Experimental Investigation of Algorithms for Simultaneous Localization and Mapping

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***Abstract*—This paper describes a mobile robot system designed for simultaneous localization and mapping. The architecture of a robotic mobile system based on the mini-tractor chassis is considered. The existing and modern methods and approaches to solving the SLAM problem are described, as well as the results of experimental studies of the work of methods on a mobile robot. A description of the developed robotic system for solving the navigation problem and constructing a route map is given. The issues addressed in this paper include the design, development and experimental testing of the mobile robot. The advantages, disadvantages of the algorithm, as well as the direction of further research are described in this work.**

Keywords — simultaneous localization, mapping, microcontroller, robot programming, mobile robot, robot control

I. Introduction

Today, robotics is a high-tech, engineering industry that is successfully developing in many advanced countries. Robotic systems increase productivity and competitiveness, monotonous and repetitive work is transferred from person to machine, thereby contributing to the development of industry, automotive, medicine, military affairs, cosmonautics and many other areas. The most technologically advanced countries in the world began the transition to robotic systems.

Research in the field of mobile robotics is conducted in many organizations around the world. First of all it is worth noting such an organization as Boston Dynamics - the largest developers of robots for the US Army. The leading world universities, in turn, are recognized by the Massachusetts Institute of Technology (USA), the University of Bonn (Germany), the University of London (England).

In the modern design of robotic systems, the complexity of the architecture, the need for computing power requires a distributed and modular organization of the system software architecture [1]. Also, these systems must take into account the classic problems of industrial robotics associated with sensors and actuators.

In accordance with this, the basic requirements that the software (and its components) of a complex robotic system must meet include:

- parallel and distributed architectures;
- modularity;
- safety and fault tolerance;
- real time and efficiency.

In the process of developing the architecture of the robot control system, transparency of the control systems is necessary. Important role is played by scalability, reusability, efficiency and fault tolerance.

The most important success factor in the development of the robot control architecture is the use of a mechanical platform, sensors, motors, movement mechanisms, power supplies, electronic control, microcontroller systems, servo drives, programming languages, pneumatics and open source software [2], [3].

A common problem solved by the control system of an autonomous mobile robot is the definition of the position of the controlled object and the construction of the obstacle map of the surrounding terrain. For the solution, computer algorithms are used to process data from various optical devices and sensors for determining the distance traveled.

In recent years, a number of simultaneous localization and mapping (SLAM) systems have been introduced, operating in real time, able to work on a significant number of video recordings from open sets of data of varying degrees of complexity. They are taken with the help of manual and mobile cameras mounted on mobile robots, with high results for the accuracy of the map and the reconstruction of the trajectory of the camera) [4].

Currently, the methods for solving the SLAM problem are rapidly developing. This is due to increased productivity of computers, improved quality of sensors and the emergence of new ones, as well as the development of robotics. There are a lot of studies to solve the SLAM problem: EKF-SLAM, FastSLAM, DP-SLAM and others. The method of solving similar problems is the expanded Kalman filter (EKF) [5],[6]. Currently, there exists and is actively developing an alternative approach, called FastSLAM, which is based on the so-called particle filter (Particle Filter, Monte Carlo methods). Unlike EKF in FastSLAM, one large map is considered as a collection of local sub-maps, which allows you to remove the dependency of landmarks from each other and thus significantly reduce the time to recalculate the system state estimate [7],[8].

Nevertheless, each of these methods has its own limitations and drawbacks, which once again underscores the need to improve the cartography algorithms of the terrain with autonomous mobile robots, which leads to a problem in their modification and integration with other systems [9]. This disadvantage is absent in the proposed algorithm definition of the position of the controlled object and the construction of the obstacle map of the surrounding area. The algorithm is used on the basis of camera motion trajectories obtained using the most accurate and modern single-camera SLAM system. The implemented two-dimensional representation of the map allows you to work with a dynamic environment and requires technical processing, such as scaling. The task of SLAM is very important, since without its solution it is very difficult to create an autonomous robot.

II. ARCHITECTURE OF THE ROBOTIC MOBILE SYSTEM BASED ON THE CHASSIS OF THE MINI-TRACTOR "BELARUS-132"

The design methodology is a process that describes the formal and algorithmic behavior of the elements of the robotic system during its operation and includes the following stages *"Fig. 1"*:

- modeling of robotic systems;
- development of control algorithms for the robotic system;
- synchronization of nodes and development of the architecture of the robotic system;
- testing at the software and hardware levels [3].

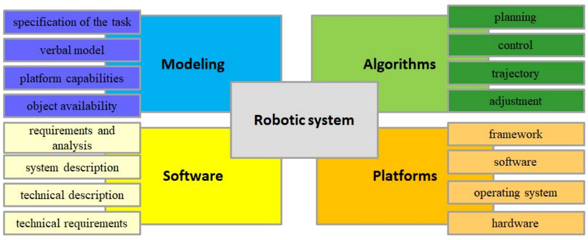

Fig.1. The design methodology of a robotic system

The robotic system is a combination of hardware and software components as two separate layers that can be integrated to create robotic systems . Hardware components, such as sensors, robotic levers, navigation panels are the components of the system [10,12,13,14]. Hardware components are monitored and controlled by a control layer, which is essentially represented as a set of drivers (as system code) for interacting with hardware Fig. 1.

The mechatronic system of chassis motion control consists of sensors, microcontroller control system and actuators Fig. 2. The system provides on-off, control of executive devices by commands from the central on-board computer, reception of signals from sensors and their issuance to the central on-board computer in the form of control signals. The system is open at the interface level of the command formats [10] ,[12].

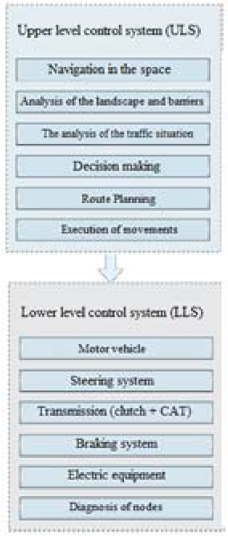

Fig.2. General view of the robotic system based on mini tractors "Belarus 132"

The interaction of the components of mobile robotic system by using various kinds of controllers "Fig. 3" [15].

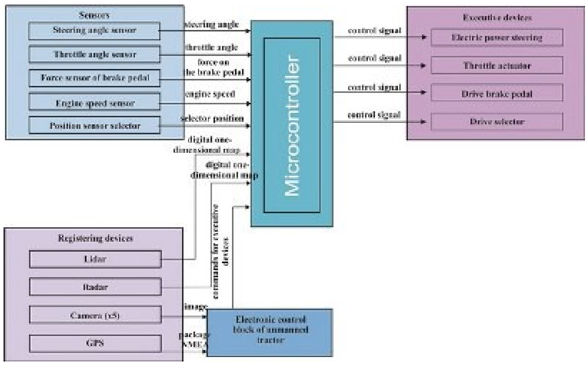

Fig.3. The composition of the control system of mobile robotic system

As actuators for the selection of driving modes, the electromechanical actuators of SKF and Hiwin are used, the characteristic features of which are:

- degree of protection - IP54;
- temperature range - -40 - +80 ºC;
- pulling force 300 N;
- stroke of 150 mm;
- presence of a resistive position sensor.

One of the modules of the mechatronic system is shown in Fig. 4. shows the appearance of the robotic system based on the chassis of the mini tractor "Belarus 132" [2], [10]. [11].

Fig.4. Robotic system

The structural scheme of the mechatronic control system connections of chassis movement of the robotic system is shown in Fig. 5.

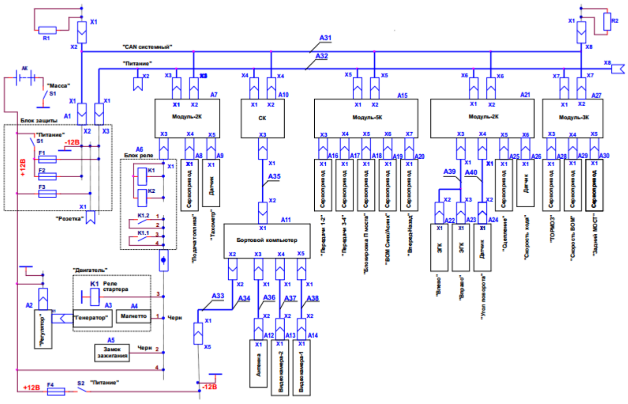

Fig.5. Structural diagram of the mechatronic motion control system of the chassis of the robotic system

The control system of the robotic system consists of the upper and lower levels. The top-level system provides the functions of navigation, terrain analysis, decision-making, planning and execution of traffic [10,11]. The low-level system includes steering, transmission, node diagnostics, electrical equipment management Fig.6.

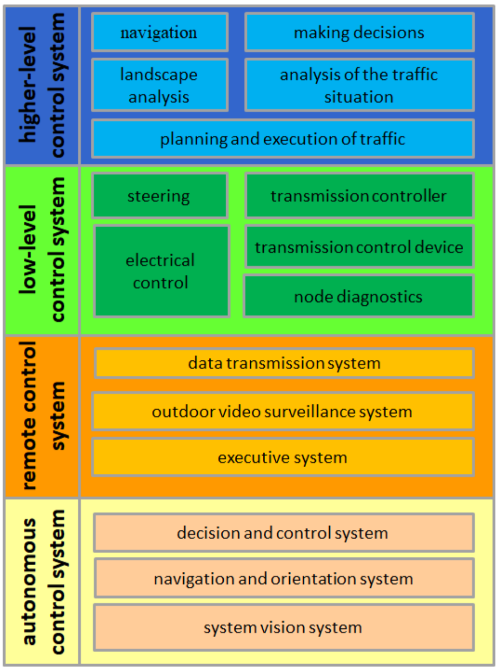

Fig.6. Control system of robotics system

To study the problem of controlling a mobile robot on the basis of the Belarus-132 mini tractor chassis with a mechanical transmission, a dynamic model was developed in the Matlab / Simulink environment using the SimScape component library Fig. 7. To specify the characteristics, the technical characteristics of the Belarus-123 mini tractor were used. With the help of this model the following tasks were solved:

- modeling and research of the dynamics of the mobile robot with a given transmission control vector;
- selection of parameters of individual nodes to achieve the specified characteristics of control devices;
- synthesis of transmission controller algorithms.

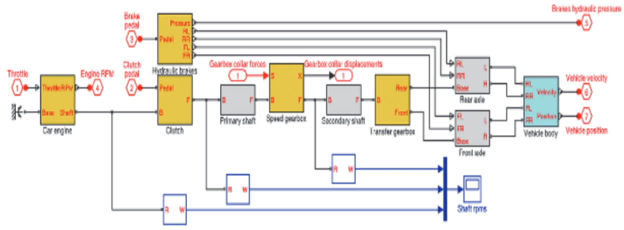

Fig.7. General scheme of the dynamic model of the mobile robot on the basis of the chassis of the mini-tractor "Belarus-123".

III. EXPERIMENT ON SIMULTANEOUS LOCALIZATION AND MAPPING

The work of a mobile robot in a room is considered, the plan of which is unknown in advance. The mobile robot is equipped with a scanning range finder, which will determine the obstacles. It is required in real time to determine the position of the mobile robot in the coordinate system associated with the room (localization problem), and also to build a room map reflecting the walls and fixed objects [15], [16].

To build the localization system and to map, the advanced Kalman filter and FastSLAM algorithms is used. The structure of the navigation system of the mobile robot is shown in Fig. 8.

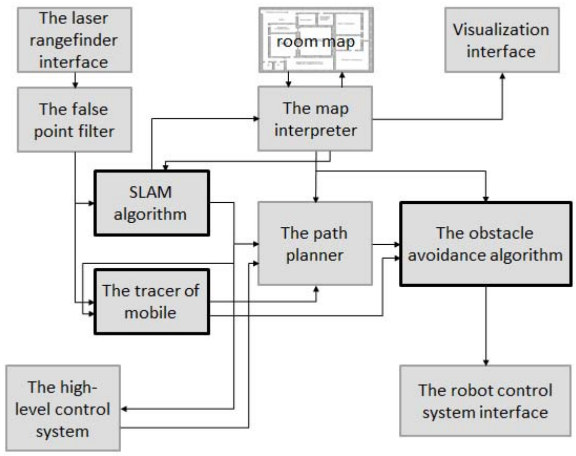

Fig.8. Functional diagram of the navigation system of the mobile robot

A. The EKF algorithm

The Kalman filter is a recursive filter that estimates the state vector of a dynamic system using a series of incomplete and noisy measurements. The Kalman filter is designed for recursively overestimating the state vector of an a priori dynamical system, i.e. to calculate the current state of the system, you need to know the current measurement, as well as the previous state of the filter itself [17]. The state of the filter at time k is in two variables: X_k - estimation of the state vector of the dynamic system; P_k - covariance error matrix (measure of the accuracy of the state vector estimation). EKF is very similar to a simple Kalman filter, except that it can be used in nonlinear processes. EKF is one of the most common methods for solving the SLAM problem [18]. It allows not only to refine the assessment of the position of the robot on the map, but also the position of all the found landmarks. Typically, the process of assessing the state of the system, in the context of SLAM, is divided into three stages:

1) updating the system state assessment based on odometer data;

2) updating the assessment of the state of the system based on re-discovered landmarks;

3) adding new landmarks to the system.

For all its attractiveness, EKF nevertheless has its drawbacks, which include, first of all, the limitation on the number of reference points in the system. This is connected with the fact that the matrix P has a dimension mxm, where m - the number of found landmarks. At each stage of updating the matrix P, each element of it must be updated, which is why the complexity of the algorithm is $O(m^2)$. Thus, EKF is the most applicable in a situation where the environment does not have a very large number (several hundred) of easily distinguishable landmarks.

B. *FastSLAM algorithm*

Suppose that the mobile robot is in one-dimensional space, and its position is characterized by one variable. Then $p(x)$ will be a probability distribution x having a Gaussian shape. In the case if x reflects the position of the robot and landmarks in a multidimensional space, then the probability distribution $p(x)$ will determine the probabilities of all possible state variables [19]. $p(x| \{u_0, u_1, ..., u_i\}, \{z_0, z_1, ..., z_i\}$ describes the probabilities of all values of the current state of the system, such as sensor readings and information about the movement of the robot obtained at the time i. They also have an appointment P_i and X_i in the expanded Kalman Filter, only there they are presented in a much more complicated form. We introduce the notation $Ui=\{u0, u1, ..., ui\}$ and $Zi=\{z0, z1, ..., zi\}$, x in turn, includes the position of the robot v and the position of the landmarks $p0, p1,...,pm$. $p(x| Ui,Zi)$ can be represented in the following form(1):

$$p(x|U_i, Z_i) = p(v, p_0, p_1, ..., p_m|U_i, Z_i) \quad (1)$$

The evaluation of the position of the landmarks depends on the evaluation of the position of the robot [20]., which means that $p(v,p0,p1,...,pm| Ui,Zi)$ can be represented in the following form (2):

$$\begin{aligned} &p(v, p_0, p_1, ..., p_m|U_i, Z_i) = \\ &= p(v|U_i, Z_i) \cdot p(p_0, p_1, ..., p_m|U_i, Z_i, v). \end{aligned} \quad (2)$$

Due to the independence of the landmarks observations from each other $p(p0, p1,...,pm| Ui,Zi,v)$ can be divided into m independent expressions:

$$\begin{aligned} &p(v|U_i, Z_i) \cdot p(p_0, p_1, ..., p_m|U_i, Z_i, v) = \\ &p(v|U_i Z_i) \cdot p(p_0|U_i Z_i, v) \cdot p(p_1|U_i Z_i, v) \cdot ... \cdot \\ &\cdot p(p_m|U_i Z_i, v). \end{aligned} \quad (3)$$

As a result, the resulting expression for the probability distribution has the form:

$$p(x|U_i, Z_i) = p(v|U_i Z_i) \cdot \Pi_m \, p(p_m|U_i Z_i, v). \quad (4)$$

FastSLAM simultaneously tracks several possible routes, while Kalman's advanced filter does not store even one, but only works with the position of the robot - the last step of the current route. In its original form, FastSLAM saves the route, but uses only the previous step in the calculations [19] , [21], [22].

C. *Results of experimental studies*

For experimental studies, a simulation environment for the process of studying cavities of building structures was developed by an autonomous mobile robot on the basis of the chassis of the mini tractor Belarus-132. As the basis of the system of local navigation and cartography, the expanded Kalman filter was chosen. The guidelines in this case are the angles formed at the intersection of the corridors. To assess the accuracy of the map, the maximum and average deviations of the angles coordinates on the constructed map from the coordinates of the corners on the original map were calculated. The tests were carried out on three maps of different configuration and length. The results of the experiment are presented in Table - 1.

TABLE I. EXPERIMENT RESULT

The total length of corridors (m)		
31,11	19,46	33,83
The maximum length of the corridor (m)		
7,8	6,67	4,61
The average deviation of coordinates		
0,16	0,19	0,13
The maximum deviation of coordinates (m)		
0,16	0,2	0,18

The deviations of the coordinates of the constructed map from the coordinates of the real map were calculated from the formula:

$$r_i = \sqrt{(x_{pi} - x_{ni})^2 + (y_{pi} - y_{ni})^2}, \quad (5)$$

where x_{pi} and y_{pi} are the coordinates of the i angle on the real map, x_{ni} and y_{ni} are the coordinates of the corresponding angle on the constructed map.

From the results of the experiment it can be seen that the accuracy of mapping is high (the average deviation of the angles from their actual position is not more than 0.2 m), even with a sufficiently large total length of the corridors. You can also notice that the accuracy of the map depends on the topology, as well as on the total and maximum length of the corridors.

IV. CONCLUSIONS

Currently, in the scientific world, both the Kalman advanced filter and the FastSlam approach are used to build local navigation and map building systems. The choice of this or that method depends on the required accuracy of the system and its speed, on the parameters of the environment, such as the presence of landmarks, their number and physical characteristics, and many other factors. In recent years, the FastSlam algorithm is gaining in popularity and gradually extrudes Kalman's advanced filter. In this paper, both approaches have been investigated, model experiments have been carried out, and corresponding conclusions have been drawn. For further, more in-depth studies, the FastSlam algorithm is chosen, and currently works are being carried out to conduct in-situ experiments, approaches are being developed to create multi-agent systems based on the FastSlam algorithm.

ACKNOWLEDGMENT

This work is supported by the Ministry of Education and Science of the Republic Kazakhstan.

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