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Although Zadeh defined the basic operations of fuzzy set theory over thirty years ago (Zadeh, 1965), fuzzy logic-based controllers have just recently become the technique of choice for many researchers in robotics. Fuzzy logic controllers allow for the integration of high-level, human-designed plans to operate along side immediate, reactive actions in a successful manner. The key to this line of research has been the development of the concept of *behaviors*.

Behaviors as a method of controlling robots were inspired by Brooks' *subsumption architecture* (Brooks, 1986). Generally, a *behavior* is a simple, focused, perceptual trigger and associated action. An example might look like: **IF obstacle-on-right THEN turn-left**. The **obstacle-on-right** is the perceptual trigger that activates the robot to **turn-left**.

The ideas of behaviors and fuzzy logic were a perfect match; behaviors provide an abstract interface for humans to enter plans, and fuzzy logic provides a method for dealing with inexact variable values. A robot under the control of a fuzzy logic, behavior-based rule (such as **IF obstacle-on-right THEN turn-left**) will act in an appropriate manner when **obstacle-on-right** has a value somewhere between absolute true and absolute false. The hope is that general, robust functioning can be attained with just a few simple behaviors mediated by a fuzzy logic controller (Saffiotti, Ruspini, and Konolige, 1993).

Our goal was to integrate learning into this well-known methodology. Although some success has been reached without learning, we believe that learning will be necessary as we require robots to process more complex sensory information, and require them to perform more complex tasks.

One obvious problem to assign to a learning module might be the problem of creating the fuzzy logic rules. However, this is exactly where human expertise benefits a fuzzy logic controller the most. That is, humans are able to efficiently and effectively write the abstract rules, such as **IF obstacle-on-right THEN turn-left**. We believe that a much better task for a learning module is in the recognition and categorization of the perceptual triggers (i.e., **obstacle-on-right**). Although **obstacle-on-right** can be gleaned directly from low-level sonar sensors, more sophisticated perceptions cannot. For instance, consider the goals of attempting to get close to dogs, but avoiding cats. The human module in the controller can easily create the rules (i.e., **IF cat THEN reverse**). The hard portion of the problem is coming up with the appropriate truth values for the categories **cat** and **dog**.

Our solution to this problem was to insert an artificial neural network between the low-level sensors and the fuzzy logic controller. Artificial neural networks can be trained (via back-propagation or some other method) to read in low-level sensors, and produce activation values on output nodes. The output values, representing possibly high-level categories (like "cat"), can be used directly (or nearly directly) in a fuzzy logic controller. This methodology is quite general. For example, a network can be trained to read in 2D visual images and sonar readings, and produce output nodes representing the presence or absence of a cat. In addition, such a network's output activation will typically gracefully drop as the input image looks less like a cat. As the output value is treated as a likelihood value in the fuzzy logic controller, this is exactly the desired behavior.

Alone, such a network's use is limited. However, when used in coordination with hand-crafted rules in a fuzzy logic control system, the results can be quite general and robust.

References

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