UDC 004.9
DOI https://doi.org/10.32782/2521-6643-2024-2-68.8

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MOBILE ROBOT NAVIGATION BASED ON LASER RANGE-METRY METHODS

The article is devoted to solving the problem of finding people who are under the debris of destroyed buildings, which requires an urgent solution to ensure an effective rescue operation. The primary focus of this research is the development and refinement of a navigation system for a mobile rescue robot. This paper specifically explores localization techniques and methods for constructing a map of an unknown environment, which are crucial for the robot's effective operation in complex and dynamic settings. The overarching goal of the study is to identify the most adaptable and precise navigation method that can effectively manage the movement of a mobile robot in environments characterized by unpredictable and shifting obstacles. To solve the tasks, modern methods of laser telemetry and SLAM methods (Simultaneous Localization and Mapping) are used in the work, which are used to accurately create a map of the territory and localize the robot on it. The research proposes an innovative algorithm for the navigation system of a mobile robot, which leverages laser telemetry to meticulously scan the surrounding area. It has been shown that scanning process is essential for real-time data acquisition, enabling the robot to make informed decisions regarding its movement. It is stated that, the proposed lidar-based navigation method is particularly advantageous as it facilitates the creation of a detailed spatial map, even in environments where the layout is not known in advance. This approach allows for the precise determination of the robot's position within the mapped space, ensuring that the robot can navigate effectively and avoid potential hazards. It is proved that, the integration of these advanced techniques significantly enhances the robot's ability to perform in search and rescue missions, where the accurate and timely localization of trapped individuals is of paramount importance.

Key words: *mobile robot, navigation system, laser range finder, scanning lidar, terrain map, dynamic obstacles.*

Стрельцов О. В., Гриньов М. А., Скалозуб В. Ю., Буюклі Д. М. Навігація мобільного робота на основі методів лазерної дальнометрії

Стаття присвячена вирішенню проблеми пошуку людей, які знаходяться під уламками зруйнованих будівель, що потребує невідкладного вирішення для забезпечення ефективної рятувальної операції. У статті розглянуто використання сучасних технологій залучення до пошуково-рятувальних робіт мобільних роботів, здатних самостійно орієнтуватися в складних умовах завалів. В даній роботі основним об'єктом дослідження виступає система навігації, призначена для таких мобільних пошукових роботів. Предметом дослідження є методи визначення місця розташування робота та побудови карти невідомої території, що є критично важливим для успішного виконання завдань пошуку і порятунку. Метою даного дослідження є визначення найбільш універсального та точного способу навігації, який дозволить ефективно керувати рухом мобільного робота в умовах наявності динамічних перешкод, що постійно змінюються. Для вирішення поставлених завдань в роботі використані сучасні методи лазерної далекометрії та SLAM-методи (Simultaneous Localization and Mapping), які застосовуються для точного створення карти території та локалізації робота на ній. У рамках дослідження запропоновано новий алгоритм керування навігаційною системою мобільного робота, який базується на використанні методу лазерної далекометрії для сканування навколишнього середовища. Показано, що метод дозволяє детально сканувати простір навколо робота та забезпечує отримання точних даних про розташування об'єктів і можливих перешкод. Зазначено, що запропонований підхід до навігації, що базується на використанні лідара, надає роботу можливість створювати карту простору навіть у тих випадках, коли структура цієї території невідома заздалегідь. Використання методу дозволяє точно визначати позицію робота на створеній карті, що є ключовим для забезпечення безпечного та ефективного руху в умовах завалів. Показано, що

використання лідара значно підвищує точність орієнтації робота в просторі, що в свою чергу, сприяє успішному виконанню рятувальних операцій, де швидкість та своєчасність має вирішальне значення. Доведено, що завдяки цим можливостям робот здатний уникати перешкод та швидко адаптуватися до змінної ситуації, що виникає під час проведення пошукових робіт у завалах.

Ключові слова: *мобільний робот, система навігації, лазерний далекомір, скануючий лідар, карта місцевості, динамічні перешкоди.*

Introduction. Currently, in most developed industrial countries, there is active development in the field of mobile robotics. A mobile robot is a device capable of autonomously moving through space and performing assigned tasks with a high degree of independence. Military organizations and security services show particular interest in the development of such robots, as they can perform tasks in environments that are hazardous to human life. Additionally, there is growing interest in robots designed to assist in daily life, such as vacuum cleaner robots and guide robots, as well as in entertainment devices like robotic dogs and quadcopters [1].

Despite significant advancements in robotics, navigation remains the primary challenge in developing such devices. The onboard control system of a robot must be capable of planning routes, managing movement parameters, accurately processing data from sensors about the surrounding environment, and determining its own coordinates in complex environments with dynamic obstacles. Existing navigation systems are well-suited for use in industrial settings, where the environment is deterministic and static.

However, in unknown environments, existing navigation algorithms either do not provide sufficient accuracy and reliability for robot localization or require significant computational resources. This affects the size and weight parameters, as well as energy consumption, which in turn impacts the duration of autonomous operation [2].

The aim of this research is to find the most versatile and precise navigation method for controlling the movement of a mobile robot in environments with dynamic obstacles.

Methods of mobile robot navigation. Currently, there are three main navigation schemes for mobile robots.

Global navigation involves determining the absolute coordinates of the robot while moving over long distances in open terrain, where GPS is used to obtain the coordinates. This method provides a relatively high accuracy with an error range of 1-3 meters but cannot be used in enclosed spaces.

Local navigation determines the current position of the robot relative to a specific point, usually the starting point, and is suitable for performing tasks within a predefined area. However, its accuracy is limited, with errors reaching up to 150 meters.

Personal navigation enables the robot to identify parts of its own structure and interact with nearby objects. It is used for robots equipped with manipulators and includes the use of encoders, orientation by markers, line following, and so on, but it suffers from limited system flexibility.

The most promising direction in improving mobile robot navigation systems is the capability to store a complete map of the environment in the robot's memory. Three-dimensional maps are the most effective, yet their storage and processing by the onboard control system require substantial computational resources. The task of creating a map involves maintaining a description of the surrounding environment so that, in the future, the robot can determine its position on it. This map is used to plan potential movement trajectories or to select the optimal position for object capture [3].

Analysis of the methods and tools for mobile robot navigation has demonstrated that one of the most effective approaches for route mapping is the use of a scanning laser rangefinder. Research findings in the field of mobile robot navigation indicate that the use of a laser rangefinder allows for achieving high localization accuracy.

The core of a laser rangefinder is a LiDAR (Light Detection and Ranging). LiDAR is a device that implements a technology for acquiring and processing information about distant objects using electromagnetic radiation. The operating principle of LiDAR is illustrated in Fig. 1 [4].

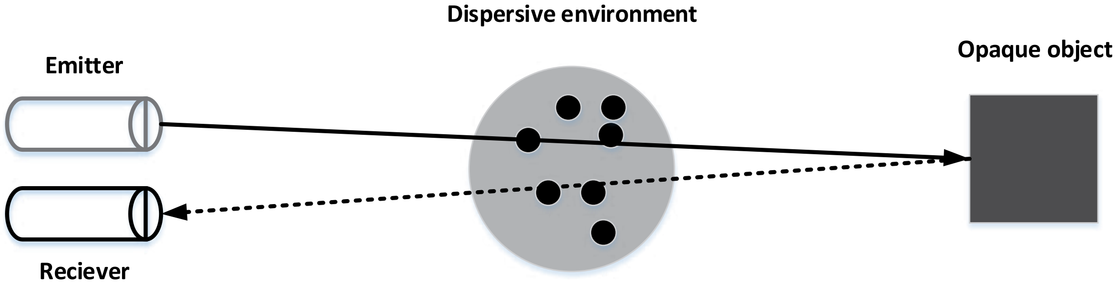

Fig. 1. The principle of lidar operation

The directed beam from the emitter is reflected from the targets and returns to the receiver. The distance to a point on the object's surface can be calculated as

$$L = 0.5 \times c \times t, \quad (1)$$

where c – speed of light; t – the total time the light travels to the reflection point and back; L – distance to the reflection point [5].

In the table 1 shows data showing the dependence of the response time on the distance to the object.

Table 1

Dependence of the response time on the distance to the target

Distance	1m	10m	100m	1km	10 km	100km
Time	6.7 ns	67ns	0.67 us	6.7 us	67 us	0.67s

Most lidars consist of three parts: a transmitter, a receiver, and a control system (Fig. 2).

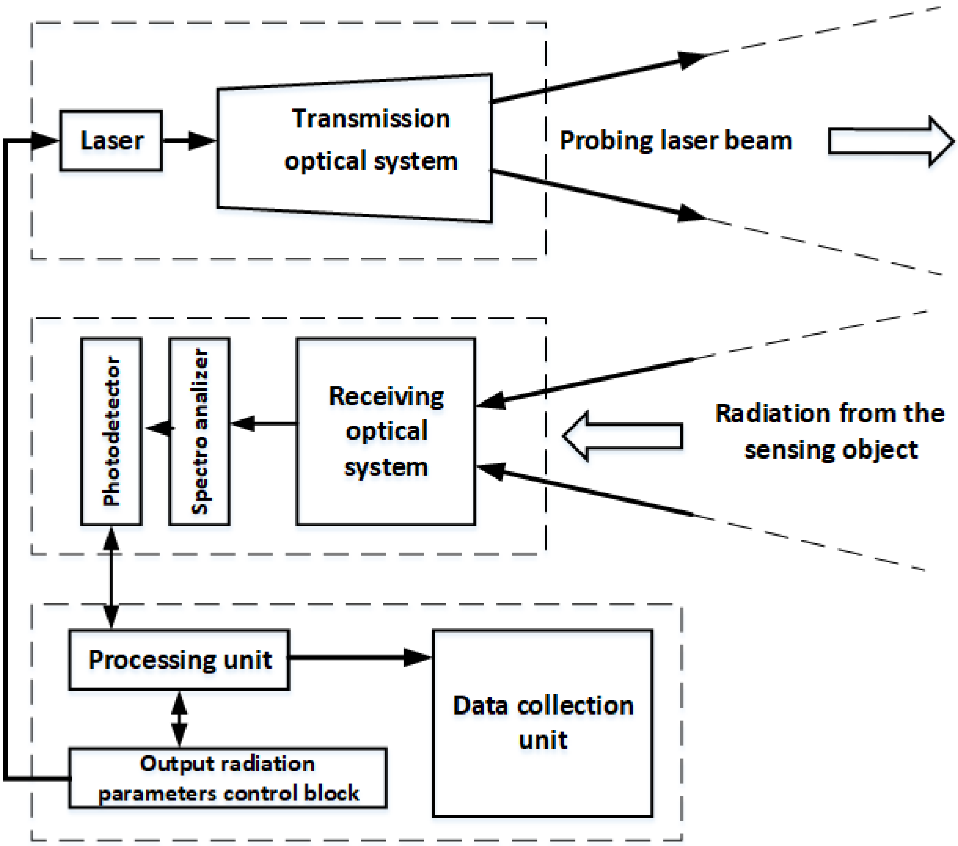

Fig. 2. The lidar structure

The transmitter comprises a radiation source, which is typically a laser, and an optical system for shaping the outgoing laser beam, allowing for control over the spot size and beam divergence. In the majority of designs, the emitter is a laser that generates short pulses of light with high peak power.

The pulse repetition rate or modulation frequency is selected such that the interval between consecutive pulses is no shorter than the response time from detected targets, which may be located beyond the calculated operating range of the device. The receiver consists of a lens, a spectral and/or spatial filter, a polarization component, and a photodetector. The radiation reflected and scattered from the object under investigation is collected by the receiving optics and then passes through a spectral analyzer. This device isolates the wavelength range for observations and filters out background radiation at other wavelengths. The analyzer can be a complex, precisely tuned mono- or polychromator or a set of narrow-band filters, including a notch filter that blocks radiation at the wavelength of the laser transmitter [6].

The emitter and receiver unit can either be separated by a considerable distance or integrated into a single block. The axes of the transmitter and receiver may be aligned (coaxial configuration) or separated (biaxial configuration) [7].

The control system of the LiDAR performs the following functions:

– regulating the operating mode of the LiDAR;

– controlling the frequency of the probing laser radiation;
– measuring the energy in the outgoing and received laser beams at both frequencies;
– processing data to obtain the spectral characteristics of the atmosphere, as well as detecting and determining the concentrations of impurities based on the "spectral signatures" of molecules stored in the computer's database;
– managing the LiDAR targeting system towards the object of study [8].

Research progress. The subject of this study is a navigation system designed for a mobile search robot intended to detect individuals trapped under debris from collapsed structures. The challenge in navigating such robots lies in determining their position in space while moving through a dynamic and unpredictable environment.

In general terms, the navigation problem can be defined as follows: a certain space contains a mobile robot equipped with a laser rangefinder. A target point is specified that the robot must reach to perform a specific task. It is necessary to establish a control law for the mobile robot that ensures its movement from the initial position to the target point. This task is complicated by several problems, conditions, and constraints:

1. The robot must determine its location in space to accurately position itself relative to the target point.
2. It is necessary to avoid static obstacles, which requires building a map of the environment.
3. Dynamic obstacles complicate the map-building process.
4. The robot's movement to the target point must be optimized in terms of time.

Solving the navigation problem for a mobile robot in space requires simultaneously addressing the issues of localization and map building, or updating the map with newly detected objects. Currently, either the task of localization based on an existing map or the task of map construction given a known robot trajectory is solved. A general approach that simultaneously addresses these tasks with the required accuracy and independently of the environmental characteristics does not yet exist. Moreover, solving these tasks is significantly complicated by the fact that navigation sensors have errors, making it impossible to determine the exact trajectory of movement.

It was decided to represent the robot's location within a system of local coordinates related to the robot's initial position, as a priori information about its location in space is not available. The robot autonomously constructs a map of its path.

In robotics, SLAM methods (simultaneous localization and mapping) are commonly used for robot navigation and positioning. SLAM methods allow for the construction of a map of an environment whose structure is initially unknown and the determination of the robot's position on it. The use of SLAM methods enables the optimization of the robot's trajectory, but only in a static environment. Figure 3 shows the maps built by the robot's navigation system before applying SLAM methods (Fig. 3a) and after (Fig. 3b) [9].

In a dynamic environment, the movement of obstacles cannot be calculated in advance, as the environment is generally non-deterministic, making it impossible to pre-plan a route that ensures safe navigation.

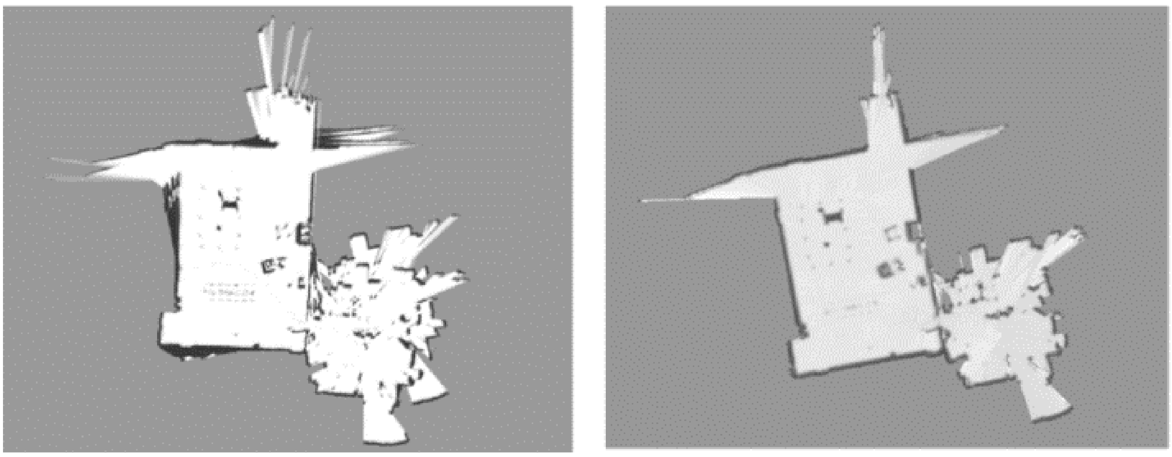

Fig. 3. Optimization of the terrain map using SLAM methods:
a- before application ("raw data"); b – after processing one of the SLAM methods

To avoid collisions with dynamic obstacles, it is necessary to determine their current positions and predict their movement trajectories. This allows the robot to follow a planned trajectory while deviating at the appropriate moment to maneuver around obstacles. Therefore, an effective solution for navigating in a dynamic environment involves considering the movement of obstacles directly within the control loop of the mobile robot [10].

This study proposes an algorithm for a navigation system that accounts for the dynamics of the robot's movement, the positions of obstacles, and avoids collisions with them. The control algorithm for the rescue robot's navigation system is illustrated in Fig. 4.

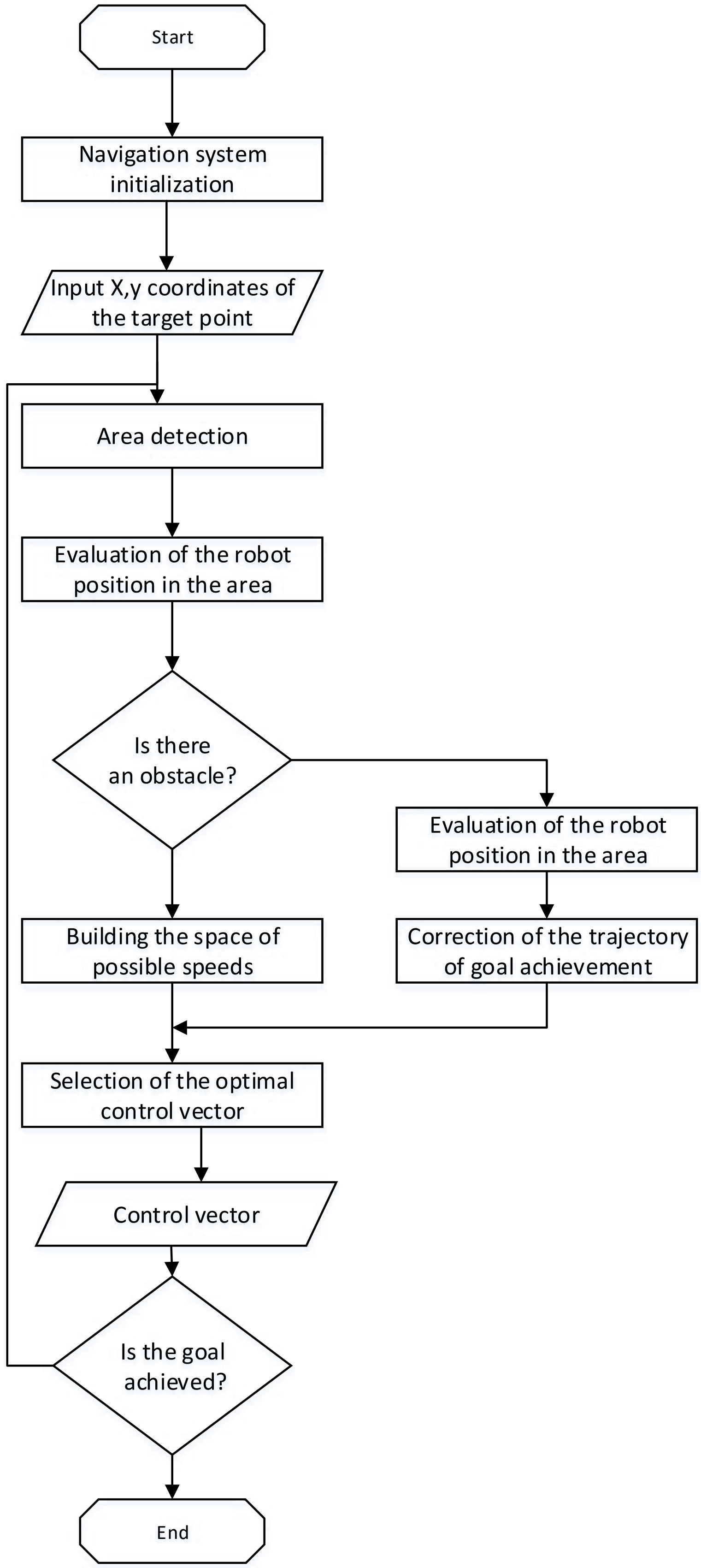

Fig. 4. Algorithm of control system of search robot navigation

The operation of the proposed navigation system for the rescue robot functions through a series of well-defined stages that enable it to navigate efficiently in complex environments. Initially, the lidar, a crucial component of the system, generates a detailed three-dimensional point cloud, which accurately represents the robot's surrounding environment. This point cloud consists of numerous data points that capture the spatial characteristics of the area, including any potential obstacles. The data collected by the lidar is then transmitted to the robot's navigation system, where it is processed to construct an initial map of the area. This map provides a visual representation of the environment, highlighting both the layout of the terrain and the location of any obstacles that could impede the robot's movement.

Once the initial map and obstacle map are established, the navigation system determines the robot's position within this mapped environment. With this information, the system continuously updates both the map and the obstacle map as the robot moves. This dynamic updating process is critical because it allows the navigation system to adapt to changes in the environment, such as moving obstacles or changes in terrain. At each step of the algorithm, the navigation system refines the map of obstacles and accurately assesses the robot's current position relative to these obstacles.

The continuous flow of data from the lidar plays a crucial role in enabling the navigation system to constantly optimize the control vector, which is essentially the set of commands that dictate the robot's movement. As the lidar scans the environment, it generates a real-time stream of data that captures the spatial characteristics of the robot's surroundings, including any obstacles that may be present. This data is immediately analyzed by the navigation system, which uses advanced algorithms to update the map of the environment and refine the obstacle map. By processing this updated information, the system can dynamically adjust the robot's path to avoid collisions and ensure that it follows the most efficient route to its intended target destination.

The design of the entire control process is inherently iterative, meaning that the system continuously re-evaluates the robot's trajectory as it receives new data from the lidar. This iterative approach allows the navigation system to make real-time adjustments to the robot's movements, ensuring that it can respond effectively to any changes in the environment, such as the sudden appearance of a new obstacle or a shift in the terrain. This adaptability is particularly important in rescue missions, where the environment is often unpredictable and can change rapidly. The navigation system's ability to adjust the robot's path on the fly is key to its success in navigating through complex and potentially hazardous areas.

Conclusion. The proposed navigation method for a mobile robot using lidar offers the capability to construct a detailed map of an environment with an unknown and potentially complex structure, while simultaneously determining the precise position of the robot within that environment. This advanced approach allows the robot to navigate effectively in unfamiliar or dynamically changing surroundings.

However, the necessity of employing rigid logic within the navigation system imposes certain limitations, notably reducing the robot's maneuverability and overall speed. These constraints can hinder the robot's ability to respond quickly to sudden changes in the environment or to take the most efficient paths. Therefore, to address these challenges and optimize the movement trajectory of the robot, it is advisable to incorporate artificial intelligence (AI) technologies into the navigation system. By integrating AI, the robot can adapt to its surroundings more fluidly, make real-time decisions, and enhance its navigation capabilities, leading to improved performance in complex scenarios.

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