Implementing automaton behavior with fuzzy controllers

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Abstract: Structural diagrams of control automata using fuzzy controllers for building control systems are proposed, types of behaviors of such automata that differ from the traditional ones by the possibility of parametric and structural adaptation of behavior, the formation of parallel activity relative to the state activity interval are described. Examples of the use of the proposed functional structures are given.

Keywords: Control systems, control machines, fuzzy controllers.

1 Introduction

Since the middle of the last century, finite automata have been used as a model of control devices for discrete and logical control [1 - 5]. These automata are defined as a tuple [6]

$$A=<S, X, Y, s_0, \delta, \lambda>, \tag{1}$$

where S is a finite nonempty set (of states); X is a finite non-empty set of inputs (input alphabet); Y is a finite nonempty set of exits (output alphabet); $s_0 \in S$ - initial state; $\delta : S \times X \to S$ - transition function; $\lambda : S \times X \to Y$, $\lambda : S \to Y$ - functions of the outputs of the Mealy and Moore automata, respectively.

Such machines have limited behavior in the control system. They lack the mechanisms of structural adaptation of the automaton; the activity of the exits is rigidly "tied" to the time of the activity of the state. The need for an extended automaton behavior arises in the design of integrated and cognitive control systems [7 - 10]. An integrated system is such a system that combines several interconnected subsystems, for example, built according to the principle "control device at the *i* - level is the object of control at the *(i + 1)* - level of control". In the cognitive system, knowledge and elements of cognitive behavior, such as perception, judgment, planning, learning, and others, are used to achieve management goals.

The behavior proposed in [11] is possible when an automaton is defined as a tuple

$$A=<X, Y, S, s_0, C, c_0, F>, \tag{2}$$

where C is the set of controls; c_0 is the initial control; F is the set of functions of the automaton in its states. The element f_i of the set F for the i -th state is defined by the functions of this state

$$f_i = <\mu_i, \lambda_i, \sigma_i>, \tag{3}$$

where μ_i is the activation function, λ_i is the output, σ_i is the structure function.

2 Purpose of research

On the basis of definitions (2) and (3), automata with non-binary elements forming the automaton sets *X, Y, S* and *C* can be built. At the same time, the author-accessible publications lack the functional structures and mechanisms for realizing the behavior of automata, built on the basis of tuples (2) and (3), which complicates their practical application.

The purpose of this work is to study the functional structures and mechanisms for implementing the extended behavior of automata constructed using Fuzzy controllers**.**

3 Analysis of publications

Fuzzy controller is a functional block that implements one of the fuzzy inference algorithms [12 - 15]. In the functional structures of the fuzzy control systems, the controller takes the place of the PID controller in the loop "outputs of the control object — sensors — controller — actuators — inputs of the control object" or is used in conjunction with the PID controller to improve its characteristics. With the help of the fuzzy controller, continuous object control is implemented.

The IEC 61131-7 [16] standard describes a unified FCL (Fuzzy Control Language) language for building a fuzzy controller. Such a description is made in the form of a functional block, which is included in the controller program of the facility control. These programs are written in one of the languages recommended by the IEC 61131-3 standard [17, 18].

These standards note the advantages of fuzzy controllers compared to other types of controllers, including the simplicity of the implementation of the parametric adaptation of the controller, but there are no recommendations for using fuzzy controllers to build control machines with both binary and non-binary elements of automaton sets.

4 Materials and methods

First consider the use of a fuzzy controller for constructing a classic control automaton based on a tuple (1) with binary elements of the sets *X, Y,* and *S*. The block diagram of the control automaton based on the fuzzy controller is shown in Fig. 1.

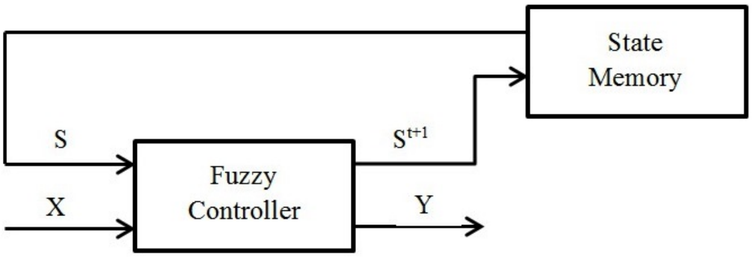

Fig. 1. Structural diagram of the control machine based on fuzzy controller

To build the control automaton, the fuzzy controller was used together with the state memory block of the automaton. The controller has two groups of inputs and two groups of outputs. Inputs *X* of the controller are connected to the outputs of the control object. The current state *S* of automata is fed to the inputs *S* of controller. A new state value is formed at the outputs S^{t+1}, into which the control automaton passes to the transition. And outputs *Y* are connected to executive mechanisms or to inputs of output operating automatic machines.

The controller's operation will be described in the traffic light control system, the block diagram of which is shown in Fig.2.

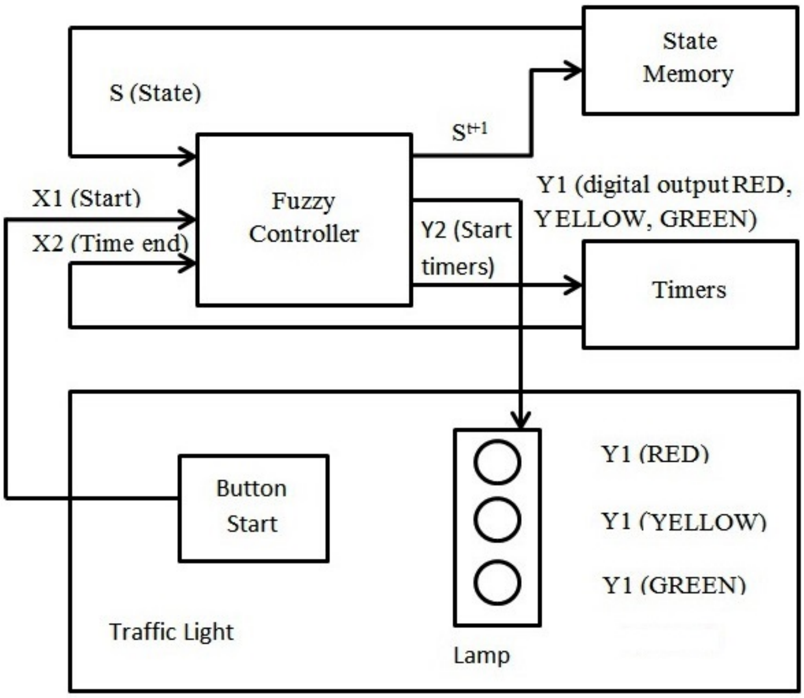

Fig. 2. Block diagram of the traffic light control system

The system implements a state machine whose graph is shown in Fig. 3.

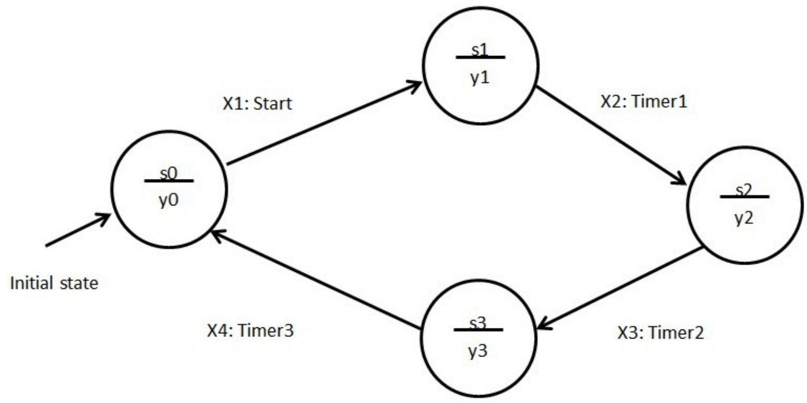

Fig. 3. Graph automatic simplified control system of traffic lights

The control device has four states (*s0* - Green, *s1* - Yellow1, *s2* - Red, *s3* - Yellow2), four transitions, and four outputs (*y0* - Green; *y1* - Yellow, Start Timer 1; *y2* - Red, Start Timer 2; *y3* - Yellow, Start Timer 3). One of transitions (*x1*) is an event transition, the rest (*x2* - *x4*) are time transitions, which is counted using timers.

The states of the automaton *S* at the input and output of a fuzzy controller are described as fuzzy variables with membership functions of the "Singletons" type [15]. They are described only for a single linguistic term. In fig. 4 examples of terms are given.

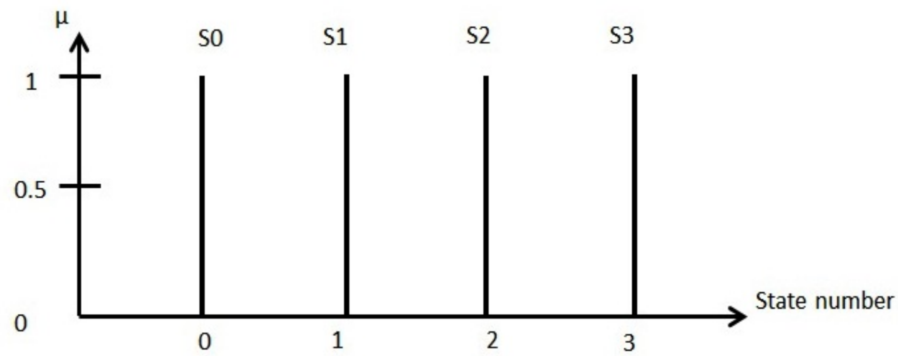

Fig. 4. The membership functions of the states on the output and the input of a fuzzy controller

The structure of the control device graph defines the control rules that are stored in the fuzzy controller's rule base. These rules are given in table 1.

Table 1. Traffic Light Control Rules

The rule	Comments
1. IF *Reset* IS *true* THEN *S* IS *s0*	Initial State
2. IF *S* IS *s0* THEN *Y* IS *y0*	Lamp «green»
3. IF *S* IS *s1* THEN *Y* IS *y1* AND Timer1 IS *Start*	Lamp «yellow» and Timer1 work
4. IF *S* IS *s2* THEN *Y* IS *y2* AND Timer2 IS *Start*	Lamp «red» and Timer2 work
5. IF *S* IS *s3* THEN *Y* IS *y3* ANDTimer3 IS *Start*	Lamp «yellow» and Timer3 work
6. If *S* IS *s0* AND *x* IS *Start* THEN S^{t+1} IS *s1*	Transition from *s0* to *s1*
7. IF *S* IS *s1* AND timer1 IS *end* THEN S^{t+1} IS *s2*	Transition from *s1* to *s2*
8. IF *S* IS *s2* AND timer2 IS *end* THEN S^{t+1} IS *s3*	Transition from *s2* to *s3*
9. IF *S* IS *s0* AND timer3 IS *end* THEN S^{t+1} IS *s0*	Transition from *s3* to *s0*

Rule 1 sets the initial state, rules 2 - 5 describe actions in the states, and rules 6 - 9 describe transitions from one state to another.

The fuzzy traffic light control model can be written in FCL notation, as shown in Figure 5.

Next, we consider the use of fuzzy controller for implementing control devices in accordance with the tuples of sets (2) and (3). Note that the activation, outputs and structures functions provided by the tuple (3) must be implemented for each state of the control unit's automaton. To do this, the control device must have a network of fuzzy controllers that interact with each other and with the operating machines of the control device through the memory of parameters, states, controls and the knowledge base. If for some states, the use of fuzzy controllers is redundant, then conventional (FSM) controllers are used to implement state functions. A generalized block diagram of a control system based on networks of operational machines that control fuzzy and FSM controllers is shown in Fig. 6.

The following types of controls are possible in this structure:

- Continuous control in the loop Control Object - Sensors - Input operating machines - Intermediate operating machines 1 - Output operating machines - Actuators. The operating machines involved in the loop perform a PID or other controller.

```
FUNCTION _BLOCK traffic light
VAR_INPUT
state, reset, start, end_timer
:real
END_VAR
VAR_OUTPUT
n_state, lamp, timer_start :real
END_VAR
FUZZYFY state
Term S0:=0;
Term S1:=1;
Term S2:=2;
Term S3:=3;
END_FUZZIFY
FUZZIFY reset
Term norm: = 0;
Term reset: = 1;
END_FUZZIFY
FUZZIFY start
Term wait: = 0;
Term start: = 1;
END_FUZZIFY
FUZZIFY end_timer
Term timer1: = 0;
Term timer2: = 1;
Term timer3: = 2;
END_FUZZIFY
DEFUZZIFY n_state
Term S0:=0;
Term S1:=1;
Term S2:=2;
Term S3:=3;
ACCU: MAX
METHOD: COGS
DEFAULT: 0
END_DEFUZZIFY
DEFUZZIFY lamp
Term green: = 0;
Term yellow: = 1;
Term red: = 2;
ACCU: MAX
METHOD: COGS
DEFAULT: 0
END_DEFUZZIFY
DEFUZZIFY timer_start
Term timer1: = 0;
Term timer2: = 1;
Term timer3: = 2;
ACCU: MAX
METHOD: COGS
DEFAULT: 0
END_DEFUZZIFY
RULE_BLOCK number1
RULE 1: IF state IS s0
THEN lamp IS green;
…..
RULE i: IF state IS s0 AND start
IS 1 THEN n_state IS 1;
…..
END_RULE_BLOCK
END_FINCTION_BLOCK
```

Fig. 5. The program of control of the traffic light in FCL notation

- Event (logical) control using the FSM controller. Input operation machines transform analog signals from sensors into an event (binary signal) at the input of the FSM controller. As a result of this controller operation, its new state and output are determined. The output operation machines initiate the activation of the actuators or count down the time intervals necessary for control.
- Hybrid control using automatic machines and FSM controller [19]. There is more than one continuous control option, each of which is activated by its controller

FSM output. At each moment of time, the active circuit of the automatic machines that is selected by this controller is active.

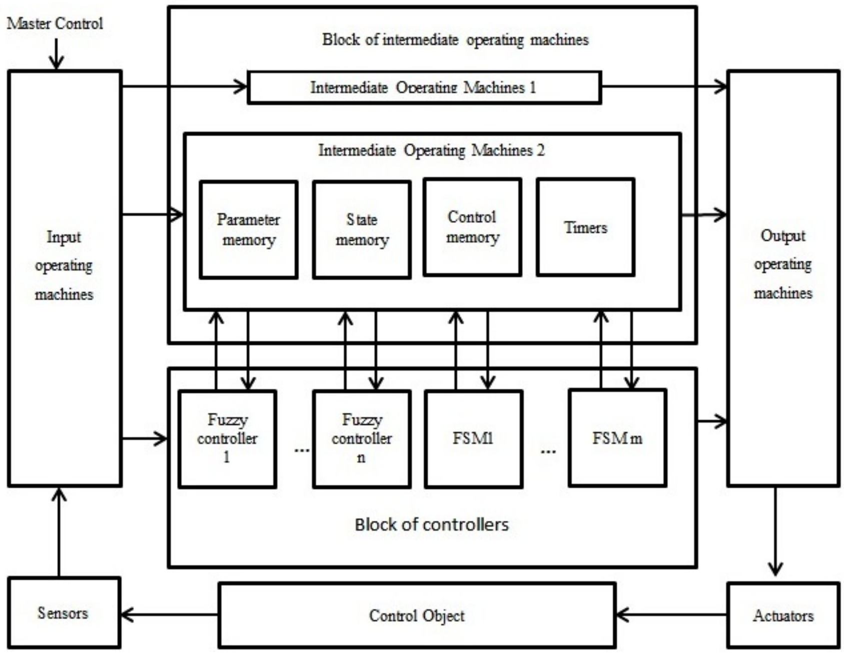

Fig. 6. A generalized block diagram of a control system based on networks of operating machines that control fuzzy and FSM controllers

- Continuous control using a fuzzy controller in the loop Control Object - Sensors - Input operating machines - fuzzy controller - Output operating machines - Actuators. The inputs of the fuzzy controller receive analog signals from the sensors. These signals are fused, processed using the fuzzy products rule base, defuzzified, and in the analog format are sent to the actuators inputs.
- Event fuzzy control with a fuzzy controller. This controller interacts with the elements of the block of intermediate operational automata 2. The inputs of a fuzzy controller are the inputs of analog and (or) discrete signals from sensors of the control object, timers, state memory and control. The processing of this data uses the appropriate membership functions and fuzzy product rules. The outputs of the fuzzy controller are the outputs of the control machine in the active state and the signals for memorizing its new active state. This control implements the activation functions μ_i (only for the active state), the outputs λ_i, and the structure σ_i. The form of these functions is described in [11].
- Advanced event fuzzy control with a fuzzy controller. This type of control differs from the previous one in that the activation function sets nonzero values of states in the vicinity of the active state. As a result, it becomes possible to activate the out-

puts in these states along with the outputs of the active state in order to post and preprocess tasks of the corresponding state.

Consider the features of the implementation of such controls by example. The fragment of the state graph of the controlling automaton with non-binary elements of the sets is shown in fig. 7.

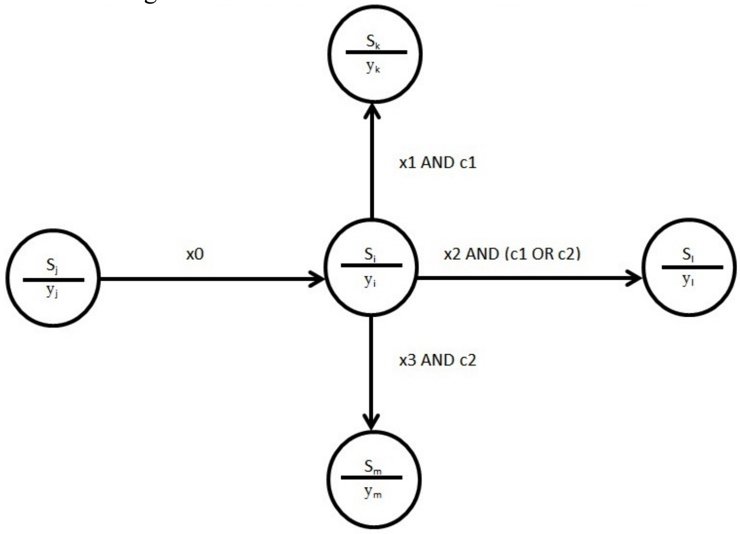

Fig. 7. Fragment of the state graph of the controlling automaton with non-binary elements of sets

The elements of the state set s_j, s_i, s_k, s_l, s_m take the values: active, post-active, pre-active or passive. The elements of the set of inputs *x0 - x3* and outputs y_j, y_i, y_k, y_l, y_m can be logical, numerical or fuzzy type variables.

Let the state s_i be active at the current time. The transition to state s_i was made from state s_j. The function of the structure sets the control *c2* in state s_i. Note that the control *c2* does not allow the transition from the state s_i to the state s_k. Activation function μ_i calculate the value of states in the vicinity of the active state: s_j is post-active, s_i is active, s_k is passive, s_l, s_m are pre-active. State values are used by the output functions of these states to determine the level and / or type of activity of the outputs. Post-activity can be used to obtain processing and storage of secondary data that were relevant in the s_j state. The pre-activity of a certain state is intended to prepare the necessary data, information and knowledge to perform actions after the activity is received by these states.

The behavior described above can be implemented with the help of fuzzy controllers like control of a traffic light. For example, to calculate the pre-activity in the s_l state of the automaton Fig.7 rules like "IF s_i IS “active” AND *x2* IS “probable” AND “structure” IS *c2* THEN s_l IS “pre-active”" are used. The variables s_i, *x2*, Structure, s_l, presented in the rule, are linguistic variables with terms and membership functions given in Table. 2.

Table.2 Description of linguistic variables

Variable name	Terms	Type of membership function
si, sl	Active	S-shaped
	Pre-active	П-shaped
	Post-active	П-shaped
	Passive	Z-shaped
x2	Probably	S-shaped
	Average probability	П-shaped
	Low probability	Z-shaped
Structure	c1	S-shaped
	c2	Z-shaped

5 Conclusion

The capabilities of control automata in the form of FSM are not enough to effectively solve the problems of constructing adaptive, integrated, and cognitive control systems.

The decision proposed in [11] about introducing into the definition of an automaton a set of controls and expanding the number of values of the automaton sets led to the need to move from the functions of the automaton as a whole to the set of state functions.

It follows that the various states of the controlling automaton may have different functions and devices for their realization. This paper describes the use of fuzzy controllers as devices for implementing state functions. The advantages of fuzzy controllers in control tasks are the ability to use the experience of experts, qualitative factors, and the availability of methods for the automatic synthesis of such controllers by training neural networks.

The technique of using fuzzy controllers is presented on examples of traffic control and a generalized control system combining fuzzy controllers and traditional FSM with a set of input, intermediate and operating machines.

Control devices based on fuzzy controllers implement a wide range of control types - continuous, discrete, hybrid, which differ in parametric and structural adaptation capabilities, are easily integrated into hierarchical control structures, and implement nonlinear controllers.

The proposed methods for constructing control automata are proposed to use cognitive monitoring systems for power transformer parameters [20] and remote laboratories for studying cognitive control systems in studies at Zaporizhzhia National Technical University.

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