Ecological Robotics: A Schema-theoretic Approach

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The goals of this joint U.S.-Mexico research project are threefold: to provide an understanding and means by which fielded robotic systems are not competing with other agents that are more effective at their designated task; to permit them to be successful competitors within the ecological system and capable of displacing less efficient agents; and that they are ecologically sensitive so that agent environment dynamics are well-modeled and as predictable as possible whenever new robotic technology is introduced. Initial studies on neuroscientifically derived schema models of the praying mantis and frog are reported that have led to simulation studies and eventual robotic implementations that can provide guidance to neuroscientists, ethologists, and roboticists alike.

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 robotics [37,19] and artificial life communities [29]. 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. It is our contention, that the use of schema theory [2] and neurophysiological and ethological modeling methods can provide credible, generalizable, and useful results in this domain.

The study of sensory guided behaviors in living animals has become significant not only for scientists working in neuroscience and computational neuroscience, but also for those studying 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 a collection of 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

The relationships between the three different research groups involved in this project are depicted in Figure 1. Biological data are used to generate abstract schema models that can either be directly imported into the *MissionLab* robotic software control system generator [32,33], or abstracted further into the context of neural networks (NSL) and then translated to abstract behavioral schemas (ASL) prior to importation into a specific robot control program. The remainder of this section describes the approach each group is taking and the methods by which their results can be smoothly integrated.

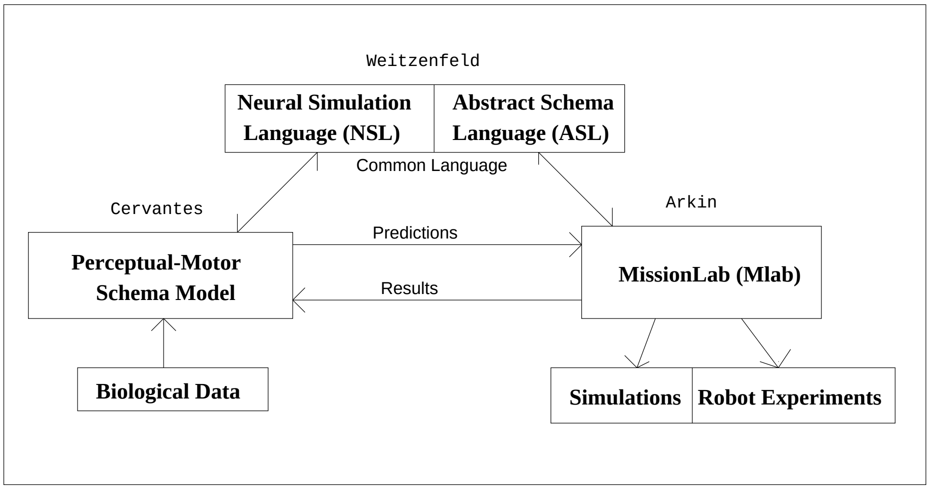


Figure 1: Interdisciplinary Interactions

1.1 Neuroscience and Ethology

The biological 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. For example, 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 [27]. 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. For example:

- 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 within reaching distance in the frontal part of the visual field.

- A predator-like stimulus may yield one of several avoidance behaviors depending upon its parametric composition. In amphibia, a large flying stimulus close to the animal releases a ducking response [21,22,28,31], whereas, in the mantis, a similar stimulus elicits a deimatic behavior (i.e., the mantis stands up, and opens the wings and forearms displaying a posture that shows a much bigger size than it has) [34].

- 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). These include 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. In the case of amphibia [20] a snapping response follows, or a grasping response in the praying mantis [13], if the stimulus is within reaching distance.

Our group has developed theoretical (i.e., neural and schema-theoretic) models of visuomotor coordination phenomena in amphibia [14,15,30,18]. 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:

- 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 100s of milliseconds).

- 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).

- 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 [22]), 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) [23,16].

Regarding motivational changes of visually guided behavior, an experiment was conducted [17] where the combined effect of changes in motivation and in the stimulus configuration (i.e., form and velocity) was evaluated. Two groups of animals were used that were fed at 19:00 hrs, and stimulated with visual dummies (i.e., worm-like and square stimulus) the following day at different times: a) toads stimulated at 9:00 am showed a low motivation to display prey-catching behavior; and b) those stimulated at noon displayed a high number of predatory responses (high motivation). These results offered the conclusion that a toad's motivational state modifies the efficacy of a prey-like visual stimulus to elicit the animal's prey-catching behavior.

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) [41] 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 extensibility 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 [40]. In terms of neural networks per se, we have developed the NSL, Neural Simulation Language, for simulation of large-scale neural networks [24,42,43].

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 a behavioral implementation. Motor schemas 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. Exemplified by our multiagent research, we have demonstrated a system which uses homogeneous units to carry out tasks of foraging, grazing, and consuming objects in a cluttered world [11,12]. 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]. 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 that utilize bounding and traveling overwatch and formation maintenance, among other objectives [32]. These complex missions can be constructed from the more basic tasks described above.

2 Ongoing Research

Most of our previous research has considered the behavioral process dynamics within an agent, and in some limited ways, collective behavior among similar agents[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[35,36]. 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[39] 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 [19] as formulated by Gibson [26] and developed further by Neisser using schema theory [38]. 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.

One study assesses 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 [25], as Lara and coworkers postulated [30], 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 currently extending the software development systems in a number of ways:

1. *Distributed implementation of ASL on a network of heterogeneous workstations.*

   A preliminary distributed implementation of ASL has been completed, which enables the combined execution of distributed and multi-threaded schema instances in a single environment. The system is designed platform-independent, supporting a number of underlying shared and distributed, inter-process communication and synchronization libraries.

2. *Integration of ASL with NSL (giving a new meaning to the name NSL to stand for the unified system: Neural Schema Language).*

   The distributed ASL implementation has been linked to NSL providing an integrated software platform for the distributed simulation of hierarchical neural networks, ranging from low-level neural network implementations to higher-level schema tasks. This prototype supports the modeling and simulation of modular and distributed neural networks by utilizing schema assemblages as means of linking independently developed neural models. Furthermore, current work will permit the modeling and simulation of more complex neural models than currently supported, ranging from the simpler leaky integrator neural model to the more complex detailed neural models, including those taking into consideration transmission delay and electrical aspects, such as compartmental and synaptic models.

3. *Integration of ASL/NSL with MissionLab to provide for a tightly integrated software environment.*

   An important goal in pursuing a powerful software environment to enable both simulation and robot testing of ecological agents is the coupling of ASL/NSL with *MissionLab* in a tightly integrated environment. A former prototype was developed a few years ago integrating neural networks modeling in NSL within a sensorimotor testbed in robotic applications[24]. ASL/NSL and *MissionLab* differ in some of their basic modeling capabilities (neural networks in NSL and robot control in *MissionLab*), yet they have a common unifying theme in schema-based modeling providing a basis for integrating the two systems. In pursuing this integration we have identified different levels of analysis:

- Modeling: ASL/NSL supports neural networks and continuous coordination, while *MissionLab* supports finite state automata and continuous coordination. An extended schema model will support finite state automata, continuous coordination, and neural network modeling.
- Simulation Language: Both systems provide an architecture independent simulation language that permits the execution of schemas under different simulation architectures. Yet, ASL is based on an interactive configuration language that defines dynamic schema assemblages, while *MissionLab* translates from a configuration independent language to a architecture dependent language.
- Simulation Architecture: The ASL/NSL system supports a distributed simulation architecture executing on heterogeneous workstations, while *MissionLab* supports both the AuRA architecture and the UGV architecture. Being able to support a number of related simulation architectures under a unified modeling environment will show the flexibility of the schema-based approach.
- Implementation Language: The ASL/NSL system is implemented under both C++ and Java, while *MissionLab* is implemented under C++. The integration of both systems will extend the support to a wider range of platforms under both C++ and Java.
- Execution Environment: ASL/NSL supports a fully simulated environment while *MissionLab* supports both a simulated and actual robot environment. The integration of both systems will support the two domains, with the extended modeling capabilities, thus providing a more powerful robot testing arena.
- Graphics: ASL/NSL supports both Web based Java interactive displays and Tcl/Tk interactive displays in heterogeneous workstations, while *MissionLab* supports Unix Motif displays. The integration of the two systems will greatly enhance the graphic capabilities of the unified software system.
- Inter-process communication and synchronization: Underlying the two systems, different inter-process communication and synchronization libraries are used. Due to the software and hardware platform independent design of both systems, different libraries can be used depending on the efficiency offered.

4. *Development of a meta-level architecture to optimize run-time execution, including considerations for real-time processing constraints.*

   As part of the integration effort of the two languages, a meta-level architecture is being developed to monitor and control the execution of the two systems and enable utilization of different underlying of communication and synchronization schemes. It will be possible to optimize according to the processing needs by taking into consideration integration aspects between the two systems as well as real-time execution constraints. This meta-level facility will provide additional monitoring capabilities to analyze load balancing aspects of the system as well as help the modeler understand where processing and communication bottlenecks occur in the simulation models.

MissionLab affords the additional capacity for multi-robot testing. 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.

3 Schema-based Praying Mantis Modeling

Revisiting the high-level goals of this research:

- To provide strong task/environment fit with agent, enhancing its survivability (i.e., finding a suitable ecological niche).
- To make robots successful competitors that can potentially displace less efficient agents.
- To make them sufficiently sensitive to adaptation by including suitable models of agent-environment system dynamics.

In our attempt to provide solutions to these problems, we develop a series of models of specific biological organisms that facilitate this study. In many animals (e.g., toads and the praying mantis) visuomotor integration implies a complex transformation of sensory signals, since the same locus of retinal activation might release different types of motor actions: some directed towards the stimulus (e.g., prey-catching); and others directed towards an opposite part of the visual field (e.g., predator avoidance). Furthermore, the efficacy of visual stimuli to release a response (i.e., type of behavior, intensity, and frequency) is determined by a series of factors:

1. The stimulus situation (e.g., form, size, velocity of motion, the spatio-temporal relationship between the stimulus and the animal)
2. The current state of internal variables of the organism, especially those related to motivational changes (e.g., season of the year, food deprivation, time interval between feeding the animal and the time of experimentation)
3. Previous experience with the stimulus (e.g., learning, conditioning, habituation).

We have chosen first to study the praying mantis and its environmental dynamics. Models have been developed using schema theory as the basis for expression that will ultimately lead to the fielding of these results on a Hermes II robot for testing (Fig. 2). This article reports the basis for these simulation studies that will lead to the final robotic implementation.

The repertoire of mantis behavior appears in the ethogram depicted in Figure 3. In our first modeling efforts for mantis behavior we have abstracted away much of this complexity, with the intent to re-introduce it in future model iterations. Our initial model encompasses 4 different visuomotor behaviors (that are also surprisingly similar to frog ethology):

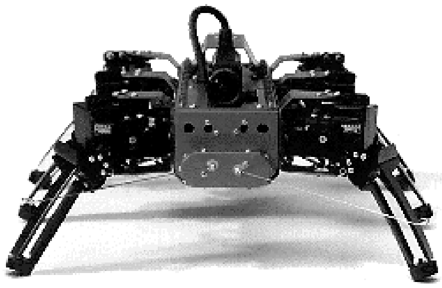


Figure 2: Hermes Robot (photograph courtesy of IS Robotics, Somerville, MA)

- Prey Acquisition: this behavior first produces orienting, followed by approach (if sufficiently far), then grasping by the mantis when the target is within reach.
- Predator Avoidance: At the most abstract level, this produces flight of the insect. But when considered in more detail there are several forms of avoidance behavior. A large flying stimulus can yield either a ducking behavior or a fight-type response referred to as deimatic behavior where the insect stands up and opens its wings and forearms to appear larger than it is.
- Mating: This is an attractive behavior generated by a female stimulus during the mating season producing an orienting response in male followed by approach, then actual mating.
- Chantlitaxia: This involves an agent's search for a proper habitat (i.e., finding its niche). The praying mantis climbs to higher regions (e.g., vegetation) when older, actively searching for a suitable place to hunt. Frogs move towards large blue regions, usually associated with water that provides both edible prey and a means to maintain proper body humidity.

This ethologically-derived schema model initially starts as a purely abstract depiction of behavioral relationships (Fig. 4 top). This is then translated into an operational schema model that more effectively depicts the data flow within the system (Fig. 4 middle). Finally it is implemented within the *MissionLab* robot mission specification system for testing in simulation (Fig. 4 bottom).

A graphical depiction of the simulation output of the model shown in Figure 4 appears in Figure 5. The right side figure shows the mantis moving away from the large gray disk (its hiding place) in search of food and mates as the internal motivational variables representing its hunger and mating needs change over time. A three dimensional window on the right also shows the simulation world that the mantis is housed in. Predators can also be introduced into the simulation and the agent's responses observed and recorded. The intent of the simulation is to serve as the way station for testing the control algorithms that will ultimately be ported to the Hermes II robot (Fig. 2). The exact same control code that runs in the simulation will be used on the robot, standard practice for the *MissionLab* system.

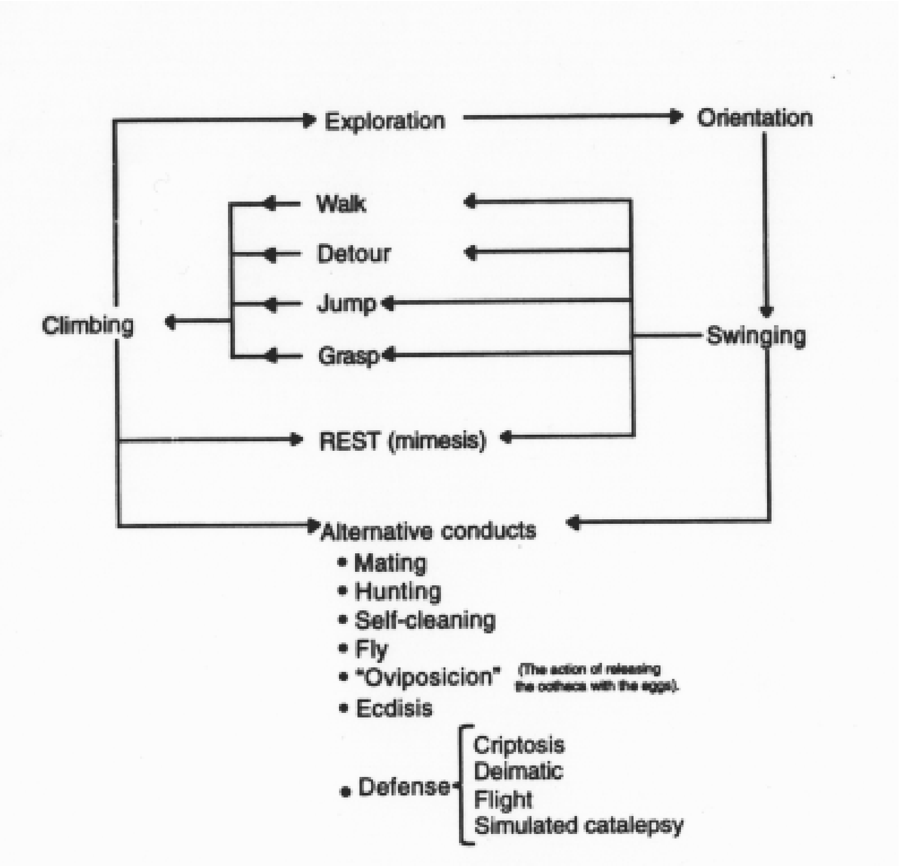
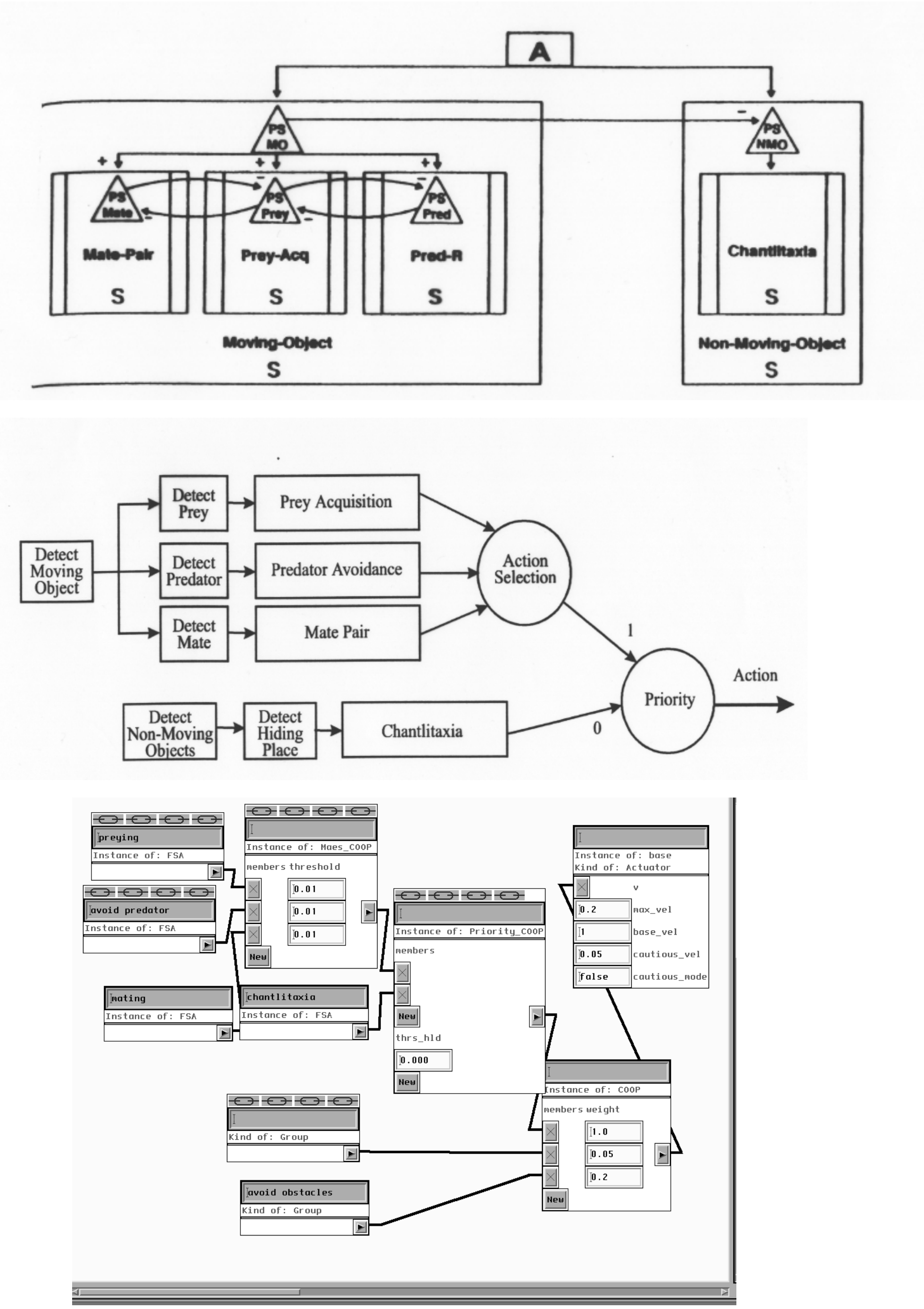


Figure 3: Mantis Ethogram



preying
Instance of: FSA

avoid predator
Instance of: FSA

mating
Instance of: FSA

chantlitaxia
Instance of: FSA

Instance of: Maes_COOP
members threshold
0.01
0.01
0.01

Instance of: Priority_COOP
members
thrs_hld
0.000

Instance of: base
Kind of: Actuator
v
0.2 max_vel
1 base_vel
0.05 cautious_vel
false cautious_mode

Instance of: COOP
members weight
1.0
0.05
0.2

Kind of: Group

avoid obstacles
Kind of: Group

Figure 4: Visuomotor Behaviors of Mantis. (Top) Model-developed by Cervantes (Middle) Abstract Adapted model (Bottom) Model as implemented in *MissionLab*

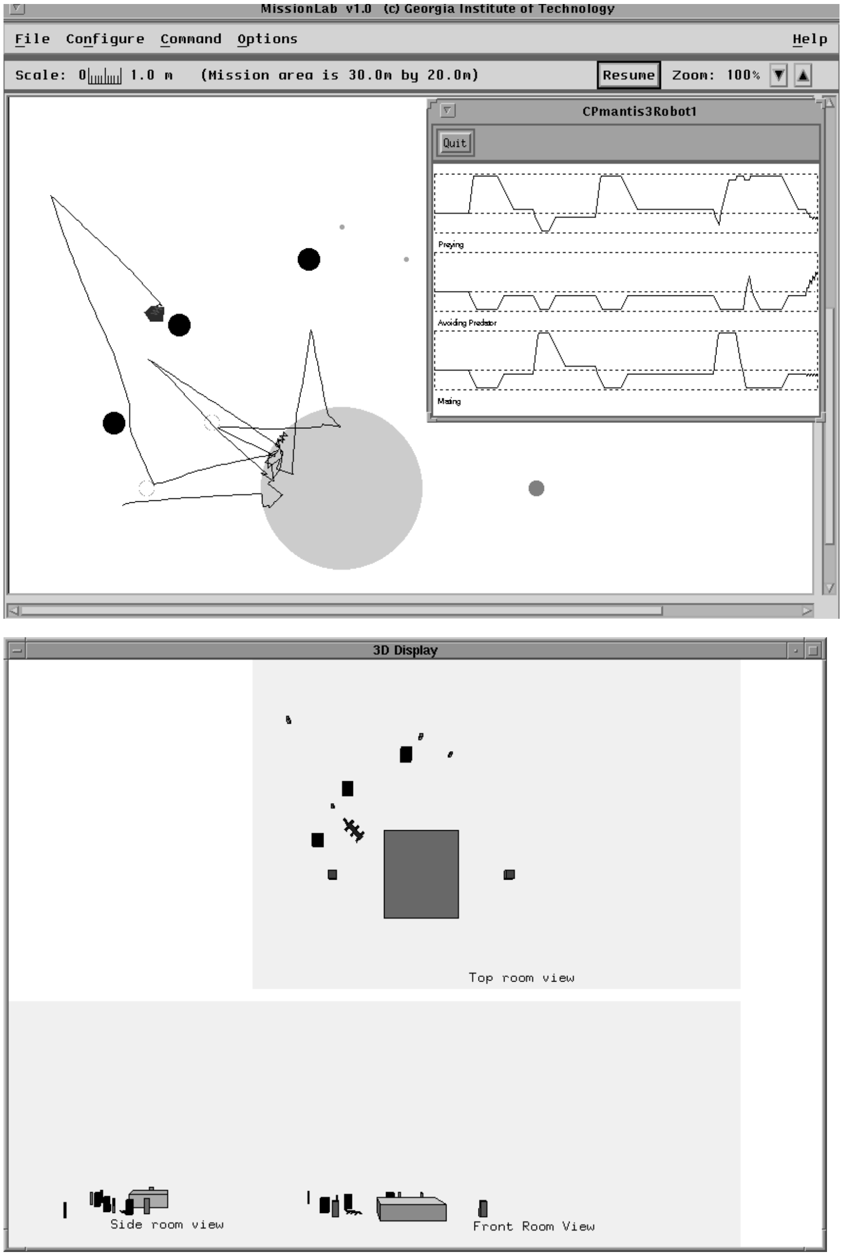


Figure 5: *MissionLab* Mantis Simulation (Top) 2D view (Bottom) 3D view

4 Summary

This article shows how scientists from a range of disciplines can work together using schema-theoretic methods as an interlingua. in particular, agent-environment interactions of the praying mantis have been used as a model to show how ethological studies can lead to robotic implementations. The studies themselves can assist in providing a basis for determining the means by which robot's can discover their own ecological niche within the world.

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