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PROTOTYPING OF A TWO-WHEELED MOBILE ROBOT FOR SUSTAINABLE MANUFACTURING DEVELOPMENT BASED ON TRIANGULATION METHOD AND SOFTWARE DEVELOPMENT

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ABSTRACT

This article presents a mobile robot prototyping and software development for its control production. A created robot prototype moves using a two-wheeled base and is equipped with ultrasonic sensors. This design allows increasing the maneuverability of the robot and reducing the turning radius. The specific arrangement of the sensors allows expanding the area of obstacle detection. The developed software includes receiving data from the sensors, processing them and constructing a movement trajectory in accordance with the target and the current environment state. The trajectory is constructed using the triangulation method. This allows accurately determining the distance to the obstacle, constructing a rational movement trajectory and going around obstacles that may arise on the path of the robot. A number of experiments were conducted that allow us to say that the obstacle detection range is sufficient for a timely response and change the trajectory of movement.

Keywords: *Mobile Robot, Triangulation, Ultrasonic Sensor, Two-Wheeled Robot, Software for Mobile Robot*

1. INTRODUCTION

Modern technologies require improved automation and labor savings. The concept of Industry 4.0 has led more and more industries to discover the possible implementation of robotic systems. Industrial robots have become one of the driving forces behind automation [1-4].

Many researchers write about the benefits of using industrial robots. E. Z. Wang and others in their paper [5] found that industrial robots could significantly improve manufacturing energy intensity. Authors in [6] note that robotic systems are flexible and this is the key advantage to raise competitiveness. Researchers in [7] also say about high flexibility and they also distinguish benefit of cost efficiency and multi-functionality of industrial robot. The fact that industrial robots allow to produce high-quality products cost-effectively is also said by scientists in [8]. They also note that robots operate with high endurance, speed and precision. In [9] authors also write about an increased accuracy and productivity in the industries ensuring the cost savings and the reduced resource utilization with robots using.

To successfully perform the specified functions, robots are equipped with various sensors, such as sensors of mechanical quantities (linear, angular displacements, distances, accelerations, forces and moments), vision systems, temperature, current and voltage meters, light intensity, radioactive and magnetic fields, acoustic sensors, ultrasonic sensors, and infrared sensors, water detectors and gas analyzers and others [10-13]. All of them have a different degree of sensitivity, measurement quality, and operation speed and, accordingly, the cost. It is

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necessary to choose equipment for the robot based on the tasks that are set for it, including the rational selection of sensor sensitivity. We should note that the price of the robot is of key importance. Too expensive robots may not bring the desired economic effect.

Separately, it must be said about mobile robots, that is, about robots that move in production. For them, there is a separate task of moving in a given direction with the need to calculate the trajectory and the ability to avoid obstacles. In order to avoid obstacles, we have to know the distance to them. The distance to surrounding objects can be measured using radars or lidars, sonars, ultrasonic sensors, infrared rangefinders, ToF cameras that is, using radiation of different wavelengths. All these sensors have their advantages and disadvantages. We also have to consider the robot usage environment when choosing such sensors.

We should note that the cost of development is determined by the cost of the hardware itself used for it, as well as the cost of the software. At the same time, in order to achieve maximum economic efficiency, it is necessary to find a balance between the necessary and sufficient accuracy of data received from sensors. The higher the accuracy, that is, the sensitivity of the sensor, the higher its price. So, to solve the problem, it is necessary first of all to choose equipment that meets the requirements of both accuracy and price.

Since the robot is a device capable of performing certain actions, the creation of a control system for it becomes a necessary paramount task. So, after choosing the equipment for the developed robot, it is necessary to create software to control such a robot. It should be noted that it is absolutely irrational to use standard software. It may be redundant, that is, it contains both the necessary functions and those that will not be used in the developed robot. It may also contain features that are not applicable in our robot environment. On the other hand, if the standard software is not redundant, then it may not contain the necessary functions, and may not take full advantage of our mobile robot. Software for mobile robot must take into account movement support system and sensors used for the robot. Since the developed robot is mobile, we can talk about developing a navigation system for it. An important element of mobile robots is the navigation system and the control of such a system [14]. The navigation system allows the robot to move to a given goal by independently calculating the movement trajectory. That is, having the necessary information from the sensors, such a system allows the robot to independently plan its path. This means that the need for operator intervention in controlling the movement of the robot is practically eliminated. This increases the reliability of the system being developed, since the subjective factor (human factor) is practically removed.

Therefore, an important task facing the developers of the corresponding robots is to increase their maneuverability and control efficiency in complex navigation conditions, an example of which is real production. An important aspect of such development is also the creation of autonomous systems that operate without significant operator intervention. This leads to the fact that the stage of robot prototyping and the development of its software containing an appropriate navigation system is an urgent task. This study is devoted to these key issues that will determine the choice of the main directions of presentation of the article.

2. LITERATURE REVIEW

According to the control method, 3 groups of robots can be distinguished: robots with program control, working according to a predetermined rigid program; adaptive control robots; robots with intelligent control (with artificial intelligence).

"Rigid" control of a robot with a predetermined program has a number of advantages, including the reliability of the program. But there are also a number of disadvantages here, among which we note the lack of flexibility and the difficulty of readjusting the control program. Basically, such control is used on non-mobile robots. Such robots cannot quickly adapt to changing environmental conditions.

Robots equipped with artificial intelligence have advanced functionality compared to adaptive robots, including the ability to self-learn.

Robots with adaptive control are able to respond flexibly to changes in the environment. To do this, they need sensory systems capable of providing information about the state of the environment. The software of such robots should provide this information obtaining and the actions that the robot must perform, taking into account the whole variety of data received. Nowadays a lot of scientists are interested in such software development. We will highlight just a few of these works. In [15] authors propose to use only onboard monocular cameras for their adaptive image-based visual servo control strategy. Researchers in their paper [16] implement robot control through onboard visual sensing. Papers [17-20] also propose visual control system using (visual sensors). Authors in [21] propose to use magnetic, angular rate, and gravity sensor arrays to control a mobile platform. Scientists [22] report a hybrid analog-digital computing platform enabled by memristors on a mobile inverted pendulum robot. Through its use they achieve optimal control performance. In [23] there is proposed to use two lidars and then a deep convolutional neural network. All of these sensors have limitations in use. Many of them are demanding on environmental conditions, such as lighting, dust, smoke, noise, etc. Some of them have insufficient sensitivity and range. Part of them is simply very expensive.

Some researchers also propose to use ultrasonic sensors to detect obstacles [24-29]. But they have some disadvantages. Some of them can be removed using several of these sensors [30]. It should be noted that the cost of the created robot is largely determined by the cost of the sensors that the robot is equipped with. Since one of the challenges facing us is to reduce the cost as much as possible, but with the ability to perform the tasks assigned to the robot, we chose ultrasonic sensors for our work. We analyzed the advantages of ultrasonic sensors, including their ease of use, reliability, economy (and cost), neutrality to environmental influences, that is, the ability to work in dusty, smoky rooms, as well as in rooms with high noise levels. As a result, it was decided to use this type of sensors.

Scientists choose different control algorithms for adaptive robots. Among them we can highlight the following. In [31] researchers present Asynchronous implementation of Deep Neural Network-based Model Reference Adaptive Control. S. Calinon introduces a varied range of techniques employing Gaussian distributions on Riemannian manifolds in [32]. And so on.

All these systems solve different tasks related to the control of robots. In this paper we are interested in a narrow area of control, namely, robot path planning with the ability to bypass obstacles. In [28] scientists use ultrasonic sensors and they propose algorithm that is based upon an iterative non-linear filter, which utilizes matches between observed geometric beacons and an a-priori map of beacon locations, to correct the position and orientation of the vehicle. Other methods can be used here as well [33]. Broad, rather than deep, coverage of key and foundational algorithms, with popular algorithms and variants considered in [34] in the context of different robotic systems. Authors [35] introduces a global classification of path planning algorithms, with a focus on those approaches used along with autonomous ground vehicles, but is also extendable to other robots moving on surfaces, such as autonomous boats. In [36] the principle of fuzzy-based control proposed by Sugeno is used to develop the motion controller in order to plan motion. Zhe Sun et al. in [37] propose a robust nonsingular terminal sliding mode control scheme for the path-following problem of Mecanum-wheels omnidirectional mobile robot. In their approach they use such famous formulas as Lyapunov function, a Runge–Kutta formula and so on. In [38] authors solve some problems, including autonomous learning in path planning by to utilizing neural networks. Researchers [39-41] use Deep Reinforcement Learning to navigate their robot. Based on dueling network architectures for deep reinforcement learning (Dueling DQN) and deep reinforcement learning with double q learning (Double DQN), a dueling architecture based double deep q network (D3QN) is adapted in paper [42]. In [43] path planning algorithm based on Probability and Fuzzy Logic as a duality technique to enhance the performance of Fuzzy Logic alone is presented. In article [44] an approach based on the combination of RRT* and B-spline is proposed for smoothing the path which is generated by RRT*-based algorithms, which are one of the most famous groups of algorithms in artificial intelligence.

All the described algorithms are quite interesting and give good results. They are different, but they are all very complex and operate with large amounts of information. These solutions are interesting, but quite difficult to understand and implement, including for software development. We must take into account that the algorithms associated with prediction, the use of neural networks, learning, not only use current data from sensors, they store huge amounts of data from previous measurements. Consequently, the software is complicated by the processing of large data arrays, which leads to a significant slowdown in its work. It also increases the cost of its development. In many cases, perhaps, this can be neglected. However, as part of our work, we strive to make the simplest software that has the highest performance. Also, its development should have the lowest possible cost. So, we propose to use triangulation method in order to detect obstacles and bypass them. This method is very simple, very fast, and it shows an acceptable accuracy in the working conditions of the developed mobile robot.

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Thus, in order to eliminate the shortcomings of previously developed robotic systems, among the main tasks of this study aimed at ensuring the maneuverability and efficiency of robot control, the following should be indicated:

the feasibility of using the triangulation method, taking into account the offset rotation inward in relation to each other of the ultrasonic sensors, which allows for a significant expansion of the obstacle detection area;

justification of a two-wheeled mobile robot using to increase its maneuverability in a specific limited space of real production;

development of appropriate simple but effective software aimed at processing and constructing the trajectory of the robot's movement in accordance with the goal and the current state of the environment;

conducting a series of experiments to study the main characteristics of the developed mobile robot.

3. TRIANGULATION METHOD AND ITS MAIN CHARACTERISTICS

According to the conditions of the task, in production a mobile robot needs to move towards a given object. At the same time, there may be obstacles on its way that must be noticed, bypassed and it has to continue moving towards a given goal.

So, it is necessary to develop such software that among other things will allow robot to perform these operations (notice an obstacle, lay a new movement trajectory, continue moving towards the goal).

The main operation principle of our software is laid precisely in the logic of orientation and finding objects in space using sensors and the triangulation method. The very idea is that knowing the distance between the sensors on the robot and knowing the distance to each of them, we can calculate the exact location of the object.

Figure 1 schematically shows the appearance of the robot and its "vision" field with an obstacle located beyond the line of vision.

Next, if the robot moves forward, it "bumps" into an obstacle and both of its sensors read information about the location of the obstacle.

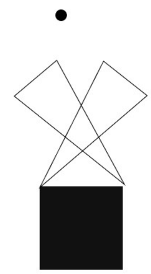

Figure 1: The Appearance of the Robot and Its "Vision" Field with an Obstacle Located beyond the Line of Vision

In figure 2 the process of finding an obstacle is depicted.

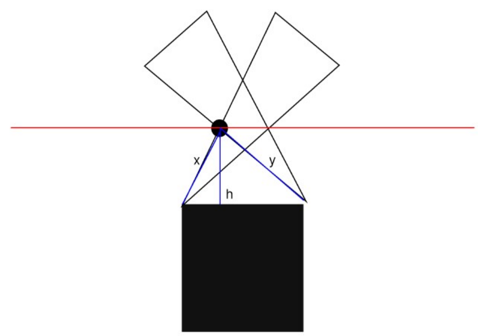

Figure 2: An Obstacle in the Robot's Field of Vision

Now when the obstacle is in the field of view for both sensors, knowing the distance x and y, as well as the distance between the sensors themselves, it is not difficult to determine the height h, which will be the distance to the front line of the case. Also, knowing that the obstacle has reached the minimum distance to the body and knowing which of the sensors it is closer to, it is possible to conclude in which direction the turn will be made.

After turning and moving forward, the obstacle falls into the field of vision of one of the sensors, and then it is clear in which direction to turn next to bypass the obstacle.

Figures 3-4 show a further turn.

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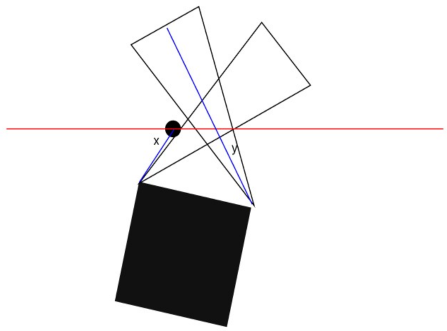

Figure 3: Robot's Turn

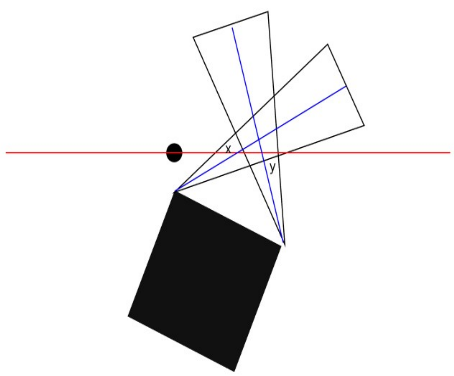

Figure 4: Robot's Turn and Further Movement

Also, by slightly changing the code, it is possible to achieve the completely opposite result and with great accuracy set the robot in front of the point by calibrating the distance of each of the sensors accordingly.

Figures 5 show visually how the robot can be positioned exactly in front of an obstacle.

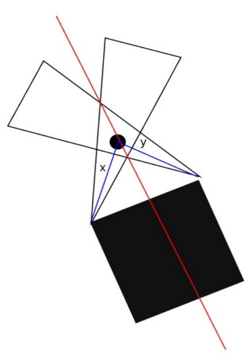

Figure 5: The Obstacle Is Centered Directly in Front of the Robot

Thus, when the distance from one sensor becomes equal to the distance to the other, it means that the object is centered and it is possible to interact with it to achieve the set goal.

Calculation of the distance to obstacles using sensors

The HC-SR04 ultrasonic sensor uses the principle of echolocation to determine the distance to objects by emitting ultrasonic waves and analyzing their reflections. The time it takes for the wave to travel from the sensor to the object and back is measured and used to determine the distance. This distance can be determined using formula:

$$D=1/2\bullet T\bullet C, \tag{1}$$

where D is the distance to the object; T is the time for which the wave travels; C is the speed of sound in air, which is approximately 340 m/s.

Since this project uses 2 sensors to measure the distance, the formulas for finding the height of a triangle based on 3 known sides (2-3) were used for their correct operation.

$$P = (a+b+c)/2, \tag{2}$$

where a, b, c are known sides; P is the perimeter.

$$H = 2/a \cdot (p(p-a)\,(p-b)\,(p-c))^{1/2}, \tag{3}$$

where a, b, c are known sides; p – perimeter; H – height.

Thus, in the area about 20°-30° in front of the robot, the exact location of the object in space can be determined. And further, knowing the distance to each of the sensors, make a decision about the direction of movement of the mobile platform.

4. GENERALIZED BLOCK DIAGRAM OF A TWO-WHEELED MOBILE ROBOT

At first, we must note, that the design of the robot determines its control system and software. We decided to implement a two-wheeled robot, as such a robot has increased mobility compared to three and four wheeled devices. In particular, if it is necessary, it can turn around its axis. An additional third wheel was installed to balance our robot. A series of tasks was solved to maintain balance by the robot. However, their detailed description is beyond the scope of this article.

We have chosen an Arduino Mega 2560 as a main node of our robot. Arduino Mega 2560 is a powerful and flexible platform for developing a

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variety of projects, including robotics, automation, and the Internet of Things (IoT). This board is a good solution for projects that require a high level of computing power and a lot of interaction with sensors or other devices.

Next, the L293D bridge was chosen, which is an important component in robotics projects, as it allows us to control the speed and direction of rotation of the motors. This integrated power bridge is a four-channel control motor designed specifically to control loads such as direct current (DC) motors and stepper motors. It is suitable for use in robotic systems where simple and efficient motor control is required.

The HC-SR04 was chosen as the ultrasonic sensor, which is an ultrasonic distance sensor widely used in robotics projects to determine the distance to objects and detect obstacles. This sensor is easy to use and highly accurate, ideal for applications in robot navigation systems and automatic control projects.

The next DC3V-6V was chosen because it is a compact and powerful DC motor with a 1:48 gear ratio that is widely used in various robotics projects and designs to drive related devices.

The list of used components for the electrical circuit is given below. Arduino Mega 2560 (one piece); electric drive with H-bridge (one piece); gear motor (two pieces); ultrasonic distance sensor; battery 9 V.

The electrical circuit uses an Arduino Mega 2560 microcontroller as the main control node. This microcontroller is the central element of the system, performing calculation and control functions. A 9V battery is used to power the system, which provides the necessary power for all system components. An electric drive with an H-bridge provides control of two motor-reducers, which allows the work to move at the required speed and control its direction. The main sensors of the system are two HC-SR04 ultrasonic distance sensors, which are mounted with a slight inward bias to allow the triangulation method to accurately determine the position of objects relative to the robot's center and thus determine the path of movement more precisely.

This configuration allows the robot to perform spatial measurements, adapt to changes in the surrounding environment and choose the optimal path of movement. The electrical circuit is designed to ensure the reliability and durability of all components, as well as to ensure the accurate and stable operation of the environmental recognition system.

The assembly of the robot model was divided into the following main stages:

– assembly of a moving platform containing wheels, motors and Plexiglas for the device main components future mounting;

– the board, microcontroller and bridge connecting and connection of the external power source. An example is shown in figure 6;

– ultrasonic sensors mounting and all components assembly into the final model. The mounting results are shown in figures 7-9.

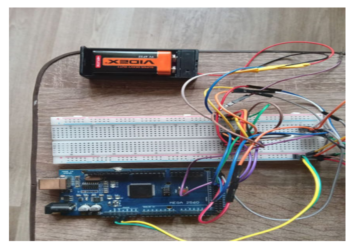

Figure 6: The Main Components Connecting to the Board

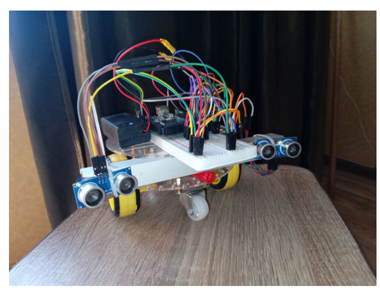

Figure 7: Assembled Robot, Front View

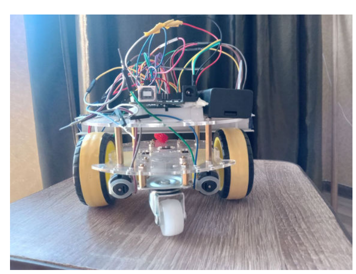

Figure 8: Assembled Robot, Rare View

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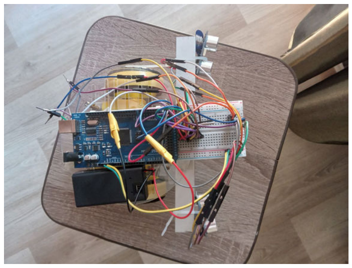

Figure 9: Assembled Robot, Top View

This integrated two-wheeled robot, equipped with an environment recognition system, is a powerful tool for interaction and navigation in the real world. It can be used in various fields, including automation of production processes, robotics, autonomous transport systems and security systems. Thanks to its ability to adapt to different conditions and needs, this robot can open up a wide range of possibilities for optimizing work processes and increasing production efficiency.

Separately, it is necessary to cancel the low cost of the developed robot, which makes it possible to use it in conditions of man-made disasters, as well as demining, which is extremely relevant now.

5. MOBILE ROBOT SOFTWARE

The software of the robot was developed taking into account its design, in particular, the presence of two driving wheels and installed ultrasonic sensors.

In the written software, after the system is loaded, the main components of the robot are automatically activated, including ultrasonic sensors and motors. This happens immediately after the drivers of these components are loaded into the system.

The user program processes the data from the ultrasonic sensors, which are turned easily into the middle. This makes it possible to use the triangulation method to accurately determine the position of objects relative to the center of the robot.

Based on the data from the sensors, the program determines which way the robot should move, taking into account the location of the nearest objects. The robot is able to independently adjust its path to avoid obstacles.

The program provides access to detailed information about engines and ultrasonic sensors, which is obtained from the relevant system resources.

When finished, the user can safely shut down the system through the user interface.

Due to the fact that the Arduino Mega 2560 microcontroller was selected as the main component in the module nodes, Arduino IDE version 2.1.0 is used as the software development environment.

Before starting work, it is necessary to define the constant variables that will be used when writing the program. This is done in order to centralize global values and in the future to be able changing their values in one place to change them throughout the code.

```
#define TRIG_PIN_1 23
#define ECHO_PIN_1 22
#define ECHO_PIN_2 24
#define TRIG_PIN_2 25

#define DRIVE_POS_1 28
#define DRIVE_NEG_1 29
#define DRIVE_POS_2 26
#define DRIVE_NEG_2 27

#define FORWARD 0
#define BACKWARD 1
#define RIGHT 2
#define LEFT 3

#define NO_BARRIERS 0
#define BARRIER_LEFT 1
#define BARRIER_AHEAD 2
#define BARRIER_RIGHT 3
```

Further, after defining the global variables, the board pins are initialized, at this moment, the operating modes of the pins that were defined earlier in the global variables are set. The serial port is also initialized for transferring logs to the console and debugging the program.

```
void setup() {
  Serial.begin(9600);
  pinMode(TRIG_PIN_1, OUTPUT);
  pinMode(ECHO_PIN_1, INPUT);
  pinMode(TRIG_PIN_2, OUTPUT);
  pinMode(ECHO_PIN_2, INPUT);
  pinMode(DRIVE_POS_1, OUTPUT);
  pinMode(DRIVE_NEG_1, OUTPUT);
  pinMode(DRIVE_POS_2, OUTPUT);
  pinMode(DRIVE_NEG_2, OUTPUT);
}
```

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After defining and initializing the ports that are necessary for controlling the robot, the functions responsible for the movement of the robot are initialized.

– left turn function:

```
void moveLeft() {
  digitalWrite(DRIVE_POS_1, HIGH);
  digitalWrite(DRIVE_NEG_1, LOW);
  digitalWrite(DRIVE_POS_2, HIGH);
  digitalWrite(DRIVE_NEG_2, LOW);
}
```

– right turn function:

```
void moveRight() {
  digitalWrite(DRIVE_POS_1, LOW);
  digitalWrite(DRIVE_NEG_1, HIGH);
  digitalWrite(DRIVE_POS_2, LOW);
  digitalWrite(DRIVE_NEG_2, HIGH);
}
```

– forward move function:

```
void moveForward() {
  digitalWrite(DRIVE_POS_1, HIGH);
  digitalWrite(DRIVE_NEG_1, LOW);
  digitalWrite(DRIVE_POS_2, LOW);
  digitalWrite(DRIVE_NEG_2, HIGH);
}
```

– backward move function:

```
void moveBackward() {
  digitalWrite(DRIVE_POS_1, LOW);
  digitalWrite(DRIVE_NEG_1, HIGH);
  digitalWrite(DRIVE_POS_2, HIGH);
  digitalWrite(DRIVE_NEG_2, LOW);
```

– stop function:

```
void stop() {
  digitalWrite(DRIVE_POS_1, LOW);
  digitalWrite(DRIVE_NEG_1, LOW);
  digitalWrite(DRIVE_POS_2, LOW);
  digitalWrite(DRIVE_NEG_2, LOW);
}
```

After the main functions of the robot's movement have been defined, a function is created that gives a simple unified interface for controlling the robot's movement, to which only the direction is transferred in the form of a global variable, which was defined at the very beginning of the program:

```
void movePlatform(int direction) {
  String direction_str;

  switch (direction) {
    case FORWARD:
      moveForward();
      direction_str = "forward";
      break;
    case BACKWARD:
      moveBackward();
      direction_str = "backward";
      break;
    case RIGHT:
      moveRight();
      direction_str = "right";
      break;
    case LEFT:
      moveLeft();
      direction_str = "left";
      break;
    default:
      Serial.println("Unknown direction");
      return;
  }

  Serial.print("Platform moved ");
  Serial.println(direction_str);
}
```

Next, the main function for the implementation of robot orientation using the triangulation method is defined – the function of determining the time it takes for a sound wave to reach the sensor from a theoretical obstacle.

```
long getDuration(int echo, int trig) {
  digitalWrite(trig, LOW);
  delayMicroseconds(5);
  digitalWrite(trig, HIGH);
  delayMicroseconds(10);
  digitalWrite(trig, LOW);
  return pulseIn(echo, HIGH);
}
```

After that, a function was implemented that simultaneously calculates 3 indicators – the distance from the left sensor to the obstacle, the distance from the second sensor to the obstacle, and based on these values, calculates the distance from the front line of the robot body to the obstacle using the triangulation method.

```
float getDistances(float* distances) {
  int duration = getDuration(ECHO_PIN_1,
TRIG_PIN_1);
  distances[0] = duration / 58.2;
  delay(30);
  duration = getDuration(ECHO_PIN_2,
TRIG_PIN_2);
```

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```
   distances[1] = duration / 58.2;
   delay(30);

   if(distances[1] > 30)
     distances[1] = 30;
   if(distances[0] > 30)
     distances[0] = 30;

   int diff = distances[0] – distances[1];
   if(diff >= 5)
     return distances[1];
   if(diff <= -5)
     return distances[0];
   float p = (distances[0] + distances[1] + 20)/2;
   float height = 2*sqrt(p*(p-20)*(p-
distances[0])*(p-distances[1]))/20;
   return height;
 }
```

Having finished defining the main functions of the program, there is an entry into an endless cycle in which the distance to the theoretical obstacle is continuously read, the direction of movement is determined and the movement itself is carried out. Also, before the function, a variable is created that takes the value of the distance from the obstacle to each of the sensors.

```
static float distances[2];

void loop() {
  float height = getDistances(distances);
  while(isnan(height)) {
    moveBackward();
  }
  int state = NO_BARRIERS;
  int direction;
  if (getDistances(distances) < 20) {
    stop();
    delay(100);
    if(distances[0] >= distances[1])
      direction = LEFT;
    else
      direction = RIGHT;

    while(getDistances(distances) < 20) {
      movePlatform(direction);
      delay(50);
    }
    movePlatform(direction);
  }
  else {
    movePlatform(FORWARD);
  }
  delay(100);
}
```

6. SEVERAL CHARACTERISTICS OF THE DEVELOPED MOBILE ROBOT

In our work, we use two HC-SR04 ultrasonic rangefinders. In accordance with the technical specifications described by the manufacturer, this sensor measures the distance in the range from 0 to 1.5m. Moreover, the recommended distance is from 2 cm to 80 cm. In this case, the declared accuracy is 3 mm. However, we conducted a series of experiments that showed that for solving our problems, a distance to an obstacle of up to 3 m is acceptable. The first obstacle we experimented with was a wooden box. The graph of errors is shown in figure 10.

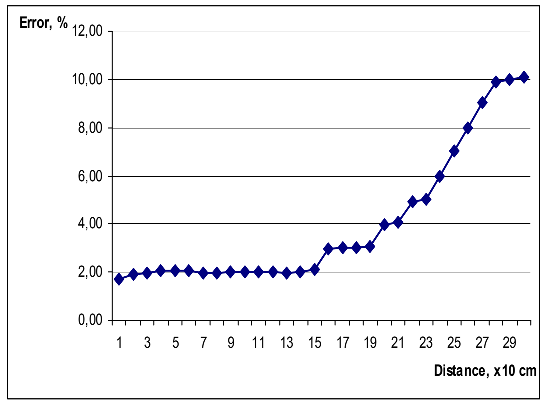

Figure 10: Errors Graph for the Experiment with a Wooden Box

The second obstacle we experimented with was a plastic cylinder. The graph of errors is shown in figure 11.

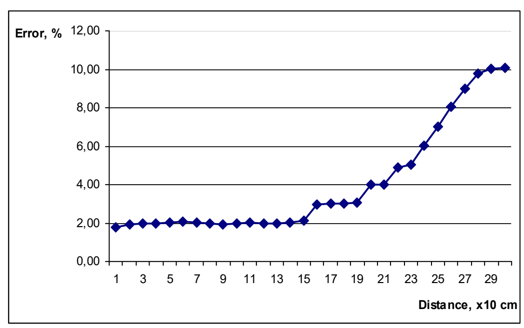

Figure 11: Errors Graph for the Experiment with a Plastic Cylinder

From these graphs, we can see that for our conditions, the material (wood or plastic) as well as the shape (box or cylinder) are not decisive in detecting an obstacle. Indeed, up to 80 cm, the error in determining the obstacle is about 2%, which represents a very high accuracy. From 90 cm to 3 m, the error gradually increases to 10%, which in principle is an acceptable result. At a greater distance, the robot practically does not see obstacles. However, since it is moving in the direction of the target, it detects it when approaching an obstacle on the way.

The sensors performed well both in good light and in the dark. It is also good at identifying objects of different colors. However, when conducting experiments with curtains made of fabric and foam rubber, it proved to be practically unsuitable. The sensor did not detect a fluffy cat. Objects with a flat, smooth surface are optimal for measuring distance.

Next, we conducted a series of experiments to identify the area in which the selected ultrasonic sensor best detects obstacles. The result graph is shown in figure 12.

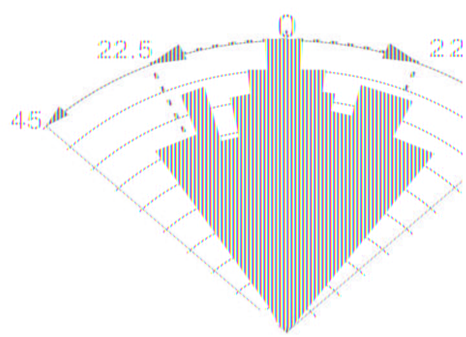

Figure 12: Test Result to Find the Best Obstacle Detection Area for One Sensor

From figure 12 we can see that the best obstacle detection is achieved in a sector whose degree measure is 30°. At the same time, when the object is located directly in front of the sensor, that is, with a zero offset relative to it, the detection distance is the greatest.

We also tested how the two sensors work together. Figure 13 shows the result of testing the joint operation of two sensors.

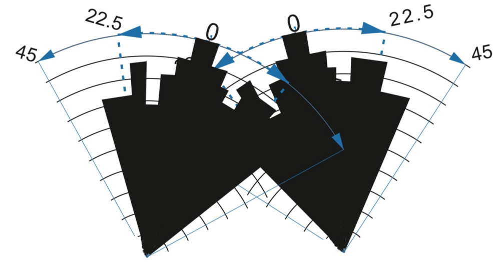

Figure 13: Test Result to Find the Best Obstacle Detection Area for Two Sensors

As mentioned above, the sensors are slightly turned inward towards each other. Accordingly, the areas of detection of obstacles are superimposed, therefore, the area of detection of obstacles is greatly expanded.

Among the limitations of the proposed development, the following should be indicated. First of all, such limitations are imposed by the environment of use of the developed prototype. In particular, in this aspect, the maneuverability of the robot will be less effective in the case of multiple obstacles or a very complex trajectory for achieving the set goals. Given the maneuverability of the proposed prototype, attention should also be paid to the stability of the corresponding robot when performing certain tasks. Therefore, as limitations for the use of such a robot, the range of tasks it performs should be indicated. However, in general, such limitations are not critical, since the use of the corresponding robots is aimed at performing a number of specific tasks. At the same time, prototyping allows us to identify problematic aspects of the proposed development in advance, carry out the necessary improvements and limit the range of tasks performed.

7. SOME COMPARATIVE ASPECTS OF THE PROPOSED PROTOTYPE WITH EXISTING ANALOGUES

Compared to existing similar systems, it is necessary to note some advantages of our development.

First of all, we note the increase in the robot's maneuverability due to the creation of a two-wheeled robot, for example, in comparison with the systems described in [22]-[28], [45]-[47]. However, it should be noted that in each specific case, the robotic platform is used to solve its specific tasks. Thus, the proposed prototype of a mobile robot occupies a certain niche in studies of this kind, where the key point is the robot's mobility.

At the same time, an important aspect is the availability of an extended obstacle detection range, which is achieved through the use of ultrasonic sensors and their special arrangement – turning them towards each other. In this context, such an application surpasses the mobility of robotic systems described in [15]-[20], where onboard visual sensing systems are used. At the same time, the main task of the proposed prototype is to detect obstacles, not to identify them. Systems with onboard visual sensing allow for the identification of obstacles, which is essential when solving more complex problems using mobile robots. In [28], several sensors are also present, but to solve simple problems of robotic system mobility, it is sufficient to use only two sensors. This allows for significant economic efficiency, expansion of the scope of use of such systems and the achievement of a multiplier effect from their use by dividing a complex problem into a number of simple subtasks.

The use of a simple but effective obstacle detection system due to the special placement of ultrasonic sensors and the use of the triangulation method allows the implementation of the corresponding software. Such software is characterized by a clear structuring of commands, ease of their implementation and the ability to implement the technology of adaptive control of the robot depending on the presence of obstacles on the path of movement. This is how the proposed prototype differs from that considered in works [14], [33]-[43], which allows achieving the simplicity of implementing the corresponding software and its necessary modification. The structuring of the considered software, if necessary, allows it to be supplemented with the necessary components to improve the efficiency of the robot's movement in difficult conditions with minimal losses. In general, the considered prototype of the mobile robot contributes to the implementation of various ideas for solving the tasks set for their subsequent implementation to improve real production.

8. CONCLUSION

In order to achieve increased mobility and ensure the efficiency of movement in real production conditions, the concept of prototyping the corresponding robotic system and its software is presented and considered in the work.

A prototype robot design has been developed based on a two-wheeled system that allows achieving maximum mobility, in particular, due to rotation around its axis. For effective detection of obstacles, it is proposed to use ultrasonic sensors that are located with a slight rotation towards each other. In the methodological aspect, the triangulation method is used to increase the efficiency of obstacle detection. This, together with increased mobility, allows to level out the narrowness of the emerging field of view and to achieve an increase in the reaction to potential obstacles and their possible bypass if such obstacles arise suddenly.

The structure and simplicity of the proposed software allows modifying the robot prototype to solve various problems, achieving adaptive control in a complex environment of real production. This also contributes to the expansion of the functionality of the proposed mobile robot.

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