Fuzzy Communication in Collaboration of Intelligent Agents

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Abstract: - This paper presents some examples for fuzzy communication and intention guessing from the real life to the cooperation of intelligent mobile robots. In a special experimental environment a new communication approach is investigated for intelligent cooperation of autonomous mobile robots. Effective, fast and compact communication is one of the most important cornerstones of a high-end cooperating system. In this paper we propose a fuzzy communication system where the codebooks are built up by fuzzy signatures. We use cooperating autonomous mobile robots to solve some logistic problems.

Key-Words: - Intention guessing, Robot cooperation, Fuzzy communication, Fuzzy signatures

1 Introduction

The intelligent cooperation is a new and very exiting research field in autonomous robotics. If one would to plan or build a cooperating robot system which has intelligent behaviors, there aren't programmed the all scenarios appear in the life of robots, he realizes that effective, fast and compact communication is one of the most important cornerstone of the high-end cooperating system. The communication itself is very expensive so generally speaking, it is much more advisable to build up as big as possible contextual knowledge bases and codebooks in distant on-board robot controller computers in order to shorten their communication process 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 the other(s). It seems 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.

We propose a fuzzy communication system where the codebooks are built up by fuzzy signatures. Fuzzy signatures which structure data into vectors of fuzzy values, each of which can be a further vector, are introduced to handle complex structured data. 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 signature is 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.

After an overview of this type of fuzzy communication the paper will deal with some real scenarios of autonomous mobile robot cooperation.

Research towards extending this fuzzy communication method to more complex robot cooperation is going on currently.

2 Fuzzy communication

There are orthogonally contradicting interpretations of the idea of Fuzzy Communication. In [1] a scenario is described where the lack of precise and sufficient information in a business environment leads to employees creating their own fictive scenarios where they fill the information vacuum with conjecture and wrong assumptions, which eventually leads to catastrophic results. Another kind of scenario is taken from the Laboratory for International Fuzzy Engineering Research (Yokohama) that operated between 1989 and 1995 as the spiritual center of applied fuzzy research in Japan [2]. This latter gives a positive example for using fuzzy elements for compressed and effective communication between humans.

Scenario (based on a presentation at LIFE [2])

Director Tanaka receives a new secretary, Ms. Sato, on Monday. When Mr. Tanaka returns from lunch, he calls Ms. Sato and the next conversation follows:

> *'Ms. Sato, I would like to have a cup of tea.'*
> *'Yes, Mr. Tanaka. Do you prefer hot or cold tea?'*
> *'Hot tea, please.'*
> *'Do you prefer black or green tea?'*
> *'Give me black tea.'*
> *'Do you need sugar?'*
> *'No sugar, please.'*
> *'Any milk to the tea?'*
> *'No, thank you.'*

So, Ms. Sato prepares the tea according to the request. On Tuesday, after lunch the director calls Ms. Sato again.

> *'May I have a cup of tea?'*
> *'Yes, Mr. Tanaka. Black tea, again?'*
> *'Yes.'*
> *'No sugar, no milk?'*
> *'Exactly as you say.'*

Now fewer questions led to the same action by the secretary.

On Wednesday, when Mr. Tanaka arrives, he does not say anything but

> *'May I?'*
> *'The usual tea?'*
> *'Yes.'*

On Thursday, when the director comes in after lunch, Ms. Sato asks him:

> *'May I prepare your usual tea?*
> *'Yes, thank you.'*

The Monday conversation consisted of a request and four questions and informative answers (9 sentences altogether). On Thursday there was no more need for any request, the fact that Mr. Tanaka arrived after lunch triggered the single yes/no question and after confirmation the tea was prepared (two sentences only). In the first example the story is about some employees who misinterpreted the behavior of the new chairman, having a certain "codebook" in the sense of fuzzy communication in [3], which contained rules that were not valid any more for the new situation. Thus meta-communication leads to false assumptions. In the "tea example" the codebook was built up by learning in the head of Ms. Sato, and it was adequate for the situation thus communication with Mr. Tanaka evolved into a very effective one.

In the tea scenario, the formal determination of the codebook contents could be something like "If Mr. Tanaka arrives after lunch (T), he likes to drink hot (H) black tea (B) without milk ($\neg M$) and without sugar $(\neg S)$." With logical symbols it is:
$T \to B \,\&\, T \to H \,\&\, T \to M \,\&\, T \to \neg S$

If this codebook remains valid (Mr. Tanaka does not change his tea drinking habits), the simple formal model might be sufficient for the future. We might assume that this was not Ms. Sato's first secretary position and she had learned various other contexts valid in different environments, which she essentially discarded at the point of entering Mr. Tanaka's office. In addition to the newly learned codebook elements, she has the general background knowledge base (common knowledge) that contains information like "After lunch people often *drink* coffee, tea, water or cold drinks", "There are hot and cold tea", "There are short, long and cappuccino style coffee", "People drinking tea or coffee *sometimes* add sugar and/or milk", etc. Concerning the codebook learning procedure, the next continuation of the scenario will clarify that a more structured codebook model should be applied more appropriately in order to keep the codebook flexible enough for accepting changes and additions easily. It should be remarked that expressions like *often* or *sometimes* might be formally interpreted by Precisiated Natural Language introduced by L. A. Zadeh [4] as a tool for describing verbally non-exact adverbs, modifiers, hedges, etc. that might play important roles in modeling complex imprecise phenomena, both in everyday life and in the applied sciences. Next a possible continuation of the above scenario is given.

Scenario (continued)
One day Mr. Tanaka arrives from lunch and Ms. Sato asks the everyday question:

> *'May I prepare your usual tea?'*

This time the answer is

'No, today I prefer coffee.'
'Do you drink it long or short?'
'Short please.'
'Any sugar?'
'No, thank you.'
'Any milk?'
'Yes, some milk, please.'

This way the knowledge base in the codebook might be formulated as the following:
"If Mr. Tanaka arrives after lunch (*T*), he usually likes to drink hot black tea (*B*) without milk $(\neg M)$ and without sugar $(\neg S)$, and sometimes he prefers short (*E*) coffee (*C*) with some milk (*M*) but no sugar $(\neg S)$."
Formally it could be:

$$(T[usually] \to B \,\&\, T[usually] \to H \,\&\, T[usually] \to \neg M \,\&\, T[usually] \to \neg S,$$
$$T[sometimes] \to C \,\&\, T[sometimes] \to E \,\&\, T[sometimes] \to M \,\&\, T[sometimes] \to \neg S).$$

However, it is much more reasonable to order the information into a structured way:

$$(T[usually] \to B \,\&\, T[sometimes] \to E,$$
$$B \to H \,\&\, \neg M \,\&\, \neg S,\ C \to E \,\&\, M \,\&\, \neg S).$$

Such codebook elements can be quite well formulated by using PNL, fuzzy logic and fuzzy sets. In the continuation of the scenario obviously the context has not changed in the sense that its already existing elements were not discarded but further elements had to be added. Generally it may not be expected that in a context like in the above scenario, where a human environment gives the base for the context, and human interactions are involved, the codebook could ever be considered as final or completed.
Both examples tell about communication between two or more humans, i.e. "man-man" communication. In both cases, from meager information the original contents should and in the latter case it also could be reconstructed. Often the problem to solve involves "man-machine" or even, "machine-machine" communication. It is possible that a similar communication channel can be opened between man and machine or between two machines where just the "skeleton" or even the "approximate skeleton" of the information that is supposed to be put through will be or can be transmitted. It is an open question, whether that kind of context dependent reconstructive type fuzzy communication that was used in the tea and coffee scenario could be utilized for engineering or other applied science purposes in the practice.

3 Fuzzy communication of cooperating robots

One of the most important parameters of effective cooperation is the 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 [5]. 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 [6].

3.1 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 posses 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.1 presents an 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.

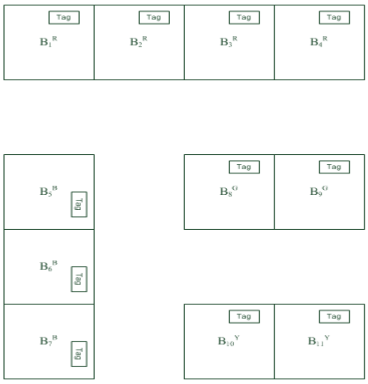
Fig.1. Examples of box arrangement

There are just a few essentially different robot positions allowed. Because two robots are needed for pushing or turning a box, at each side of the boxes, two spaces are available for the robots manipulating them: the “counterclockwise position” and the “clockwise position” (see Fig.2). The cooperating combination of robots is denoted by $C^{b}_{i,j,(k)}$ 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.2), $C^{i}_{1,2}=P$ 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; $C^{i}_{1,2}=RC$ stands for “counterclockwise rotation combination”; and $C^{i}_{1,2}=RW$ denotes “clockwise rotation combination”.

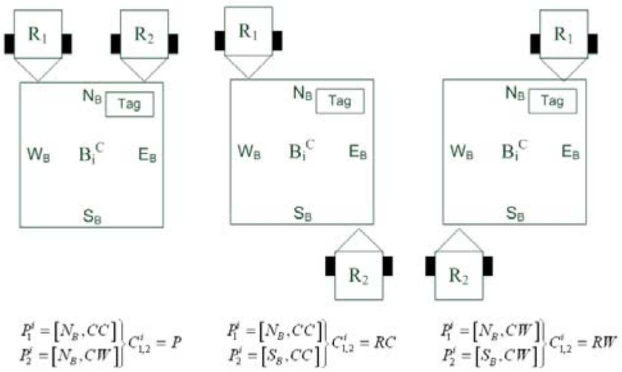

Fig.2. Allowed combinations of two robots for moving the table

Eventually “stopping combination” is mentioned where two robots intend to do a move operation (shift or rotate), and another robot that has recognized the goal box configuration positions itself to prevent a certain move. $C^{i}_{1,2,3}=ST$ is essentially a three robot combination, where either R_1 and R_2 are attempting a shift and R_3 positions itself to prevent it, or R_2 and R_3 / R_1 and R_3 are starting a rotation and R_1 and R_2 prevent it, knowing that the intended move is wrong from the point of view of the goal configuration. However, in $C^{i}_{1,2,3}=ST$ it is sufficient that R_1 takes up its $P^{i}_{1}=[N_B, CC]$ position if R_3 is aware that both the shift and the rotate counterclockwise combinations would be wrong from the point of view of the goal, thus R_3 immediately stops the maneuver by assuming the $P^{i}_{3}=[S_B, CW]$ position, thus preventing both shift and clockwise rotation. This is an exception where a two robot combination other than the ones listed in Fig.2 is legal as a temporary combination, clearly signalizing “stop this attempt as it is in contrary to the goal “.

3.2 Fuzzy signatures

The original definition of fuzzy sets was $A: X \rightarrow [0,1]$, and was soon extended to *L-fuzzy sets* by Goguen [7]

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

$A_L : X \rightarrow L$, L being an arbitrary algebraic lattice. A practical special case, *Vector Valued Fuzzy Sets* was introduced by Kóczy [8], 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 (right).

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 [9, 10]. Let us consider an example. Fig.3 shows a fuzzy signature structure.

The fuzzy signature structure shown in Fig. 1 can be represented in vector form. Here [x_{11} x_{12}] from 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. Finally, the fuzzy signature structure will become x = [x_{221} x_{222} x_{223}] in the example.

The relationship between higher and lower level is govern 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.

Let a_1 be the aggregating associating x_{11} and x_{12} used to derive x_1, thus $x_1 = x_{11} a_1 x_{12}$.

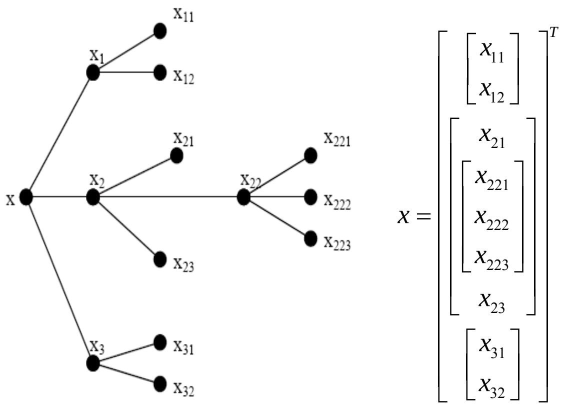

Fig.3. A Fuzzy Signature Structure

By referring to Fig.3, the aggregations for the whole signature structure would be a_1, a_2, a_{22} and a_3. The aggregations a_1, a_2, a_{22} and a_3 are not necessarily identical or different. The simplest case for a_{22} might be the min operation, the most well known t-norm.

3.3 Fuzzy signature classes

On basis of the features of the boxes the robot can build a fuzzy signature for each box [11]. 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 (2), the main signature has three sub-signatures.

$$B_i^c = \begin{bmatrix} P \\ AR \\ DY \end{bmatrix} \tag{2}$$

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. The box is "in direction" if its reference side lays near to any main compass direction (Fig.4).

It is important that the real position of a box has two other parameters: the latitude and the longitude of its reference point, but it does not have any importance to decision making only in navigation, so we abandon these parameters here.

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.

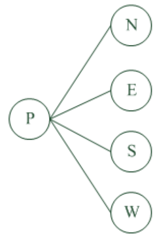

Fig.4. Box position fuzzy signature

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.5 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.

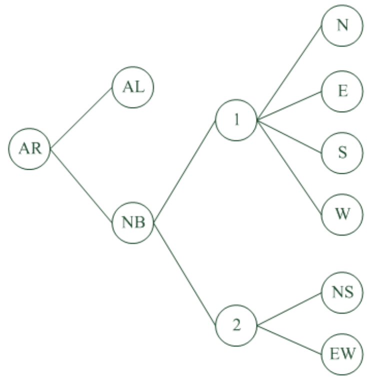

Fig.5. Box arrangement fuzzy signature

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.6, 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.

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. In this paper we do not consider the robot signatures in detail because they do not have an important role in the primary decision making.

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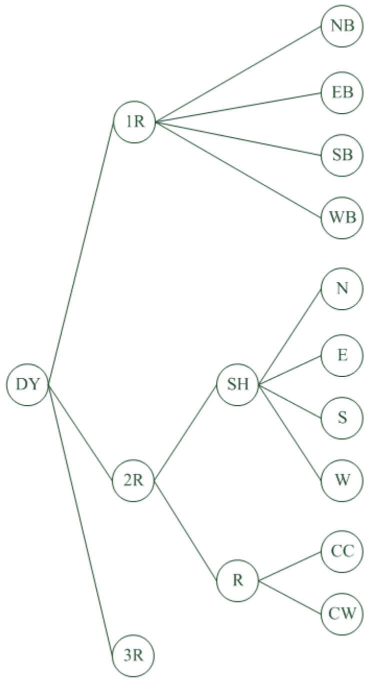

Fig.6. Dynamic fuzzy signature

3.4 Fuzzy decision

The above described fuzzy signatures enable robots to recognize a situation in the warehouse, and then the robots use their codebooks to take action accordingly. Let us see the codebook, namely a hidden fuzzy decision tree, in the robot controller. For simplicity we have cut the decision tree to sub-trees, then arranged them in a logical sequence. The robot takes decisions from some simple cases to more complex ones. The Fig.7 shows the entry point of the decision process. This figure depicts the steps of decision making based on fuzzy signatures, where the diamond shaped objects denote the elementary decisions (decision milestones) and hide the fuzzy signatures that are used. The used and hidden signatures are presented by a grey arrow with the signature name.

It is important to mention here this is only a local task and the final decision making needs the global signatures and other robot signatures, but these are beyond the scope of this paper. The first step in the local decision is to search for the nearest box, after which the box signature is built up or updated. In the next level, the position of the box is investigated which is described by the *P* signature. If the membership value of any good direction (N, E, S or W) is high enough, then the decision process steps to the next level and takes the arrangement (*AR*) and dynamic (*DY*) signatures of the box, if not then there is a simple decision: the box must rotate. Which direction? This is dependent on the global state of system, which is described by global signatures.

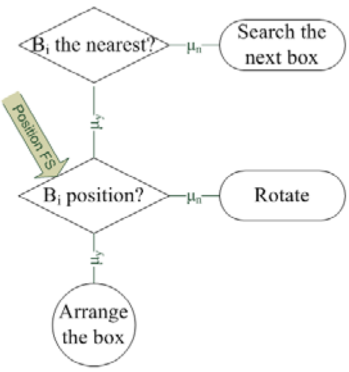

Fig.7. Entry point of decision task

The arrangement and dynamic signatures are used in a partially parallel way. The Fig.8 shows the whole decision task from this point. The robot analyzes the arrangement and dynamic of the box. If three robots work on it then there is a Stop combination and our robot (R_i) does not have any task on this box, it must search the next box. If two robots work on it and the guessed result points to higher order then R_i leaves it and searches the next near box. If the box has one or two neighbors in a good combination then the membership degree of “on the place” is raised and any dynamic (shift or rotate) is forbidden so if there any robot combination the R_i should go to the Stop position. Of course, if the neighbors of the box are not in a good place then more analysis is necessary to take the appropriate decision. If one robot waits for help there, then R_i decides which is a good position for pushing or turning the box and goes to this position. The most complex decision problem appears when any robot is not at the box; in this case R_i needs to take a decision about the box alone. This higher level problem is not covered in this paper.

Based on the above considerations it is possible to build some elements of the context and codebook for cooperating robots. It takes the form of a decision tree, where the inputs are the fuzzy signatures of the observations, the first level outputs are intention guesses and the second level outputs the concrete actions of the corresponding robot.

4 Conclusion

Fuzzy communication contains vague or imprecise components and it might lack of abundant information. If two entities (man or machine) are communicating by a fuzzy channel, it is necessary that both ends possess the same codebook. The codebook might partly consist of common knowledge but it usually requires a context dependent part that is either learned by the communicating entity or defined by expert knowledge.

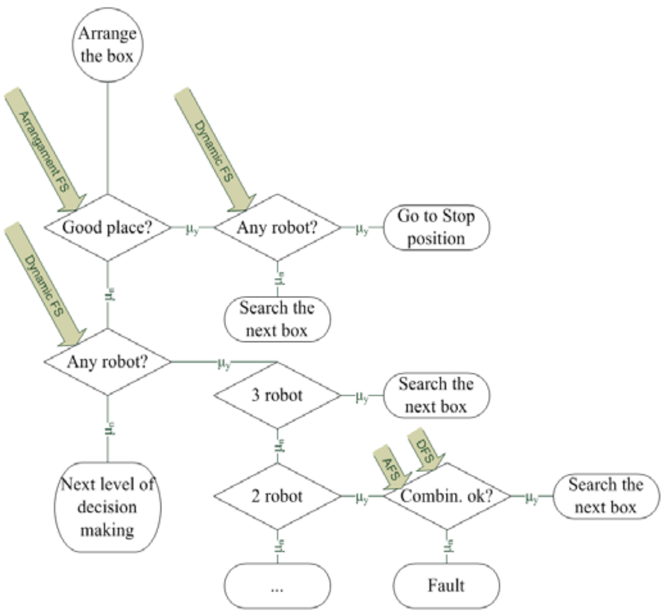

Fig.8. The decision task

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 "abundant communication". This advantage can be deployed in many areas of engineering, especially where the use of the communication channel is expensive in some sense, or where there is no proper communication channel available at all. We suggest that in distant locations and dangerous environment, further in applications where human friendly user interfaces are important, such as intelligent man-machine communication, the advantages of well designed CDRC communication systems be deeper investigated in the future.

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