Developing a Multi-Agent Fuzzy-based Control Architecture for Autonomous Mobile Manipulators

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Abstract: Controlling a robotic system, while reaching a certain degree of autonomy and complexity, is carried by the establishment of its control architecture. The control process is intended through achieving general goals and/or reacting to changes of the environment. An autonomous robot is required to meet some design specifications and behavior requirements: its reactivity to environment change, its reliability and its fault-tolerance, etc. However, A control architecture of a robot must ensure that the robot will achieve, in real-time, its tasks despite all the constraints. The control is required to be reactively fast but also thorough, while maintaining some properties such as stability and robustness. The main objective we are intending to achieve is to design our own approach for autonomous control of mobile manipulators. The expected approach is meant to be thorough and generic as possible. It should offer a real-time reactive response, while maintaining a fault-tolerance capabilities and a robust control.

1 STAGE OF THE RESEARCH

Throughout the literature, there has been a substantial effort devoted to autonomous control of mobile manipulators. The resulted works brought up different control approaches based on different techniques and practices.

As a part of a research project intended for the *control and supervision of mobile manipulators for the telerobotics in a constrained environment*, we are working on the development of a novel generic architecture for autonomous control of such robots. The suggested approach is based on *Fuzzy-Logic Reasoning* for the cognitive part. The implementation is done through a *Multi-agent System* scheme.

2 OUTLINE OF OBJECTIVES

Controlling a robotic system (mobile, manipulator or mobile manipulators), while reaching a certain degree of autonomy and complexity, is carried by the establishment of its control architecture. The control process is intended through achieving general goals and/or reacting to the changes of the environment.

An autonomous robot is required to meet some design specifications and behavior requirements such as reactivity to environment changes, reliability and fault-tolerance, etc. However, a control architecture of a robot must ensure that the robot will achieve, in real-time, its tasks despite all the internal and external constraints. The control is required to be reactively fast but also thorough, while maintaining some properties (stability, robustness, etc.).

The main objective we are intending to achieve is to design our own approach for autonomous control of mobile manipulators. The expected approach is meant to be thorough and generic as possible. It should offer a real-time reactive response, while maintaining a fault-tolerance capabilities and a robust control.

3 RESEARCH PROBLEM

A mobile manipulator is constituted by uniting two disjointed mechanical sub-systems, the mobile base

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and the manipulator. Each one has its own features and offers different capabilities. The coupling of these two heterogeneous parts has the benefit of combining the mobile base locomotion with the manipulation capabilities of the manipulator. The resulted system will have an enlarged accessible workspace and numerous new features. However, this alliance increases the complexity of the control process and path planning, especially for tasks that require an imposed trajectory for the end-effector of the robot. In such a case, infinity of configurations for both mobile base and manipulator are possible.

4 STATE OF THE ART

A control architecture design should meet defined requirements. The existing research experience, so far, seems to have not figured out a definitive paradigm for the distribution and/or coordination of the functionalities required for all the autonomous robots (Medeiros, 1998).

In the literature, numerous studies have focused on proposing control architectures for mobile manipulators. Each proposition gives a specific way to solve the control problem. Some approaches provide a total decoupling between the different sub-systems constituting a mobile manipulator. While performing a task that requires the involvement of the two sub-systems, the control process is carried out sequentially among the two disjoined entities. There are, also, models for synchronizing the control of the mobile base and the manipulator.

To achieve the operations and the tasks that the robot must perform, each designer uses his own approach. This latter involves the deployment and the structuration of the internal functions to achieve the final objectives assigned by a higher-level operator.

In the following section, we present a review of the main control approaches for autonomous robots, discuss their major properties and propose a classification into two different classes depending on the techniques used for controlling the robot.

4.1 Classical Control Approaches

Considered as classical, this first class is based on the study of mathematical models for both mechanical sub-systems (manipulator and mobile base). Controlling a mobile manipulator consists of computing the motion of the manipulator joints and that of the mobile base. For this aim, the study of both *Direct* and *Inverse Kinematic Models* of the robot is needed.

Using the mathematical models to control mobile manipulators produces good and accurate results, and offers a fairly exact control for repetitive tasks in controlled and known environments (industrial robotics for example). In this case, when the robot is required to repeat a trajectory thousands of times, very complicated computation of these models is done, in most cases, off-line with the ability to optimize path covered, energy consumption, time spent, etc. while performing a task. However, some robotic environments using mobile manipulators are not completely known but, in contrast, evolutionary. Which could result to a very poor performances in real-time control, due to the computational resources needed to come out with a response in a limited time period. Besides, it must be noted that classical approaches have the disadvantage of computing time which is quite important depending on the high number of *degrees-of-freedom* of the robot, especially in frequently-changed and not completely known environments. According to Brooks (Brooks, 1986), traditional robotics seems unable to deliver real-time performances in a dynamic world.

Moreover, it should be noted that the methods used for computing the *Direct Kinematic Models* represented generic rules, whereas the computation of the *Inverse Kinematic Models* were constructed according to the mechanical structure of the robot. Finally, these models don't tolerate any change in the mechanical structure of the robot (malfunction of one or more joints of the manipulator for example) without adding specific modes for failures treatment. When a fault occurs, the possibility of offering a *minimum service* until repairing the breakdown is an important element of the *Quality of Service* (Delarue, 2007).

4.2 Multi-Agent Fuzzy-based Control Approaches

When working with complex problems with large dimensions, the resolution of control problems for mobile manipulators is very difficult using traditional mathematical models. Several approaches have described the process allowing the end-effector of such a robot to reach a Cartesian position in its workspace, without using the *Inverse Kinematic Model* or differential-equation solvers. Some of these works can be found in (Duhaut, 1999); (Erden, 2004); (Colle, 2006), etc.

4.2.1 General Principle

Multi-agent and *Distributed Artificial Intelligence Techniques* offer simple solutions (Colle, 2006). Each joint is implemented as an agent. Every agent tries to align the position of the end-effector of the robot with that of the target, while being independent of the motions and positions of the other joints, and with no prior knowledge of the actions of the other agents. By acting recursively, the other agents controlling the other joints try to do the same job. A global behavior can emerge, consequently, from all the local agents which will satisfy the desired objective (reaching the desired position).

In contrast to classical control approaches, *Multi-agent Approaches* offer methods that use the agent paradigm by proposing a decomposition of the robot control into a set of distinct agents. The *Multi-agent Approaches* benefit of all the advantages of distributed problem solving. The *Multi-agent System* perspective made it possible to consider the architecture as a compound of simpler modules, which gave way to easier design of the whole system. In addition, the need for massy mathematical models, *Inverse Kinematic Models* and differential-equation-solutions is overcome. Therefore, there is a considerable decrease in design effort and computation time compared to classical approaches. Moreover, with such a usage of *Multi-agent Systems*, the control architecture is more flexible to be applied to any robot (Erden, 2004).

To solve a complex problem, a *Multi-Agent System* can emerge a global behavior using several agents. Each of these latter has a confined knowledge and limited actions ability. *Fuzzy Logic*, *Neural Networks* and/or *Genetic Algorithms* associated with *Multi-agent Systems*, can provide high-level control for complex systems (Tournassoud, 1992); (Guessoum, 1997).

4.2.2 Fuzzy-Logic Control

Fuzzy Logic is a mathematical formulation that copes with uncertainty in information (Klir and Folger, 1992). Fuzzy control has proven to be a successful control approach to many complex non-linear systems or even non-analytic ones. It has been suggested as an alternative approach to conventional (classical) control techniques in many situations (Precup and Hellendoornr, 2011). Such a control is characterized by the use of linguistic rules to manipulate and implement human knowledge in control systems so as to handle the uncertainty present in the environment (Passino and Yurkovich, 1998).

4.2.3 Advantages of Multi-Agent Heuristic-based Control Approaches

Multi-agent Heuristic-based Control Approaches don't require the precise mathematical model of the robot to be controlled. However, if the model exists, it can be used for the simulation and for the test of the control strategy. The main advantages of such controllers are given as follows (Godjevac, 1995); (Singh, 2008):

- No need to have a mathematical model of the robot (data is either unavailable, incomplete or the process is too complex).
- It is possible to implement expert-human knowledge and experience using comprehensible linguistic rules.
- Thanks to dedicated processors, it is possible to control fast processes.
- Such techniques allow building robust and smooth controllers starting from heuristic knowledge and qualitative models.
- These approaches allow considering imprecise, vague and unreliable information; and integrating symbolic reasoning and numeric processing in the same framework.

Throughout our literature study, the objective of all the reviewed works we referred to was to test the performances of the multi-agent heuristic-based design of control approaches in simulation. Moreover, all the studies were applied on a simple case of a service mobile manipulator undertaking a specific task in two-dimension workspace. Unfortunately, to our knowledge, no works were done on real physical robots in three-dimension space.

5 METHODOLOGY

The design phase of a control architecture is the most strategic one for the development of a controller. However, it is necessary to understand and to identify the needs to design and implement the approach in a proper manner. With the increasing complexity of architectures, using a development methodology is very necessary. Nevertheless, the absence of such a methodology covering the whole life cycle of a *Multi-agent System* makes the task very difficult and complicated (Hentout, 2008). The *Multi-agent Approach* poses,

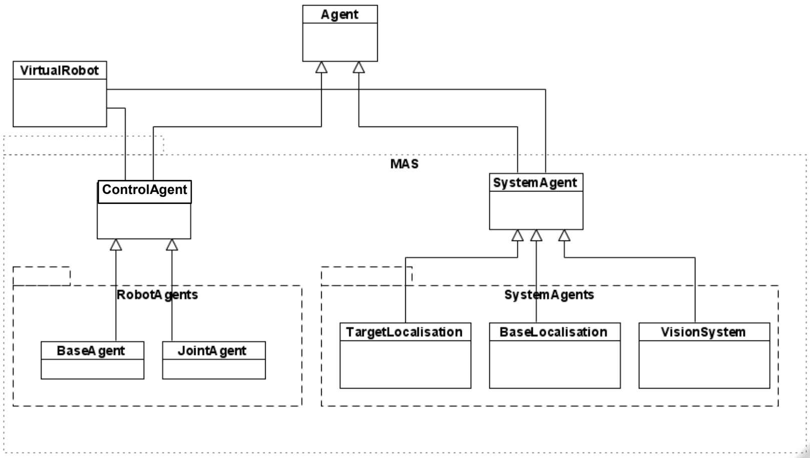

Figure 1: Structure of the *Multi-Agent System* package.

moreover, the problem of the management and control of agents and their shared resources. A constraint that should not be overlooked when designing such a control system is the lack of information. This lack is mainly due to the measurement errors delivered by the physical sensors of the robot.

The combined use of *Fuzzy-Logic Reasoning* with *Multi-agent Approach* has the benefit of offering a *Distributed Fuzzy Control System* with smaller fuzzy sub-systems instead of one big centralized fuzzy system. Therefore, adopting an architecture/approach is a technological problem for the designer, who is supposed to consider the required degrees of reactivity, intelligent behavior and the related implementation cost. The type of the robotic system, its technical specifications and the required level of autonomy are the most important constraints while designing a novel approach. Typically, the differences are the ease with which approaches can be developed, and the efficiency with which tasks can be achieved.

The control architecture we are developing is meant to be as generic as possible. It is intended to fulfill a list of requirements and specifications related to autonomous control of mobile manipulators. Some of which are *robustness* and *fault-tolerance*, *programmability*, *extensibility* and *scalability*:

Robustness is proven through the ability of the fuzzy-logic reasoning to handle imperfect inputs.

- *Fault tolerance* is guaranteed with the aptitude, of the used *Multi-agent System,* to handle unexpected events and sudden malfunctions. These latter will be countered via the possibility of offering a minimum service functionalities in case of one or more joints of the manipulator break down.
- Thanks to a scalable structure and a modular design, new features can be developed and added progressively without modifying the existing ones.

5.1 Presentation of the Control Architecture

Our work is dedicated to develop a novel control architecture for autonomous mobile manipulators using a *Multi-agent fuzzy-based control approach*. This architecture is responsible for controlling the robot while sharing the control of the heterogeneous sub-systems.

The implementation of the control architecture is being done by using *Java Netbeans 7.0*. Furthermore, for the implementation of the fuzzy-based part, we are using the open source library for fuzzy systems *jFuzzyLogic* developed by (Cingolani and Alcala-Fdez, 2012) and available from *jfuzzylogic.sourceforge.net*.

Choosing the suggested model is justified by the generic nature of the proposed agent models and by the possibility of integrating the whole in a modular, more general, robotic system.

We refer to each agent as a separate *Thread*. In addition, we propose the use of two distinguished types of agents as showed in Figure 1 *(i) SystemAgents* and *(ii) ControlAgents.* Both of which has a distinctive purpose. More details are given in the following sub-sections.

5.1.1 System Agents

This first type of agents is more complex than the second one. The agents of this type inherit from the *SystemAgent class*. They all belong to the same package, *SystemAgents,* and have the same outline structure. They are meant for the processing and tuning of data issued from the different sensors equipping the robot.

Such agents may comprise several features regarding the control process. The modules we propose are *(i) Module of Vision, (ii) Module of Localization of the robot in its environment* and *(iii) Module of Localization of the targets.* However, this list of modules is not thorough. Other modules may be proposed and integrated progressively into the control architecture.

5.1.2 Control Agents

Inheriting from the *ControlAgent class*, the agents of this type are regrouped in the *RobotAgents package*. As its name suggests, a *ControlAgent* is dedicated to the control process itself. Each agent is assigned to control one mechanical sub-system, which can be either the mobile base or one of the joints constituting the manipulator.

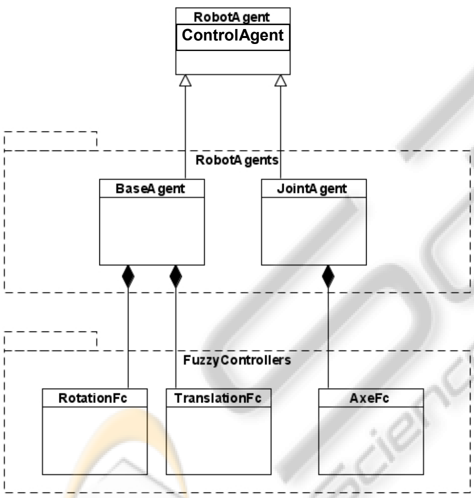

Figure 2: Composition of the *ControlAgents*.

The set of control agents are brought together to reach a high-level goal. An emergent behavior is arisen (using reactive agents with poor own world knowledge) which overall can solve a higher-level problem than each agent, by itself, can achieve. The composition of the *ControlAgents* is given in Figure 2.

Through our study, we are more interested by this type of agents. Such an agent produces the control instructions directed to its respective controlled sub-system (mobile base or manipulator). The cognition part is ensured by using fuzzy-based modules, called *Fuzzy Controllers*.

A fuzzy controller is the entity offering the intelligence of the system. It is based upon a *Fuzzy Inference System*, which compute the entries of a *fuzzified* values of linguistic variables through a set of fuzzy-logic rules. A fuzzy controller produces, as an output, the *deffuzified* values for the corresponding velocity (rotation and translation velocity of the mobile base, angular velocities of the joints of the manipulator).

A *ControlAgent* is designed using one or more fuzzy controllers.

5.1.2.1 *BaseAgent*

Figure 3 shows a synoptic structure for the *BaseAgent* where:

- (X_T, Y_T, Z_T): it represents the operational coordinates of the target to be reached by the end-effector of the robot.
- (X_E, Y_E, Z_E): it is the current position of the end-effector of the robot.
- ($Dist_1$, …, $Dist_n$): they represent the distances separating the mobile base to obstacles (1, …, n) present in its environment.
- E_angle: it represents the computed angular error between the current position of the end-effector and the desired target to be reached.
- E_distance: it is the distance error between the current position of the end-effector and the final target.

BaseAgent is composed of two fuzzy controllers *(i) RotationFC* and *(ii) TranslationFC*. They control, respectively, the rotation and translation velocities of the mobile base.

The intended scheme is considered as a generic structure of a higher-level abstraction, which would be applicable to most mobile base systems. However, a lower-level middle-layer will be implemented for each specific mechanical structure of a mobile base. It should be declared that obstacles avoidance capabilities will be implemented and fitted into the *BaseAgent*.

5.1.2.2 *JointAgent*

JointAgent is a reactive agent dedicated for controlling one of the manipulator joints. Each *JointAgent* is composed of one fuzzy controller that assures the velocity control output of the corresponding joint. Figure 4 gives a synoptic

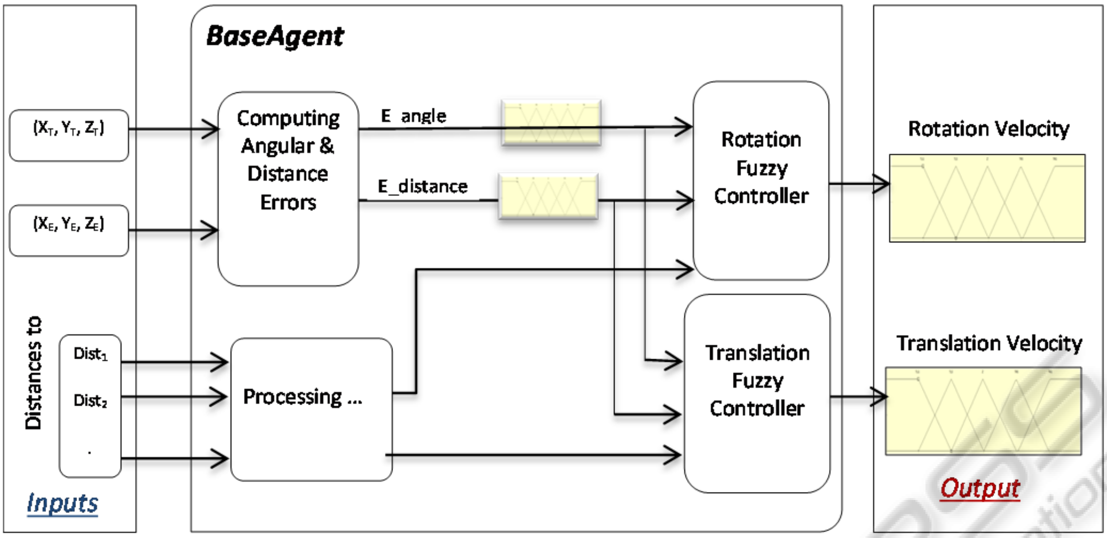

Figure 3: A synoptic scheme for the internal structure of the *BaseAgent*.

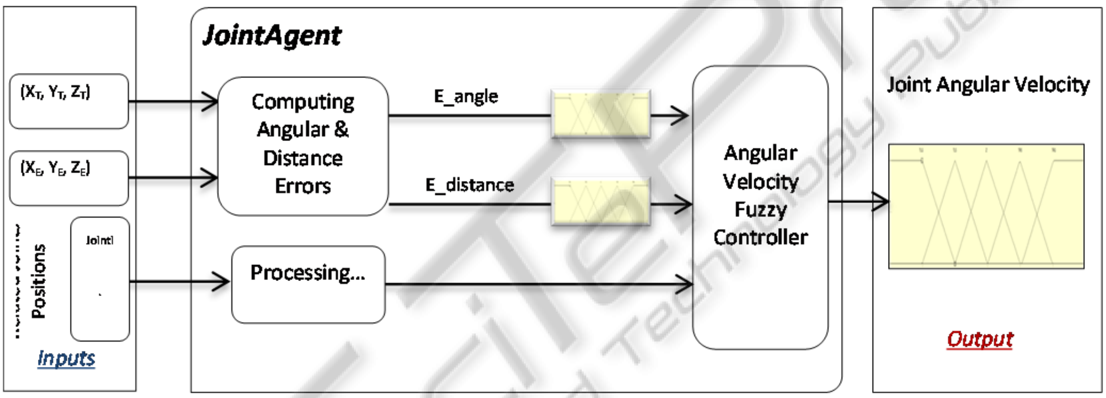

Figure 4: Inner synoptic structure for the *JointAgent*.

scheme for this kind of *ControlAgents* where:

- (Joint$_i$, …, Joint$_l$): they are the other joints of the manipulator related to the current controlled joint. They are defined as the joints that affect the position of the end-effector in a mutual way, i.e., the movement of one of the related joints influences, more or less, the traveled path of the end-effector in the same way.

5.1.3 Fuzzy Controllers

The two following figures (Figure 5 and 6) illustrate some examples of the used *Fuzzy Membership Functions* of the different controllers of the *BaseAgent*:

- In figure 5, the two first *Fuzzy Membership Functions* represent the entries of the *RotationFuzzyController*. They are respectively *(i) E_angle* and *(ii) E_distance*. The third function is the deffuzified output which represents the *Rotation Velocity* value of the *BaseAgent*.

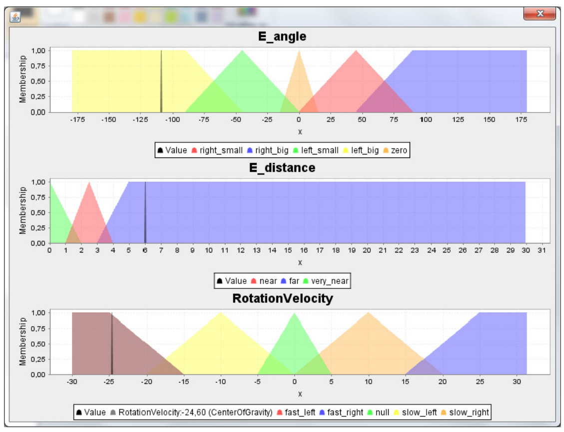

Figure 5: Fuzzy membership functions of the *RotationFuzzyController* for the *BaseAgent*.

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RULE 1: IF E_angle IS left_big AND E_distance IS far THEN
             RotationVelocity IS fast_left;
RULE 2: IF E_angle IS left_big AND E_distance IS near THEN
             RotationVelocity IS slow_left;

RULE 3: IF E_angle IS right_big AND E_distance IS far THEN
             RotationVelocity IS fast_right;
RULE 4: IF E_angle IS right_big AND E_distance IS near THEN
             RotationVelocity IS slow_right;

RULE 5: IF E_angle IS zero THEN
             RotationVelocity IS null;
RULE 6: IF E_distance IS very_near THEN
             RotationVelocity IS null;

RULE 7: IF E_angle IS left_small AND E_distance IS far THEN
             RotationVelocity IS slow_left;
RULE 8: IF E_angle IS right_small AND E_distance IS far THEN
             RotationVelocity IS slow_right;
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Figure 8: Rules-Block used for the *RotationFuzzyController*.

- Likewise, Figure 6 represents the two inputs *(i) E_angle* and *(ii) E_distance,* and the output, *Translation Velocity,* for the *TranslationFuzzyController* of the *BaseAgent.*

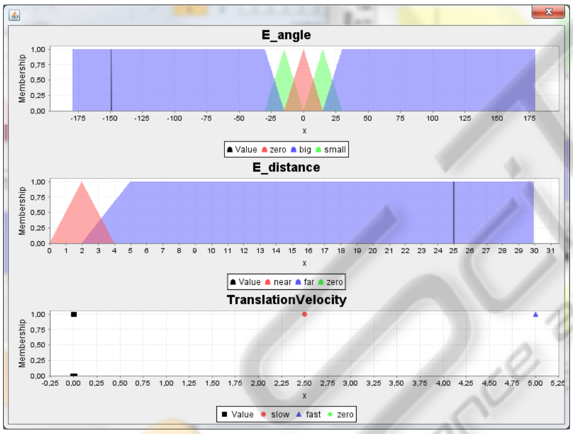

Figure 6: Fuzzy membership functions of the *TranslationFuzzyController* for the *BaseAgent*.

5.2 Presentation of the Control Approach

The objective set for the *ControlAgent* is to move the end-effector of the robot as close as possible to the desired goal, while considering that all of the other ones as stationary.

The *Control Agents,* in our approach, implement this simple reactive behavior in a parallel way based on their local knowledge. They are autonomous and independent with, as a criterion, a local distance minimization. A global emerging behavior will arise satisfying the main objective.

Every single *ControlAgent* admits as an entry the computed value of the current position of the end-effector of the robot computed by using the *Direct Kinematic Model* of the manipulator. Each agent, also, needs the current position of the target in order to compute *E_distance* and *E_angle*. Furthermore, each *JointAgent* requires, besides the current position of the controlled articulation and the instant positions of all its related joints.

In figure 7, each agent is supposed to know the position of the end-effector and the influence of its movement according to the target position in a three-dimensional workspace.

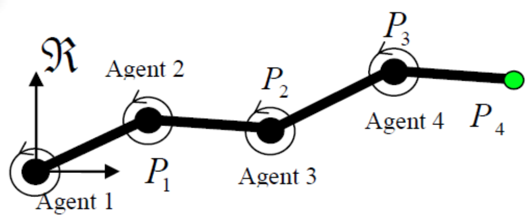

Figure 7: Four Parallel *JointAgent* extent (Delarue, 2007).

The position of the end-effector, in our case, is computed by using the *Direct Kinematic Model.* However, our approach will, also, work with other external modules for computing the instant positions of the end-effector by using, for example, cameras, laser measurement sensors, etc.

The cognitive effort throughout the proposed approach is contained within the fuzzy-logic rules, which are inserted in the fuzzy inference system of each fuzzy controller. The following figure (Figure 8) shows a narrow example from the set of rules used in the *RotationFuzzyController.*

6 EXPECTED OUTCOME

Based on *Artificial Intelligence* techniques used for problem solving, we proposed a novel control architecture for autonomous mobile manipulators. The control process is mainly distributed on several concurrent agents, with independent behaviors, combining reactive and deliberative capacities. This class provides an alternative to the use of mathematical models to control such robots. It offers results that approximate human behaviors, and improves tolerance to certain faults and mechanical failures. Throughout this paper, we have reviewed some recent research works which proposed interesting models for the control of autonomous mobile manipulators.

The future works tends to achieve a thorough testing for the proposed approach in different scenarios. In addition, a comparison of the obtained results should be made with the existent control architectures.

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