Fuzzy Relational Architecture in Robot Control based on Visual Feedback

M.Bonković*, D.Stipaničev* and M.Štula*
* Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture,
University of Split, Split, Croatia

Abstract— **Fuzzy relational model describes system's behavior by a nonlinear mapping between its variables and it could be applied for the prediction of system behavior. In this paper, we further develop the ideas of using fuzzy relations in construction of internal models for control purposes. The architecture based on the fuzzy relational model was developed. Fuzzy relations were used to describe the behavior of simple reactive agents. Their task was to predict the existing and desired system's states and to control the system in desired direction. The procedure was illustrated by example of visually controlled robot system, giving him the ability (property) to reach the desired target point. That was one of the basic building blocks in emergent behavior/ functionality of the system.**

I. INTRODUCTION

The emergence of complex behavior in a system consisting of interacting simple elements is among the most fascinating phenomena of our world. During the past 10-20 years a growing number of scientists have started to do research in non-traditional and multi/ interdisciplinary areas involving modeling and simulation of systems with many interacting components, aiming at an increased understanding both in what mechanisms are important for generating complex emergence behavior, and to search for general laws, patterns and characteristics of these multi-component systems.

The theory of complex systems [1] recognizes the complex system at the micro-level as a system with:

- large number of components or agents,
- agents are characterized by
  - limited capability (bounded rationality)
  - their own variables (status, movement, etc)
  - their own rules for interaction
  - may be adaptive
- interactions are usually local

From this point of view, systems are usually modeled according to the bottom-up methodologies in which we model the mechanisms at the microscopic level, and observe what happens at the macro-level of the system.

On the other side, complex systems macro-level characteristics may show:

- Difficult to predict dynamics in detail
- sensitivity to initial conditions
- Multiple equilibriums

On this level, top-down modeling is more appropriate, which attempts to find equations that sufficiently well describe how the macroscopic (aggregated) variables change in time.

Since a lot of uncertainty and fuzziness is employed in a complex system behavior it seems reasonable to use fuzzy set theory for modeling and control the agent's behavior [2], [3], [4]. One part of this theory is particularly suitable for this task. That is the theory of **fuzzy relations** [5], [6] and especially the theory of **fuzzy relational modeling** [7]. Fuzzy relational models are appropriate way to represent uncertainty of the external world. They can be used in cases when it is not possible to construct a precise functional mapping between the state-space of internal model and state-space of external world which assumes that it could be used for modeling macro and micro level characteristics of the complex-system.

In this paper we are exploring ideas about using **fuzzy relational model** as a tool for complex system modeling, prediction and control. In the next section, short recapitulation of fuzzy relational model theory is presented. Section three describes our case study – robot control using un-calibrated visual feedback and shows how the fuzzy relational model could be transformed into the control procedure which defines control agent's behavior architecture. Experimental results are described in the section four, while section five concludes the paper.

II. FUZZY RELATIONAL MODEL

Fuzzy modeling relation FMR* is a binary fuzzy relation between the world state space W and the model state space M [7]. For example in discrete case FMR* could be shown as a fuzzy matrix whose columns correspond to system's real world state-space (w_j), and rows to internal, model state-space (m_i). Table 1. shows the matrix FMR*.

The elements r_{ij} , i=1,…,I, j=1,…J express degrees to which elements of the world state-space W belong to the elements of the model state-space M and vice versa. Each row of table 1 defines a membership function of fuzzy set m_i* from the model state space whose support set is the real world state-space W. Situation is similar for each column of Table 1., which defines a membership function of a fuzzy set w_j* from the world state space whose support set is state-space of the model M.

W / M	w_1	...	w_j	...	w_J
m_1	r_{11}	...	...	...	r_{1J}
...	...	...	...	...	...
m_i	r_{i1}	...	r_{ij}	...	r_{iJ}
...	...	...	...	...	...
m_I	r_{I1}	...	...	...	r_{IJ}

TABLE 1.
FUZZY MODELLING RELATION FMR*

It is important to emphasis that using this approach it is possible to construct internal model of representation of the real world with various levels of abstraction. The level of abstraction is directly connected with cardinality of the model state-space M. At the lowest level of abstraction the state-space model is the same as the state-space of the world (M=W). If we introduce more elements in the model state-space M, the level of abstraction diminishes and contrary, reducing the cardinality of the set M, the level of abstraction increases [7].

The system's input-output relationship which could be described in terms of fuzzy relational matrix equation:

$$q_i^*=w_i^*\bullet R^* \qquad (1)$$

where, «•» is the symbol for max-min composition operator, w_i^* is the fuzzy input defined on the discrete support set created by aggregation of original input set w_i and q_i^* is a fuzzy output defined on the discrete support set created by aggregation of original output set q_i, and R* is a fuzzy relation between input and output sets:

$$q_i^*(q_i)=\sup_{w_k\in W}\left[\min(w_i^*(w_i),R_i^*(w_i,q_i))\right] \qquad (2)$$

For a single-input single-output system the fuzzy relation R* is similar to the fuzzy matrix shown in Table 1. Instead of discrete input and output values w_i and q_i, input and output fuzzy sets w_i* and q_i* have to be used and values

$$R^*(i,j)=p_{ij} \qquad (3)$$

are interpreted in terms of possibilities and expressed as a simple linguistic rule:

[IF w_i* THEN q_i*] with possibility p_{ij} (4)

So the same form of fuzzy relational model could be used for the mapping from real inputs to model inputs from model inputs to model outputs and from model outputs to real outputs. We have applied this idea in robot control based on visual feedback.

III. ROBOT CONTROL SYSTEM ARCHITECTURE

The robot control system is considered non-deterministic if the factor of uncertainty is connected, either with input and output data (x and y) or with input and output relationship (S). 3D robot control based on **un-calibrated visual feedback** is such a case and it could be treated as a complex system. It consists of a pair of CCD cameras and a robot arm. The task is to position the end-effector of the manipulator using information gained **only** from the pair of cameras arbitrary positioned around the robot. Their position is not known and the control signal, which guides the robot end-effector to the target point, is based on the visual feedback only. Fig.1. shows a schematic diagram of the system.

Input information were not precisely defined and control algorithm was described by linguistic rules. In such a case the fuzzy approach could be applied because both

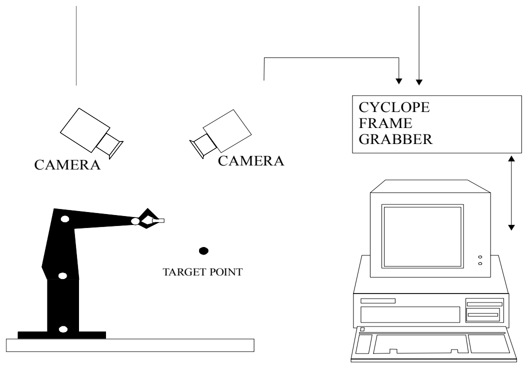

Figure 1. Robot control based on uncalibrated visual feedback

input and output data and input and output relations could be represent with fuzzy relations.

The control system can be treated generally as a mapping from the set of inputs X to the set of outputs: $S: X \rightarrow Y$. Inputs X is information extracted from sensors transformed into the form suitable for further processing. Outputs Y are appropriate control actions. In our case inputs were defined by feature vector $\underline{\mathbf{x}} = (x_1, x_2, x_3)^T$= =[SOD,VVM,ΔVVM]^T, where SOD=d_1+d_2 ,VVM is **Virtual Visual Measure** which represents errors between actual and final end effector positions, both calculated on

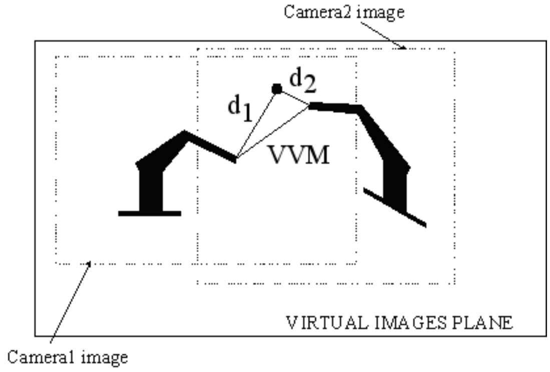

Figure 2. Construction of the virtual images plane and definition of feature vector elements

images captures by the cameras (Fig.2.) and ΔVVM is its increment [8].

The robot used in experiments was RRR type robot, so the outputs were defined by desired joint angle changes JAC = $(y_1, y_2, y_3)^T = (\Delta\theta, \Delta\varphi, \Delta\psi)^T$. The robot control system was based on three control agents:

a) **PlPA** (**Pl**ane **P**ositioning **A**gent) - responsible for joint angle θ, which rotates the robot around its body. It is activated first and its action is connected with VVM. If VVM decreases PlPA is active, if VVM start to increase again, PlPA stops and activates both PoPA agents.

b) **PoPA-φ** (**Po**int **P**ositioning **A**gent) is responsible for joint angle φ. His action is connected with SOD. If SOD decrease PoPA-φ is active, when SOD start to increase, PoPA-φ stops and activates PoPA-ψ.

c) **PoPA-ψ** is the same as PoPA-φ except he is responsible for angle ψ. If SOD decrease PoPA-ψ is active, when SOD start to increase, PoPA-ψ stops and activates PIPA agent.

The fuzzy control rules of all agents were the same [8]. The max-min inference was used, sum of distance (SOD) was expressed by fuzzy sets {centre, close, middle, far}, the new fuzzy variable - **VAS - V**isual **A**pproach **S**peed was introduced and used as new input and the output was calculated in terms of **JAC** - **J**oint **A**ngle **C**hanges .

In this paper we would like to describe this control architecture it in terms of fuzzy relational model architecture which give us additional features. Using fuzzy relational models for modelling inputs and outputs a less accurate data could be used.

Fig.3. shows the whole procedure schematically.

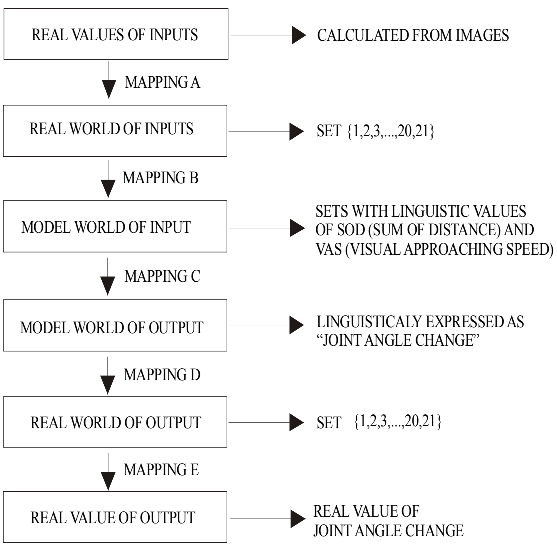

Figure 3. The control procedure expressed as relations between different worlds

In our case it was not possible to identify the elements of the fuzzy modeling relations for both inputs and outputs, so the idea of hierarchically organized fuzzy models whose degree of abstraction decreases [7] was applied. The same procedure was applied also in cases when it was not possible to obtain the consensus between control agents about appropriate control action. This means that in some cases it was not possible to relate the input feature vector with appropriate control action. In such cases the theory of hierarchically organized fuzzy models was used. The hierarchical model was used starting from mapping A with different degrees of precision. The mapping A was the procedure which transforms the real inputs calculated from images (SOD, VVM) and measured in pixels into the new inputs (SOD*, VVM*) defined on the discrete support set created by aggregation of original pixel set. The second step was mapping B - the fuzzy relation which maps the world state-space of inputs to model state-space of inputs. It defines the degrees to which each element from the real world (in our cases it was the integer from 0 to 21) belongs to each element of model world (linguistic variable). The third mapping C was the linguistic mapping from the model world of inputs to the model world of outputs. After that in mappings D and E the abstraction level was decreased until the real worlds of outputs were reached. Fig. 4

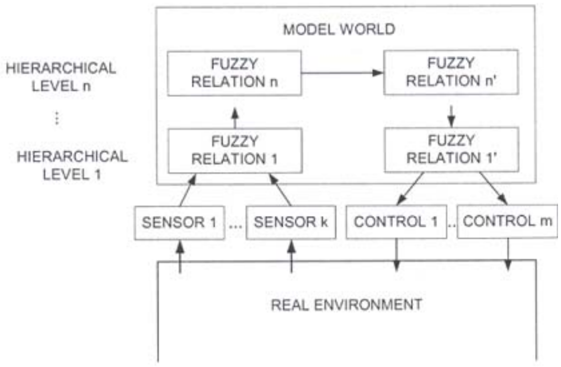

Figure 4. Fuzzy relational model arcitecture

shows the situation schematically.

The highest and the most abstract level was model world inputs – model world outputs, but it was the least precise. The real world – model world level was the most precise one and not so abstract. The most abstract level in our experiment was the part called **supervisor.** Its task was to coordinate the agent's activity. Without this level control agents run sequentially, and with its activity the result was co-operative action whose final task was to reach the target point and to bring the feature vector $\underline{\mathbf{x}}=(x_1,x_2,x_3)^T = [SOD, VVM, \Delta VVM]^T$ to zero.

IV. EXPERIMENTAL RESEARCH

A series of experiments were performed where the performance of the control algorithm has been measured. We have used robot MICROBOT TechMover [10], a three segment RRR robot structure with joint angles θ, φ and ψ.

The experiments were recorded using video - marker based tracking system described in [9]. Robot end-effector was marked with bright circle on the black background. Its initial position and the target location were labelled by the mouse click on the images of both cameras (Fig.5). For different initial position of robot end-effector, and for the arbitrary cameras position, we have recorded the appropriate measure distance from robot end-effector to the target position on both images (SOD) and virtual visual measure (VVM). The goal of the control algorithm was rough target approach, so the robot stops when the distance of the end-effector and target point becomes less than 20 pixels. The whole procedure usually has finish in approximately 20 iterations.

Figure 5. First picture - Starting scene taken by the first camera,
Second picture - Starting scene taken by the second camera
Third picture - Final scene taken by the second camera

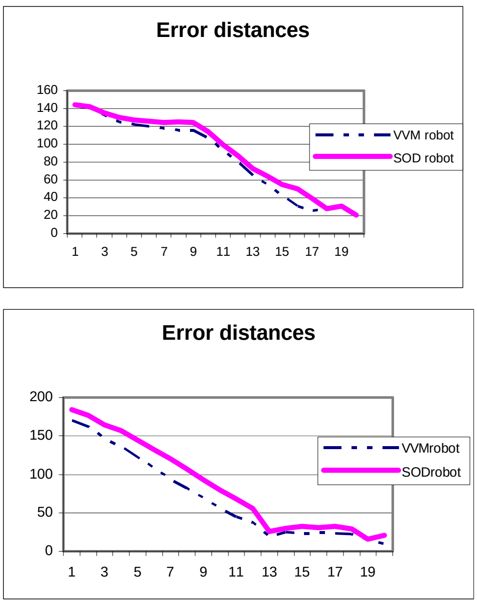

Figure 6. Error distances for different starting positions

The image frequency was 10 Hz. It is also worth to notice that the whole procedure could be characterized as the look – then - move procedure, which deteriorated the approaching speed. Fig. 6. shown the error distances for the different robot end-effector start position. The results were quite satisfactory and the introduction of supervisor has resolved few situations in which the control agents running separately could not found appropriate control actions, so the improvements in comparison with non fuzzy [9] and standard fuzzy agent [8] were recorded.

V. CONCLUSION

This paper presented the relational model system constructed by the composition of different level of fuzzy modelling relations. The procedure was illustrated by robot control based on un-calibrated visual feedback. The control algorithm was based on fuzzy agents actions (micro level activity), which run in cooperation (macro level activity) to perform the given task – reaching the point by the end effector. The paper shows how relational model can be effectively used for modelling complex system characteristic at micro and macro level.

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