KAUNAS UNIVERSITY OF TECHNOLOGY

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DETECTION OF MOBILE ROBOT COORDINATES USING THE KNOWN ENVIRONMENTAL INFORMATION

Summary of Doctoral Dissertation
Technological Sciences, Electrical and Electronic Engineering (01T)

2016, Kaunas

This doctoral dissertation was prepared in Kaunas University of Technology, Faculty of Electrical and Electronics Engineering, Department of Automation during the period of 2011−2016.

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English Language Editing:
UAB “Synergium”

Dissertation Defence Board of Electrical and Electronic Engineering Science Field:
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The official defence of the dissertation will be held at 1:00 p.m. on 29 August, 2016 at the public meeting of the Dissertation Defence Board of Electrical and Electronic Engineering Science Field in Dissertation Defence Hall at Kaunas University of Technology.

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A summary of the doctoral dissertation was sent on 29 July, 2016.
The doctoral dissertation is available on the internet at http://ktu.edu and at the library of Kaunas University of Technology (K. Donelaičio St. 20, 44239 Kaunas, Lithuania).

KAUNO TECHNOLOGIJOS UNIVERSITETAS

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MOBILIOJO ROBOTO KOORDINAČIŲ NUSTATYMAS NAUDOJANT ŽINOMOS APLINKOS INFORMACIJĄ

Daktaro disertacijos santrauka
Technologijos mokslai, elektros ir elektronikos inžinerija (01T)

2016, Kaunas

Disertacija rengta 2011–2016 metais Kauno technologijos universiteto Elektros ir elektronikos fakultete Automatikos katedroje.

Mokslinis vadovas:
Prof. dr. Kastytis Kiprijonas ŠARKAUSKAS (Kauno technologijos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija – 01T).

Redagavo:
UAB "Synergium"

Elektros ir elektronikos inžinerijos mokslo krypties disertacijos gynimo taryba:
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Disertacija bus ginama viešame elektros ir elektronikos inžinerijos mokslo krypties disertacijos gynimo tarybos posėdyje 2016 m. rugpjūčio 29 d. 13 val. Kauno technologijos universiteto Disertacijų gynimo salėje.

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Disertacijos santrauka išsiųsta 2016 m. liepos 29 d.
Su disertacija galima susipažinti internetinėje svetainėje http://ktu.edu ir Kauno technologijos universiteto bibliotekoje (K. Donelaičio g. 20, 44239 Kaunas).

INTRODUCTION

The main problem of all moving mobile autonomous devices is navigation in space. Mobile robots are autonomous mobile platforms able not only to independently move to a target location, perform certain tasks and return, but also to function as tele-operators.

A new method and algorithms have been developed in this study which could be applied in flexible automated production serviced by mobile robots. The movement of autonomous mobile robots in such production lines is not restricted by railing constructions or other rigid connections; the performed tasks and movement routes are specified for mobile robots which are readily available and the closest to the target at a particular moment.

In order to perform the attributed tasks, mobile robots have to accurately move from the initial coordinates towards the target; at the same time, they have to navigate in the environment so that they can return to the specified route if they deviate from their movement trajectory. Deviation of mobile robots carrying out maintenance of flexible production from the specified coordinates may occur due to certain lateral factors such as oil spills or foreign objects on the path.

Additional hardware and technologies are often employed in order to detect a mobile robot's position in the environment. This thesis proposes two methods for the detection of coordinates on the basis of known environment profile analysis.

Research relevance

Nowadays, problems related to global navigation in an open environment have been successfully solved; however, application of such navigation has become a problematic issue in terms of mobile autonomous robot orientation in the enclosed space of manufacturing premises.

The mobile robot performing any manufacture-related tasks in enclosed premises/spaces has to deal with various obstacles ranging from uneven floors to problems related to errors made within the employed hardware.

The issue of the detection of the mobile robot's position coordinates is extremely topical. The mobile robot has to be at the specified coordinates in order to successfully perform the assigned manufacturing task. The robot can plan its subsequent actions and move safely from point *A* to point *B* only if its position coordinates are known.

This thesis proposes a new method allowing the detection of the mobile robot's position coordinates only by using a profile of the known environment. The objective is to propose algorithms which could detect the mobile robot's position without additional navigation equipment. Such a system for the detection of position coordinates is relevant and could be applied in flexible automated production where the manufacturing process is serviced by autonomous mobile robots.

Specific requirements are set for the method to be created. The requirements include fast detection of position coordinates and adaptation of the method for profiles of different configurations. The algorithms proposed in this thesis satisfy the outlined requirements.

The aim of the research is to develop a method for the detection of the position coordinates of the mobile robot performing service in the field of flexible automated production only on the basis of the known environment profile information and to test the method's functionality.

The objectives are as follows:

1. to analyse the existing methods for the detection of the mobile robot's position coordinates which could be employed for the purposes of the research aim;
2. to improve the methods for the detection of the mobile robot's coordinates in a known environment;
3. to investigate the functionality and operation of the improved methods for the detection of the mobile robot's coordinates in a known environment in case of the presence of differing profiles and dynamic obstacles in the target environment;
4. to propose additional requirements for a flexible automated production system using mobile robots for transportation of parts.

Scientific novelty

1. A new method for the detection of the coordinates in a known environment based on the fitting of the known environment profiles is analysed.
2. A new method for the detection of the coordinates in a known environment based on the use of a known environment profile's centre of gravity is developed and analysed.

Practical value of research results

Application of the created principles enabling the detection of the mobile robot's position coordinates in a known environment without additional hardware when movement trajectories are automatically formed by a supervising control system allowing the solution of the planning issues related to the mobile robot's movement trajectories. The developed method is universal and may be used in the manufacture processes and in the social sphere (service robots) serviced by mobile robots.

Hypotheses

1. Development of the method for the detection of the mobile robot's position coordinates on the basis of the information of a known environment profile configuration.

2. Application of the method for the detection of the mobile robot's position coordinates on the basis of the information of a known environment profile configuration in case of dynamic obstacles in the environment.

Thesis approval

The main results of the doctoral research have been published as one publication in the ISI Web of Science list, two publications in conference proceedings and three presentations at international scientific conferences.

Structure of the thesis

The thesis consists of an introduction, four parts, conclusions, a list of references and a list of the author's publications. The total scope of the thesis is 90 pages including 72 figures, 1 table and 79 bibliographic references.

1. METHODS OF MOBILE ROBOT POSITION DETECTION IN ENCLOSED ENVIRONMENT

One of the main problems of all the existing independently moving autonomous, i.e. unmanned, mobile robotic devices is the detection of their position coordinates in the surrounding environment.

It has to be noted that a mobile robot performing various tasks in enclosed manufacturing premises has to deal with various obstacles ranging from facing a variety of interferences from different objects and new emerging obstacles on the carriageway [1] to problems related to errors of the hardware in use [3, 4, 5]. Despite all these hindrances, a mobile autonomous robot has to move freely to the target location, form a precise profile of the surrounding environment and detect its own actual position in the environment in order to quickly and efficiently perform the attributed task [6, 7].

A mobile device detects its position coordinates on the basis of various additional external systems, i.e. various sensors, external navigation devices, etc., by employing a cyclical sensor survey. On the level of hardware, every cycle may be supported by sensors of various types and operating principles thus creating different amount and intensity data streams.

There are a number of ways to detect a moving object's position. They can be defined as either relative or absolute. Relative position detection methods are inertial navigation [9] and odometry [10, 11]. The absolute position detection method includes active beacons [12, 13, 14].

The choice of different methods and algorithms depends on the tasks to be set and on the requirements for a system. The majority of position detection systems are based on the principles of trilateration and triangulation [2, 8, 15], using ultrasound [16, 17, 61], radio waves [18], etc., scene analysis [8, 19, 20] and proximity [8].

Literature sources [8] also distinguish a few techniques for range measurement: Received Signal Strength (RSS) [21, 22], Time of Arrival (ToA) [23, 24], Time Difference of Arrival (TDoA) [25, 26] and Received Signal (RSP) [27]. For position detection in space, various tags, landmarks [29, 30], etc. are used.

A few other frequently used classifications of position detection systems in an enclosed environment are distinguished in scientific literature [30, 31]:

- position detection based on passive position detection systems (electrical cables [31], tags [31], beacons [12, 13], landmarks [31]);
- position detection based on active position detection systems (inertial navigation [9, 10] and odometric systems [11]);
- position detection using hybrid systems [43−48].

A passive position detection system receives and processes information about position coordinates and other movement characteristics obtained from an external source; meanwhile, an active system itself detects the position. Global navigation algorithms are passive navigation systems, and local navigation may only be passive.

Position detection using hybrid systems apart from additional equipment (landmarks [33, 34, 35, 36] and inertial equipment [37, 28]), also use many algorithms based on 2D and 3D [39, 40, 41, 42] simultaneous localisation and mapping (SLAM) of the environment surrounding the mobile robot [43−48]. Such systems use various computer vision systems.

Literature sources [51] describe how a mobile robot's position coordinates can be detected by analysing the information about the environment surrounding the robot. Such information may be provided by a gradually scanning device, e.g. a scanner.

Information provided by a scanner may be used to create an environment profile which, in turn, could help to find out the coordinates of the mobile robot's position. The analysis of a known environment profile may provide information about the movement and position of the mobile robot and could help to evaluate the movement speed and position of other dynamic objects [51].

Table 1.1 presents a comparison of position detection methods [8, 31, 32] in terms of several parameters, i.e. system error and operation distance.

In summary of the data on errors and distance provided in literature, it can be stated that the smaller the size of the used premises, the smaller is the error in detecting the coordinates of the mobile robot's position.

It was also noticed that many existing methods and algorithms for the detection of the mobile robot's coordinates in one way or another require additional external hardware (video cameras, accelerometers, etc.) and additional equipment (active beacons, tags, landmarks).

Use of additional hardware leads to the creation of new algorithms and methods realising synchronisation of the robot's internal control system and navigation hardware as well as communication establishment.

Table 1.1. Comparison of position detection systems.

Position detection system	Error	Distance
GPS	1–10 m	Global
Tags (RFID technology)	From a few cm to 10 m	1–50 m
Landmarks	1–2 m	50 m
Beacons	Approx. 7 cm	5 m
Inertial navigation and odometry	1% of the size of premises	Unlimited
Mapping	From 10 cm to a few meters	Premises
Infrared ray systems	Up to a few meters	1–10 m
Radio frequency systems	Approx. 1 m	10–100 m
Ultrasound systems	1–3 cm	2–10 m

1.1. Conclusions of Chapter 1

1. The literature analysis showed that the detection systems of the moving object's position in an indoor environment are divided into passive, active and hybrid positioning systems. The passive positioning system receives and processes the information about its location coordinates and other characteristics of its movement, the active system establishes the location position itself, and in the hybrid positioning systems, various computer vision tools are used.
2. The analysis of the positioning methods in a known environment showed that additional external hardware (video cameras, accelerometers, etc.), and various assistive devices (tags, landmarks and others) are necessary for many existing methods of the moving object's coordinate detection.
3. The literature analysis showed that various SLAM algorithms are applied to identify the mobile robot's position coordinates but the error of these methods fluctuates from several tens of centimetres to a meter.
4. The method that was found in the literature to detect the position coordinates is where the coordinates are detected performing the environmental scan. The data of the scientific works has shown that the mobile robot's control system possesses the ability to gather information about the surrounding environment, and it restores the environment profile by using the scanner. However, in this case, as the obtained scientific simulation results show, the robot's position is determined only by analysing the environment characteristic points

rather than by the whole environment. Another deficiency of such a method is that the environment must be rectangular.

2. DETECTION OF MOBILE ROBOT POSITION COORDINATES USING THE KNOWN ENVIRONMENT PROFILE

2.1. Possibilities of detection of mobile robot position coordinates according to the known environment profile

When any autonomous mobile robot performs a task, it is controlled by its own internal control system and an external control system which constantly follows the movement of a mobile device. The internal control system – the supervisor – is a computer system with a programme assigning tasks to free production-maintaining robots and establishing their navigation trajectories.

This system follows how the assigned manufacture-related tasks are being realised in real time and how mobile robots perform navigation on a specified trajectory. The system also anticipates possible conflicts and corrects the routes so that any obstacles are avoided. In order to perform these actions, an external control system needs to know where the mobile robot is at a particular point of time and whether it has deviated from the specified movement trajectory.

When the mobile robot moves along the assigned route, it solves its own autonomous tasks, i.e. the robot scans the environment (follows the coordinates of its own position) and transfers the scanned information over feedback devices to an external control system. If any dynamic and/or static obstacles appear on the path of the mobile robot forcing it to deviate from the specified movement path, the supervisor corrects the movement trajectory and position parameters so that the deviation is minimal.

The robot’s scanning system possesses technical possibilities to perform the scanning of the visible environment and to present the data needed for the calculation of position coordinates. Due to various technical reasons, the robot’s position may not coincide with the position specified by the supervisor as to where the robot should be at a particular point of time. However, an external control system has the possibility to get profile information of the mobile robot performing a manufacture-related task from the point where the robot has to be, compare it with the environment information detected by the robot from its actual point, and, based on that, find the coordinates of the robot’s position as well as to evaluate whether a deviation has occurred. If there is no deviation, no actions have to be taken; however, if a deviation has occurred, the route of the mobile robot has to be corrected for the successful performance of the manufacturing task.

Possibilities of current computer systems allow the solving of additional tasks assuming that the control system of the mobile robot has a time reserve.

Of note is the fact that mobile robots have various scanning devices for the observation of the environment; therefore, by scanning the environment they can collect information about it, create a profile of the "visible" environment and compare it with the profile given by an external control system (supervisor), which has a mathematical model of the known environment.

There are different mathematical models for comparison of information. However, the results of comparison are two-fold: information may or may not coincide, and no particular information about the object to be reached can be obtained. Thus here two possible research and analysis methods are employed allowing the detection of the coordinates of a moving object (in this particular case, the mobile robot) on the basis of the profile information of the environment "visible" by the robot and information received from the supervisor.

2.2. Method for detection of mobile robot position coordinates based on fitting of known environment profiles

The method for the detection of a mobile robot's position coordinates according to a known environment profile is based on the comparison of two profiles (profile scanned by the mobile robot and profile formed by the supervisor).

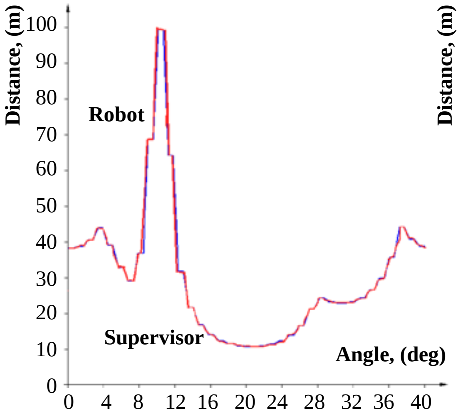
The mobile robot uses its scanning devices to scan the environment and creates a profile of the "visible" environment from the point where it is at a particular time. In parallel, an external control system scans the environment and determines the profile of the "visible" environment from the position where the mobile robot is supposed to be at that moment. When the profiles of the "visible" environment generated by the mobile robot and the supervisor are obtained, they can be compared.

First case: the profiles coincide (Fig. 2.1a), the mobile robot is in the position followed by a supervising system.

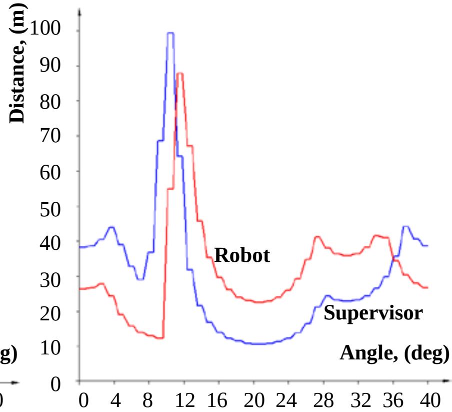
Second case: the profiles of the mobile robot and a supervising system do not coincide (Fig. 2.2b), i.e. the mobile robot has deviated from the specified coordinates due to accidental reasons and its position does not match the given coordinates.

There are a few ways to detect the position coordinates of the mobile robot. The first method is based on the fitting of known environment profiles [6]. For each scanning angle, the difference between the measurements of two profiles is calculated, and then all the obtained differences of scanning angles are summed. The obtained result shows the deviation from the actual coordinates. After the detection of the deviation from the coordinates, the supervisor determines the profile from a different point.

If the obtained result is worse (greater) than the previous one, it can be stated that the new chosen point is even further from the actual coordinates of the mobile robot; yet if the result is better (smaller), it means that the robot is approaching the precise position.



a)



b)

Fig. 2.1. Environment profiles provided by the supervisor and scanned by the robot: a) the robot scanner scans in the same direction and from the same point as the supervisor; b) the robot scanner scans in the same direction as the supervisor, but from the position where the robot actually is, and the supervisor determines the profile from the point where the mobile robot is supposed to be [6]

This means that in order to get the final result, the algorithm for the change of the supervisor's search coordinates is to be applied. A classical optimization task must be applied to the detection of the coordinates of the mobile robot's position after the deviation where the profile mismatch is optimized after the supervisor has changed the coordinates. The result of the profile comparison is the functional optimization which is known as the optimization criteria.

2.3. Method for detection of mobile robot position coordinates based on known environment profile centre of gravity

Another method for the detection of the mobile robot's position coordinates is based on the determination of the centre of gravity of a known environment profile [7]. A scanned profile (in this case, a profile of a known environment, i.e., manufacturing premises) comprises a closed figure. Any figure has one peculiar point, i.e. the centre of gravity. No matter from which point in the same profile environment the scan is performed, the centre of gravity will always be on the same point from the perspective of a profile.

In order to realise this method, two profiles of the same environment are required. One profile is generated by the supervisor with known coordinates which can be flexibly changed, and the centre of gravity of the environment profile has accurate coordinates. Another required profile is generated by the robot which scans the environment and determines the centre of gravity from the perspective of its own position coordinates.

Each of these profiles has a shifted reference point from the perspective of the centre of gravity. This occurs due to the fact that the mobile robot accepts that it is at the point with zero coordinates. If these points where the mobile robot and the supervisor are do not coincide from the perspective of absolute coordinates, the profiles are different, but the centre of gravity has the same coordinates. Thus if the absolute coordinates of the supervisor are known, the absolute coordinates of the centre of gravity are also clear, and they can thus help to detect the absolute coordinates of the mobile robot. The mobile robot scans the environment by changing the angle of the scanner direction and measuring the distance to the closest obstacle. When the environment is scanned at 360º, a series of points are obtained. The points are the peaks of a convex polygon. In the case of a 2D space, this polygon may be called an environment profile. When a known environment profile is obtained from the position where the mobile robot is at a particular point of time, the centre of gravity of this profile can be calculated. In parallel, an external control system generates an environment profile from the position where the mobile robot is supposed to be and, thus, calculates the centre of gravity of the generated profile.

Generally, the coordinates (x_C and y_C) of the centre of gravity of a plane figure defined by surface S are calculated as follows [7]:

$$x_C = \frac{1}{M} \iint_S x \cdot \sigma(x, y)\, dx\, dy; \qquad (2.1)$$

and

$$y_C = \frac{1}{M} \iint_S y \cdot \sigma(x, y)\, dx\, dy. \qquad (2.2)$$

Here, M is the mass of a polygon figure and $\sigma(x, y)$ is the density which is required when the figure is not homogeneous or its thickness is changeable [7]. Mass is calculated as follows [7]:

$$M = \iint_S \sigma(x, y)\, dx\, dy. \qquad (2.3)$$

When the mobile robot moves inside the manufacturing premises, information about the environment profile is needed in order to detect the position coordinates. This information allows the calculation of the position of the centre of gravity. Other parameters are not significant as the environment is homogeneous. When calculations and modelling have been performed, it is accepted that density equals 1 ($\sigma = const = 1$) in expressions (2.1−2.3). When density equals 1, mass $M \Rightarrow S$, expressions for the detection of mobile robot coordinates become simpler [7].

$$x_C = \frac{1}{M} \iint_S x \cdot dxdy; \tag{2.4}$$

and

$$y_C = \frac{1}{M} \iint_S y \cdot dx\,dy. \tag{2.5}$$

The obtained coordinates of the centre of gravity of the supervisor's and robot's environment profiles are compared. If the mobile robot is in the coordinates specified by a supervising system, i.e. there is no deviation (due to foreign moving objects/mechanisms or a technical fault) from the given coordinates, then the values of the centre of gravity of the environment profiles generated by the supervisor and the mobile robot should coincide (Fig. 2.2a).

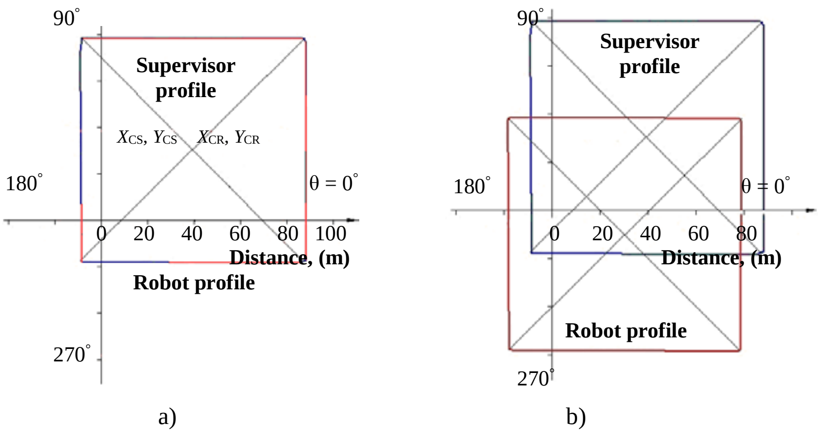


Fig. 2.2. Environment profiles and their centres of gravity provided by the supervisor and scanned by the robot: a) the robot scanner scans in the same direction and from the same point as the supervisor; b) the robot scanner scans in the same direction as the supervisor, but from the position where the robot actually is, and the supervisor determines the profile from the point where the mobile robot is supposed to be

If the deviation of the mobile robot from the coordinates specified by an external control system occurs, then the values of the centre of gravity of the “visible” environment profiles provided by the supervisor and scanned by the mobile robot will not coincide (Fig. 2.2b).

The point from which the known environment is scanned is not significant; therefore, the position of the centre of gravity of a profile figure will always be the same with respect to the profile, which means that the obtained difference between the centres of gravity allows the calculation of the coordinates of the robot’s position.

It is clear that the known environment profile will be finite only in the case of an enclosed environment, i.e. when there are no points that are too far for the scanner.

2.4. Conclusions of Chapter 2

1. Two methods for the detection of the mobile robot’s position coordinates are presented and analysed. The methods are based on the analysis of the environment profile information obtained by the scanning system of the mobile robot and by the supervisor.
2. The first method is based on the fitting of known environment profiles generated by the mobile robot and the supervisor. It is proposed that the fitting task should be solved so that the differences between the profiles generated by the robot and modelled by the supervisor be minimal even when the coordinates possessed by the supervisor about the mobile robot position change. This means that a classical nonlinear programming optimisation task is applied.
3. The other method is based on the detection of the centre of gravity of a known environment profile figure. It is shown that it is possible to detect the actual coordinates of the mobile robot position in a known environment if the coordinates of the centre of gravity of a known environment profile separately determined by the supervisor and the mobile robot and robot coordinates where it is supposed to be at a particular point of time calculated by the supervisor are known. The centre of gravity of a profile generated by the mobile robot and the supervisor should then be at the same point because both profiles coincide.

3. DEVELOPMENT OF THE METHODS FOR DETECTION OF MOBILE ROBOT POSITION COORDINATES IN A KNOWN ENVIRONMENT

3.1. Realisation and analysis of functionality of the method for detection of mobile robot position coordinates based on a known environment profile fitting

The method for the detection of the mobile robot's position coordinates according to a known environment profile is based on the comparison of a few profiles (generated by the mobile robot and the supervisor). In order to compare information about the known environment profiles generated by the mobile robot and the supervisor, the difference in terms of profile area, i.e. the absolute integral minimum of the profiles difference criterion, has to be considered (Fig. 3.1).

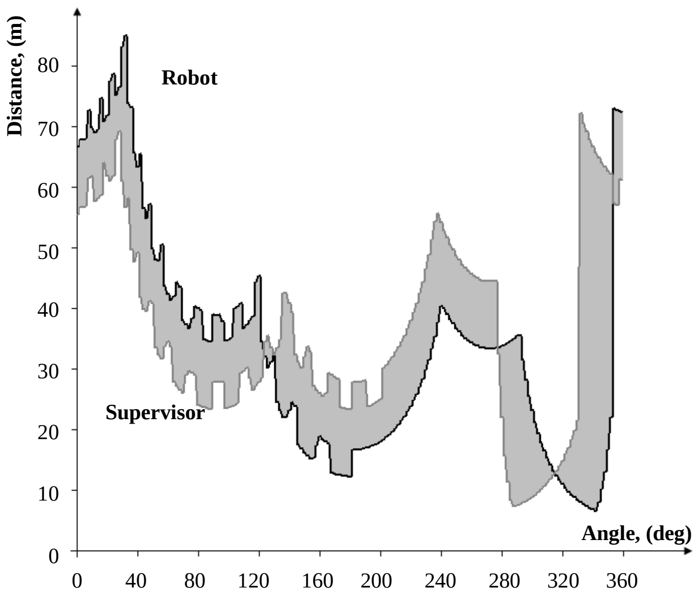


Fig. 3.1. Profiles generated by the supervisor and the mobile robot. The difference between profiles is marked in grey

Absolute integral minimum of the profiles difference criterion is calculated as follows:

$$E = \int_{0}^{360} \left| F_{S\alpha} - F_{R\alpha} \right| d\alpha \Rightarrow \min; \qquad (3.1)$$

where $F_{S\alpha}$ and $F_{R\alpha}$ refer to the beam length of the profiles modelled by the supervisor and scanned by the mobile robot. The lengths match the same scanning angle direction. α is the scanning interval (in degrees) of the scanner.

Upon the coincidence of the supervisor's and mobile robot's coordinates, the integral criterion of the profile difference will be equal or close to zero.

If the coordinates of the supervisor and the mobile robot differ, the integral criterion of the profile difference will not equal zero.

When the profiles do not match, the optimization procedure is carried out. According to the optimization algorithm, the supervisor changes the robot's coordinates so that the integral criterion of the profile differences should decrease. When the integral criterion of the profile differences no longer decreases, the optimization is complete because the supervisor has found the nearest coordinates to those where the robot currently is.

3.1.1. Choice of optimisation strategy. Multidimensional methods of steepest descent

In order to find the mobile robot's position coordinates, the detection needs to be performed by changing coordinates *x* and *y*; therefore, multidimensional optimisation methods are the most appropriate for such detection. The simplest multidimensional space has two coordinates; the criterion function value in such a case would be the third coordinate, i.e. the criterion function would be depicted as the surface on a three-dimensional space. If two parameters are changed, the criterion is a spatial surface; if there are more than two parameters, the surface is multidimensional and is otherwise known as a hypersurface [49].

In multidimensional methods, new information about the environment is obtained through scanning, and new values of extremities are searched for. If the result following the calculations is lower than found previously, the information is useful; and if the obtained result is greater, the information is useless. In order to perform further calculations, the best value, particular coordinates and other necessary parameters are entered into the memory.

The aim of all the multidimensional methods is to perform as few calculations as possible in the search of extreme values. Many multidimensional optimisation methods use information about a gradient. The gradient's physical nature can be best reflected on a three-dimensional space. According to [49], if we take any point on the surface of a three-dimensional space, the highest ascension from this point will match the gradient's direction, and the direction of the highest slope will be reverse to the gradient's direction. The majority of methods that are gradient-based are called the steepest descent methods. Since calculations are performed not by fluxions but by changes, only the gradient that is close to the actual one is calculated. There are various calculation algorithms, and many calculation methods have been created on their basis.

A variety of optimisation methods have appeared because of the different nature of optimisation criterion function. Gradient methods have a drawback because they tend to conduct detection to the closest extremity. The studies of the authors [6, 7] have shown:

- if a profile is homogeneous (the homogeneity convex polygonal profile with only minor fluctuations, without strongly protruding parts), the criterion function has only one minimum;
- if a profile is homogeneous but there is insignificant variation in profile limits, the criterion function has many local minimums; however, if a large initial optimum search step is chosen, a local minimum with a value close to the global minimum may be found;
- if a profile is non-homogeneous, i.e. it possesses protruding walls, niches, etc., it cannot be stated that the detected minimum will be global and the method cannot be applied for detection.

For these reasons, it is advisable to use the optimization method independent from the direct gradient search because more time is spent on additional gradient calculations. In the literature [52] it is recommended to use the Simplex or Rosenbrock optimization method. However, applying the Simplex method after each search the simplex value needs to be recalculated; therefore the optimization criterion calculation time also increases.

Meanwhile, the Rosenbrock method, unlike the gradient methods and the Simplex method, carries out the search in each coordinate direction in order to calculate the algorithm so that the performed steps were always successful [52].

First, the method for the detection of the mobile robot position coordinates according to a known environment profile was tested by way of analysis of the simplest circular environment profile where there are no angles or static and dynamic obstacles.

For the analysis of the functionality of the method for the detection of the mobile robot's coordinates in case of a known environment profile, the virtual environment Centaurus CPN was used [50].

The operation of the models formed in a virtual environment was tested on a personal laptop with technical parameters as follows: Intel® Xeon® CPU 5110 processor, 1.6 GHz (4 nuclei), 8.00-GB RAM, and 64-bit operating system.

Figure 3.1a presents the surface illustrating the change of criterion function in a completely empty circular space. Since there is only one substantially expressed extremity on this surface, the solution of an optimisation task is not problematic for such a functional value. Figure 3.2a shows the reverse value of functional *E* surface as such an illustration is clearer.

The analysis of a simple configuration circular environment profile demonstrated that in the case of Rosenbrock's optimisation algorithm, a small initial step (1% of the starting coordinate) was sufficient in order to detect the mobile robot's position coordinates.

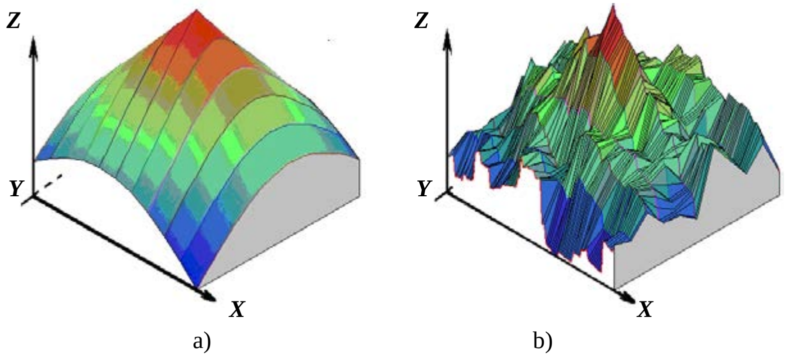


Fig. 3.2. a) Reverse value surface of circular profile criterion function; b) reverse value surface of manufacturing premises (with obstacles) criterion function when there is one global extremity and multiple local extremities that can be clearly seen on the surface section

The modelling results showed that, in case of scanning the environment at an interval of 1°, the *x* and *y* coordinates of the mobile robot were detected with a 0.1 mm error (Fig. 3.3).

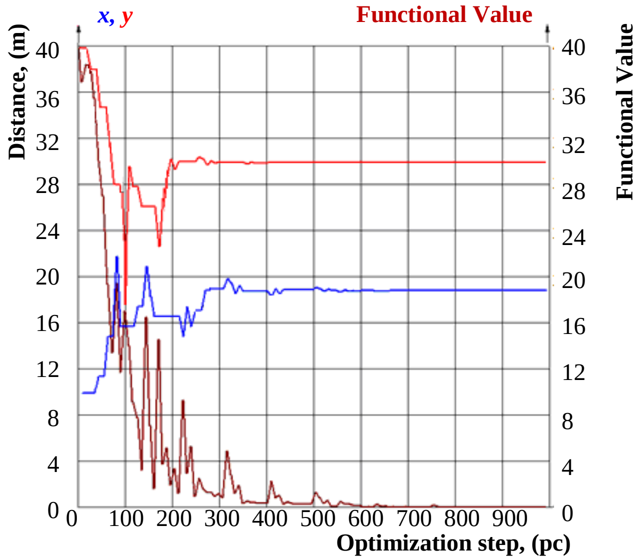


Fig. 3.3. Detection of a mobile robot's position coordinates in a polygonal profile by Rosenbrock's optimisation algorithm (change of *x* and *y* coordinates and functional value) when the environment scanning interval is 1°

Further, the method was tested on square and polygonal profiles at the same environment scanning interval as for a circular profile.

Rosenbrock's optimisation algorithm is realised in a different way when additional static obstacles appear (polygonal profile). In such a case, the functional surface looks complicated and possesses multiple local extremities (Fig. 3.2b). For the optimisation algorithm to work efficiently, a greater initial search step (10% of the starting coordinate) should be chosen.

The modelling results also showed that, in case of scanning the environment at an interval of 1°, the *x* and *y* coordinates of the mobile robot were detected with a 0.1 mm error. This precision coordinate search is conducted in order to demonstrate that the algorithm of the profile fitting method functions and allows a maximum of 0.1 mm error to be reached in coordinate detection.

The speed of detection of the mobile robot's position coordinates was analysed with the profile scanning interval at 1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, 18 and 36 degrees and the given error for detection of coordinates at 0.1 mm, 1 mm, 1 cm, and 10 cm. The results obtained from the analysis of 3 profiles are presented in Figures 3.4−3.6

The study demonstrated that the coordinates were determined in 7.79 s in case of a square profile, in 7.29 s in case of a circular profile, and in 10.92 s in case of a polygonal profile (when the environment was scanned at every single degree).

The detection time of the mobile robot's position coordinates depends on the chosen scanning interval.

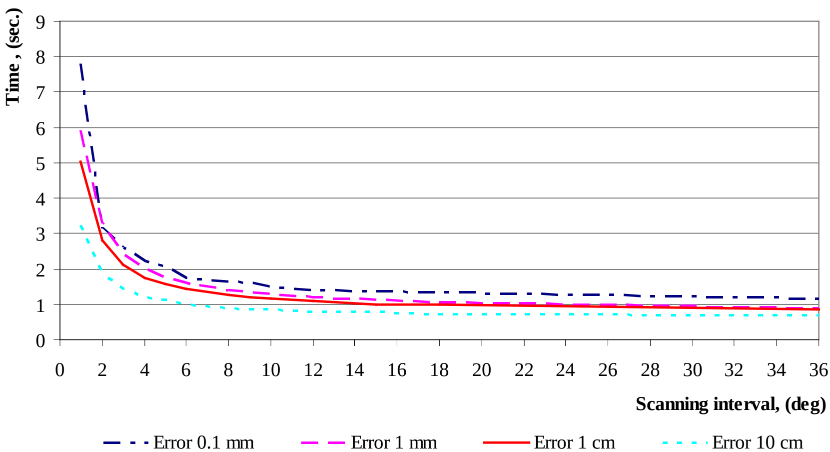


Fig. 3.4. Dependence of the detection time of the mobile robot's position coordinates on the scanning interval (square profile) based on the method of fitting of known environment profiles

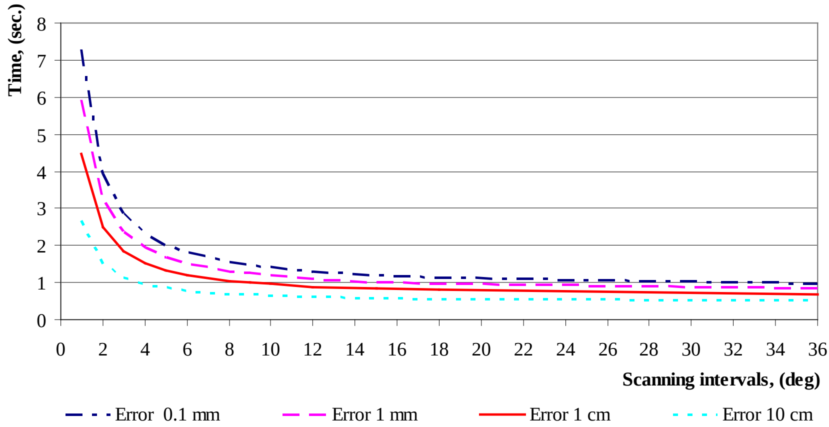


Fig. 3.5. Dependence of the detection time of the mobile robot's position coordinates on the scanning interval (circular profile) based on the method of fitting of known environment profiles

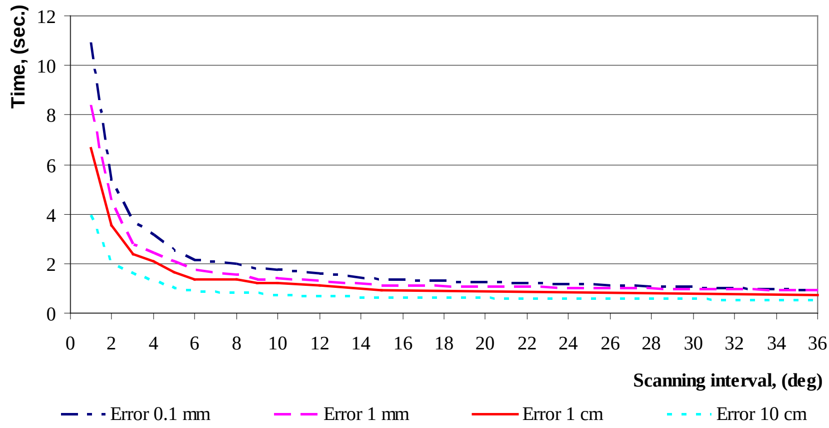


Fig. 3.6. Dependence of the detection time of the mobile robot's position coordinates on the scanning interval (polygonal profile) based on the method of fitting of known environment profiles

The smaller the environment scanning interval is, the more time is required to detect the coordinates.

The time needed for the detection of position coordinates depends on the profile complexity. The fastest results are obtained in the environments where visible environment profiles are not distorted in comparison with the original.

In the environments with simple configuration, the scanning interval may be increased in order to minimise the time needed for the detection of coordinates.

In case of very simple and symmetric profiles (circular and square), position coordinates are detected at an error of 0.1 mm and a scanning interval at 36º. However, for more complicated profiles (with static obstacles), such scanning intervals become too big and position coordinates may not be detected.

Thus, with respect to the data obtained, it can be stated that when the profile fitting method is used and simple configuration profiles (square, circular, polygonal) are taken, the scanning interval needs to be in the range of 5−10º.

In this thesis, it is accepted that the mobile robot moves at the speed of 1 m/s. Therefore, the detection of position coordinates with a millimetre or a tenth of a millimetre error is inappropriate since the robot can cover a distance of 1 m in one second, and the coordinate detection time at each scanning step is about 1 s or even higher, so when the coordinates are detected, it will have moved at least 1 m further.

In summary of the obtained results, the detection of the mobile robot's coordinates based on a visible environment profile by one or the other optimisation method is of an iterative nature. Exactly for this reason, the detection of the mobile robot's coordinates using the profiles fitting method takes from 0.8 to 11 seconds.

3.2. Realisation and analysis of the method for detection of mobile robot position coordinates based on the known environment centre of gravity

3.2.1. Mathematical substantiation of the method

Let us suppose that the centre of gravity of the profile-defined environment is known, and the "visible" environment is limited by a contour comprising a convex polygonal (Fig. 3.7). When the position of the mobile robot changes from point *A* to point *B*, the "visible" environment profile of the mobile robot also changes but the centre of gravity of the polygonal figure is at the same point from the perspective of profile *C*.

When the position of the mobile robot changes from point *A* to point *B*, the "visible" environmental profile changes as well, but the polygonal shape centre of gravity with respect to *C* profile remains in the same place. This point (*C*) is the coordinates on the absolute environmental profile centre of gravity which are known by the supervisor in advance. Figure 3.7 shows the situation when the mobile robot has deviated from the task movement route from point *A* to point *B*. Point *A* is the position in which the mobile robot must be and where the supervisor is. Point *B* is the position, where the mobile robot actually is. Both the supervisor and the mobile robot by developing the environmental profile from the different positions consider that they appear in the zero coordinates (the supervisor at [x' y'], and the mobile robot at [x'' y'']), i.e. they calculate the coordinates of the relative environmental profile centre of gravity. The supervisor knowing the absolute coordinates of the centre of gravity and having the coordinates of the relative centre of gravity and the robot's relative centre of gravity can calculate the absolute coordinates of the mobile robot's position.

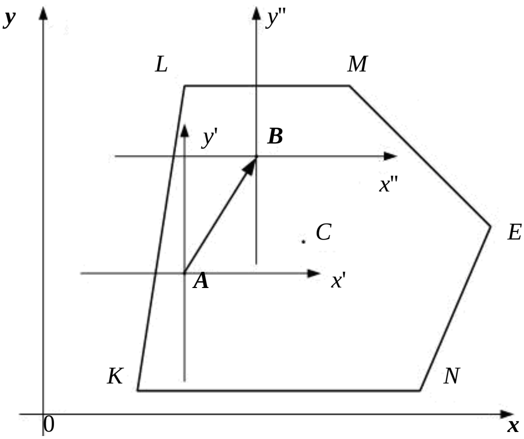


Fig. 3.7. When the position of the mobile robot changes (points *A* and *B*), the "visible" environment profile also changes, but the centre of gravity of figure ENKLM is at the same point from the perspective of profile *C*

Coordinates of the centre of gravity of a plane figure (x_C and y_C) are calculated on the basis of expressions [7]:

$$x_C = \frac{1}{M} \iint_S x \cdot dx\, dy; \tag{3.2}$$

and

$$y_C = \frac{1}{M} \iint_S y \cdot dx\, dy. \tag{3.3}$$

A moving mobile robot "sees" the environment from a changing position $(x_R; y_R)$. If profile coordinates $(x'; y')$ are read from the position of the robot (scanner), the environmental contour coordinates in the system of non-moving coordinates $(x; y)$ are as follows:

$$x = x' + x_R, \quad y = y' + y_R. \tag{3.4}$$

When $\sigma = const = 1$, the coordinates of the centre of gravity of a polygonal with the number of apices n are calculated as follows:

$$x_C - x_R = \frac{1}{6M}\sum_{i=0}^{n-1}(x_i' + x_{i+1}')(x_i' y_{i+1}' - x_{i+1}' y_i'); \qquad (3.5)$$

$$y_C - y_R = \frac{1}{6M}\sum_{i=0}^{n-1}(y_i' + y_{i+1}')(x_i' y_{i+1}' - x_{i+1}' y_i'). \qquad (3.6)$$

Thus coordinates K_R of the mobile robot's position may be illustrated by a column matrix:

$$K_R = \begin{bmatrix} X_{CS} - X_{CR} + X_S \\ Y_{CS} - Y_{CR} + Y_S \end{bmatrix}; \qquad (3.7)$$

where X_{CS} and Y_{CS} are the coordinates of the profile's centre of gravity from the point of view of the supervisor's zero coordinates; X_{CR} and Y_{CR} are the coordinates of the profile's centre of gravity from the point of view of the mobile robot's zero coordinates; and X_S and Y_S are a position point of the supervisor on the plane of coordinates. It does not matter at which angle the mobile robot scanner begins scanning because the distance between the centre of gravity and the actual coordinates of the mobile robot is the same; therefore, if the robot's rotation angle deviation from its starting point is known, its detected centre of gravity C_α may be transformed as follows:

$$C_\alpha = \begin{bmatrix} \sqrt{X_{CR}^2 + Y_{CR}^2} \times \cos(arctg\left(\frac{Y_{CR}}{X_{CR}}\right) - \alpha) \\ \sqrt{X_{CR}^2 + Y_{CR}^2} \times \sin(arctg\left(\frac{Y_{CR}}{X_{CR}}\right) - \alpha) \end{bmatrix}; \qquad (3.8)$$

where α is the angle at which the robot turned from its specified task.

In order to avoid unnecessary calculation (3.8) and to directly conduct the detection of coordinates based on dependence (3.7), the mobile robot should have a position-orienting device which could be used for strict fixation of an initial scanning angle.

Thus the detection of position coordinates using both the known environment profile and the known environment centre of gravity methods requires the mobile robot and its external control system to have the same starting point of the environment profile. Operation and functioning of this method were tested on circular, square and polygonal profiles (Figs. 3.8–3.10). In environments of simple configuration, the position coordinates were determined with a 0.1 mm error.

It was determined that the time spent on the detection of coordinates changed within the range of 0.01 s and 0.162 s when the scanning interval was changed.

Detection of the mobile robot’s position coordinates is based on the method of a known environment profile’s centre of gravity giving a better speed in comparison with the method of the fitting of known environment profiles.

The application of this method may help to avoid iteration procedures and significantly improve the speed in the detection of coordinates.

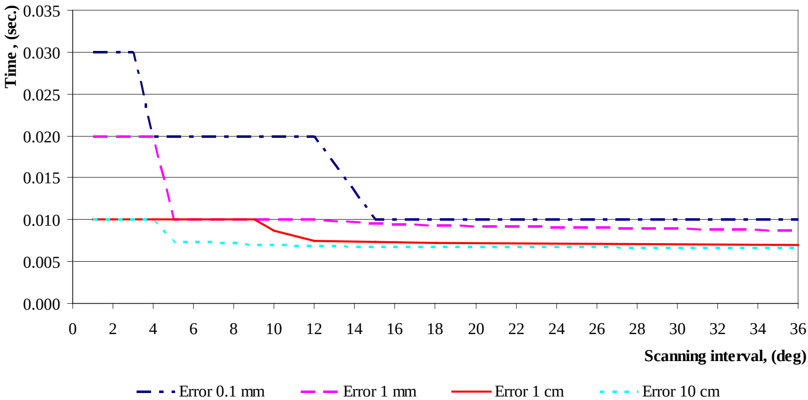


Fig. 3.8. Dependence of detection time needed for the mobile robot’s position coordinates on the scanning interval (square profile) based on the centre of gravity method

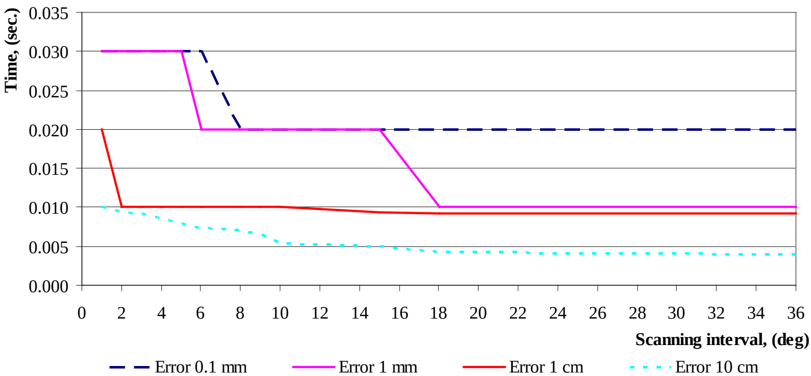


Fig. 3.9. Dependence of the detection time needed for the mobile robot’s position coordinates on the scanning interval (circular profile) based on the centre of gravity method

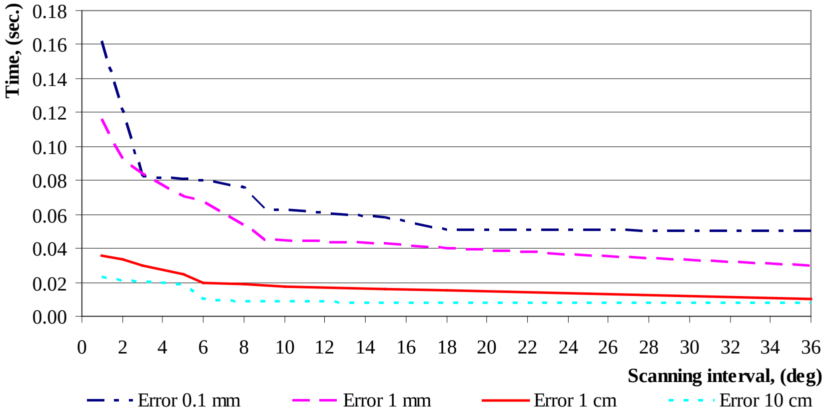


Fig. 3.10. Dependence of the detection time needed for the mobile robot's position coordinates on the scanning interval (polygonal profile) based on the centre of gravity method

Considering the fact that the coordinates are detected in dynamics (the robot moves at a speed of 1 m/s), a mismatch between the coordinates found by the supervisor and the coordinates which the robot acquires over time until they are fixed by using the profiles fitting method is unacceptably high; thus further only the coordinates of the mobile robot position detection by the method of the centre of gravity will be used in this work.

The more complicated the environment configuration is, the smaller scanning intervals are needed; therefore, we continue to investigate a variety of configurations in the industrial environment scan which will be performed at an interval of 1 degree.

3.3. Detection of mobile robot position coordinates in a more complicated configuration environment

In a flexible automated manufacture where there is no line production, mobile robots are used for the transportation of parts and other products. Mobile devices perform various manufacture-related tasks like transportation of products to ordinary construction controlled machines; therefore, the manipulators may need to service 1–1.5 m high spaces.

E.g. robot Seekur Jr [60] weighs 77 kg, and can transport 40 kg. The height of the platform where the manipulators are mounted is 494 mm, the width is 835 mm and the length is 1051 mm. Having evaluated the equipment placed in the dock, the length can be increased to 1198 mm. The robot's maximum speed is 1.2 m/s.

The mobile robot which provides maintenance for manufacturing mechanisms may perform the transfer of a product being transported to controlled machines in 2 ways. The first is a precise positioning of the mobile robot to the exchange position. This method is appropriate for robots that are fixed in their positions. However, in this case, the mobile robot's hardware parts are more expensive because precise positioning is required.

Second, all the autonomous mobile robots have the equipment to park on the dock, which is necessary in order for the mobile robots to automatically recharge their working power source. Depending on the size of the robot and its purpose, a wide variety of technical solutions on how to park on the dock have been created beginning from the dock search system and ending with the positioning and locking on the dock systems. Various docking systems have been created for small-sized robots starting from the mechanical structures (funnel-shaped form, robot shell-shaped form and so on) and the infrared systems with the initial positioning accuracy of 1.5–3.5 cm [53–56]. To achieve the specific goals of this, the most suitable robotic equipment to park on the dock has been chosen which uses the infrared positioning systems with a mechanical guide at the back thus positioning the robot both on the battery charging and on the working position of the manipulator at the machine tool. The initial positioning systems for such robots are between 7–15 cm [57–59]. Approaching the machine tool, the mobile robot is directed by the guide to the dock, and with the help of the machine tool equipment it is accurately positioned on the exchange position. The guide is compensated by the directional deviation in this way significantly simplifying the overall mobile robot's control system hardware part. This validates the further highlighted 6 cm coordinate detection error. When the mobile robot arrives at the exchange position, the proper positioning will be ensured. Guides will compensate deviations from the direction thus significantly simplifying the hardware of the mobile robot's control system. Therefore, further in this thesis, a 6 cm error for the detection of coordinates is accepted. When the mobile robot approaches the exchange point, appropriate positioning may be ensured.

Profiles of manufacturing premises where the process is serviced by mobile robots are more complicated than it can be considered from the first glance. Ideally circular or square premises are rare. Manufacturing premises with many angles or other protruding static obstacles such as columns are more common.

Let us suppose that the manufacturing process takes place in closed premises with dimensions 100 × 100 m (Fig. 4.1). Machines produce separate parts for various purposes. Blanks of parts and produced parts are stored in the storeroom. Different types of blanks are there: the first blank for the first part; the second blank for the second part; the third blank for the third part, etc. The duration of the manufacturing process of different machines is different. Mobile robots take produced parts from machines and transport them to the storeroom; also, they transport the necessary blanks from the storeroom to the manufacturing premises. The produced parts are transported by robots to the storeroom. The premises where parts and blanks are stored are also serviced by other systems ensuring placement of blanks and transportation of parts so that positions in the storeroom accessible by the robot are always ready for work (Fig. 4.1).

In the course of the manufacturing process, machines produce parts which have to be transported by the mobile robot closest to the manufacturing machines to the storeroom or other manufacturing machines. The mobile robot also has to perform an opposite instruction, i.e. to directly transport a blank required for further manufacturing from the storeroom.

The research algorithm is as follows: since the mobile robot can deviate in any direction in any place of the premises, the detection of the position coordinates is performed at various points even in the case of maximal deviation distances.

In the detection of the mobile robot's position coordinates, it is accepted that the robot always deviates from its specified coordinates at the same point, and the robot's position coordinates specified by the supervisor are positioned in all the directions at the same distance from the actual robot's position, for example, at 10, 20 or more metres. Such big distances are taken in order to, first, determine whether the position coordinates are appropriately detected in the case of big deviations and, second, to find out the time required for the detection of coordinates.

In the initial stage of the research and modelling, the point of the supervisor's position was selected at a certain distance randomly, and it was observed with what error the realistic mobile robot position is defined. It is noted that depending on which side the mobile robot is removed from the task coordinates received from the supervisor, the error rate differs a few times, so it was decided to carry out the research for a given point in all possible situations. Therefore, further research was carried out as follows: it was considered that the mobile robot deviated to the current (real) coordinate received as the supervisor's task and equally-spaced positions outlined by 360 degrees with respect to the current position of the robot. Depending on the environmental profile configuration and other obstacle placement in the environment and the supervisor's task position, the error can vary, so it was assumed that the robot's position coordinates received as the supervisor's task during the study will be placed in all directions at a certain distance. Describing the error change in the polar coordinate system it can be observed how, depending on the scan angle direction, the error of the position coordinate detection changes.

Thus, first, the situation was analysed as follows: the robot deviated from the given coordinates to the point [50.00 50.0], and the robot's position coordinates specified by the supervisor were positioned in all the directions at 10, 20, 30 and 40 m distances.

The results demonstrate (Fig. 3.11) that the error in detecting the mobile robot's position coordinates does not exceed 4 cm.

Although in the real environment an external control system will never allow the mobile robot to deviate from the specified coordinates at 20−40 or more metres, the results illustrated in Figure 3.11 show that the method operates and determines the place of the mobile robot in such a case, too.

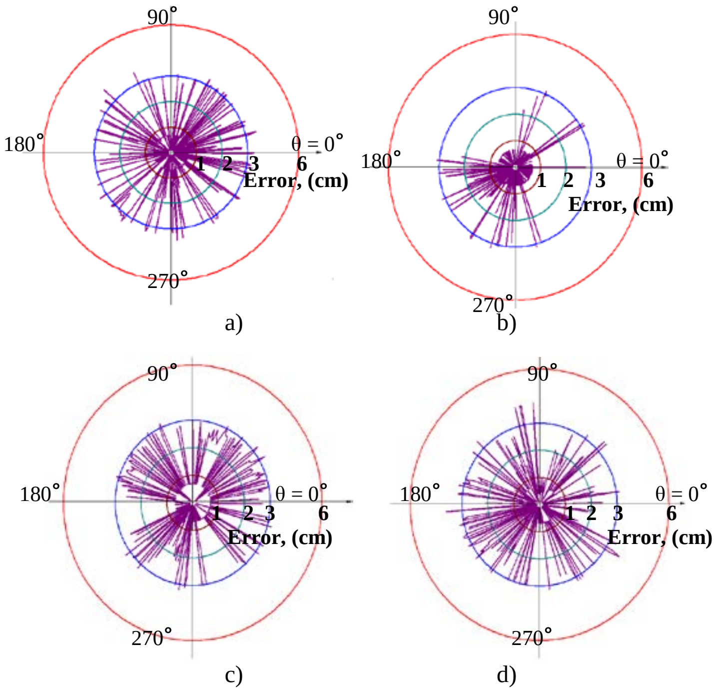


Fig. 3.11. The obtained error when the mobile robot is in the coordinates [50.0 50.0] and the actual coordinates (specified by the supervisor) are positioned in all the directions: a) at a 10 m distance; b) at a 20 m distance; c) at a 30 m distance; d) at a 40 m distance

Also, we analysed how the error of detection of the mobile robot's coordinates changes when the robot is in points [30.0 30.0], [30.0 70.0], [70.0 70.0] and [70.0 30.0] and the coordinates of the robot's position specified by an external control system are positioned in all the directions at 5, 10 and 20 m distances. The results demonstrate that the configuration of the environment where the mobile robot operates significantly influences the error in detecting the position coordinates.

The further the mobile robot is from obstacles, the smaller is the error of the position coordinates and, vice versa, the closer the mobile robot moves to obstacles, the greater is the error in the detection of its position coordinates.

In those cases when the mobile robot deviates from the specified coordinates at a greater distance, the performed environment scanning from any position produces the accuracy in detecting the mobile robot's position coordinates which does not exceed 6 cm.

Regardless of the distance between the mobile robot's and supervisor's positions, the application of the method of the known environment profile's centre of gravity allows the detection of the position coordinates within the range of 0.026–0.298 s (Fig. 3.12).

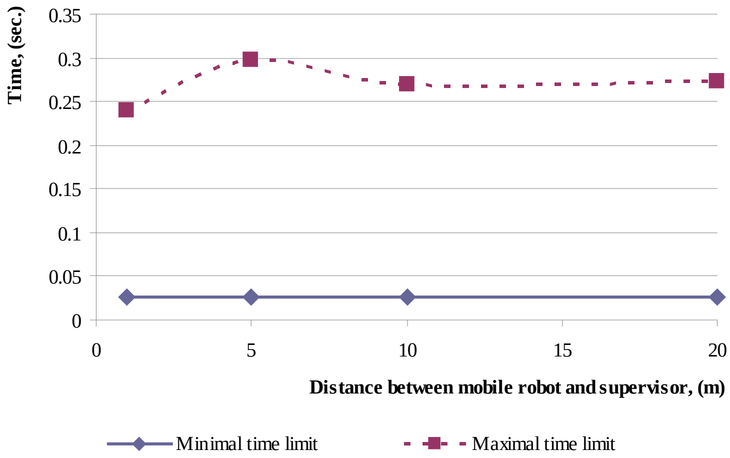


Fig. 3.11. Time interval within which the mobile robot's position coordinates are detected in the manufacturing environment

Such time dispersal is obtained due to the fact that being close to the walls and other obstacles it is necessary to adjust the coordinates of the centre of gravity by doing the repeated calculations. Repeated coordinate recalculation is carried out with the coordinates of the position where the robot coordinates were established, and for this fact the profile form changes thus becoming closer to the robot detection form and hence its position coordinates are calculated more accurately. This adjustment can be terminated when newly received coordinates differ from the previous ones by less than 6 cm.

3.4. Conclusions of Chapter 3

1. Two methods for the detection of the mobile robot's position coordinates based on the use of information about a known environment profile were tested.

2. It has been determined that the detection of the mobile robot’s coordinates on the basis of the known environment profile fitting method and application of one of the optimisation methods is iterative.
3. The conducted analysis of the methods shows that the mobile robot and an external control system (supervisor) need to have the same reference point of the obtained environment profile.
4. It has been determined that the time required for the detection of the mobile robot’s position coordinates depends on the environment scanning interval, configuration of static obstacles and the mobile robot’s deviation from the specified coordinates. The smaller the deviation is, the faster is the detection of the position coordinates.
5. It was found that the duration of the search applying the profile fitting method (for circular, square and polygon profiles) to define the mobile robot coordinates is 10 m, and the scanning step is 10 resulting in the relay timeframe of 4.48 s to 6.65 with 1 cm coordinates error.
6. It was found that the duration of the search applying the centre of gravity method (for circular, square and polygon profiles) for the mobile robot’s coordinate search when the deviation is 10 m, and the scanning step 10 is from 0.01 s to 0.072 s with 1 cm coordinates error.
7. In the course of modelling, it has been determined that the method of the centre of gravity allows the detection of the mobile robot’s position even when the difference from the actual robot’s position and the position where it is supposed to be is up to 40 m. In this case, the error in detecting the position coordinates does not exceed 6 cm, and the time required for the detection is within 0.05 s to 0.256 s depending on the profile configuration.
8. The mobile robot’s position coordinates are detected when the robot is moving. For this reason, the method of a known environment profile’s centre of gravity should be applied for the detection of the coordinates. The conducted comparative analysis demonstrates that, in case of various simple profile configurations (for circular and square profiles) when the environment scanning interval is 1º, the robot’s position can be detected 250 times faster and with polygon profile and about 68 times faster when the centre of gravity method is applied in comparison with the detection of mobile robot’s position coordinates based on the known environment profile method. The method based on the fitting of profiles is appropriate for the detection of the mobile robot’s position only when speed is not one of the major requirements for the system.

4. REQUIREMENTS FOR A SYSTEM OF DETECTION OF MOBILE ROBOT POSITION COORDINATES

4.1. Influence of configuration of manufacturing premises on the error and time of detection of mobile robot position coordinates

Since the error in detecting the mobile robot's position coordinates varies depending on the size of the obstacles and their number in the manufacturing space, the influence of highly protruding obstacles on the accuracy of the coordinate detection was analysed. The manufacturing environment was supplemented with different areas, i.e. an area for people where robots are not allowed and an area where the assembling of parts is performed. Such a profile was analysed from several perspectives.

First, it was determined how the error in detecting position coordinates changed when the mobile robot was in point [50.0 60.0], and the coordinates specified by the supervisor were positioned in all the directions at a 10 m distance. Second, error change was analysed when the robot was in the points of the environment shown in Figure 4.1, i.e. [30.0 30.0], [30.0 70.0], [70.0 70.0] and [70.0 30.0], and the robot position coordinates specified by an external control system were positioned in all the directions at 5 and 10 m distances.

The tests performed in various points of such manufacturing space demonstrated that some results obtained from the perspective of the robot's position profile did not satisfy the requirements raised for the system of position coordinate detection.

The modelling results demonstrated that the error in detecting the mobile robot's position coordinates increased when highly protruding obstacles appeared in the environment. Because of protruding obstacles, the robot and the supervisor calculate centres of gravity of a different profile and they do not coincide.

Therefore, in the space with such profile features as highly protruding parts of premises, the obtained results are unacceptable. In such premises, either robot movement areas should be restricted or the configuration of the manufacturing space should be changed.

In order to minimise the time spent on the detection of the coordinates and the error, the manufacturing space should be designed as illustrated in Figure 4.1, i.e. all the mechanisms, the auxiliary area for people where robots are restricted and a separate area for the assembling unit should be positioned along the walls thus leaving more space for the mobile robot's movement inside the premises.

Figure 4.1 illustrates the space where accuracy and speed were analysed when the mobile robot deviated from the specified coordinates to the following points: [50.0 50.0] (point *A*), [30.0 30.0] (point *B*), [30.0 70.0] (point *C*), [70.0 70.0] (point *D*) and [70.0 30.0] (point *E*); when the robot's position coordinates specified by the supervisor were positioned in all the directions at 10, 20 and

30 m distances; when the mobile robot was in the centre of the environment at 5 and 10 m distances; and when the robot was in the other marginal positions.

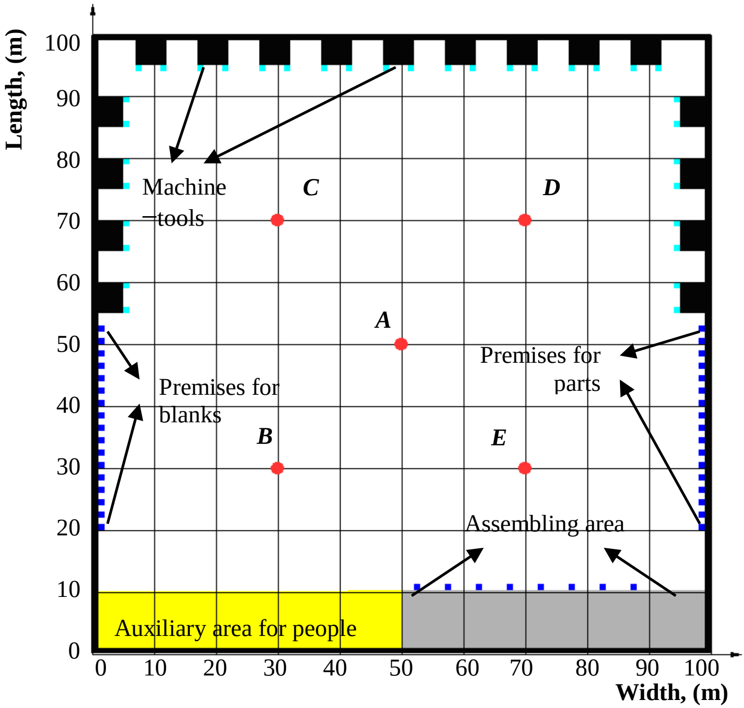


Fig. 4.1. Configuration of manufacturing premises with marked points where scanning takes place

The results obtained demonstrated that a desirable 6 cm error in detection of position coordinates might be achieved if the manufacturing premises were designed as illustrated in Figure 4.1.

Figure 4.2 illustrates the correlations between time and robot-supervisor distance. It is demonstrated here that the position coordinates are detected within 0.031–0.243 s.

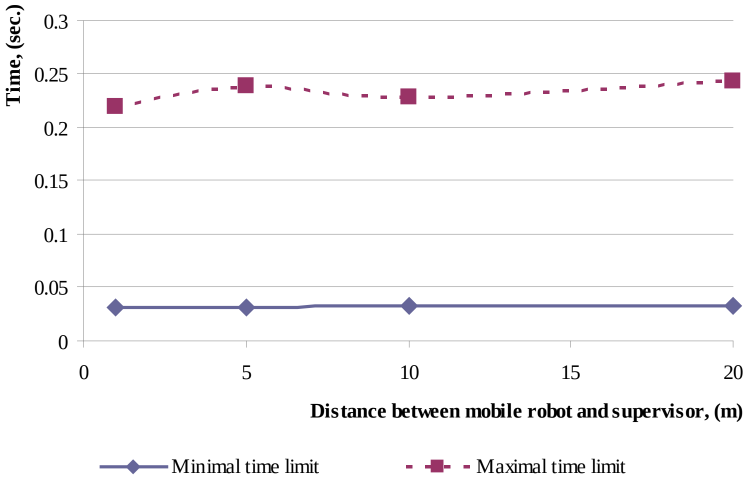


Fig. 4.2. Time interval within which a mobile robot's position coordinates are detected in the manufacturing premises environment in case of a large deviation

4.2. Influence of extra obstacles in the manufacturing environment on time and error in detection of mobile robot position coordinates

In the manufacturing environment where the process is serviced by mobile robots, apart from static obstacles (mechanisms, etc.), dynamic obstacles (mobile robots) will also appear. Dynamic obstacles and their positioning in the manufacturing environment influence the obtained view of an environment profile as well as the error and speed in detecting coordinates.

The speed and accuracy in detecting coordinates were analysed in a manufacturing environment profile (Fig. 4.1) with dynamic obstacles positioned at different points.

According to the obtained results, the detection of the mobile robot's position coordinates is still possible with a smaller than 6 cm error when a dynamic obstacle approaches the mobile robot to such a distance that it blocks no more than 11.3° of the scanner's scan profile. In this study, the accepted diameter of the mobile robot is 1 m; thus, its coordinates are detected with a 6 cm error if another robot is not closer than 5 m because in such a case it covers less than 11.3° angle and does not block the environment profile. This also applies to static obstacles, i.e. different constructions and objects in the area.

Since an external control system knows where each mobile robot should be at each point of time and forms an optimal movement trajectory, it may also influence how a system detecting coordinates works. Checking of the mobile robot's position coordinates should be performed when the distance between the robot and the closest dynamic or static obstacle is greater than the limitations of the system detecting coordinates allows.

All the previous research studies on the detection of the mobile robot's position coordinates were performed when the mobile robot was at a further distance from the analysed profile's margin than 20% of the maximal size of the premises. This helped to evaluate the influence of the profile configuration and placement of mechanisms in the premises. However, situations are also possible when the mobile robot has to approach the target position and take or place a product, and the distance between the robot and a wall decreases to the minimum. Until this moment, the robot's coordinates should be checked in order to have an error-free positioning procedure.

The conducted research showed that position coordinates could be determined with a smaller than 6 cm error when the mobile robot deviated from the positioning point at a 0.5 m distance in all the possible directions.

An external control system plans the mobile robot's movement trajectory and needs to evaluate that each mobile robot should approach the positioning device forward and at reduced speed when a certain distance is left to this device.

The obtained results also helped to analyse how the error in detecting position coordinates changed when 11 mobile robots moved in different points of the manufacturing environment at the same time. In such a case, the greater the concentration of dynamic obstacles at a certain point is, the greater is the error in detecting the mobile robot's position coordinates.

The greatest error was obtained at the points where the mobile robot was surrounded by other moving vehicles; however, the error did not exceed 6 cm. In such points where the distance between the robot and dynamic obstacles was greater, position coordinates were detected with a 1 cm error.

There are such positions and points where coordinates are detected with the greater than 6 cm error. In these points, the accuracy in detecting coordinates reaches the limit of 7 cm because some robots are close to the defined critical distance limit. The conducted research demonstrates that checking of the mobile robot's position coordinates is advisable at least every 1 s so that even in the worst case the robot would deviate from the given coordinates by no more than 1 m; then, the detection of the coordinates should not cause greater problems.

4.3. Evaluation of influence of mobile robot scanner error

The mobile robot's scanning system operates with a certain error and, thus, less significantly influences the accuracy of the position coordinate detection in comparison with the error provided by a used scanner. This occurs due to the fact that the mobile robot's scanning system performs integration of obtained data due to which the final result gives a smaller error upon the evaluation of the error of the scanner's beams.

In this study, when modelling was performed, it was found that the given error influenced the accuracy in the detection of the mobile robot's position coordinates. Three cases were analysed: when a scanner's given error was ±1%, ±2% and ±5%, and the maximal scanning beam was 70 m. When the space is scanned from point [50.0 50.0], the longest possible beam given by a scanner is 70 m. Deviations in the profile generated by the mobile robot are influenced by a scanner measurement error.

Let us assume that the given scanner error is in the range of ±1% (70 cm); then, the mobile robot's position coordinates following the method of the known environment profile's centre of gravity are determined with a 0.03% (2 cm) error.

An advantage of the detection of the mobile robot's position coordinates based on the method of a known environment profile's centre of gravity is obvious: when the scanner's given error is within the range of ±2% (1.4 m), the position coordinates are determined with a 0.09% (6 cm) error; when the error is 5% (3.5 m), position coordinates are determined with a 0.16% error (11 cm); and when the error is ±10% (7.0 m), position coordinates are determined with 0.7% (50 cm) error. The error given in this method in the detection of the centre of gravity coordinates is 25 times lower than the error given by a scanner.

4.4. Requirements and recommendations for a flexible automated manufacturing system using mobile robots for transportation of parts

Analysis of the data obtained in the research allows the definition of the main requirements and recommendations for the system of the detection of the mobile robot's position coordinates.

First, it is necessary to note that the detection of the mobile robot's position coordinates is performed by using the method based on the use of the centre of gravity.

Requirements and recommendations for manufacturing environment: Since the detection time of coordinates depends on the configuration of the static obstacles, the manufacturing environment should be designed so that mechanisms and other units are positioned along the walls.

Requirements and recommendations for a positioning system of manufacturing mechanisms. Positioning systems of manufacturing mechanisms should fix the mobile robot so that its manipulation system is always in a precisely determined position or they should themselves perform precise positioning of an object taken from the mobile robot. It is advisable to use a battery recharging system for the robot docking system. The errors from the exact location are very different and depend on the same industrial mechanisms, as well as on what accuracy is needed to transfer the loads robot - machine and machine-robot.

The requirements and recommendations for the flexible automated manufacturing system.

1. It is of urgent importance that the mobile robot and an external control system (supervisor) have the same starting direction of environment profile scanning.
2. It is recommended that an error given by a scanner does not exceed ±2%.
3. A checking interval of the mobile robot's position coordinates should match the speed of the robot: the greater is the robot's speed, the denser is the interval. The maximal interval between measurement intervals should not exceed the time during which the robot moves 1 m.
4. The mobile robot must approach the dock from the front in order for the parking on the dock and manipulator positioning to be carried out properly.

Requirements and recommendations of the mobile robot parameters used in the flexible automated production:

1. Environment scanning interval should not exceed 1º.
2. Checking of mobile robot coordinates needs to be performed at the starting point of positioning. The mobile robot can reach this position from any angle and with any orientation of its direction; however, it is necessary to properly change the direction of the robot; therefore the robot chassis structure must be such that the robot can rotate about its axis without changing its coordinates and can move towards the positioning device forwards and slowing down.
3. It is advisable to perform the checking of position coordinates no less frequently than the time the robot travels the distance of 1 m, when the supervisor assesses the robot's route at the turning moment and the current environmental situation in relation to other moving robots.

Requirements and recommendations for an external control system. An external control system should preferably perform transference of only the necessary information about a profile where the robot should at a particular point of time be to the robot's external control system. Then, the robot should itself perform the detection procedure of coordinates and communicate to the supervisor which, in turn, would make further decisions. When the supervisor plans mobile robot movement trajectories, it should ensure that the detection of robot position coordinates is conducted only if any obstacle blocks less than 11.3º angle for the robot's scanner.

4.5. Conclusions of Chapter 4

1. It has been determined that the time required for the detection of coordinates and detection error depends on the configuration of obstacles (both static and dynamic).
2. It has been determined that in the manufacturing room where the profile is a polygonal shape, there are some positions where it is impossible to determine the coordinates of the robot with the required accuracy.
3. It has been determined that mobile robot position coordinates may still be detected with a smaller than 6 cm error if any static or dynamic obstacles block no more than 11.3º of the scan profile.
4. It has been determined that the checking of the mobile robot's position coordinates should be performed only when the distance between the robot and the closest moving object is greater for it to block 11.3º of the scanned environment profile.
5. Since there are many mobile robots in the manufacturing environment and the supervisor has to solve tasks related to both robot navigation and task distribution, it is expedient to delegate the checking of the mobile robot's coordinates to the robot's control system and to transfer the obtained result to an external control system which would conduct further robot control.
6. It was experimentally determined that position coordinates might be determined with a smaller than 6 cm error when the mobile robot is in front of the positioning device and moves towards it even if the distance between the robot and a static obstacle is smaller than 1 m.

CONCLUSIONS

1. The literature analysis showed that the mobile robot coordinate detection methods which are applied in practice and use a variety of algorithms require additional external hardware (tags, beacons, etc.). The only method that demonstrates the possibility of the mobile robot's coordinate detection by using a scanner also does not guarantee the ability to reach the targets as it determines other objects in the known environment using the environmental characteristic points at simple configuration environment profiles.
2. Two detection methods of the mobile robot's coordinates in a known environment have been developed that use only the robot's scanner to collect the information. In the first method which is based on matching the environmental profiles, the coordinate search algorithm was developed, the optimization strategy was formed, the coordinate detection times were set for various profiles and scanning step. In the second method of the mobile robot detection coordinates in a known

environment, which is based on the use of the centre of gravity, it was found that the scanning must be performed in steps of 1°, and it must be carried only when the dynamic obstacles do not obscure more than 11.3° premises profiles, the requirements for a space profile have been set to ensure successful coordinate search.

3. It was determined that the coordinates of the mobile robot's position are determined approximately 50 times faster by applying the centre of gravity method, and the profile fitting method is applicable only when robots move slowly or are fixed in their position. It has been determined that checking of the mobile robot's position coordinates should be performed only in such a case when the distance between the robot and its closest moving object is greater than the value allowing it to block 11.3° of the scanned environment profile. In this case the mobile robot's position coordinates may be detected with a smaller than 6 cm error. It was found that the profile form of the premises must be the convex polygon with respectively placed equipment.
4. When mobile robots provide services in automated manufacture, the position coordinate testing interval should match the robot speed, i.e. the greater is the speed, the denser is the interval. The maximal interval between measurement intervals should not exceed the time during which the robot moves 1 m. In order to obtain reliable results, the error provided by a scanner should not exceed 2–3%.

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REZIUMĖ

Darbo aktualumas

Šiais laikais sėkmingai išspręstos globaliosios navigacijos atviroje aplinkoje problemos, tačiau tokios navigacijos taikymas tampa probleminis kalbant apie mobiliojo autonominio roboto orientaciją uždarose gamybinių patalpų erdvėse.

Mobilusis robotas, atliekantis įvairias gamybines užduotis uždarose patalpose/erdvėse, susiduria su įvairiausiais trukdžiais pradedant patalpos grindų netolygumais ir baigiant problemomis dėl naudojamos aparatūrinės įrangos klaidų.

Mobiliojo roboto padėties koordinačių nustatymo problema labai aktuali. Mobilusis robotas turi būti tose koordinatėse, kurios jam yra nurodytos, nes tik tada bus įvykdyta jam priskirta gamybinė užduotis. Žinodamas savo buvimo vietos koordinates, jis gali planuoti tolimesnius veiksmus, saugiai judėti iš taško *A* į tašką *B*.

Šiame darbe siūlomas naujas metodas, leidžiantis naudojant tik žinomos aplinkos teikiamą informaciją nustatyti mobiliojo roboto padėties koordinates. Siekiama pasiūlyti algoritmus, kurie mobiliojo roboto padėtį nustatytų be papildomos navigacinės aparatūrinės įrangos. Tokio pobūdžio padėties koordinačių nustatymo sistema yra aktuali ir gali būti taikoma lanksčioje automatizuotoje gamyboje, kurią padeda vykdyti autonominiai mobilieji robotai.

Kuriamam metodui yra keliami tam tikri reikalavimai. Pirmiausia, padėties koordinačių nustatymo greitaveika, taip pat adaptacija įvairios konfigūracijos profiliams. Šiame darbe sukurti algoritmai šituos reikalavimus atitinka.

Darbo tikslas ir uždaviniai

Darbo tikslas – išplėtoti mobiliojo roboto, naudojamo lanksčioje automatizuotoje gamyboje, padėties koordinačių nustatymo žinomoje aplinkoje metodą, pagrįstą tik matomos aplinkos teikiamos informacijos analize, ir patikrinti metodo funkcionalumą.

Darbo uždaviniai

1. Išanalizuoti egzistuojančius mobiliojo roboto padėties koordinačių nustatymo metodus, kurie galėtų tikti darbo tikslui pasiekti.
2. Patobulinti mobiliojo roboto koordinačių nustatymo žinomoje aplinkoje metodus.
3. Ištirti patobulintų mobiliojo roboto koordinačių nustatymo žinomoje aplinkoje metodų funkcionalumą ir veikimą, esant įvairiems profiliams ir dinaminėms kliūtims tiriamoje aplinkoje.
4. Pateikti papildomus reikalavimus lanksčios automatizuotos gamybos sistemai, naudojančiai mobiliuosius robotus detalėms transportuoti.

Mokslinis naujumas

1. Ištirtas naujas koordinačių nustatymo žinomoje aplinkoje metodas, pagrįstas žinomos aplinkos profilių sutapatinimu.
2. Išplėtotas ir ištirtas naujas koordinačių nustatymo žinomoje aplinkoje metodas, pagrįstas žinomos aplinkos profilio svorio centro panaudojimu.

Darbo rezultatų praktinė vertė

Sukurtų principų, realizuojančių mobiliųjų robotų padėties koordinačių nustatymą žinomoje aplinkoje nenaudojant papildomos aparatūros – kai judėjimo trasos automatiškai formuojamos naudojant valdymo sistemą su supervizoriumi – taikymas leidžia efektyviai spręsti mobiliųjų robotų judėjimo trajektorijų planavimo klausimus. Išplėtotas metodas yra universalus ir gali būti pritaikytas gamybiniuose procesuose bei socialinėje sferoje (paslaugų robotai), kur naudojami mobilieji robotai.

Ginamieji teiginiai

1. Mobiliojo roboto padėties koordinačių nustatymo, naudojant tik žinomos aplinkos profilio konfigūracijos informaciją, metodo plėtotė.
2. Mobiliojo roboto padėties koordinačių nustatymo, naudojant tik žinomos aplinkos profilio konfigūracijos informaciją, metodo pritaikymas, kai aplinkoje yra dinaminės kliūtys.

Bendrosios tyrimų išvados ir rezultatai

1. Atlikus literatūros analizę nustatyta, kad judančių objektų koordinačių nustatymo metodai, kurie yra taikomi praktikoje, ir jiems naudojami įvairūs algoritmai reikalauja papildomos išorinės aparatūros (žymės, švyturiai ir kt.). Vienintelis metodas, kuriame naudojamas skeneris aplinkai analizuoti, taip pat neužtikrina darbe iškelto tikslo pasiekimo, kadangi nustato kitų objektų padėtį žinomoje aplinkoje naudodamasis aplinkos charakteringaisiais taškais, esant nesudėtingos konfigūracijos patalpos profiliams.
2. Išplėtoti du mobiliojo roboto padėties koordinačių žinomoje aplinkoje nustatymo metodai, pagal kuriuos informacijai rinkti naudojamas tik roboto skeneris. Taikant pirmąjį metodą, kuris yra pagrįstas patalpos profilių sutapatinimu, sudarytas koordinačių paieškos algoritmas, nustatyta optimizavimo strategija, apskaičiuota koordinačių nustatymo trukmė įvairiems profiliams ir skenavimo žingsniui. Antruoju mobiliojo roboto padėties koordinačių žinomoje aplinkoje nustatymo metodu, kuris yra pagrįstas patalpos svorio centro panaudojimu, nustatyta, kad skenavimą reikia vykdyti ˛ingsniu 1°, skenavimą vykdyti tik tada, kai dinaminės kliūtys

neužstoja daugiau nei 11,3° patalpos profilio, taip pat nustatyti reikalavimai patalpos profiliui.

3. Eksperimentiškai apskaičiuota, kad mobiliojo roboto padėties koordinatės yra nustatomos vidutiniškai 50 kartų greičiau taikant svorio centro metodą, o profilių sutapatinimo metodas taikytinas tik tuo atveju, kai robotai juda lėtai ar stovi vietoje. Nustatyta, kad jei tarp roboto ir kito artimiausio judančio objekto atstumas yra didesnis, negu skenuojant patalpą jis užstos 11,3° patalpos profilio, padėties koordinatės nustatomos su ne didesne nei 6 cm paklaida. Nustatyta, kad patalpos profilio forma turi būti iškiliojo daugiakampio, atitinkamai joje išdėstant įrenginius.
4. Mobiliųjų robotų, naudojamų lanksčioje automatizuotoje gamyboje, padėties koordinačių tikrinimo intervalas turėtų būti tuo tankesnis, kuo didesnis yra robotų judėjimo greitis. Patartina, kad maksimalus intervalas tarp matavimų neviršytų laiko, kol robotas nueina 1 metrą. Norint gauti patikimus rezultatus reikia, kad skenerio paklaida neviršytų ±2–3 %.

UDK 621.865.8(043.3)
SL344. 2016-07-19, 3 leidyb. apsk. l. Tiražas 60 egz. Užsakymas 284.

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