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Nagib Callaos  
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# Multi-Robot Cooperation by Fuzzy Signature Sets

László T. KÓCZY

Department of Telecommunications and Media Informatics,  
Budapest University of Technology and Economics,  
H-1117, Budapest, Magyar tudósok krt. 2., Hungary  
Email: koczy@tmit.bme.hu

Inst. of Mechanical, Electrical Engineering and Information Technology,  
Széchenyi István University,  
H-9026, Győr, Egyetem tér 1., Hungary

and

Áron BALLAGI

Department of Automation,  
Széchenyi István University,  
H-9026, Győr, Egyetem tér 1., Hungary  
Email: ballagi@sze.hu

## ABSTRACT

This paper presents a novel method for control cooperating robots without any explicit communication line. Fuzzy signatures are used as complex state description method for intention guessing and action selection. Finally a possible cooperative robot application on a realistic example with missing data components will be shown.

**Keywords:** robot cooperation, fuzzy signatures, intention guessing

## 1. INTRODUCTION

Fuzzy signatures structure data into vectors of fuzzy values, each of which can be a further vector, are introduced to handle complex structured data [1, 2, 3, 4]. This will widen the application of fuzzy theory to many areas where objects are complex and sometimes interdependent features are to be classified and similarities / dissimilarities evaluated. Often, human experts can and must make decisions based on comparisons of cases with different numbers of data components, with even some components missing. Fuzzy signatures were created with this objective in mind. This tree structure is a generalization of fuzzy sets and vector valued fuzzy sets in a way modeling the human approach to complex problems. However, when dealing with a very large data set, it is possible that they hide hierarchical structure that appears in the sub-variable structures.

This paper deals with fuzzy signatures as complex state description method in field of control of mobile robots and robot cooperation.

Intelligent cooperation is a new research field in autonomous robotics. If one would plan or build a cooperating robot system which has intelligent behaviors, one could not program the all scenarios which may appear in the life of the robots, and would realizes that effective, fast and compact communication is one of the most important cornerstones of a high-end cooperating system. We assume settings where communication itself is very expensive, so generally speaking it is advisable to build up as large as possible contextual knowledge bases and codebooks in the distant on-board robot controller computers [5, 6]. Clearly, this is in order to shorten their communication process. This is appropriate if it significantly reduces the amount of information that must be transmitted from one to another, rather than to concentrate all contextual knowledge in one of them, and then to export its respective parts whenever they are needed in the other(s). It appears to be very important in the cooperation and communication of intelligent robots or physical agents that the information exchange among them is as effective and compressed as possible [7].

In this paper we propose a fuzzy communication system where the codebooks are built up by fuzzy signatures. After an overview of this type of fuzzy communication we will deal with some real scenarios of autonomous mobile robot cooperation. The base idea of this example has come from the partly unpublished research projects at LIFE [8]. The paper presents a cooperation system where a group of autonomous intelligent mobile robots is supposed to solve transportation problems according to the exact instruction given to the Robot Foreman ( $R_0$ ). The other robots have no direct communication links with  $R_0$  and all others, but can solve the task by intention guessing from the actual movements and positions of other robots, even though they might not be unambiguous.

## 2. FUZZY SIGNATURES

The original definition of fuzzy sets was  $A: X \rightarrow [0,1]$ , and was soon extended to *L-fuzzy sets* by Goguen [9].

$$A_s : X \rightarrow [a_i]_{i=1}^k, a_i = \left\{ \begin{matrix} [0,1] \\ [a_{ij}]_{j=1}^{k_i} \end{matrix} \right., a_{ij} = \left\{ \begin{matrix} [0,1] \\ [a_{ij}]_{j=1}^{k_{ij}} \end{matrix} \right. \quad (1)$$

$A_s : X \rightarrow L$ ,  $L$  being an arbitrary algebraic lattice. A practical special case, *Vector Valued Fuzzy Sets* was introduced by Kóczy [1], where  $A_{v,k} : X \rightarrow [0,1]^k$ , and the range of membership values was the lattice of  $k$ -dimensional vectors with components in the unit interval. A further generalization of this concept is the introduction of fuzzy signature and signature sets, where each vector component is possibly another nested vector as Eq. (1) shows it.

Fuzzy signature can be considered as special multidimensional fuzzy data. Some of the dimensions are interrelated in the sense that they form sub-group of variables, which jointly determine some feature on higher level. Let us consider an example. Fig. 1 shows a fuzzy signature structure.

The fuzzy signature structure shown in Fig. 1 can be represented in vector form as follow:

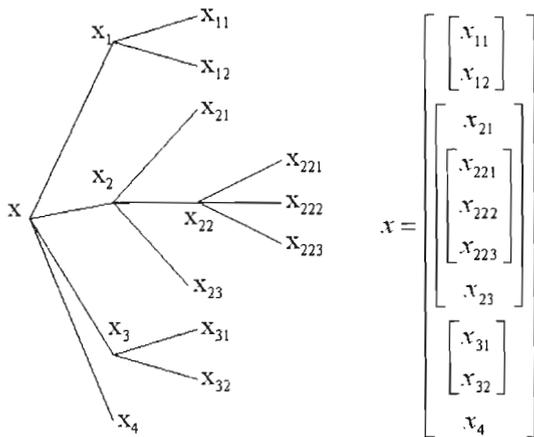


Figure 1. A Fuzzy Signature Structure

Here  $[x_{11} \ x_{12}]$  form a sub-group that corresponds to a higher level compound variable of  $x_1$ .  $[x_{221} \ x_{222} \ x_{223}]$  will then combine together to form  $x_{22}$  and  $[x_{21} \ [x_{221} \ x_{222} \ x_{223}] \ x_{23}]$  is equivalent on higher level with  $[x_{21} \ x_{22} \ x_{23}] = x_2$  and  $[x_{31} \ x_{32}] = x_3$ . Finally, the fuzzy signature structure will become  $x = [x_1 \ x_2 \ x_3 \ x_4]$  in the example.

The relationship between higher and lower level is governed by the set of fuzzy aggregations. The results of the parent signature at each level are computed from their branches with appropriate aggregation of their child signature.

Each of these signatures contains information relevant to the particular data point  $x_0$ ; by going higher in the signature structure, less information will be kept. In some operations it is necessary to reduce and aggregate information obtained from another source (some detail variables missing or simply being locally omitted). Such a case occurs when interpolation within a fuzzy signature rule base is done, where the fuzzy signatures flanking an observation are not exactly of the same structure. In this case the maximal common sub-tree must be determined and all signatures must be reduced to that level in order to be able to interpolate between the corresponding branches or roots in some cases [4].

## 3. FUZZY SIGNATURE SETS

The basic structure of fuzzy signature sets is similar to that of fuzzy signatures, the only difference being that instead of having fuzzy variables on the leaves of the structure, membership functions are present (see Fig. 2). The only constraint for the membership functions is that their domain must be the  $[0,1]$  interval [10].

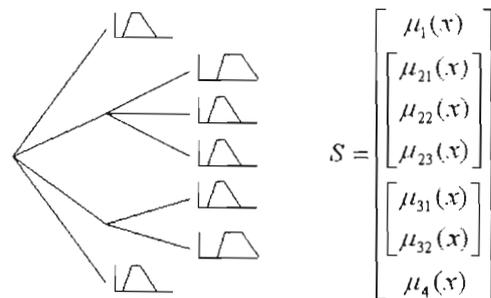


Figure 2. The tree structure and the vector form of an example fuzzy signature set

## 4. SIGNATURE STRUCTURE MODIFICATION: THE AGGREGATION OPERATORS

The advantages of fuzzy signatures lie in organizing the available data components into a hierarchy. This hierarchy determines the arbitrary structure of our fuzzy signature observations. As some of the components of this arbitrary structure might be missing from the specific observations, some kind of structure modifying operation is essential when comparing these differently structured signatures.

Aggregation operations result in a single fuzzy value calculated from a set of other fuzzy values, while satisfying a set of axioms. The most common operators are the maximum, minimum and arithmetic mean operator [11, 12].

Aggregation operators can be used to transform fuzzy signature structures by reducing a sub-tree of variables to their parent node. It is necessary to mention that only whole sub-trees of the structure can be reduced. The fuzzy value (or fuzzy set) assigned to the parent node is calculated by aggregating the fuzzy values (or fuzzy sets)

of its children using the aggregation operator of the parent node. This way, the depth of this branch of the structure is reduced by one.

This procedure can only be performed when all elements of the aggregated sub-tree are leaves of the structure and have an assigned value. If one of the elements of the sub-tree branches out into a sub-tree of its own, in order to reduce the whole sub-tree to the original parent node, first the sub-sub-tree has to be reduced to its parent node (which is the child node of the original sub-tree's parent node) by aggregation. After performing the aggregation, the original sub-tree can also be reduced.

For example, to reduce the sub-tree of node  $x_i$ , first the sub-tree of node  $x_{i2}$  has to be aggregated. The value obtained can then be used when calculating the aggregate value from the sub-tree of  $x_i$ . This recursive procedure is shown in Fig. 3, where  $@_i$  denotes the aggregation operator of node  $x_i$ .

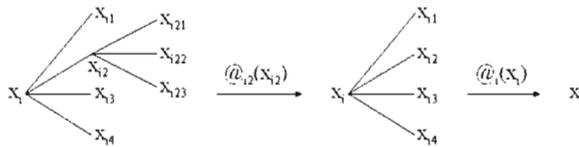


Figure 3. Recursion used to reduce a sub-tree with several layers

Because of these terms, when reducing a signature to a predefined structure it is wise to use a bottom-up method. This means to start the reduction from the leaves of the structure and work your way up one sub-tree at a time towards the intended structure.

According to the definition of fuzzy signatures, aggregation operators define the connection between a component, and its sub-components, therefore the aggregation operators are not necessarily identical for all the nodes of the structure. Finding the relevant aggregation operator for each node is a very important problem of fuzzy signatures, because when comparing two signatures, the obtained results may greatly depend on the aggregation operators used to reduce the signatures to a common structure.

It is also important to mention that when reducing a signature's sub-tree, some information is lost in all cases, because the calculated aggregated value can be the same for many different values and differently structured sub-trees.

In order to reduce fuzzy signature sets to a different structure aggregation has to be generalized to work not only on fuzzy values but on fuzzy sets as well.

When aggregating fuzzy sets, the membership values for each element  $x$  of  $[0,1]$  (the domain of the fuzzy sets on the leaves of the structure) are calculated for all the fuzzy sets which are subject to the aggregation. The original aggregation operator is then used on these membership values to obtain the aggregated membership value belonging to  $x$ . Let the fuzzy sets in the sub-tree be  $A_i$ . The membership function of the aggregated fuzzy set  $G$  is given in Eq. (2), where  $h$  denotes the aggregation operator.

$$G = h(A_1, A_2, \dots, A_k)$$

$$\forall x \in [0,1] \quad \mu_G(x) = h\{\mu_{A_1}(x), \mu_{A_2}(x), \dots, \mu_{A_k}(x)\} \quad (2)$$

The aggregation of two fuzzy sets ( $A_1$  and  $A_2$ ) is shown in Fig. 4. In the example, the aggregation operator is the arithmetic mean operator. The resulting fuzzy set (denoted by  $G$ ) is marked with a broken line.

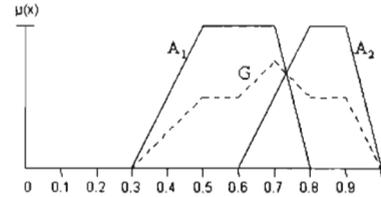


Figure 4. Aggregation of two fuzzy sets with the arithmetic mean operator

### Weighted Relevance Aggregation Operator

With the introduction of weights [13] for each node of the fuzzy signature structure additional expert knowledge about the field can be contained within the model. The relevance weight depicts how relevant a node is in its parent's sub-tree. The weights of the nodes are taken from the  $[0;1]$  interval, and it is not necessary for the weights of the leaves in a sub-tree to add up to 1. A method for learning weights was shown in [14].

The most general form of aggregation operators is the Weighted Relevance Aggregation Operator (WRAO) introduced by Mendis *et al.* in [15]. The values and weights belonging to each child  $l$  in the sub-tree are denoted by  $x_l$  and  $w_l$  respectively. The definition of the WRAO is as follows:

$$@_i(x_1, x_2, \dots, x_n; w_1, w_2, \dots, w_n) = \left\{ \frac{1}{n} \sum_{i=1}^n (w_i \cdot x_i)^p \right\}^{\frac{1}{p}} \quad (3)$$

where  $p$  is the aggregation factor of the above function. The well-known aggregation operators are all special cases of WRAO depending on the value of  $p$  in (3).

- $p \rightarrow -\infty$ , WRAO  $\rightarrow$  minimum
- $p = -1$ , WRAO = harmonic mean
- $p \rightarrow 0$ , WRAO  $\rightarrow$  geometric mean
- $p = 1$ , WRAO = arithmetic mean
- $p \rightarrow \infty$ , WRAO  $\rightarrow$  maximum

## 5. FUZZY COMMUNICATION OF COOPERATING ROBOTS

One of the most important parameters of effective cooperation is efficient communication. Because communication itself very expensive, it is much more advisable to build up as large as possible contextual knowledge bases and codebooks in robot controllers in order to shorten their communication process. That is, if it essentially reduces the amount of information that must be transmitted from one to another, than to concentrate all contextual knowledge in one of them and then to export

its respective parts whenever they are needed in other robot(s). It appears to be very important in the cooperation and communication of intelligent robots or physical agents that the information exchange among them is as effective and compressed as possible [7].

**The system in hand**

Let us examine a subset of our overall robot cooperation problem work in practice. There is a warehouse where some square boxes wait for ordering. Various configurations can be made from them, based on their color and tags. We have a group of autonomous intelligent robots which try to build the actual order of boxes according to the exact instructions given to the  $R_0$  (foreman) robot. The other robots have no direct communication links with  $R_0$ , but they are able to observe the behavior of  $R_0$  and all others, and they all possess the same codebook containing the base rules of storage box ordering. Every box has an identity color and tag on one side of it. The individual boxes can be shifted or rotated, but always two robots are needed for actually moving a box, as they are heavy. If two robots are pushing the box in parallel the box will be shifted according the joint forces of the robots. If the two robots are pushing in opposite directions positioned at the diagonally opposite ends, the box will turn around the center of gravity. If two robots are pushing in parallel, and one is pushing in the opposite direction, the box will not move or rotate, just like when only a single robot pushes. Under these conditions the task can be solved, if all robots are provided with suitable algorithms that enable intention guessing from the actual movements and positions, even though they might be unambiguous.

Fig. 5. presents some example of how eleven boxes can be arranged. The robots would move or push the boxes, so one box has max two neighbors on their opposite sides. The tag of the box, which is always on the Relative-North side of the box (as we will see below), must be visible (so do not adjoin any other object), so the box can touch others only the East or/and West sides.



Figure 5. Examples for box arrangement

In the description two direction sign systems are used, the absolute direction with letters N, E, S, W as in the usual sense for North, East, South and West. The second direction sign system is a box relative system where the sides of a box are  $N_B$ ,  $E_B$ ,  $S_B$  and  $W_B$  respectively (Fig. 6). The position of the objects (boxes and robots in this case) always can be described by the absolute course, latitude and longitude of the object. One object relative

position to a box is described by the box relative system, i.e. which side of the box is touched by that object.

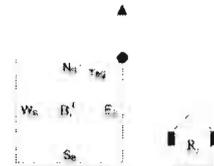


Figure 6. Symbols of boxes and robots

The box has a  $B_i^c$  sign which means that is the  $i$ -th Box with  $C$  color (e.g.: R for red). The  $R_j$  is the sign of the  $j$ -th robot. The  $R_0$  is a distinct one, namely it is the robot foreman, the only robot that exactly knows the task on hand.

The cooperating combination of robots is denoted by  $C_{i,j,(k)}^b$  where  $i,j$  and  $k$  is the number of the robots ( $k$  appears only in stopping combinations), and  $b$  is the number of the box. There are three essentially different combinations (Fig. 7.),  $C_{1,2}^i = P$  is the “pushing or shifting combination”, when two robots ( $R_1$  and  $R_2$ ) are side by side at the same side of the table;  $C_{1,2}^i = RC$  stands for “counterclockwise rotation combination”; and  $C_{1,2}^i = RW$  denotes “clockwise rotation combination”.

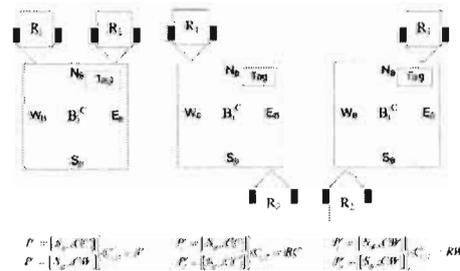


Figure 7. Allowed combinations of two robots for moving the table

**Fuzzy signature classes**

On basis of the features of the boxes the robot can build a fuzzy signature for each box. This signature built up on a template or class, and every box has its own instance of the Box fuzzy Signature Class (BSC). This signature records the position, the arrangement, the dynamic and the robots working on the actually box. Let us see the construction of this fuzzy signature class. As can be seen in Eq. (4), the main signature has three sub-signatures.

$$B_i^c = \begin{bmatrix} P \\ AR \\ DY \end{bmatrix} \quad (4)$$

The first is the position ( $P$ ) sub-signature which describes the actual fuzzy position of the box (e.g.: Nearly North). It has four leaves namely the points of the compass, North, East, South and West (Fig. 8).

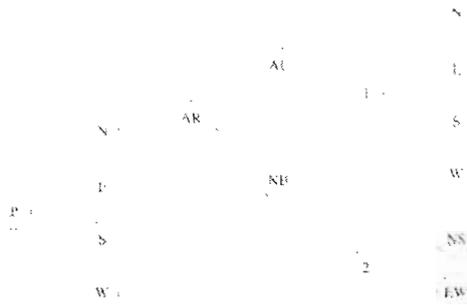


Figure 8. Box position and arrangement fuzzy signatures

The second branch of box fuzzy signature is the arrangement that describes the box's connections to other boxes. As it was described above, a box can connect to none, one or two other boxes. Therefore the signature has two main branches for the no connection case, and for the connected case, which has two other branches for connect to one, connect to two boxes. The leaves describe the side of connection. As we see this signature we can observe that there are some surprising permitted connect positions in it (e.g.: North or tag side). These are very useful for decision making about wrong positions and wrong dynamic of the box. The Fig. 8 presents the arrangement signature (*AR*) where *AL* is the "alone" (no connection) branch, *NB* are the neighbor boxes: one or two and the direction of the join.

The next branch is the dynamic feature (*DY*) of the box, which is valid if robots work on the box and records what the robots are doing: push or rotate, and in which direction. This signature includes all the valid combinations of robots, and all valid movements of boxes. This is shown in Fig. 9, with the number of robots at a box (*1R*, *2R*, *3R* respectively), the effect of this combination of robots (*SH* as shift and *R* as rotate) and the direction.

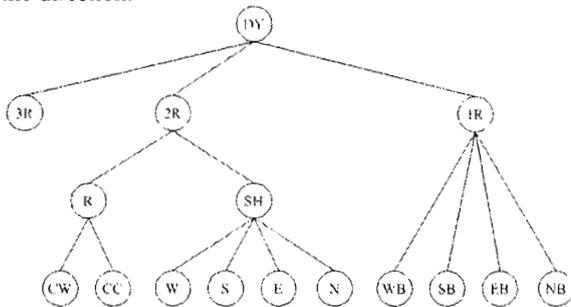


Figure 9. Dynamic fuzzy signature

These three output fuzzy signatures are able to describe the actual states of the box and give a basis for the fuzzy decision process in the robot control. Every robot builds its actual knowledge-base from the fuzzy signature classes and then boxes are assigned individual signatures in each individual robot controller.

The second necessary fuzzy signature class is the Robot state fuzzy Signature Class (RSC), which describes the state of each robot. This represents the dynamic and working behavior of the robot.

The leaves of the actual structures are fuzzy sets or membership functions therefore fuzzy signature sets are used in decision making and action selection mechanism. The detailed steps of inference on fuzzy signature sets are beyond the extent of this paper.

## 6. RESULTS

There is built up a simulated arena, where three robots cooperate to arrange some boxes. Every robot has the above described algorithms for intention guessing and action selection.

The Fig. 10 presents some steps of arranging process. Firstly the robots search the nearest disordered box and take a combination for pushing or rotating it. If they reach a pivot point then take a new combination and do it cyclic till order the actual box. This task recurs until all box get to the good place.

Numerous scenarios are simulated and result a good collaboration with 90 % of acceptability. The videos of the simulations will be downloadable from our website in the near future.

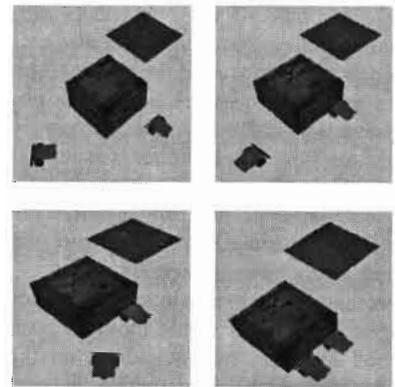


Figure 10. The robots take the starting combination

## 7. CONCLUSIONS

In this paper the notion of fuzzy signatures was introduced and their main advantages were stated. The most important operator, the aggregation operator used for structure modification was presented.

Our results show that the method gives acceptable results on the test cases, although these could be further improved by modifying certain parameters of the model (the relevance weights and the aggregation operators in the arbitrary fuzzy signature structure). In the future a method for learning these key parameters from the input-output pairs used for modelling could be developed and later implemented.

In this paper we presented the usage of fuzzy signature based algorithms on field of mobile robotics. These methods were used in totally other level of robot control. Fuzzy communication contains vague or imprecise components and it might lack abundant information. If two robots are communicating by a fuzzy channel, it is necessary that both ends possess an identical part within the codebook. The codebook might partly consist of

common knowledge but it usually requires a context dependent part that is learned by communicating. Possibly it is continuously adapting to the input information. If such a codebook is not available or it contains too imprecise information, the information to be transmitted might be too much distorted and might lead to misunderstanding, misinterpretation and serious damage. If however the quality of the available codebook is satisfactory, the communication will be efficient i.e. the original contents of the message can be reconstructed. At the same time it is cost effective, as fuzzy communication is compressed as compared to traditional communication. This advantage can be deployed in many areas of engineering, especially where the use of the communication channels is expensive in some sense, or where there is no proper communication channel available at all.

Here we illustrate clearly that the communication among intelligent robots by intention guessing and fuzzy evaluation of the situation might lead to effective cooperation and the achievement of tasks that cannot be done without collaboration and communication.

## 8. ACKNOWLEDGEMENT

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