну модель системи керування, розроблено структурно-функціональну схему, описано алгоритм оброблення команд, обчислення кутів повороту, а також реалізовано трирівневу систему керування: лінійною швидкістю, кутом орієнтації коліс і кутовою швидкістю всієї платформи. Описано розроблений макетний зразок мехатронного вузла керма. Моделювання, проведене в середовищі *Simulink*, підтвердило працездатність запропонованої системи.

Ключові слова: мобільний робот; AGV; інтелектуальне виробництво; метод керування; автоматизована система.

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