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Automatic Correction of an Automated Guided Vehicle's Course Using Measurements from a Laser Rangefinder

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Abstract: In order for AGVs to be able to effectively carry out the tasks assigned to them, it is important to accurately determine their position and orientation in the working space. Having data on the location of an AGV is crucial for the navigation process, and the most commonly used odometry method is unreliable due to errors. To correct these errors, additional measuring systems are used. These systems use a variety of sensors. Some of the most widely used types are laser rangefinders. These sensors are also used in the automatic course correction methodology that is developed and presented in this article. The measurements from laser rangefinders are used to determine the shift of the actual trajectory from the set one, and then to guide the AGV to the previously set course. The developed methodology is experimentally verified on the basis of several dozen test drives. The conducted experimental studies prove the correctness of the developed methodology. The proposed course correction algorithm can be implemented in most working conditions, and guarantees correct passage over the given route.

Keywords: automated guided vehicle; odometry errors; measurement methods; correction of the course

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1. Introduction

Automated guided vehicles (AGV) have been transporting and storing products and materials for many years in various industries and areas of activity, including in factories, warehouses, distribution centers, office buildings and hospitals [1,2]. In order for AGVs to successfully carry out the tasks entrusted to them, it is necessary to correctly implement the two most important goals of mobile robotics, i.e., location and navigation. The location is the AGV's knowledge of where it is in the workspace. Without this knowledge, it is impossible to navigate, i.e., to determine the route, and, thus, to reach the designated point. Location and navigation processes have been important research topics for many years, and have led to the improvement of many recognized and verified techniques, as well as the development of new ones. In the case of AGVs, the most common navigation technique is odometry. The main assumption of odometry is to determine the present position of the vehicle on the basis of the distance traveled through a characteristic point of the vehicle. Although this method can provide accurate information over short periods of time, its disadvantage is the unlimited accumulation of position errors over time [3–15].

Odometry errors are divided into two groups: executive errors resulting from imperfections of the real object and errors resulting from the operating conditions (wheel slip, surface unevenness). To reduce the negative impact of these errors on the operation of AGVs, additional measurement methods are used. Most of the AGV tasks require a reliable location for a long time; therefore, additional sensors are needed to correct odometry errors. As measurement techniques are subject to continuous development, the number of methods used to correct odometry errors is increasing [16–18].

Among the additional measurement techniques, we distinguish two main groups of techniques that are used. The first group includes techniques in which measurements are performed with a constant frequency, e.g., laser, gyroscopic and GPS techniques. The second group consists of techniques in which the measurement is performed after the vehicle approaches a specific point, line or reference surface. Examples of such techniques are magnetic, vision, laser and ultrasonic methods [19,20]. After the measurement is made, the vehicle course is corrected. One of the most frequently used measurement techniques supporting odometry is the technique using laser rangefinders. Laser rangefinders can be used in mobile robotics in a number of different ways. Their properties, such as their good precision and measurement accuracy, make them very effective in range measurements, so they can be used in any task that is solved with mobile robotics. Using a laser rangefinder, an AGV vehicle can create a map of an unknown environment, extracting its characteristic features (e.g., walls, corners), and in the next stage, it can locate itself on the map by measuring the distance to these objects [21–24]. Thanks to this method, it is possible to perform absolute measurements of the position and orientation of the vehicle on the map, which can be used to eliminate odometry errors [7,25]. In other methods used for the location of AGVs, laser rangefinders are employed, which use artificial orientation points installed in specific places in the working space of the AGV [26]. Measurements from laser rangefinders are also used in methods for optimizing the robot path planning process [27]. They are also applicable to new measurement techniques using neural networks. An example is [28], the authors of which proposed an algorithm for laser detection of people and for avoiding obstacles for a mobile robot that is used to transport materials inside hospitals. The authors used the deep learning method along with a neural network for the effective classification of each laser scanning point.

Another example of the use of laser rangefinders is [29]. The authors proposed an approach using a laser rangefinder to determine the distances of all obstacles surrounded within a given range of angles. The AGV can follow the specified object according to the rational intensity of the reflection and the range of the object detected from the rangefinder.

Systems that use probabilistic methods are also used in the navigation of AGVs. In these systems, based on the estimation of errors in subsequent items, corrections are made in the calculation algorithm [30–34]. Other papers [35,36] have presented the simplest solution based on odometry. The implemented program calculates and introduces corrections to the computational algorithm based on the measurements of the end position error in two runs achieved in opposite directions. Another paper [37] presented the implementation and experimental validation of a trajectory tracking and damage detection algorithm for AGV sensors and actuators based on many positioning modules, including laser scanners. The algorithm used an extended Kalman filter (EKF). In [38], the authors proposed a method for solving the problem of AGV vehicle location within the known problem of simultaneous location and map construction (SLAM). The studies covered SLAM location based on EKF and the detection of landmarks, odometry and inertial measurement unit (IMU) measurements, as well as laser scanners. In [39], research was carried out on the issue of AGV navigation in an industrial environment with frequently changing hall layouts. The autonomy of an AGV is very helpful in such cases. The vehicle carries out a set of tasks, among which we can distinguish planning, perception, route planning and route tracking as the tasks that an industrial vehicle must perform. The extended Kalman filter uses information from the odometry and laser navigation system to estimate the position of the vehicle. Another paper [40] presented a solution in which the robot used laser rangefinders to study the environment and learn the placement of objects in this environment. This process took place in several stages. In the first stage, the robot learned the initial alignment, while the second stage involved the detection of changes in the arrangement of objects. The final step in the process was to return each object to its previous position, which involved object tracking, map updates and path planning. SLAM was implemented using EKF.

Another paper [41] described the use of the Kalman filter to analyze data from laser rangefinders. The filtered data made it possible to determine the position of the vehicle in relation to the reference line and to calibrate the navigation system. Laser rangefinders were also used in conjunction with vision systems. Examples of such applications are presented in [42].

The aim of this article is to present the developed methodology for the automatic correction of the AGV vehicle course. The developed methodology uses laser rangefinders to drive the vehicle on specific sections of the route, and to automatically correct the current position of the vehicle within a specific section of the route. The proposed methodology for the automatic course correction using a laser rangefinder to drive an AGV vehicle is a solution that simplifies and, at the same time, reduces the costs of the navigation system.

The organization of the article is as follows. Section 2 characterizes the research object, as well as the laser rangefinders that were used. The main method of navigation used—odometry—is also described. Section 3 presents the proposed methodology for automatic course correction, the results of the experimental research and their analysis. Section 4 contains a summary and final conclusions.

2. Materials and Methods

2.1. Method of Navigation for the Automated Guided Vehicle

The research results presented in the article concern an AGV vehicle in which odometry was used. This is the basic method for determining the position of an AGV [43]. In odometry, the current position of the vehicle is determined on the basis of the distance traveled by the characteristic point of the vehicle (Figure 1). The directional angle α is determined on the basis of the difference between the speeds of the left wheel v_L and the right wheel v_R.

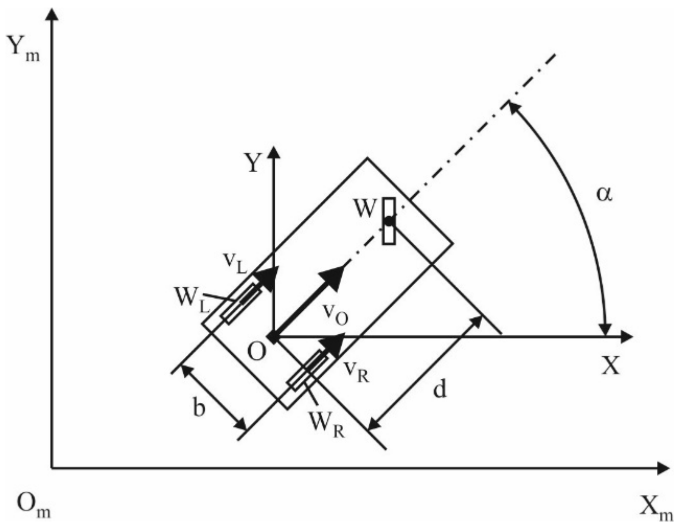


Figure 1. An AGV vehicle in the adopted coordinate system.

Odometry is a method consisting of counting the distance traveled by a vehicle's wheels (W_L, left wheel; W_R, right wheel) and determining the change in the directional angle α of the vehicle movement at each calculation step. This method is used in vehicles with two independently driven wheels. The rotation of the vehicle about a vertical axis of rotation that passes through the point O and the change in the directional angle α is achieved by varying the rotational speeds of two independently driven wheels.

The vehicle position and actual position of the O point in the base reference system $X_mO_mY_m$ (Figure 1), in the i + 1 iteration, are given by the relationship in (1), assuming that the iteration i is expressed by a state vector, ($x(i)$, $y(i)$, $\alpha(i)$):

$$\begin{bmatrix} x(i+1) \\ y(i+1) \\ \alpha(i+1) \end{bmatrix} = \begin{bmatrix} x(i) \\ y(i) \\ \alpha(i) \end{bmatrix} + \begin{bmatrix} \Delta t \cdot v_O(i+1) \cdot \cos(\alpha(i) + \Delta t \cdot \omega(i+1)) \\ \Delta t \cdot v_O(i+1) \cdot \sin(\alpha(i) + \Delta t \cdot \omega(i+1)) \\ \Delta t \cdot \omega(i+1) \end{bmatrix} \quad (1)$$

Equations (2) and (3) show the relationships for speed of $v_O(i+1)$ and $\omega(i+1)$:

$$v_O(i+1) = (v_R(i+1) + v_L(i+1))/2 \quad (2)$$

$$\omega(i+1) = (v_R(i+1) - v_L(i+1))/b \quad (3)$$

where $v_R(i+1)$ and $v_L(i+1)$ are the speeds of the left and right wheels, respectively; b is the wheelbase of the driven wheels.

The quantities $v_R(i+1)$ and $v_L(i+1)$ can be written using Equations (4) and (5):

$$v_R(i+1) = \omega_R(i+1) \cdot r \quad (4)$$

$$v_L(i+1) = \omega_L(i+1) \cdot r \quad (5)$$

The relationships for angular speed $\omega(i+1)$ and speed $v_O(i+1)$ are as follows:

$$\omega(i+1) = (\omega_R(i+1) - \omega_L(i+1)) \cdot r/b \quad (6)$$

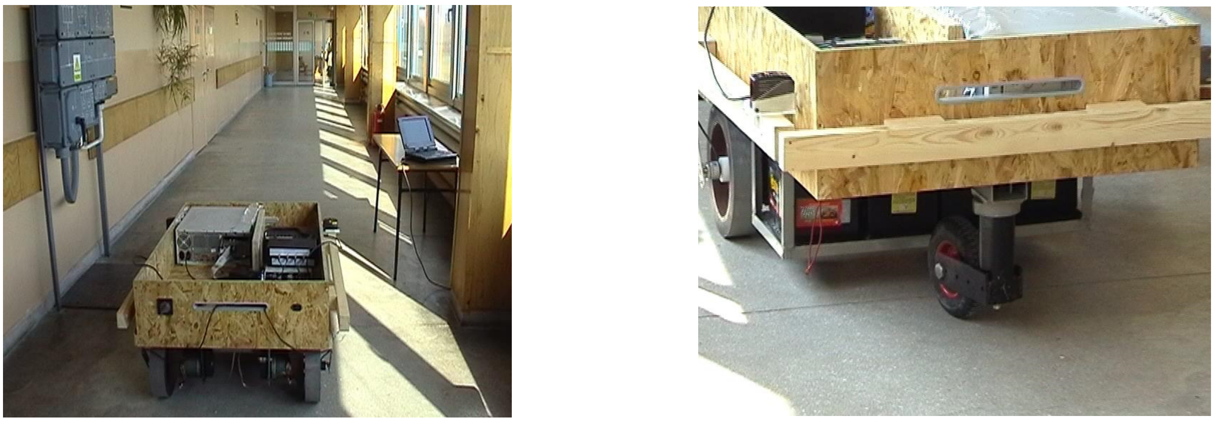
$$v_O(i+1) = (\omega_R(i+1) + \omega_L(i+1)) \cdot r/2 \quad (7)$$

where $\omega_R(i+1)$ and $\omega_L(i+1)$ are the angular speeds of the left and right wheels, respectively; r is the radius of the drive wheels.

The above considerations apply to the case where the wheels are rigid, they roll without slipping, the contact of the wheel with the road is the point and the radiuses r of the drive wheels are the same.

2.2. Research Object

The subject of the research was an automated guided vehicle designed to transport products and materials (Figure 2). The vehicle is a three-wheeled structure equipped with two driving wheels and one independent turning wheel. The vehicle is designed to move on smooth surfaces due to the lack of flexible suspension. It is set in motion and steered by two independently driven wheels.



(**a**) (**b**)

Figure 2. The automated guided vehicle that is the subject of this research: (**a**) rear view of the vehicle; (**b**) front view of the vehicle.

The technical parameters characterizing the AGV are as follows:

- The mass of the vehicle with batteries is 200 kg;
- The maximum working speed is 1 m/s;
- The vehicle is able to carry loads of up to 100 kg;
- The vehicle dimensions 1.24×1.04 m;
- The driving wheels are made of metal around the circumference with a rim of vulcanized rubber;

- The on-board steering system comprises an on-board PC computer, acquisition cards and a computer program with an implemented control algorithm written in C++;
- Sensors are used to measure the distance, angular position and deviation from a given direction. Two types of sensors are used in the AGV: MHK40 encoders and LT3 Banner laser rangefinders.

Figure 3 shows a diagram of the AGV with its accessories.

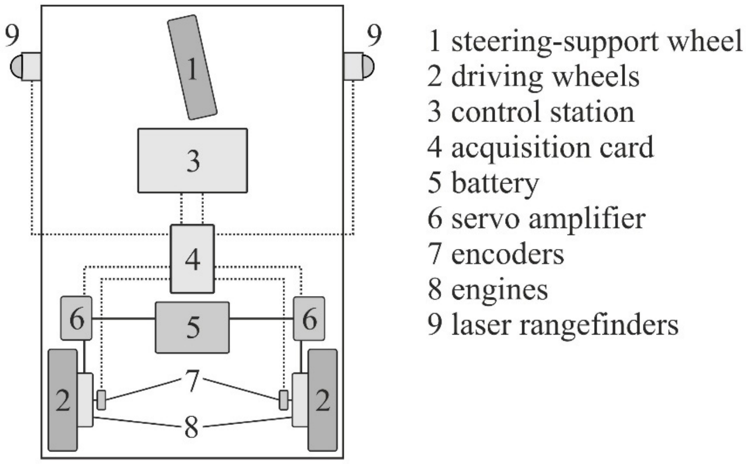


Figure 3. The scheme of the automated guided vehicle.

The sensor used is the time-of-flight laser sensor. The LT3 sensor uses pulsed laser technology to produce highly accurate results. The sensor's laser operates at a frequency of one million pulses per second. The microprocessor records the time needed for the impulse to travel to the object and back. Every millisecond, a thousand pulses are recalculated and their averaged value is output. The long detection range allows the recognition of very small or difficult-to-recognize objects, even if the observation is carried out from a considerable distance. The sensor parameters are presented in Table 1.

Table 1. Laser rangefinder parameters.

Parameter	Range/Value
measurement range	diffusion Mode: 0.3–5 m reflective Mode: 0.5–50 m
reading resolution	low level: max 1 mm at 200 mm high level: max 5 mm at 200 mm
settling time	1 s
response settling time	1; 10; 100 ms
min working window size	diffusion mode: 20 mm reflective mode: 40 mm
linearity	diffusion mode: ±30 mm (0.3–1.5 m) ±20 mm (1.5–5.0 m) reflective mode: ±60 mm (0.5–50 m)
temperature coefficient	diffusion mode: <2 mm/°C reflective mode: <3 mm/°C
output type	0–10 V
max load value	1 kΩ
short-circuit and reverse polarity protection	YES
supply voltage	12–24 V
current consumption UT = 24 V	max 108 mA
ambient temperature	0 . . . +55 °C

3. Results

3.1. Methodology for Automatic Course Correction

A moving vehicle, thanks to distance measurements using laser rangefinders, is able to determine its current position in relation to the adopted reference surface. The simplest solution used for this purpose is to measure the distance from a given surface with two laser rangefinders. After appropriate calculations, the angle between the vehicle axis and the given surface can be determined. Knowing the angle and distance of the vehicle from the reference surface and characteristic markers, the actual trajectory of the selected point of the vehicle can be determined.

By comparing the real trajectory with the calculated trajectory for the selected point on the route, one can correct the coordinates and generate a fragment of the trajectory bringing the vehicle to the set path. From a theoretical point of view, this solution is very simple. From a practical point of view, it is not applicable, as a result of the various errors that occur. In real conditions, when the vehicle is in motion, it is not possible to precisely determine the angle of the vehicle axis in relation to the base surface on a short section of the route (s = 0.5–1.5 m). This is the first fundamental error in such a course of proceedings. The second error results from the fact that the vehicle is moving along a curvilinear trajectory while bringing the vehicle to the correct route. In the proposed rate correction algorithm, the most rational solution seems to be dividing the correction process into two stages. In the first stage, the bearing from the laser rangefinder on the selected side of the vehicle is used to determine the shift of the real trajectory from the set one. The value of this offset is taken into account in the odometry algorithm. During the assumed i calculation steps necessary for the vehicle to cover the distance s = 1 m in each iteration, a constant value equal to $1/i$ of the determined shift is added to or subtracted from the stored trajectory. After this sequence of the i iteration is completed, the virtual trajectory tracking point approaches the given route. Then, it covers a distance of 0.5 m, guided by the odometry method. In the second stage, the control system uses measurements from a laser rangefinder to guide the AGV vehicle at a designated distance from the reference surface.

In this stage, an additional correction of the position takes place at the beginning, and only then is the vehicle aligned parallel to the given surface. There is a need to apply additional position correction results from the incorrect determination of the distance between the vehicle and the given surface. In the first stage of the correction process, the laser rangefinder installed in the vehicle measures the distance perpendicular to the longitudinal axis of the vehicle. If the vehicle is not parallel to the base surface, the distance measured by the laser is not the actual distance of the vehicle from the set surface. In order to determine the actual distance of the vehicle from the reference surface, the measurement should be perpendicular to the given surface.

The algorithm of the developed methodology is presented in Figure 4.

In the experimental studies aimed at verifying the developed methodology, several dozen tests were carried out with an AGV vehicle along a specific route. All tests confirmed the correctness of the adopted methodology, and the analytical section presents examples of routes on which the developed methodology was verified.

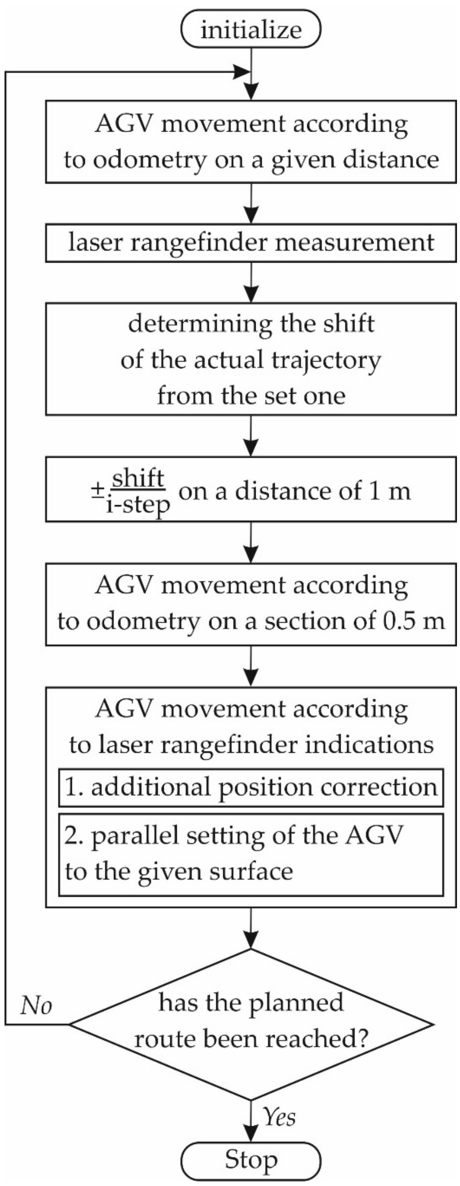


Figure 4. Automatic course correction algorithm.

3.2. Analysis of the Research Results

Two cases were tested in the experimental studies. In the first case, the vehicle was parallel to the reference surface, and in the second case, the vehicle was not parallel to the reference surface (Figure 5).

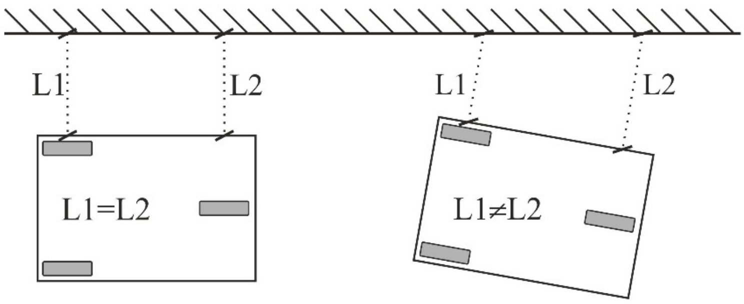


Figure 5. Parallel and non-parallel alignments of the AGV with respect to the reference surface.

Figures 6 and 7 show the test runs, in which the automatic route correction was tested. In both cases, at the beginning of the vehicle's movement, the position of the trajectory actually realized by the vehicle does not coincide with the set trajectory. However, the computational process aimed at determining the course of the theoretical trajectory does not take errors into account, and the calculated trajectory coincides with the set one. This can be seen in both figures in the first eight meters of the distance traveled. In the first case, in Figure 6, the real motion trajectory is parallel to the originally set one. The vehicle axis is parallel to the given direction of movement. After measuring the distance from the base surface l, the first coordinate correction is made. After this correction, the vehicle changes its route, trying to return to the originally assumed trajectory. Distance measurements are taken and recorded throughout the entire movement. The use of these measurements for driving a vehicle along the assumed base surface can be observed only after covering the assumed section of the route necessary to return to the assumed trajectory.

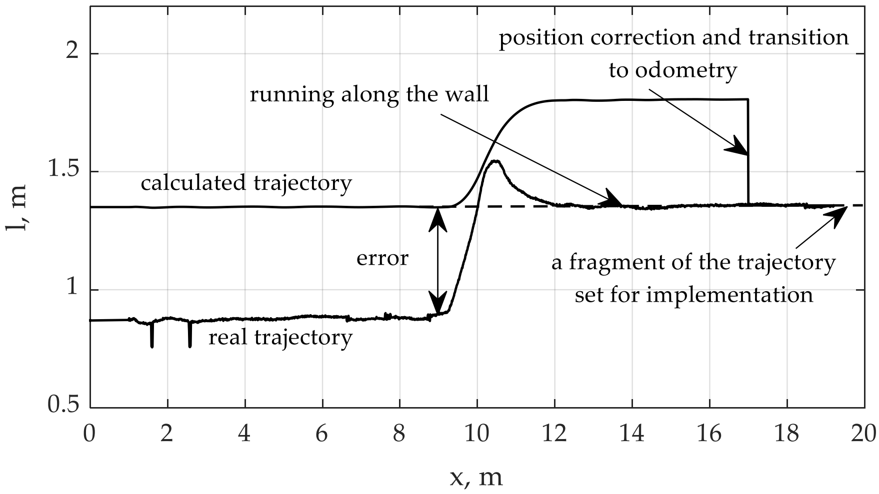


Figure 6. The courses of the real and theoretical trajectories with a parallel position.

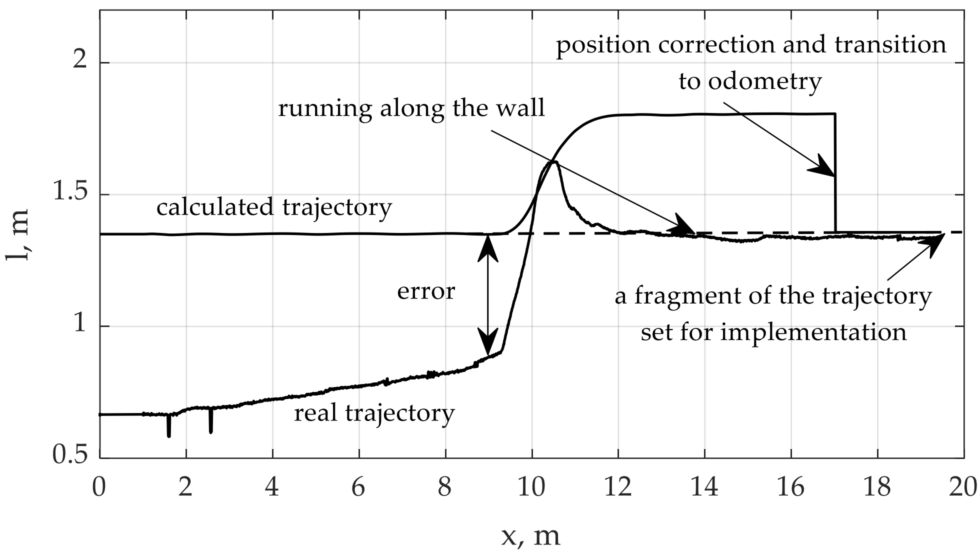


Figure 7. The courses of the real and theoretical trajectories with a non-parallel position.

Figure 7 shows a situation in which the vehicle is not running parallel to the base surface. The trajectory calculated by the computer initially coincides with the given trajectory. Data from the laser rangefinder provide information regarding the actual course of the trajectory and indicate not only the shift, but also the angular deviation from the set route. Such a situation may take place each time, such as after the vehicle exits a turn or after long straight sections have been completed. In the example shown in Figure 7, the course angle and position are corrected.

The conducted research on the automatic route correction was also aimed at determining the minimum section of the route necessary to travel along the adopted reference surface in order to set the vehicle axis parallel to the given surface. After correcting the course, the computer system needs to correct the coordinates used for the calculations and switch to driving the vehicle by odometry. The last position, as well as the angular position of the longitudinal axis of the vehicle in relation to the set trajectory along the distance of the movement at a constant distance from the base surface, is very important for the further course of the vehicle route.

As shown in Figure 1, two characteristic points can be distinguished in the vehicle—point O, lying on the longitudinal axis of the vehicle between the driving wheels, and point W, also lying on the longitudinal axis of the vehicle 1 m from the O point towards the front of the vehicle. There is also a vertical axis, around which the whole vehicle rotates, passing through point O. The W point is the point that follows the trajectory. During the tests, between 9 and 12 m of the traveled route, the vehicle performed a curvilinear motion (Figure 8).

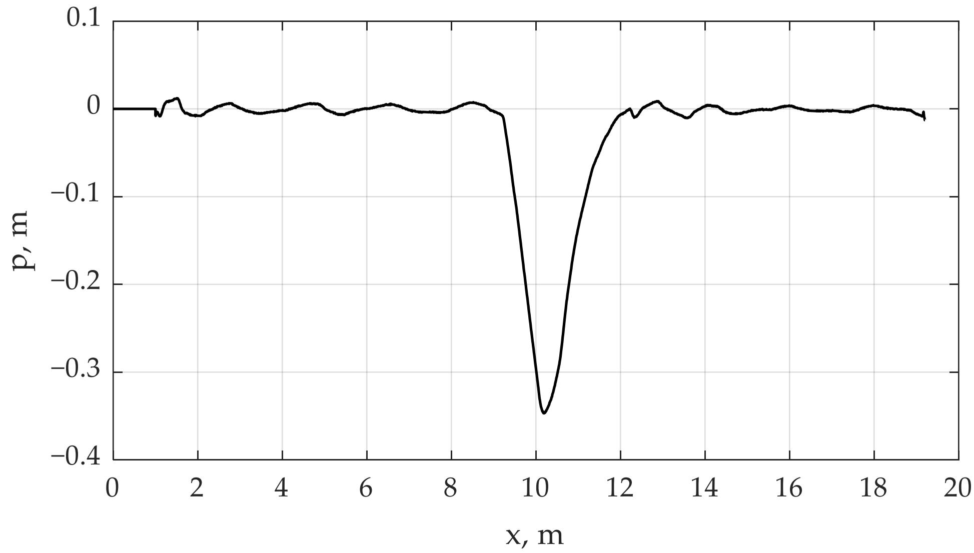


Figure 8. The difference in the positions of points O and W of the vehicle p.

The purpose of this movement was to guide the vehicle to a given trajectory and to pre-align the angular position of the vehicle axis with respect to the reference surface. During the curvilinear motion, the angle between the vehicle axis and the given direction changed. This angle can be determined from the trajectory courses of points W and O. These courses were determined on the basis of the data recorded in the sample, and are shown in Figure 9.

Knowing the trajectories of the selected points W and O on the route section realized by the vehicle, it was possible to determine the angle between the longitudinal axis of the vehicle and the set trajectory β. The results of such calculations, illustrating the course of the deviation angle as a function of the distance traveled, are shown in Figure 10.

Based on the observation of Figures 6–10, it can be assumed that on the 12th meter of the distance traveled, i.e., already on the 2nd meter of the rectilinear section of the movement, the position of the vehicle in relation to the base surface, and in particular the angle between the longitudinal axis of the vehicle and the assumed direction of movement, does not change significantly. The angle between the vehicle axis and the given trajectory is characterized by small oscillations that decrease with the distance traveled. After covering the next 2 m of the road, i.e., at 14 m distance, the angular deviations of the vehicle axis in relation to the set trajectory (Figure 10) do not exceed 0.01 rad.

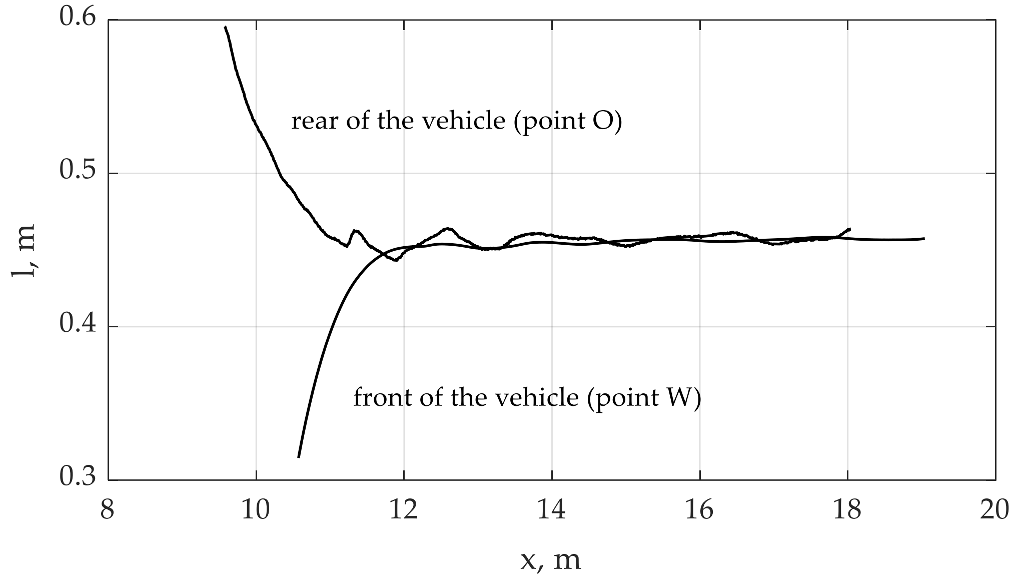


Figure 9. The course of the locations of the selected points W and O of the vehicle on a given route section.

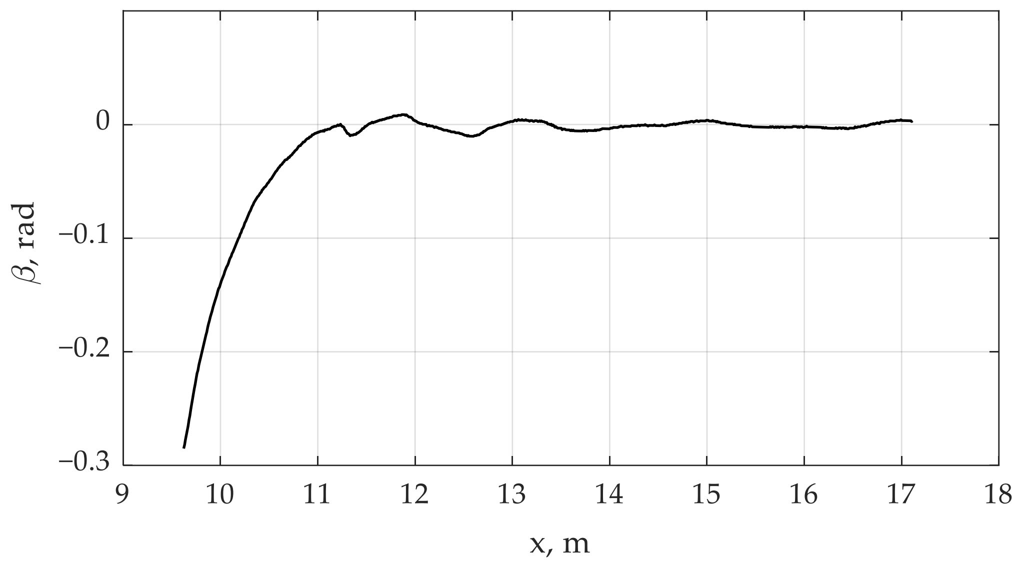


Figure 10. Course of the angles of deviation of the vehicle axis from the given direction of movement.

4. Conclusions

In experimental studies verifying the effectiveness of the developed methodology for automatic course correction, several dozen test drives of the AGV were carried out. The rides were carried out along the assumed route inside the building, and took place in conditions and surroundings which allowed for uninterrupted operation of the laser rangefinders. The conducted test drives, in addition to confirming the effectiveness of the developed methodology, also allowed us to determine the minimum length of the route section on which the vehicle should be driven based on the indications of the laser rangefinder at a fixed distance from the reference surface. It was assumed that the length of this section should be 4 m.

Laser rangefinders are devices that, despite being easy to use, are characterized by advanced measuring functions which make them efficient and accurate measuring devices. Their advantages include, first of all, their accurate range measurement ability, high sampling frequency and high angular resolution. However, they also have some limitations that have been taken into account when designing a measuring system equipped with a laser rangefinder and developing an automatic course correction methodology. One of the limitations which we considered is that most laser rangefinders measure a specific measurement plane, so obstacles or other elements of the environment located above or below the plane are not detectable. The second limitation, which has also been taken into account, is that laser rangefinders are unable to detect optically transparent materials. In addition, laser rangefinders are sensitive to dusty environments. The presence of dust can interrupt the laser beam, which could falsify the measurement. The accuracy of the measurement can also be affected by the vibration of the object. We also paid attention to the distance and position of the sensor in relation to the measuring surface. This cannot be too small or too large, and the sensor cannot be set at too sharp an angle [44,45]. In the experimental tests carried out to verify the developed methodology for course correction, the vehicle was moving inside a building in which no dust was observed; therefore, there was no fear of interrupting the laser beam during the measurements. The use of the laser rangefinder was limited to measuring the planar distance of the vehicle from the reference surface. The elements of the working space in which the vehicle was moving, most often the walls of the rooms, were taken as reference surfaces. In the absence of an appropriate reference area on a given section of the route necessary to update the course, it is possible to create this using very inexpensive means. It should also be remembered that such surfaces are not transparent. The distance of the laser rangefinder mounted on the AGV from the walls was within the measuring range of the sensor. During the measurements, the sensor was also not set at too sharp an angle, which would make it impossible to perform a correct measurement. The impact of the vehicle's vibrations on the measurement of the laser rangefinder mounted on it was also eliminated due to, among other factors, the smooth surface on which the vehicle was moving.

Thus, in the proposed automatic course correction methodology, the aforementioned limitations of the rangefinders did not have a negative impact on its implementation.

The proposed position correction algorithm allows for the elimination of the negative impact of odometry errors. When using odometry alone, the accuracy of determining the position is influenced by many sources of errors, which in turn lead to position errors, including the distance error directed along the assumed trajectory, the error perpendicular to the assumed trajectory and the orientation error.

The presented vehicle is designed to transport loads and goods in warehouses and production halls. Thus, the vehicle should move in narrow corridors, e.g., between racks. In order to be able to perform the transport tasks entrusted to it, it is important that it moves in accordance with the recorded virtual trajectory. The measure of the efficiency of the developed algorithm is the achievement of the actual position of the vehicle in accordance with the position recorded in the virtual trajectory. The entire position correction process should take place over a section of a satisfactory length, and the target effect of its operation should be the extension of the trajectory length covered by the AGV.

The length of the route section freely covered by the AGV depends on the vehicle's surroundings and operating conditions, the distribution of the load on the vehicle and the position of the longitudinal axis of the vehicle in relation to the set trajectory in the initial phase of movement on a rectilinear section.

Uneven loading of the vehicle results in a deviation from the set trajectory. The vehicle, in these conditions, performs a curvilinear motion. Incorrect positioning of the vehicle in relation to the set direction of movement may be the result of mistakes made when changing the direction of movement, e.g., during turns or incorrect initial setting. The impact of single random errors in the form of, for instance, an obstacle is not so significant. However, it is never certain that there are only single obstacles in the vehicle's path. Under unfavorable conditions, there may be many of them, and their impact may add up.

Therefore, in order to increase the positioning accuracy, an additional navigation system should be used. The proposed solution using a laser rangefinder was aimed at simplifying, and, at the same time, reducing the cost of the navigation system while achieving satisfactory experimental results.

Considering the above, it was assumed that in order to provide a sufficient amount of data to drive the vehicle by means of odometry and automatic route correction, it would be sufficient to equip the vehicle with encoders measuring the rotational speed of the driving wheels and two laser rangefinders to measure the distance. Distance measurements with laser rangefinders should be perpendicular to the longitudinal axis of the vehicle. The error caused by measuring the distance not perpendicular to the given surface does not introduce any major disturbances to the developed and tested methods. The cost of a measuring set configured in this way is the lowest compared to other solutions, and the proposed system is characterized by high accuracy.

The proposed methodology will be used to develop a vehicle motion model with an appropriate position correction algorithm to ensure that the vehicle travels a given route. Due to the purpose of the vehicle, it will move around the halls and corridors of warehouses or buildings. As part of the planned research, the authors also plan to focus their attention on the impact of AGV vibrations on the laser rangefinder measurements during its movement.

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