Fuzzy Cooperation of Autonomous Robots

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1 Abstract

In this paper a fuzzy interaction among robots in a group is presented as an alternative solution to the classical protocols used in architectures for the cooperation of robots. In order to achieve this goal, the integration of previous works carried out on fuzzy behaviors and on cooperative architectures at the Intelligent Agents Lab. (LAI) has been used. This cooperation/coordination protocol is necessary to successfully control a group of autonomous robots. The protocol will take into account the fuzzy controllers used in the design of the robots. Three different fuzzy protocols have been considered and tested, both in a simulator and in real robots. The results of the experiments carried out and the conclusions obtained are presented.

2 Introduction

Within the context of multi robot interaction, our approach mainly considers the coordination problem from two complementary points of view: the communication and the behavior perspectives. Firstly, the coordination of robots may be achieved by explicit communication between individuals, usually performed through messages. Secondly, the global coordination of a group may be implicitly influenced by the effects of a robot behavior, which are manifested through its actions and the changes made in the world. These direct and indirect ways of coordination are very useful complementary mechanisms for obtaining a high level - intentional - cooperative robot, and can be integrated in a unique model.

In this paper, a fuzzy protocol for the coordination of robots in a group is presented as an alternative solution to the protocols used in more classical architectures [Noreils93], [Parker94], [Asama91]. This kind of coordination protocol provides a more flexible and soft behavior, by means of fuzzy knowledge representation and reasoning. In fact, inaccuracies and uncertainties of sensor data or in robot action execution, as well as hardware errors like communications failures, are easily coped with a fuzzy approach. In particular, the adoption of the fuzzy philosophy can be exploited in order to leave vague or undetermined both the recipient of a message and its content. This will provide a smoother communication. Moreover, it can be also adopted in order to produce a softer fusion of the robot behaviors, not only at the low level of reactive tasks, such as motor control, but also at the high intentional level of cooperation.

The integration of previous works on practical experiments on fuzzy behaviors [Matellán95], [Reignier94] and on cooperative robot architectures [Sommaruga95] has been considered as the basis for achieving an architecture of cooperative robots. A first model has been defined and can be summarized in Figure 1. The main idea consists of considering a two levels architecture for the control of autonomous robots: a reacting low level, which carries out all the basic and instinctive activities of a robot (e.g. moving, turning, avoiding, etc.); and a coordinating high level, which controls intelligent activities, such as the cooperative behavior. In this paper, an analysis of the communication perspective has been considered according to fuzzy principles. An experiment is described in order to present the potential influence of a fuzzy communication on the behavior of a real mobile robot.

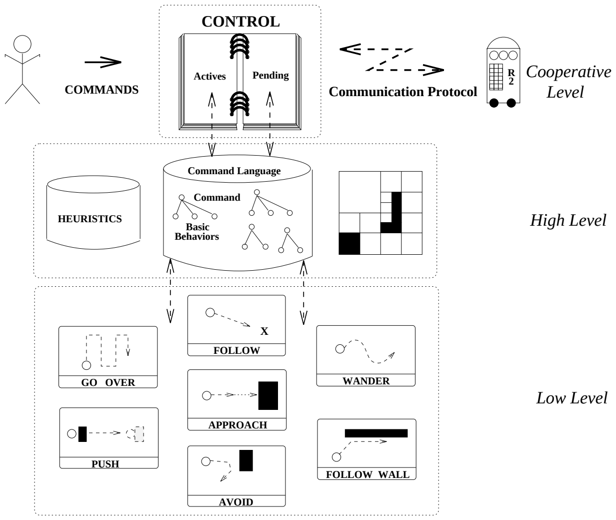


Fig. 1.: Architecture of the Robots

3 Fuzzy Protocol

Some previous works have shown that robots can take advantage of the fuzzy reasoning [Zadeh73], [Zimmer90] theory. In this way, we have used reactive fuzzy controllers to cope with the uncertainties of a particular situation in the control of autonomous robots [Matellán95]. These fuzzy *behaviors* have been designed to become part of the global architecture shown in Figure 1. The architecture has been thought to coordinate robots in cooperative tasks. This implies the necessity of communicating some informations between the robots. This communication will be based on a fixed protocol, where classical protocols have usually been adopted to communicate traditional information. A new approach for the communication of fuzzy information among robots is here presented.

In this work, the tentative protocol will not be a closed interchange of *crisp* concepts identically defined in all the robots. The term *crisp* means that the value of a variable, or any other information to be exchanged between the robots, is defined in exact numeric terms. This means that in order to design our protocol we will have to face some semantic problems.

Let us illustrate these concepts by means of a simple example. Let us suppose that a robot, which is sensing the real environment through its sensors, gets some knowledge about an object width. This concept (width) will be defined in the controller using a *fuzzy variable* referred to as *width*. The value of the variable is obtained by the corresponding fuzzification process and it is expressed by the activation levels of the *linguistic labels* defined over the variable range. For instance, the variable *width* can be defined by the set of labels {VERY HIGH, HIGH, SMALL and VERY SMALL}. The knowledge about the object width that our robot has got would be expressed in fuzzy terms as: VERY HIGH (0.8), HIGH (0.5), SMALL (0.2) and VERY SMALL (0), where 0.8, 0.5, 0.2 and 0 represent the degree of membership of the sensors measures to the linguistic variables respectively.

When the labels are defined the domain of the variable has to be considered. For example, when defining the variable *width* the domain is fixed to 0 - 1000. In most of the cases the domain is fixed by the physical requirements. For instance, the domain of a variable concerning the distance to an object measured by a sensor, will be fixed by the sensor range. If the sensor range is 0 - 1023 (as in the Khepera robot), that range will be the one of the variable.

Now, if our robot wants to share its knowledge about the object, there will be three possible communication methods in order to exchange the information with other robots (see Figure 2):

1. The communication of fuzzy variables.
2. Communication of the fuzzy labels.
3. The communication of protocol concepts.

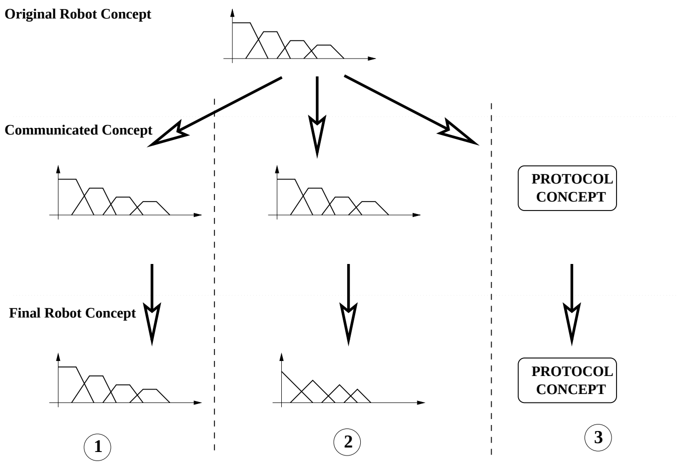


Fig. 2.: Three communication protocols

The first method is based on the communication of fuzzy variables stored as a set of linguistic labels values. These labels will have been defined by a set of functions defined over the domain of the variables. That is, the activation value of the labels is calculated using that function (named *membership* functions). Usually the values are asigned by simple functions such as the linear ones.

Then, if we send the whole variable, the labels of all robots will use the same domain and the same membership functions. In that case, the receiver gets the same fuzzy information that the sender robot has got. In the example, this means that we have sent the definition of the labels { VERY HIGH, HIGH, SMALL and VERY SMALL }, through its membership functions, and the activation values: VERY HIGH (0.8), HIGH (0.5), SMALL (0.2), VERY SMALL (0).

The second method uses labels defined over different domain ranges of the variables. This means that each robot will use the same labels to define the fuzzy variable *width*, that is { VERY HIGH, HIGH, SMALL and VERY SMALL }, but the domain now would be different.*For example, the robot can use the domain 0 - 2000 instead of the previous 0 - 1000.*

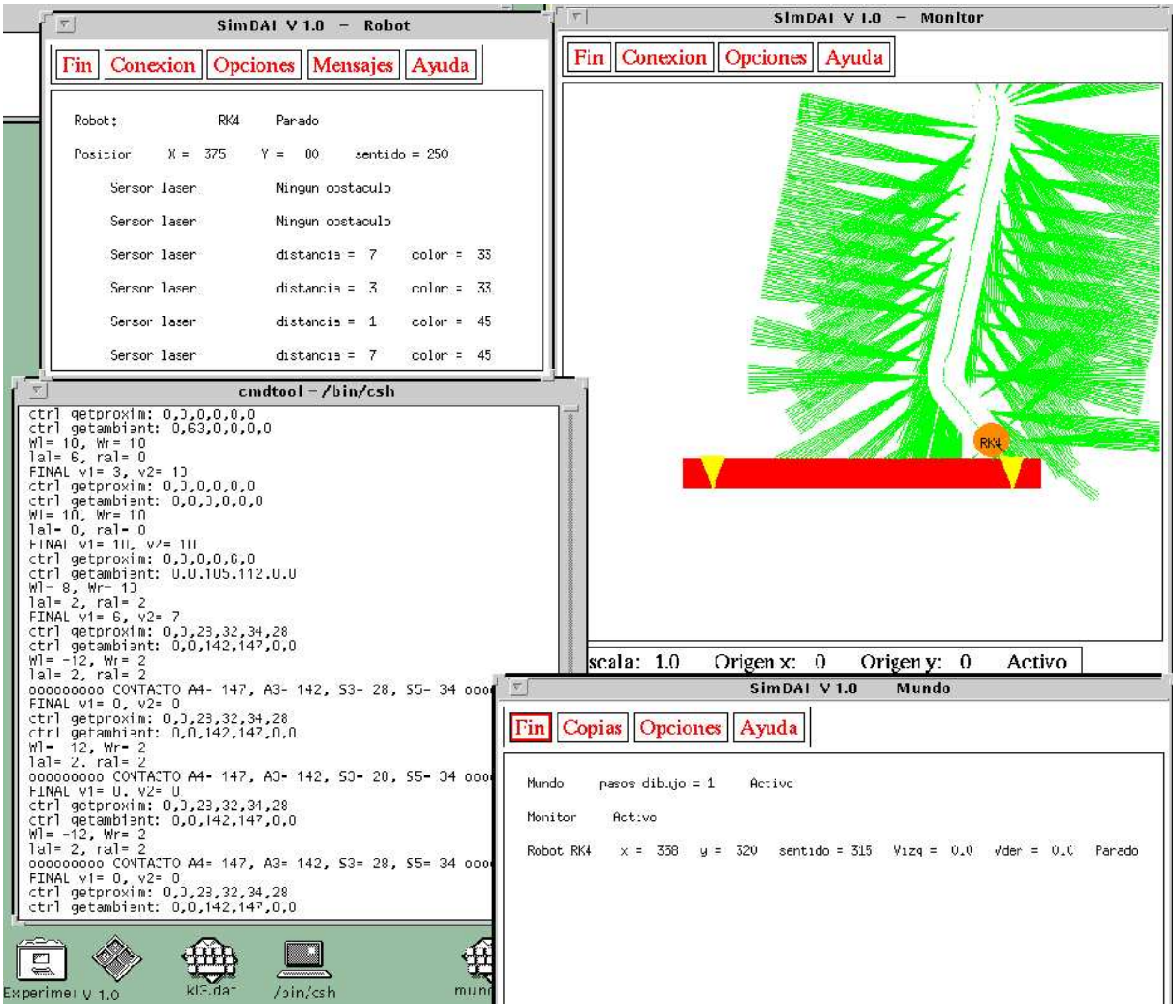
This means that the receiver robot uses the labels defined over a different domain, using its own membership functions (labels). This makes the robots have got the same information. But, they have got the same subjective *impression.* For instance, the concept wide for a small robot (let's say 6 cm. in diameter) can be defined as VERY HIGH for an object in the range 6-12 cm. When this information is transmitted to a greater robot, let's say a 30 cm. diameter one, where VERY HIGH is defined in the range 30-60 cm, the information actually exchanged would be different, but the idea (VERY HIGH) about width is the same.

In order to solve this problem it would be possible to tune the knowledge inside each robot. In the previous example, if the big robot knows that the other one is smaller, then the information received from it can be translated from VERY HIGH to SMALL inside the receiver. In this case, what is transmitted is the idea (VERY HIGH), but what the receiver has received is the real information. This solution leads us to a third method where independent and shared concepts, in the form of linguistic labels for the fuzzy variables, are used.

In the third method, a concept which results from the interpretation of the linguistic variable that a robot wants to transmit, is used. This means that a global concept is defined as a communication protocol. In example, the fuzzy variable values would be translated into activation values of a new set of labels, {ENORMOUS, GREAT, NORMAL, SMALL, TINY}. Then, just one of these labels is exchanged in the communcation.

From this point of view, this is a simple communication protocol. Due to the fact that concepts are not defined in the same way in each robot, the same concept is differently interpreted from each robot point of view. This case is similar to human communications: one person has a perfect image of a situation that he/she has lived but when he/she communicates this information he/she uses a rule-base to translate his/her experience into words, which implies a reduction of the global information stored in the brain. Then, these words are transmitted to the other person, who translates them into thoughts using his/her own rule base.

In the example, the system can consider that all the information in the fuzzy variable can be summarized by the concept GREAT, which is the transmitted information. Thus, all the robots have the same concepts defined as a protocol. The other robot may adopt this limited information doing a different interpretation as according to the sender robot characteristics.



```
Robot:              RK4     Parado

Posicion    X =  375    Y =   00    sentido = 250

     Sensor laser           Ningun obstaculo

     Sensor laser           Ningun obstaculo

     Sensor laser           distancia =  7    color =  33

     Sensor laser           distancia =  3    color =  33

     Sensor laser           distancia =  1    color =  45

     Sensor laser           distancia =  7    color =  45
```

```
ctrl getproxim: 0,0,0,0,0,0
ctrl getambient: 0,63,0,0,0,0
Wl= 10, Wr= 10
lal= 6, ral= 0
FINAL v1= 3, v2= 10
ctrl getproxim: 0,0,0,0,0,0
ctrl getambient: 0,0,0,0,0,0
Wl= 10, Wr= 10
lal- 0, ral- 0
FINAL v1= 10, v2= 10
ctrl getproxim: 0,0,0,0,0,0
ctrl getambient: 0,0,105,112,0,0
Wl- 8, Wr- 10
lal= 2, ral= 2
FINAL v1= 6, v2= 7
ctrl getproxim: 0,0,23,32,34,28
ctrl getambient: 0,0,142,147,0,0
Wl= -12, Wr= 2
lal= 2, ral= 2
ooooooooo CONTACTO A4- 147, A3- 142, S3- 28, S5- 34 ooo
FINAL v1= 0, v2= 0
ctrl getproxim: 0,0,23,32,34,28
ctrl getambient: 0,0,142,147,0,0
Wl-  12, Wr- 2
lal= 2. ral= 2
ooooooooo CONTACTO A4- 147, A3- 142, S3- 20, S5- 34 ooo
FINAL v1= 0. v2= 0
ctrl getproxim: 0,0,23,32,34,28
ctrl getambient: 0,0,142,147,0,0
Wl= -12, Wr= 2
lal= 2, ral= 2
ooooooooo CONTACTO A4= 147, A3= 142, S3= 28, S5= 34 ooo
FINAL v1= 0, v2= 0
ctrl getproxim: 0,0,23,32,34,28
ctrl getambient: 0,0,142,147,0,0
```

scala: 1.0   Origen x: 0   Origen y: 0   Activo

```
Mundo     pasos dibujo = 1     Activo

Monitor     Activo

Robot RK4   x =  358   y =  320   sentido = 315   Vizq =  0.0   Vder =  0.0   Parado
```

Fig. 3.: The Simulated environment

4 Experiments

In order to prove the different alternatives of communication, some experiments have been carried out using both a simulator and real robots. The simulator used, SimDAI [Sommaruga96], is a distributed version of the ERA simulator, presented last year at the SIRS95 [Sommaruga95]. SimDAI allows the simulation of a group of independent robots, running on different computers, which carries out simple tasks in a user-defined world shared by the robots. It is also provided a mechanism to let the robots communicate each other.

The real robots used in the experiments have been two Khepera mini-robots [Mondada93]. This 5.5 cm. of diameter mini-robot has got two independent motors and 8 infrared sensors. The sensors can measure both the distance to objects or the ambient light. The robots can work autonomously or attached to a computer through the serial port.

A simulated world (Figure 3) which resemblances the real one (Figure 4) has been defined in order to design the experiments before being implemented in the real world. The same controllers have been used in both cases, except the differences in the treatment of the sensors. The Khepera's distance and ambient sensors have been simulated in SimDAI as laser and sonar sensors respectively, see [Sommaruga96]. This difference is due to the distinct ranges of the sensors in the simulator and in the real robot.

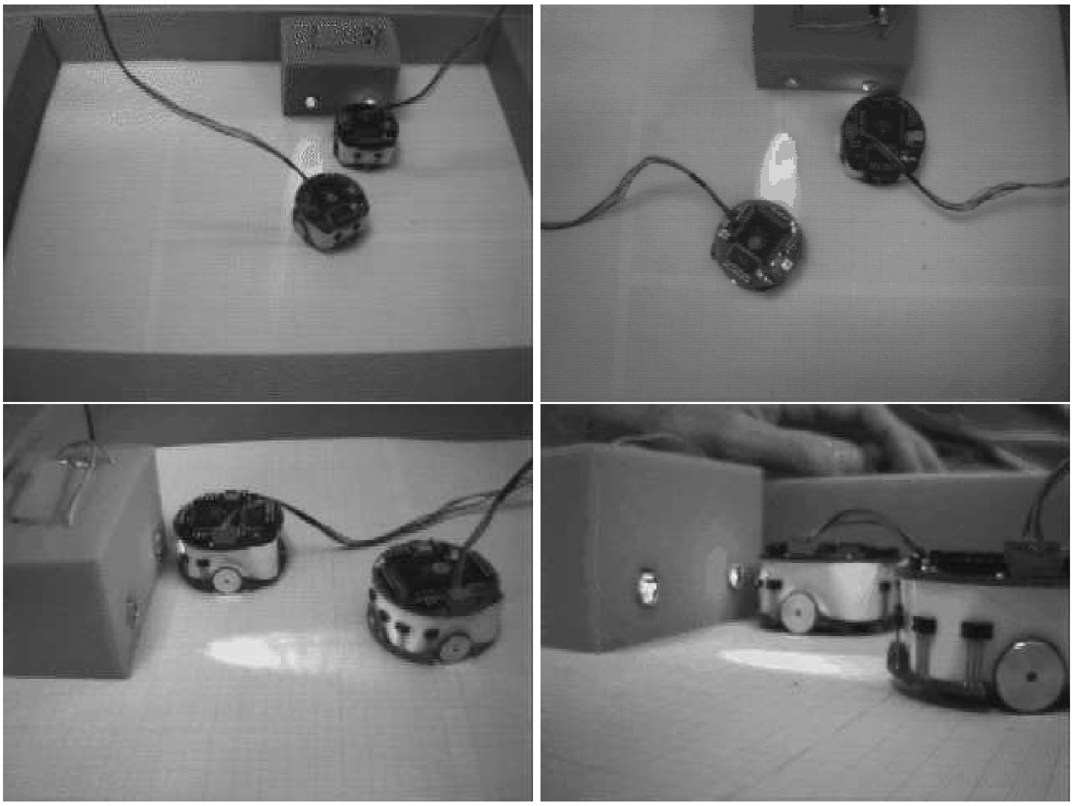


Fig. 4.: The experimental environment

In the next section only the real experiment is described, considering the simulation results less significant.

4.1 Description of the experiments

The experiments carried out aim to show the influence of the fuzzy communication in a coordinated behavior. The global goal of the experiment was to push an object, in a cooperative way, by two robots. This task can be divided into two main tasks, prepare to push and push. In order to prove the communication alternatives it has been considered the first task to be the relevant one. This task has been divided into three different phases:

1. The first robot finds the object.
2. It aligns to the object and sends a description of its alignment to the second robot.
3. The second robot tries to align exactly as the first one.

The first phase can be carried out by a simple fuzzy controller, as the one previously developed [Matellán95] or it is also possible to use other kinds of controllers. A version of a reactive controller from V. Braitenberg [Braitenberg84], has been adapted in order to recognize the correct alignment position.

Once the robot has found the object, it aligns to it in a particular way. This phase needs a more precise control phase than the previous one because the alignment will determine if the cooperative task will be well accomplished or not. Using a real robot such as the Khepera, the definition of the alignament has to be done in terms of the sensor measurements and is taken into account in the controller.

In that way, we have been working in the definition of the alignment in fuzzy terms of variables referred to the sensors of the Khepera robot. Thus, we have supposed that a robot, using a standard controller, has been aligned when its proximity sensors and its ambient light sensors returns a particular fuzzy values. Then, the robot will inform the other one *how* it is aligned. At this point the three different communication alternatives already mentioned are considered.

Besides the three fuzzy alternatives, the most traditional communication method has also been considered. It consists of exchanging the crisp concepts. In this case, the sender tells the other robot the exact measurements of its sensors. This solution will be the ideal one if the two robots were physically identical, including its sensors sensibility, and also if there were no errors in the measurements.

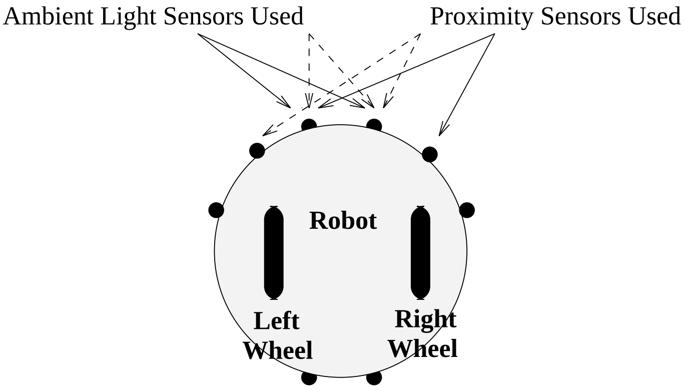


Fig. 5.: Sensors distribution used in the experiment

In order to show the performance of the different solutions we have made some experiments in the real environment shown in Figure 4. This experiment was previously designed in the simulator SimDAI [Sommaruga96] and then implemented in the real world. In the simulated one, the task was to align in front of a predefined position of an object. That position was indicated in the simulated object using a different color, as shown in Figure 3.

With respect to the real case, an artificial object with two lights has been built (see Figure 4). Those lights are the points where the robots have to be aligned to. When one of the robots get aligned, it sends its perceived environment to the other robot using one of the methods previously commented. In the real experiment, the environment was perceived using the proximity sensors and the ambient light sensors. In order to simplify the controller, only the sensors shown in Figure 5 are used. Depending on the side of the object where the robot is going to align, the proximity sensors used are the ones indicated by the dashed arrows (align to the left ligth) or the ones indicated by the continuous arrows (align to the right).

Being the Khepera sensors very sensitive to the external environment some preliminary experiments were made to choose a significant configuration, adjusting the starting points for the robots or the ambient light in the lab. A final configuration which makes the robots find the light easily has been chosen, because the goal was to test the communication protocol and not the controllers used.

In the final experiment environment, we have measured the distance to the object to know how the communicated values have been used by the controller. In some situations, the time needed by the second robot to align can give us a valuable information. For instance, if the first robot sends the crisp (numerical) values measured by its sensors, the second robot is unable to align in a reasonable time. This is due to the fact that in the real world there is a very low probability that a group of sensors of the second robot measures exactly the same of the corresponding sensors of the first robot. Therefore, a maximum running time has been introduced, and a time out considered. This problem was the origin of this work. However, in most cases the time variable only measures the quality of the controller. For example, the time employed in the alignment, when the fuzzy communication is used, depends on external conditions and only measures the quality of the controller used in presence of these events.

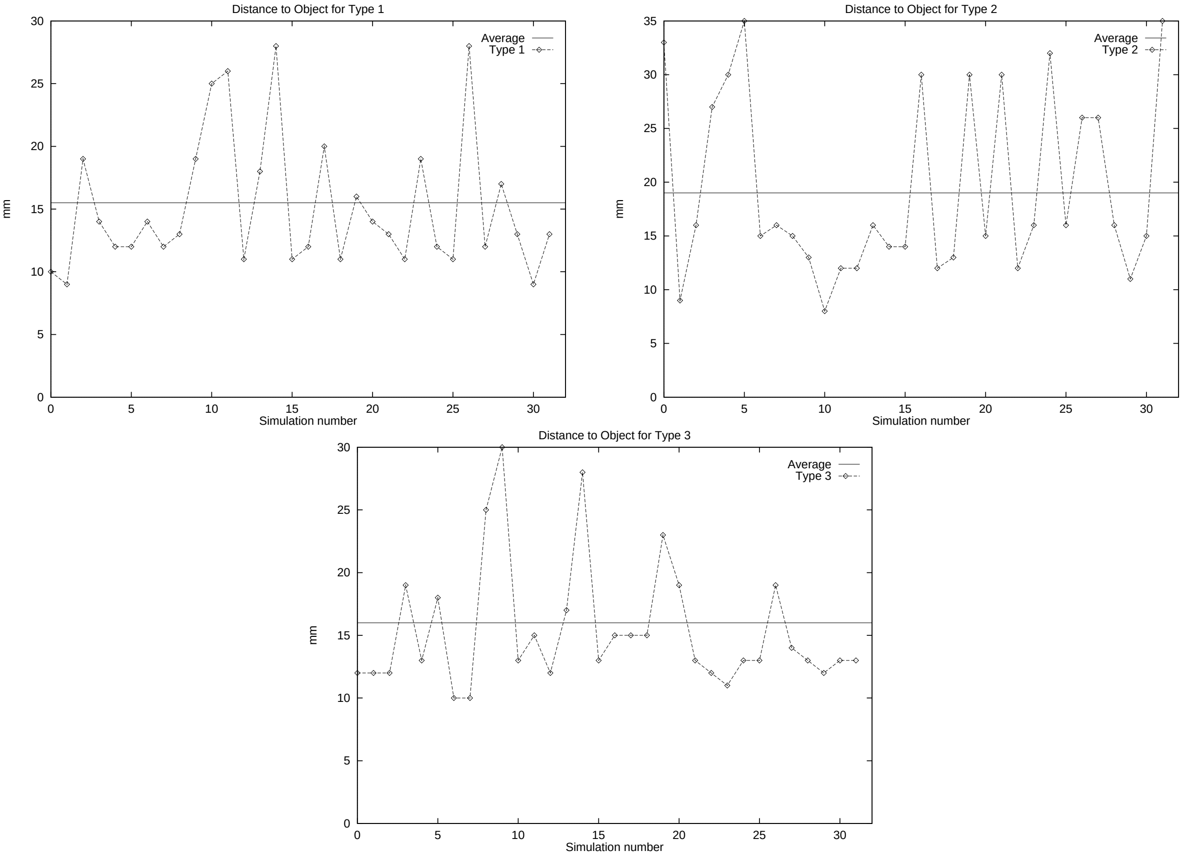


Fig. 6.: Graphical results of the experiments

4.2 Results

A number of trials has been repeated for each type of fuzzy communication, and the relevant parameters have been measured. The results obtained are shown in the graphics of Figure 6. The average distance to object for the communication types one, two and three were, respectively, 15.125, 19.375 and 15.375. It can be appreciated how the first method is the most accurate, it is the one which stops in a way more similar to the first robot. This was predictable because this method is the one which passes more information to the controller.

The second one is the less accurate in the alignment because the labels were defined in a different way, happening that a real *near* distance resulted being greater than a communicated *far*.

The third one is similar to the first one in its performance, because the two robots share the same interpretation of a concept. Thus, the robot aligns, less accurately than in the first one. This method performs in a good way because it is more fault-tolerant in presence of external noise. Moreover, this method uses less communication resources because it only needs to exchange a single concept.

The last case, the communication of crips concepts, produces, as expected, disastrous results, never being able to align the robot and always generating a timeout in the search.

5 Conclusions and Further Work

In this paper we have presented three methods of communication between mobile robots in order to carry out a global task. The communication has been based on the exchange of fuzzy messages instead of classical crisp messages. In general, all the three fuzzy methods allow a softer, more reliable and flexible communication among the robots, letting the robot to increase the semantic of the messages and obtaining better alignments than the obtained using the crisp communication, which never aligns.

Among the three methods it has emerged that the preferable one, in normal conditions, would be the third one, because it provides an acceptable performance with the least use of communication resources. This method is also the most fault-tolerant in presence of external events.

A number of similar experiments are envisaged to be carried out in order to prove the effectiveness of fuzzy communication in more complex tasks.

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