Visually-guided NeuroEthological Autonomous Robots: An Adaptive Middleware Approach to Distributed Embedded Mobile Systems

1. Project Outline

In studying the brain, researchers take a multidisciplinary collaborative approach involving neuroscientific experimentation, theoretical brain modeling and robotics experimentation, as depicted in Figure 1.

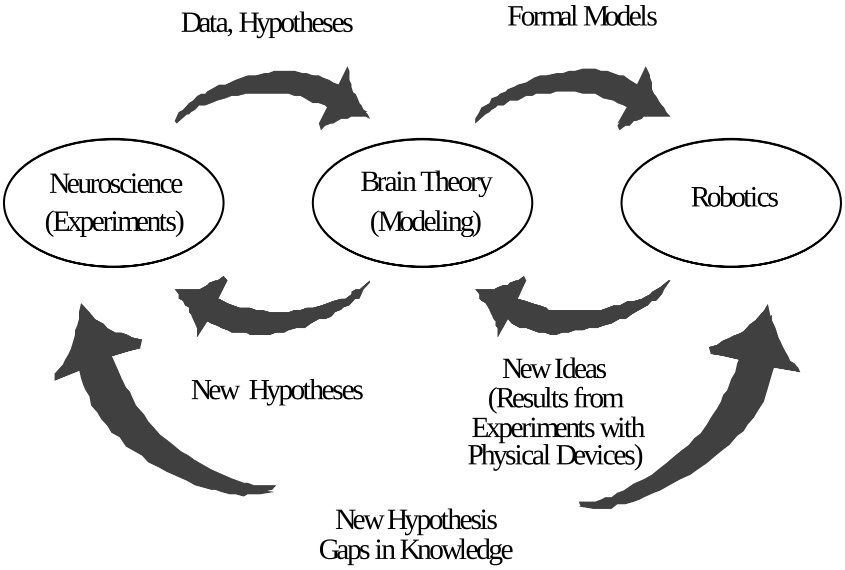

Figure 1. Collaborative research cycle in neuroscience.

In the quest to understand the workings of the brain most of the neuroscientific work has concentrated on the "Neuroscience-Brain Theory" research cycle [5]. While some work has been done on the "Brain Theory-Robotics" research cycle, this has been somewhat limited due mostly to real-time robot processing constraints to the otherwise expensive nature of biological neural computation. For this reason, all too often, research is conducted in terms of behavior-based robotics (see [6]) with robotic architectures lacking a strong biological basis for their working assumptions and any formal underpinnings (neural, behavioral, and computational) for the results they obtain. It is our intention to conduct research in terms of neuroethological robots intended to replicate brain modeling to ultimately provide credible, generalizable, and useful results in the robotics domain.

In Figure 2 we show a diagram of the embedded distributed robotic architecture to be used as part of this project.

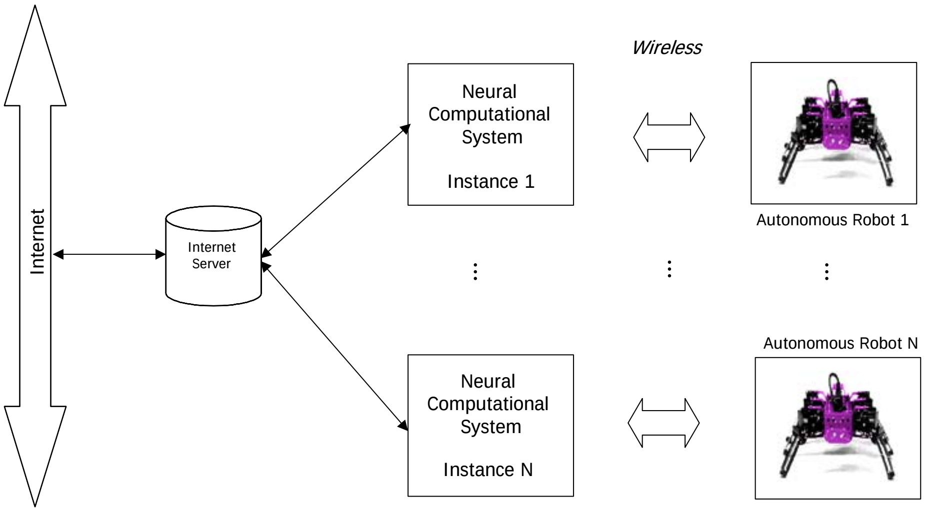

Figure 2. Embedded Distributed Robotic System.

2. Biologically Inspired Robotics- Background

2. 1 Robots, Schemas and Neural Networks

Through experimentation and simulation scientists are able to get an understanding of the underlying biological mechanisms involved in living organisms. These mechanisms, both behavioral and structural, serve as inspiration in the development of neural-based autonomous robot architectures. Some examples of animals that have been studied in developing new robotic systems are: frogs and toads [1], praying mantis [12], cockroaches [10], and hoverflies [14]. To address the underlying complexity in building such biologically inspired neural based robotics systems, we usually distinguish among two different levels of modeling, behavior (*schemas*[3]) and structure (*neural nets* [2]).

1. At the behavioral level, neuroethological data from living animals is gathered to generate single and multi-animal systems to study the relationship between a living organism and its environment, giving emphasis to aspects such as cooperation and competition between them. Examples of behavioral models include the praying mantis *Chantlitaxia* ("search for a proper habitat") [12] and the frog and toad (*rana computatrix*) prey acquisition and predator avoidance models [15]. We describe behavior in terms of perceptual and motor *schemas* [3] decomposed and refined in a recursive fashion. Behaviors, and their corresponding schemas, are processed via the Abstract Simulation Language ASL [44]. For example, in Arkin et al. [7] we describe a praying mantis prey-predator model as a basis for *ecological* robotics, designed and implemented at the behavior level using finite state automata [8].
2. At the structural level, neuroanatomical and neurophysiological data are used to generate perceptual and motor neural network models corresponding to schemas developed at the behavioral level. These models try to explain the underlying mechanisms for sensorimotor integration. Examples of neural network models are tectum and pretectum-thalamus responsible for discrimination among preys and predators [11], the prey acquisition and predator avoidance neural models [13] the toad prey acquisition with detour behavior model involving adaptation and learning [16] and higher-level models such as the monkey oculomotor system controlling eye saccades [20]. Neural networks are processed via the Neural Simulation Language NSL [47]. Models that involve neural networks are usually limited in scope as in [24], while more complex models [4][48] are simplified in terms of their inherent neural complexity.

For example, let us consider the toad´s “prey-predator” visuomotor coordination mode, in particular the toad’s prey acquisition with detour involving both schema and neural network modeling levels, described in Weitzenfeld et al. [45]. In developing this particular model a number of experiments were designed involving a toad and a barrier in front of a prey, with the barrier fencepost gaps having similar width [17], as shown in Figure 3:

1. **Experiment I**: A 10cm wide barrier with the toad starting from a long enough distance (15-25cm) in front of the barrier and the worm 10cm behind the barrier. The experiment shows (in 95% of the trials) reliable detour behaviors from the first interaction with the 10cm barrier producing an immediate approach towards one of the edges of the barrier.
2. **Experiment II**: A 20cm wide barrier where the "naïve" toad (a toad that has not been yet exposed to the barrier) tends to go towards a fencepost gap in the direction of the prey (this was the case for 88% of the trials). The toad initially approaches the fence trying to make its way through the gaps. During the first trials the toad goes straight towards the prey thus bumping into the barrier. Since the toad is not able to go through a gap it backs-up about 2cm and then reorients towards one of the neighboring gaps.
3. **Experiment III:** A 20cm wide barrier where the "trained" toad, after 2 (43%) or 3 (57%) trials, is already detouring around the barrier without bumping into the barrier. The behavior involves a synergy of both forward and lateral body (sidestep) movements in a very smooth and continuous single movement.

A schema computational model is defined in terms of schema hierarchies representing a distributed model for action-perception control. The schema computational model follows a tree or graph-like structure as shown in Figure 4. At the schema level, blocks correspond to *schemas* or *behavior agents* representing animal or robot behavior.

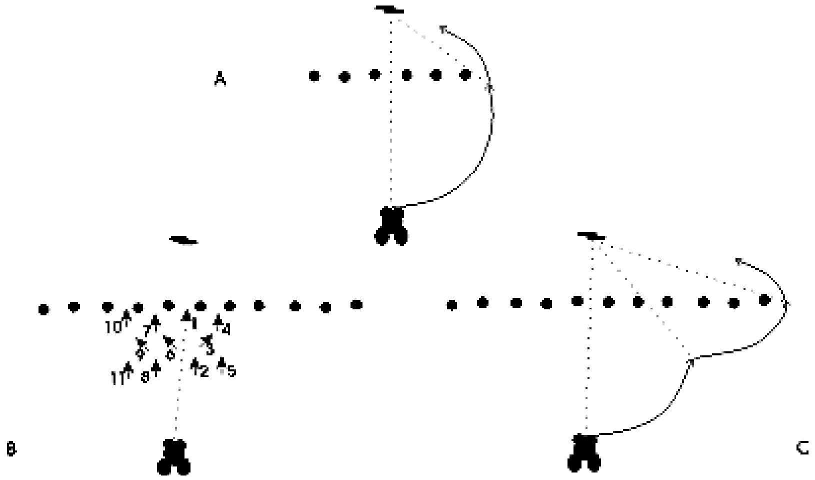

Figure 3. A. Approach to prey with single 10cm barrier with immediate detour. B. Approach to prey with single 20cm barrier: first trial with toad in front of 20cm barrier (numbers indicate the succession of the movements). The toad directly approaches de center of the barrier requiring successive trials to manage the detour around it. C. Approach to prey with single 20cm barrier. After 3 trials the toad detours directly around the 20cm barrier. Arrowheads indicate the position and orientation of the toad following a single continuous movement after which the toad pauses.

In order to simulate models like the prey acquisition or predator avoidance integrating across schemas and neural networks we integrated our two modeling languages ASL and NSL under a single simulation system, NSL3.0 [47]. The NSL/ASL system permits schemas and neural networks modeling by following either top-down or bottom-up modeling approaches. In the top-down approach a complete system is first described at the schema level with schemas implemented by neural modules when available. In the bottom-up approach neural models are developed and then integrated in creating more complete schema systems.

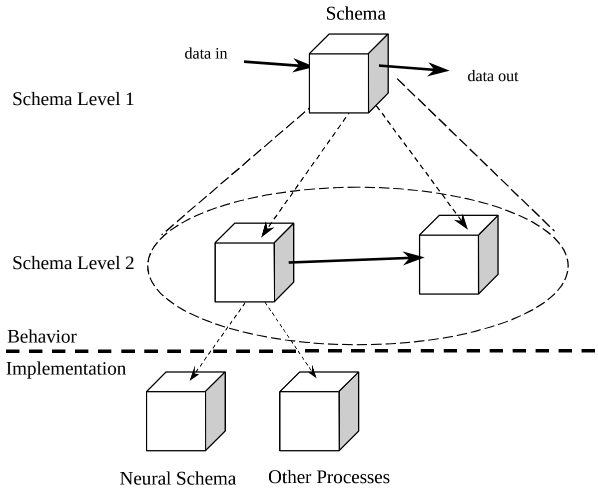

Figure 4. The ASL/NSL model is based on hierarchical interconnected schemas. Schemas at a higher level (level 1) are decomposed (dashed lines) into additional connected (solid arrow) subschemas (level 2). At the lowest level schemas are implemented by neural nets or other processes.

At the schema level schemas are interconnected by matching schema interfaces consisting of multiple unidirectional control/data, input and output ports, as shown in Figure 5. When doing connections, output ports from one schema are connected to input ports from other schemas, and when doing relabelings, ports of similar type (input or output) belonging to schemas at different levels in the hierarchy are linked to each other. The hierarchical port management methodology enables the development of distributed architectures where schemas may be designed in a top-down and bottom-up fashion implemented independently and without prior knowledge of the complete model or their final execution environment, encouraging component reusability.

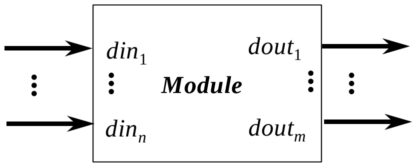

Figure 5. Each schema may contain multiple input, din_1,...,din_n, and output, $dout_1$,...,$dout_m$, ports for unidirectional communication.

The schema representation for our prey acquisition (with detour) and predator avoidance models is depicted in Figure 6. It described in terms of schema and neural modeling levels. One of the main modeling challenges we've encountered is the complexity inherent to linking independently developed neural models, such as a Retina [36], Stereo [30], etc., where input and output specifications do not necessarily match. For example, the original Stereo, MaxSelector, Tectum and Pretectum models all considered direct visual input instead of R2, R3, and R4 retina class cells. This was done in order obtain quicker results and make them independent from other models. At this time it is necessary to reexamine them in order separate what relates to actual visual input versus specialized modules processing while specifying how to modify these models to accept R2, R3, and R4 output coming from the retina module. To complicate matters further, the logic of one module may be based on different assumptions to that of other related module, e.g. different experiments, parameters or time frequencies. Yet, if we do not manage this integration, it will not be possible to "reuse" neural modules in more comprehensive neuroethological models, an important objective in this project.

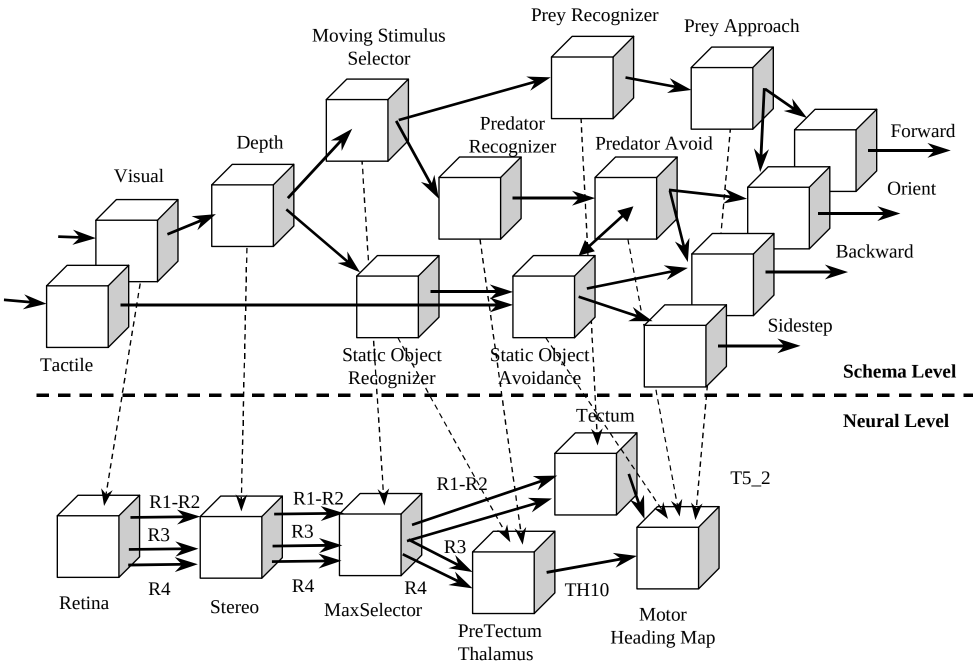

Figure 6. Prey-Predator Frog and Toad Model Architecture.

Our goal is to extend and integrate the neural models corresponding to the “neural level” in Figure 6 in developing the underlying prey acquisition and predator avoidance neuroethological robotic systems. This comprehensive model will be simulated under the NSL/ASL system and then experimented with the MIRO robotic system.

2.2 Simulation and Experimentation

In addition to integrating independently developed neural models into more comprehensive neural systems, as part of our quest to develop neuroethological robotic systems, it is also necessary to further extend and integrate the underlying processing systems, both simulation and robotics systems. There are many concerns with complex models integrating both schema and neural level modeling. The most important of these concerns is the time it takes to process large neural networks. In general, neural network models produce and consume large amounts of data and take a very large number of processing cycles to obtain meaningful results. This is further exacerbated by the fact that a comprehensive schema-neural model includes multiple neural modules, such as in our example in Figure 6. While workstation environments have been sufficient in processing smaller neural networks with no more than a few hundred "simple" neurons, large neural networks consisting of thousands or millions of neurons and connections among them can require many hours of simulation. That is the case of a retina model [36] consisting of more than 100,000 neurons and half a million interconnections. To solve this problem, the original simulation systems have been extended to either parallel and/or distributed computation. In general high-end computer environments are more expensive than networks of workstation or personal computers and in most cases they are harder to program, thus making inexpensive computers a much more feasible solution. In such a way, we have extended our original NSL simulation to a distributed architecture [49][50]. The general approach in the distributed environment is to process the time consuming neural modules on different machines. In robotics experimentation the problem is even worse since real time world interaction is required. Thus, to enable neural-controlled robotic systems it is crucial to reduce processing time.

Another concern is that simulation is not the same as real-world robotic experimentation. In particular, many shortcuts are taken in simulation. For example, simulated cameras and world objects are usually quite ideal; cameras have large visual fields while objects have perfect sizes. Once the model is experimented upon with real robots cameras vary in the size of their visual fields and objects are much harder to recognize. As part of our initial model experimentation with real robots, an interesting result from our prey acquisition with detour behavior has been the problem of “losing” the prey once the robot orients towards one of the edges of the barrier. In the simulated version the robot always perceived the prey as well as predators. A simple solution to this problem has been to add another motor to control a pan camera motion that can always point straight into the prey independently of robot movement. While we have already done some experimentation it is interesting to note that we can get additional inspiration from other neurobiological models, in particular the oculomotor system in monkeys [20] responsible for the control of eye saccades among other functions. An interesting function of the oculomotor system is the control of “memory” saccades where the eye’s fovea redirects itself to a stimulus from information previously perceived, something of particular interest to the prey acquisition and predator avoidance models. This is an example where simulated models do not deal with many specific issues originating from actual embodied robot experimentation. While the prey acquisition and predator avoidance models we have described involve toads and frogs, the oculomotor system involves monkeys, thus varying quite a bit in terms of the neurobiological systems involved. As part of this proposal we will experiment with these separate models in building more comprehensive robot systems.

2.3 Embedded Mobile Robots

The MIRO Embedded Robotic Architecture (ERA) consists of a distributed computational system offering processing resources to the robot via wireless communication. In particular, we have linked MIRO to the NSL/ASL neural simulation system and a video/image processing system specific to our robotics domain. Under such an architecture: (i) time-consuming processing is carried out in the distributed computational system, and (ii) sensory input, motor output and other limited tasks are carried out in the robot. During each processing cycle, the robot sends to the computational system, sensory (video and tactile) input to be processed by both the video/image system and the distributed NSL/ASL system [50]. At the end of each cycle the distributed computational system sends back motor output to the robot. Cycles continue indefinitely or until some task is accomplished. The computational system provides the robot’s “intelligence”, while the robot does very limited “on-board” processing.

3. Research Plan

Most of our collective research to date has focused on defining the embedded robotics architecture and basic middleware requirements. We have an initial prototype of the MIRO embedded robotic system with linkage to the NSL/ASL system. In terms of modeling we have prototyped under such architecture a schema level model of the frog´s prey-acquisition model with and without detour behavior. The model, initially developed as a simulation, has been ported to an embedded robot where preliminary experiments have been done. We are yet to fully complete the comprehensive neuroethological prey-acquisition and predator avoidance models and experiment with single and multiple robots in a real world environment. As part of this work we will extend and integrate existing neural modules responsible for the “neural level” implementation shown in Figure 3. Additionally, we will extend the oculomotor system in providing with camera control as an extension to memory saccade behaviors.

Visually guided neuroethological robotics research will focus on neural modeling, simulation and experimentation on robotic systems, studied and designed in terms of the following research components:

3.1 Visuomotor Model Development

While many neural models have been developed in relation to experimental visuomotor coordination, most of these address particular aspects of the overall model and do not provide linkage between them. It is our objective to provide mechanisms to extend these independently developed neural modules into a single comprehensive model that can provide neurobiological control in robotic systems. The particular models we will be working on are prey acquisition (with and without barriers) and predator avoidance models. As part of the theoretical work we will extend and integrate a number of neural modules responsible for visuomotor coordination in frogs and praying mantis. Since many of these modules have already been developed by different scientists and have been ported to the NSL simulation system our work concentrates on extending and integrating them. These neural modules include (but are not limited to): Retina, MaxSelector, Depth Perception, Tectum, PreTectum (Thalamus) and Motor Heading Map. An important modeling challenge involves integrating across multiple neural modules where hypothesis may vary and gaps may occur. For example, a particular neural module may have outputs that do not match the expected inputs from the next module, or data may not be directly processed as received. At the systems level the challenge is unifying and formalizing input and output data protocols from and to modules, including corresponding temporal frequencies. Additionally, we will be exploring the oculomotor system in designing a neurobiological camera controller following theoretical and experimental work on memory saccades. As part of the experimental work, the resulting model would be initially tested in the NSL/ASL simulation system and then experimented in the complete robotic system. The experiments will involve single and multiple neural based robots, where these robots may behave as both as preys and predators.

3.2 NSL/ASL Simulation System

Currently the NSL/ASL simulation systems exist in two different stand-alone versions, one based on Java and the other on C++. The original C++ version has been extended into a distributed environment while the newer Java version only exists in its sequential version. Since the MIRO robotic system has been developed in Java, it is crucial to extend the NSL Java version into a distributed environment in order to achieve tighter integration across modules. For this purpose we will take the original NSL/ASL C++ distributed design and port it into a Java distributed environment. Additionally, we will add distributed monitoring capabilities available in the original C++ distributed version and add them to the Java distributed system. As part of the process of integrating independently developed neural modules into a single comprehensive model, it is necessary to implement at as part of the simulation system a common protocol that both schema and neural modules must follow in providing matching data and frequencies when distributed across machines.

3.3 Image Processing

Another computationally intensive task is that of image processing, where models receive visual input from the environment. This input needs to be preprocessed in order to be usable by the neural model. In particular our toad and frog neural models recognize moving rectangles. At this time, objects are recognized by the system by their color (blue for prey and red for predator). To make the system more faithful to actual models and reliable under real world conditions it is necessary to extend our object recognition to true forms instead of colors. While this can become a complex task, the advantage we will have is that toads and frogs recognize preys and predators if they move and by their relative length (horizontal rectangles correspond to preys and vertical rectangles correspond to predators). Additionally, image processing is part of the computational cycle, thus, processing time will affect overall model performance. Our objective is to integrate image processing into the schema level processing specification.

3.4 MIRO Robotic System

The MIRO embedded robotic architecture handles very limited tasks at this moment. It incorporates “off-board” sensory and motor servers where sensory, visual and tactile, data obtained from the robot is transmitted to the neural processing system. Once a cycle of processing is completed, the neural processing system sends output to the motor server that forwards it back to the robot as control commands. While the existing MIRO architecture has served as an initial system prototype, we need to extend it in its handling of real-time images and integrate it with the distributed neural system. We also need to extend the wireless network design to consider different protocols. Additionally, we need to specify a set of basic control commands in handling tasks independently of the particular robotic hardware or underlying communication architecture.

4. Specific Research

4.1 Visuomotor Model Development:

- Study, extend and integrate visuomotor coordination models related to prey-acquisition (with and without detour) and predator avoidance. These modules include: Retina, MaxSelector, Depth Perception, Tectum, PreTectum (Thalamus) and Motor Heading Maps.
- Study, extend and integrate the oculomotor system in designing a memory saccade based model to control the robot camera. As part of this work we will analyze how the two models can be integrated in a single robotic system.
- Integrate schema and neural modules to create a single comprehensive model where schema modules provide high-level behavior specification and neural modules provide low-level behavior implementation.
- Conduct simulated and robotic experiments on visuomotor coordination model of prey-acquisition (with and without detour) and predator avoidance with single and multiple robots.

4.2 NSL/ASL Simulation System:

- Extend the original NSL/ASL C++ distributed architecture into a NSL/ASL Java distributed environment.
- Extend the original NSL/ASL C++ distributed monitoring capabilities into the NSL/ASL Java distributed environment.
- Specify the data protocols (data formats and frequencies) that must be incorporated into the input and output data to provide integration across independently developed neural modules.

- Design and incorporate these protocols into the distributed NSL/ASL Java system.

4.3 Image Processing:

- Extend object recognition from color based to “moving stimulus”.
- Integrate image processing at schema level in order to manage data communication in a unified manner.
- Evaluate and optimize image processing performance.

4.4 MIRO Robotic System:

- Extend the MIRO robotic system to handle real time images.
- Extend the MIRO robotic system wireless communication design.
- Integrate MIRO robot system with the NSL/ASL Java distributed system.
- Specify basic set of control commands for transmitting data and controlling remote tasks.

5. Bibliography

[1] Arbib M.A., Levels of Modeling of Mechanisms of Visually Guided Behavior, Behavior Brain Science 10:407-465, 1987.
[2] Arbib M.A., The Metaphorical Brain 2, Wiley, 1989.
[3] Arbib M.A., Schema Theory, in the Encyclopedia of Artificial Intelligence, 2nd Edition, Editor Stuart Shapiro, 2:1427-1443, Wiley, 1992.
[4] Arbib M.A., Erdi P. and Szentagothai J., Neural Organization: Structure, Function and Dynamics, MIT Press, 1998.
[5] Arbib M.A., The Handbook of Brain Theory and Neural Networks, MIT Press, 2002
[6] Arkin R.C., Behavior Based Robotics, MIT Press, 1998.
[7] Arkin R.C., Ali K., Weitzenfeld A., and Cervantes-Perez F., Behavior Models of the Praying Mantis as a Basis for Robotic Behavior, in Journal of Robotics and Autonomous Systems, 32 (1) pp. 39-60, Elsevier, 2000.
[8] Arkin R.C., Cervantes-Perez F., and Weitzenfeld A., Ecological Robotics: A Schema-Theoretic Approach, Intelligent Robots: Sensing, Modeling and Planning, eds. R.C.Bolles, H.Bunke, and H.Noltemeier, pp 377-393, World Scientific, 1997.
[9] Balch T., and Arkin R.C., Communication in Reactive Multiagent Robotic Systems, Autonomous Robots 1:1(27-52), 1994.
[10] Beer R. D., Intelligence as Adaptive Behavior: An Experiment in Computational Neuroethology, San Diego, Academic Press, 1990.
[11] Cervantes-Perez F., Lara R., and Arbib M.A., A neural model of interactions subserving prey-predator discrimination and size preference in anuran amphibia, Journal of Theoretical Biology, 113, 117-152, 1985.
[12] Cervantes-Perez F., Franco A., Velazquez S., and Lara N., A Schema Theoretic Approach to Study the 'Chantitlaxia' Behavior in the Praying Mantis, Proceeding of the First Workshop on Neural Architectures and Distributed AI: From Schema Assemblages to Neural Networks, USC, October 19-20, 1993.
[13] Cervantes-Perez F., Herrera A., and García M., Modulatory effects on prey-recognition in amphibia: a theoretical 'experimental study', in Neuroscience: from neural networks to artificial intelligence, Editors P. Rudoman, M.A. Arbib, F. Cervantes-Perez, and R. Romo, Springer Verlag Research Notes in Neural Computing, Vol 4, pp. 426-449, 1993.
[14] Cliff D., Neural Networks for Visual Tracking in an Artificial Fly, in Towards a Practice of Autonomous Systems: Proc. of the First European Conference on

Artificial Life (ECAL 91), Editors, F.J., Varela and P. Bourgine, MIT Press, pp 78-87, 1992.

[15] Cobas A., and Arbib M.A., Prey-catching and Predator-avoidance in Frog and Toad: Defining the Schemas, J. Theor. Biol 157, 271-304, 1992.

[16] Corbacho F., and Arbib M.A., Learning to Detour, Adaptive Behavior, Volume 3, Number 4, pp 419-468, 1995.

[17] Corbacho F., and Weitzenfeld A., Learning to Detour, in The Neural Simulation Language NSL, System and Applications, MIT Press, 2000 (in publication).

[20] Dominey P.F., and Arbib M.A., A Cortico-Subcortical Model for Generation of Spatially Accurate Sequential Saccades, Cerebral Cortex, 2:153-175, 1992.

[21] Estrin D., Govidian R., and Heidemann J. (Eds), Special Issue on Embedding the Internet, Communications of the ACM 43(5), May 2000.

[24] Fagg A., King I., Lewis A., Liaw J., and Weitzenfeld A., 1992, A Testbed for Sensorimotor Integration, Proceedings of IJCNN '92, Baltimore, MD, 1:86-91.

[28] Gutierrez-Nolasco S., Venkatasubramanian N., and Weitzenfeld A., Miro: Distributed Architecture for Adaptive Autonomous Robots, Technical Report, 2002.

[30] House D., Depth Perception in Frogs and Toads: A study in Neural Computing, Lectures Notes in Biomathematics, Springer-Verlag, 1985.

[31] Jennings J.S., Whelan G., and Evans W.F., Cooperative Search and Rescue with a Team of Mobile Robots, In 8th International Conference on Advanced Robotics, pp 193-200, 1997

[35] Sukhatme G.S., and Mataric M., Embedding Robots into the Internet, Communications of the ACM, May 2000.

[36] Teeters J.L., and Arbib M.A., A model of the anuran retina relating interneurons to ganglion cell responses, Biological Cybernetics, 64, 197-207, 1991.

[39] Venkatasubramanian N., and Talcott C.L., Composition of Resource Management Activities in Distributed Systems, Technical Report, 1999.

[44] Weitzenfeld A., ASL: Hierarchy, Composition, Heterogeneity, and Multi-Granularity in Concurrent Object-Oriented Programming, Proceedings of the Workshop on Neural Architectures and Distributed AI: From Schema Assemblages to Neural Networks, USC, October 19-20, 1993.

[45] Weitzenfeld A., A Multi-level Approach to Biologically Inspired Robotic Systems, en Proc of NNW 2000 10th International Conference on Artificial Neural Networks and Intelligent Systems, Prague, Czech Republic, July 9-12, 2000.

[46] Weitzenfeld A., and Arbib M.A., A Concurrent Object-Oriented Framework for the Simulation of Neural Networks, Proceedings of ECOOP/OOPSLA '90, Workshop on Object-Based Concurrent Programming, Ottawa, Canada, OOPS Messenger, 2(2):120-124, April, 1991.

[47] Weitzenfeld A., Arbib M.A., and Alexander A., The Neural Simulation Language: A System for Brain Modeling, MIT Press, July 2002.

[48] Weitzenfeld A., Cervantes F., and Sigala R., NSL/ASL: Simulation of Neural based Visuomotor Systems, in Proc. of IJCNN 2001 International Joint Conference on Neural Networks, Washington DC, July 14-19, 2001

[49] Weitzenfeld A., Gutierrez-Nolasco S., ASL/NSL: A Multi-level Computational Model for Distributed Neural Simulation, in Proc of SCSC 2000 Summer

Computer Simulation Conference, Vancouver, Canada, July 16-20, 2000.

[50] Weitzenfeld A., Peguero O., Gutierrez-Nolasco S., NSL/ASL: Distributed Simulation of Modular Neural Networks, in Proc. of MICAI 2000 Mexican International Conference on Artificial Intelligence, LNAI 1793, Springer, April 14-18, Acapulco, Mexico, 2000.

[51] Weitzenfeld A., Gutierrez-Nolasco S., and Venkatasubramanian N., MIRO: An Embedded Distributed Architecture for Biologically inspired Mobile Robots, Accepted for publication in the 11th International Conference on Advanced Robotics (ICAR-03), Coimbra, Portugal, June 30- July 3, 2003.

[52] Weitzenfeld A., Embedded Mobile Systems: From Brain Theory to Neural-based Robots, Accepted for publication in the 11th Mediterranean Conference on Control and Automation (MED-03), Rhodes, Greece, June 17-20, 2003.