Ecological Robotics: A Schema-theoretic Approach

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An in-depth understanding and dynamic modeling of the relationship a robot has with its environment (i.e., the overall ecology) is important to ensure that fielded robotic systems are:

- Not competing with other agents that can do the task more effectively and hence prove themselves useless.
- Successful competitors within the ecological system and can potentially displace less efficient agents.
- Ecologically sensitive so that agent-environmental system dynamics are well-modeled and as predictable as possible whenever new robotic technology is introduced.

Little emphasis to date has been placed on this ecological approach within mobile robotics research, although some related research has been conducted in the recent past in the context of the artificial life community. All too often, however, these approaches lack both a strong biological basis for their working assumptions and any formal underpinnings (neural, behavioral, and computational) for the results they obtain. We address these problems directly using schema theory and neurophysiological and ethological models to provide credible, generalizable, and useful results in this domain. These systems are currently grounded in robotic simulations and ultimately in actual robotic hardware.

The study of sensory guided behaviors in living animals has become of general significance not only for scientists working in neuroscience and computational neuroscience but also for scientists working in robotics and distributed artificial intelligence, who are using functional principles generated from the study of living animals as models to build computer based automata that display complex sensorimotor behaviors. Our research effort, which follows these lines, is tied together by software tools including: NSL, a neural simulation language; ASL, an abstract schema language; and *MissionLab*, a schema-based mission-oriented simulation and robot implementation environment.

1. Background and Motivation

1.1 Neuroscience and Ethology

Our group has been studying visuomotor coordination phenomena in amphibia (toad) and insects (praying mantis). These animals live within a three dimensional environment, rich in multiple modes of sensory signals, but their behavior is mainly guided by visual information. From an ecological point of view, these animals react to visual environmental domains of interaction which can be classified into two groups: moving and non-moving objects. Diverse stationary objects may influence the animal's next action which, in general, is directed to improve the animal's survival chances, e.g., frogs moved towards zones in the visual field where blue is preponderant, a situation that might be associated with the presence of prey to eat, and of water to maintain its body humidity [23]. In the case of the praying mantis, when it is placed in an open field with no mobile objects around, it executes several motor actions that conform to what we have called the *chantlitaxia* (i.e., in search of a proper habitat) behavior.

Different moving objects may elicit a specific behavior from these animals: (a) during the mating season, the presence of a female frog in the male's visual field yields an orienting response towards the female, followed by an approaching action if the female is far away, or a clasping behavior if the female is withing reaching distance in the frontal part of the visual field; (b) a predator-like stimulus may yield one of several avoidance behaviors depending upon its parametric composition, in amphibia, a flying large stimulus close to the animal releases a ducking response [18,19,25,27], whereas, in the mantis, the same stimulus elicits a deimatic behavior (i.e., the mantis stand up, and opens the wings and forearms displaying a posture that shows a much bigger size than it has) [28]; and (c) the presence of a potential prey may elicit one of several actions, depending on the spatio-temporal relationship between the prey and the animal (i.e., amphibia or insect), an orienting response towards the part of the visual field where the prey is located, followed by an approaching behavior when the prey is located far afield in the frontal part of the visual field and a snapping response, in the case of amphibia [17], or a grasping response in the praying mantis [12] if the stimulus is at a reaching distance.

Our group has developed theoretical (i.e., neural and schema-theoretic) models of visuomotor coordination phenomena in amphibia [13,14,26,16]. These results have allowed us to postulate the underlying mechanisms of visuomotor integration and have developed into a parallel distributed neural processing system, in which those neural structures receiving direct input from the retina (retinula in the insects) represent more than a visual (sensory) map. Rather they are the site of integration of external stimuli coming through the retina, and signals generated in brain structures that might be involved in the processing of information related to motivational factors and learning processes. The animal's response towards, or away from, visual stimuli could be described as the integration of neural signals generated by dynamic systems working at different time scales: (a) Activation Dynamics, signals activated in the animal's nervous system by the presence of a visual stimulus in its visual field (e.g., prey-catching may take 100's of msecs.); (b) Motivational Dynamics, some changes in factors that modulate the animal's motivation to display certain behaviors (e.g., prey catching intensity varies depending on the time of the day); and (c) Time-varying Dynamics, learning processes require at least the occurrence of one activation dynamic process to modify future interactions with the same kind of stimulus (e.g., the bee sting at the toad's tongue is enough for preventing that toad from catching bees in the future [19]), whereas other learning processes require a longer training (e.g., stimulus specific habituation is accomplished after stimulating repetitively the toad with the same stimulus for few minutes to an hour and a half) (e.g., see papers in [20,15]).

1.2 Frameworks for Expression

There have been a number of attempts to define a methodology for the analysis of large complex dynamic systems such as these. One approach is schema theory [2] which lays down the conceptual framework for knowledge representation inspired from biological and cognitive studies. ASL (Abstract Schema Language) [34] follows a hierarchical model, enabling top-down and bottom-up designs, supported by a concurrent language permitting a distributed implementation, while integrating neural network processing. ASL's main characteristics are its dynamic and asynchronous nature, and the inclusion of dynamic schema assemblages as the basis for composition. Essentially a schema is a template from which many instances can be created, in a fashion similar to that of object-oriented systems. The behavioral description of a schema describes how an instance of that schema will behave in response to external communications. As action and perception progress, certain schema instances need no longer be active, while new ones are added as new objects are perceived and new plans of action are elaborated. A schema assemblage, the basis for aggregation, is a network of schema instances, and it may be considered a schema for further processing. Since a schema may be decomposed into any number of component schemas, there may be virtually any level of abstraction. The major properties introduced in ASL:

- **Delegation**: Schema implementation may be chosen in a dynamic way, via the ASL high-level language or by delegating processing to neural networks.
- **Wrapping**: Previously developed code may be statically linked within a schema.
- **Heterogeneity**: Incorporation of two different programming concepts, neural processing and procedural processing, into a single model.
- **Encapsulation**: A schema instance includes a public interface while all data and its particular implementation are internal, thus providing flexibility and extensiblity since local changes to its internal data structure and implementation do not affect its interaction with other schema instances. Furthermore, the communication abstraction of input and output ports permits greater flexibility in communication and in the design of schema architectures.
- **Reusability**: Following object-oriented abstractions, such as inheritance, the definition of schemas as shared templates from which schema instantiation takes place, permits their reusability in new schema definitions.

In order to integrate neural processing with schemas into a single computational model, it was first necessary to design a distributed environment where neural entities can be mapped as multi-granular concurrent processes [33]. In terms of neural networks per se, we have developed the NSL, Neural Simulation Language, for simulation of large-scale neural networks [35].

1.3 Robotic Embodiment

To realize these models within robotic systems, we have adopted the framework of the Autonomous Robot Architecture (AuRA) [5], using motor schemas to provide the reactive component of navigation. Motor schemas (behaviors) are selected and instantiated in a manner that enables the robot to interact successfully with unexpected events while still striving to satisfy its higher level goals. Multiple active schemas are usually present, each producing a velocity vector driving the robot in response to its perceptual stimulus. The resultant vectors are combined as necessary according to the underlying animal model and normalized to fit within the limits of the robot vehicle, yielding a single combined velocity for the robot. These vectors are continually updated as new perceptual information arrives, with the result being immediate response to any new sensory data. Advantages of this approach include rapid computation and the ability to be mapped onto parallel architectures making real-time response easily attainable. Modular construction affords ease of integration of new motor behaviors simplifying both system maintenance and the ease of transfer to new problem domains. Motor schemas readily reflect uncertainty in perception, when such a measure is available, and also react immediately to environmental sensor data. These factors all contribute to the needs of a motor control system that will successfully assist a robot's intentional goals.

Our earlier work [9,11], describes our position on integrating biological bases for multiagent teams. Even earlier work from our laboratory [8,6,7] shows the influence that biological models have had on our control methods for robotic systems. Exemplifying our multiagent research, we have demonstrated a system which uses homogeneous units to carry out tasks of foraging and retrieval of objects, grazing, and consuming objects in a cluttered world [11]. We have extended our research in schema-based navigation [4,3] to include patterned sequences of behaviors [1] and their use in multiagent navigation. This approach to reactive navigation has been previously demonstrated in a variety of application domains. Emergent behavior is evidenced as the phenomena of recruitment, the shared effort of many robots to perform a task, which occurs even in the absence of communication between the agents [10].

Our earlier studies have focussed on 3 tasks: object foraging, consuming, and grazing [11]. Foraging consists of searching the environment for objects (referred to as attractors) and carrying them back to a central location. Consuming requires the robot to perform work on the attractors in place, rather than carrying them back. Grazing is similar to lawn mowing; the robot team must adequately cover the environment. More recently we have focussed on complex mission scenarios for ARPA involving scenarios that utilize bounding and traveling overwatch and formation maintenance, among other objectives. These complex missions can be constructed from the more basic tasks described above.

We have studied cooperation extensively in multiagent robot systems. Recruitment has been defined as "communication that brings nestmates to some point in space where work is required" [24]. It is our working premise that although communication mechanisms can enhance the speed in which convergence of multiple agents at a common work location occurs, recruitment-like behavior in the absence of direct communication between the agents can also occur, and we have observed this in simulation. We have also developed simple communication mechanisms: state communication and goal communication, that enhance the performance of the social system in quantifiable ways [11]. Results include the spontaneous appearance of recruitment in the absence of any communication (previously reported in [10]) for multiagent scenarios, and a quantitative analysis of both state and goal communication between these agents for various multi-robot, multi-goal scenarios. These results have been ported to two of our Denning robots.

2. Ongoing Research

Most of our previous research has focussed on the behavioral process dynamics within an agent, and in some limited ways, collective behavior among similar agents (e.g., [11]). In so doing we have neglected significant aspects of the environment that can and should be incorporated into a systemic view of a robotic agent's place within the world. We are now focussing on this broader view of robotics, to gain a fuller understanding of how an agent participates with its environmental processes.

McFarland, for some time, has advocated the concept of an agent's ecological niche [29,30]. This view mandates that in order to have a successful robotic implementation, a robot must find its place within the world, i.e., its niche. This niche will enable it to survive and successfully compete with other agents. This perspective holds not only for robotic systems but organizations as well - the novelty lies in its application to robotic systems. McFarland's work has to date heavily emphasized economic pressures, but of course there are also many others.

A series of models, using schema theory, represents an agent's participation with its world. This involves the extension of our common schema-theoretic approach to incorporate external, as well as internal, processes. Fortunately, schema-theory is quite amenable to this strategy, which we demonstrate initially from a modeling perspective and then using robotic simulations (and ultimately implementations). Steels and McFarland [32] have begun to explore these issues experimentally, but have not brought powerful modeling tools to the table, nor have looked closely at the biological underpinnings of the problem. Our research does both. There is also a relationship to the school of ecological psychology as formulated by Gibson [22] and developed further by Neisser using schema theory [31]. We have previously shown a connection between affordance-based perception and perceptual schemas [6]. We continue to explore this avenue in light of new biological data.

Our research focuses on three major questions:

1. How can agent/environmental processes be modeled using a formal schema-based approach?
2. How can our research in multiagent robotic systems be extended to include not merely cooperative agents, but other complex interactions as well, e.g., competition where agents are not only to be viewed only as other robotic systems but also as any constraining environmental processes?
3. How can predictive models generated from biological systems be used to drive robotic experiments, and conversely how can the results of those robotic experiments provide information for the conduct of additional neuroscientific/ethological data gathering?

One of our specific projects involves the study of how praying mantises react to different aspects of their environment, by placing them in various experimental situations. We are interested in what strategies they might use, and whether or not these strategies are fixed or may be modulated by the outcome of the animal's interactions with diverse environmental situations. We have developed schema-theoretic models of the "Chantlitaxia" behavior, including results of an ontogenetic study that suggest that the linkage between the integration of sensory signals, and the activation and control of global motor patterns is not parametric [21], as Lara and coworkers postulated [26], but rather it is a modulated process (i.e., function) that varies depending on the state of a diversity of factors (e.g., animal's age). Some of our preliminary observations suggest that, as the praying mantis grows, it might use this kind of behavior to move to a proper habitat: young mantises live in the bushes, while adult ones stay in the higher part of trees.

As both robotic systems and neural network models increase in their sophistication, it becomes crucial to simulate and analyze the interaction of an increasing number of functional and structural subsystems. While progress has been made in modeling the less sophisticated robotic and single neural network systems, we have reached the stage where it is necessary to define a framework for developing multi-level neural architectures in particular, in their application to robotics. Thus, the design and implementation of a schema based model, utilizing very large neural networks developed in a hierarchical fashion in the robotics domain, processing in a distributed environment, is being undertaken. This involves the extension of our preliminary ASL model to address issues arising from the integration of ASL with neural network simulation in NSL, while implemented in a distributed environment.

We are also designing and implementing the Neural-Schema Simulation Language (NSSL), the integration of NSL/ASL, enabling distributed simulation of hierarchical neural networks, ranging from low-level neural network implementations to higher-level schema tasks. *MissionLab* affords the additional capacity for multi-robot testing and is a significant component of this research. The results obtained using the animal models are currently being tested in simulation studies and then will be ported to real robotic platforms through the use of this software testbed.

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