Fuzzy Logic for Cooperative Robot Communication

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Abstract. This paper proposes a new approach which applies a recently developed fuzzy technique: Fuzzy Signature to model the communication between cooperative intelligent robots. Fuzzy signature is not only regarded as one of the key solutions to solve the rule explosion in traditional fuzzy inference systems, but also an effective approach for modeling complex problems or systems with a hierarchical structure. Apart from the application of fuzzy signatures, another modeling structure of pattern-matching with possibility calculation is designed for the further intentional inference of cooperative robot communication. By the combination of these two theoretical issues, a codebook for intelligent robot decision making has been developed, as well as its implementation - a Cooperative Robot Communication Simulator.

Keywords: Fuzzy Logic; Cooperative Robots; Codebook; Fuzzy Signature; Possibility Calculation.

1 Introduction

Scenario of Co-operating Intelligent Robots [8]: There is a set of identical oblong shaped tables in a room. Various configurations can be built from them, such as a large U shape, a large T shape, a very large oblong, rows of tables, etc. A group of autonomous intelligent robots is supposed to build the actual configuration according to the exact instructions given to the "Robot Foreman" (R_0). 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 posses the same codebook containing all possible table configurations. The individual tables can be shifted or rotated, but two robots are always needed to actually move a table, as they are heavy. If two robots are pushing the table in parallel, the table will be shifted according to the joint forces of the robots. If the two robots are pushing in the opposite directions positioned at the diagonally opposite ends, the table will turn around the center of gravity. If two robots are pushing in parallel, and one is pushing in the opposite direction, the table will not move. Under these conditions the task can be solved, if all robots are provided by suitable algorithms that enable "intention guessing" from the actual movements and positions, even though they might not be unambiguous.

N.T. Nguyen et al. (Eds.): KES-AMSTA 2008, LNAI 4953, pp. 401–410, 2008.

2 Fuzzy Signature

Fuzzy signature has been regarded as an effective approach to solve problem of rule explosion in traditional fuzzy inference systems: constructing characteristic fuzzy structures, modeling the complex structure of the data points (bottom up) in a hierarchical manner [6], [2], [9]. Fuzzy signatures result in a much reduced order of complexity, at the cost of slightly more complex aggregation techniques.

The original definition of fuzzy sets was $A : X \to [0, 1]$, and was soon extended to *L-fuzzy sets* [3]:

$$A_S :\to [a_i]_{i=1}^{k}, a_i = \begin{cases} [0,1] \\ [a_{ij}]_{j=1}^{k_i} \end{cases}, a_{ij} = \begin{cases} [0,1] \\ [a_{ijl}]_{l=1}^{k_{ij}} \end{cases} \tag{1}$$

$A_L : X \to L, L$ being an arbitrary algebraic lattice. A practical special case, *Vector Valued Fuzzy Sets* was introduced by [5], where $A_{V,K} : X \to [0, 1]^k$, and the range of membership values was the lattice of k-dimensional vectors with components in the unit interval. The general concept of fuzzy signature is a nested vector, where each vector component can be another nested vector structure. So it can be described as a generalized vectorial fuzzy set with possible recursive vectorial components, consequently, it is a generalization of valued fuzzy sets and denoted by [6]:

$$A : \ X \to S^{(n)}, \tag{2}$$

where $n \geq 1$ and

$$S^{(n)} = \prod_{i=1}^{n} S_i, \tag{3}$$

$$S = \begin{cases} [0,1] \\ S^{(m)} \end{cases} \tag{4}$$

and $\prod$ describes Cartesian product.

In fact, we can consider fuzzy signature as a special kind of multi-dimensional fuzzy data. Some of the dimensions are formed as a sub-group of variables, which jointly determine some feature on a higher level. Figure 1 illustrates an example of fuzzy signature structure.

3 Fuzzy Signatures Construction for Cooperative Robot Action Inference

The process of constructing fuzzy signature has also been discussed in [11]:

Let S_{S_0} denote the set of all fuzzy signatures whose structure graphs are sub-trees of the structural ("stretching") tree of a given signature S_0. Then the signature sets introduced on S_{S_0} are defined by:

$$A_{S_0} : X \to S_{S_0} \tag{5}$$

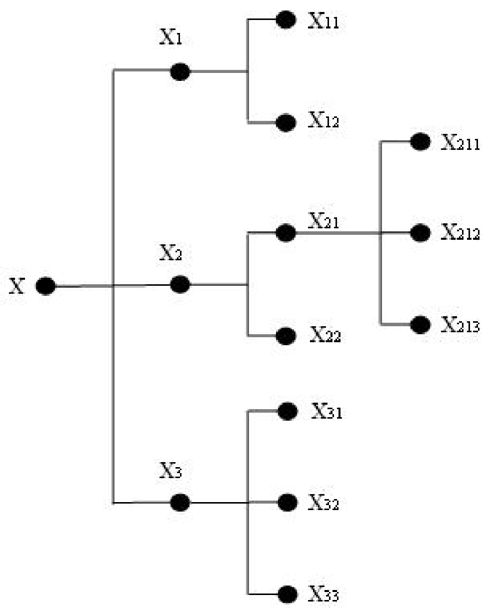


Fig. 1. Fuzzy Signature Structure

In this case, the prototype structure S_0 describes the "maximal" signature type that can be assumed by any element of X in the sense that any structural graph obtained by a set of repeated omissions of leaves from the original tree of S_0 might be the tree stretching the signature of some A_{S_0}.

In fact, there are two approaches to construct the sub-structures of the fuzzy signature, S_0 [1], [10], [11]:

1. Predetermined by a human expert in the field.
2. Determined by finding the separability from the data.

In our cooperative robots case, as we are handling complex circumstances and we actually do not have enough data, so we will only use the first approach to construct the fuzzy signatures. Based on the context of the robots scenario, we propose the use of an alternative form of fuzzy signature, which uses a better hierarchical structure where the internal nodes are simple, while the leaves are populated with small rule bases, generally of 1 variable. The effect is to retain the much reduced order of complexity, and to also substantially reduce the complexity of aggregations to simple combinations of basic fuzzy functions [7].

Before we start constructing the fuzzy signatures, we need to clarify some instructions and assumptions about the CRC framework:

1. *Instructions:*
   (a) A group of intelligent robots of size 1×1: $R_i : R_0, R_1, ..., R_n$, R_0 is the "foreman";

   (b) A set of random shape tables of size 1×2: $T_1, T_2, ..., T_n$;
   (c) A set of possible configurations made up of tables: $S_1, S_2, ..., S_n$, one of them is the final task.
2. *Assumptions:*
   (a) "Foreman" (R_0) represents a human-being (controlled by a human);
   (b) Only the "Foreman" (R_0) knows the final task;
   (c) Other robots (R_i) do not know the final task, but they know all the possible table shapes ($S_1, S_2, ..., S_n$);
   (d) Other robots (R_i) know who the foreman (R_0) is.

In order to construct the fuzzy signatures for inferring the foreman's following action, we need to figure out which "attributes" will be essentially related to foreman's intentional action based on the current situation. Since the current situation is that there are a set of tables, if the foreman is intended to do something, he should go and touch a particular table first or get closer at least. So the first "essential attribute" is the "Distance" between the foreman and each table in the environment. Figure 2 illustrates the membership function of "Distance". Actually, there exists a possible situation that can not be handled by "Distance"

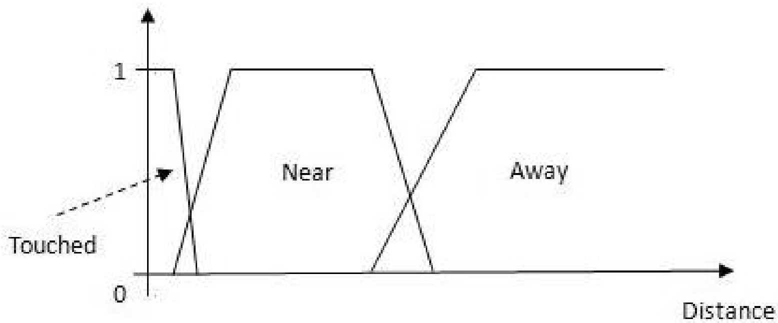
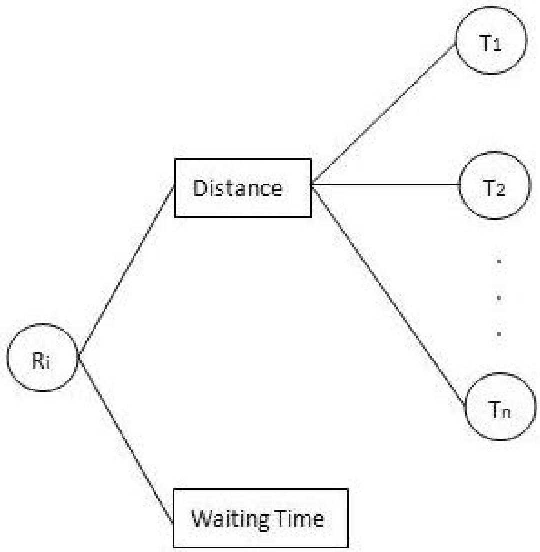


Fig. 2. Membership Function of Distance

only: if the foreman moves towards to a table then touches it, but after that he moves away or switches to another table immediately, the other robots still can not infer what the foreman is going to do. In order to solve this problem, we need to add another "essential attribute" called "Waiting Time" (the membership is similar in shape to Figure 2 and is not shown) which is used to measure how long a robot (R_i) stops at a particular spot. The reason why we need to measure the stopping time is that it is too difficult for a robot to perceive the meaning of the scene using instantaneous information (a snapshot) only [4].

By combining the "Waiting Time" with the previous item "Distance", the final fuzzy signatures for intention inference will be formed to the structure in Figure 3.

Under this circumstance, other robots will be able to infer the foreman's next action according to his current behavior. For instance, if the "Distance" between



$$R_i = \begin{bmatrix} Distance \begin{bmatrix} T_1 \\ T_2 \\ . \\ . \\ . \\ T_n \end{bmatrix} \\ WaitingTime \end{bmatrix}$$

Fig. 3. Fuzzy Signatures for CRC

the foreman (R_0) and a table (T_i) is *Touched*, meanwhile foreman's "Waiting Time" at that spot is *Long*, then it implies the foreman is "Waiting for Help" which means another robot (R_i) should go to T_i and help the foreman. Otherwise if neither of the condition is satisfied, which means other robots will not think the foreman is going to carry out any intentional action because they can not figure it out by observation of the foreman's current behavior.

4 Pattern Matching with Possibility Calculation

So far we have discussed the problem of inferring the foreman's intentional action by constructing the fuzzy signatures based on the foreman's current behavior. In some sense, it means other robots still have to count on the foreman completely and it actually does not show that these robots are intelligent enough that can help the foreman to finish the final task effectively and efficiently as well as truly reduce the cost of the communication between them.

In order to improve the modeling technique, it is important for us to consider the current situation after each movement of a table, which means other robots should be able to guess which table shape is supposed to be the most possible one according to foreman's previous actions and the current configuration of tables. The solution here is to measure how close the current table shape matches each of the possible shapes after the foreman's intentional actions. Therefore, apart from the previous fuzzy signatures, another modeling structure has been constructed for robot's further decision making (see Figure 4). The following figure shows another tree structure with all the leaves representing each possible table shape

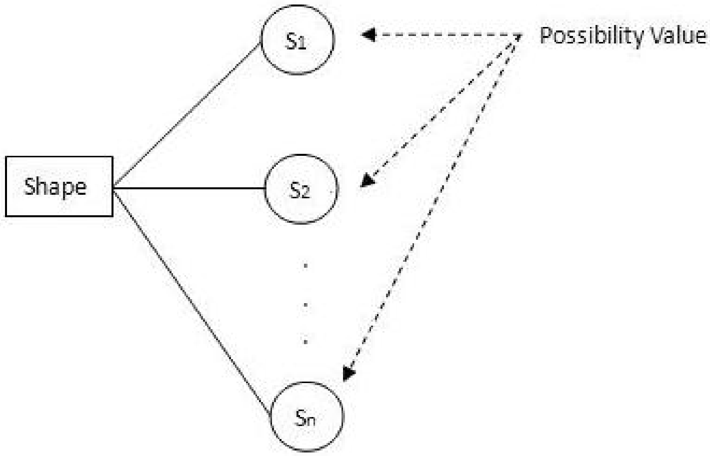


Fig. 4. Structure of Pattern Matching with Possibility Calculation

as well as its possibility value respectively. The following strategies show how this structure works:

We have a set of tables: $T_1, T_2, ..., T_n$; the total number of tables is n:

1. IF foreman and a robot push a table to a place which matches one of the possible table shapes: S_i;
   THEN increase the Possibility value of S_i: $PV_{S_i} + 1/n$;
2. IF foreman and a robot push a table to a place which does not match any of the possible table shapes;
   THEN none of the Possibility values will change;
3. IF foreman and a robot push a table which matched S_i to a place where does not match any of the possible shapes;
   THEN decrease the Possibility value of S_i: $PV_{S_i} - 1/n$;
4. IF foreman and a robot push a table which matched S_i to a place where matches another possible shape: S_j;
   THEN decrease the Possibility value of S_i: $PV_{S_i} - 1/n$;
   AND increase the Possibility value of S_j: $PV_{S_j} + 1/n$;
5. IF two robots (neither is foreman) push a table to a place where matches one of the possible table shapes: S_i;
   THEN the Possibility value of S_i, ie, PV_{S_i} will not change;

From the above strategies we can find that the possibility value of a possible shape S_i will only change when the foreman is one of the working robots who carry out the action, otherwise the possibility value will not change. The reason why we model the situation like this is due to the initial assumption mentioned that the foreman is the only robot who knows the final task so that we assume all the actions carried out by the foreman are directly related to the final task. Since other robots do not know the final task, their actions are not considered to be definitely correct and directly related to the final task so none of the possibility values will change according to these actions.

4.1 Codebook for Cooperative Robot Communication

1: IF Foreman (R_0)'s *Distance* to T_i is **NOT Touched** OR *Waiting Time* is **NOT Long** THEN Foreman (R_0) is **moving around or no action**:
- IF *Possibility Value* of S_i (PV_{S_i}) is the **highest** one THEN take S_i as the **final task**; AND calculate the distances between each table and S_i;
  - IF T_i's *Distance* to S_i is the **Shortest** THEN *Move* T_i *to* S_i;
    - IF Foreman (R_0) *Moves to* C_{ST} *(Stop)* THEN *Move back and Go to* ***2***;

2: IF Foreman (R_0)'s *Distance* to T_i is **Touched** AND *Waiting Time* is **Long** THEN Foreman (R_0) is **waiting for help**:
- IF R_i's *Distance* to Foreman (R_0) is the **Shortest** THEN the following action of R_i: *Move to* T_i *and Go to* ***3***;
  - ***3:*** Choose to *Shift* T_i (C_{SH})
    - IF R_0 *Moves away* THEN **Go back to *1***;
    - IF R_0 dose NOT carry out the action combination (*Waiting Time is Long*) THEN Choose to *Rotate* T_i (Go to ***4***);
    - IF R_0 carries out the action combination THEN **Keep Pushing**;
      - IF T_i's *stopping position* matches part of S_i THEN $PV_{S_i} + 1/n$;
      - IF T_i's *stopping position* does NOT match part of S_i THEN **Go back to *1***;
      - IF T_i's *initial position* matched part of another possible shape: S_j THEN $PV_{S_j} - 1/n$;
  - ***4:*** Choose to *Rotate* T_i (C_{CC} or C_{CW})
    - IF R_0 *Moves away* THEN **Go back to *1***;
    - IF R_0 does NOT carry out the action combination (*Waiting Time is Long*) THEN Choose to *Shift* T_i (Go to ***3***);
    - IF R_0 carries out the action combination THEN **Keep Rotating**;
      - IF T_i's *stopping position* matches part of S_i THEN $PV_{S_i} + 1/n$;
      - IF T_i's *stopping position* does NOT match part of S_i THEN **Go back to *1***;
      - IF T_i's *initial position* matched part of another possible shape: S_j THEN $PV_{S_j} - 1/n$;

5 Evaluation

The experiments we designed mainly focus on the difference between robots completely controlled by human-beings and robots working with the codebook, as well as how well these robots are able to cooperate with the foreman to finish a task in our CRC simulator. The following table is the basic setup for all the experiments.

Table 1. Basic Instructions for Experiments

Item	Description
Number of Tables	4
Test Cases ("Table Shapes")	1. Horizontal Rows (HR) 2. Vertical Rows (VR) 3. T Shape (T) 4. U Shape (U)
Test Times (Repetitions)	5
Robot's Speed	About 3 movements per second
Measurements	1. Number of robot steps 2. Number of table movements (Shifting or Rotating) 3. Time to finish a task

5.1 Experiment Description

Experiment 1: Two robots are manually controlled by two players. Players are allowed to have verbal communications.

Experiment 2: One robot with Codebook cooperates with the Foreman who is manually controlled by a player.

Experiment 3: Two robots with Codebooks cooperate with the Foreman who is manually controlled by a player. Foreman and one robot move one table to a place which fits into the final task, then the two robots finish the rest of the work.

5.2 Results of Experiments

Although we allowed players to have verbal communications in experiment 1, the human-controlled robots still took the most steps on average to finish each of the test tasks. The reason for this phenomenon is that players might have different decisions in dynamic situations. Therefore, it is possible for them to decide to move different tables at the same time rather than aiming at the same target, or placing the same table with different route plans, which will cost them extra steps to reach the common target or correct previous incorrect actions. That is, notwithstanding the explicit communication (talking) possible, it may be only

Table 2. Average Robots Steps, Table Movements and Time: 2 Humans

Experiment 1	Horizontal Rows	Vertical Rows	T Shape	U Shape
Robot A (Controlled by human)	163.0	136.8	149.2	127.4
Robot B (Controlled by human)	141.6	159.0	151.2	143.4
Total Robots Steps	**304.6**	**295.8**	**300.4**	**270.8**
Shifting Movements	40.0	43.0	42.8	38.6
Rotating Movements	7.2	6.8	7.2	5.6
Total Movements	**47.2**	**49.8**	**50.0**	**44.2**
Time (s)	74.6'	75.0'	77.6'	62.2'

Table 3. Average Robots Steps, Table Movements and Time : 1 Human + 1 Robot

Experiment 2	Horizontal Rows	Vertical Rows	T Shape	U Shape
Foreman (Controlled by human)	112.4	110.6	113.6	108.4
Robot A	153.6	141.4	156.4	143.2
Total Robots Steps	**266.0**	**252.0**	**270.0**	**251.6**
Shifting Movements	39.2	40.6	41.0	36.8
Rotating Movements	6.8	4.8	4.8	4.8
Total Movements	**46.0**	**45.4**	**45.8**	**41.6**
Time (s)	66.0’	56.0’	61.8’	55.8’

Table 4. Average Robots Steps, Table Movements and Time : 1 Human + 2 Robots

Experiment 3	Horizontal Rows	Vertical Rows	T Shape	U Shape
Foreman (Controlled by human)	28.6	26.8	29.0	24.4
Robot A	115.6	103.8	118.2	106.8
Robot B	143.4	142.8	150.0	132.0
Total Robots Steps	**287.6**	**273.4**	**297.2**	**263.2**
Shifting Movements	42.0	40.2	43.6	41.8
Rotating Movements	7.4	4.8	7.2	6.0
Total Movements	**49.4**	**45.0**	**50.8**	**47.8**
Time (s)	69.0’	65.0’	71.4’	64.0’

after incompatible moves that humans notice that they are following different plans.

The result in experiment 2 is quite good compared with the other two experiments. Since the robot with the codebook could infer the human-controlled foreman robot’s action by observation and cooperate with it, it is not necessary for the player to communicate with the other robot directly, which is different from the situation in experiment 1. So the player can make his own decision without any other disturbance, which leads to a big improvement in all the cost, including robots steps, table movements and time.

In most of the test cases, the total steps made in experiment 3 is more than experiment 2 but still better than robots totally controlled by humans. Apart from the second test case (Vertical Rows), the robots in experiment 3 made the most table movements in the rest of the test cases. The main reason here would be suboptimal strategies of route planning and obstacle avoidance.

Each player had a few minutes training time to become familiar with the keyboard controls and possible tasks before the real test in experiment 1, but the results show that they still took the longest time in most of the test cases. In experiment 2, with the cooperation of another robot, the foreman worked in an efficient way so that they took the shortest time in each case. One robot initially followed the Foreman to move one table to the place where fits the final task in the last experiment, then these robots finished moving the rest of the tables in a slightly longer time, but still shorter than experiment 1 in most cases.

6 Conclusion

The modeling approach and methodology provided in this paper for constructing the basic framework for cooperative robot communication is context dependent reconstructive communication. By the construction of fuzzy signatures and pattern matching with possibility calculation, we constructed codebook based on the cooperative robot communication scenario.

Through the implementation and evaluation of the CRC simulator, we safely arrive at the conclusion that we can successfully model the communication between the cooperative robots by our designed codebook. In addition, according to the results of the evaluation, the performance of the codebook for robot decision making has reached the effect and efficiency we expected. It has also proved that it is possible to improve the approach to be able to make the robots work more effectively and efficiently than one fully controlled by human-beings even with direct communication for completing cooperative tasks.

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