UDC 629.3.062

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CONTROL STRATEGY FOR A MOBILE PLATFORM WITH AN OMNI-DIRECTIONAL DRIVE

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СТРАТЕГІЯ КЕРУВАННЯ МОБІЛЬНОЮ ПЛАТФОРМОЮ З ВСЕНАПРАВЛЕНИМ ПРИВОДОМ

Purpose. Mobile robots are used in many areas of industry and commerce. This paper describes research on and development of a mobile platform, which is based on the concept of a ball-on-ball balancer, with two electrical drives at an angle of 90° providing a velocity vector in any direction in the horizontal plane. The purpose is to implement an originally novel principle for an omnidirectional mobile platform of very high agility, which is able at any given situation to move immediately in any direction without additional steering movements or steering mechanism.

Methodology. In advance of the design and implementation of the control strategy for the mobile device, the method of theoretical modelling of the vehicle's properties and behaviour was applied. The developed theoretical and numerical dynamic models take into account all the control parameters which allow for the determination of the critical value of angular acceleration of the driving wheel. This is needed to prevent any slippage of the ball as this would result in the loss of accuracy of positioning. The equations of motion were implemented in the platform controller and tested.

The mobile platform consists of a ball of 0.2 m radius driven in the X-Y plane by two wheels that are attached to servo motors. The mobile platform is controlled by a CAN PLC controller interfacing with the motor drives, accelerometers and a laser sensor for feedback. Wireless communication provides the interface with the station controller via Wi-Fi and XBee Series 2 modules.

Findings. The experimentally obtained results show that the mobile platform can be reliably controlled using the ball-on-ball balancer principle with the developed control algorithm. Additional application of a sensor for guiding the mobile platform along obstacles or guiding lines improves the accuracy of the movement.

Originality. The originality of the control strategy for a mobile platform with an omnidirectional drive, proposed at the paper, is the avoiding slippage by limiting the platform acceleration to below the critical value by means of monitoring and limiting the lead values of the feedback control loop of the driving wheels.

Practical value. Development of control strategy for the mobile robot, which is based on the concept of a ball-on-ball balancer with two electrical drives at an angle of 90° providing a velocity vector in any direction in the horizontal plane.

Keywords: *mobile robots, omnidirectional mobile platform, sensor-guidance, dynamic modelling, control strategy design.*

An analysis of the recent research and publications. An omnidirectional drive is widely used in mobile platforms as it allows movement of a robot in any direction without any steering wheel or steering mechanism. There are many types of omni-drives and their control [1–6]. Lee et al [7] reported an omni-directional ball drive comprised of a large ball driven by three motors with rollers attached.

Unsolved aspects of the problem. The main challenge with omni-drives for mobile robots is the positional control due to possible slippage of the drive. The developed drive concept is based on active control a small ball on top of a large ball, called the ball-on-ball balancer, which was reported in [8]. Two peripheral electrical drives at an angle of 90° to each other allow a velocity vector at the top point of

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the lower ball in every direction of the horizontal plane. By removing the smaller top ball and putting the system upside-down on the floor, the basic principle of an agile, mobile platform is obtained.

Objectives of the article:

- to use the mathematical modelling of the kinematic behaviour of the ball-based drive to justify the control strategy for a mobile platform with an omnidirectional drive;

- to develop the mobile platform and to carry out an experiment for testing of proposed control strategy for a mobile platform with an omnidirectional drive.

Presentation of the main research and explanation of scientific results.

The developed mobile platform, shown in fig.1, consists of the frame, the ball of 0.2 m radius, two driving wheels, two servo motors with drives, a CAN PLC controller, two accelerometers, Wi-Fi and XBee Series 2 communication modules, and a battery. Additionally, a Leuze Electronic ODSL9/C6 laser sensor is used to measure the distance to a target. The software platform is the CodeSys environment, which provides an interface with the controller and visualization of the control parameters. In order to achieve accurate positioning and control of the robot, a theoretical model was developed.

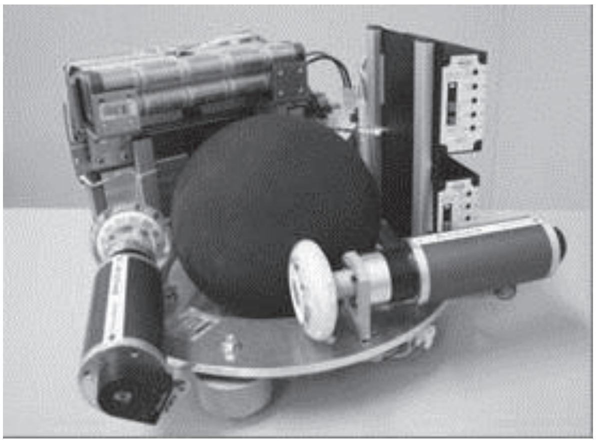


Fig.1. Photo of the implemented mobile platform with high agility

Theoretical Modelling of the Mobile Platform Dynamics. Mathematical modelling of the kinematic behaviour of the mobile platform was carried out with the purpose of increasing the control reliability of the mobile platform and avoiding slippage. The mathematical modelling of the kinematic behaviour of the ball-based drive was carried out for the combination of special cases: when the movement of the ball is permanently perpendicular around the same axis of symmetry; at the same time the symmetry axis performs a parallel translational motion in space; and the centre of gravity moves along a plane. The friction coefficient between the driving wheel and ball is higher than between the ball and floor surface. Therefore, only slippage between the ball and floor is taken into account. Fig. 2 shows the free-body diagram of the "roller-ball-flat surface" system.

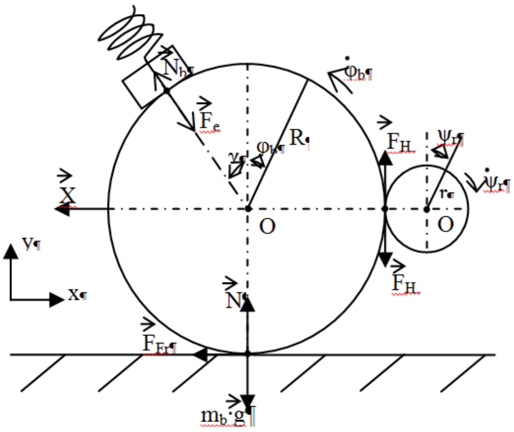


Fig.2. Free-body diagram of the "roller-ball-flat surface" system : look at the formulas (1) and (2)

The coupling force between the driving wheel and ball is considered to be permanently without slippage. As presented in [9], the movement equations are reduced to Newton equations for translational movement relative to the centre of mass of the ball, and to the torque equation relative to the symmetry axis, as follows

$$\begin{cases} x: \quad -m_{rob} \cdot \ddot{x}_b - F_{FR} = 0 \\ y: \quad -m_b \cdot g - F_{el} \cdot \cos(\gamma) + N + F_{H.b} = 0 \end{cases}; \qquad (1)$$

$$F_{FR} \cdot R - J_b \cdot \ddot{\varphi}_b - F_{H.b} \cdot R = 0, \qquad (2)$$

where m_{rob} – mass of the mobile platform (11 kg); $\ddot{x}_b$ – linear acceleration of ball, m/sec^2; F_{Fr} – friction force of a ball with a surface over which it moves, N; m_b – mass of the ball (3 kg); g – acceleration of gravity (9.8 m/sec^2); F_{el} – force of reaction of a spring on pressure from the side of ball, N; γ – angle between reaction force vector of a spring and an axis "y" (30^0); N – reaction force of the floor surface caused by the pressure of the ball, N; $F_{H.b}$ – rotary force (as a result of the driving force of a wheel), N; R – radius of the ball (0.2 m); $\ddot{\phi}_b$ – angular acceleration of the ball, rad/sec^2; and J_b – inertia of the ball, kg·m^2

$$J_b = 2 \cdot m_b \cdot R^2 / 5 . \qquad (3)$$

It has to be noted that in the given dynamic equations of the mobile platform, "passive" friction forces of rolling at all points of contact are not taken into account, as they are much smaller than other forces.

For efficient control of the mobile platform, it is necessary to monitor the movement direction and the distance which the platform has travelled. The distance can be calculated from the measured angular velocity of a driving wheel as follows

$$x_{rob}(t)=\int_0^t \dot{x}_{rob}(t)dt=\int_0^t \dot{x}_b(t)dt=\int_0^t \dot{x}_{rol}(t)dt= \\ =r\cdot\int_0^t \dot{\psi}_{rol}(t)dt=R\cdot\int_0^t \dot{\varphi}_b(t)dt \quad , \qquad (4)$$

where x_{rob} – distance travelled during time t, m; $\dot{x}_{rob}$ – linear speed of the mobile platform, m/sec; $\dot{x}_{rol}$ – linear speed of the driving wheel, m/sec; $\dot{\psi}_{rol}$ – angular speed of the driving wheel, rad/sec; r – radius of the driving wheel (0.02 m).

However, these relations are only valid for the case where coupling friction occurs between the ball and the surface on which the ball moves. As known, the character of friction between a body and surface changes depending on the forces which influence the moving body and the starting conditions. Consequently, this leads to different motion equations. After the beginning of slippage, the friction force practically ceases to depend on the angular acceleration of the ball and superposed forces, and is constantly equal to a critical value

$$F_{FR.crit}=\mu\cdot N\,,$$

where μ – sliding friction coefficient, in this case of rubber against polymeric synthetic material (0,4).

With (1–4), the analytical relationship between the linear acceleration of the mobile platform (ball) and angular acceleration of a driving wheel is established. The following equation takes into account the slippage of the ball against the surface on which it moves

$$\ddot{x}_b(t)=\begin{cases} \ddot{\psi}_{rol}(t)\cdot r \quad if \quad \ddot{\psi}_{rol}(t)<\ddot{\psi}_{rol.crit}\ ; \\ -\dfrac{J_b\cdot\mu\cdot r}{R^2\cdot m_{rob}\cdot(1+\mu)}\cdot\ddot{\psi}_{rol}(t)- \\ -\dfrac{m_b\cdot g+F_{el}\cdot\cos(\gamma)}{m_{rob}\cdot(1+\dfrac{1}{\mu})} \quad if \quad \ddot{\psi}_{rol}(t)\geq\ddot{\psi}_{rol.crit}\ , \end{cases}$$

where $\ddot{\psi}_{rol.crit}$ is the value of angular acceleration of the driving wheel at which the slippage between the ball and the surface on which it moves begins

$$\ddot{\psi}_{rol.crit}=-\frac{\mu}{r\cdot(m_{rob}+m_{rob}\cdot\mu+\frac{2}{5}\cdot m_b\cdot\mu)}\times \\ \times(m_b\cdot g+F_{el}\cdot\cos(\gamma))\ .$$

Control Strategy of the Mobile Platform. As presented in [9], the control strategy is to avoid slippage by limiting the platform acceleration to below the critical value. This is achieved by means of monitoring and limiting the lead values of the feedback control loop of the driving wheels. The new control algorithm was tested with the platform moving straight along a wall. This movement was obtained with a distance measuring laser sensor interfaced to the mobile platform (fig.3).

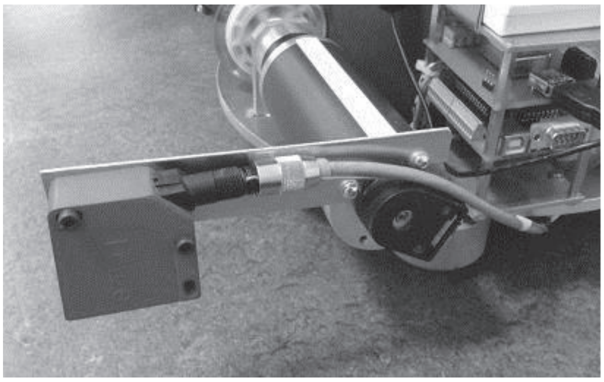


Fig. 3. Mobile platform with the distance measuring laser sensor

The laser sensor was interfaced with the platform controller providing feedback. Since the sensor outputs an analogue current relating to the distance and the platform controller (PLC) has only analogue voltage inputs, a 470 Ω resistor was put in between the line and ground, and a wire was taken from the above the resistor to the analogue input. This would allow the 4–20 mA signal to use almost the entire range of the 0–10 V analogue voltage input to the PLC. To calibrate the sensor, values on the sensor's LCD were compared to the values read by the PLC. From these measurements, a set of linear sections of readings was determined. The PLC code was developed for the laser sensor by using the generated graph that is shown in fig. 4. The datasheet for the sensor declared that the output current can be deemed linear during Series 2; and that Series 1 and Series 3 are assumed to be linear for their respective areas. Although the measuring range of the sensor was relatively small, the high accuracy and stability of the measured distance meant it would be more effective at being used for controlling movement.

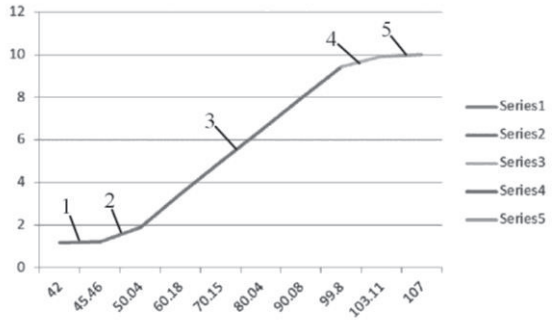
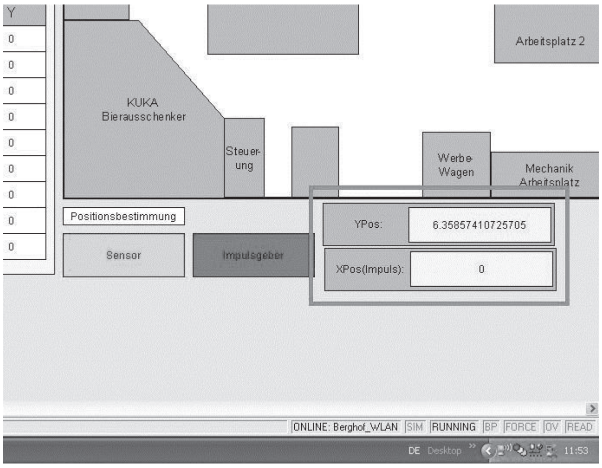


Fig. 4. Sensor calibration graph

The CodeSys environment PID controller was utilised to control the movement in a straight line. The CodeSys interface is shown in fig. 5. The values relate to the X and Y coordinates of the Robot. The X value given is always as calculated from the rotary encoder. The Y value will either show the sensor reading or the value calculated from the rotary encoder, depending on which button is selected to the left of these values: *Sensor* or *Impulsgeber*. Both values are given in centimetres.

In order to visualise the platform movements calculated from the sensor and encoder data, the *Control Graphs* object was created in the controller interface. Figure 6 shows the graphs of the X (top) and Y (bottom) movements of the mobile platform. The black line on each graph refers to the desired location of the mobile platform (internal variables *X Soll* and *Y Soll*). The red line indicates the actual position of the mobile platform at that moment. On the X graph, this will always be the value from the rotary encoders. On the Y graph, this will vary between the rotary encoder value and the sensor value, depending on which option is selected on the visual interface object.



YPos: 6.35857410725705

XPos(Impuls): 0

ONLINE: Berghof_WLAN SIM RUNNING BP FORCE OV READ

Fig. 5. Controller visual interface

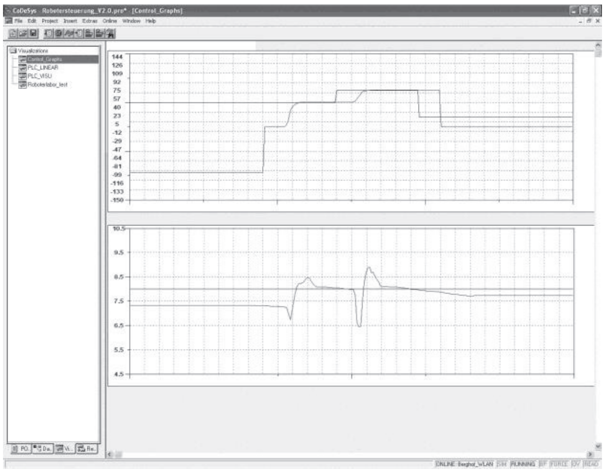


Fig. 6. Graphs of mobile platform movement along the X and Y axes of fixed Cartesian coordinate system

Experimental work. The original mobile platform programming made use of the *Linearfahrt* (Linear Drive) function block to move the robot. This function compared the current location to the desired location and calculated the average speed that had to be achieved for each of the X and Y axes, so that the robot would travel in a straight line to the next point. The movement was then split up into three sections for both the X and Y movements: acceleration, a constant speed, and a deceleration section. For each section, the programming made use of the earlier calculated values to carefully provide linear acceleration and movement from point A to point B. Although effective, the movement basically relied on an open loop system, comparing values to the rotary encoder to ensure ’movement’ was proceeding as expected. With the sensor now installed to provide accurate measurements, a closed loop control system could be utilised.

The CodeSys environment has a built-in PID controller. The previous *Linearfahrt* function block was modified to suit the new design. All the previous control instructions were removed to avoid confusion, and the new, simpler PID controllers were added. One was added for both the X and Y controllers. With the PID controllers initiated and functioning, it was necessary to tune them. With the *D* multiplier set to 0 and the *I* multiplier set to 1, the *P* multiplier was altered until stable control was established. From there, the *I* multiplier was brought in. The PID controller parameters were initially tuned without the ball, using only the data from the encoders (fig. 7). The platform was programmed to move in the X direction while maintaining a fixed Y, which was measured by the laser sensor.

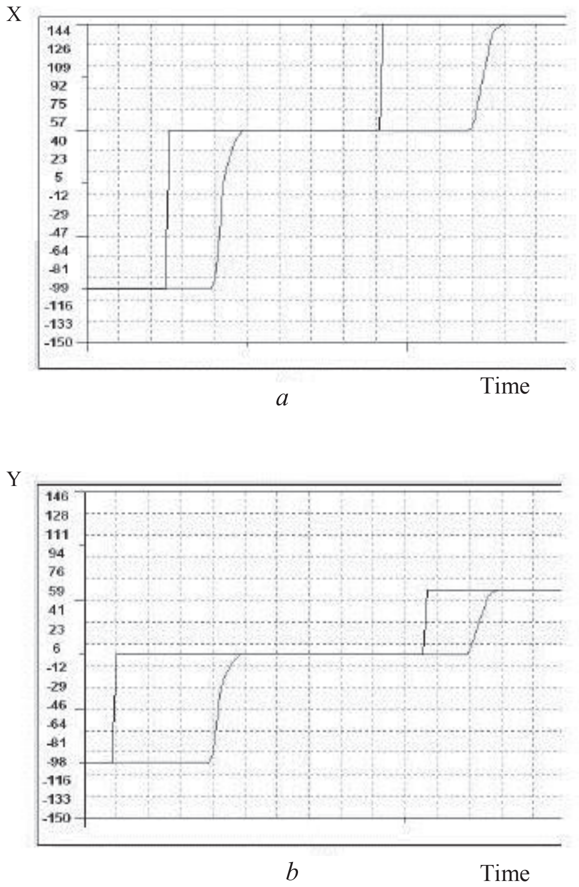


Fig. 7. PID control of the servo motors without the movement of the mobile platform : a – for axe X ; b – for axe Y of fixed Cartesian coordinate system

In experiments, a drift occurs when the platform is stationary. This is attributed to the slight difference between the motor controller’s ground level and the 0 V analogue outputs from the PLC, obtained in measurements.

Fig. 8 shows the results of movements of the mobile platform. The blue rectangles indicate times when the platform was commanded to move from one position to a new position. Each movement took between 2 and 3 seconds. The Y values are those recorded from the laser sensor. Although movement in the Y axis doesn't look smooth, the correct position is always achieved. The jerk motion can be attributed to the rotation in the movement of the mobile platform.

As a result, the modified mobile platform control procedure is as follows:

- Create connection to mobile platform from CodeSys.
- Open the *PLC VISU* Object.
- At the bottom of the window, select if you want to use the analogue sensor (*Sensor*) or the rotary encoders (*Impulsgeber*) to determine the platform's position.
- Select whether you want to make one linear movement (*Einzel Bahnfart*) or several successive movements (*Automatische Bahnfart*).
- Fill in the required values and click the appropriate start (*Starten*) button.

Clicking *Reset* at any time will stop movement and reset the rotary encoder sensor values to zero.

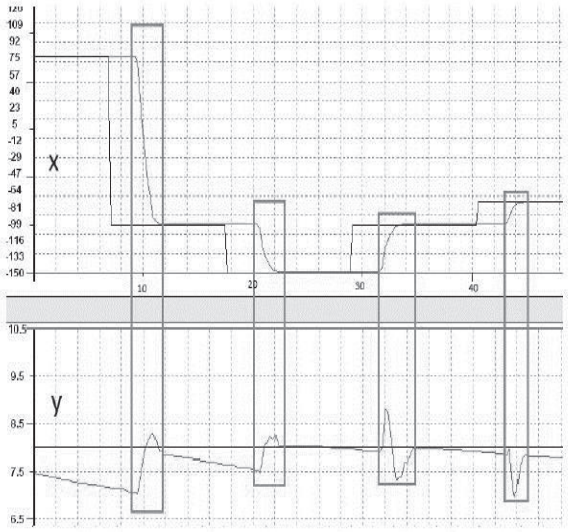


Fig. 8. Measured mobile platform movements for motion in a straight line : X and Y – the axes of fixed Cartesian coordinate system

Conclusion. In this paper, the development of a mobile platform with an omni-directional drive was presented. The platform drive is based on the concept of a ball-on-ball balancer with two electrical drives at an angle of 90°, which provide mobile platform movements in the horizontal plane. The mobile platform consists of a ball of 0.2 m radius driven in the X-Y plane by two wheels attached to two servo motors. The mobile platform is controlled by a CAN PLC controller with the motor drives, accelerometers and laser sensor for feedback. Wireless communication provides the interface with the station controller via Wi-Fi and XBee Series 2 modules.

The developed theoretical and numerical dynamic models take into account all the control parameters, with the aim to determine the critical value of angular acceleration of the driving wheel. This is needed to any slippage of the ball, as this would result in the loss of accuracy of positioning. The equations of motion were implemented in the platform controller.

The experimentally obtained results show that the mobile platform can be reliably controlled using the ball-on-ball balancer principle with the developed control algorithm.

Acknowledgments. The authors would like to acknowledge the support provided by General Motors South Africa, through the GMSA Chair of Mechatronics, and by the German Academic Exchange Service (DAAD) as well as Baden-Wuerttemberg Foundation, Germany.

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Мета. Мобільні роботи використовуються в багатьох сферах промисловості та комерції. Ця стаття описує дослідження та розробку мобільної платформи, в основу якої закладена концепція балансування шару на шарі, із двома розміщеними під кутом 90° електричними приводами для забезпечення вектору швидкості у будь-якому напрямі в горизонтальній площині. Ціллю є створення оригінального та нового принципу розробки всенаправленої мобільної платформи дуже високої маневреності, що здатна в будь-якій ситуації швидко переміститися в любому напрямку без необхідності додаткових рухів руля або рульового механізму.

Методика. Розробці та реалізації стратегії керування для мобільного пристрою передує застосування методу теоретичного моделювання властивостей та поведінки транспортного засобу. Розроблені теоретичні та чисельні динамічні моделі враховують усі параметри керування, що дозволяє визначити критичне значення кутового прискорення приводного колеса. Це необхідно для запобігання будь-якого проковзування шару, оскільки це може призвести до втрати точності позиціонування. Рівняння руху були реалізовані в контролері платформи та перевірені експериментально.

Мобільна платформа складається з шару радіусом 0,2 м, рух якого у площині X-Y забезпечується двома колесами, що приєднані до серводвигунів. Мобільна платформа керується за допомогою CAN PLC контролера, що взаємодіє з двигунами приводів, акселерометрами та лазерним датчиком для реалізації в системі зворотного зв’язку. Взаємодія з контролером станції забезпечується за допомогою бездротового зв’язку через Wi-Fi та модулі XBee Series 2.

Результати. Експериментально отримані результати показують, що на основі концепції балансування шару на шарі з розробленим алгоритмом керування може бути здійснене ефективне керування мобільною платформою. Показано, що додаткове застосування датчика для спрямування мобільної платформи вздовж перешкод або орієнтирів покращує точність руху.

Наукова новизна. Оригінальністю стратегії керування мобільною платформою зі всенаправленим приводом, запропонованої в роботі, є уникнення прослизання шляхом обмеження прискорення платформи до рівня нижче критичного значення за допомогою моніторингу та обмеження основних величин у контурі зворотного зв'язку за приводними колесами.

Практична значимість. Практичною значимістю є обґрунтування стратегії керування мобільним роботом, що заснована на концепції балансування шару на шарі з використанням двох електричних приводів під кутом 90° для створення вектору швидкості в будь-якому напрямку в горизонтальній площині.

Ключові слова: *мобільні роботи, всенаправлена мобільна платформа, датчик спрямування, динамічне моделювання, створення стратегії керування*

Цель. Мобильные роботы используются во многих сферах промышленности и коммерции. Эта статья описывает исследование и разработку мобильной платформы, в основу которой заложена концепция балансирования шара на шаре, с двумя размещенными под углом 90° электрическими приводами для обеспечения вектора скорости в любом направлении в горизонтальной плоскости. Целью является создание оригинального и нового принципа разработки всенаправленной мобильной платформы очень высокой маневренности, которая способна в разных ситуациях быстро переместиться в любом направлении без необходимости дополнительных движений руля или рулевого механизма.

Методика. Разработке и реализации стратегии управления для мобильного устройства предшествует применение метода теоретического моделирования свойств и поведения транспортного средства. Разработанные теоретические и численные динамические модели учитывают все параметры управления, что позволяет определить критическое значение углового ускорения приводного колеса. Это необходимо для предотвращения любого проскальзывания шара, поскольку это может привести к потере точности позиционирования. Уравнения движения были реализованы в контроллере платформы и проверены экспериментально.

Мобильная платформа состоит из шара радиусом 0,2 м, движение которого в плоскости X-Y обеспечивается двумя колесами, присоединенными к серводвигателям. Мобильная платформа управляется с помощью CAN PLC контроллера, который взаимодействует с двигателями приводов, акселерометрами и лазерным датчиком для реализации в системе обратной связи. Взаимодействие с контроллером станции обеспечивается с помощью беспроводной связи через Wi-Fi и модули XBee Series 2.

Результаты. Экспериментально полученные результаты показывают, что на основе концепции балансирования шара на шаре с разработанным алгоритмом управления может быть осуществлено эффективное управление мобильной платформой. Показано, что дополнительное использование датчика для направления мобильной платформы вдоль препятствий или ориентиров улучшает точность движения.

Научная новизна. Оригинальностью стратегии управления мобильной платформой со всенаправленным приводом, предложенной в работе, является предотвращение проскальзывания путем ограничения ускорения платформы на уровне ниже критического значения с помощью мониторинга и ограничения основных величин в контуре обратной связи по приводным колесам.

Практическая значимость. Практической значимостью является обоснование стратегии управления мобильным роботом, которая основана на концепции балансирования шара на шаре с использованием двух электрических приводов под углом 90° для создания вектора скорости в любом направлении в горизонтальной плоскости.

Ключевые слова: *мобильные роботы, всенаправленная мобильная платформа, датчик направления, динамическое моделирование, создание стратегии управления*

Рекомендовано до публікації докт. техн. наук В. Фрюхауфом . Дата надходження рукопису 11.03.14.