MIRO: An Embedded Distributed Architecture for Biologically inspired Mobile Robots

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Abstract

Nature has always been a source of inspiration in the development of robotic systems. As such, the study of animal behavior (ethology) and the study of the underlying neural structure responsible for behavior (neuroethology) have inspired many robotic designs. In general, neuroethological based systems tend to be more complex than ethological ones thus being more expensive to compute, a common problem to both simulation and robotic experimentation. To overcome this problem, it is necessary either to incorporate very powerful hardware or, particularly in the case of mobile robots, embed the robot via wireless communication into remote distributed computational system where expensive computation can take place. While the first approach simplifies the overall robotic architecture it results in bulky and expensive robots. The second approach results in smaller and less expensive robots, although involving more complex architectures. The work presented in this paper discusses the second approach that of embedding mobile robots to distributed computational systems. We describe our current work in conducting neuroethological robotic experimentation using the MIRO (Mobile Internet Robotics) system linked to the NSL/ASL neural simulation system. In optimizing overall system performance, communication between the robot and the computing system is managed by an Adaptive Robotic Middleware (ARM).

1. Introduction

Many different approaches have been proposed in recent years in controlling autonomous robots. Lately, one of most popular has been that of behavioral based robotics [4], both in terms of technological as well as biologically inspired robotics, such as those imitating animal "ethology". In addition to the study of animal behavior "neuroethological" intends to model neural structure as related to behavior. It should be noted that there exist many robot architectures that do incorporate some kind of neural processing, although most of them are of the artificial neural type involving non-biological training capabilities [26]. Yet, there are important motivations behind the design of "neuroethological" robots. One reason is in providing inspiration for future robotics architectures, as has happened before with neural architectures. Another important reason involves neuroscientific experimentation where currently most work is done in terms of simulation. By providing with an experimentation platform many issues that over simplified in simulation can be further analyzed by providing with embodiment.

One important concern with neuroethological robotic experimentation involves how to achieve real-time performance considering the expensive nature of neuroscientific processing. One approach to overcoming this challenge is to have "super-robots" in analogy to supercomputers, something that usually results in prohibitively expensive and bulky robotic systems. A second approach is to incorporate simpler and less expensive robotic hardware although embedding it to an inexpensive network of computers. Under such a computing architecture time-consuming processing will be done remotely outside the robotic hardware, with the robot sending sensory input and receiving motor commands via wireless communication. Such an approach reduces the robot's physical size, power requirements as well as cost. A number of robotic architectures embedded into the Internet have already been proposed [25] involving a large number of applications [10]. These efforts, most of them involving teleoperation, have highlighted the potential of the Internet when linking remote robotic devices to humans or other computational resources in a distributed fashion. Yet, to take advantage of such embedded architectures it is first necessary to overcome restrictions in wireless transmission bandwidth, unreliable communication or even complete failures.

In this paper we discuss our current work on embedded robotics, where (1) at the application level biologically inspired neural based behaviors make it possible to experiment with neuroethological robot architectures, while, (2) at the systems level adaptive middleware support the embedded robotic system in a transparent fashion.

2. Biologically inspired Mobile Robots

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 having inspired robotic systems are frogs and toads [1], praying mantis [12], cockroaches [9], and hoverflies [14] among others. To address the underlying complexity in building such biologically inspired neural based robotics systems we usually distinguish among two different levels of modeling, behavior and neural networks [2].

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") [11] 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. Schema hierarchies represent a distributed model for action-perception control. Behaviors, and their corresponding schemas, are processed via the Abstract Simulation Language ASL [29]. For example, in Arkin et al. [5] we describe a praying mantis prey-predator model as a basis for *ecological* robotics, designed and implemented exclusively at the behavior level using finite state automata [6].

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] and the toad prey acquisition with detour behavior model involving adaptation and learning [16]. Neural networks are processed via the Neural Simulation Language NSL [32]. Models that involve neural networks are usually limited in scope as in [19], while more complex models [33] are simplified in terms of their inherent neural complexity. For example, let us consider the toad´s "prey-predator" visuomotor coordination model described in Weitzenfeld et al. [30], with schema and neural level components shown in Figure 2. The diagram shows two levels of modeling granularity. At the schema level, blocks correspond to *schemas* or *behavior agents* representing animal or robot behavior. At the neural level, blocks represent neural networks, some having a direct correspondence to brain regions [31]. One of the main concerns with neural networks has been the expensive nature of computation. For example, a "typical" retina model [27] may consist of more than 100,000 neurons and half a million interconnections requiring many hours of simulation. This has lead to a number of distributed neural processing architectures [34].

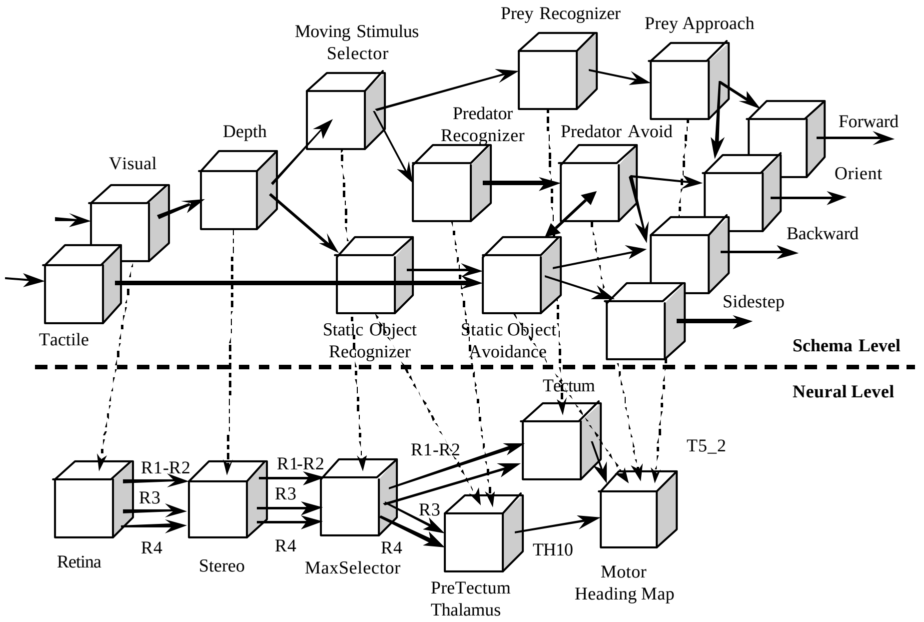

Figure 1. Toad's prey-predator visuomotor coordination model architecture with schema and neural level modules.

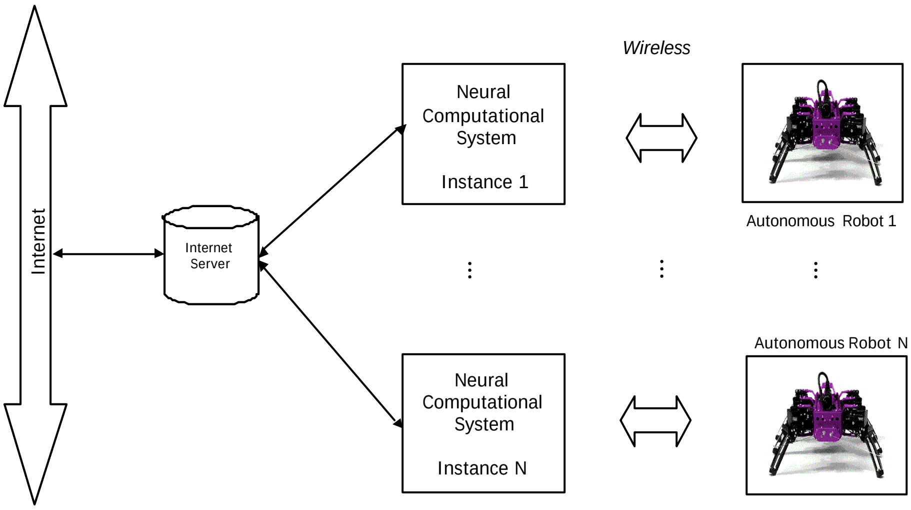

Figure 2. MIRO embedded robotic architecture consisting of multiple autonomous robots linked to their own instance of the distributed neural computational system. All such instances are connected to Internet for remote monitoring.

3. Embedded Distributed Architecture

As part of our current work in the design of embedded distributed architecture we have developed the MIRO (Mobile Internet Robotics) system as shown in Figure 2. The architecture consists of multiple robots, each one connected to its own particular copy or instance of the neural computational system where communication is done in a wireless fashion. Processing is distributed among the actual robotic hardware and the remote computational system. Although it would be possible in principle to share robot "intelligence" among multiple robots, we keep a fully autonomous robot architecture in providing with truly neuroethological experimentation. Other application could easily take advantage of information sharing (see [7] for a discussion on distributed versus centralized robotic systems). Under our MIRO architecture: (i) time-consuming processes are carried out in the (neural) computational system, implemented using the distributed NSL/ASL system while (ii) sensory input, motor output and other limited tasks are carried out in the robot hardware.

A typical computation cycle involves the robot initially sending sensory input (visual and tactile) data to the neural computational system. The neural computational system would then process the sensory input cycling through its neural modules while finally sending motor output back to the robot. These cycles continue indefinitely or until some specific task is completed. In such a way, the computational system provides the robot's "intelligence", while the robot does limited processing.

The major challenge in the distributed architecture relates to the always-changing network and environment conditions (such as transient failures, disconnections, or reduced connectivity).

For such purpose we have developed an Adaptive Robotic Middleware (ARM) framework managing communication between the robot and neural computational system in adapting to changing conditions, primarily that of communication, a major concern when video is involved.

The great advantage of a middleware approach is that it provides with transparent mechanisms in enhance application response at run-time [20][21][28]. Most current middleware frameworks dynamically add and remove components at run time without interrupting system operation with communication services usually tailored to static conditions [18][22][23][24]. This approach is not well suited for highly mobile environments, where resource and power constraints, together with security issues (authentication, authorization and communication secrecy or integrity) pervade the application. In such environments, the communication framework must be able to automatically reconfigure itself in order to respond to changes in the communication environment, a critical aspect in an embedded real-time architecture.

In such a way, the middleware architecture allows specification of communication requirements in a high level manner that can be later associated with low-level specific architectural implementations using a comprehensive set of basic communication protocols. The middleware is responsible in determining *how*, *when* and *what* information should be modified in order to match communication fluctuations. For example, bandwidth adaptation enables information delivery in a manner sensitive to the resources available, and may entail the use of techniques such as media conversion and compression to achieve the desired results.

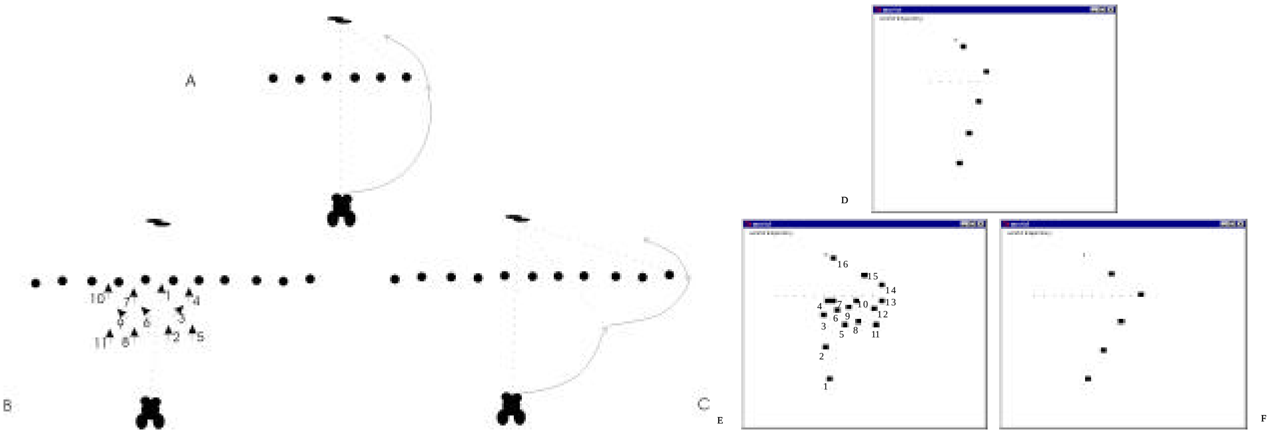

Figure 3. A. Approach to prey with single 10cm barrier with immediate detour. B. Approach to prey with single 20cm barrier: first trial with toad in front of 20cm barrier (numbers indicate the succession of the movements). The toad directly approaches de center of the barrier requiring successive trials 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 diagrams D-F we see corresponding simulated results.

4. Experiments and Results

We have prototyped the MIRO robot architecture with a number of experiments involving prey acquisition predator avoidance. For example, in Figure 3 we show (left) three different experiments involving a toad and a barrier in front of a prey, where fencepost gaps interposed [17] together with simulation results (right) for the corresponding experiments. The original simulations were developed in the NSL C++ system and then ported to the newer NSL Java system, currently linked to the MIRO robotic architecture. To monitor system results, Internet-linked aerial cameras as well as the robot cameras were included, as show in Figure 4 (left). Note that one of the key advantages of the MIRO distributed architecture is that neural behaviors can be visualized at the same time as the actual experiments it performing, as shown in Figure 4 (right). Obviously there is an additional penalty to pay in performance but it is well worth during model development or fine-tuning.

In Figures 5 we show sample output for one of the experiments, involving prey acquisition with a 10cm barrier showing direct detour. The experiment was carried out on a single Lego-based robot connected in a wireless fashion to the MIRO system. A wireless camera was added on top of the robot transmitting video in a wireless fashion to remote video capture devices. Initial experiment control, experiment monitoring and model visualization we all carried out from Internet via a client-server architecture involving applets and servlets.

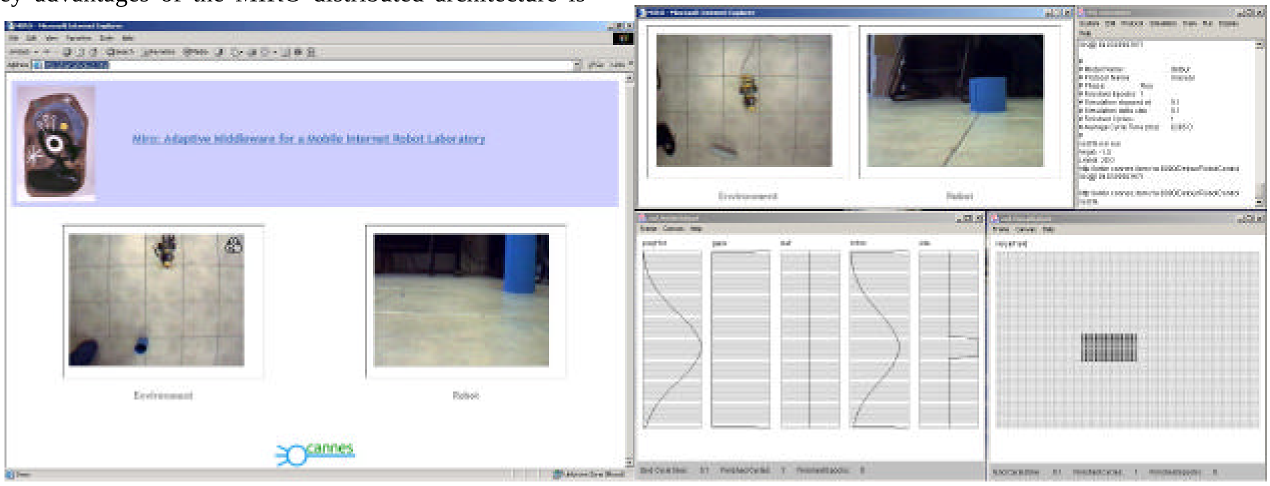

Figure 4. Left: Internet aerial view of autonomous robot and robot's camera view of "blue" prey-like stimulus. Right: NSL frames showing results from different visual and neural modules in a basic prey acquisition robot experiment (without barrier).

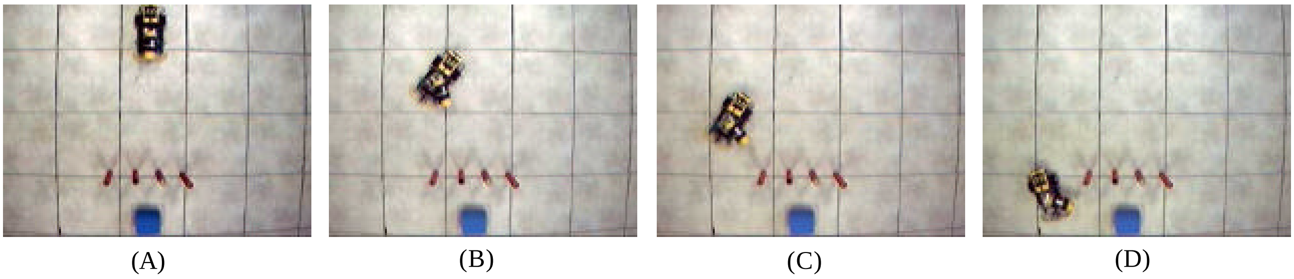
(A) (B) (C) (D)

Figure 5. Results from prey acquisition experiment for 10cm barrier with direct detour around barrier.

5. Discussion

The work presented in the paper overviews the challenges and complexity in modeling autonomous robots inspired by biological systems in terms of both behavior and neural structure. One of the motivations behind this work is to provide neuroscientists with robotic experimentation capabilities as well as prototyping new robotic architectures. One primary concern with neural processing is the extensive nature of computation, a crucial concern with real time robotics. To improve on performance and reduce the size and cost of robots, we have developed an embedded distributed robot architecture supported by adaptive middleware managing overall architecture and communication.

While most time-consuming tasks can take advantage of the distributed robotic system by processing them remotely, there are a number of issues that arise from such a distributed architecture, such as what happens when communication between the robot and computational system actually fails or becomes extremely slow or unreliable. The robot could respond in many ways, simply waiting without doing anything until communication is restored, ending its mission, or performing other more limited tasks that may put it back in action. Additionally the robot could actively search for a location where communication can be reestablished.

As part of the process of robot experimentation we have taken models previously simulated under NSL where their correctness is first tested. After that, the models are prototyped under the MIRO robot architecture to test their behavior under real world conditions. The MIRO architecture has proven quite beneficial providing real-time monitoring capabilities of both external as well as internal robot behavior. Among the interesting aspects that have emerged from the robot experiments is the problem of “losing” the prey once the robot directs itself around the barrier. While this can be solved by a “pan” control on the camera, where the camera can always “look” into the prey, it raises an interesting number of issues such a recalling prey positions from memory such as with memory saccade models [8].

Until now we have experimented with single robot neuroethological models, such as prey acquisition and predator avoidance. We are currently working on multi-robot experimentation with self-made robots, where each robot instantiates its own prey, robot or predator behavior.

In general, the MIRO architecture and the Adaptive Robotic Middleware are currently at the prototype stage and have not yet been completed. We expect that once we complete and integrate these two architectures we will be able to incorporate more complex neuroethological models as currently done.

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References

[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] Arkin, R.C., Behavioral based Robotics, MIT Press, 1998.

[5] 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.

[6] Arkin, R.C., Cervantes-Perez, F., and Weitzenfeld, A., 1997, "Ecological Robotics: A Schema-Theoretic Approach", "Intelligent Robots: Sensing, Modelling and Planning", eds. R.C.Bolles, H.Bunke, and H.Noltemeier, pp 377-393, World Scientific.

[7] Balch, T. and Arkin, R.C., Communication in Reactive Multiagent Robotic Systems, Autonomous Robots, 1, pp 1-25, 1994.

[8] Dominey, P., and Arbib, M.A., A cortico-subcortical model for generation of spatially accurate sequential saccades, Cerebral Cortex, 2, pp 153-175, 1992,

[9] Beer, R. D., *Intelligence as Adaptive Behavior: An Experiment in Computational Neuroethology*, San Diego, Academic Press, 1990.

[10] Goldberg, K., and Siegwert, R., (eds), Beyond Webcams: An Introduction to Online Robots, MIT Press, 2002.

[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., Lara, N., 1993, 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. Learning to Detour, *Adaptive Behavior*, Volume 3, Number 4, pp 419-468, 1995.

[17] Corbacho, F., and Weitzenfeld, Learning to Detour, in *The Neural Simulation Language, A System for Brain Modeling*, MIT Press, 2002.

[18] Costa F.M., and Blair G.S., Integrating Meta-information Management and Reflection in Middleware, in Proceedings of the International Symposium on Distributed Objects and Applications (DOA'00), September 2000.

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

[20] Gutierrez-Nolasco, S., and Venkatasubramanian, N., "A Composable Reflective Communication Framework", in Proceedings of the IFIP/ACM Workshop on Reflective Middleware, April 2000.

[21] Gutierrez-Nolasco, S., and Venkatasubramanian, N., A Reflective Middleware Framework for Communication in Dynamic Environments, Proc of the International Symposium on Distributed Objects and Applications (DOA'02), October 2002.

[22] Kon F., Roman M., Liu P., Mao J., Yamane T., Magalhães L.C., and Campbell R.H., Monitoring, Security and Dynamic Configuration with the Dynamic TAO Reflective ORB, in Proceedings of the IFIP/ACM International Conference on Distributed Systems Platforms and Open Distributed Processing, Springer Verlag (1795):121-143, April 2000.

[23] Loyall J., Schantz R., Zinky J., and Bakken D., Specifying and Measuring Quality of Service in Distributed Object Systems, in Proceedings of the First International Symposium on Object-Oriented Real-Time Distributing Computing (ISORC'98), April 1998.

[24] Pal P.P., Loyall J., Schantz R., Zinky J., Shapiro R., and Megquier J., Using QDL to specify QoS aware Distributed (QuO) Application Configuration, in Proceedings of the Third IEEE International Symposium on Object-Oriented Real-Time Distributed Computing (ISORC'00), March 2000.

[25] Sukhatme, G.S., and Mataric, M.J., Embedding Robots Into the Internet, Communication of the ACM, 43(5) pp 67-73, Special issue on Embedding the Internet, D. Estrin, R. Govidian, and J. Heidemann, eds., May 2000.

[26] Sutton, R., and Barto, A., Reinforcement Learning: An Introduction, MIT Press, 1998.

[27] 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.

[28] Venkatasubramanian N., Deshpande M., Mohapatra S., Gutierrez-Nolasco S., and Wickramasuriya J., Design and Implementation of a Composable Reflective Middleware Framework, in Proceedings of the IEEE International Conference on Distributed Computer Systems (ICDCS-21), April 2001.

[29] 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.

[30] Weitzenfeld A., 2000, "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, Julio 9-12.

[31] Weitzenfeld, A., Arbib, M., 1991, 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.

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

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

[34] Weitzenfeld A., Gutiérrez, S., 2000, "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.