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MATHEMATICAL MODELS OF MOBILE ROBOTS IN THE DIGITAL TWIN CONCEPT: COMPARATIVE ANALYSIS AND RESEARCH OF USAGE TRENDS

Abstract: The article explores mathematical models of mobile robots in the Digital Twin concept, taking into account current trends in the development of robotic systems and Industry 5.0. **The purpose of the study** is to conduct a comprehensive qualitative, numerical, and comparative analysis of kinematic models of mobile robots and determine the patterns of their use in digital twins and scientific publications. **The object of research** is the process of functioning of mobile robots in a dynamic environment in conditions of digital representation of their behavior. The subject of research is mathematical models of motion, in particular Unicycle, Differential Drive, Bicycle, Omni-directional and Ackermann, as well as methods of their application in navigation and control systems. The scientific novelty of the work lies in the systematization of approaches to modeling the motion of mobile robots in the SE(2) state space, conducting a comprehensive comparative analysis of their characteristics, and conducting the first-ever study of trends in the use of these models based on data from the international scientometric database Scopus for 2022–2025. The results obtained showed that the Differential Drive model occupies a dominant position among the studied models, demonstrating the highest dynamics of the growth of the number of publications, which is due to its optimal combination of computational simplicity and physical adequacy to real robotic platforms, while other models have a narrower specialization or increased complexity of implementation. The analysis confirmed that the choice of a mathematical model for a digital twin is determined by a compromise between the accuracy of reproduction, the complexity of calculations and the requirements for control and navigation systems. The results obtained can be used in the development of digital twins of mobile robots, autonomous navigation systems, multi-robot systems and intelligent manufacturing platforms.
Ключові слова: Digital Twin, mobile robots, kinematic models, Differential Drive, Unicycle model, Bicycle model, Omni-directional model, Ackermann model, SE(2), Scopus analysis, Industry 5.0

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МАТЕМАТИЧНІ МОДЕЛІ МОБІЛЬНИХ РОБОТІВ У КОНЦЕПЦІЇ ЦИФРОВОГО ДВОЙНИКА: ПОРІВНЯЛЬНИЙ АНАЛІЗ ТА ДОСЛІДЖЕННЯ ТЕНДЕНЦІЙ ВИКОРИСТАННЯ
Анотація: У статті досліджуються математичні моделі мобільних роботів у концепції цифрового двійника з урахуванням сучасних тенденцій розвитку робототехнічних систем та Індустрії 5.0. Метою дослідження є проведення комплексного якісного, числового та порівняльного аналізу кінематичних моделей мобільних роботів та визначення закономірностей їх використання в цифрових двійниках та наукових публікаціях. Об'єктом дослідження є процес функціонування мобільних роботів у динамічному середовищі в умовах цифрового представлення їхньої поведінки. Предметом дослідження є математичні моделі руху, зокрема одноколісної, диференціальної, велосипедної, всенаправленої та Аккермана, а також методи їх застосування в системах навігації та управління. Наукова новизна роботи полягає в систематизації підходів до моделювання руху мобільних роботів у просторі станів SE(2), проведенні комплексного порівняльного аналізу їх характеристик та проведенні першого в історії дослідження тенденцій використання цих моделей на основі даних міжнародної наукометричної бази даних Scopus за 2022–2025 роки. Отримані результати показали, що модель Differential Drive займає домінуюче положення серед досліджуваних моделей, демонструючи найвищу динаміку зростання кількості публікацій, що зумовлено її оптимальним поєднанням обчислювальної простоти та фізичної адекватності реальним роботизованим платформам, тоді як інші моделі мають вужчу спеціалізацію або підвищену складність реалізації. Аналіз підтвердив, що вибір математичної моделі для цифрового двійника визначається компромісом між точністю відтворення, складністю розрахунків та вимогами до систем керування та навігації. Отримані результати можуть бути використані при розробці цифрових двійників мобільних роботів, автономних навігаційних систем, багатороботних систем та інтелектуальних виробничих платформ.
Ключові слова: цифровий двійник, мобільні роботи, кінематичні моделі, диференціальний привід, модель одноколісного велосипеда, модель велосипеда, всенаправлена модель, модель Аккермана, SE(2), аналіз Scopus, Індустрія 5.0

Introduction.

In the current conditions of development of intelligent production systems and the concept of Industry 5.0, the use of digital twin technology for modeling, monitoring and optimization of mobile robotic systems is of particular relevance [1,2]. The use of digital twins allows creating virtual models of robots that reproduce their behavior in a real environment and provide the opportunity to study control algorithms, navigation and interaction with a dynamic environment without conducting complex full-scale experiments [3,4]. The basis for building such systems are mathematical models of mobile robots, in particular kinematic models of the Unicycle [5], Differential Drive [6], Bicycle [7], Omni-directional [8] and Ackermann [9] types, which determine the structure of movement, control parameters and accuracy of digital representation of a physical object. At the same time, there is a significant increase in the number of studies devoted to the use of these models in the tasks of creating digital twins, autonomous navigation and collaborative robotics [10-12]. However, the issue of comparative analysis of the advantages and limitations of these mathematical models, as well as the study of trends in their use in modern scientific publications, remains insufficiently systematized. In this regard, it is relevant to conduct a comprehensive analysis of mathematical models of mobile robots in Digital Twin systems and study the dynamics of their use in scientific publications in recent years.

Recent research and publications analysis.

The analysis of the above publications shows that modern research in the field of mobile robotics is focused mainly on reviews of kinematic structures, approaches to trajectory planning, generalization of motion models and comparison of specialized chassis architectures. At the same time, it is important not only to describe existing approaches, but also to assess their suitability for building digital twins and comparative analysis of trends in the use of models. That is why the above sources should be considered as a scientific basis that confirms the relevance of the chosen direction. In the article Tagliavini Luigi and Colucci Giuseppe, et al., a review of the current state of wheeled mobile robots is proposed and a kinematic comparison of three omnidirectional movement strategies is performed, which makes it possible to assess the constructive and kinematic advantages of various omnidirectional platforms [13]. This approach cannot be directly used within the framework of the study of digital twins of basic motion models, since it focuses only on a narrow class of omni-directional systems and does not cover the comparison of Unicycle, Differential Drive, Bicycle and Ackermann in a single analytical framework.

In the work of Sarcinelli-Filho Marcos and Carelli Ricardo, a generalized consideration of kinematic models of ground and air robots is proposed, which makes it possible to form a theoretical basis for describing the motion of robotic systems [14]. Such an approach cannot be used as a complete solution, since it is mainly of an educational and theoretical nature and does not contain a comparative analysis of the trends in the application of models in the Digital Twin concept.

In the study of Poduval Divya R. and Rajalakshmy P., a review of autonomous mobile robots with a focus on the general principles of navigation, sensors and autonomy is proposed, which makes it possible to determine the place of mobile platforms in modern intelligent systems [15]. This solution cannot be directly used, since it does not perform a deep analysis of mathematical kinematic models in the SE(2) state space and their suitability for building digital twins.

In the article by Alexa Ovidiu and Ciobotaru Tudor, et al., a thorough review of mathematical models for evaluating the kinematics and dynamics of wheeled and tracked unmanned ground platforms is proposed, which makes it possible to trace the evolution of methods for describing the motion of real robots [16]. Such an approach cannot be directly used as the basis of this study, since it is focused on a much wider class of platforms, including tracked ones, and does not form a specialized comparison of the basic kinematic models of mobile robots in the context of Digital Twin.

In the paper by Pantoja-García José S. and Rodríguez-Molina Arturo, et al., a generalized kinematic model for heterogeneous architectures of wheeled mobile robots is proposed, which makes it possible to unify the description of different types of chassis within a single formalism [17]. The proposed approach cannot be used as a complete alternative, since its main emphasis is on mathematical unification, and not on qualitative, numerical and bibliometric comparison of specific models in the practice of digital twins.

In the study by Simerean Andreea C. and Tătar Marius O., a systematic review of tetrahedral mobile robots is proposed, which makes it possible to assess the prospects of non-traditional configurations of mobile platforms [18]. This solution cannot be used, since the study is devoted to highly specialized robot morphology and does not allow for a universal comparative analysis of classical kinematic models, which are most often used in Digital Twin.

In the article Kadar Ferenc and Tătar Marius O. a review of mobile robots with reconfigurable whegs-wheel modules is proposed, which makes it possible to analyze hybrid approaches to locomotion in complex conditions of movement [19]. This approach cannot be directly applied within the framework of the presented study, since it concerns specialized mechanisms of movement and does not provide a comparison of the basic models Unicycle, Differential Drive, Bicycle, Omni-directional and Ackermann according to the criteria of a digital twin.

In the paper Badamasi Muhammad A. and Kabir Isah K., and others a review of classical and heuristic methods of trajectory planning of autonomous mobile robots is investigated, which makes it possible to systematize algorithms for building routes in complex environments [20]. Such a method cannot be used, since it describes mainly planning algorithms, and not mathematical kinematic models of movement, which are the primary basis for the formation of a digital twin of a mobile platform.

In the study by Xia Tao and Li Dong, et al., a review of trajectory planning methods for many mobile robots is proposed, which makes it possible to evaluate the features of coordination, conflict avoidance and collective movement in multi-robot systems [21]. This approach cannot be directly used for the purposes of this study, since it focuses on the problem of multi-robot planning, and not on the fundamental comparison of kinematic models that determine the structure of the digital twin of a single mobile platform.

In the paper by Zhang Zhuo and Wang Zexing, and Zhang Xuping, a kinematic analysis and comparative evaluation of a new four-wheeled omnidirectional mobile robot with redundant drive and trajectory tracking confirmation is proposed, which makes it possible to evaluate the advantages of the new design in terms of controllability and movement accuracy [22]. The proposed solution cannot be used as a universal basis, since it is dedicated to a separate new platform and does not solve the problem of a broad comparative analysis of basic mathematical models of mobile robots and trends in their use in the international scientific space.

In general, it can be stated that all the publications considered form an important scientific foundation for the study of mobile robotics, but each of them highlights only a separate aspect of the problem: specialized chassis types, generalized kinematic formalisms, navigation reviews or planning algorithms. That is why the need for a comprehensive study that combines qualitative, numerical and comparative analysis of basic mathematical models of mobile robots with the study of trends in their use in the Digital Twin concept remains relevant, which justifies the necessity and scientific timeliness of the research performed in the manuscript.

The purpose of the research is to conduct a comprehensive qualitative, numerical and comparative analysis of kinematic models of mobile robots and determine the patterns of their use in digital twins and scientific publications..

Main material presentation.

In the problems of mobile platforms numerical modeling and their digital twins construction, various models of state space representation are used, which differ in the level of detail, consideration of physical effects and type of motion description. The most basic is the configuration space Special Euclidean Group in 2D (SE(2)) [23], where the state is given by the coordinates of position and orientation, which is suitable for kinematic models such as Unicycle or Differential Drive and is widely used in trajectory planning problems. An extension of this approach is the phase space of states, in which velocities and sometimes accelerations are added to the coordinates, which allows taking into account the dynamics of the system and using optimal control methods such as Model Predictive Control (MPC) or Linear Quadratic Regulator (LQR) [24,25]. To more accurately reflect real conditions, dynamic state models are used, including forces, moments, mass-inertial parameters and interaction with the environment, which is especially important for high-speed or loaded platforms. In navigation tasks in complex environments, an extended state with sensory variables is also used, which includes estimates of the position of obstacles, sensor states, or uncertainty parameters, which is typical for Simultaneous Localization and Mapping (SLAM) [26] and systems using Extended Kalman Filter (EKF) [27] or Unscented Kalman Filter (UKF). In addition, stochastic and probabilistic representations of the state space are used in modern research, where the state is described not by point values, but by probability distributions, which allows taking into account measurement noise and environmental uncertainty [29,30]. Thus, the choice of a state space model is determined by the balance between computational complexity and the required accuracy of the digital twin, as well as the specifics of the tasks of control, navigation, and interaction of a mobile robot with a dynamic environment.

The state space SE(2) in numerical modeling tasks of digital twins of mobile robots defines the complete configuration of the platform on the plane as a combination of its position and orientation and is given by the state vector $q = [x, y, \theta]^T$, where (x, y) - Cartesian coordinates, and θ - angle of rotation relative to the global coordinate system [31]. From a mathematical point of view, this is a group of rigid motions that combines translations and rotations, and it is this structure that allows us to adequately reflect the kinematics of mobile platform motion in a digital twin.

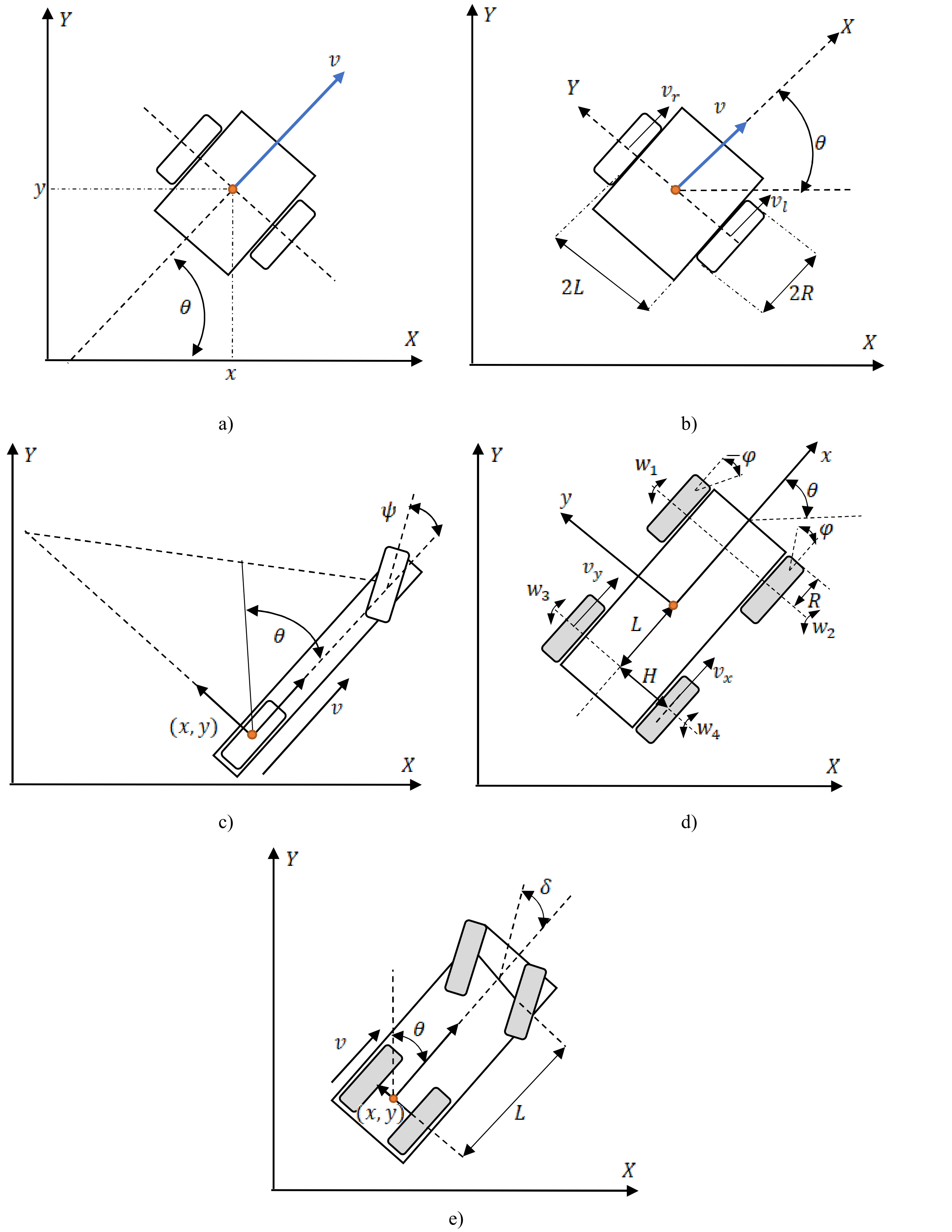
Table 1 shows a comparison of the basic mathematical equations of kinematics for mobile robot models that are most often used in constructing digital twins in the SE(2) state space.

Table 1- Comparison of the basic mathematical equations of kinematics for mobile robot models that are most often used in constructing digital twins in the SE(2) state space.

Model	State vector	Control input	Mathematical equations	Model feature
1	2	3	4	5
Unicycle model [5,32]	$q = [x, y, \theta]^T$	$u = [v, w]^T$	$\dot{x} = v\cos\theta$ $\dot{y} = v\sin\theta$ $\dot{\theta} = w$	The simplest kinematic model describing the motion of a robot as a material point with orientation
Differential Drive model [6, 33]	$q = [x, y, \theta]^T$	$u = [v_l, v_r]^T$	$\dot{x} = \frac{R}{2}(v_r + v_l)\cos\theta$ $\dot{y} = \frac{R}{2}(v_r + v_l)\sin\theta$ $\dot{\theta} = \frac{R}{L}(v_r - v_l)$	Takes into account separate speeds of left and right wheels; corresponds well to real two-wheeled platforms
Bicycle model [7,34]	$q = [x, y, \theta]^T$	$u = [v, \delta]^T$	$\dot{x} = v\cos\theta$ $\dot{y} = v\sin\theta$ $\dot{\theta} = \frac{v}{L}\tan\delta$	Simplifies a four-wheel platform to a single front steered wheel
Omni-directional model [8, 35]	$q = [x, y, \theta]^T$	$u = [v_x, v_y, w]^T$	$\dot{x} = v_x\cos\theta - v_y\sin\theta$ $\dot{y} = v_x\sin\theta + v_y\cos\theta$ $\dot{\theta} = w$	Allows movement in any direction without necessarily changing orientation
Ackermann model [9, 36]	$q = [x, y, \theta]^T$	$u = [v, \delta]^T$	$\dot{x} = v\cos\theta$ $\dot{y} = v\sin\theta$ $\dot{\theta} = \frac{v}{L}\tan\delta$	Geometrically closer to the automotive platform, where steering is taken into account

* where: x, y - robot coordinates in the global system; θ - robot orientation angle; v - linear velocity; w - angular velocity; v_l, v_r - left and right wheel velocity; r - wheel radius; L - robot base or distance between wheels/axles; δ - steering wheel angle; v_x, v_y - velocity components in the local robot system.

Figure 1 shows kinematic diagrams of mobile platforms with different types of control models in the state space SE(2).



a) Unicycle model [5,32]; b) Differential Drive model [6,33]; c) Bicycle model [7,34];
d) Omni-directional model [8,35]; e) Ackermann model [9,36]
Figure 1 - Kinematic diagrams of mobile platforms with different types of control models in the SE(2) state space

As can be seen from Fig. 1a, the kinematic scheme of the Unicycle model in the SE(2) state space is presented, where the platform state is given by the minimal vector $q = [x, y, \theta]^T$, and the control is determined by the linear velocity v

and angular velocity w (Table 1). Qualitatively, this model is the most generalized and compact, since it describes the robot motion as the movement of a material point with an orientation without explicit consideration of the chassis design. This makes it convenient for forming a digital twin at the early stages of modeling. Numerically, its advantage lies in the minimal dimensionality of the state space and simple equations: $\dot{x} = vcos\theta$; $\dot{y} = vsin\theta$; $\dot{\theta} = w$, due to which the trajectory integration is stable, fast and low-cost in terms of computational resources. In a comparative aspect, this model is inferior to others in terms of physical detail, but surpasses them in terms of simplicity of implementation, versatility and ease of use in algorithms for planning movement, localization and basic prediction of the state of a digital twin. According to Fig. 1b, the Differential Drive model is shown, in which the same state space SE(2) is supplemented with physically meaningful control variables v_l and v_r, corresponding to the speeds of the left and right wheels. Qualitatively, such a scheme better reflects the real structure of two-wheeled mobile platforms, since the rotation and translational motion arise as a consequence of the difference or equality of the speeds of the wheels, which provides a direct connection between the chassis geometry and the behavior of the robot. Numerically, this model is described by the equations: $\dot{x} = \frac{R}{2}(v_r + v_l)cos\theta$; $\dot{y} = \frac{R}{2}(v_r + v_l)sin\theta$; $\dot{\theta} = \frac{R}{L}(v_r - v_l)$, where parameters r and L allow us to quantitatively assess the influence of wheel radius and base on maneuverability: with increasing difference $v_r - v_l$ the angular velocity increases, and with increasing L the turn becomes more inertial. Compared to the Unicycle model, this scheme is more accurate for digital twins of two-wheeled platforms, although somewhat more complex, but it provides a better balance between mathematical simplicity, physical interpretability and suitability for practical implementation. Fig. 1c shows the kinematic scheme of the Bicycle model, in which a four-wheeled or automobile platform is reduced to a simplified equivalent system with one front steered wheel and a base L. Qualitatively, this model well reflects the transport nature of traffic, when the orientation changes not due to independent wheel drive, but due to the steering wheel rotation angle ψ or δ, which provides smoother and geometrically more plausible trajectories. Numerically, its dynamics are given by the relations: $\dot{x} = vcos\theta$, $\dot{y} = vsin\theta$, $\dot{\theta} = \frac{v}{L}tan\delta$, from which it can be seen that at constant v increasing the steering angle causes a nonlinear increase in angular velocity, and increasing the base L reduces the sensitivity of the platform to rotation. In comparison, this model is more physically correct for ground transport robots than Unicycle, but less universal for platforms with independent drive, and its main advantage for a digital twin is an adequate reproduction of the geometry of the turn and the radius of curvature of the trajectory. Fig. 1d shows an Omni-directional model, in which motion in SE(2) space is implemented through independent velocity components v_x, v_y and angular velocity w, and the kinematics takes into account the features of a multi-wheeled omnidirectional chassis. Qualitatively, this scheme is the most maneuverable among all considered, since it allows the platform to move along two axes of the plane without the mandatory coordination of the direction of velocity with the current orientation of the body, which is especially important for mobile manipulators, logistics robots and collaborative systems in narrow working areas. Numerically, such a model is given by the equations: $\dot{x} = v_x cos\theta - v_y sin\theta$; $\dot{y} = v_x sin\theta + v_y cos\theta$; $\dot{\theta} = w$, This means that the platform has three independent levels of control in the plane, i.e. its kinematics matrix is more complete than the Unicycle, Differential Drive and Bicycle models, where the direction of translational motion is rigidly connected to the longitudinal axis of the body. In a comparative aspect, this model provides the highest functional flexibility of the digital twin, but requires more complex control, more accurate calibration and consideration of slip, so in terms of computational simplicity it is inferior to more classical kinematic schemes. According to Fig. 1e, the Ackermann model is depicted, which is a development of automotive kinematics taking into account the steering of the front axle and the geometric limitations of the chassis. Qualitatively, this scheme most adequately describes real automotive, Automated Guided Vehicle (AGV) and service transport platforms [37], which are characterized by limited lateral movement, smooth turning and the presence of a pronounced dependence between the steering angle, the base L and the radius of turn. Numerically, its model in the SE(2) state space has the same structure as the Bicycle model, i.e.: $\dot{x} = vcos\theta$; $\dot{y} = vsin\theta$l $\dot{\theta} = \frac{v}{L}tan\delta$ but the interpretation of the parameters is more physically accurate, since it is directly related to the geometry of the steering mechanism and the angle of deflection of the steered wheels. Compared to the Bicycle model, this scheme is more engineeringly justified for transport platforms, compared to the Differential Drive, it is less maneuverable in a limited space, and compared to the Omni-directional model, it is significantly inferior in freedom of movement, but surpasses most models in the realism of reproducing the automobile mode of movement in a digital twin.

Thus, the combined qualitative, numerical and comparative analysis of kinematic schemes in the SE(2) state space shows that the Unicycle model is the simplest and most convenient for basic numerical modeling, the Differential Drive provides the best fit for two-wheeled mobile platforms, the Bicycle and Ackermann are appropriate for transport robots with steering, and the Omni-directional model provides maximum maneuverability and functional flexibility. From the point of view of building digital twins, the choice of a particular model is determined by a compromise between the accuracy of physical reproduction, computational complexity, chassis structure and requirements for control and navigation algorithms in a dynamic environment. The advantages and disadvantages of motion models are presented in Table 2

Table 2 – Advantages and disadvantages of movement models

Movement model	Brief description	Advantages	Disadvantages
1	2	3	4
Unicycle model	Kinematic model of a unicycle robot with control via linear velocity v and angular velocity ω.	Very simple mathematical structure; convenient for analytical modeling and trajectory planning algorithms (A*, D*, MPC); well suited for numerical modeling and testing of navigation algorithms.	Does not account for the real design of robots with two or more wheels; ignores dynamics and slippage; digital twin accuracy is limited for real platforms.
Differential Drive model	Robot model with two independent drive wheels (left and right velocity v_l, v_r)	Describes mobile platforms more realistically; simple control implementation; integrates well with sensor models (LiDAR, cameras, IMU); widely used in ROS and autonomous navigation systems	Limited maneuverability (no lateral movement); accumulation of odometry errors; more difficult to model wheel slip and surface irregularities.
Bicycle model	A simplified car-type model where the front wheels are combined into one steered wheel.	Describes transport platforms and autonomous carts well; allows for turning radius; suitable for trajectory prediction and MPC control.	Less accurate for robots with independent wheels; ignores complex chassis kinematics; requires additional parameters for accurate modeling.
Omni-directional model	Robot model with omni- or mecanum wheels that allow movement in any direction.	Full maneuverability (3 DOF in a plane); ability to move without changing orientation; high positioning accuracy in narrow spaces; useful for warehouse or collaborative Industry 5.0 robots.	More complex kinematic equations; sensitivity to slip; complexity of hardware implementation and control; requires more complex control algorithms
Ackermann model	Kinematic model of automotive control with Ackerman geometry.	Realistically describes automotive and AGV platforms; provides physically correct turning geometry; suitable for simulations of autonomous transportation systems.	Limited maneuverability in tight spaces; more difficult to plan trajectories in dense environments; not suitable for robots with independent wheel drive.

The analysis of the basic mathematical models of the movement of mobile collaborative robots shows that each of the considered models has its own area of expedient application depending on the level of detail of the digital twin and the requirements for control and navigation systems. Simplified models of the Unicycle type provide high computational efficiency and ease of integration into planning algorithms, while Differential Drive allows you to more accurately reproduce the kinematics of real two-wheeled platforms. The Bicycle and Ackermann models are more adequate for transport robots with steering, providing a physically correct representation of movement trajectories, while Omni-directional models provide maximum maneuverability and flexibility in dynamic environments. Thus, the choice of a model for building a digital twin is determined by a compromise between accuracy, computational complexity and requirements for the functionality of the robotic system. To further summarize the results obtained, it is advisable to consider Table 3 – Comparison of the effectiveness of basic kinematic models of mobile robots according to key criteria used in the development of digital twins of collaborative robots and motion planning systems.

Table 3. – Comparison of the effectiveness of basic kinematic models of mobile robots according to key criteria used in the development of digital twins of collaborative robots and motion planning systems.

Model	Maneuverability	Computational complexity	Digital twin accuracy	Suitability for trajectory planning algorithms	Typical areas of application
1	2	3	4	5	6
Unicycle model	Medium	Very low	Low (simplified abstraction)	Very high – convenient for A*, D*, MPC, RL	Theoretical research, testing of navigation algorithms
Differential Drive model	Medium	Low	High for two-wheeled platforms	High – integrates well with SLAM and	Service robots, warehouse AGVs, mobile collaborative robots

				ROS	
Bicycle model	Medium	Low	Medium	Average – used in motion prediction tasks	Autonomous transport platforms, robotic carts
Omni-directional model	Very high	Medium	High for omni/mecanum platforms	High – convenient for local planning	Warehouse work, mobile manipulators, HRC systems
Ackermann model	Low–medium	Medium	High for automotive platforms	Medium – more difficult in narrow environments	Autonomous vehicles, AGV transport platforms

To study the trends in the use of the models considered above, presented in Table 1 and Figure 1, it is proposed to analyze publications in the international metric database Scopus for the period from 2022 to 2025 [38]. An example of queries for the keyword “Unicycle model” is given below.:

TITLE-ABS-KEY("Unicycle model") AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English"))

TITLE-ABS-KEY("Unicycle model") AND TITLE-ABS-KEY("control" OR "trajectory planning" OR "navigation") AND PUBYEAR > 2021 AND PUBYEAR < 2026 AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English")) (1)

As a result of the research in the international metric database Scopus on "keywords" such as: Unicycle model, Differential Drive model, Bicycle model, Omni-directional model, Ackermann model according to the following forms of search queries presented in 1, total references to 1849 manuscripts of articles in English were obtained. The results of the analysis of publications in the international metric database Scopus for the period from 2022-2025 by "keywords" are presented in Table 4.

Table 4 - Results of the analysis of publications in the international metric database Scopus for the period from 2022-2025 by "keywords"

Model	Year				Total
	2022	2023	2024	2025	
1	2	3	4	5	6
Unicycle model	14	16	23	21	75
Differential Drive model	211	239	320	682	1452
Bicycle model	70	58	89	91	308
Omni-directional model	1	2	5	2	10
Ackermann model	-	-	2	2	4

The results obtained (Table 4) indicate a significant uneven distribution of scientific publications between different kinematic models of mobile robots. The most intensive growth is demonstrated by the Differential Drive model, the number of publications for which increases sharply in 2025, which indicates its dominant role in modern research on mobile robotics and digital twins. The Bicycle model is characterized by moderate stable dynamics with minor fluctuations, which indicates its application in specialized tasks, in particular autonomous transport. The Unicycle model demonstrates a gradual increase in interest, which is associated with its use as a basic mathematical model in theoretical research. At the same time, the Omni-directional and Ackermann models have a low level of representation, which may be due to their narrower applied specialization or the complexity of implementation in practical systems. For the convenience of analyzing the data obtained from Table 4, let us present them in the form of a graph “Publications by Robot Motion Models (2022-2025)” which is presented in Figure 2.

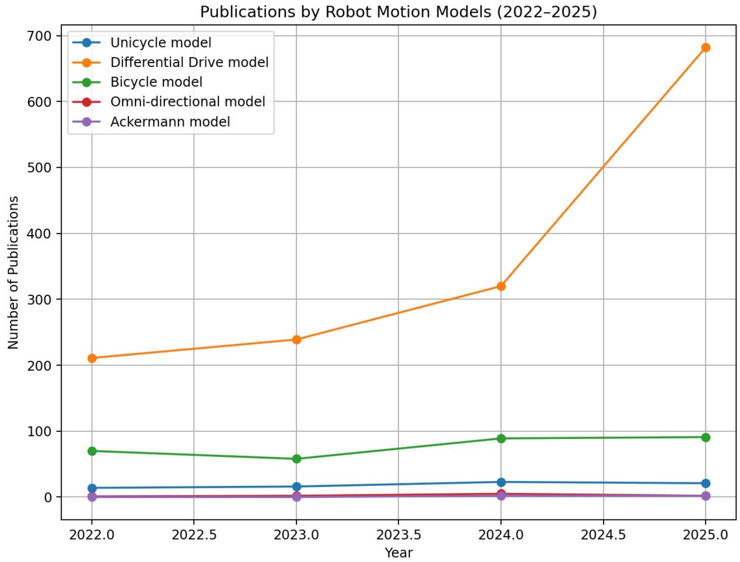


Figure 2. – Publications by Robot Motion Models (2022-2025)

The results obtained (Table 4 and Fig. 2) demonstrate that the number of publications for the Differential Drive model (1452 works) significantly exceeds other models, in particular by more than 4.7 times compared to the Bicycle model (308) and by almost 19 times compared to the Unicycle model (75), which indicates its dominant position in the scientific space. This trend is explained by the fact that the Differential Drive provides an optimal balance between computational simplicity (low complexity, as in the Unicycle) and physical adequacy to real two-wheeled platforms, which is critically important for building digital twins in navigation, SLAM and collaborative control tasks. Qualitatively, this model is the most universal for real service and warehouse robots (AGV), which are widely used in Industry 5.0, while the Omni-directional and Ackermann models have a limited scope or increased implementation complexity. The sharp increase in numbers in 2025 (from 320 to 682 publications, i.e. more than 2 times) reflects the active implementation of ROS-oriented systems, multi-robot platforms and digital twins, where Differential Drive is the de facto standard. In a comparative aspect, it is the combination of ease of integration, availability of hardware implementation and high correspondence to physical systems that determines its significantly higher usage rates compared to other kinematic models.

Conclusions.

As a result of the study, it was found that mathematical models of mobile robots in the Digital Twin concept form the basis for adequate reproduction of kinematics, dynamics and interaction of robotic systems in a digital environment, ensuring a balance between modeling accuracy and computational efficiency. The qualitative and comparative analysis showed that simplified models of the Unicycle type are effective for theoretical research and planning algorithms, while Differential Drive provides the most optimal combination of physical reliability and practical feasibility for two-wheeled platforms. Numerical analysis of publications in the Scopus database confirmed the dominance of the Differential Drive model, which reflects its key role in modern tasks of autonomous navigation, SLAM and collaborative control of mobile robots. At the same time, the Bicycle and Ackermann models demonstrate the feasibility of application in transport systems, while Omni-directional models provide increased maneuverability in complex dynamic environments, but require more complex control algorithms. The results obtained indicate that the choice of a mathematical model for a digital twin is determined by a compromise between the level of detail, the type of platform, and the requirements for control and navigation algorithms. Thus, the results of the study can be effectively used in the design of digital twins of mobile robots, the development of autonomous navigation systems, multi-robot systems, as well as in the optimization of logistics processes and intelligent production within the framework of the Industry 5.0 concept.

Conflict of interest

The authors declare that they have no conflict of interest, in particular financial, personal, authorial or any other nature, which could affect the research, as well as the results published in this article.

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