Запропоновано метод локалізації та навігації мобільного робота в середовищі зі змінними властивостями за умов обмежених можливостей для дистанційного керування, що передбачає можливість перемикання режиму керування роботом в стан автономної навігації. Метод базується на комбінованому застосуванні нечіткої моделі і RL-алгоритму, який дозволяє покращувати набір нечітких правил, використовуючи сигнали підкріплення Запропоновано удосконалення методу локалізації мобільних об'єктів з використанням технології iBeacon та NFC у просторі з відомими картами приміщень, що дозволяє скоротити кількість необхідних для локалізації передавачів.

В роботі модифіковано алгоритм визначення маршруту руху мобільних об'єктів з використанням методу Jump Point Search (пошук шляху по стрибковим точкам). Суть модифікації полягає у використанні в алгоритмі манхеттенської відстані між координатами точок маршруту. Це дозволяє зменшити вплив окремих викидів на результати обчислень в порівнянні з базовим алгоритмом.

Отримані результати можуть бути використані в системах керування мобільним роботом в середовищі зі змінними властивостями за умов обмежених можливостей для дистанційного керування. Результати тестування запропонованих методів та відповідних обчислювальних процедур підтверджують їх працездатність та перспективи практичного застосування. Застосування наведеного підходу дозволяє враховувати конфігурації перешкод та корегувати стратегію навігації для поліпшення якості системи (у 95 % тестових експериментів мобільний робот досягав мети в середовищі з різними типами перешкод)

Ключові слова: мобільний об'єкт, локалізація, автономна навігація, нечіткий регулятор, керування з підкріпленим навчанням

LOCALIZATION AND NAVIGATION OF MOBILE ROBOTS IN AN ENVIRONMENT WITH VARIABLE PROPERTIES

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1. Introduction

Localization and navigation tasks are fundamental for efficient operation of such mobile objects as mobile robots or other mobile controlled devices. Control systems (remote or stand-alone) must be equipped with localization means and algorithms of tracking the route that has to be observed to reach the target. In order to navigate mobile controlled objects, the most possible accuracy of indications of their location is most often required.

Localization within buildings has become an urgent topic because of development of navigation of moving objects in production, defense industry, trade, health care, extraordinary state monitoring, etc. The global positioning system which is most widely used in open areas has drawbacks that render impossible its use in establishing location of objects moving indoors. The main disadvantage of this system consists in the need for direct visibility between the satellite and the receiver. For successful autonomous navigation indoors, the mobile object control system must build routes and control parameters of movement (for example, set turning angle of wheels and speed of their rotation). In addition, this system must correctly interpret the environmental information received from sensors and constantly monitor current coordinates.

Development of a combined approach involving possibility of performing both remote (using the principles of supervisory control) and autonomous navigation of mobile objects, for example, mobile robots (MR) is an urgent task. In this case, quality of localization and navigation of autonomous MR (AMR) in complicated dynamic environments being considered in this paper can be improved by means of computation intelligence (in particular, fuzzy and neural network models).

2. Literature review and problem statement

Let us consider existing approaches to realization of the tasks of MR localization and navigation in environments with various abilities of position control. Among current positioning and navigation systems, the Global Positioning System (GPS) that operates ground and space equipment should be pointed out. Localization within buildings has

become an urgent topic due to development of moving object navigation in production, defense industry, trade, health care, monitoring of emergency states, etc. It should be noted that obstacles and noise sources within buildings affect the GPS accuracy [1]. This is caused by ever increasing density, height and area of buildings. Under such conditions, systems of the GPS type are ineffective for positioning moving objects inside large buildings (museums, exhibition centers, educational institutions, shopping centers, hospitals, industrial shops, etc.). In this connection, a new global task in the field of positioning, i. e. localization and further autonomous navigation of moving objects in closed spaces has emerged in recent years. There are numerous technologies developed for localization of moving objects only inside buildings. The most well-known of them include systems based on technologies such as Wi-Fi, iBeacon, NFC and use of QR codes. However, they have not been widely used because of their high cost or insufficient accuracy. Urgency of this problem is confirmed by foundation of InLocation Alliance (with participation of Intel, Cisco, Sony, Nokia, Qualcomm, Broadcom, etc.) in 2012. The Alliance objective is development of methods, technologies and programs for positioning indoor objects. Let us consider some of the modern methods of localization of moving objects in environments with known local maps. The method of object localization by the signal angle is intended to detect direction of radio signal distribution by means of a receiving device. Features of its application are given in [2]. With this method, it is possible to establish signal direction by measuring time difference between the moments of signal reception by several antennas. However, it should be noted that implementation of this method requires specialized receivers sensitive to signal direction. To achieve high accuracy of localization which entails more accurate distance measurements, a complicated and hence very expensive system of sensor synchronization should be developed. Besides, at least three transmitting devices are required for a successful object localization which also affects cost of the system based on this method as noted in [3].

The tasks of localization of controlled moving objects are closely related to the tasks of their navigation. For example, there is an unconditional requirement of accurate spatial positioning of such objects and prompt routing to the target.

In this case, robots or other moving objects need maximum possible accuracy of their location data. There are two groups of MR navigation methods: global and local. The global methods are based on the fact that a map of the area (premises) is known before the MR starts moving. Knowing its location, the final point and location of all obstacles, the MR determines the shortest path from the start to the finish and then traverses this path using the set algorithm of action. Algorithms of finding the shortest path are used to route mobile object movement in the space with known maps of premises and ability of remote navigation in the MR navigation systems. Algorithms of search for the shortest path are applied to such algorithms for a space with known maps of premises and possibility of remote navigation in the MR navigation systems. These algorithms include, first of all, the Jump Point Search (JPS) algorithm described in [4]. The JPS algorithm does not require pre-processing and additional memory resources but it is too sensitive to surges in processed data.

Local navigation methods are used in cases when an AMR does not know global map of environment or when obstacles in this environment are dynamic (they may ap-

pear and disappear or change their location). In this case, the AMR receives navigation data on the local area of external environment which is within the range of action of its sensors.

Recently, the problem of local navigation of mobile robots in a continuous environment becomes acute in conditions of limited capabilities of remote control (using external controlling computers and remote sensors). Various aspects of solving this problem have been studied in [5, 6] which state that technical capability of automatic observation, situation analysis and decision making without collision of MRs with unforeseen obstacles is often insufficient for a complicated environment.

The MR route of this type is calculated based on analysis of available information атв then corresponding actions are realized. This is especially true in the case when a mobile remotely controlled MR gets into a zone inaccessible for signals of navigation sensors. There is a promising approach that provides switching of the robot control mode to a «stand-alone navigation». Known methods of local navigation have several disadvantages including deviation from the optimal route, achievement of local minima and complexity of AMR localization as it is noted, for example, in [7]. In structured environments, when global map of environment is known, global navigation methods are used to move the AMR to the target.

It was emphasized in [8–10] that these methods usually require significant computational resources for routing the AMR movement and localization. Moreover, they cannot be used for complicated (non-structured) environments.

Therefore, it is necessary to apply methods of local navigation of AMR which are simpler from computational point of view and use a local environment map which reflects just objects within visibility of sensors. At the same time, the improved stability of the AMR control in conditions of uncertainty can be provided by means of artificial intelligence with the use of adaptive properties of artificial neural networks (ANN) which enables AMR control in complicated dynamic environments. An urgent issue consists in development of models and new intellectual adaptive control systems for the AMR which would ensure target reaching and an increase in maneuvering stability in conditions of uncertainty and change of environment properties. This work is dedicated to solving some tasks of this problem.

3. The aim and objectives of the study

This study objective is to develop a combined method of navigation and localization of wheeled MRs using fuzzy models and control algorithms with reinforcement learning.

To achieve this target, the following tasks should be addressed:

– improve methods of locating position of mobile objects using NFC and iBeacon technologies;

– to improve the method of determining route of movement of mobile objects with the use of modified Jump Point Search algorithm;

– to develop hybrid algorithms of autonomous navigation of a wheeled mobile robot using reinforcement learning in combination with fuzzy systems of MR control in an environment with variable properties;

– to construct a model of the studied MR control system for various obstacle types.

4. Localization of position of mobile objects by means of modern technologies

Let us consider some modifications of MR localization methods and peculiarities of their application in various operation modes with application of modern technologies.

An application for Android-based devices was developed to test performance of the method of remote localization of mobile objects (MO) using NFC technology (in a space with known maps of premises). Therefore, NFC tags are placed in premises where current location of the object should be determined. The identification number stored in each tag can be obtained by scanning the tag using an appropriate device. To obtain information about current location, a computer device supported by NFC technology is used. To determine location, a unique NFC tag number called a UID (unique identification number) is read out. This unique number is stored in the internal database of the program in which information about current location can be obtained using the unique number.

Following all necessary settings and selection of the MO route points, the device will screen the same route map and a path through the selected points will be constructed.

The proposed system of MO localization with the help of this technology is based on the principle of verification of the MAC address of the nearest transmitter with the address database and further display of current MO location on the device screen. The nearest transmitter is established using the RSS parameter (signal strength). If distances between transmitters and the receiver device are known, location of the object can be calculated using the LSE method which enables determination of the MO coordinates:

$$\begin{cases} r_i = \sqrt{(x-x_i)^2 + (y-y_i)^2}, \\ r_j = \sqrt{(x-x_j)^2 + (y-y_j)^2}, \end{cases} \quad i,j \in 1\ldots N. \tag{1}$$

For effective AMR localization, it is necessary to take into account initial estimate of its spatial position. The AMR position determined by the Kalman filter (KF) essentially depends on the initial estimate. When initial position estimate is close to the actual position, the localization system will be able to accurately determine actual position of the robot. Otherwise, the system generates an estimate of the situation which is only locally optimal and does not correspond to the actual robot position. It is also desirable to use Bayes filtering (BF) for AMR localization. BF makes it possible to combine two data types (odometrical and p-data) while on the whole different hypotheses regarding actual localization of AMR are presented here by distribution of probability of the robot presence in a set of possible positions on the map [11]. This representation allows one to consider each position on the map as a possible AMR state (spatial position) the probability of which is estimated. In the general case, this makes it possible to recursively estimate the system state based on estimation of its evolution and the measurements used for this state. To apply such filtering to localization and navigation of the AMR, it is necessary to have models of the robot, sensors and environment. It is promising to study methods and technologies for combined AMR control in the case when the topological map contains both closed areas and the areas where improved navigation quality is available with the use of satellite systems.

5. Navigation of a wheeled mobile robot in an environment with variable properties

Let us consider possibility of a combined realization of two navigation modes:
– the mode of remote control of a wheeled MR by means of localization of its position in premises that are within the reach of observation sensors (mode A);
– the mode of transition to fully autonomous MR control (according to the C1, C2 and C3 strategies discussed hereinafter) if it is located within the premises inaccessible for remote localization (mode B).

Mode A. To search for the shortest way of movement of a mobile object in a space with known maps of premises and the possibility of remote navigation, apply the modified Jump Point Search algorithm (search for the path by jump points). The JPS algorithm accelerates the path search by excluding some route points that have to be reviewed in a general case.

Unlike similar algorithms, JPS does not require pre-processing and additional memory resources. Fig. 1 shows an example of a jump point determined by conditions of obtaining the optimal route. The jump starts at the x point and proceeds diagonally to the intermediate y point of the route. It is possible to get from the y point to the z point in k steps horizontally. Thus, z is the successor of the point for a jump from the x point and in turn this defines the y point as a successor to the jump from the x point.
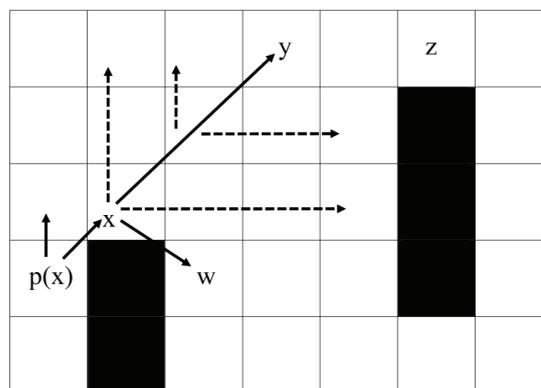
Fig. 1. An example of a jump based on the modified JPS algorithm

The proposed approach consists in formation of a sequence of visit points according to the modified JPS algorithm using Manhattan distance. In most cases, this measure of distance leads to the same results as for the common Euclidian distance but the effect of individual large differences (surges) decreases. Manhattan distance between coordinates of the MR route points is determined as follows:

$$l(x,y) = |x_2 - x_1| + |y_2 - y_1|. \tag{2}$$

Mode B. For autonomous navigation of a wheeled MR in an unknown environment with bypass of obstacles, a method is proposed with the use of the fuzzy Takagi-Sugeno model which makes it possible to use fuzzy controllers (FC) to implement various types of robot behavior in presence and absence of proprioceptive information. Generation of control signals according to the algorithms that are in line with the accepted strategies is based on sensor measurements made to

determine the target position and measurement of distances to obstacles as indicated in [12].

The kinematic model of the considered MR is represented in a discrete time by the following equations:

$$x_r(k+1) = x_r(k) + T_0 V_r(k) \cos(\theta_r(k)),$$

$$y_r(k+1) = y_r(k) + T_0 V_r(k) \sin(\theta_r(k)),$$

$$\theta_r(k+1) = \theta_r(k) + T_0 \frac{V_r(k)}{l} \mathrm{tg}(\alpha(k)), \qquad (3)$$

where θ_r is the MR orientation relative to the horizontal axis; d_{rf} is the distance between the MR and the target; θ_{rf} is the angle between the current orientation of the MR and the current orientation of the target; t is the length of the chassis; D is the MR width; D_{ro} is the distance from the MR to the target; θ_o is the angle between the MR orientation and the obstacle; α and V_r are control actions of the MR (the angle of turn of the front wheel and the linear speed of movement, respectively); T_0 is the period of quantization of signals in time.

The AMR control system under consideration is composed of units that take into account 5 types of fuzzy behavior using the Takagi-Sugeno model of zero order. These types of behavior include Target Seeking Behavior (TSB), Front Obstacle Avoider (FOA), Right Obstacle Avoider (ROA), Left Obstacle Avoider (LOA) and Velocity Reducing Behavior (VRB).

Assume that the AMR has 7 ultrasonic sensors for detecting obstacles in three directions (straight, to the right and to the left). The sensors are grouped into three modules (according to directions) and three sensors are used for each of the modules to generate the best movement control. One of the possible variants of positioning sensors on the AMR and their placement in modules is as follows:

– MD1 module to avoid front obstacles (FOA) which uses distances $d1$, $d2$, $d3$;

– MD2 module to avoid right obstacles (ROA) which uses distances $d2$, $d4$, $d6$;

– MD3 module to avoid left obstacles (LOA) which uses distances $d3$, $d5$, $d7$.

Ci sensors measure distances di, $i=1,...,7$. Let us consider two types of the AMR behavior control strategies depending on presence or absence of obstacles in the direct observation zone:

– C1 is the strategy for AMR control in a straight movement to the target;

– C2 is the strategy for AMR control when avoiding obstacles.

The C1 strategy makes it possible to realize «AMR movement to the target» action on the basis of knowledge of the AMR position relative to the coordinates of the navigation environment (that is, orient the robot in the direction to the target). The target point is determined from two input variables: distance between the AMR and the target (d_{rf}) and the angle between the current AMR orientation and the current target orientation (θ_{rf}). The proposed structure of the system of robot control during its movement to the target is shown in Fig. 2.

The M1 module compares actual AMR coordinates with the target coordinates to calculate «AMR-target» distance and the angle of the predicted motion, θ_d. Then the M2 module compares this angle value with the current AMR orientation to calculate the angle between the AMR axis and the target (θ_{rf}). The proposed FC uses two variables (d_{rf} and θ_{rf})

to calculate two control actions: u_1 (turning angle of the front wheel) and u_2 (the AMR speed). The following designations were adopted for linguistic variables of the system input and output: Z (Zero), S (Small), M (Middle), B (Big), VB (Very Big), NG (Negative Big), NM (Negative Middle), NP (Negative Small), PS (Positive Small), PM (Positive Middle) PB (Positive Big), L (Low).
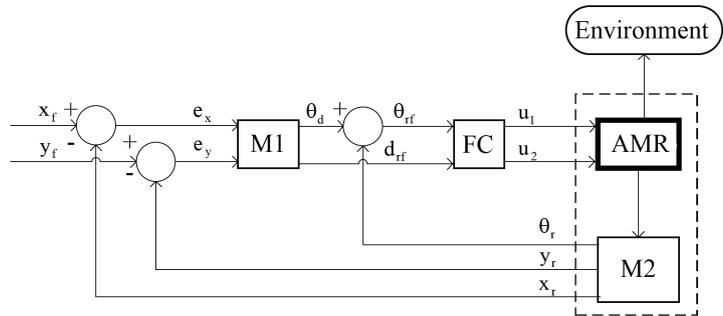
Fig. 2. Structure of the AMR control system for the C1 strategy

Triangular membership functions were used to make the input variables fuzzy (an example of such a function is shown in Fig. 3). The membership functions for two control actions (distance from the AMR to the target and the angle between the current AMR orientation and the current target orientation) are represented by instantaneos impulses.
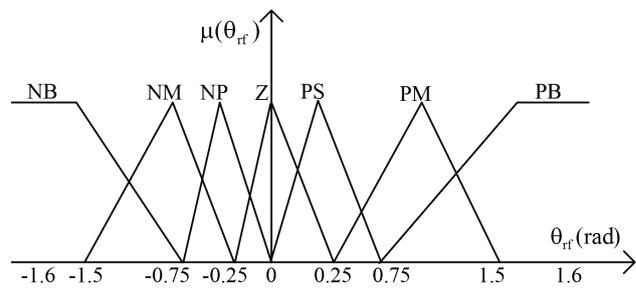
Fig. 3. Membership functions for θ_{rf}

In order to implement the control system using linguistic variables and membership functions for the input and output variables, derivation rules were generated. Connection between different input and output variables was represented using 35 rules. Table 1 describes fuzzy rules for implementation of the MR behavior in a straight movement to the target (C1 strategy).

Table 1

Fuzzy rules for the C1 strategy

Actions (α, V_r)		θ_{rf}						
		B	NM	NS	Z	PS	PM	PB
d_{rf}	Z							
		α	PB	PS	Z	Z	Z	NS	NM
		V_r	Z	Z	Z	Z	Z	Z	Z
	S	α	PB	PB	PM	Z	NM	NB	NB
		V_r	L	L	L	L	L	L	L
	M	α	PM	PM	PS	Z	NM	NB	NB
		V_r	L	L	M	M	M	L	L
	B	α	PM	PS	PS	Z	NS	NS	NM
		V_r	L	M	B	B	B	M	L
	VB	α	PM	PM	PS	Z	NS	NM	NM
		V_r	L	M	B	VB	B	M	L

Let us consider the C2 strategy which generates adequate actions to avoid collisions with one-type (simple) obstacles if one or more objects are detected in the AMR area using perceptual means (straight, to the right or to the left).

Two control structures for moving the AMR in an obstacle-free space will be considered. The first structure is based on one type of behavior while avoiding obstacles and uses measurement of the distance and the angle between the AMR center and the obstacle. It is assumed that the obstacles have form of a circle (the collision risk zone is determined by a periphery around the center of the obstacle). The second structure uses a control system based on a set of five varieties of behavior to perform the task of AMR navigation for different types of environment. The first implemented strategy is based on the use of the FC which can be used for less complicated environments with the same type of obstacles. Following measurement of distance D_{ro} and angle θ_o, necessary control actions (U_o) are formed. Fig. 4 presents the proposed structure of the AMR navigation system the global task of which is realized by activating one of the following types of behavior: moving to the target or bypassing obstacles in three directions (straight, to the right and to the left). Using sensor measurements (the M2 unit), the M1 unit makes it possible to determine input values of fuzzy variables. The M3 unit performs the FC functions for the case of straight movement to the target in absence of obstacles in the AMR vicinity corresponding to the C1 strategy. The M4 unit performs the FC functions in the event of appearance of obstacles in the near vicinity of the MR which is consistent with the current implementation of the C2 strategy.
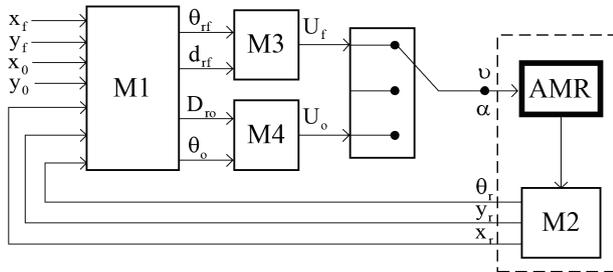
Fig. 4. Structure of the AMR control system
for the C2 strategy

Let us consider the C3 strategy which generates adequate actions in the event that the AMR environment may contain obstacles of different shapes (polygons, walls, ellipses, etc.). In this case, the AMR should be able to successfully bypass these obstacles without collision. A necessity of acquisition of correct and accurate information about environment for performing navigation taking into account the obstacle shape appears. The navigation system structure is presented in Fig. 5.

This strategy makes it possible to implement autonomous navigation of the AMR during its movement to the target if the robot does not receive any information from perceptual sensors and the immediate environment does not contain obstacles. This condition is fairly mild in terms of the environment in which the AMR is moving. In the case of obstacles (static or dynamic) that hinder the AMR movement to the target, the robot must have an effective ability to bypass obstacles.

For the «turning angle» output variable (the GSB controller), the same sets of impulses are used as for the «move to the target» strategy. For the three controllers of obstacle bypass (FOA, ROA and LOA), the set distribution of fuzzy bands for different sensors is used. According to the selected structure of the AMR control system, the M3 supervisor uses only the controller of movement to the target for selecting actions (α and V_r) if the environment is free from obstacles. In the event of an obstacle, one of the possible actions to avoid collisions will be activated according to the situation, and in parallel, the task of movement speed will be activated. The AMR should reduce speed in the event of an obstacle. To do this, the overall architecture of the navigator is modified by adding a fuzzy Velocity Reducing Behavior (VRB) controller. Its task is to generate the value of setting the current AMR speed (V_a).
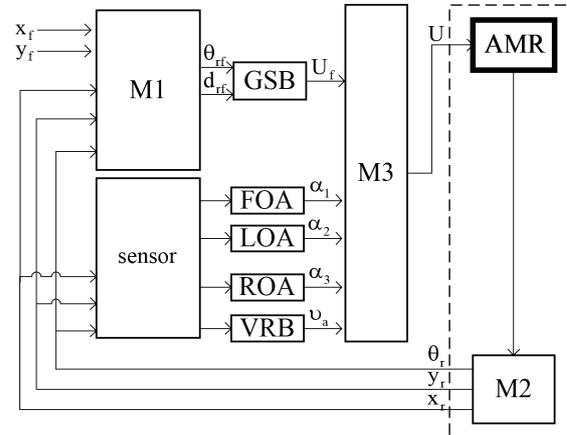
Fig. 5. Structure of the AMR control system
for the C3 strategy

This value is added to the current value to reduce speed according to the following recurrence equation:

$$V_r(k+1) = V_r(k) + V_a(k). \qquad (4)$$

Its task is to generate the value of setting the AMR current speed (V_a). This value is added to the current value to decrease speed according to the following recurrence equation: the current AMR speed (V_a) and the minimum distance to the nearest obstacle (D_{min}) are input variables. Inputs for V_a and D_{min} are made fuzzy using the specified membership functions with linguistic variables S (Small), M (Middle) and B (Big). Use of such distribution has made it possible to form a table of speed change using six fuzzy rules. In the system under consideration, possibility of improving quality of fuzzy AMR control with the use of RL-learning was provided which enables use of a priori knowledge to adapt fuzzy rules of control based on maximization of the average value of obtained reinforcements. The scheme of formation of such reinforcements is considered in [13]. The principle of operation of the proposed modified algorithm of fuzzy control with RL-learning (Q-FUZM) consists in obtaining a plurality of conclusions for each fuzzy rule and an association for each derivation of a quality function that will be estimated using a fixed membership function. When adjusting according to the Q-FUZM algorithm, the fuzzy controller of the mobile robot should correct conclusions from the TC rules based on the reinforcement signals r. The task is to approximate the quality function Q with the following fuzzy function SIF (System Inference Fuzzy) where s_t is the current state of the AMR movement; $w_i(s)$ is SIF coefficients determined by the defined membership functions; ci is conclusions of fuzzy rules; m is the number of fuzzy rules. The process of

learning according to the Q-FUZM algorithm using the renewal procedure allows one to define a set of rules taking into account values of the reinforcement signal. For example, the values of reinforcement used to train the procedure of changing the AMR speed: –4 if the AMR encounters an obstacle; –1 if $d_i > D_{max}$ and V_r is low for $i = 1...3$; –1 if $d_i < D_{max}$ and V_r increases for $i = 1...3$; 0 for other cases. This signal is used to determine the best numerical interpretation of the linguistic terms being used. Advantage of the proposed approach consists in the possibility of a combined implementation of two modes: remote control of the wheeled MR and the mode of transition to completely autonomous MR control (for the considered C1, C2 and C3 strategies). The first mode is implemented by locating the MR position in premises that are within the reach of the observation sensors. The second mode is used in the case of finding the MR in the areas of premises that are inaccessible to remote localization.

6. The results obtained in modeling the systems of localization and navigation of mobile objects

For the experimental study of the proposed approach to localization and navigation of MR, the LEGO Mindstorms NXT 2.0 robotic platform was used. The choice of this platform is explained by its availability, flexibility and variety of equipment. The software implementation of the proposed approach within the framework of the chosen platform was performed using the NXT-G language. The first floor of the educational and production building was used as an experimental site. It includes an open zone (9 m^2) and a zone in the room with reinforced concrete walls (total area about 220 m^2). Obstacles having square, rectangular, convex and more complex shapes that simulated different types of environment were placed in the site area. In total 14 models of environment with different types of obstacles and their location were used. Wheeled AMRs equipped with an appropriate set of 7 ultrasonic sensors were used in the experiment. Experimental studies have revealed advantages and disadvantages of using some modern technologies (in particular, NFC and iBeacon technologies) in the systems of localization of the current position of mobile objects (in mode A). Fig. 6 shows an example of implementation of the localization method based on iBeacon technology. The corresponding system consisted of iBeacon transmitters and a computing device that receives and processes information from the transmitters. The computing device evaluated level of the signal coming from the iBeacon transmitters in the process of localization. The signal strength was used to determine the nearest transmitter. The transmitter with the best signal was considered to be the closest to the object being localized. Signal level studies have shown that signals from iBeacon transmitters are less susceptible to noise and their range is greater than that of alternative Bluetooth technology.

An important problem of application of the considered approaches to localization of mobile objects is placement of transmitters in space. In the process of the experimental study, a scheme of such placement using the «1-coverage method» for the studied problems of MO localization was used which makes it possible to reduce number of transmitters in space. An example of constructing an MO route using the NFC technology and rectangular obstacles is shown in Fig. 7.
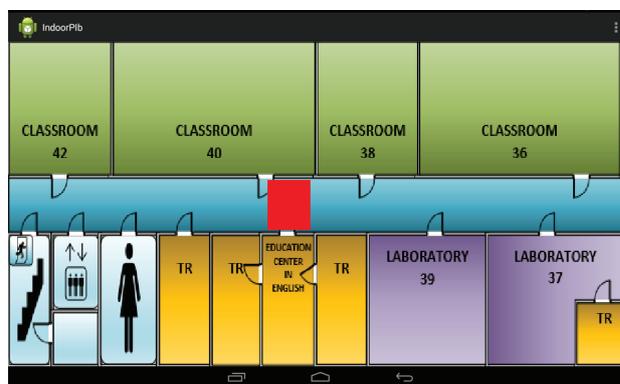
Fig. 6. Implementation of the method of MO localization using the iBeacon technology
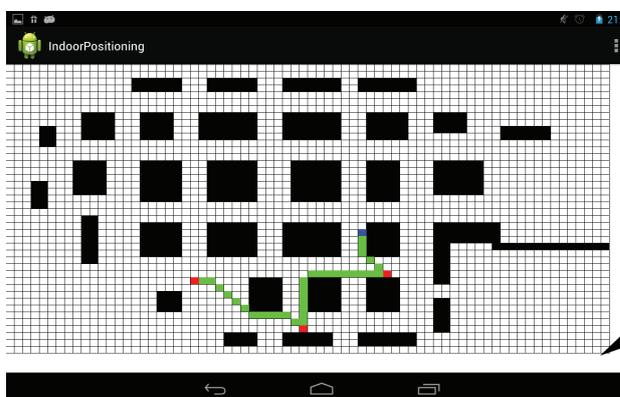
Fig. 7. An example of constructing the MO route using the NFC technology

According to the experimental results, numerous examples of modeling navigation of wheeled MRs using fuzzy controllers and combined «NR-QFUZM» controllers (in environments with various types of obstacles) have been obtained to confirm effectiveness of the proposed control schemes. The environments used took into account limitation of modeling and MR movement in various situations including those for an open space and a space with static obstacles. Fig. 8 gives examples of implementation of the navigation method in mode B for the C3 strategy (with obstacles) with the «HP-QFUZM» controller.
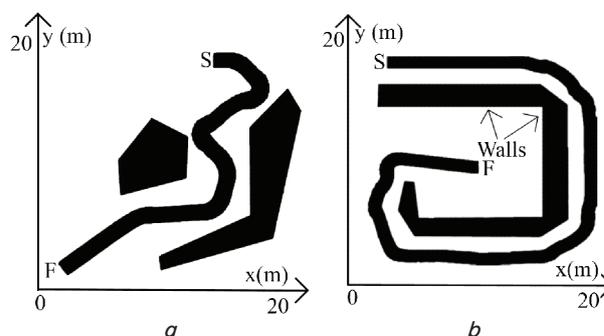
Fig. 8. Examples of the MR paths for the C3 strategy: for complex obstacles (*a*); for walls (*b*)

In general, 200 experiments were conducted to test the C1, C2 and C3 strategies. Positive results (the AMR passing the route from point *S* to point *F*) have been obtained:

100 % for the C1 strategy (AMR control in a straight movement to the target); 98 % for the C2 strategy (AMR control in bypassing one-type obstacles); 92 % for the C3 strategy (AMR control in bypassing one-type obstacles).

The results obtained in modeling provide acceptable solutions for autonomous navigation of MRs in complicated environments. The test results indicated the possibility of autonomous navigation of wheeled mobile robots using algorithms of reinforcement learning and fuzzy controllers. The rule base of the autonomous MR navigation system improves during the learning process. Application of the given approach makes it possible to take into account obstacle shape and adjust the navigation strategy to improve the system's quality. It should be noted that the obtained results are of a study nature and the possibility of their practical application should be confirmed by further experiments with the use of more powerful and functionally advanced AMR types.

7. Discussion of results obtained in studying the methods of localization and navigation of mobile objects

Quality of localization and navigation of stand-alone mobile robots can be enhanced by means of computing intelligence that makes it possible to realize control in complex dynamic environments. Known methods of local navigation have a number of shortcomings including deviation from the optimal route, reaching of local minima and complexity of AMR localization.

The proposed models and methods of intellectual control of AMR movement provide the target approach and possibility of maneuvering under uncertainty. In particular, methods for determining current position and routing of mobile objects were improved. The improvement essence is as follows:

– combined use of iBeacon and NFC technologies in a space with known maps of premises was proposed (according to the examples given in Fig. 6, 7) which makes it possible to reduce number of transmitters necessary for localization (task 1);

– algorithm of determining the mobile objects route was modified using the method of Jump Point Search (search for the way through the jump points). The essence of modification consists in application of the Manhattan distance between the coordinates of the route points in the algorithm (Fig. 1). This reduces impact of individual surges on the calculation results compared with the basic algorithm (task 2);

– an approach for conducting the AMR navigation in an environment with variable properties at limited possibilities of remote control was proposed. This approach provides the possibility of switching the robot control mode to autonomous navigation with combined application of a fuzzy model and RL-methods (according to the aforementioned schemes of AMR movement control). This enables improvement of the set of fuzzy rules using reinforcement signals (task 3);

– the test results (task 4) indicate that this approach allows one to take into account obstacle shapes and adjust the navigation strategy to improve the system quality.

Disadvantages of the proposed methods include difficulties in estimating prospects for their widespread implementation which was caused by limitedness of the obstacle types under consideration and the nature of possible environment changes.

Further studies of the possibility of improving the methods of localization and navigation of mobile objects in an environment with variable properties can be performed in the following directions:

– study of the possibility of using neural network models in the considered approach to designing navigation systems for mobile objects;

– practical implementation of the proposed methods for actual MRs;

– application of the presented MR control schemes for an environment with dynamic obstacles;

– modification of the presented approach by applying evolutionary methods (for example, genetic algorithms);

– development of hybrid algorithms of autonomous navigation of a wheeled mobile robot with the use of reinforcement learning in combination with fuzzy systems for MR control in an environment with variable properties.

8. Conclusions

1. The method of localizing mobile objects was improved by means of a combined use of NFC and iBeacon technologies in a space with known maps of premises which reduces the number of transmitters required for localization.

2. An algorithm of determining the route of movement of mobile objects using the Jump Point Search method was developed. The modified algorithm uses the Manhattan distance between coordinates of the route points which reduces impact of individual surges on the results of calculations compared with the basic algorithm.

3. A hybrid method of autonomous navigation of a mobile robot in an environment with variable properties in conditions of limited possibilities for remote control was proposed. The proposed approach provides for the possibility of switching the robot control mode to autonomous navigation with a combined application of a fuzzy model and RL-methods. This ensures improvement of the set of fuzzy rules using reinforcement signals.

4. Modeling of the investigated MR control system for various types of obstacles was performed. The test results indicate the possibility of autonomous navigation of wheeled mobile robots using algorithms of reinforcement learning and fuzzy controllers was considered in the study. The base of rules of autonomous MR navigation system improves during the learning process. Application of the given approach enables taking into account obstacle shapes and adjustment of the navigation strategy to improve the system quality (the MR achieved target in an environment with various types of obstacles in 95 % of experiments).

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