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## Explorations in Evolutionary Robotics

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*We discuss the methodological foundations for our work on the development of cognitive architectures, or control systems, for situated autonomous agents. Our focus is the problems of developing sensorimotor control systems for mobile robots, but we also discuss the applicability of our approach to the study of biological systems. We argue that, for agents required to exhibit sophisticated interactions with their environments, complex sensorimotor processing is necessary, and the design, by hand, of control systems capable of such processing is likely to become prohibitively difficult as complexity increases. We propose an automatic design process involving artificial evolution, wherein the basic building blocks used for evolving cognitive architectures are noise-tolerant dynamical neural networks. These networks may be recurrent and should operate in real time. The evolution should be incremental, using an extended and modified version of a genetic algorithm.*

*Practical constraints suggest that initial architecture evaluations should be done largely in simulation. To support our claims and proposals, we summarize results from some preliminary simulation experiments in which visually guided robots are evolved to operate in simple environments. Significantly, our results demonstrate that robust visually guided control systems evolve from evaluation functions that do not explicitly require monitoring visual input. We outline the difficulties involved in continuing with simulations and conclude by describing specialized visuorobotic equipment, designed to eliminate the need for simulated sensors and actuators.*

**Key Words:** *evolutionary robotics; autonomous agents; genetic algorithms; SAGA; sensorimotor coordination; neural networks*

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of this wider biological framework applies to the development of artificial cognitive systems.

One distinguishing consequence of this focus on artificial neural networks as generators of behaviors within particular environments is a dependence on working with *animals* (i.e., artificial creatures [Wilson, 1985; Brooks, 1986, 1990b]), either real physical robots or simulated autonomous agents situated in some virtual reality. It should be noted that the problems encountered in ensuring adaptive sensorimotor coordination in real robots, or in virtual agents within appropriate simulated worlds, are sufficiently similar to the problems encountered by animals that there is a strong potential for fruitful interdisciplinary study. For example, McFarland (1990) has proposed a number of mathematical analogs between adaptive behaviors in animals and adaptive behaviors in robots.

The work described here involves using a form of simulated evolution, based on an extended genetic algorithm, to develop neural network control systems for mobile robots. Taking a further cue from biology, our definition of *control system* includes parameters determining the robot's sensors (and, in principle, motors), so the sensorimotor *morphology* of the robot is evolved *concurrently* with the controller networks.

As hinted at earlier, our rationale for employing artificial evolution centers on a belief that the task of designing sensorimotor control systems in which there are many interactions between subcomponents is sufficiently difficult that as required behavioral and, hence, neural complexity increases, purely manual techniques are unlikely to be sufficient. Automatic techniques have been successfully developed in other fields, such as operations research, to aid in complex tasks previously performed entirely by hand. Although the need for automation in other fields lends some support to our claim that it will be needed in the field of autonomous agent design, this does not guarantee that techniques developed for other domains will transfer easily to ours.

Indeed, in order to exploit fully the potential of simulated evolution, it is necessary to employ a form of genetic algorithm that is significantly extended from the straightforward genetic algorithms used in applications that can be reduced to function optimization (Goldberg, 1989; Holland, 1975). Necessary adaptations to genetic algorithms are summarized here and discussed fully in Harvey (1992a, 1992b, 1993).

To begin, we present our rationale, which proposes that an evolutionary approach to the design of robots can be expected to supercede design by hand, and we explore issues arising from this. After setting the stage with these theoretical considerations, we report on preliminary simulation experiments involving the use of an extended genetic algorithm to evolve control networks for simple robots equipped with a few

## 1 Introduction

There is a similarity between the engineering problem of creating a successful autonomous robot intended to act in complex noisy environments and the scientific problem of proposing a plausible model for mechanisms underlying the generation of adaptive behavior in an animal. Both tasks essentially involve *designing* a system that satisfies given constraints, and this design process requires skilled creative insight, something we believe is impossible to formalize. The work presented here is motivated by the concern that for both problems, the sheer complexity of designing cognitive systems may severely curtail the possibilities for progress if we continue to rely on purely intuitive and manual techniques. For this reason, we are attempting to develop automatic techniques that will be of use both in building intelligent autonomous robots and in understanding how animals are "built." The bulk of this article concentrates on the development of such a technique for building control systems, or *cognitive architectures*, for autonomous robots, but we do discuss briefly how this might be applied to problems in biology.

In our attempts to develop artificial cognitive systems, we assume that the study of biological cognitive systems can be highly informative. The recent increase of interest in artificial neural network research has given rise to a proliferation of work in the literature that lays claims to biological inspiration or biological plausibility. Yet the vast majority of such research is motivated almost entirely by physiological observations (i.e., that the nervous systems underlying cognition in animals can, at certain levels of abstraction, be modeled as networks of simple processing units operating in parallel). We, in common with a number of other authors, believe that it is necessary to study cognition from a much wider biological perspective.

In particular, we consider it essential to acknowledge that in the context of cognition, neural networks in animals serve the function of coordinating perception and action in order to generate adaptive behaviors, a point long stressed by Arbib (see, e.g., Arbib, 1989). In the biology literature, study of the neural mechanisms underlying the generation of behaviors is known as *neuroethology* (*ethology* being the study of animal behavior), and so we consider our work to be closer to computational neuroethology (Beer, 1990; Cliff, 1991b) than to computational neuroscience (Srinowski, Koch, & Churchland, 1988). However, adopting an ethological perspective also requires that ecological factors be taken into account: Whether a particular behavior is adaptive depends crucially on the immediate environment and ecological niche of the animal.

The study of neural function in ethological, ecological, and evolutionary contexts is standard practice in biology but much less common in artificial neural network research. A major portion of this article is devoted to a discussion of how adoption

