Two modular neuro-fuzzy system for mobile robot navigation

M V Bobyr 1, V S Titov 1, S A Kulabukhov 1, V I Syryamkin 2
1Department of Computer Engineering, Southwest State University, Kursk, Russia
2National Research Tomsk State University, Tomsk, Russia
E-mail: max_bobyr@mail.ru

Abstract. The article considers the fuzzy model for navigation of a mobile robot operating in two modes. In the first mode the mobile robot moves along a line. In the second mode, the mobile robot looks for a target in unknown space. Structural and schematic circuit of four-wheels mobile robot are presented in the article. The article describes the movement of a mobile robot based on two modular neuro-fuzzy system. The algorithm of neuro-fuzzy inference used in two modular control system for movement of a mobile robot is given in the article. The experimental model of the mobile robot and the simulation of the neuro-fuzzy algorithm used for its control are presented in the article.

1. Introduction
The Moving of the mobile robot on a flat surface with the unknown location of obstacles complicate the development of neuro-fuzzy systems for controlling mobile robots. It is connected with the lack of information about the obstacles on the mobile robot's movement from the starting point to the finish. In this connection developers of the control systems for mobile robots' navigation use complex software codes and algorithms for determining the contours of objects in their way.

In their paper Zhu and Yang [1], Lee and Chiu [2] described the control system of the navigation for mobile robot based on neuro-fuzzy method. Later it was improved by Algbahi and etc. [3] due to the introduction into it soft computing and genetic algorithms. Pandey and etc. [4] in their work presented a model for bypassing obstacles based on adaptive neuro-fuzzy inference system (ANFIS) model. The output signal in this model is the angle of rotation of the mobile robot. However, in the article is not specified how output linear function for the ANFIS is formed. Besides it is not indicated how the signal for turning of the mobile robot is transmitted from the microcontroller to its engines. When operating with help of MotorShield driver it is only possible to transmit the signals of PWM and delay time to the port of engine control. Exactly the angle turning of the mobile robot depends on delay time.

Traditionally, for controlling of the mobile robot turning used encoders. It complicates hardware and software implementation of the mobile robot, as well as increasing of its power consumption.

Limitation of the review works is the fact that the rigidly mounted on platform of the mobile robot ultrasonic distance sensor does not allow to scan the area around the robot. Therefore, to scan the space around the mobile robot and determining distances to obstacles it is necessary to rotate it around itself. Installation of ultrasonic sensor on the spindle servo will allow to scan the space around the mobile robot without rotation itself.

Thus, the problem of a mobile robot control and synthesis of methods of formation of the signals received from the sensors of the mobile robot and transmission them from the microcontroller to its engines is actual.
To solve this problem the authors propose to use the system of decision-making control based on neuro-fuzzy inference. The mobile robot hardware is implemented on the microcontroller Arduino MEGA.

2. Kinematic scheme of the mobile robot

2.1. Structural scheme of the mobile robot

The proposed mobile robot uses a four-wheeled platform, two digital line sensors, three infrared distance sensors, ultrasonic distance sensor located on the spindle servo and microcontroller Arduino Mega (Figure 1).

![Diagram of mobile robot](image)

**Figure 1.** Mobile robot.

Connecting the engines to the Arduino MEGA board performed through the Motor Shield driver. Motor Shield is installed on top of the Arduino MEGA board. Four distance sensors and two sensors lines are connected to the Troyka Shield board. Troyka Shield is installed on top of the Motor Shield board. Detailed connection scheme Motor Shield and Troyka Shield drivers is presented in Figure 2.
2.2. Statement of the problem for mobile robot movement

Let the mobile robot operate in two modes. In the first mode the mobile robot moves along the line. Two digital line sensors are used to control its movement, located in the front part of the robot, and fixed below the platform (Figure 1).

The second mode is to search for self-purpose and construction of the route of movement with the ability to bypass obstacles. Three infrared and one ultrasonic distance sensors are used to monitor the distance between the objects and the mobile robot. It is considered that the robot found the target when running over the surface indicated with a black cross. Thus, digital line sensors must be in logical unit state.

3. Modes of operation of the mobile robot

3.1. The first mode of operation of the mobile robot

In the first mode, when the mobile robot starts, power is passed to its motors and after that the robot moves along the line. There are two options for controlling the movement of the mobile robot along the line. In the first option used only one-line sensor which is fixed exactly above the line and the robot moves strictly along it. In the second option, two-line sensors are used, which are fixed on the both sides of the black line. The sensors monitor the white background, and if the robot runs over the black line, then they will switch to a logic zero. The authors in the work used a second method of controlling the position of the black line (Figure 3). The program code in which the moment of leaving the mobile robot from the black line is monitored, is shown in Figure 4 [5].
3.2. The second mode of operation of the mobile robot

In the second mode, the mobile robot independently performs the search of the way. Here two modular situations are possible.

The first modular situation. The mobile robot's movement along a straight line. To find the way it uses from the central infrared sensor the information about the obstacle located in front of it (Figure 5).

```c
int leftLinePin = 9;
int rightLinePin = 6;
int leftDirPin = 4;
int leftSpeedPin = 5;
int rightDirPin = 7;
int rightSpeedPin = 8;
int runSpeed = 120;

void setupMotorShield() {
  pinMode(leftDirPin, OUTPUT);
  pinMode(leftSpeedPin, OUTPUT);
  pinMode(rightDirPin, OUTPUT);
  pinMode(rightSpeedPin, OUTPUT);
}

void go() {
  analogWrite(leftSpeedPin, runSpeed);
  analogWrite(rightSpeedPin, runSpeed);
}

void stop() {
  analogWrite(leftSpeedPin, 0);
  analogWrite(rightSpeedPin, 0);
}

void goForward() {
  digitalWrite(leftDirPin, HIGH);
  digitalWrite(rightDirPin, HIGH);
  go();
}

void turnLeft() {
  digitalWrite(leftDirPin, LOW);
  digitalWrite(rightDirPin, HIGH);
  go();
}

void turnRight() {
  digitalWrite(leftDirPin, HIGH);
  digitalWrite(rightDirPin, LOW);
  go();
}

void setup() {
  setupMotorShield();
}

void loop() {
  boolean whiteLeft = digitalRead(leftLinePin);
  boolean whiteRight = digitalRead(rightLinePin);
  if (whiteLeft == whiteRight) { goForward();
  } else if (whiteLeft == HIGH) { stop();
  } else if (whiteRight == HIGH) { turnLeft();
  } else if (whiteLeft) { turnRight();
  }
}
```

Figure 3. The first method of mobile robot movement.

Figure 4. The program code of the robot movement along the line.
If the robot has found an obstacle, it stops. Next, the microcontroller passes commands to rotate the servo. Rigidly fixed the ultrasonic sensor on the spindle servo scans the area around the mobile robot (Figure 5, yellow background). After that is determined the distance to the most distant object and the angle to which it is necessary to rotate the robot for further movement. Next is calculation of the time delay for turning of the mobile robot to the resulting angle using fuzzy MISO-system [6–8]. Inputs of fuzzy MISO-systems are the speed of movement of the mobile robot and the angle of its turning. And the output is time delay required for turning of the mobile robot to the calculated angle (α=63°, Figure 5). After calculating the delay time, the robot is turning to the calculated angle and continues its movement.

The second modular situation. The robot moves along a narrow corridor and receives the information about an obstacle on left (L1), in front (L2) and on right (L3) from the infrared sensors (Figure 6).

If from the right infrared sensor (L3) (Figure 6) received information about the absence of obstacles, then is used neuro-fuzzy system in which the result variable is the angle of the turning to the right (αR).

The inputs of neuro-fuzzy system is the information about the distance to the object on the left (L1) and in front (L2). In the reverse situation, if we know the information L2 and L3 about the distance to
the object then the neuro-fuzzy system will allow to determine the angle of the turning to the left (αₐ). Considering the mentioned above, will give a block scheme of neuro-fuzzy MIMO-system (Figure 7).

Figure 7. Neuro-fuzzy MIMO-system.

Conditions selecting of calculation output values of neuro-fuzzy MIMO-system depends on the rules (1) and (2).

\[
\begin{align*}
\text{if } \max(L_1; L_2) < L_3 \text{ then } R, \\
\text{if } \max(L_2; L_3) < L_1 \text{ then } L.
\end{align*}
\]

On the arrival of the robot to a deadlock all the infrared sensors report about a short distance to the object. In order to get out of the deadlock, the robot moves backward and makes a 180° turn (Figure 8).

Figure 8. The exit from the deadlock.

The search of target is the main task of the robot when it moves in the second module situation (Figure 9). The completion of movement of the robot is the time when he moves up on the black cross. This moment is fixed by digital line sensors. After that the microcontroller generates a signal to stop the mobile robot.
4. Neuro-fuzzy control system for the mobile robot

To calculate the resulting variables of two modular the neuro-fuzzy MISO-system $\alpha, \alpha_L, \alpha_R$ is used the model described in the article [9–13]. The model consists of six sequential execution steps.

Step 1. Fuzzyfication of the input parameters. Triangular membership function is described by the formula (3), and the trapezoidal membership function - by formula (4).

$$f(x; a, b, c) = \begin{cases} 
0, & x \leq a; \\
\frac{x-a}{b-a}, & a \leq x \leq b; \\
\frac{c-x}{c-b}, & b \leq x \leq c; \\
0, & c \leq x.
\end{cases}$$  \hspace{1cm} (3)

$$f(x; a, b, c, d) = \begin{cases} 
0, & x \leq a; \\
\frac{x-a}{b-a}, & a \leq x \leq b; \\
\frac{d-x}{d-c}, & c \leq x \leq d; \\
0, & d \leq x.
\end{cases}$$  \hspace{1cm} (4)

where $a, b, c, d$ are the parameters of the membership function; $x$ is a quantitative value of the input parameter.

Step 2. Determination of values of MF for every implication of the input parameters, based on the information received from distance sensors.

Step 3. Synthesis of the knowledge base, which contains fuzzy rules of the type «If … then».

Step 4. Creation of a fuzzy ratio matrix. Soft arithmetic operations [14, 15] are used while calculating MIN (5) and MAX (6)

$$\min_\delta(x_1, x_2) = \frac{x_1 + x_2 + \delta^2 + \sqrt{(x_1-x_2)^2 + \delta^2}}{2}. \hspace{1cm} (5)$$

$$\text{soft-max}(x_1, x_2) = \frac{1}{2} \cdot \max(x_1, x_2) + 0.5(1 - \gamma)(x_1 + x_2). \hspace{1cm} (6)$$

Step 5. Defuzzification of the output parameters. This method is based on determining the area of triangular and / or trapezoidal membership functions [10] of input and output variables using a universal formula (7) (Figure 10).
where \( h \) is height of the geometrical figure; \( b_1, b_2, b_3 \) are the width of low, middle and upper base of the geometrical figure.

Using this method eliminates the need for global aggregation operations used in traditional fuzzy models.

Step 5.1. Determine the total area of the shape output value by formula (7).

Step 5.2. Determine areas of every output terms depending on the height values of the degrees of applicability.

Step 5.3. Determine areas of every output terms depending on the height values of the degrees of applicability by formula (8).

\[
S_n = \begin{cases} 
S_n = 0, & \text{than } h = 0; \\
S_n = \frac{h}{2}, & \text{than } h = 1; \\
S_n = \frac{h}{2}(b_1 + b_3), & \text{than } h = (0, 1).
\end{cases}
\]  

(8)

Step 5.4. Determine the total area of the shape with transformed membership functions by formula (9).

\[ S_{trans} = \sum_{i=1}^{n} S_i. \]  

(9)

Step 5.5. Determine the ratio of the total area of the shape of the output variable and the total area of the shape with transformed membership functions by formula (10).

\[ D = \frac{S_{trans}}{S_{glob}}. \]  

(10)

Step 5.6. Determine the proportional relationship by formula (11)

\[ y_{defuz} = \left[D \cdot (y_{final} - y_{start})\right] + y_{start}, \]  

(11)

where \( y_{final}, y_{start} \) are final and start values of the range of values of the output variables.

Step 6. The learning procedure. In this step, using the method of back propagation error occurs ANFIS learning. Here is a correction of transformed membership functions as long as the value \( y_{defuz} \) (11) becomes as close to the reference value according to the formula (12)

\[ y_{out} = (w) + \delta(y_{defuz} - y_{ref}), \]  

(12)

where \( \delta \) is neuro-fuzzy inference system learning step (\( \delta=0.01 \)).

As shown in the article [10], the weighting parameter \( w \) is the ratio of \( n/2 \) used to determine the total area. In the first step of learning where \( w = n / 2 = 2.5 \).
5. Experimental research
The scheme of the experimental model of the mobile robot working in two modes is shown in Figure 11. The mobile robot is collected on Pirate 4WD platform.

To test the efficiency of the proposed neuro-fuzzy model of mobile robot control system was performed simulation. To solve this problem, the program in Visual Basic language was written and implemented in MS Office Excel.

![The experimental mobile robot.](image)

*Figure 11. The experimental mobile robot.*

The membership function for one of the input variables ($L_1$) has a triangular form (Figure 12).

![Triangular membership functions for the input variable - distance $L_1$.](image)

*Figure 12. Triangular membership functions for the input variable - distance $L_1$.*

For example, when $L_1 = 5, L_2 = 8$, the result is being formed for output variable equal to $\alpha_R = 71^\circ16'$ degree on output of neuro-fuzzy system with usage of hard formulas for searching minimum and maximum. When used in fuzzy inference soft arithmetic operations, this value is equal to $\alpha_R = 68^\circ85'$. The graph of the resulting surface is shown in Figure 13.
6. Conclusion

Using the soft arithmetic operations in the fuzzy inference [11–15] provides additive neuro-fuzzy models. It was established that defuzzification on the basis of the differential areas allows to take account of all information features arriving at the input of the neuro-fuzzy model. Experimental research of mobile robot functioning in two modes using neuro-fuzzy control system ensured the successful completion of all the tasks put in front of it.

Acknowledgments
This study (research grant No № 8.2.24.2018) was supported by the Tomsk State University competitiveness improvement programme, grant President RF MD-707.2017.8 and state assignment: Agreement № 2.3440.2017/4.6.

References
[1] Zhu A, Yang S X 2007 IEEE Trans. Syst. ManCybern. Appl. Rev. 37 (4) 610—621
[2] Lee C H, Chiu M H 2009 Expert Syst. Appl. 36(5) 8993—8999
[3] Algabri M, Mathkour H, Ramdane H, Alsulaiman M 2015 CHB 50 42—56
[4] Pandey A, Kumar S, Pandey K K, Parhi D 2016 Perspectives in Science 8 421–423
[5] Bobyr M, Luneva M, Yakushev A 2017 MATEC Web of Conferences 129 doi: 10.1051/matecconf/201712901064
[6] Bobyr M V, Yakushev A S and Milostnaya N A 2016. Fuzzy algorithm of a mobile robot’s motion. International Conference on Industrial Engineering, Applications and Manufacturing. IEEE Inc. (DOI: 10.1109/ICIEAM.2016.7910971)
[7] Bobyr M V, Kulabukhov S A, Milostnaya N A 2016 2ND International conference on industrial engineering, applications and manufacturing (ICIEAM) doi: 10.1109/ICIEAM.2016.7910970
[8] Kruglova T N 2010 Vestnik komp’yuternyh i informatционnyh tehnologii (8) 28–35
[9] Bobyr M V, Milostnaya N A, Kulabuhov S A 2017 Applied Soft Computing Journal 59 19–32 doi: 10.1016/j.asoc.2017.05.040
[10] Bobyr M, Titov V, Belyaev A 2016 MATEC Web of Conferences 79 01052 doi: 10.1051/matecconf/20167901052
[11] Garcia-Rodriguez R, Parra-Vega V 2017 Engineering Applications of Artificial Intelligence 65 43–50 doi: 10.1016/j.engappai.2017.07.013
[12] Sedov V A, Sedova N A, Glushkov S V 2016 Vibroengineering PROCEDIA 8 453–458
[13] Sedova N A., Sedov V A., Glushkov S V 2016 Vibroengineering PROCEDIA 8 506–511
[14] Bobyr M V, Kulabukhov S A 2017 Journal of Machinery Manufacture and Reliability 46(3) doi: 10.3103/S1052618817030049
[15] Pham D T, Fahmy A A 2005 In IFAC Proceedings 16 170–175 doi: 10.3182/20050703-6-CZ-1902.01453