Computational Intelligence Models

FUZZY TECHNIQUES IN ROBOTIC SYSTEMS CONTROL

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Abstract: *New area of robotic systems application is in the field closely connected with the human society. That is the service robots, the robotic medical systems, robotics for risky environment etc. The most important problem in robotic control system now is not the technical realization but the compatibility the robotic system with human. One of the ways to approach the control techniques the possibilities of human-operator without any special knowledge in the field of robotics and control systems is the fuzzy logic techniques. Some examples of such approach are presented below.*

Keywords*: fuzzy logic, linguistic variables, mobile robot, fuzzy-neural net, operation planning, scene recognition, human-robot interface.*

Introduction

The modern trend of robotics is the inclusion of intelligent robots in human society. New area of robotic applications may be found in medicine, space investigation, agriculture etc. as service robotics. To create the robot compatible with human we suppose it is necessary to provide the anthropomorphism at the level of perception and reasoning. The most suitable approach to solve the problem are the fuzzy technologies. Some new results in this field are presented in the paper.

Three levels are possible to distinguish in the control system of intelligent robot: reflection level, tactical level and the level of the purpose designation. The lower level may be named by analogy to the living creature as reflection level. The stereotypes of reactions are forming here in accordance with the current situation. The situation itself may be determined as a composition of fuzzy conditions. Such approach makes it possible to use the human's perception and experience to determine the necessary rules for robot sensory system. Using the suitable algorithms of fuzzy inference the fuzzy controller may be formed to control the movements of manipulation or mobile robot. Mention that in the latter case the membership functions depend of current robot position because the scale of the image is continuously changing due the robot movement.

The next level named a tactical make it possible to compose the more complicate modes of behavior using the typical elements from the knowledge base. The latter accumulates the human experience in form of fuzzy rules. The principles of automatic inherence of the sequence of movements may be the same as in the case of human reasoning. Some of them are also under discussion.

We suppose that the hybrid neural-fuzzy approach is the most suitable for the realization of fuzzy controller for intelligent robot. It allows not only to form the basic rules of behavior but also to tune the fuzzy controller parameters using the backward error propagation algorithm. Usually to teach robot to fulfill the typical operations we use the principle “the teacher – the pupil”. The new direction in this field is the self-teaching of robot using the “emotion block” as a part of the neural network.

The upper level of the system under discussion is the level of the purpose designation by human. The modern stage of the problem is the dialogue planning between human and robot using the language close to natural one. The dialogue is the most convenient form for human operator both for situation analysis and for robot control. The fuzzy form of relations in the external world and linguistic variables allow cooperating with robots the persons without a special preparation. That is why we hope that our approach will help to solve the problem of human – robot compliance. The theoretic background of the fuzzy logic control is well known to day. So the main attention we pay below to the applications of the fuzzy technique to the robotic control systems realization.

Representation of the external world by robotic system

A modern robotic system can to move in the external world and to fulfill the necessary complicated operations using manipulators. Robot is equipped with the computer vision system and a net of information devices proved the reconstruction of the image of real situation in the external world. So the robot can work autonomously. But at the same time the autonomy of robot is an illusion. The task for robot is stated by human – either previously or in the real time scale. The more deep is the robotics penetration through modern society life the more actual become the problem of compatibility between robots and human.

The first problem here is the "mutual" understanding of the external situation which has not been known beforehand. To reach such understanding it is necessary to apply in the human-robot dialogue the same relations which are natural for human in his usual life. That is the natural relations [Pospelov , 1989] such as <*a1 is far and a little to the right at a2*>. Such types of relations are extensional ones. To describe the current scene also the intentional relations are employed. For example *to be adjacent to; R_2 - to be inside of; R_3 - to be outside of; R_4 - to be in the centre of; R_5 - to be on the same line as; R_6 – to be on the same plane as; R_7 - to have zero projection on, R_8 - to be on the surface of.* Two unary relations are also proposed: R_{00} – *to be horizontal* and R_{01} – *to be vertical*, as well as 28 elementary spatial binary relations.

The set of specified objects in the current scene, the relations between them and transformation rules constitute a formal language for environment representation that is similar to a natural language. Scene description in this language allows for a formal semiotic representation that uses the spatial-temporal relations logic. For example a complex relation <*a_1 is on the surface S far and to the right*> can be written as $(a_1\ R_8\ S)\&(a_0\ d_5\ f_7\ a_1)$, where a_0 – is the observer, with respect to whom the distance d and orientation f relations are formulated.

Since the environment is ever-changing due the motion of the observed objects as well as to the motion of the robot itself, the scene description changes in time respectively. This circumstance requires that we take into account not only spatial but also temporal relations in the external world, such as *to be simultaneous with, to be prior to, to follow* etc.

Practically the task of the environment recognition may be solved by application of 3D computer video system (CVS) with the structural light [Mikhaylov, 2005]. The system consist of high definition TV-camera and pulse source, which generate special light flat matrix on work scene. In result CVS forms 3D description of the real work scene as Cartesian coordinates data file. Moreover, CVS forms set of the elementary triangles; every triangle includes three nearest points of scene.

The algorithms of the objects identification are based on the fuzzy features comparison of the objects detected on the working scene and of the objects accessed in the data. At first it is necessary to apply the fuzzification procedure for such geometric features measured by computer vision system as D – the distance for the obstacle, W – the width of the object, L , R – the distances from the main axis of robot platform to the left or to the right edge of the obstacle, H – the height of the obstacle etc. For example: *the object is* *extensive, flat, horizontal, does not high, to the right, does not distant*, etc. The linguistic variables allow the user easily to expand the list of the possible objects using their characteristic features.

The fuzzy classifier realized the Mamdany fuzzy inference procedure determined the type of the object [Volodin . 2011]. The first maximum approach is applied on the defuzzyfication stage. The choice of the fuzzy features for object classification as well of the production rules and membership functions depend of the task under consideration. It may be different depending on the importance of those either another features for the task to fulfill by the robotic system. Analysis of the typical situation for indoor work proved to determine the types of the obstacles such as *Wall, Door, Threshold, Block*, etc. The typical obstacles are presented in the data base by the vectors of fuzzy features obtained from the CVS. Among them are the coordinates and dimension of the object, the mutual disposition of the objects, their geometrical characteristics etc. Note that the geometric description of the obstacles and the separate objects may demand the special robot movements of cognitive type to obtain the information necessary to determine the type of unknown object. The fuzzy features allow identifying of the object also in the case when the object description is incomplete for obstacles or shadows. In such cases the cognitive behavior of the robot may be planned to seek the information necessary for the object classification. For example the special position of the robot vision system may be needed for the satisfactory observation.

The identification algorithms is the fuzzy logic inference using the previously determined classification rules and fuzzy features of the reference model of the objects possessed in the knowledge base. The base also contains the production rules of object classification and the corresponding maneuvers representation. The fuzzy features of the objects are represented by the membership functions for the corresponding linguistic variables. These functions are to be correlated with the robot and its computer vision system technical characteristics. For example the meaning *the doorway width is enough* is determined by the robot dimension itself. The meaning *the obstacle high does not enough* is determined by the dimension of the robot platform. The meaning *the obstacle is distant* is restricted by the CVS characteristics. The membership functions of the linguistic variables are to be assigned beforehand during the calibration procedure of the 3D CVS as a part of a definite mobile robot.

The situation in the working scene in the whole may be represented as a kind of fuzzy chart where binary relations between all the objects have been determined. Robot is one of these objects. Such a fuzzy chart allows the robot control system to determine its own position in relation for the bench-marks.

The important peculiarity of the mobile robot control system is in the fact that the scale of the image is continuously changing due the robot movement. That is why the membership functions for mobile robot sensing system depend of the distance. In this case the 3D membership functions had been introduced.

But the main advantage of a fuzzy identification system is the possibility of the robot –human dialogue about the environment and the objects around the robot, which is necessary for the prescribed operations fulfillment.

Mobile robot behavior in the 3D external world

It seems quite possible to use the term “behavior” for autonomous mobile robot work in the partially undetermined world. We can represent the stereotypes of behavior determined by the characteristic situation as production rules “*if the situation is* S_i *than the tactics is* T_i“. The *tactics* here is the list of production rules of typical stereotypes of behavior represented with the linguistic variables. These rules determine the previously described robot movement for ever typical situation. For example: “*if the obstacle is near and to the left then go around slow and anticlockwise*”. The typical movement (*go around slow and anticlockwise*) in its turn also may be determined by a list of production rules contained in the data base [Yuschenko, 2012].

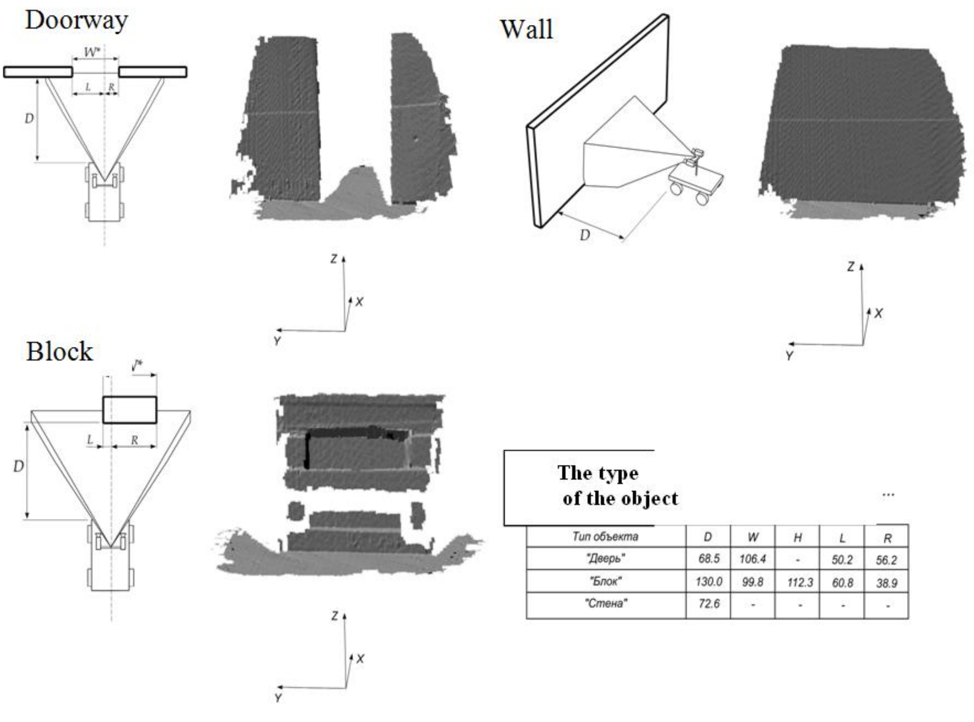
Such a data base allow to the user to develop the new tactics such as: “to pursuit the moving objects”, “move to the prescribed object”, “pass the doorway”, “go around the obstacle” etc.

In general the tactics of robot behavior may be determined with a task frame: <current situation > <robot characteristics > <tactics name > <the objects and obstacles > < the conditions of the operation feasibility> .

Robot’s characteristics such as dimension parameters (weight, power of drivers, possible velocity etc.) are contained in the data base. These characteristics together with the features of the environment (relief, the ground parameters, the types of the obstacles) determine the possibility of the prescribed operation feasibility. The latter may include also the post condition to be satisfied after operation fulfillment such as a stable robot position. The conditions of feasibility for such operation as the objects persecution or the obstacle avoidance are to be classified in accordance with their features beforehand.

In the case when some slots of the operation frame are empty the robot has itself to plan a movement of cognitive type to find the necessary information [Yuschenko, 2005] For example the parameters of the doorway to pass through. The cognitive operations are also contains in the robot knowledge base as a list of fuzzy production rules.

In our experimental investigation we supposed that the most part of indoor situations might be represented as a combination of the next typical objects: “Wall”, “Threshold”, “Block”, “Left angle”, ”Right angle”, “Doorway” (Fig.1). Every object detected by the 3D computer vision system is classified as one of the typical objects via the fuzzy inference procedure discussed above. Then the necessary movement trajectory may be planned.



Тип объекта	D	W	H	L	R
"Дверь"	68.5	106.4	-	50.2	56.2
"Блок"	130.0	99.8	112.3	60.8	38.9
"Стена"	72.6	-	-	-	-

Fig. 1. The typical obstacles and their parameters

The next linguistic variables were introduced: “The object position” (to the right, to the left, in the centre); “The object height” (tall, middle, law), “The object width”(wide, compact), “Distance to the object (dangerous, safety, the edge of the vision area)., The number of the terms of the linguistic variables may be easily expanded if necessary.

The experiment has been fulfilled in the laboratory rooms using a small mobile robot equipped with the 3D vision system described above (Fig. 2).

As it was mentioned above the scale of the image producing by the CVS based on the robot platform is changing during the robot movement. So it is important to take into consideration the membership functions as the functions of current distance to the obstacle. So for the terms of the linguistic variable “object height” the membership functions are formed taking in consideration the angle of the TV camera arrangement on board of the robot (Fig.3). The object classified as tall on the edge of the vision area may be classified as middle at the distance dimension. The same is for the linguistic variable “object position”. The object situated at the centre may be founded as to the right at small distance (Fig.4). It make possible to plan the maneuver beforehand. For example begin to plan the walking round the block at the safe distance from the obstacle.

The identification of the obstacles has been developed in accordance with the prescribed classification rules. For example: “slow and wide object is a Threshold”; “slow and compact object is a Block”; “ Tall or middle object to the left is a Left angle”;“ Tall and wide object in the center is a Wall” . Note that the conjunction of the features related both to the features of the object and to its position leads to description of the situation in the whole from the description of separate objects. An example of the real experiment presented on the Fig.1 where the robot determined the object “The doorway” as “The tall object to the left (Left angle) and The tall object to the right (Right angle)at almost the same distance”. To realize the operation: “To walk into the doorway” the condition of feasibility of operation “The doorway is free” is to be examined. The condition has not been fulfilled in the case when the system has found another obstacle (Block for example) between the Left and the Right angles.

After the situation has been determined completely the necessary trajectory may be planned as sequence of the typical operations contained in the data base as it described above. Consideration of 3D-membership functions (Fig.4,b) taking in consideration their relation from distance allowed the planning of the robot movement beforehand without stopping the robot. Such mode of control can improve the safety of operations and eliminate the possibility of collision. It may be extremely important in the case of appearance of moving objects allowing to correct the trajectory and to avoid the possible collision.

Fig. 2. Mobile robot equipped with the 3D computer vision system in experiment.

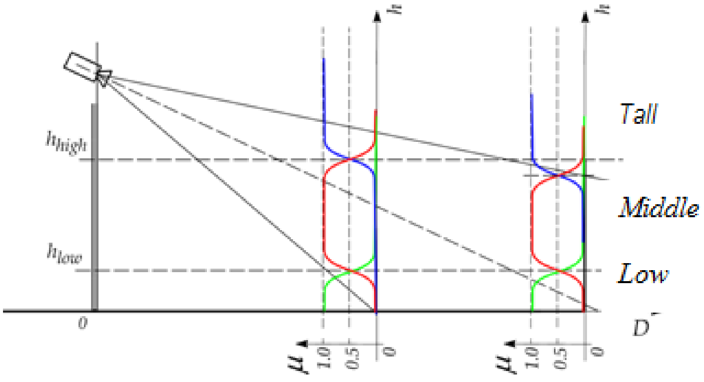
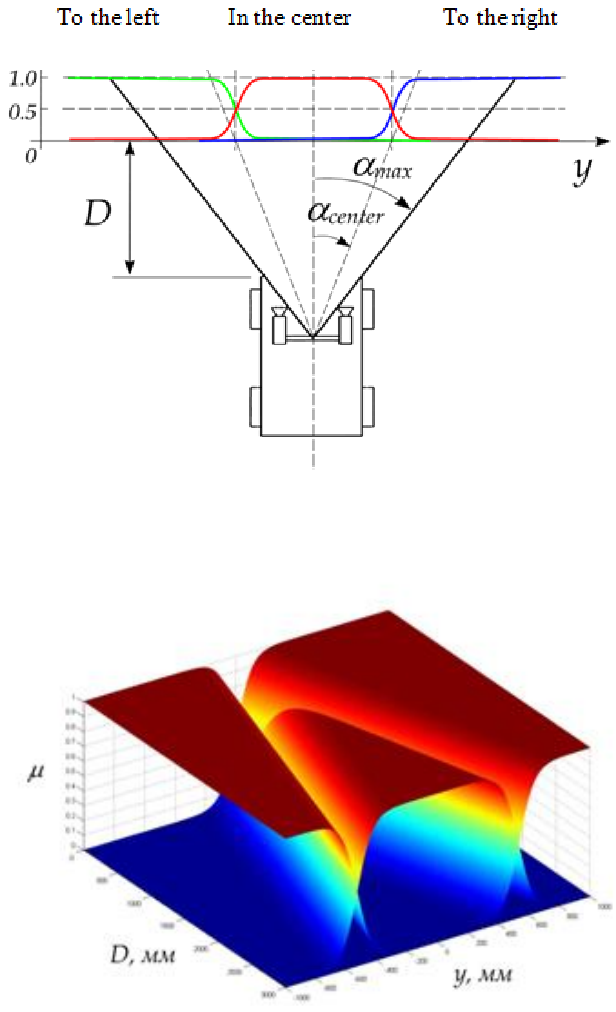


Fig. 3. Membership functions “Tall”, “Middle”, “Low”



(a)

(b)

Fig.4. Membership functions “To the left”, “To the right”, “In the centre” (a) and their relation from the distance (b)

Mobile fire reconnaissance robot control.

The image of the current situation may include not only the fuzzy variables determine the space relations and the linear dimensions of the objects but other fuzzy peculiarities of the environment. Such problem arrives in the task of autonomous control of a mobile robot applied for an indoor fire guarding. Such robot is equipped with the sensors of temperature, humidity, pressure, concentration of CO and CO_2 etc.. All the information proceeded in real time scale may be presented in the form of the fuzzy reports. For example " *the temperature is low, the humidity is high , the smoke is dense"*. Such information make it possible to understand the real position of the robot to the fire source. There are different strategies of the robot behavior are possible. In the case of real danger the robot has to leave the dangerous zone. Otherwise it has to move towards in the direction of the unobservable fire source and to recognize the type of the fire and the strategy of the firefighting [Tachkov, 2012]. The vector of the fire parameters is computed on board in real time scale. One of them (or some parameters forming a scalar estimation) is chosen as a most important. The robot movement now may be interpreted as the movement in the scalar field of the fire parameter along the gradient of the field. In this case at the every moment of time the robot moves toward the maximum of the chosen parameter – main fire factor MFF (for example, the temperature of the environment or the concentration of CO_2).

Let the gradient direction is determined with the angle $\varphi(\vec{r},t)$ oriented along the increasing meaning of the MFF (let it be a temperature) (Fig. 5) Then the equality takes place:

$$\varphi(\vec{r},t)=\theta(t)+\eta(t),$$

where $\eta(t)$ – is the angle of anticipation. From this equation we may obtain the velocity of the anticipation angle changing:

$$\frac{d\eta}{dt}=\upsilon\cdot\vec{u}(\theta)\cdot\vec{\nabla}\varphi-\omega+\frac{\partial\varphi}{\partial t}$$

Where $\vec{\nabla}\varphi$ is the MFF gradient in the point of the robot position in the direction determined by the angle φ, υ is the linear velocity of the robot, ω is the angular velocity and $\vec{u}(\theta)$ – is an ort of OX axis .

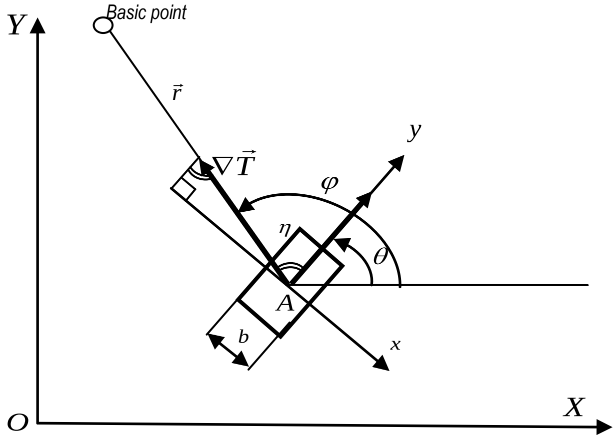


Fig.5. Self-guidance of the robot to the basic point ($\nabla\vec{T}$ is the gradient of the temperature field)

The kinematics equations of the robot are the next

$$\begin{cases} \frac{dr}{dt} = -\upsilon\cdot\cos(\varphi-\theta) \\ r\frac{d\varphi}{dt} = \upsilon\cdot\sin(\varphi-\theta) \end{cases}.$$

We may also put $r = 2K\cdot\frac{\upsilon}{\omega}\cdot\sin\eta$ and $\omega = \frac{2K\cdot\upsilon\cdot\sin\eta}{r}$, $\omega = K_H\cdot\dot{\varphi}$

The last equation is the law of proportional navigation with the coefficient $K_H=2K$, $K>0$.

For the fire in the closed room the proportional navigation law may be prescribed as

$$\omega = \frac{K_H\cdot\upsilon\cdot\Delta T}{b\cdot\left(T(r)-T_0+\varepsilon\right)},$$

where ΔT is the difference of the temperature from the left and the right boards of the robot platform $T(r)$ is the temperature in the point A, and T_0 is the initial temperature in the room and ε is a small value.

The formulas above allow to realize the fuzzy mode of control of the mobile robot based on the principle of the proportional navigation. The linguistic variables for input of the controller we choose the distance from obstacles to the right, to the left, and forward, the temperature, angular velocity of the MFF gradient. The output linguistic variables are the linear and the angular velocities of the robot movement.

The base of knowledge of the robot includes the lists of production rules for obstacles avoidance and rules for self-guidance to the virtual basic point. The membership functions for input variables connected with the distance, direction to the obstacles and temperature were determined with expert appraisal. The problem was to form such functions for the angular velocity of the MFF gradient. We choose three levels of the angular velocity – negative, positive and small (Fig. 6). The output membership functions are of singlton type. To tune the membership functions we used the linear equation between the output variable – the angular velocity of the robot platform from the input variable $\dot{\phi}$: $\omega = K_H\cdot\dot{\varphi}$. Defuzzification was produced by the centre of gravity method (Fig. 6).

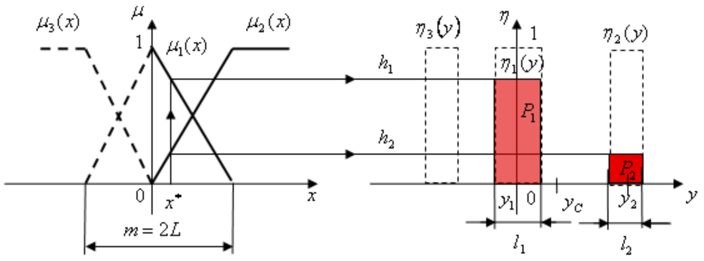


Fig. 6 The membership function tuning

The analytic presentation of the membership functions are the next:

$$\mu_1(x)=\begin{cases}0, & h_1(y_C)<0\\ \dfrac{-f\cdot(y_C-y_2)}{(y_C-y_1)-f\cdot(y_C-y_2)}, & 0\le h_1(y_C)\le 1\\ 1, & h_1(y_C)>1\end{cases}\quad \mu_2(x)=\begin{cases}0, & h_2(y_C)<0\\ \dfrac{y_C-y_1}{(y_C-y_1)-f\cdot(y_C-y_2)}, & 0\le h_2(y_C)\le 1\\ 1, & h_2(y_C)>1\end{cases},$$

where $f=l_2/l_1$ is the weight of the membership functions $\eta_1(y)$ and $\eta_2(y)$.

The experimental mobile robot with the temperature sensors at the right and the left board is shown at Fig.7. The mass of the robot is 1,26 kg and the width of the platform is about 0,1 m. The robot equipped with the visual sensors and the necessary algorithms to avoid the obstacles (see above).

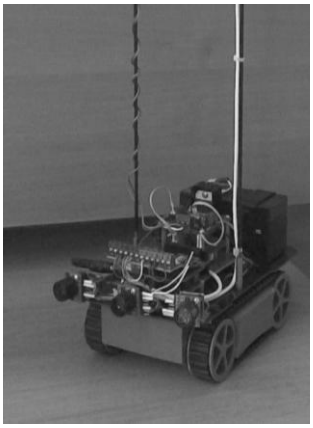


Fig. 7 The fire reconnaissance mobile robot

The robot is equipped with DC-drivers and can work autonomously. It is necessary to underline that the proportional navigation coefficient K_H determined in accordance with the parameters of the robot and of the control system. The experiments show that the stability and the quality of the transient responses also depend of this coefficient. To determine the stability interval the absolute stability criterion was applied.

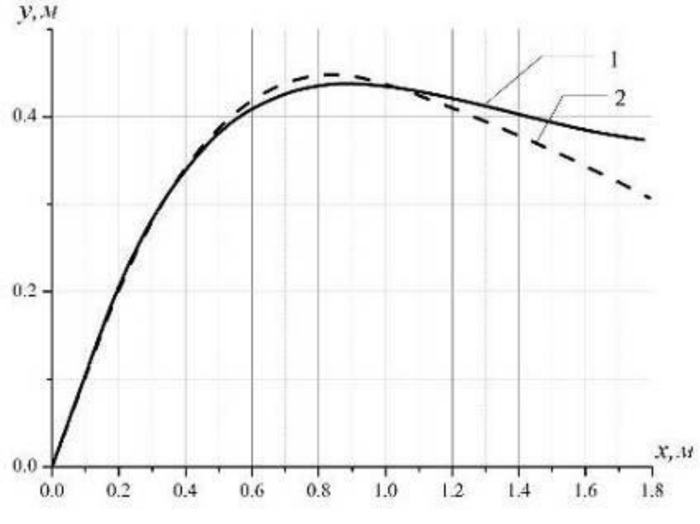


Fig 8. The divergence of the real trajectory 2 of the robot from the preplanned one 1.

Experiments showed that the divergence between the experimental robot trajectories and the simulation results is not more thay 5-7 cm (Fig.8), which is a satisfactory result taking in configuration the robot sizes.

Medical Intravascular microrobot control using a fuzzy finite state automata concept

The aim of the investigation is the development of the instruments and technologies for diagnostics and treatment of tube-like human's organs such as blood vessels and intestines. The medical microrobots may be applied to move along the tube-like organs by the same way as a worm (i.e. using a peristaltic principle). An experimental model of microrobot (Fig.9) has three segments which contracting successively to ensure progressive movement of the device [Savrasov, 2006]. The diameter of the robot is smaller than the same of the blood vessel. So it is pressed to the internal cover of the vessel by the special planes to avoid the thrombosis of the vessel. Every segment of robot contain three contact elements, pressure sensors and a regulator to control the pressure of the elements to the internal surface of the vessel. Aboard the robot a micro-video camera has been mounted to inform the surgeon of the situation inside the vessel and other micro-devices. The supporting plates carry tensometric sensors to control the contact forces. The driver of the robot is of hydraulic type with physiologic solution to avoid the danger of embolism.

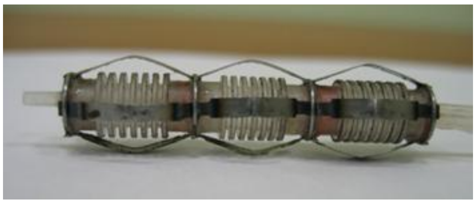


Fig.9. A microrobot model

Microrobot is a part of the robotic system including also a hydro-driver mounted in the stationary part of the system and intelligent interface of the operator. The surgeon-operator has opportunity to observe the inner surface of the vessel by visual sensors mounted aboard the robot and to control the robot movement along the vessel. The construction of the microrobot has to guarantee the stable position of the robot in the moving blood flow and its movement inside the vessel without any damage of the inner surface.

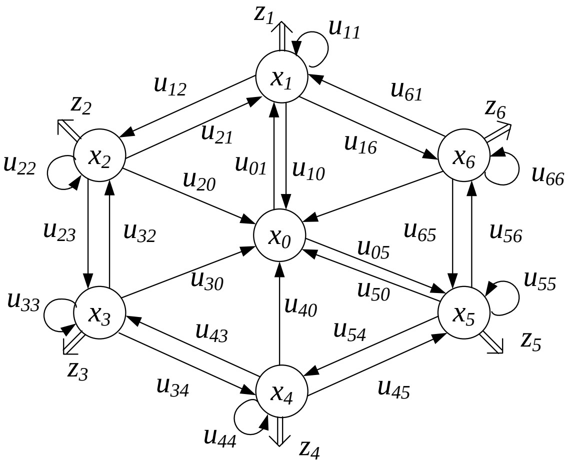


Fig.10. Finite state automata model determining the robot movement

The peculiarity of the microrobot movement is in its cyclic type. The segments of the robot contracts successively and during the cycle they may posses only one of two states – active (contracted) or passive (stretched). The conditions of the transition from one state to another depends of the contact forces values necessary to reach a stable position of the robot in the vessel. Such conditions may be formulated as a fuzzy production rules. So the mathematical model based on the fuzzy finite state automata concept has been proposed [Voynov , 2005].

Graph of the finite state fuzzy automata (Fig.10) has 6 states corresponing the states of microrobot on Fig.9. The states indicated as: x_i (i = 0…6); input alphabet is $U = \{u_{ij}\}$, and u_{ij} is a command to change the state i into state j (i = 0,…6, j = 0, …,6), output alphabet is $Z = \{z_i\}$, and z_i is a symbol of transition into state i. After receiving the operator's command such as "forward, backward, stop" etc. the control system forms a chain of operations to perform the command.

The active contact planes also have been presented as a finite fuzzy automata controlled with the corresponding regulator. The input linguistic variable is the force of pressure of the contact plane and output variable is the velocity of the pressure process. Individual tuning of the membership functions provide the smooth pressing process necessary for it safety. The same model describes the pressure sensors. So the logic level of robot control is a 3-levels net of finite state automata (Fig. 11). The lower level includes regulators of the contact sensors and controls the process of pressing the contact plates to the internal surface of the vessel. The middle level contains the monitors of three segments of robot providing their coordinated work in accordance with the prescribed task. The upper level is a monitor of the driver providing the robot movement by computing the control signals to the robot segments in accordance with the operator's command.

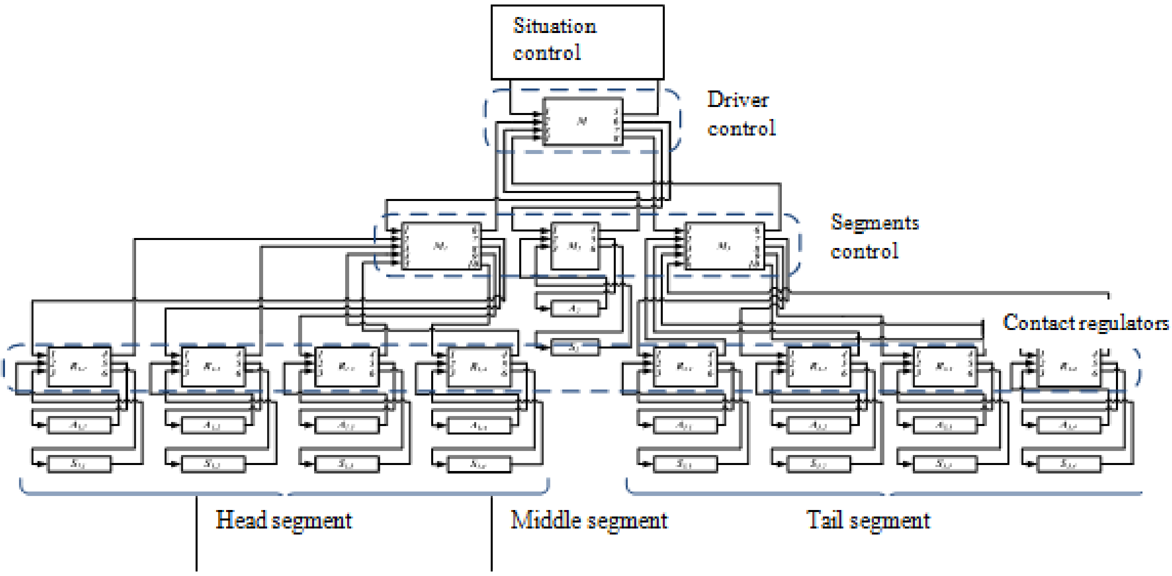


Fig. 11

In the problem cases of calcite deposition on the inner surface of the vessel the robotic system can support the surgeon's decision. The micro-video device forms an image of the situation which is analyzing by the computer expert system and possible decisions are presenting to the surgeon. In the crucial situations the control may be transferred to the surgeon.

Mention that the principles discussed above does not depend of the number of the robot segments. So the same model may be developed for robot with more number of segments which is more close to it biological prototype – the swarm. Such microrobots will possess more wide possibilities to penetrate to the distant parts of the human body to perform diagnostics or medical operation in the less traumatically way for the patient and make such operations safer.

Conclusion

The fuzzy control technique are wide spread to day for every application connected fith fuzzy information proceeding and with human factors. The approach allows to solve such problems as obstacles identification in the indoor navigation, the navigation in extremal condition with an information shortage, in medicine as a mean making the diagnostic and surgeon operation safer for patient. The fuzzy control system allows robot both to fulfill the stated task autonomously in partly determined environment and work under operator's control using the natural speech dialogue. We suppose that fuzzy logic technique makes it possible to control the service robots for the person without special knowledge which is one of the main goals of the future human-robotic society.

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Major Fields of Scientific Research: Control theory, Control of “intelligent” robots, Human-robot interface and compliance