Control System of a Robotic Irrigation Machine Based on the Mamdani Fuzzy Algorithm

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Abstract. The article analyzes the tasks that can be solved by agricultural robots. The purpose of the study was the robotization of the "Fregat" type crop irrigation machine by the fuzzy control of irrigation technological processes, which allows to control the irrigation rate. It is proposed to use in a robotic irrigation machine the analog valve-setter of the speed of the last cart, powered by electricity. It is recommended to include a diagnostic subsystem in the fuzzy control system of the flow control valve, which includes sensors for measuring the soil moisture and the slope of the irrigation machine in various areas of the field. The mathematical model of fuzzy control of the irrigation machine is developed based on the software control of the water supply depending on the terrain of the field, the speed of irrigation machine and soil moisture to reduce water consumption and improve the efficiency and quality of irrigation. The Mamdani algorithm, which is implemented in the MATLAB package, is proposed as a fuzzy inference system. The formalization of the description of the indicators of the irrigation machine is carried out by specifying linguistic variables. The proposed mathematical model can be used in the design of control systems for other robotic agricultural machines.

1. Introduction
In the modern world in developed countries, there is an increase in the value of quality and human life expectancy, and in this regard, the replacement of people with robots, including mobile ones, is being actively introduced in those areas of production where there are technological limitations due to the threat to human life and health. In addition, mobile robotics can significantly increase the economic efficiency of enterprises by delegating human functions to automatic devices when performing work that does not require a high degree of intelligence, for example, heavy and long monotonous operations that are easy to algorithmize. This can be unmanned transportation of goods or details, automatic sorting, packaging and distribution of goods in a warehouse or in a workshop [1-6].

In agriculture, there are also many labor-intensive, but easily formalized tasks that can be solved with the help of mobile robots. For example, driving various agricultural equipment along a certain route, unloading, loading and distributing agricultural products in the field and in warehouse, conducting preparatory operations before sowing (preparing the soil, filling the sowing machine-tractor unit with vegetable seedlings or seeds), treating crops in fields and greenhouses with pesticides, insecticides, fungicides and fertilizers. Mobile robots can successfully collect and pack finished
products (seedlings, vegetables, fruits), sort vegetables and fruits, and not only separate substandard specimens, but also divide the crop into groups by size, weight or quality. The use of mobile robots makes it possible to organize flexible, fully automated production lines at agricultural processing enterprises [1, 7-9].

The use of robotic systems in agriculture in comparison with other areas of industry has features associated with a significant territorial extent and spread over a large area of agricultural enterprises. In addition, it is necessary to take into account the seasonality of work, the strong dependence on climatic and weather conditions, the need for contact with animal and plant organisms, which vary greatly in their characteristics and have their own special requirements for interaction with them [1-4].

Solving these and other similar problems with the help of robotic systems will increase productivity in agriculture, and, consequently, will lead to a reduction in the cost of agricultural products. One of the directions of scientific and technological progress in the field of irrigation at the present stage of development is the modernization of existing and the creation of new irrigation machines that implement low-intensity, environmentally safe, resource-saving irrigation technologies, primarily through their mechanization and automation. This is especially true for the "Fregat" irrigation machines, which are widely used in all areas of Russia, due to the simplicity of their design, high reliability and good consistency with the technology of crop cultivation. The performance of the irrigation machine is strongly influenced by the terrain of the field, the type of agricultural crops planted in the field, the speed of irrigation machine, soil moisture and soil type [6].

The article discusses an approach to creating a robotic irrigation machine based on a "Fregat"-type irrigation machine. For this purpose, a mathematical model that describes the technological process of irrigation using analog electric-powered valve -setter of the speed of the last cart, taking into account the incompleteness and inaccuracy of the initial data, was developed. For the "Fregat" irrigation machine, it is proposed to include a diagnostic subsystem in the control system, which includes sensors for measuring the soil moisture and the slope of the irrigation machine in various areas of the field.

2. Experimental section

2.1. Features of the "Fregat" irrigation machine

The "Fregat" irrigation machine, despite its numerous advantages, has a number of disadvantages. When watering according to the usual technology, before starting the machine, the desired watering rate is set using a valve-setter of the speed of the last cart. In this case, the irrigation rate and the time of one full turn change and depend on the number of strokes per minute of the hydraulic cylinder of the last support. For the irrigation machine DM-454-100, with the values of this indicator 4.6, 3.45 and 2.75 strokes per minute, the irrigation rate is provided in the amount of 300, 400 and 500 m³/ha, respectively, and the duration of one turn of the machine is 61, 81 and 102 hours, respectively [10].

The valve-setter of the speed of the last cart can be rotated at an angle from 0 to 90°. When the valve-setter is fully open, the speed of the last cart, and, consequently, the entire irrigation machine, is maximum, but the water consumption is minimal. So, for the irrigation machine consisting of 16 carts at a flow rate of 100 l/s (the flow rate is due to the device and the number of sprinkler nozzles) with a fully open valve, the irrigation rate will be 240 m³/ha [10].

In the course of the conducted studies and calculations, it was found that the dependence of the irrigation rate on the number of hydraulic cylinder strokes of the last cart of the "Fregat" irrigation machine, built on the basis of data from [10], is close to an exponential dependence (the following equation is obtained: \[ y = 1048 \times e^{-0.27 x} \]). Fig. 1 shows the dependence obtained on the basis of experimental data [10], and, for comparison, the calculated trend line (exponent). The calculations were performed in Microsoft Excel.

The irrigation rate and the time of full rotation of the Fregat irrigation machine at different positions of the valve-setter are discrete values, as well as the positions of the valve-setter themselves (this is due to the device of the Fregat irrigation machine - operation from the hydraulic system [10]). This leads to the fact that watering is carried out in cycles for a certain time. To ensure uniform irrigation of the
entire area of a real field that has a certain terrain, humidity and soil structure, etc., an additional cycle with a different water flow rate may be required, i.e. another intermediate position of the valve-setter may be required. Even in the same field, the humidity in different parts of it may be different [10].

Therefore, it is desirable to use an analog valve-setter that allows to adjust the position of the valve-setter during the irrigation process, depending on the state of the field in a particular area and specific natural, weather and other conditions. In addition, there are shortcomings in the irrigation technology, in particular, the traditional technology is applicable only when watering conditionally aligned areas. It is necessary to add here the lack of reliable methods and controls that would determine with high accuracy the entire range of rain characteristics, including energy, which complicates the choice of criteria for evaluating rain irrigation equipment [10].

It should be noted that the terrain of the field is different for different fields and different sections of the same field and it affects the speed of movement of the irrigation machine on the field. Soil moisture and soil type affect the traction properties of the "Fregat" irrigation machine. As a result, changes in these indicators will affect the provision of uniform watering over the entire field area. So, there is an incompleteness and inaccuracy of the initial data, i.e. there is uncertainty that makes it difficult or even impossible to apply accurate quantitative approaches, developed on the basis of traditional methods, to describe the technological processes of irrigation by the irrigation machine. On the one hand, traditional methods of constructing models do not lead to satisfactory results when the initial description of the problem to be solved is obviously inaccurate and incomplete. On the other hand, the desire to obtain comprehensive information to build an accurate mathematical model of a complex real situation often leads to a loss of time and money, since this is in principle impossible [8-11]. All situations that arise when watering a field with a robotic irrigation machine are quite difficult to implement using traditional mathematical models, so it is proposed to use mathematical models that take into account the incompleteness and inaccuracy of the initial data, specifically, fuzzy control based on the theory of fuzzy sets. The fuzzy inference system used in the fuzzy control of a robotic irrigation machine is the process of obtaining fuzzy conclusions about the required control of an object based on fuzzy conditions or assumptions that represent information about the current state of the object. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned [12-20]. Fuzzy inference algorithms differ mainly in the type of rules, logical operations, and a variety of defuzzification methods and are well known: Mamdani, Sugeno, Larsen, and Tsukamoto. Analysis of these algorithms has shown that the Mamdani algorithm is most often used for fuzzy inference, which is due in particular to the fact that it is embedded in the MATLAB package.

Figure 1. Dependence of the irrigation rate on the number of hydraulic cylinder strokes of the last cart of the "Fregat" irrigation machine.
2.2. Mamdani algorithm

The development and application of fuzzy inference systems includes a number of stages that are implemented on the basis of fuzzy logic [21-30]:

1. Rule-Base Generation

Rule is an expression of the form «IF A THEN B», where A is the condition (or antecedent) of the rule and B – the conclusion (or consequent) of the rule. A and B are some expressions of fuzzy logic that are most often represented in the form of fuzzy statements of the form «β IS α». A fuzzy statement includes a linguistic variable β and one of the terms of this variable α represented by a fuzzy set. Linguistic variable is a variable whose values are words in a natural language. It is defined as a tuple (β, T(β), X), where β is the name of the linguistic variable, T(β) is the collection of linguistic values of β, each of which is a fuzzy variable on the set X, X is a universe of discourse. A fuzzy variable is a tuple <α, X, Α>, where α is the name of the fuzzy variable, X is a universe of discourse, A is a fuzzy set on the X universe. The antecedents are constructed using logical operation «AND» and the consequents are simple.

2. Fuzzification of the input variables

Fuzzification is the process of transformation the input variables, which are crisp numbers, into fuzzy sets that is performed by the use of the information in the knowledge base. At the stage of fuzzification values of all input variables are associated with specific values of the membership functions of respective linguistic terms used in the antecedents of the rules.

3. Aggregation of sub-conditions

Aggregation is a procedure of determining the degree of truth of antecedent for each rule of the fuzzy inference system. For this purpose the values of the membership functions of terms of linguistic variables obtained at the fuzzification stage are used. Aggregation of sub-conditions is performed using the logical operation «AND».

4. Activation of sub-conclusions

Activation in fuzzy inference systems is a procedure of finding the degree of truth of each of the elementary logical statements (sub-conclusions) that make up the consequent for each rule of the fuzzy inference system.

5. Accumulation of conclusions

Accumulation is the process of finding the membership function for each of the output linguistic variables. The purpose of accumulation is to combine all the degrees of truth of sub-conclusions to obtain the membership function of each of the output variables. The result of accumulation for each output linguistic variable is defined as the union of fuzzy sets (max operator) of all sub-conclusions of the fuzzy rule-base with respect to the corresponding linguistic variable:

\[ \forall x \in X, \quad \mu_{A \cup B}(x) = \max \{ \mu_A(x); \mu_B(x) \} \]

6. Defuzzification

Defuzzification is the process that maps a membership functions for the output linguistic variable to a crisp (numeric) value. The transition from the membership function \( \mu(x) \) of the output linguistic variable to the crisp value \( y \) of the output variable is made by Centre of Gravity method, which returns the center of gravity of the fuzzy set along the x-axis:

\[ y = \frac{\int_{\mu_{\min}}^{\mu_{\max}} x \cdot \mu(x) dx}{\int_{\mu_{\min}}^{\mu_{\max}} \mu(x) dx} \]
3. Results section

In the case of controlling a robotic irrigation machine, it is proposed to create additional software based on the integrated MATLAB Fuzzy Logic Toolbox package, which contains tools for designing fuzzy logic systems. It is proposed to draw up the rules of fuzzy control on the basis of the expert's knowledge and experience, as well as modeling the operator's work. For the reason mentioned earlier, it is proposed to use the Mamdani algorithm for fuzzy inference. The mathematical model was built for one type of plant and taking into account the fact that the field has the same type of soil, and the sprinklers installed on a robotic irrigation machine are designed for a water consumption of 100 l/s. To determine the input and output variables, we will conduct a small analysis of the dependence of water flow on other parameters. The water consumption depends on the speed of movement of the irrigation machine on the field under other constant conditions (water consumption by sprinklers, the number of carts, etc.). And the speed of movement is determined by the number of strokes of the cylinder of the last cart of the robotic irrigation machine, and this parameter, in turn, depends on the angle of rotation of the valve-setter. Since the ball valve with an analog control of angle from 0 to 90° is supposed to be installed as a valve-setter, the output variable on which the irrigation rate depends will be the "Angle of rotation of the ball valve". For fuzzy inference system were used the input linguistic variables "Soil moisture" and "Landform" (Fig. 2).

The input variables, taking into account their smallest and largest values, are set as follows. Fuzzy variables were described by a trapezoidal membership functions (Fig. 3).

1. The linguistic variable "Landform", the degree of slope of the terrain:
   "<Landform", {"NegativeHigh", "NegativeMedium", "Zero", "PositiveMedium", "PositiveHigh"}, [-5, 5]>
   Fuzzy variable "NegativeHigh": <NegativeHigh, [-5, 5], [-5 -5 -4 -3]>.
   Fuzzy variable "NegativeMedium": <NegativeMedium, [-5, 5], [-4 -3 -2 -1]>.
   Fuzzy variable "Zero": <Zero, [-5, 5], [-2 -1 1 2]>.
   Fuzzy variable "PositiveMedium": <PositiveMedium, [-5, 5], [1 2 3 4]>.
   Fuzzy variable "PositiveHigh": <PositiveHigh, [-5, 5], [3 4 5 5]>.

2. The linguistic variable "Soil moisture", %:
   "<Soil moisture>, {"Very small", "Small", "Medium", "High", "Excess"}, [20, 90]>
   Fuzzy variable "Very small": <Very small, [20, 90], [20 20 30 35]>.
   Fuzzy variable "Small": <Small, [20, 90], [30 35 45 50]>.
   Fuzzy variable "Medium": <Medium, [20, 90], [45 50 60 65]>.
   Fuzzy variable "High": <High, [20, 90], [60 65 75 80]>.
   Fuzzy variable "Excess": <Excess, [20, 90], [75 80 90 90]>.

The output linguistic variable "Angle of rotation of the ball valve", grad:
Fuzzy variable "Very, very small": <Very, very small, [0, 90], [0 0 5 14]>
Fuzzy variable "Very small": <Very small, [0, 90], [5 14 19 28]>
Fuzzy variable "Small": <Small, [0, 90], [19 28 33 42]>
Fuzzy variable "Medium": <Medium, [0, 90], [33 42 48 57]>
Fuzzy variable "High": <High, [0, 90], [48 57 62 71]>

**Figure 3.** Membership functions of linguistic variables.

Fuzzy variable "Very High": <Very High, [0, 90], [62 71 76 85]>
Fuzzy variable "Very, very High": <Very, very High, [0, 90], [76 85 90 90]>

Rule-Base was generated as follows:

**RULE 1:** IF the "Landform" is "NegativeHigh" AND the "Soil moisture" is "Very small", THEN the "Angle of rotation of the ball valve" is "High".

**RULE 2:** IF "Landform" is "NegativeHigh" AND "Soil moisture" is "Small" THEN "Angle of rotation of the ball valve" is "Medium".

**RULE 3:** IF "Landform" is "NegativeHigh" AND "Soil moisture" is "Medium", THEN "Angle of rotation of the ball valve" is "Small".

**RULE 4:** IF "Landform" is "NegativeHigh" AND "Soil moisture" is "High", THEN "Angle of rotation of the ball valve" is "Very small".

**RULE 5:** IF "Landform" is "NegativeHigh" AND "Soil moisture" is "Excess" THEN "Angle of rotation of the ball valve" is "Very, very small".
RULE 6: IF "Landform" is "NegativeMedium" AND "Soil moisture" is "Very small", THEN "Angle of rotation of the ball valve" is "Very high".

RULE 7: IF "Landform" is "Medium negative" AND "Soil moisture" is "Small" THEN "Angle of rotation of the ball valve" is "High".

RULE 8: IF "Landform" IS "NegativeMedium "AND" Soil moisture "is "Medium", THEN "Crane angle" is "Medium".

RULE 9: IF "Landform" is "Medium negative" AND "Soil moisture" is "High", THEN "Angle of rotation of the ball valve" is "Small".

RULE 10: IF "Landform" is "NegativeMedium" AND "Soil moisture" is "Excess" THEN "Angle of rotation of the ball valve" is "Very small".

RULE 11: IF the "Topography" is "Flat" AND the "Soil moisture" is "Very small", THEN the "Angle of rotation of the crane" is "Very, very high".

RULE 12: IF the "Topography" is "Flat" AND the "Soil moisture" is "Small", THEN the "Angle of rotation of the crane" is "Very high".

RULE 13: IF the "Landform" is "Zero" AND the "Soil moisture" is "Medium", THEN the "Angle of rotation of the crane" is "High".

RULE 14: IF the "Landform" is "Zero" AND the "Soil moisture" is "High", THEN the "Angle of rotation of the crane" is "Medium".

RULE 15: IF the "Landform" is "Zero" AND the "Soil moisture" is "Excess", THEN the "Angle of rotation of the crane" is "Small".

RULE 16: IF "Landform" is "PositiveMedium" AND "Soil moisture" is "Very small", THEN "Angle of rotation of the ball valve" is "High".

RULE 17: IF "Landform" is "PositiveMedium" AND "Soil moisture" is "Small" THEN "Angle of rotation of the ball valve" is "Medium".

RULE 18: IF "Landform" is "PositiveMedium "AND" Soil moisture "is "Medium", THEN "Angle of rotation of the ball valve" is "Medium".

RULE 19: IF "Landform" is "PositiveMedium" AND "Soil moisture" is "High", THEN "Angle of rotation of the ball valve" is "Small".

RULE 20: IF "Landform" is "PositiveMedium" AND "Soil moisture" is "Excess" THEN "Angle of rotation of the ball valve" is "Very small".

RULE 21: IF the "Landform" is "PositiveHigh" AND the "Soil moisture" is "Very small", THEN the "Angle of rotation of the ball valve" is "High".

RULE 22: IF "Landform" is "PositiveHigh" AND "Soil moisture" is "Small" THEN "Angle of rotation of the ball valve" is "Medium".

RULE 23: IF "Landform" is "PositiveHigh" AND "Soil moisture" is "Medium", THEN "Angle of rotation of the ball valve" is "Small".

RULE 24: IF "Landform" is "PositiveHigh" AND "Soil moisture" is "High", THEN "Angle of rotation of the ball valve" is "Very small".

RULE 25: IF the "Landform" is "PositiveHigh" AND the "Soil moisture" is "Excess", THEN the "Angle of rotation of the crane" is "Very, very small".

The surface of the fuzzy inference system is shown in Fig. 4.
4. Discussion section and conclusions

The robotization of "Fregat"-type irrigation machine is proposed to be carried out due to fuzzy control of irrigation technological processes, which allows controlling the irrigation rate throughout the entire irrigation season, regardless of various uncertain factors affecting the quality of irrigation. It is
proposed to use in a robotic irrigation machine the analog valve-setter of the speed of the last cart, powered by electricity. It is recommended to include a diagnostic subsystem in the fuzzy control system of the flow control valve, which includes sensors for measuring the soil moisture and the slope of the irrigation machine in various areas of the field. The mathematical model of fuzzy control of the irrigation machine is developed based on the software control of the water supply depending on the terrain of the field, the speed of irrigation machine and soil moisture to reduce water consumption and improve the efficiency and quality of irrigation. The Mamdani algorithm is proposed and implemented in MATLAB as a fuzzy inference algorithm. This mathematical model can also be used in the design of control systems for other types of automatic irrigation machines.

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