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Fuzzy Selection and Blending of Behaviors for Situated Autonomous Agent

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Abstract

Intelligent control is a field of research attempting to attain demanding control goals in complex systems. To do so, many methods and theories must be combined and used efficiently. We propose a new control architecture that tries to unify the principles and characteristics associated with intelligence. This architecture uses behaviors as its basic control components. These behaviors are selected dynamically and their actions are combined according to the intentions of the agent. Introspection of its reactions is one major new ability given to the agent by this architecture. A simulated world for mobile robots is used to validate the characteristics and the principles associated with our proposed architecture. This article focuses on the use of fuzzy logic for the implementation of the architecture in this particular application.

1. Introduction

The design of autonomous agents that must act in unknown, dynamic, noisy and partially predictable environments is a difficult task. The area of intelligent control attempts to reach these demanding control goals in complex systems by combining and extending theories and methods from areas such as control, computer science and operation research [3]. Fuzzy logic is one of the methodologies associated with intelligent control. To avoid the problem of rule formulation for high dimension control problems, decomposition on smaller, hierarchical or modular rule bases is a popular solution. For example, Li [11] uses parallel fuzzy rule bases called 'perception-action' behaviors to control a mobile robot in uncertain environments. Others like Berenji *et al.* [5] and Yager [18] use hierarchical rule bases according to their priority or their specificity. In a more general manner, Lavrov [9] proposes the use of modular rule bases selected by a fuzzy meta-controller. Fuzzy logic is also used to integrate different aspects needed for intelligent control. For example, deSilva [17] uses fuzzy logic to integrate knowledge-based soft control with hard control algorithms by using fuzzy information and degrees of resolution in a control hierarchy. Also, to control an autonomous mobile robot, Saffiotti *et al.* [16] combine reactivity and goal-directed planning to design a fuzzy controller, while Goodridge *et al.* [8] use a fuzzy behaviors along with a motivational state.

But fuzzy logic is only one part of the solution in designing intelligent controllers. There is an actual need to integrate the disparate disciplines and methods useful in intelligent control [1, 7]. In our work, we have developed a new control architecture that tries to unify the principles and characteristics associated with intelligence [14, 15]. This architecture evolved from the hierarchical and modular views in designing fuzzy controllers, to a more general approach allowing the use of reactivity, emergent functionality [6], introspection, motivation, planning and deliberation. This article presents this architecture and its fuzzy modules implemented for validation using a simulated world for mobile robots.

2. Characteristics of the simulated mobile robot

As a complex problem, we wanted to develop an autonomous agent having to deal with various goals like managing its energy, its purposes and its well being. To do this, we have used a simulated world for mobile robots called *BugWorld* [2]. An agent in *BugWorld* has a circular body equipped with distance sensors (similar to range finders) for detecting obstacles and targets. In our experiments, the agent is placed in a room where it can find targets and a charging station. The agent must be able to efficiently reach the targets and must survive by recharging itself when needed. The agent knows nothing about the environment it is in, but has a limited memory to acquire knowledge that can be helpful in its task. For sensing, the agent has at its disposal eight proximity sensors for obstacle, each separated by 45° starting from its nose. There are also two target sensors, one on each side. One target in the room is used as a charging station. The agent can also read the amount of energy available, its speed and its rotation. For actions, the agent can control the speed, the rotation and a variable for the color of the agent.

3. Fuzzy logic for intentional selection of behaviors

Autonomy, learning, adaptation, perception, reasoning, modeling, judging, planning, deliberating, goals, needs, behaviors, reactivity, emergence, holism, introspection, motivations, emotions: these are all concepts associated with intelligence. The unification of all of these concepts is not an essential condition to characterize a natural or an artificial system as intelligent, but it can help improve the level of intelligence manifested or required. This is one goal of the architecture proposed.

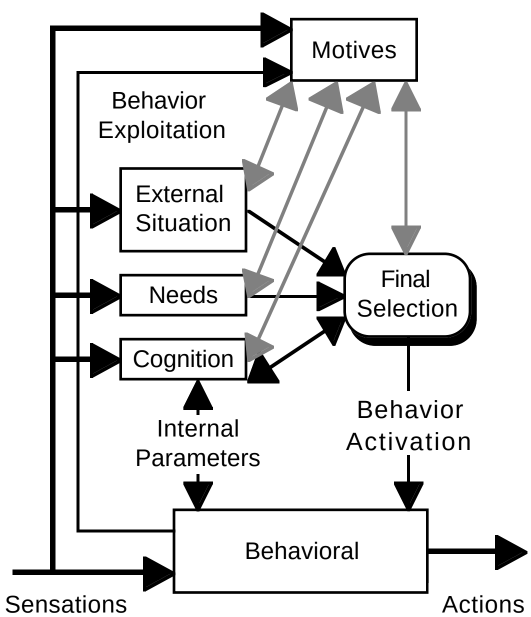

Figure 1. Control architecture proposed

This architecture consists of six modules as illustrated in Figure 1. The *Behavioral* module is a behavior-based system [6, 13]. It is made of different behaviors connecting sensory information to actuation. It defines the agent's skills for reacting to the situations encountered in the environment. But to have a more general mechanism for behavior-based system, we must consider the possibility of selecting behaviors dynamically and changing their respective priority, according to the situations encountered and the internal states of the agent. We must also allow the blending of the commands formulated by the exploited behaviors, according to an appropriate arbitration scheme (and not always consider a subsumption mechanism [6]). So, with the proposed control architecture, the activated behaviors all run in parallel and their resulting commands are blended according to their respective importance, to obtain the control actions.

The relevance in using each behavior is determined by three recommendation modules. The *External Situation* module evaluates special external conditions in the environment that can affect behavior selection. The *Needs* module selects behaviors according to the needs and goals of the agent. The third recommendation module, called the *Cognition* module, is for cognitive recommendation. This module learns things about the external environment and how the agent operates in it by observing its reactions, behavior selections and from information sensed from the environment. It can then exploit this acquired knowledge or some innate knowledge to plan or to prepare the use of behaviors. Cognitive recommendations can be influenced by behaviors via the *Internal Parameters* link, like they can influence behavior reactivity using the same link. These three recommendation modules suggest the use of different behaviors to the *Final Selection* module, which combines them appropriately to establish the activation of the behaviors (*Behavior Activation*). An active behavior is allowed to participate to the control of the agent, and it is said to be exploited if it is used to control the agent (by reacting to the sensations associated with the purpose of the behavior). Finally, the *Motives* module is composed of motives used to examine and to coordinate the proper working of the other modules. Motives are influenced by the environment, the internal drives of the agent, its knowledge and by observing the effective use of the behaviors (*Behavior Exploitation*). The agent is then able to adapt its emerging behavior to its needs, its knowledge and its ability to satisfy its intentions.

For the experiments with the simulated world for mobile robots, fuzzy logic is used for behaviors and the blending of their control actions, as in Saffiotti *et al.* [16]. It is also used by the *External Situation* module and the *Needs* module for recommending behaviors, and by the *Final Selection* module for combining these recommendations. A topological graph, having some similarities with the work of Mataric [13], is used by the *Cognition* module to construct an internal representation of the environment based on experiences of the agent. Finally, activation levels as in Maes [12] are used for motives. This article only describes the fuzzy modules used for experimentation. A description of the topological graph and the motives used can be found in [14, 15].

3.1. Fuzzy behaviors

A fuzzy behavior uses rules and linguistic variables to establish the relation between sensations and actions. The processing steps are similar to the ones for fuzzy systems, i.e. fuzzification, rule inference and defuzzification. The fuzzy conjunction operator $\otimes$ used is the minimum, and the fuzzy disjunction operator ⊕ used is the maximum. Defuzzification is done by using the center of area method [10], allowing the blending of the actions given by the behaviors as in Saffiotti *et al.* [16]. The only difference with the fuzzy inference steps is that rule firing strength μ_{Bx} is affected by the μ_{act}, the activation of the behaviors, given by the *Final Selection* module. This operation is presented by relation (1) for rule *r* of the behavior *j*. Linguistic variables *B* and *C* refer to fuzzy variables associated with a control variable.

$$\mu_{C_{rj}}(Action) = \otimes\left[\mu_{B_{rj}}(Action), \mu_{act}(j)\right] \qquad (1)$$

Twelve behaviors are used in our experiments. The first is EMERGENCY, which is responsible for moving the agent when immediate danger is detected in its front. The rules are presented in Figure 2. Using this behavior, the agent slows down if it is in front and very close to an obstacle; it turns away from an obstacle at its side (the variable *x* is for *left* or *right*, and *y* denotes the opposite direction); and it makes a wide turn left when the obstacle is right in its front.

```
<Slow-down-danger>
    IF      Danger-in-front
    AND     NOT (Speed-Null)
    THEN    Slow-down-fast
<Danger-x>
    IF      Danger-front-x
    AND     NOT (Danger-front-y)
    THEN    Turn-y
<Danger-in-front>
    IF      Speed-Null
    AND     Danger-in-front
    AND     Danger-front-right
    AND     Danger-front-left
    THEN    Turn-left-big
```

Figure 2. Rules for the EMERGENCY behavior

Other behaviors include AVOID to move away from obstacles, SPEED to maintain a constant cruising velocity, ALIGN to follow boundaries, TARGET to search for a target, RECHARGE to search for a charging station and to energize the agent, BACKING to move back, MADNESS to make the agent turn around on itself, TURN90 to move away from a boundary, TURN180 to make a U-turn, ALARM to express some internal state of the agent by changing its color to red, and a behavior for identification of topological states (used by the *Cognition* module [15]).

Rules for the TURN180 behavior are presented in Figure 3. The behavior starts by slowing down the agent. It then makes it turn away from a boundary until the other side is perceived by the agent. The underlined antecedents and consequences of the rules are adjusted by the *Cognition* module via the *Internal Parameters* link before using the behavior, to select the rotation side.

```
<Immobilization>
    IF      NOT(Speed-almost-null)
    THEN    Slow-down-fast
<Turn-180-left>
    IF      NOT(Side-left-near)
    AND     Speed-almost-null
    THEN    Turn-left
<Turn-180-left-end>
    IF      Side-left-near
    AND     Back-near
    AND     Speed-almost-null
    THEN    Turn-left
```

Figure 3. Rules for the TURN180 behavior

3.2. *External Situation* and *Needs* modules

These two modules recommend the use or the inhibition of behaviors. They are implemented using fuzzy logic. The operations consist of fuzzification and rule inference, and the results are fuzzy measures of the desirability or the undesirability of behaviors. This differs from the approach of Saffiotti *et al.* [16] which uses only a desirability measure given from a local perceptual space. The difference between these two modules is that the *Needs* module can use motives as antecedents in its rules.

```
<Danger>
    IF      Danger-in-front
    OR      Danger-front-right
    OR      Danger-front-left
    THEN    EMERGENCY
<Obstacle>
    IF      Obstacle-in-front
    THEN    AVOID AND NOT(TARGET)
<Normal>
    IF      NOT(Obstacle-in-front)
    THEN    SPEED AND ALIGN
<Topological states>
    IF      NOT(Speed-null)
    AND     NOT(Rotation-null)
    THEN    TOPOLOGICAL STATE IDENT.
<Charging>
    IF      Speed-almost-null
    AND     Charging-station-visible-left
    AND     Charging-station-visible-right
    THEN    NOT(ALIGN)
```

Figure 4. Rules for the *External Situation* module

Figure 4 shows the rules used by the *External Situation* module, and Figure 5 presents rules for the *Needs* module.

In these rules, an undesired behavior is a consequence preceded by NOT. The antecedent *Want-Recharge* is associated with the motive EAT, while *Fulfillment-small* and *Fulfillment-big* are based on the FULFILLMENT motive. This last motive is an accomplishment motive used to monitor when the agent needs to find targets.

```
<Want-to-recharge>
    IF      Want-Recharge
    THEN    RECHARGE, NOT(MADNESS)
            NOT(TURN90) AND NOT(TARGET)
<Charging-station-near-x>
    IF      Want-Recharge
    AND     Charging-station-visible-x
    THEN    NOT(SPEED)
<Charging-station-nearer-x>
    IF      Want-Recharge
    AND     Charging-station-nearer-x
    THEN    NOT(ALIGN)
<Difficulties>
    IF      Distress-exists
    THEN    BACKING, ALARM
    AND     NOT(ALIGN)
<Accomplishment>
    IF      Fulfillment-small
    THEN    TARGET
<Happiness>
    IF      Fulfillment-big
    THEN    MADNESS, NOT(SPEED)
    AND     NOT(ALIGN)
```

Figure 5. Rules for the *Needs* module

3.3. Fuzzy influences on motives

The agent has five basic goals in the environment: to find a charging station and recharge itself; to reach targets; to detect improper use of its behavior according to its intentions; to explore the environment and acquire knowledge from it; and to use this knowledge when the agent judges it is accurate enough. Motives are responsible for coordinating and supervising these goals according to the actual experiences of the agent in the environment. To do so, ten motives are used by the agent. Each one has its own activation mechanism and can be influenced by sensations (internal or external), behavior activation or exploitation, internal variables of the recommendation modules, or by other motives. One important influence on motives is the observation of *Behavior Exploitation*. Because behaviors are fuzzy, *Behavior Exploitation* is a fuzzy measure defined in relation (2), approximating the contribution or the importance of the behavior to the fuzzy control actions formulated before defuzzification. It combines the activation of a behavior with its reactivity to the environment.

$$\mu_{exp}(j) = \mu_{act}(j) \otimes \left(\oplus \left[\mu_{B_{rj}}(Action) \right] \right) \qquad (2)$$

Two motives which monitor the good operation of the agent are particularly influenced by *Behavior Exploitation*. The motive DISTRESS is used to monitor the proper working of behaviors like EMERGENCY, AVOID and SPEED. These first two behaviors must normally be exploited very briefly to move the agent away from trouble areas. However, if their μ_{exp} remains approximately constant for a long period of time, this may be a sign of conflict between the behaviors used. For the SPEED behavior, a full exploitation for a long period of time is also a sign of trouble indicating that the agent is not able to reach its desired velocity. The SPEED behavior is composed of only two rules indicating when to increase or to decrease the speed of the agent. These rules use two fuzzy linguistic variables overlapping by 50% at the desired velocity, so a constant behavior exploitation of 0.5 indicates normal working condition. The other motive, called DECEPTION, increases when the agent is moving away from a target or a charging station. This is detected by a decrease in the exploitation of the TARGET or RECHARGE behaviors respectively. This motive influences the use of the TURN180 behavior via the *Cognition* module.

3.4. *Final Selection* module

The fact of using desirability and undesirability for recommending behaviors has been inspired by the hedonic axiom which indicates that the organisms direct their behaviors to minimize aversions and maximize desirable outcomes [4]. Here, *Behavior Activation* is evaluated based on a hedonic continuum established from the fuzzy desirability and undesirability measures. First, these measures are respectively combined for each behaviors using the fuzzy disjunction operator maximum. Then, the desirability is subtracted to the undesirability measure and the behavior is activated if the result is greater than zero. Relation (3) shows these operations where *m* represents the recommendations from the three recommendation modules. So, to be activated, the desirability of the behavior must be higher than its undesirability.

$$\mu_{act}(j) = \max\left(0, \oplus\left[\mu_{des_m}(j)\right] - \oplus\left[\mu_{und_m}(j)\right]\right) \quad (3)$$

4. Experimental results

For our experimentation, when the agent reaches a charging station, the agent detects that it is recharging by sensing an increase of its energy level. It stops recharging when its energy level is maximum. Figure 6 illustrates

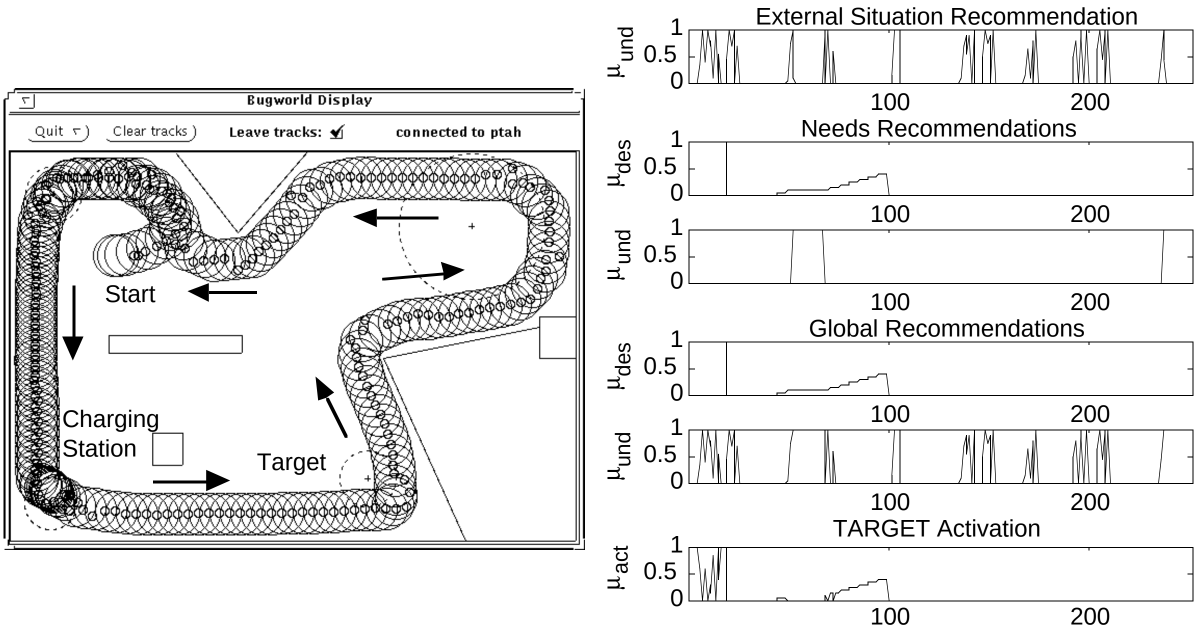

Figure 6. Trace and recommendations of the TARGET behavior

the initial trajectory followed by the agent starting from a given point in the environment. This environment comes with *BugWorld*. The agent starts by reaching the upper left corner target and continues its path by following boundaries. It stops at the lower left corner where the charging station is located. It then continues to follow boundaries, reaching the lower right target and the upper right target successively. After that, the agent again reaches the upper left target and the charging station. Recommendations for the behavior TARGET are presented with this figure. The *External Situation* module inhibits the use of TARGET when an obstacle is detected in front of the agent (see rule *Obstacle* of Figure 4). The *Needs* module is in favor of using TARGET when the motive FULFILLMENT is small, but not when the agent is recharging (see rules *Want-to-recharge* and *Accomplishment* of Figure 5). The global recommendations are obtained from the fuzzy disjunction of respectively the desirability and undesirability measures formulated by the recommendation modules. The activation of TARGET is the result of relation (3).

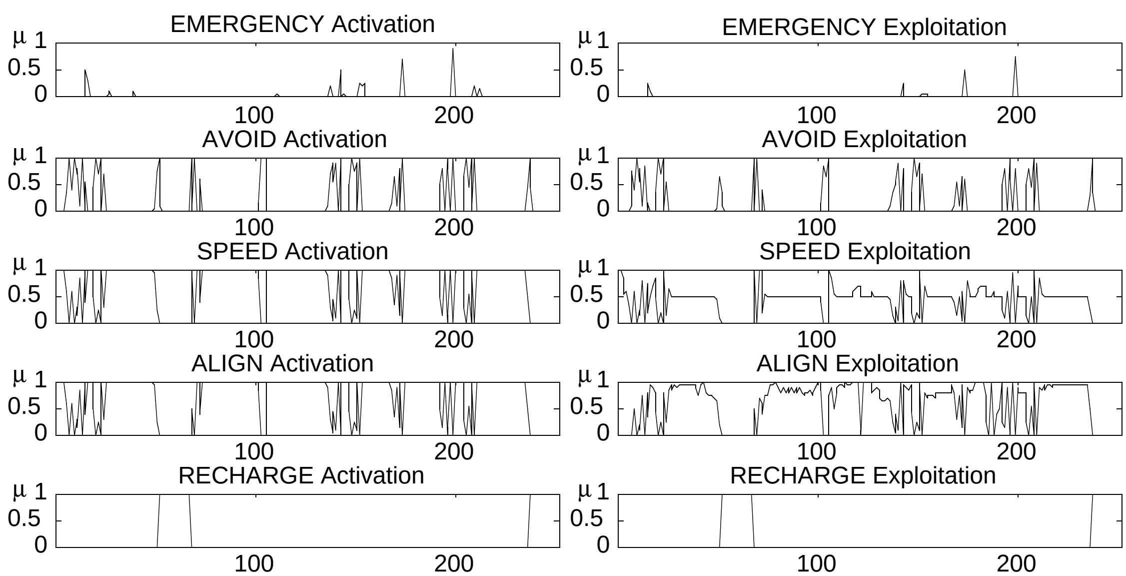

Figure 7. Behavior activation and exploitation

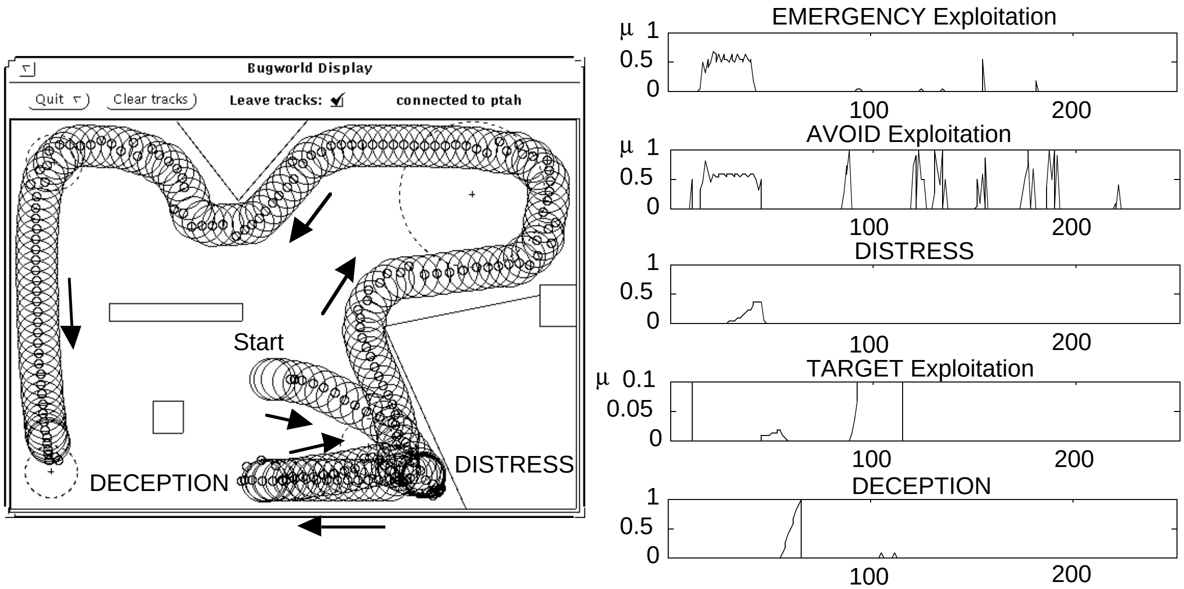

Figure 8. Trace and conditions for the motives DISTRESS and DECEPTION

An activated behavior does not mean it is exploited. In Figure 7, the exploitation of the behaviors activated for the trace presented in Figure 6 are shown. The activation of the EMERGENCY behavior is very similar to its exploitation because it is activated (see rule *Danger* of Figure 4) by the same reacting conditions of the behavior (see Figure 2), as for the AVOID behavior. The SPEED and ALIGN behaviors are activated by the same rule here (see rule *Normal* of Figure 4), but their exploitations are quite different. Finally, the RECHARGE behavior is activated and exploited directly in this case when the agent passes through the charging station, showing opportunism to recharge itself.

In Figure 8, the agent starts from another point in the environment. Because of a conflict between EMERGENCY, AVOID and ALIGN behaviors, the agent gets stuck in the lower right corner. The simultaneous constant exploitation of EMERGENCY and AVOID excites the motive DISTRESS from which the BACKING behavior is recommended by the *Needs* module. The agent then starts moving towards the charging station, but observes a decrease in the exploitation of the TARGET behavior. This indicates that it is moving away from a target which, in this case, is the upper right target. The motive DECEPTION is then increased and the agent makes a U-turn by using the TURN180 behavior. The agent continues its path by following boundaries until it reaches the charging station.

Other environments have also been used during our experiments. In one case, a moving obstacle is placed in

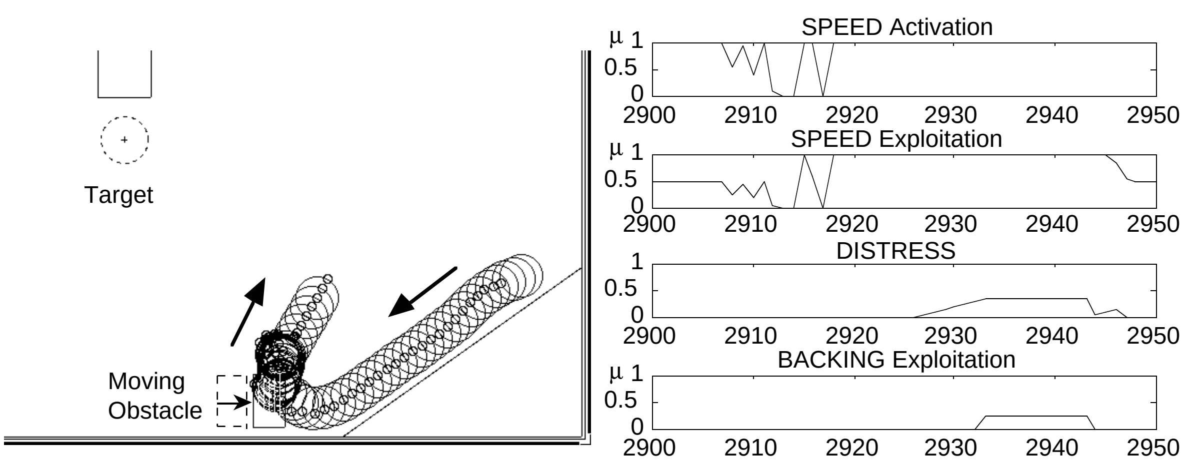

Figure 9. DISTRESS motive when a mobile obstacle came toward the agent

the same room with the agent. In Figure 9, the obstacle is moving toward the agent. The agent tries to move away from the obstacle, but could not do so because its back side collides with the moving obstacle. The agent does not have any behaviors to avoid obstacles from its back. But, by observing that the SPEED behavior is fully exploited for a long period of time (because the agent wants to move ahead but simply cannot get some speed), the motive DISTRESS is excited so that the BACKING behavior can be used.

5. Conclusion

This article focused on the use of fuzzy logic for the implementation, blending, selection, exploitation and recommendation of behaviors in a new control architecture. Because of its ability to deal with vagueness, fuzzy logic proved to be quite useful for the design of an agent having to deal with various constraints. The use of fuzzy behaviors reacting to the external events helps the agent adapt to the environment, while the introspection made by the fuzzy behavioral exploitation measure makes the agent adapt to its own limitations in interacting with its external environment and its internal intentional senses. The notion of behavior and the architecture modules can also help make the decomposition of fuzzy rule bases needed for high dimensional or complex problems. With this architecture, other types of mechanisms could be used in its modules and modules can be used, if needed, according to the purpose of the system to be controlled. This way, the proposed architecture tries to unify the different aspects associated with intelligent behavior.

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References

[1] Albus, J.S., “Outline for a theory of intelligence”, *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 21, no. 3, pp. 473-509, May/June 1991.

[2] Almàssy, N., “BugWorld: A distributed environment for the development of control architectures in multi-agent worlds”, Tech. Report 93.32 (ftp anonymous, almassy@ifi.unizh.ch), Department of Computer Science, University Zurich-Irchel, December 1993.

[3] Antsaklis, P., “Defining intelligent control. Report of the task force on intelligent control”, *IEEE Control Systems*, pp. 4-5 & 58-66, June 1994.

[4] Beck, R.C., *Motivation. Theories and Principles*, Second Edition, Prentice Hall, 1983.

[5] Berenji, H.R., Chen, Y.Y., Lee, C.C., Jang, J.S., and Murugesan, S., “A hierarchical approach to designing approximate reasoning-based controllers for dynamic physical systems”, in *Uncertainty in Artificial Intelligence 6*, Bonissone, P.P., Henrion, M., Kanal, L.N., and Lemmer, J.F. (ed.), Elsevier Science, 1991, pp. 331-343.

[6] Brooks, R.A., “A robust layered control system for a mobile robot”, *IEEE Journal of Robotics and Automation*, vol. RA-2, no. 1, pp. 14-23, March 1986.

[7] Corfield, S.J., Fraser, R.J.C., and Harris, C.J., “Architecture for real-time control of autonomous vehicles”, *Comput. Control. Eng. J.*, vol. 2, no. 6, pp. 254-262, November 1991.

[8] Goodridge, S.G., Luo, R.C., and Kay, M.G., “Multi-layered fuzzy behavior fusion for real-time control of systems with many sensors”, in *Proc. IEEE Int'l Conf. on Multisensor Fusion and Integration for Intelligent Systems (MFI)*, Las Vegas, October 1994, pp. 272-279.

[9] Lavrov, A.A., “Modular reconfigurable controllers with fuzzy meta-control”, in *Proc. IEEE Int'l Conf. on Fuzzy Systems*, 1994, pp. 1564-1567.

[10] Lee, C.C., “Fuzzy logic in control systems: fuzzy logic controller”, *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 20, no. 2, pp. 404-435, March/April 1990.

[11] Li, W., “Fuzzy logic-based 'perception-action' behavior control of a mobile robot in uncertain environments”, in *Proc. IEEE Int'l Conf. on Fuzzy Systems*, 1994, pp. 1626-1631.

[12] Maes, P., “A bottom-up mechanism for behavior selection in an artificial creature”, in *From Animals to Animats. Proc. First Int'l Conf. on Simulation of Adaptive Behavior*, The MIT Press, 1991, pp. 238-246.

[13] Mataric, M.J., “Integration of representation into goal-driven behavior-based robots”, *IEEE Trans. on Robotics and Automation*, vol. 8, no. 3, pp. 304-312, 1992.

[14] Michaud, F., “Nouvelle architecture unifiée de contrôle intelligent par sélection intentionnelle de comportements”, Ph.D. Thesis, Department of Electrical and Computer Engineering, Université de Sherbrooke, May 1996 (in French).

[15] Michaud, F., Lachiver, G., and Le Dinh, C.T., “A new control architecture combining reactivity, deliberation and motivation for situated autonomous agent”, in *Proc. Conf. Simulation of Adaptive Behavior*, September 1996.

[16] Saffiotti, A., Ruspini, E., and Konolige, K., “A fuzzy controller for Flakey, an autonomous mobile robot”, Technical Note 529, SRI International, March 1993.

[17] de Silva, C.W., *Intelligent Control: Fuzzy Logic Applications*, CRC Press, 1995.

[18] Yager, R.R., “On a hierarchical structure for fuzzy modeling and control”, *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 23, no. 4, pp. 1189-1197, July/August 1993.