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CONTROL SYNTHESIS FOR 4WS VEHICLE-ROBOT MODEL FOR TRAFFIC PROGRAM MOTION

Об'єктом дослідження є автономний колісний мобільний робот моделі 4WS (Four Wheel Steering). Необхідність в таких дослідженнях продиктована обмеженнями застосування роботів моделі 2WS (Two Wheel Steering) для вирішення завдання досягнення множинних цілей, пов'язаних з недостатньою їх маневреністю і безпекою руху. Це і є одним із найпроблемніших місць даної моделі.

Таке завдання було успішно вирішено для досягнення одиночної цілі цією моделлю, включаючи рух реверсом для зчленованого екіпажу, проте характер траєкторії з множинними цілями робить таке завдання практично нерозв'язним. Для її вирішення успішно застосована конструкція автономного мобільного робота DDMR моделі. Переваги ж 4WS моделі в порівнянні з 2WS в сенсі підвищення маневреності привели до дослідження можливості її використання для вирішення цього завдання.

У цьому дослідженні реалізована можливість синтезу керованого руху автономного мобільного робота моделі 4WS по програмній траєкторії, що задається в явному, неявному, параметричної вигляді або законом зміни її кривизни. При цьому кут повороту передніх коліс є функцією кривизни програмної траєкторії, а задніх – функцією кута повороту передніх. Особливістю синтезованого управління для 4WS моделі є зв'язок з управлінням для моделі 2WS. Управління для цієї моделі синтезується спочатку і являє собою самостійну цінність. Таке управління є еталонним: за емпіричною залежністю визначається віртуальний радіус, для якого обчислюється таке управління для 4WS моделі, щоб вона рухалася по траєкторії моделі 2WS. Поворот задніх коліс (синфазно з передніми або в протифазі) розглядається при цьому у вигляді додаткового управління.

Важливою особливістю дослідження є розробка програмного забезпечення, яке дозволило виконати чисельне моделювання синтезованого управління в математичному пакеті Maple і наочну візуалізацію маневрів руху в системі Unity 3D.

Результати чисельного моделювання та їх візуалізація дозволяють зробити висновок про можливість застосування синтезованого закону для управління автономними мобільними роботами, що створюються за 4WS моделлю.

Ключові слова: *автономний мобільний колісний робот, 4WS, 2WS, умова Акермана, закон управління, мехатрона система, кут бокового ковзання, кут нишпорення.*

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1. Introduction

Autonomous mobile wheeled robots are becoming more advanced mechatronic systems that use electronic control systems and algorithms to improve their maneuverability. One of the areas of work in this area is the use of rear wheels as steering, along with front wheels, as well [1, 2]. Such development is directly related to safety issues [3, 4], since the increase in speed and, especially, the performance of maneuvers is an obvious development trend in modern robotics. In this regard, designers and developers face new challenges in finding ways to modernize such systems aimed at improving manageability and stability [5].

This study is a further development of work related to the possibility of the movement of robotic wheel systems along programmed trajectories [6–8]. And also, including articulated crews [9]. However, in these works, 2WS (Two-Wheel Steering) models were considered, but in connection with some practical tasks, it became necessary to design a wheeled autonomous robot of increased maneuverability, using the advantages that the 4WS (Four-Wheel Steering) model has for this.

The use of such a model is relevant from the point of view of the possibility of its increased maneuverability and traffic safety, which allows solving problems inaccessible to the 2WS model: movement in confined circumstances, in a narrow corridor, avoiding obstacles.

2. The object of research and its technological audit

The object of research is a 4WS autonomous wheeled mobile robot. Let's consider a flat bicycle model of its movement according to the kinematic scheme shown in Fig. 1.

In Fig. 1: δ_o and δ_i – the angles of rotation of the outer and inner wheels, determined taking into account the position of the instantaneous center of speed O, C is the position of the center of mass, l – the wheelbase, w – the track gauge.

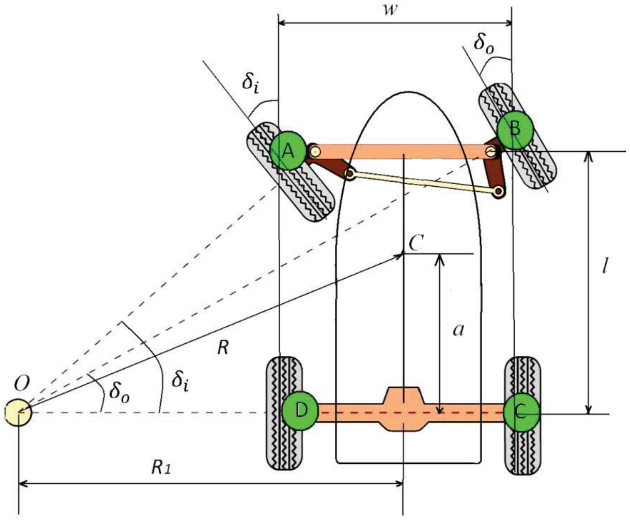


Fig. 1. Kinematic diagram of a four-wheeled vehicle [7]

A feature of this object of research is the possibility of being used as steered, along with front, also rear wheels. Accordingly, there is a need to synthesize quality control for such a system in order to maximize the use of its advantages in maneuverability and stability of movement compared to models in which only the front wheels are controllable.

The subject of research is mathematical models of the kinematics of the controlled movement of autonomous mobile wheeled robots with all-wheel control with the possibility of synthesizing a control law for them to move along programmed paths.

3. The aim and objectives of research

The aim of research is synthesizing control for realizing the movement of an autonomous 4WS mobile robot along a programmed (analytically defined) path based on the developed law for the 2WS model, considering it as a special case of the model under study.

To achieve this aim it is necessary to perform the following objectives:

1. Develop a mathematical model for the 4WS model, expanding the 2WS model with additional control for the rear wheels.
2. Perform a qualitative analysis of this model to obtain an empirical control law for this model based on a model with two steering wheels.
3. Check the correctness of the model by means of numerical modeling and perform software visualization of the movements of this model in all possible modes.

4. Research of existing solutions of the problem

Since cars with all-wheel control demonstrate superiority over their basic counterparts both in maneuvers at low speeds and in behavior when driving at high speeds, they solve the problems of control synthesis using various approaches and methods. Among such methods, one should single out a robust control method [10, 11]. The results of numerical simulation show that the developed reliable μ-synthesis controller can only improve some of the performance characteristics of a closed-loop 4WS vehicle. The adaptive control method [12, 13] shows a slight improvement in the controllability and stability of the vehicle of this model, thanks to the control of the input-output signal isolation. In [14, 15], fuzzy logic methods are proposed, however, the developed controller solves only some aspects of the vehicle sideways stability. The optimal control method [16, 17] demonstrates a smaller deviation from the transient response of the proposed steering controller, and the stability time is shorter, which improves the steering wheel of the vehicle. However, the task of moving along the programmed path is not considered in these solutions.

Traditional approaches are also used: the Lyapunov function method and the back-stepping method based on them, as well as the proportional control system [18]. The simulation results presented in this work and road test data show that the system with independent rear-wheel control studied here has better kinematic harmony and responsiveness than a conventional 4WS. Studies of such a model may be the subject of subsequent work.

Some control laws are synthesized according to the results of numerous computational experiments: in [19], the law is formulated for changing the position of the steering pole from the value of the reference angle for the vehicles. In this work, the control is synthesized for multi-axle vehicles, and its applicability to the 4WS model requires special research. The very same approach in the form of computational experiments is used in the present study. An approach seems to be interesting using a genetic algorithm based on a linear quadratic governor with variable parameters for independent four-wheel steering [20]. However, the practical implementation of this algorithm and experimental verification are not mentioned.

An analysis of these approaches led to the conclusion that they are difficult to implement and require rather cumbersome calculations. At the same time, they are intended to improve individual characteristics of all-wheel control without solving the task of following the programmed path.

5. Methods of research

In this study, to solve this problem it is possible to use an exclusively analytical approach using the Ackerman kinematic condition and methods of the dynamics of solids, the mathematical apparatus of the theory of stability and control. And symbolic transformations, numerical methods and heuristic search algorithms are also used.

6. Research results

6.1. Control synthesis for 2WS Model. First, let's solve the problem of kinematic motion control of a four-wheeled vehicle made according to the 2WS model.

For this model, the Ackerman condition, which allows the wheels to rotate without slipping, has the form:

$$\cot(\delta_o)-\cot(\delta_i)=\frac{w}{l}, \qquad (1)$$

where δ_o and δ_i – the angle of rotations of the outer and inner wheels, determined taking into account the position of the instantaneous center of speeds; l – the rotation wheelbase; w – the gauge.

The center of mass of the controlled robot moves along a circle of radius R (with curvature $\rho = 1/R$). Let's note that in the general case, the program trajectory can be defined by an explicit/implicit function, parametrically, by the radius of curvature, piecewise-continuous function, etc. The curvature of the trajectory is determined by the known formulas of differential geometry, the radius of curvature, based on Fig. 1, is found by the formula:

$$R = (a^2 + l^2 \cdot \cot^2(\delta))^{(1/2)}, \tag{2}$$

where the angle δ is determined by the average value of the cotangent of the angle of rotation of the steered wheels and is equivalent to the angle of rotation of the corresponding bicycle model; a – the distance from the center of mass to the rear axle. This angle is selected as a control parameter and can be calculated as:

$$\delta = \cot^{-1}\left(\frac{(R^2 - a^2)^{1/2}}{l}\right). \tag{3}$$

The system of differential equations describing the motion of the model under consideration (changes in the Cartesian coordinates of the center of mass and the course angle) has the form:

$$\begin{cases} \dot{x} = v \cdot \cos\psi, \\ \dot{y} = v \cdot \sin\psi, \\ \psi = v \cdot \tan\dfrac{\delta}{l}, \end{cases} \tag{4}$$

where $\dot{x}$ – the longitudinal component of the velocity of the center of mass; $\dot{y}$ – the transverse component; ψ – the heading angle; v – the linear velocity of the center of mass.

The numerical integration performed in the Maple system confirms the coincidence of the program (blue) and real (red, obtained from the integration results) trajectories (Fig. 2).

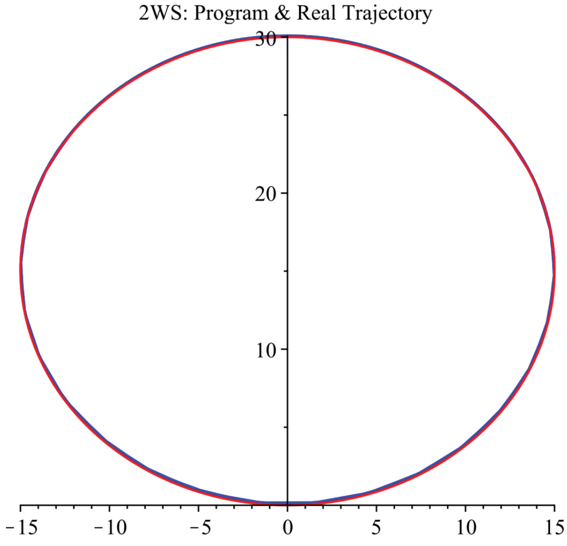


Fig. 2. The movement along the programmed path $R = 15$ m

The program path is defined parametrically in the form:

$$x(t) = R \cdot \cos\left(v \cdot \frac{t}{R}\right),$$

$$y(t) = R \cdot \sin\left(v \cdot \frac{t}{R}\right), \tag{5}$$

where t – the time parameter.

Some trajectory offsets are made for clarity.

6.2. 4WS model, model comparison. 4WS has the same difference from the 2WS model (Fig. 1) that it has the possibility of additional control by turning the wheels of the rear axle (Double-Ackerman steering mode).

Thus, the system of differential equations (4) can be written in the form:

$$\begin{cases} \dot{x} = v \cdot \cos\psi, \\ \dot{y} = v \cdot \sin\psi, \\ \psi = v \cdot \dfrac{\tan\delta_f + \tan\delta_r}{l}, \end{cases} \tag{6}$$

where δ_f – the angle of rotation of the front wheels; δ_r – rear.

Any rear-wheel control system that adds to the front-wheel steering must be carefully tuned. As an example of such a setup, let's consider the open loop algorithm developed in [21] to keep the lateral angle of rotation equal to zero at slow speeds and zero yaw at high speeds. This controller was used by Honda (Japan), and in 1987 was the first 4WS system integrated into mass production cars. At low speeds, the rear wheels are out of phase to the front wheels, which reduces the wheelbase length and improves maneuverability. At high speeds, the rear wheels rotate in phase with the front wheels, which increases the effective wheelbase and improves stability. Whether this algorithm is suitable for the designed autonomous robot with a small wheelbase requires further study and, possibly, the tuning curve will be changed based on empirical data.

According to this algorithm, the angle of rotation of the rear wheels functionally depends on the angle of rotation of the front:

$$\delta_r = K \cdot \delta_f, \tag{7}$$

where the expression is proposed for K:

$$K = \frac{-b + v^2 \cdot \dfrac{M \cdot a}{C_r \cdot l}}{a + v^2 \cdot \dfrac{M \cdot b}{C_f \cdot l}}, \tag{8}$$

in which a, b – the distance from the front/rear wheels to the center of mass, m; M – the mass of the robot, kg; l – the length of the wheelbase, m; v – the speed of movement, m/s; C_f, C_r – front/rear «cornering stiffness», N/rad.

For the proposed robot model with the specified necessary parameters, the dependence of the coefficient K on the speed v has the form Fig. 3.

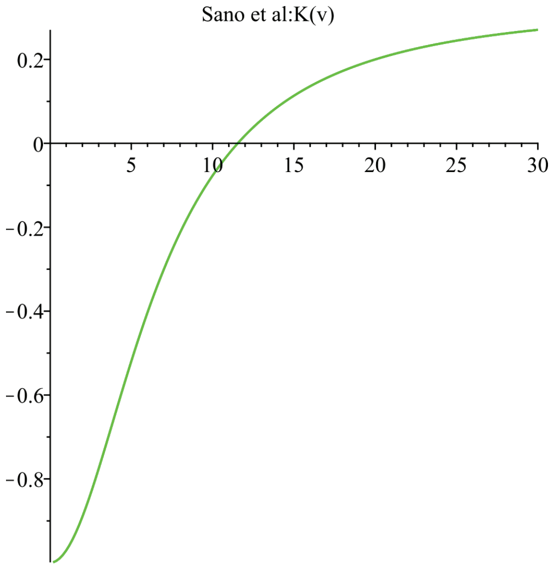


Fig. 3. The dependence of the coefficient K on speed according to the open loop algorithm

The dependence of the angle of rotation of the rear wheels (blue curve) on the angle of rotation of the front wheels (straight line – abscissa) is shown in Fig. 4. The rear wheels rotate at small steering angles, first in one direction, and then, as the steering angle increases, in the other direction.

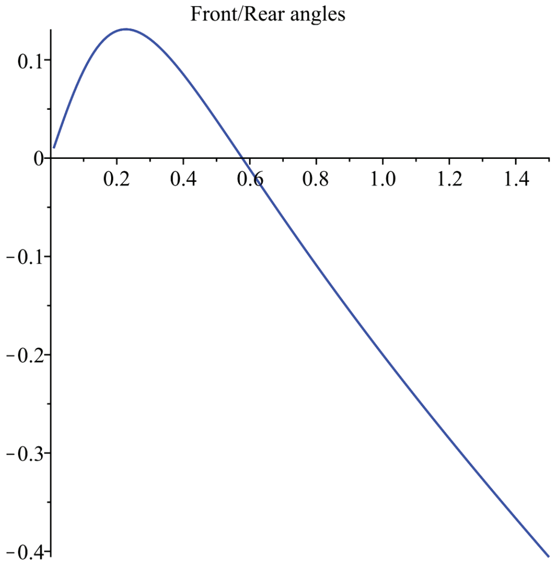


Fig. 4. The dependence of the angle of rotation of the rear wheels from the angle of rotation of the front

With the same rotation of the front wheels, the turning radius of the 4WS model in comparison with 2WS decreases or increases depending on its speed, as shown in Fig. 5 and Fig. 6. Moreover, at a speed of ~11.5 m/s, which corresponds to $K=0$, the trajectories of these models are identical. A value of $K=-1$ corresponds to a minimum turning radius $R'=R/2$, a value of $K=1$ corresponds to a crab-like movement.

The use of control systems for all four wheels is aimed at improving the maneuverability of a wheeled robot when parking or turning in cramped conditions, that is, reducing the turning radius and increasing its directional stability during sharp maneuvers at high speed.

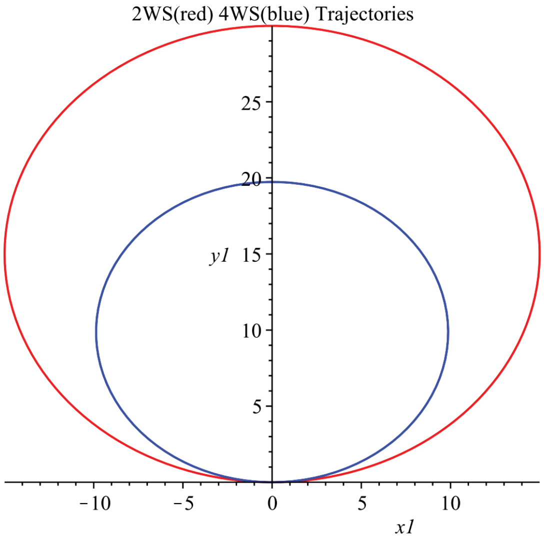


Fig. 5. Comparison of turning radii of 4WS and 2WS models at a speed of 5 m/s

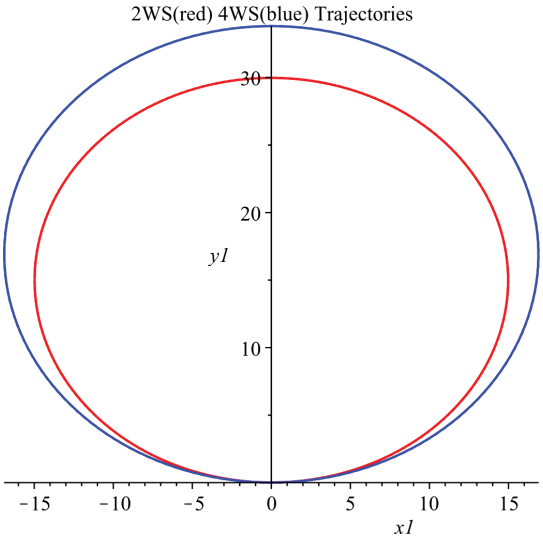


Fig. 6. Comparison of turning radii of 4WS and 2WS models at a speed of 15 m/s

The 4WS system works in two modes. At low speed, the rear wheels turn in the direction opposite to the front ones, and when maneuvering the same curvature, the front wheels will need to be rotated at a smaller angle. That is, the steering sensitivity will be higher, and in addition, the robot will become more maneuverable. And when driving at high speed – in a fast bend or rearrangement maneuver – the rear wheels using the 4WS system, on the contrary, will turn a small angle in the same direction as the front ones. The robot will move along an arc of lesser curvature and greater radius. The moment turning the vehicle around the vertical axis will be less – therefore, the risk of loss of directional stability and the development of skidding of the rear axle will also decrease.

One of the obvious advantages is increased maneuverability in tight spaces and when parking. The second point is increased stability during sharp maneuvers at high speed.

6.3. Control synthesis for 4WS Model. The control is synthesized in such a way as to ensure the movement of the 4WS model along the path of the 2WS model corresponding to the desired program motion.

Based on a qualitative analysis of equations (3) and (7) and the results of numerical modeling, it is proposed to synthesize control for movement along a trajectory of radius $R'=R(1-K)$. Thus, the control for the front wheels is synthesized for this radius according to the formula (3), for the rear – according to the formula (7). In Fig. 7–9 it is shown that the proposed law gives quite acceptable results for moving along the desired programmed path at various speeds.

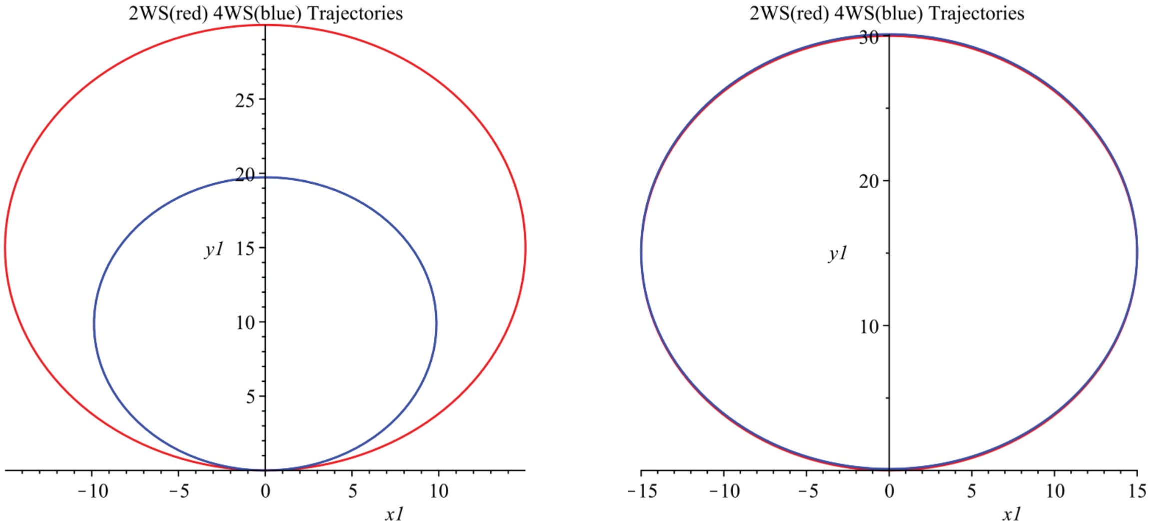


Fig. 7. The movement along the programmed path with a speed of $v=5$ m/s

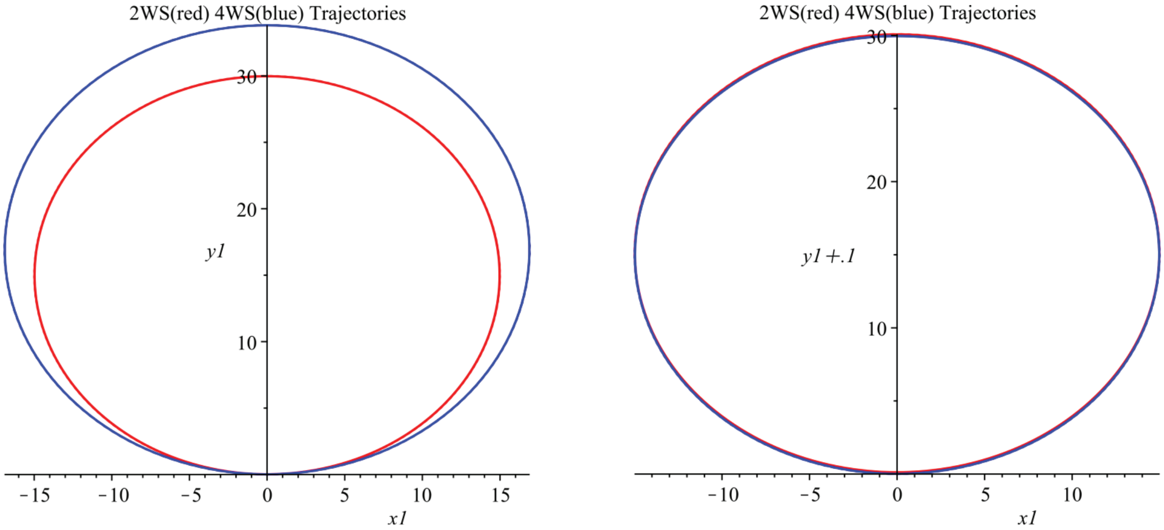


Fig. 8. The movement along the programmed path with a speed of $v=15$ m/s

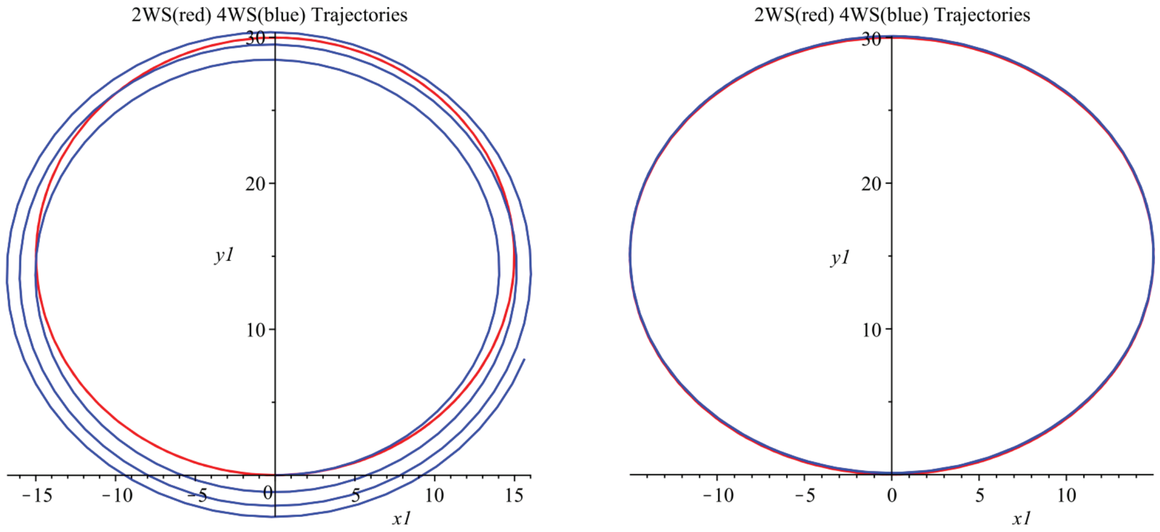


Fig. 9. The movement along the programmed path with a speed of $v=10+0.2\cdot t$ m/s

In all cases, movement along the desired trajectory $R=15$ m is ensured.

6.4. Application for numerical modeling and visualization of results. For numerical modeling the results of synthesized control, the Maple mathematical package is used – a computer mathematics system designed for a wide range of users. It is able to quickly and efficiently perform not only symbolic, but also numerical calculations.

At the same time, it has excellent means of graphic visualization and preparation of electronic documents and with equal success can be used both for simple and for the most complex calculations and calculations.

Maple is a typical integrated system that combines:

- powerful programming language (it is also a language for interactive communication with the system);
- editor for preparing and editing documents and programs;
- modern multi-window user interface with the ability to work in interactive mode;
- powerful help system with many thousands of examples;
- core of algorithms and rules for converting mathematical expressions;
- numerical and character processors;
- diagnostic system;
- libraries of built-in and additional functions;
- third-party feature packages and support for some other programming languages and programs.

For this work, the most important is another tool – OpenMaple, which provides access to Maple libraries from Windows-based applications.

Using the Open Maple API, it is possible to call maplets (scripts in the internal language of the Maple system) from within programs written in Java, C, and Visual Basic.

Such an application is implemented in C# for working with Maple scripts that synthesize in symbolic form control for various types of robotic wheel systems, performing numerical integration of the corresponding systems of differential equations and visualizing the necessary phase portraits.

To do this, the maplet executed in the Maple environment is transformed into a template using metacharacters for dynamically changing parameters in interactive mode, for example: m:={m}; R:={R}, etc.

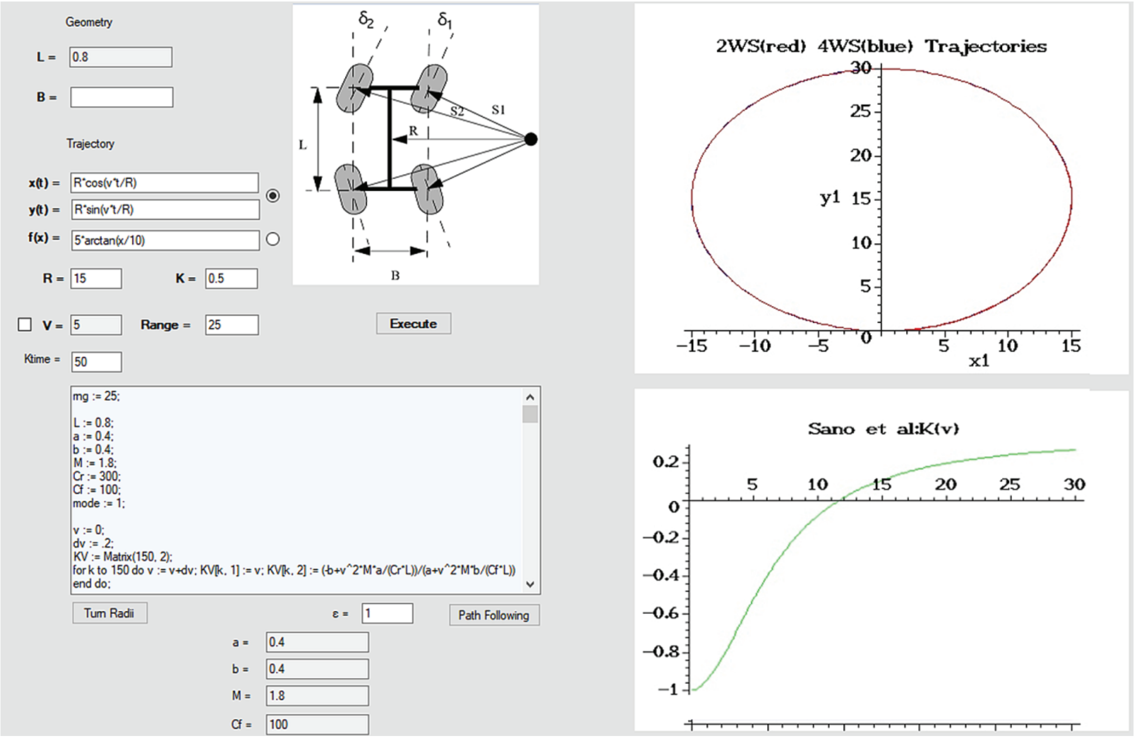
Such parameters are entered in the corresponding fields of the developed application in C# and in the used Maple script template; the mapplet is launched by clicking the [Execute] button.

A fragment of the developed application is shown in Fig. 10.

The necessary control information for visualization in the Unity 3D environment is formed from a textual representation of phase portraits recorded in json files and containing discretized information about the travel time, trajectory and rotation angles of the front and rear wheels.

The script for the Unity system is also implemented in C#, individual fragments of various types of movement of the 4WS model are shown in Fig. 11, 12.

The simulation implemented in this way allows to analyze in detail the various modes of movement of the robotic wheel system. Obviously, the software for developing computer games in the Unity 3D environment is quite suitable for modeling various scenarios of the movement of robotic wheel systems, providing a high degree of visibility and ease of analysis of these processes.



Geometry

L = 0.8

B =

Trajectory

x(t) = R*cos(v*t/R) ●

y(t) = R*sin(v*t/R)

f(x) = 5*arctan(x/10) ○

R = 15 K = 0.5

☐ V = 5 Range = 25

Ktime = 50

```
mg := 25;

L := 0.8;
a := 0.4;
b := 0.4;
M := 1.8;
Cr := 300;
Cf := 100;
mode := 1;

v := 0;
dv := .2;
KV := Matrix(150, 2);
for k to 150 do v := v+dv; KV[k, 1] := v; KV[k, 2] := (-b+v^2*M*a/(Cr*L))/(a+v^2*M*b/(Cf*L))
end do;
```

ε = 1

a = 0.4

b = 0.4

M = 1.8

Cf = 100

Fig. 10. A fragment of a Maple script automation application

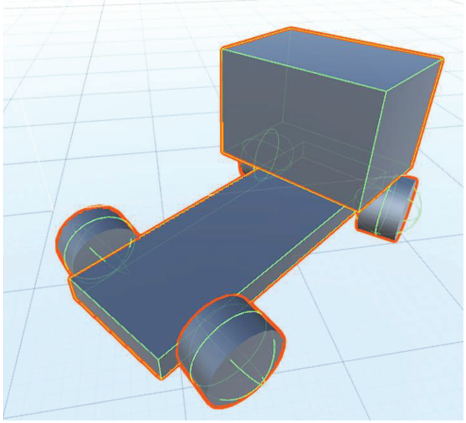


Fig. 11. The rotation of the front and rear wheels in antiphase

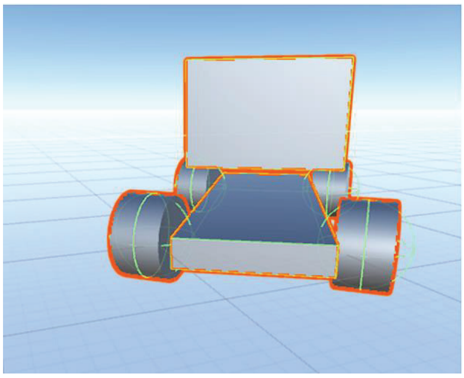


Fig. 12. In-phase rotation of the wheels

7. SWOT analysis of research results

Strengths. The strengths of the proposed method include the fact that the mathematical model of the controlled movement of an autonomous mobile robot 4WS model is based on the classical positions of solid mechanics (taking into account the presence of nonholonomic constraints). The problem of synthesizing software controlled movement is solved on the basis of strictly justified approaches of the theory of automatic control and control of dynamic systems. The correctness of the results is checked on the basis of independent numerical simulation of the system for all modes of its movement.

The implementation of the control exclusively by the analytical method based on the synthesized control for the 2WS model, taking into account the dynamic properties of the model under study, can significantly accelerate the synthesis of such a control and makes it possible to apply this approach in real time.

Weaknesses. Weaknesses include the lack of an experimental robotic device for experimental verification of the results of numerical modeling and the impossibility, in this regard, to develop corrective control using feedback.

Opportunities. The proposed approach provides an easy synthesis of control, eliminates cumbersome calculations, since it is based on establishing a connection between the studied 4WS model and the 2WS model. For this model, control is initially quite easily synthesized and then adjusted by an established empirical relationship. Another advantage of this approach is the consideration of not only kinematic, but also dynamic properties of the system. This allows to synthesize control based on the individual characteristics of an autonomous mobile robot. The prospects for further research are precisely the creation of such a model of an autonomous mobile robot with all-wheel control.

Threats. When implementing the research results, it is necessary to develop a technical device with functions that help to increase the safety and efficiency of driving a vehicle by effectively setting up the rear wheel control system. This will be achieved by choosing the optimal functional dependence of the coefficient of rotation of the rear wheels depending on the speed of the autonomous mobile robot and the angle of rotation of the front steering wheels.

8. Conclusions

1. A mathematical model is developed for the 4WS model of an autonomous mobile robot by expanding the 2WS model with additional control for the rear wheels. These extensions leads to a modification of the system of differential equations for the 2WS model. In this case, the angle of rotation of the rear wheels is a function of the rotation of the front wheels, taking into account the dynamic characteristics of a particular model of an autonomous mobile robot. Taking these characteristics into account allows to make control more accurate and flexible.
2. A qualitative analysis of the 4WS model is performed to obtain an empirical control law for this model based on a model with two steering wheels. This analysis is applied both to the system of differential equations of the 4WS model and to the corresponding rear-wheel control law. This allows to synthesize the control of the front wheels for moving along the trajectory of empirically calculated curvature, based on the curvature of the trajectory of the model with the front steering wheels.
3. The correctness of the model by means of numerical modeling and visualization of the movements of this model in all possible modes of motion at various speeds are verified. This makes it possible to confirm the high quality of control not only when driving at different speeds, but also when moving uniformly. Obviously, the speed of movement can be set analytically by any time dependence.

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