

MODELING AND MOTION CONTROL OF A MOBILE WHEELED ROBOT AT LOW SPEEDS

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Abstract:

The article deals with the issue of modeling and motion control of a mobile wheeled robot at low speeds. Attention is focused on the basic methods of mobile robot control, namely synchronous steering, Ackermann steering, and differential drive control. The main emphasis is placed on differential drive control, which is suitable for small mobile robotic platforms due to its design, good maneuverability, and ability to rotate in place. The article describes the kinematic and dynamic model of a mobile robot, taking into account quantities such as position and orientation. The proposed solution also includes the design of a control loop that enables the control of the angular velocities of the wheels and the tracking of a desired trajectory. The proposed simulation model was created in the MATLAB/Simulink environment and divided into subsystems describing kinematics, dynamics, control, and velocity transformation. The practical part of the article is devoted to the structural design and implementation of an experimental prototype of a mobile robot. The result is a functional prototype suitable for verifying the principles of mobile robotics, regulation, and motion control under real conditions.

Key words: mobile wheeled robot, low speed, differential steering, kinematic model, dynamic model

INTRODUCTION

Mobile robotics currently represents a dynamically developing field of automation with significant applications in industry, logistics, healthcare, and autonomous systems. Wheeled mobile robots are among the most widely used platforms due to their simple mechanical design, energy efficiency, and good maneuverability [1]. One of the main challenges in designing control systems for these platforms is ensuring accurate and stable motion, particularly at low speeds. In this operating mode, the nonlinear properties of the system become more pronounced, including static and dynamic friction, wheel slip, and quantization errors of measurement systems. These phenomena reduce the accuracy of trajectory tracking and may lead to degradation of control quality [2]. Wheeled mobile robots are typical examples of nonholonomic systems, whose motion is constrained by non-integrable constraints. This means that the robot is not able to move independently in all directions, which complicates the design of control algorithms [3]. For this reason, specific control methods are used, such as feedback linearization, Lyapunov-based stabilization approaches, and model predictive control. From the perspective of chassis design and motion control, several approaches are applied, including synchronous steering, Ackermann steering, and differential drive control. Differential drive control is among the most commonly used methods, mainly due to its simple implementation and suitability for autonomous systems [4].

However, at low speeds, control deviations become more significant, which requires more accurate modeling and more robust control algorithms. Control loops play an important role in the control process. In practice, PID controllers are frequently used, as they represent a compromise between implementation simplicity and sufficient control performance [5]. However, their effectiveness depends on the proper

tuning of parameters, while at low speeds the system is more sensitive to disturbances, model uncertainties, and external influences.

The aim of this article is to analyze the issue of motion control of wheeled robots at low speeds, identify the main factors affecting motion accuracy, and propose suitable control methods. Special emphasis is placed on kinematic modeling, controller design, and practical aspects of implementation under real conditions [6].

CONTROL OPTIONS FOR MOBILE WHEELED ROBOTS

The basis of a mobile wheeled robot's motion is the rolling of its wheels on the ground. The arrangement of the wheels, their drive system, and their steering directly determine what maneuvers the robot can perform and how complex its mechanical and electronic design will be.

Synchronous steering (Fig. 1) is characterized by all the robot's wheels being steered at the same angle while moving at the same speed.

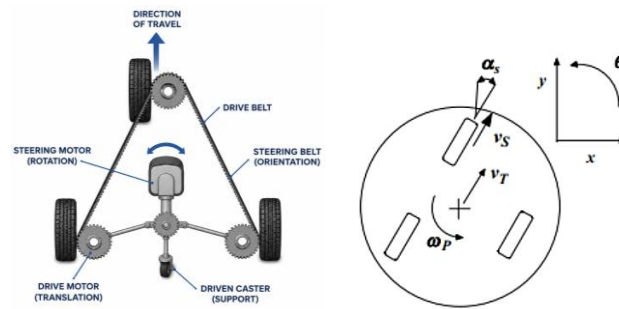


Fig. 1 Synchronous steering

Alt text: Mobile platform with synchronous wheel steering using a steering motor and a belt mechanism. The simplified kinematic model shows velocities, angular velocity, and the wheel steering angle.

Source: [7].

This approach enables very precise trajectory tracking, especially on flat and smooth surfaces where no significant wheel slip occurs. Its advantages include intuitive control and good motion stability; however, its main disadvantage is the high mechanical and control complexity, since precise synchronization of all drives and steering angles is required. This type of control is used primarily in special mobile platforms and service robots [1].

The kinematic model of this system is:

$$\begin{aligned} v_x &= v_s \cos(\alpha_s), \quad x(t) = \int_0^1 v(\sigma) \cos(\theta(\sigma)) d\sigma, \\ v_y &= v_s \sin(\alpha_s), \quad y(t) = \int_0^1 v(\sigma) \sin(\theta(\sigma)) d\sigma, \\ v_T &= v_s, \quad \theta(t) = \int_0^1 w(\sigma) d\sigma, \\ \omega_p &= 0, \end{aligned}$$

where:

v_s – speed of wheel movement,

v_T – velocity of the robot's center of mass (tangential),

ω_p – rate of change of the orientation of the center of mass relative to the robot,

α_s – wheel alignment angle.

Ackermann steering (Fig. 2) is based on principles commonly used in automotive engineering.

When cornering, the inner wheel is steered at a larger angle than the outer wheel, ensuring that all wheels follow circular paths with a common center of rotation. This minimizes wheel slip and tire wear. This model is particularly suitable for applications in which the robot moves along smooth trajectories at higher speeds, such as autonomous vehicles.

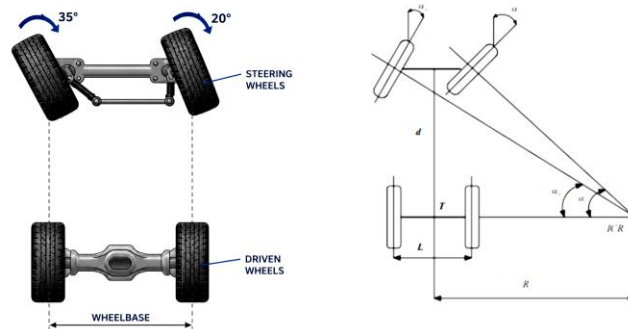


Fig. 2 Ackermann steering

Alt text: Four-wheel mobile platform with Ackermann steering, where the front steering wheels are turned at different angles during cornering. The kinematic scheme shows the wheelbase, steering geometry, turning radius, and steering angles of the front wheels.

Source: [7].

However, for small robotic platforms, it can be mechanically more complex and less flexible, especially when maneuvering in confined spaces [2, 3].

The kinematic model of this system is

$$\begin{aligned}\dot{x} &= v \cos \theta, \\ \dot{y} &= v \sin \theta, \\ \omega &= v \frac{\tan \alpha}{l}, \\ \cot(\alpha_0) - \cot(\alpha_i) &= \frac{L}{d}, \\ R &= \frac{d}{\tan \alpha'}\end{aligned}$$

where:

d – wheelbase,

L – rear axle track width,

α_0 – steering angle of the left steering wheel,

α_i – steering angle of the right steering wheel,

R – turning radius around the ICR,

ICR – instant center of rotation.

Differential drive control (Fig. 3) represents the simplest and one of the most commonly used methods for controlling mobile robots.

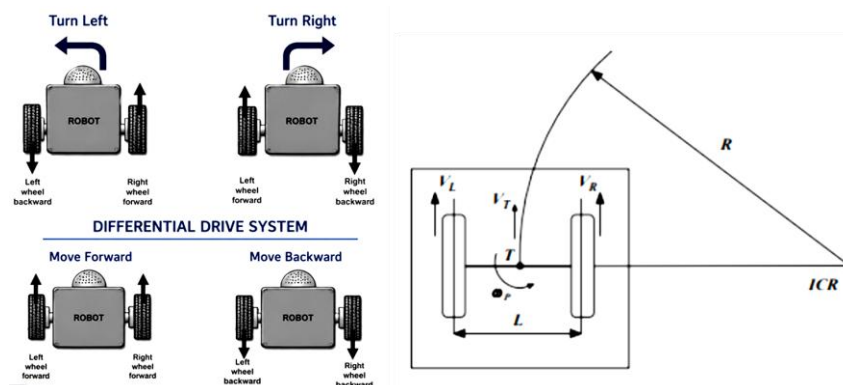


Fig. 3 Differential drive control

Alt text: Differential-drive mobile robot showing forward, backward, left-turn, and right-turn motion based on the relative directions of the left and right wheels. The kinematic scheme illustrates wheel velocities, robot translational velocity, angular velocity, wheelbase, turning radius, and the instantaneous center of rotation.

Source: [7].

The robot uses two independently driven wheels, namely the left and right wheel, while the direction and speed of motion are determined by the difference in their angular velocities. If both wheels rotate at the same speed, the robot moves in a straight line; when the wheel speeds differ, the robot turns, and when the wheels rotate in opposite directions, the robot can rotate around its own axis. This ability, known as zero-radius turning, represents a significant advantage in confined spaces and at low speeds [1, 8, 9]. Kinematic model of a system with differential control:

$$\begin{aligned}\dot{x} &= v \cos(\varphi), \\ \dot{y} &= v \sin(\varphi), \\ \dot{\varphi} &= \omega, \\ R &= \frac{L}{2} \frac{V_R + V_L}{V_R - V_L}, \\ V_T &= \frac{V_R + V_L}{2}.\end{aligned}$$

From the perspective of control implementation, the differential drive model is the most suitable for the experimental prototype used in this work, primarily due to its simplicity, low mechanical design requirements, and good maneuverability. On the other hand, it is important to note that at low speeds, nonlinear phenomena such as static friction, wheel slip, and sensor quantization errors become more pronounced, which may lead to deviations from the ideal model. Therefore, it is advisable to supplement the basic kinematic model with appropriate control and compensation algorithms [10, 11].

The mathematical model of the mobile wheeled robot prototype serves as a fundamental tool for analyzing its motion, simulating its behavior, and designing control algorithms. This model is based on the kinematic and dynamic description of the robot, taking into account its geometric configuration, wheel properties, and interaction with the environment. Figure 4 shows the global coordinate system (X, Y), which is used to describe the robot's position in space, and the local coordinate system (x, y), which is rigidly attached to the robot.

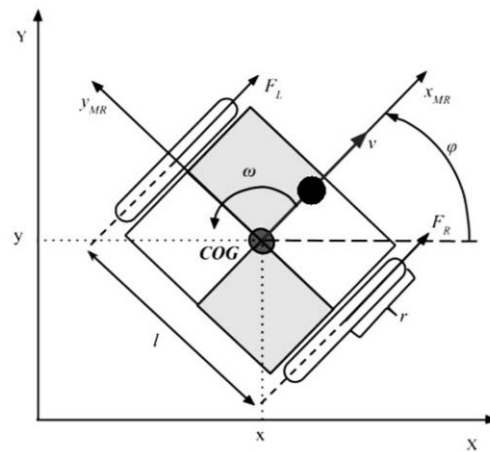


Fig. 4 Mathematical model of a mobile wheeled robot

Alt text: Wheel mobile robot with a body-fixed coordinate system, center of gravity, linear and angular velocities, and wheel contact forces. The kinematic scheme shows the robot orientation, wheel arrangement, and force components used to describe omnidirectional motion.

A key element of the model is the robot's center of mass, which represents the point at which the total mass of the robot can be considered to be concentrated. The robot's motion in a plane is defined by its linear velocity v and angular velocity ω , while its orientation relative to the global coordinate system is determined by the angle φ . Based on these parameters, the robot's trajectory can be mathematically described using the following differential equations:

$$\dot{x} = v \cos \varphi, \dot{y} = v \sin \varphi, \dot{\varphi} = \omega.$$

The model also considers the driving forces acting on the individual wheels, denoted as F_L and F_R , which generate the motion of the robot. The distance between the wheels l , also referred to as the track width,

significantly affects the robot's maneuverability. When the angular velocities of the wheels, ω_L and ω_R , are different, the robot performs rotational motion around the instantaneous center of rotation. The relationship between the angular velocities of the wheels and the resulting motion of the robot is given by the kinematic equations:

$$\begin{aligned} v &= \frac{r}{2}(\omega_R + \omega_L), \\ \omega &= \frac{r}{l}(\omega_R - \omega_L). \end{aligned}$$

These equations make it possible to transform the desired motion of the robot into specific control inputs for the individual motors, which forms the basis of differential drive control. The mathematical model created in this way is subsequently used in the robot's control structure, for example for trajectory tracking or motion stabilization. The implementation of model in control algorithms, such as PID controllers or model predictive control, enables accurate and stable robot behavior to be achieved under real operating conditions.

DYNAMIC MODEL OF THE MOBILE ROBOT

The dynamic model of a mobile wheeled robot represents an extension of the kinematic model by including force and moment effects. Unlike kinematics, which describes only geometric motion, the dynamic model takes into account physical quantities such as the mass of the robot, inertia, and the driving forces generated by the motors. The dynamic model is important for differential-drive mobile robots because it links the forces generated by the motors with the resulting linear and angular motion of the robot. This is especially relevant when the robot operates at low speeds, where friction, inertia, and actuator limitations may influence the accuracy of motion control [12, 13].

In the considered model, ideal contact between the wheels and the ground is assumed, while wheel slip and lateral skidding are neglected. The robot is acted upon by the driving forces of the right and left wheels, denoted as F_R and F_L . These forces cause both the forward motion and the rotational motion of the robot.

Based on Newton's second law, the translational motion can be expressed as:

$$M \frac{dv}{dt} = F_R + F_L,$$

where:

M – represents the total mass of the robot,

v – is its forward velocity.

The rotational motion of the robot with respect to its center of mass is given by the moment equation:

$$J \frac{d\omega}{dt} = \frac{l}{2}(F_R - F_L),$$

where:

J – is the moment of inertia of the robot,

l – is the distance between the wheels.

This relationship expresses that the difference between the forces acting on the right and left wheels causes the robot to rotate. The dynamic model therefore provides a connection between the forces generated by the motors and the resulting motion of the robot. In practice, it is mainly used in the design of controllers that must take into account the inertial properties of the system and ensure motion stability.

To achieve accurate motion control of the robot, it is necessary to implement a feedback control loop for controlling the angular velocities of the wheels. This loop ensures that the actual wheel velocities, ω_L , ω_R , follow the desired reference values, ω_{Rref} , ω_{Lref} . Feedback linearization and backstepping-based approaches are frequently used in the control of nonholonomic wheeled mobile robots, as they allow the kinematic and dynamic properties of the system to be considered within the control structure [13, 14].

The control is based on the error between the desired and actual values:

$$e = \omega_{ref} - \omega.$$

Based on this error, the control action is generated in the form of the forces F_R and F_L . In a simple case, a proportional controller can be used:

$$F_{R/L} = P(\omega_{ref} - \omega).$$

In practical implementation, it is also necessary to take into account the saturation of the control actions:

$$F_{R/L} = F_{max} \text{sign}(\omega_{ref} - \omega).$$

This ensures that the control action does not exceed the physical capabilities of the motors. This control loop makes it possible to suppress dynamic effects and ensure stable and accurate operation of the robot. Reduction represents the connection between the velocities of the robot and the velocities of the individual wheels. It is a key step in control implementation, as it enables the transformation between the global quantities v , ω and the local quantities of the wheels. The relationship between the forward velocity of the robot and the wheel velocities can be written in matrix form as:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{l} & -\frac{1}{l} \end{bmatrix} \begin{bmatrix} v_R \\ v_L \end{bmatrix}.$$

After rearrangement, the inverse relationship is obtained:

$$v_R = v + \frac{l}{2} \omega,$$

$$v_L = v - \frac{l}{2} \omega.$$

These equations determine the velocities that the individual wheels must achieve in order to produce the desired motion of the robot. Subsequently, these velocities can be converted into angular velocities using the following relationship:

$$\omega = \frac{v}{r}.$$

Reduction is essential for the implementation of control in a real system, because control algorithms work with the motion of the robot as a whole, while the control actions are applied at the level of the individual motors.

The block diagram (Fig. 5) illustrates the control structure of a mobile wheeled robot, which consists of a dynamic and kinematic model supplemented by a feedback controller. This type of control belongs to the standard approaches used in the field of mobile robotics, where the objective is to ensure accurate tracking of the desired wheel velocities and subsequently the desired trajectory of the robot [1].

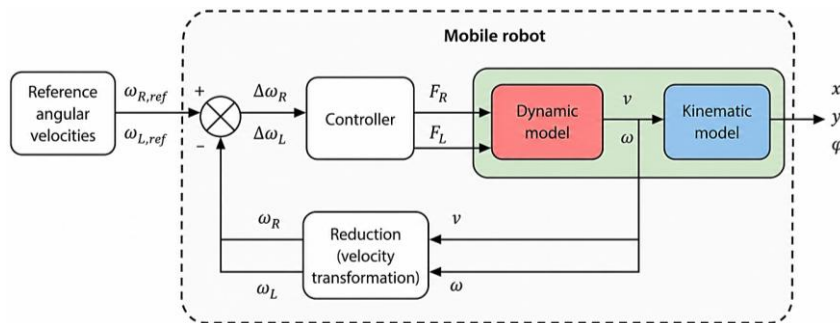


Fig. 5 Block diagram of a wheeled robot dynamic model with controller

Alt text: Block diagram of a wheeled mobile robot dynamic model with a controller, showing the processing of reference wheel angular velocities, feedback, and the dynamic and kinematic models. The model outputs the robot position and orientation (x, y, φ) .

At the input of the system, there are the reference angular velocities of the right and left wheels, $\omega_{R,ref}$ and $\omega_{L,ref}$, which define the desired motion of the robot. These quantities are compared with the actual angular velocities of the wheels, resulting in the control errors $\Delta\omega_R$ and $\Delta\omega_L$. These errors represent the inputs to the controller, whose task is to minimize the difference between the desired and actual state of the system [15].

The controller generates control actions in the form of forces F_R and F_L , which act on the individual wheels of the robot. These forces enter the dynamic model, which determines the linear velocity v and angular velocity ω of the robot based on Newton's laws of motion. The dynamic model therefore represents the transition between the force action of the motors and the resulting motion of the robot [2]. The outputs of the dynamic model are the quantities v and ω , which are subsequently processed by the kinematic model. The kinematic model calculates the position and orientation of the robot in the plane, specifically the coordinates x , y and the orientation angle φ . This model does not take forces into account but is based exclusively on the geometric relationships of the robot's motion [1].

An important part of the system is the block referred to as reduction, or velocity transformation, which provides the inverse conversion of the robot's linear and angular velocities into the angular velocities of the individual wheels, ω_R and ω_L . This block is necessary to close the control loop, as it enables feedback of the actual velocities to the controller [2]. The entire system forms a closed feedback control loop that ensures stable and accurate motion control of the robot. The advantage of such a structure is its modularity, since the dynamic and kinematic models can be designed and analyzed separately, while their combination enables a realistic description of the robot's behavior in a real environment [1, 15].

SIMULATION MODEL FOR MOTION CONTROL OF A MOBILE WHEELED ROBOT

The simulation model (Fig. 6) was created in the MATLAB/Simulink environment. It is divided into several subsystems in order to clearly separate the kinematics, dynamics, wheel control, and reduction transformation.

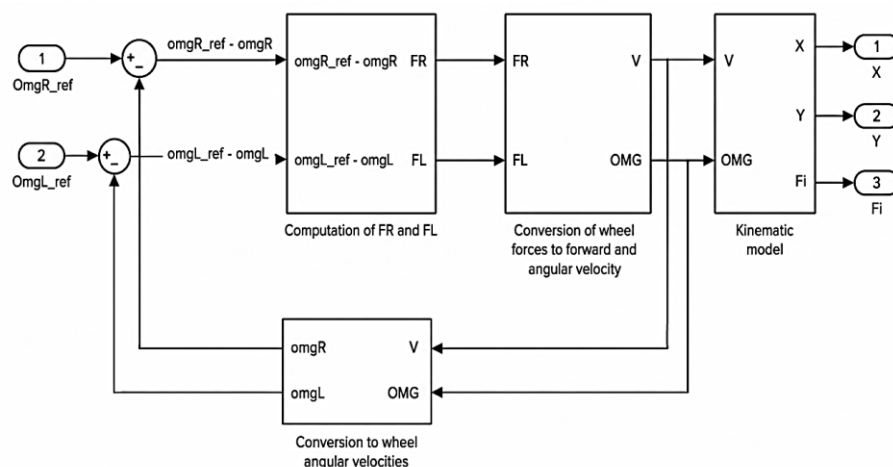


Fig. 6 Block diagram of complete simulation model of a wheeled robot

Alt text: Block diagram of the complete simulation model of a wheeled mobile robot, showing the computation of right and left wheel forces, conversion to forward and angular velocity, and the kinematic model. The feedback loop converts the robot velocities back to wheel angular velocities, while the output variables are the robot position and orientation (x , y , φ).

The kinematic subsystem calculates the position and orientation of the robot in the plane. The dynamic subsystem processes the forces generated by the motors and determines the forward and angular velocities of the robot. The wheel control subsystem compares the reference and actual angular velocities of the wheels. The reduction subsystem provides the transformation between the robot velocities and the wheel velocities.

A major advantage of the simulation model is that the control algorithm can first be verified without the risk of damaging the prototype. In the simulation, it is possible to change the initial position, the desired trajectory, the robot velocity, and the controller constants. Only after satisfactory behavior of the model is achieved should the algorithm be transferred to the real hardware. The simulation makes it possible to observe not only the robot trajectory, but also the control error, angular velocity, and the difference between the desired and actual orientation.

TRAJECTORY TRACKING ALGORITHM

The control algorithm was designed to track a predefined trajectory using the virtual vehicle method, also referred to as a virtual twin. The virtual vehicle moves along the desired path, while the real robot attempts to follow it. The control system continuously evaluates the difference between the position of the robot and the position of the virtual vehicle. The main variables include the distance between the robot and the virtual vehicle, the desired orientation angle, and the actual orientation angle of the robot. Based on the difference between these angles, the angular velocity of the robot is calculated. The desired trajectory is described parametrically as:

$$\begin{aligned}x_d &= p(s), \\y_d &= q(s),\end{aligned}$$

where:

$s(t)$ is a parameter related to the trajectory.

The objective of the control is to keep the lateral and longitudinal control errors of the robot, with respect to the desired point on the trajectory, within specified limits:

$$\lim_{t \rightarrow \infty} (|\varphi(t) - \varphi_d(t)|) \leq d_\varphi,$$

where:

d_ϕ is the maximum angular deviation of the robot with respect to the x-axis.

The control objectives are defined by the constant d_ρ . This represents the maximum allowable distance between the robot and the virtual vehicle and, according to the previously presented theory, for $t \rightarrow \infty$ the following applies:

$$\lim_{t \rightarrow \infty} \rho(t) \leq d_\rho.$$

The last input data specified at this stage are the controller constants, which are used by the control algorithm itself. In our case, a proportional control algorithm was used according to the following equation:

$$\omega = k_p(\varphi_z - \varphi),$$

where:

θ and ω are the control variables, and the difference $(\varphi_z - \varphi)$ represents the control error. The first operation in this phase is to determine the current distance between the robot and the virtual vehicle according to the following relationship:

$$\rho = \sqrt{(X - X_v)^2 + (Y - Y_v)^2}.$$

In the next step, the current value of the control variable is calculated. For a three-wheeled robot, the control variable is the angular velocity ω , whereas for a four-wheeled robot it is the angle θ , which determines the steering angle of the robot's front wheels. For a three-wheeled robot, the angular velocity is given by:

$$\omega = \frac{r}{2b} \frac{(\omega_p - \omega_l)}{2}.$$

The final operations consist of calculating the new current configurations of the robot and the virtual vehicle:

$$\begin{aligned}X(t) &= X(t-1) + v \cos[\psi(t)] \Delta t, \\Y(t) &= Y(t-1) + v \sin[\psi(t)] \Delta t, \\ \psi(t) &= \psi(t-1) + \omega(t-1) \Delta t.\end{aligned}$$

For the virtual vehicle, the new configuration is determined as follows:

$$\begin{aligned}\alpha(t-1) &= \arctg \frac{Y_v(t-1)}{X_v(t-1)}, \\ \alpha(t) &= \alpha(t-1) + \frac{v_v(t-1)}{r} \Delta t X_v = r \cos[\alpha(t)], \\ Y_v &= r \sin[\alpha(t)].\end{aligned}$$

The practical result is the control system (Fig. 7), which is able to guide the robot along the specified trajectory with a final control error approximately at the level of the permitted value.

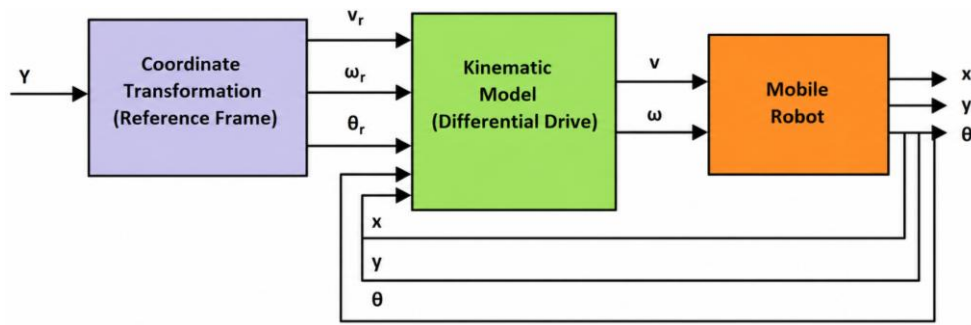


Fig. 7 Structure of the Mobile Robot Control System

Alt text: Block diagram of a mobile robot control system showing coordinate transformation, a differential-drive kinematic model, and the mobile robot block. The feedback loop uses the robot position and orientation (x, y, φ).

MOTION CONTROL ARCHITECTURE OF THE MOBILE ROBOT

The structural design of the experimental model was developed as a compact mobile platform with differential drive, consisting of two side-mounted drive wheels and one lower spherical wheel (Fig. 8). This arrangement belongs to the standard solutions used in mobile robots, as it enables simple motion control and good maneuverability [1]. The overall structure consists of a frame, an upper cover, wheels, tires, a spherical wheel holder, and additional components.

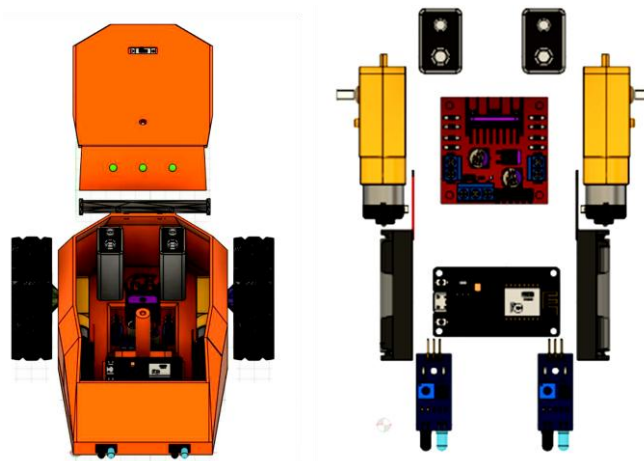


Fig. 8 3D Model of the Mobile Wheeled Robot

Alt text: 3D model of a mobile wheeled robot showing the assembled robot body with wheels and internal components, together with the main electronic and mechanical parts used in the design. The exploded view includes motors, sensors, control electronics, and the robot chassis components.

The robot frame was designed as the main load-bearing part of the structure. When designing load-bearing structures, it is important to consider not only the overall geometry of the frame but also the influence of symmetrical and asymmetrical loading, since different loading scenarios may lead to stress concentration and crack formation at critical points [19]. Its internal space was adapted to the dimensions of the electronic components, ensuring compactness and protection of sensitive elements. Openings for infrared sensors were created in the front part, openings for motor shafts were placed on the side walls, and a recessed space for the spherical wheel was designed in the lower part. The frame was manufactured using additive manufacturing technology, specifically 3D printing, from PLA material (polylactic acid). This material is frequently used in rapid prototyping due to its easy processability, sufficient strength, and biodegradability [20].

The drive wheels consist of an inner and outer disc and a flexible tire. The discs were made of PLA, while the tire was manufactured from TPU (thermoplastic polyurethane). TPU belongs to the group of elastomers with high abrasion resistance and good flexibility, which ensures better contact with the surface

and reduces wheel slip [21]. Stable contact between the wheels and the surface is essential at low speeds for accurate trajectory tracking and minimization of control errors.

The upper cover serves to protect the electronic components and also enables the mounting of control elements. It includes an opening for the main switch and openings for signal LEDs.

The selection of electronic components was carried out with regard to the functional requirements of the mobile robot, such as propulsion, control, environmental sensing, and device status indication. Two direct current (DC) motors with all-metal gearboxes were selected for wheel propulsion, providing sufficient torque and reliable operation even at low speeds. The use of a gearbox enables an increase in torque at the expense of rotational speed, which is advantageous for mobile robots operating in confined spaces [15]. An L298N H-bridge motor driver was used to control the motors. This driver enables independent control of two DC motors, including direction reversal and speed regulation using a PWM signal. This type of power driver is one of the commonly used solutions in robotics and embedded systems [19]. Two infrared sensors were implemented for obstacle detection and to increase the safety of the robot's motion. These sensors enable contactless detection of objects at short distances and are particularly suitable for simple navigation tasks and obstacle avoidance [1]. A three-position switch was used for power control, allowing the device to be turned on, turned off, and optionally switched into a service mode. The status indication of the robot is implemented using three LEDs connected in series together with a properly dimensioned resistor, which limits the current and protects the LEDs from damage. The power supply for the drive section is provided by a combination of one 9 V battery and two 1.5 V cells connected in series. A separate power supply consisting of two 1.5 V batteries is used for the control unit, which minimizes interference caused by the motor section and increases the stability of the control system.

The main control element of the robot prototype is the ESP32-WROOM microcontroller unit. This unit was selected mainly due to its integrated support for wireless communication via Wi-Fi and Bluetooth, which enables simple implementation of remote control and system monitoring. In addition, it provides sufficient computing power and a wide range of input/output interfaces for the integration of sensors and actuators [21]. One of the practically important parts of the solution is the communication between the computer and the robot control unit. In this work, communication is implemented via a Wi-Fi connection. Initially, it was necessary to connect the ESP32-WROOM to the computer via USB and configure it in the MATLAB environment. After setting the IP address, password, and port, MATLAB can send control commands to the control unit. Such a solution is suitable for experiments, as the computational part and visualization can be performed on the computer, while the robot executes commands in real space. The developed prototype confirmed (Fig. 9) that the selected concept is suitable for small indoor spaces. The robot is sufficiently compact, its production can be carried out using 3D printing, and the electronic components used are commonly available. Differential drive control enables simple maneuvering, including rotation in place.

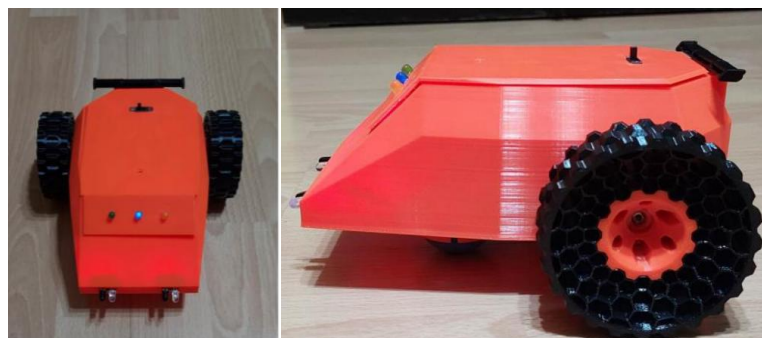


Fig. 9 Real prototype of the mobile wheeled robot

Alt text: Real prototype of a mobile wheeled robot with a 3D-printed chassis and large side wheels. They show the robot from the front-top and side views, including the body cover, wheels, front supports, and visible control elements.

The experimental prototype used in the simulation and control design was characterized by the following parameters: robot mass 0.68 kg, wheel radius 0.04 m, wheel track 0.18 m, maximum motor force 4.3 N, moment of inertia 0.0012 kg·m², and proportional controller gain 0.2. The propulsion system consists of two DC motors with metal gearboxes. The selected motors operate in the voltage range of 3–6 V, have a nominal current of approximately 100 mA, a gear ratio of 90:1, and a nominal speed of approximately 1300 rpm at 6 V. The motors are controlled by an L298N H-bridge driver using PWM signals.

CONCLUSION

In this article, the issue of motion control of mobile wheeled robots at low speeds was addressed. Attention was focused mainly on control methods, the mathematical description of motion, the development of a simulation model, and the design of an experimental prototype. The basic control concepts of mobile robots were compared, namely synchronous steering, Ackermann steering, and differential drive control. Based on their characteristics, it was shown that differential drive control represents a suitable solution, particularly for small mobile robots operating in indoor environments and requiring good maneuverability. An important part of the work was the development of the kinematic and dynamic model of the mobile robot. The kinematic model enables the motion of the robot in a plane to be described using its position, orientation, linear velocity, and angular velocity. The dynamic model extends this description by including the effects of forces, mass, and inertial properties of the system. This approach makes it possible to better understand the behavior of the robot under real operating conditions, especially at low speeds, where nonlinearities, friction, wheel slip, and control deviations become more pronounced. The proposed simulation model in the MATLAB/Simulink environment made it possible to verify the operation of individual subsystems before the actual implementation of the prototype. The model was divided into parts describing kinematics, dynamics, wheel control, and velocity transformation. Such a structure improves the clarity of the solution and allows the influence of individual blocks on the resulting motion of the robot to be analyzed separately. The trajectory tracking simulation confirmed that the proposed control algorithm is able to guide the robot along the desired trajectory with a finite control error.

The work also included the structural design and production of an experimental prototype. The robot was designed as a compact mobile platform with differential drive control, while the main mechanical parts were manufactured using 3D printing. The use of the ESP32-WROOM control unit, DC motors, a motor driver, and sensors made it possible to create a functional system suitable for practical verification of control algorithms. The advantages of the proposed solution include its simplicity, low cost, availability of components, and the possibility of use in laboratory conditions. Based on the achieved results, it can be concluded that the developed model and prototype represent a suitable basis for further research in the field of mobile robotics. In the future, the solution can be extended by more accurate control of the angular velocities of the wheels, more advanced control methods, wheel slip compensation, environmental sensing, and autonomous decision-making of the robot. A further development direction may also include the implementation of a hybrid navigation system, which is suitable for industrial mobile robots because it can improve motion reliability, obstacle avoidance, and operational safety in structured environments [22]. The proposed system therefore provides a solid basis for the further development of mobile robotic platforms intended for trajectory tracking, navigation, and testing of control algorithms under real operating conditions. For future development, the proposed mobile robot platform can be extended by obstacle avoidance, localization, and autonomous navigation algorithms. Methods such as the dynamic window approach, vector field histogram, SLAM, and Monte Carlo localization can improve the safety, reliability, and autonomy of mobile robots operating in structured or partially unknown environments [22, 23, 24, 25].

The proposed solution is primarily intended for the modeling and control of a small differential-drive mobile robot operating at low speeds in laboratory conditions. The model assumes motion on a flat

indoor surface and ideal contact between the wheels and the ground. Therefore, some real effects, such as wheel slip, lateral skidding, detailed friction characteristics, gearbox backlash, motor dead zones, and variations in battery voltage, are not explicitly included in the current model.

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