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Paper:

Expert Fuzzy-Neuro Controller Design for Wall Climbing Robot for Decontamination of Nuclear-Power Station

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The arrangement principles and design methodology for complex control framework of AI control systems are introduced. The notions of intelligence levels with top boundary ("intelligence in large") and the bottom boundary ("intelligence in small") are defined. Special methodology of AI control system design for decontamination of nuclear-power station (NPS) on the base of a wall-climbing robot (WCR) with various intelligence levels is considered. The basis of this methodology is computer simulation of dynamics for mechanical systems with the help of qualitative physics and search for possible solutions by genetic algorithm (GA). On artificial neural networks, optimal solutions are obtained and a knowledge base of fuzzy controller on WARP (Weight Associative Rule Processor) is formed. Strategy for planning, environment recognition using two types of sensors, and locomotion control to realize autonomous locomotion of the mobile robot are described. The WCR and the mobile robot for horizontal displacement with manipulators are moved in unstructured environments. Fuzzy qualitative simulation, GA and hierarchical node map, and fuzzy neural network (FNN) have demonstrated their effectiveness for path planning of the mobile robots. The results of fuzzy robot control simulation, monitoring, and experimental investigations are presented. The application of WARP to design automatic fuzzy controller for fuzzy correction motion of manipulator and WCR is examined.

Keywords: Expert fuzzy-neuro controller, Wall climbing robot, Weight associative rule processor, Decontamination, Nuclear-power plant

1. Introduction

Research and development of intelligent autonomous mobile vehicles, intended for decontamination of NPS as in Chernobyle, is an important social problems in advanced robotics. WCR for decontamination of NPS has many peculiarities compared to conventional mobile robots, which are the results of potential tasks for decontamination of NPS.[1)] Such requirements and peculiarities are correlated with high safety, maneuverability, undetermined environments, capability for use under extreme conditions such as radiation, and fulfillment of technological operations in 3D space with rigid restrictions of sizes and forms of the horizontal and vertical decontamination surfaces. The WCR represents the new generation of robotics as a mobile robot with manipulator on the board, which realizes the motion over vertical, horizontal, and slope decontamination surfaces on NPS-buildings.[2)] The sequence of the produced technological operations requires multifunctional tool changes for cleaning, decontamination, and humidity of the surfaces. The sensors for inspection are used for various types of inspection. The board manipulator of WCR produced the necessary technological operations of decontamination depending on the type of tool equipped on end effector or gripper of the board manipulator. The automation level of WCR has remained insufficient and requires significant improvement to increase the speed of operation, reliability, mobility. Different approaches to fuzzy controller design in recent studies are introduced (References 3, 4)). The basic idea behind these approaches is the formation of a lookup table for fuzzy controllers as knowledge base. In this manner, different algorithms are proposed and the advantage of fuzzy controllers is investigated. The extraction of accurate knowledge for forming the lookup table (as production rules "if...then") for fuzzy controller in most cases depends on skillness of human experts. The accuracy of the knowledge base also depends on the subjectivity of the experts.

For a class of complex mechanical systems as mobile robots, a new approach to the fuzzy controller design is suggested. In the first step, the behavior of complex dynamic mechanical systems as control object is described on the basis of qualitative physical methods. In this case, linguistic approximation of control objects and membership functions of control region are formulated. In particular, the method[5)] for formulation of heterogeneous control law is followed. The description of dynamic behavior for mechanical systems in terms of linguistic variables as the domain of possible solutions with different heterogeneous control law is formed.

In the second step, the class of better solutions is founded on this domain of possible solution with help of GA. On the basis of fitness functions, the best possible solution is tested.

In the third step, the parameters of membership functions

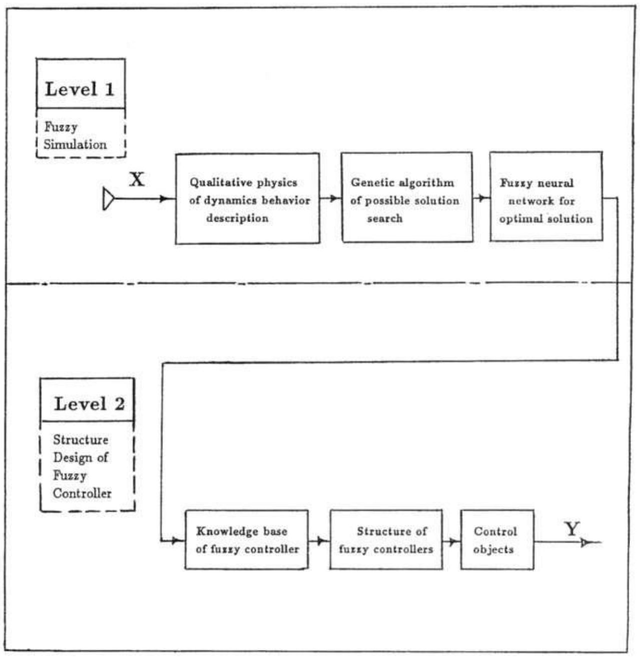


Fig. 1. Structure of fuzzy controller design.

with the help of artificial fuzzy neural networks are proposed and different types of approximate reasoning are examined.

In the fourth step, the knowledge base of fuzzy controller is formed, and sensitivity to "sabotage" production rules is examined. The structure of this approach is shown in **Fig.1**.

This fuzzy controller design methodology is examined on WARP which is intended to perform the control of the board multilink manipulator and transport system of WCR. A new type of mechatronics drive is proposed$^{6)}$ for an intelligent WCR in order to satisfy strong load characteristics with velocity and force control on a large scale.

This international research project has been conducted in the frame of cooperative investigations of intelligent mobile robots for decontamination of NPS and for service use between Japan, Italy, and Russia.

2. Fundamental Principles and Technical Characteristics of WCR

The WCR and Robotics Systems based on WCR (RSWCR) are intended for motion on vertical and sloping surfaces in complex or extreme conditions, including NPS building constructions. These robotic systems must contain three main modules: transport (proper WCR), technological, and control modules.$^{7)}$ A technological manipulator is mounted on a transport module for performing necessary technological operations during continuous motion or in brief stoppages of the transport module.$^{1,2,8)}$

Research and development of the WCR was undertaken during the 80s in Japan, U.S.A, England, Russia, and other countries, and many investigations were conducted in this field.

The main advantages of WCR in applications for decontamination of NPS building construction are the following: (1) Possibility for use at great heights under extreme conditions such as radiation ; (2) Small size of the robot and large loads; (3) Good economic efficiency of the application of the robot at great heights without special means or materials; (4) The time required to execute operations is rather short than that for conventional processes, which produces additional economic benefits.

WCR is intended for transformation of the technological modules along vertical and sloping surfaces. The robot has mass up to 40kg or more depending on modification. It must include three main modules - transport, technological, and control. Different technological modules require cleaning, painting, welding, or cutting. One of the WCR modifications is intended for overcoming crossing surfaces as "ground - wall", "wall - ceiling", and "ceiling - wall".

The main technical characteristics of WCR are that drivers are pneumatic and electromechanical type; supply pressure of the drivers is 0.6MPa; load is 20kg, 40kg, 60kg, and 100kg; sizes are 500 × 400 × 200mm and 900 × 600 × 200 mm; average velocity is 1.2 m/min (velocity can be changed depending on the type of technological operation and task); step control is discrete.

One of the WCR modification is intended for overcoming crossing surfaces as "ground-wall", "wall-ceiling," and "ceiling-wall" for Chernobyle NPS.$^{2)}$

Depending on the field of application, WCR can be supplied by different technological modules.$^{2)}$

This paper presents results from research devoted to the problem of fabricating WCR: specifically, the realization of mechanical motion control along vertical surfaces by various means, modelling of motion, investigation of maneuverability and locomotion, analysis of mechanical systems for effective execution of different industrial operations including moving from one surface to another at right angles in NPS building constructions.

To improve maneuverability and extend functional capabilities, the mobile robotics complex includes an automatically controlled horizontally-mobile robot, a connected WCR, and manipulators for providing adhesion of the WCR to the surface (**Fig.2**(a)). The complex can be controlled from a single control panel in autonomous, supervisory, or automatic mode. The control panel is located in a separate facility at a safe distance from the operations site of the robot in an emergency environment such as radiation.

On the Fig.2a and b RSWCR for different technological operation of decontamination and cleaning of vertical surfaces is shown. The main modules of the RSWCR (Fig.2(b)) are: transport (1), technological equipments (2), and control (3). The technological equipments (4) are mounted on a technological module. The transport module has vacuum grippers (5) installed on the legs and electric cables (6) for connection to the control unit (3). Two platforms (1) and (2) of the transport module (Fig.2c) are joined by means of a rotating unit (3) and a drive system. When the platform (1) is connected to the wall by means of vacuum grippers (VG), the drive system has the possibility to move the platform (2). When the platform (2) is connected to the wall, the platform (1) can then move with ease relative to the platform (2). The technological equipment (for example a painting unit (4)) are installed on the manipulator or bracket (5), and it can move according to the discrete trajectory (6) by the use of the rotating unit (3).

Special pneumatic drives are intended for lifting and putting down the legs with VG.$^{6)}$

A RSWCR can be implemented (Fig.2(e)) with a drive system mounted on one platform (1) with velocity control unit (2) and rotating unit (3). The technological equipment (4) moves along the trajectory (5) according to this scheme (Fig.2e).

Driving system with velocity control unit (Fig.2(f)) can be introduced onto the two platforms (1) and (2), making it possible to achieve a continuous trajectory (7) for both the technological equipments and the robot.

The mounting of the controlled driving systems creates additional advantages when autonomous drives are not necessary. In addition, it can take care of the limitations of the size of the bracket of the technological module. In this situation, the transport module (Fig.2(d)), includes two platforms (1) and (2), moves along the trajectory (4), and two technological devices (3) can achieve any arbitrary trajectory (5) above zone (6).

The local control system (**Fig.3**) includes: sensors (D1) installed on the drives of the transport modules and sensors (D2) mounted on the technological module, a microprocessor system (MS) with possible additional software (AS), control panel, electropneumatic converters for distribution of supply pressure to the pneumatic drives of transport motion and the pneumatic drives of the legs, and the ejector's VG systems.

In this paper, motion of the WCR with manipulator and inspection unit provided with the TV camera installed on the body (**Fig.4**) under vibrations acting through the basis and mechanical system of the robot is analyzed. Flexibility of joints is taken into account.

The matrix transfer function methods for estimating the response time, accuracy, eigen frequencies, spectrum characteristics of the WCR with technological units in the board is applied. The methods used in the paper may be applied to different types of the motion including adaptive and artificial intelligence elements motion.[9]

Experimental investigations and testing of the WCR on computerized vibration in the low frequency range 0.1-30Hz with amplitude of 2.5mm to 0.2mm are discussed. The vibrations are offered in the harmonic oscillations or random signals. Construction reliability problem was also considered. The results (Fig.4(b), (c), and (d))[9] can be applicable for designing new models of the robot intended for extreme applications such as underground stations, NPS, fire-fighting operations, submarine, and underwater environments.

The robot structure includes an adaption unit that expands its functional capabilities. This permits the construction of more flexible systems, one of which includes an inspection system for vertical piping of NPS with local joints. **Figure 5** shows a WCR design for moving inside the jointed piping. Diagnostic equipment can be installed on the robot. Robot motion is initiated by means of a power cylinder and uses alternative adhesion of the supports on the supporting tracks. When no joints (bends) are present in the

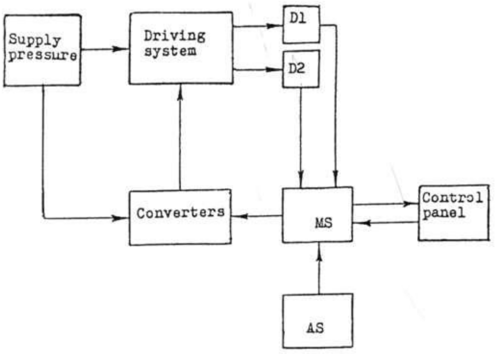
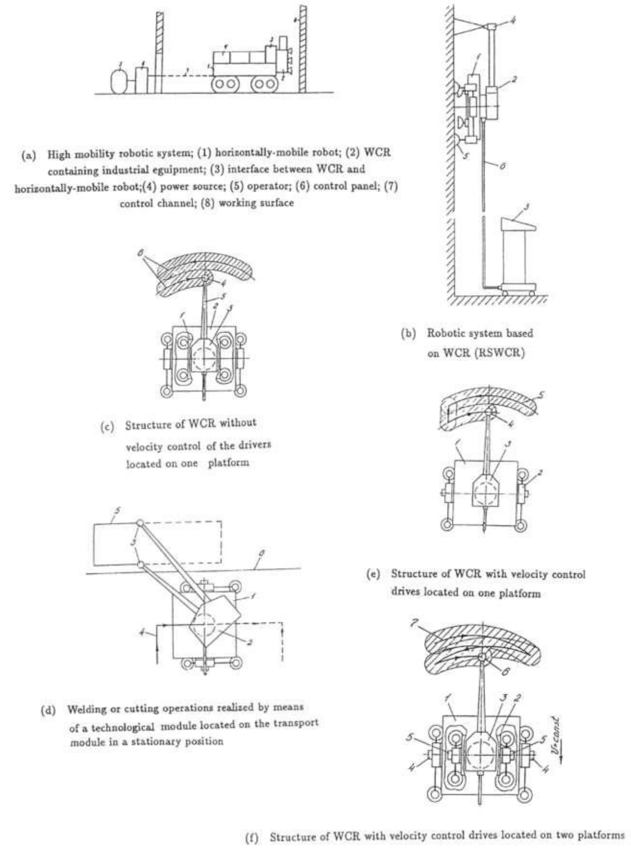


Fig. 3. Drive control system of the RSWCR.


(a) High mobility robotic system; (1) horizontally-mobile robot; (2) WCR containing industrial egipment; (3) interface between WCR and horizontally-mobile robot;(4) power source; (5) operator; (6) control panel; (7) control channel; (8) working surface

(b) Robotic system based on WCR (RSWCR)

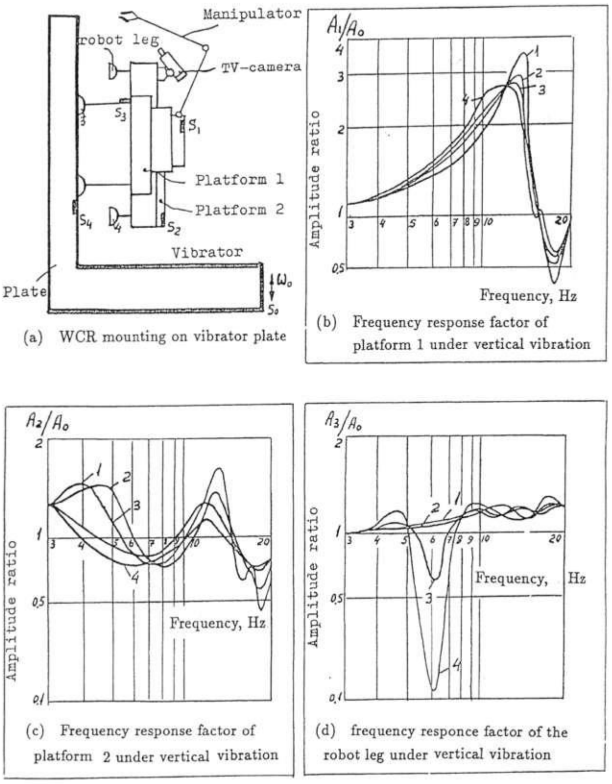
(c) Structure of WCR without velocity control of the drivers located on one platform

(d) Welding or cutting operations realized by means of a technological module located on the transport module in a stationary position

(e) Structure of WCR with velocity control drives located on one platform

(f) Structure of WCR with velocity control drives located on two platforms

Fig. 2. The structure of robotic mobile systems with WCR.



(a) WCR mounting on vibrator plate

(b) Frequency response factor of platform 1 under vertical vibration

(c) Frequency response factor of platform 2 under vertical vibration

(d) frequency responce factor of the robot leg under vertical vibration

Fig. 4. Frequency response of the WCR on vibrator plate.

pipeline, the sensors do not contact with its surface and the robot travels rectilinearly. In the case of significant bends in the piping, there will be several corrections to the position of the front belt each power cylinder cycle. After this process, the front belt attaches to the pipe surface, and the rear belt is tightened against the front belt. This motion cycle is then repeated. This construction of WCR for inspection of pipeline differs from that of References 10, 11).

One of the important design requirements of WCR development is construction of robots that are capable of automatic transmission from one surface to another. This class of robots in some sense integrates the capabilities of all WCR designs examined here. **Figure 6** presents the design of a robot capable of crossing over a surface at any angle of inclination with respect to the direction of motion (both in sign and magnitude). This design contains an integrated drive for two platforms containing a tracking mechanism with internal grippers and automatic platform direction corrector for use when the robot crosses from one surface to another. Robot rectilinear motion is initiated by a power driver that advances the tracking mechanism containing the grippers. In this case the power driver must be capable of separating only a single gripper at each time from the travel surface, while the device is held by the sum of all grippers in contact with this surface. When crossing to a surface that forms an angle up to 90° or more with the initial surface (a left turn in Fig.6), the obstacle sensor makes contact with this surface and, through the probe, activates a switch which in turn initiates the corresponding correction cylinder. Because the correction cylinders are connected to the front platform, it crosses over to the new surface. If this surface has an inclination exceeding 90°, the obstacle sensor will depress the spring-loaded element of the probe during crossing without imparting mechanical drag, and at the same time, hold the vertical switch in the closed position. When reading a new surface, contact between the surface and the obstacle sensor is broken and the vertical switch opens the rod end cavity of the corresponding correction cylinder to the outside air through the valve. In this case, the relay element recloses. When crossing to a surface that forms a negative angle with the initial surface (a right turn in Fig.6) the support sensor breaks contact with the surface, and the support switch closes. This activates the corresponding correction cylinders, and the rear platform moves downward until the support sensor makes contact with the new surface in a manner analogous to that described above. Symmetrical units on the rear platform are activated for reverse motion. The robot can be turned by duplicating this design on a common chassis and employing independent speed control over each tracking mechanism. This function is realized by the robot control system. This construction of WCR differs from that of References 12, 13).

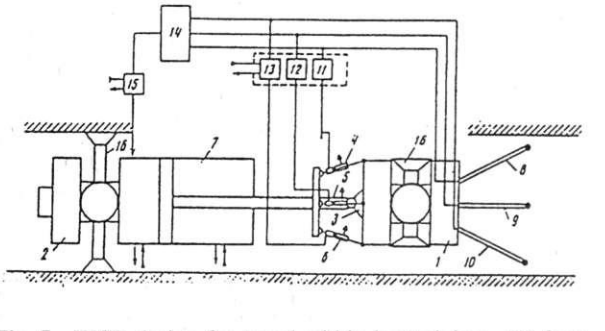


Fig. 5. WCR design for travel within bent piping: (1) front support belt; (2) rear support belt; (3) hinge; (4),(5),(6) correction cylinders; (7) power cylinder; (8),(9),(10) sensors; (11),(12),(13) correction valves; (14) OR element; (15) power valve; (16) supports.

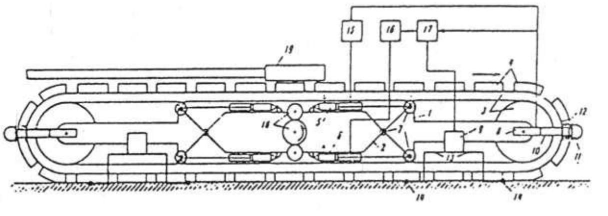


Fig. 6. Design of a WCR capable of crossing from one surface to another: (1) platform; (2) chassis; (3) track mechanism; (4) gripper; (5),(6) correction cylinders; (7) hinges; (8),(9) switches; (10) probe; (11) obstacle sensor; (12) spring; (13) support sensor; (14) supports; (15),(16) valves; (17) relay element; (18) reduction gear; (19) feed channel.

3. Methodology of AI Fuzzy Control System Design for WCR

The proposed methodology shown in Fig.1 is based on the organization of multi-leveled structure[14)] with the various intelligence levels through successive use of two methods: (1) the method of extracting control problem; and (2) the method of coordination between executive and organization levels.

As a first example, we consider the mechanical system shown in **Fig.7**. The mechanical transport model consists on executive level of two platforms, two pneumatic drivers for transportation, eight legs and vacuum grippers on every platform, pneumatic drives in each leg, a drive of TV camera intended for navigation and inspection, two links manipulators with separate drives installed on the robot platform (2), and transducers system. In the processes of motion of such a robot (Fig.7), the variable loads are acting when platform 1 or 2 rotates or when the robot interacts with obstacles or environment. It is necessary to compensate for variations on the upward and downward motion of the robot on vertical surface because, in this case, force weight vector of the robot is opposite to or coincides with the direction of mo-

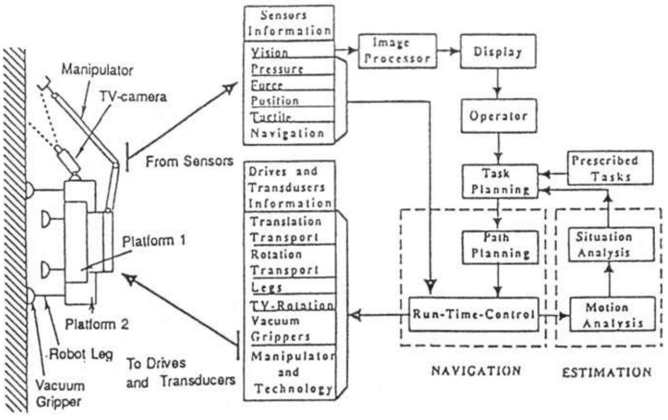


Fig. 7. Basic conception of the control system.

tion.

Mechanical system A in Fig.7 interacts on organization level with control system B, realized navigation and estimation by means of sensor information, drivers, and transducer information. Inductive position control sensors and limit sensors for position control are included in all drivers of the transport module for indicating interplanetary of the final position of each translating drive; vacuum and force sensors represent information from each gripper and its drivers. Pressure sensors are included in the ejector system of each vacuum gripper, and tactile sensors are included which are necessary for attaching to surfaces of slipping along its grippers and for different surface qualities.

As a second example, the task of cooperative control of WCR group with board manipulator on the basis of fuzzy spatio-temporal logic of actions is discussed.[15] For solving this task, the structure of intelligent workstation (on ES with deep knowledge representation and cognitive graphics) is created. The specific situation of WCR interactions on different intelligence levels in the presence of obstacles on the basis of qualitative physics (in accordance with Fig.1) in 15) is discussed in detail.

The structure of intelligent mobile robot is shown in **Fig.8** in which block I of intelligent workstation with real-time expert system (ES) and unit 2 of cognitive graphics system are shown.

The second generation ES with deep knowledge representation level is a powerful tool for solving the tasks of cooperative fuzzy control, inspection of technological operations of decontamination, and choice of fuzzy algorithms for planning and correcting trajectory motion of WCR. Each subsystem of ES motivates the self-subsisting control function to achieve purposes. This ES includes free format of knowledge representation, unit of direct and inverse fuzzy inference and production rules, which are obtained experimentally or based on the methodology indicated in Fig.1. An input/output relationship equation is expressed by fuzzy rule sets. The system determines the robot motion by image processing or with the help of ultrasonic sensors. The fuzzy controller on WARP has control rules according to a type of course, and the hierarchical ES is constructed from these rules.

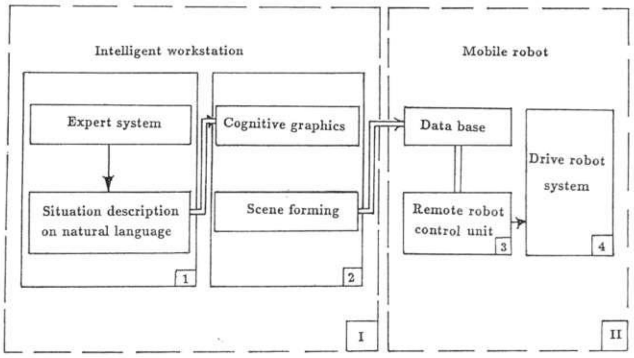


Fig. 8. Structure of intelligent mobile robot.

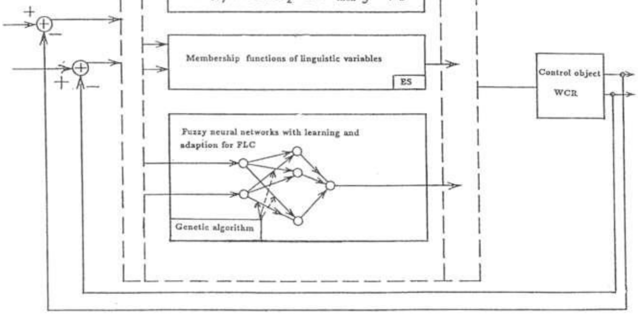


Fig. 9. The structure of fuzzy-neuro controller.

Block 2 of cognitive graphics is intended for dynamic room scene presentation and for WCR's motion trajectory planning. The working results of block 2 is knowledge base (KB) for fuzzy controllers. In the block of cognitive graphics, dynamic scene description is achieved using natural language (NL).

A mixed fames and productions approach is used for knowledge presentation. The frame part of KB is used for description of object properties, relations and actions, as well as for internal representations of NL-texts. The system visualizator realizes display of internal graphical representation that has been built in the planning stage.

The room static 3D scene (as plane of technological operation in NPS) is initial information for fuzzy controllers of autonomous WCR and manipulators solving individual tasks.

The questions of primary tasks redistribution of the two methods for solving in hierarchical structure of intelligent control system (the part B on Fig.7) and the role of "intelligence in large" and "intelligence in small" levels (accordingly cooperative control of WCR group on the base of intelligence workstation with active ES and WARP fuzzy controller on the board of autonomous mobile robot) are discussed in References 14, 15). Control (on fuzzy rules in knowledge base of neurocontroller) of the WCR course is constructed in accordance with Fig.1 on the basis of fuzzy GA and neural network with the back-propagation algorithm and different fuzzy inferences as in Reference 16) (see **Fig.9**).

In this case, the second-generation ES with deep knowledge representation level solves the tasks of cooperative fuzzy control inspection of technological operations, selection of fuzzy algorithm type for planning, and correction of navigation of mobile robots in the presence of obstacles.

4. Fuzzy Control Architecture Based on WARP

A fuzzy controller (as an example of intelligence level "in small") is a particular fuzzy device equipped with an interface suitable for driving physical actuators: it accepts deterministic values and produces a deterministic value. WARP is a dedicated (special purpose) VLSI device that can act in both of the above depicted roles whose architecture has been designed in order to efficiently exploit all the advantages of fuzzy calculus. Although WARP has been conceived as a general purpose fuzzy machine, its outstanding performances in terms of fuzzy computing allows it to be used in a vast range of applications.[17]

The innovative approach of WARP is represented by the adoption of different data structures and to be represented the membership functions characterizing the fuzzy variables of the antecedent and consequent sides of the rules. In fact, one of greatest limiting factors in the traditional fuzzy architectures is the use of the same data representation for computation connected to IF- and THEN-part of a rule.

As a reference, WARP can evaluate 32 rules, with 5 inputs and 1 output within 2μs. In order to utilize WARP, Application Development Board (ADB) has been developed as a powerful tool to develop WARP-based applications and to test physical implementations of fuzzy control.

5. Applications of Fuzzy AI Controller Design Methodology

For problem-oriented control objects as a WCR for decontamination of NPS, the proposed design methodology was investigated. Two different approaches for planning trajectory motion of WCR on basis of cognitive graphics and GA are suggested. In the first case on NL, the dynamic scene of extremal situation is described; and on the basis of cognitive graphics, the graphical pattern of dynamic scene is visualized. This scene is KB for planning of fuzzy controller on the board of WCR.

In the second case on the basis of GA (**Fig.10**), possible trajectory of WCR motion are suggested (as global solution). Then, local control with the help of fuzzy controller is examined. The simulation results (**Fig.11**) of two different approaches are tested. The software and hardware of fuzzy control system with GA in Reference 18) are described in detail.

As an example of correction method[19)] on the basis of WARP for position, velocity, and acceleration of the WCR motion, fuzzy control intended for decontamination with software and hardware techniques is suggested. A new approach for forming KB of fuzzy controller as a simulation on simple GA and multi-layered neural networks[20)] for implementing and control the motion (working parameters) of WCR in undetermined environments is considered.

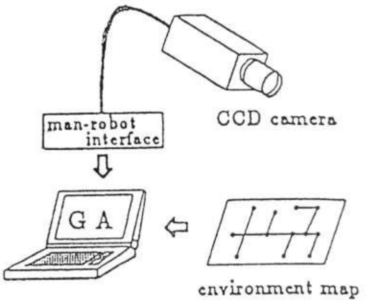


Fig. 10. Concept of planning.

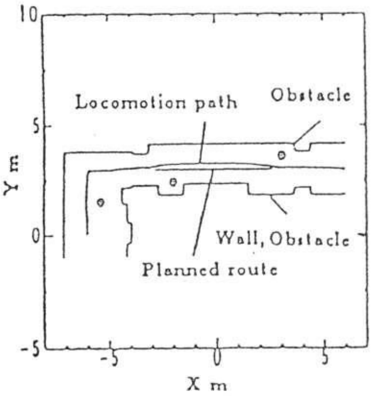


Fig. 11. Environment and path (Experiment).

The proposed correction motion control system is used in this fuzzy simulation approach intended for the calculation in lookup table of WARP controller the linguistic fuzzy rules, the coefficients, and parameters of membership function. For lookup table of WARP fuzzy controller, a new decomposition method is suggested which is unlike.[21)] In this case, when the required position for the WCR is attained, the actions of the board manipulator are produced by correlation with the WCR body motion. The example of fluent correction motion of manipulator and WCR used, a new decomposition method[19)] of lookup table and control on acceleration of error is examined.

WARP is intended to perform the control of the board multilinks manipulator and transport system of WCR.

Example 1. (Fuzzy correction motion control of WCR)

Based on former scientific results, fuzzy correction motion control of the WCR has the following peculiarities, taken into consideration on the simulation stage: (1) The application of cognitive graphics is permitted to draw the trajectory in advance as a charge-programming motion trajectory; (2) The correction motion control is realized as deviation from the cognitive graphic trajectory of WCR motion; (3) The control law is based on the position, velocity, and acceleration parameters to improve quality of control and to minimize static and dynamic errors; (4) The fuzzy control rules are applied to complex mechanical system, including WCR and mobile robot of horizontal motion with board manipulators.

In this case, the following tasks are considered: (1) fuzzy control mobile robot motion with trajectory correction on position in primitive case (what is the task of fuzzy control motion on the path between walls with enter in the room or turn near the corner); (2) fuzzy control motion with trajectory correction on position and velocity in complex case in the room with obstacles; (3) fuzzy correction motion with trajectory correction of position, velocity and acceleration on the vertical wall for WCR; (4) task of fuzzy control for fulfillment of technological operation.

A fuzzy controller for speed and steering control consists of two parts which are speed and steering control rules for mobile robot of horizontal motion and for leg drivers and platforms in WCR. These rules are also used in KB of realtime ES.

The output of fuzzy controller is expressed as a linear combination of error e(k), differentiation of error $\Delta e(k)$, and second order of error $\Delta^2 e(k) = \Delta e(k) - \Delta e(k-1)$.

The added linguistic control for $\Delta^2 e(k)$ corresponds to the derivative action of PID controller. Hence, this fuzzy logic controller could be a sort of nonlinear controller and has universal form.[22)] Fuzzy control algorithm is based on position (angle), error, velocity, and acceleration of robot's characteristics as expressed by the following state variables:

$$X_1^0, X_2^0, \cdots, X_n^0$$

Fuzzy variables characterized by linguistic variables (small, large, big etc.,) are,

$$X_1^0 \to A_1^i, X_2^0 \to A_2^i, \cdots, X_n^0 \to A_n^i$$

Linguistic approximation of fuzzy algorithm concerning m fuzzy implication

$$R_i\,(i=1,\ldots,m):$$

$$R_i:\ \mathit{If}\ [X_1^0\ \mathit{is}\ A_1^i\ (\mathit{and/or})\ X_2^0\ \mathit{is}\ A_2^i\ (\mathit{and/or})$$

$$\ldots\ (\mathit{and/or})\ X_n^0\ \mathit{is}\ A_n^i\,]$$

$$\mathit{Then}\ [u^i=f_j^i\,(X_j^0,P_j^i)=P_1^i X_1^0+P_2^i X_2^0+\cdots+P_n^i X_n^0], \qquad \ldots\ (1)$$

where u - output of i-th controller rule, determined as regression of nonlinear model by linear equation with coefficient p_j (j = 1, 2, ..., n). Connectives "and/or" determined from the perspective of quantum fuzzy logic and has semantic difference from connective syntaxes of conventional fuzzy logic.[23)]

For input variables $(X_1^0, X_2^0, ..., X_n^0)$ true-valued premise of i-th rule is,

$$W_i=\bigwedge_{j=1}^{n}\mu_{A\,j}^i\,(X_j^0)\qquad \ldots\ (2)$$

and output variable of fuzzy controller is average of weighted variable:

$$u^0=\sum_{i=1}^{m}w^i\,u^i\Big/\sum_{i=1}^{m}w^i$$

where, $\mu_{A_j}^i(X_j^0)$ is membership function of fuzzy variables A_j^i; w^i is intersection of all membership functions for R_i rule output u_i.

Algorithm of the necessity condition of Lyapunov stability has the form[24)] for this fuzzy control:

$$M_i^T D M_i - D < 0$$

for any positive definite matrix D, and the matrix M_i is the matrix of coefficients in equation (1):

$$M_i=\begin{bmatrix} P_1^i & P_2^i & \cdots & P_{n-1}^i & P_n \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \cdot & \cdot & \cdots & \cdot & \cdot \\ 0 & 0 & \ldots & 1 & 0 \end{bmatrix}$$

In this case for fuzzy PID-controller we have

$$\Delta u\,(n)=p_1\,e\,(n)+p_2\,\Delta\,e\,(n)+p_3\,\Delta^2\,e\,(n), \qquad \ldots\ (3)$$

where $\Delta^2 e(n)$ is acceleration of error $e(n)$.

We examine the following three cases of fuzzy algorithm for Eq.(3):

1. $p_1 \neq 0,\ p_2 = 0,\ p_3 = 0$
2. $p_1 \neq 0,\ p_2 \neq 0,\ p_3 = 0$
3. $p_1 \neq 0,\ p_2 \neq 0,\ p_3 \neq 0$

Fuzzy algorithm 1.

In case 1, we consider fuzzy P-controller. Here we consider the delay of data processing and of control signal transmitted from artificial vision or ultrasonic navigation sensors.

Fuzzy algorithm 2.

In the second modification, initial information about the plane of the premises of NPS is sent to the fuzzy controller from the cognitive graphics unit.

The vector of sensor information presents all data about coordinates, velocities, and accelerations.

The results of fuzzy control reflects the description frame of premises plane on inner language of cognitive graphics (**Fig.12**).

Fuzzy algorithm 3.

Fuzzy correction motion of mobile robot on position, velocity, and acceleration as a task of fuzzy control of fluent motion to stopping mobile robot position is solved. In this case, it was necessary to solve the problem of decomposition of the 3D lookup table into a 2D lookup table for fuzzy controller on the base of spatio-temporal method.[19)]

In the elaborated method, the fuzzy correction motion algorithm includes segments of trajectories {"start", "establish state", "braking"}. The segments of transient process trajectories with the help of the next logical expression are described as follows:

IF [S is "positive" and J is "zero"]
THEN [T (state of control object) is "start"]
ELSE etc.

The 2D lookup-table for T = {"start" ($\Delta^2 e < 0$), "establish state" ($\Delta^2 e = 0$)," "braking" ($\Delta^2 e > 0$)} are used as a result of solving the task of synthesis of controller structure.

Two cases are under consideration by solving the task of synthesis of controller structure: increase and decreases of error e. Three lookup tables for the first case and two lookup tables for the second case are considered.

From the condensed lookup-table it follows[21)] for different semantic expressive level of linguistic variable for acceleration error as "positive large", "positive medium" etc.. For 3D lookup table with three inputs, the number of linguistic rules is $N = m^n$ (for m = 7 and n = 3, we have N = 343 and for m = 11, N = 1341); for decomposition of 2D

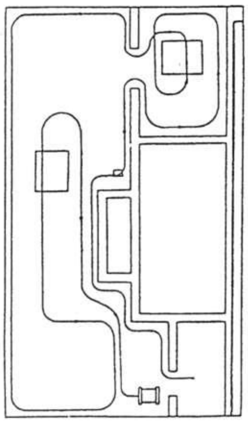


Fig. 12. Simulation of analysis of scene description.

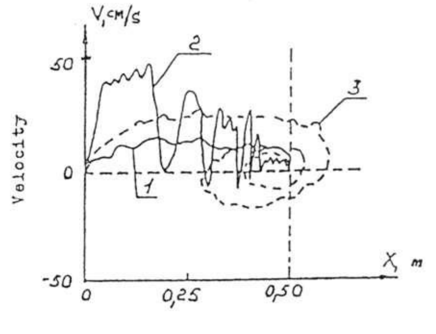
lookup table,

$(0.5mn + 2m) < N' < (2mn + m)$

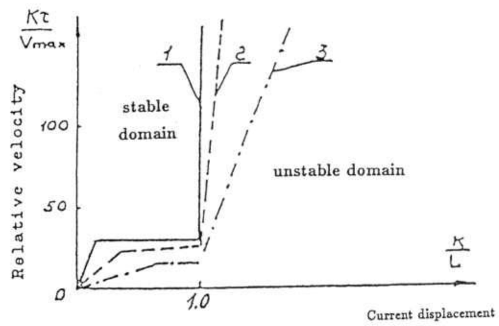
and by $m = 7$, $n = 3$ we have $39 < N' < 105$; for $m = 11$, $n = 3$, $83 < N' < 253$.

The starting position shows the mobile robot's fuzzy control of fluent motion (stopping). The control rules are

IF [e **is** *PLa and* Δe *is PM and* $\Delta^2 e$ *is*
"positive" (T is "start")]
THEN [u^* *is NLa] etc.* . . . . (4)



(a) Phase plane of fluent motion



(b) Stability domains of fluent motion

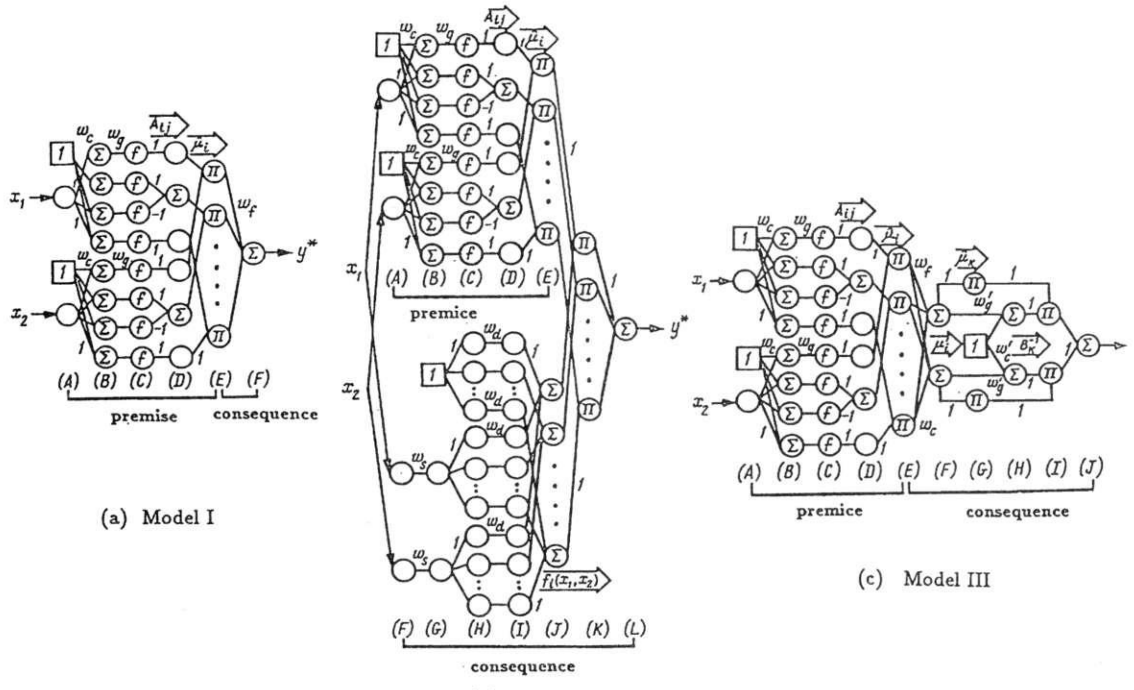
Fig. 13. Simulation of fuzzy control of mobile robot.

The results of simulation of this task are presented in **Fig.13**. In case 3, the fuzzy control on error position is used (p = 0, p = 0); in case 2, the fuzzy control on error position and change of error is used (this case was also in considered in Reference 25)). The start position was from 1.5 m to 0.5 m with variable speed (from 0.1 m/sec to 0.75 m/sec). For the case 1, the stable motion for decoupled lookup table from ($\Delta^2 e$ is "positive", $\Delta^2 e$ is "zero" $\Delta^2 e$ is "negative") is achieved and necessary condition of Lyapynov stability is fulfilled (see the necessary condition of Lyapunov stability for coefficient P_1, P_2, P_3). The domains of stability for considered algorithms of fuzzy correction of fluent motion on Fig.13b are shown. This algorithm (case 1 on Fig.13(a)) is applied as block in ES.

Example 2. (Fuzzy neural controller for manipulator of WCR)

According to Fig.1, the third step membership function parameters and different types of approximate reasoning are examined for fuzzy neural controller as on Fig.9. In this case, control object is the manipulator of WCR for welding or cutting operations, and target trajectories are the paths to perform the above operations.

Many approaches to neural network applications are based on the use of the back-propagation (BP) algorithms, and they can acquire the fuzzy inference and tune the membership functions simultaneously through learning from expert's inference data. These new networks are categorized into fuzzy neural networks (FNN).[20] The basic idea of the composition method of FNN is to realize the process of



(a) Model I

(b) Model II

(c) Model III

Fig. 14. Realization on fuzzy neural networks of fuzzy inferences models.

fuzzy reasoning by the structure of FNN and to make the parameters of fuzzy reasoning be expressed by the connection weights of neural network. Using BP algorithm, the FNN can identify the fuzzy rules and tune the membership function by modifying the connection weights of the networks.[20)]

In the reference 16), configurations of the three types of FNN - types I, II, and III (**Fig.14**) are shown.

In Fig.14, the case where the FNN having two inputs (x_1, x_2), one outputs (y^*), and three membership function in each premise are shown. The input-output relationship of the units with a symbols of f, Σ, Π and $\hat{\Pi}$, are defined in 16) as follows

$$I_j^{(n)} = \sum_k w_{jk}^{(n,n-1)} O_k^{(n,n-1)}; f: O_j^{(n)} = \frac{1}{1-e^{I_j^{(n)}}}; \sum : O_j^{(n)} = I_j^{(n)};$$

$$I_j^{(n)} = \prod_k w_{jk}^{(n,n-1)} O_k^{(n,n-1)}; \Pi : O_j^{(n)} = I_j^{(n)}; \hat{\prod} : O_j^{(n)} = \frac{I_j^{(n)}}{\sum_k I_k^{(n)}}$$

where $I_j^{(n)}$ and $O_j^{(n)}$ are the input and output of the j-th unit in the n-th layer, and $w_{jk}^{(n,n-1)}$ are connection weights between j-th unit in the (n-1)-th layer and the j-th unit in the n-th layer. According to the process of fuzzy reasoning, the FNN is divided into the premise parts and consequence parts. The premise part which consists of layers A through E is common to all three types of FNN (see Fig.14). The layers A through D are calculated by the grades of the membership functions in the premise. The layer C determines the central position and gradient of the sigmoid function in the units (parameters of connection weights w_c and w_g). The outputs of the units in layer E are obtained by the thruth values of the fuzzy rules. By appropriately initializing the weights, the membership functions $A_{1j}(x_j)$, $A_{2j}(x_j)$, and $A_{3j}(x_j)$ can be allocated on the universe of discourse as shown in Fig.2 of Reference 16), where $A_{2j}(x_j)$ is composed of two sigmoid functions. The input space (in the case of Fig.14) is divided into the nine subspaces and the thruth value of the fuzzy rule in each subspace is given by the product of the grades of the membership functions in the units in layer E as:

$$Inputs: \mu_i = \prod_j A_{i_j\,j}(x_j); \;\; Outputs: \hat{\mu}_i = \mu_i / \sum_k \mu_k$$

where μ_i is the truth value of the i-th fuzzy rule and $\hat{\mu}_i$ is normalized value of μ_i. For Fig.14, the types of fuzzy reasoning realized in the networks in the consequences are as follows.[16)]

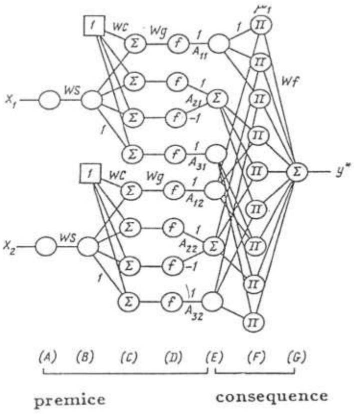
Type I (Fig.14a: Consequence - Constant):

$$R^i : IF\, x_1\; is\; A_{i_1 1} \text{ and } x_2\; is\; A_{i_2 2}$$

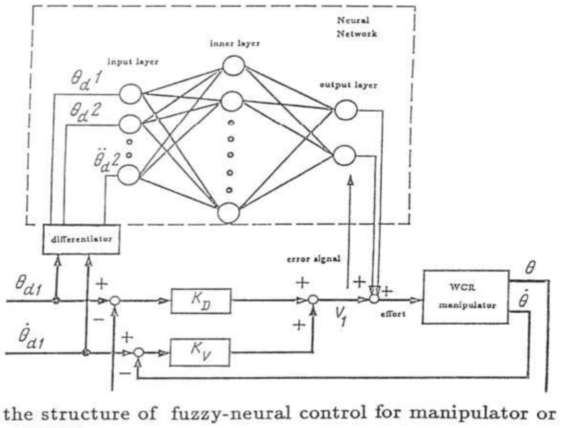
$$THEN\;\; y = f_i\,,\; i = 1, 2, \cdots, n;$$

$$y^* = \left[\sum_{i=1}^{n} \mu_i f_i \Big/ \sum_{i=1}^{n} \mu_i\right] = \sum_{i=1}^{n} \hat{\mu}_i f_i \qquad \cdots\cdots (5)$$

Type II (Fig.14b: Consequence - First-order linear equa-

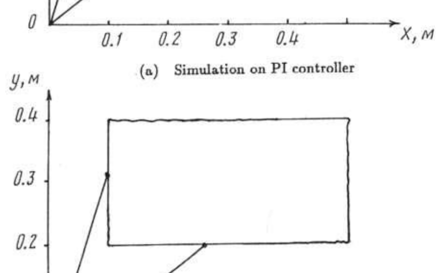


(a) Fuzzy neural network for fuzzy inference (type I)

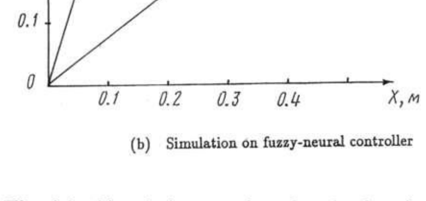


(b) the structure of fuzzy-neural control for manipulator or of WCR

Fig. 15. Fuzzy-neural controller.



(a) Simulation on PI controller



(b) Simulation on fuzzy-neural controller

Fig. 16. Simulation results of path planning.

tion):

$$R^i:\ IF\ x_1\ is\ A_{i_1 1}\ \text{and}\ x_2\ is\ A_{i_2 2}$$

$$THEN\ y=f_i(x_1,x_2),\ i=1,2,\cdots,n;$$

$$y^*=\left[\sum_{i=1}^{n}\mu_i f_i(x_1,x_2)\Big/\sum_{i=1}^{n}\mu_i\right]=\sum_{i=1}^{n}\hat{\mu}_i f_i(x_1,x_2),$$

$$f_i(x_1,x_2)=a_{i\,0}+a_{i\,1}x_1+a_{i\,2}x_2;$$

$$a_{i\,j}\ (j=0,1,2)-constant$$

Here the products of $\hat{\mu}_i$ and $f_i(x_1, x_2)$ are calculated in layer K, and the sum of the products in layer L is the inferred value of the fuzzy reasoning.

Type III (Fig.14c: Consequence - Fuzzy variable).

$$R_k^i:\ (IF\ x_1\ is\ A_{i_1 1}\ \text{and}\ x_2\ is\ A_{i_2 2}\ THEN\ y\ is\ B_k)\ is\ \tau_{R_k^i},$$

$$i=1,2,\cdots,n;\ k=1,2;$$

$$\mu_k^*=\sum_{i=1}^{n}\hat{\mu}_i\,\tau_{R_k^i};\ y^*=\left[\sum_{k=1}^{2}\mu_k^*B_k^{-1}(\mu_k^*)\Big/\sum_{k=1}^{2}\mu_k^*\right]$$

$$=\sum_{k=1}^{2}\tilde{\mu}_k^*B_k^{-1}(\mu_k^*)$$

here $\tau_{R_k^i}\in[0,1]$ is linguistic truth value of the fuzzy rule R_k^i, μ_k^*, i.e., the truth value of the consequence, and $B_k^{-1}(\mu_k^*)$ is the universe function of the membership function in the consequence $B_k(y)$, layers E through J are the consecutive part; μ_k^* and $B_k^{-1}(\mu_k^*)$ are the outputs of the units in layers F and H, respectively; the normalized truth value in the consequence $\tilde{\mu}_k^*$ is calculated in layer G, and the inferred value is obtained as the sum of the product of $\tilde{\mu}_k^*$ and $B_k^{-1}(\mu_k^*)$ in layer I through J.

For manipulator of WCR as in Fig.2d, fuzzy-neuro-controller as shown in **Fig.15**a and b is examined. The fuzzy inference in Fig.15a is similar to that of Fig.14a. It was nonlinear fuzzy PID controller on WARP.[17] In **Fig.16**a, the result of simulation of PI controller for manipulator of WCR is given. In Fig.16b, the result of fuzzy simulation with fuzzy-neuro-controller is examined. The simulation algorithm is similar to Reference 26).

6. Conclusions

The suggested design methodology of fuzzy controller on concrete mechanical systems as control objects is examined. The proposed design methods are utilized fuzzy simulation approach for the calculation in lookup table of WARP controller the linguistic fuzzy rules, the coefficients, and parameters of membership functions.

For 3D lookup table a new decomposition method which has spatio-temporal structures is suggested. The structures of designed fuzzy controllers are of robustness, adaptive, and self-organized in instructed environments. Therefore its application field is large.

The fuzzy control rules and algorithms were applied satisfactorily to complex mechanical systems such as a cooperative operations of mobile robot for decontamination of NPS with equipment and tools.

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