PROPOSAL WHITE PAPER

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Title: A Qualitative Approach to Coherent Evidential Inference

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Topic 16: Reasoning by Abductive Inference

Overview

We have developed a basic inference engine based on Coherence Theory, and tested it successfully on cybersecurity and robotics applications. We propose to extend the capabilities of the theory on which this engine is based, to implement an advanced version of this engine that learns from experience, and to demonstrate its effectiveness in three distinct applications.

Identification of the research and issues

Decision-making tools have been developed for many specific applications. Typically, these tools are crafted to exploit features that are specific to one application. This limits their interoperability and forces human decision makers in complex environments to learn many different tools. Developing a more general decision tool requires developing a more general paradigm of evidential inference.

In many applications, the decision maker is faced with evidence that is incomplete and inaccurate. This may arise from noise in the sensors, or from limitations in the knowledge available, or from the actions of a malicious adversary. Furthermore, the evidence is often gathered from a variety of sources and is represented at different granularities. It is very difficult to reach accurate conclusions from such evidence, yet this is precisely what military commanders must do in the field.

These qualities of the evidence impose requirements on the approach to evidential inference, including:

It must reach conclusions quickly,
It must display its level of confidence in its conclusions,
It must identify appropriate, relevant constructs in the evidence,
It must be able to handle uncertain and incomplete evidence,
It must be able to accept and combine a variety of kinds of evidence.

Traditional approaches based on deductive inference are very limited when faced with such situations, because their deductive reasoning methods assume that their premises are complete, consistent and true. It is possible to reason deductively about the degrees of completeness, consistency and truth of assertions, but this approach is difficult and not very tractable. For these reasons, most work in this area has focused on techniques that are not purely deductive. Two main technical approaches that have been explored are probability theory and coherence theory.

The probability theory approach uses probabilities to represent the likelihood that each piece of evidence is true. This approach has the advantage of mathematical precision, and permits a large body of theory to be brought to bear. However, reasoning about the interactions of a large number of pieces of evidence requires many joint probability distributions, which causes a profusion of large tables of probabilities. This slows such methods to a crawl; research into improving the speed of such methods is a main focus of research in this area. In addition, in some applications accurate prior probabilities are hard to obtain.

The coherence theory approach is fundamentally different from the probability approach. Whereas the probability theory approach first attempts to assign a likelihood to each piece of evidence, and from them to derive the set of most probable assertions, coherence theory does not attempt to assign likelihoods to individual pieces of evidence but rather attempts to find a subset of pieces of evidence and hypothetical conclusions that is logically consistent and explains the present situation. The advantages of this approach are that it does not require accurate prior probabilities and eliminates large tables of probabilities; however, the search for such a coherent set is known to be NP-hard [9].

Both approaches suffer from the exponential growth in the number of possibilities to consider as the amount of evidence increases. Both can be effective at displaying their level of confidence in their results, and in identifying useful constructs in the evidence. And both can fuse different kinds of evidence (although the probabilistic approach requires prior probabilites for each kind of evidence.)

An important issue that must be addressed in any work of this sort is the construction of one or more metrics to be used to evaluate the success of the approach.

Proposed Technical Approach

We propose to develop an evidential inference procedure based on coherence theory that meets all the above requirements and evaluate its success on a range of very different applications.

The concept of coherence has been widely used over the past forty years explain how people make decisions in many different areas, including natural language comprehension, visual understanding, sociology, politics and the formation of theories in science [3, 4, 6, 7, 8]. Philosophers and cognitive scientists have created a large literature exploring coherence and recently have begun computing coherence [9].

The common thread unifying all this work is that each piece of evidence is viewed as one piece of a large unknown puzzle, and the process of arriving at a conclusion consists in finding the largest set of pieces that fit together to form a satisfactory picture. All approaches to coherence rely on a *locality property*, which states that how well a piece of evidence fits into the overall picture is determined by how well it fits together with a relatively small number of other pieces of evidence (its locality), so that the overall conclusion is not found hierarchically, e.g. by refining an abstract conclusion, but rather arises by *emerging from the evidence*.

This approach has been demonstrated to be very robust in the presence of noise and incompleteness in the data across a wide range of applications. Furthermore, it has been shown to model human decision making in very uncertain situations, i.e. those in which the human does not possess sufficiently strong knowledge about the situation to see the overall decision. It is for these reasons that we selected coherence theory for our cybersecurity and robotics systems.

Our ADAPT robotics architecture [1,2] is based on cognitive principles, and the overall goal of that research project is to produce a mobile robot that comprehends its environment by constructing a realtime simulation of its environment and itself. This requires the robot to combine quickly the information from all its sensory modalities together with its knowledge of how the world can evolve. Much of this information is noisy and incomplete. Coherence theory provides a simple yet powerful approach to combining all these sources of information to produce a view of the environment that makes sense.

Our cybersecurity project presents an even more compelling reason to use coherence theory. We are building an intelligent cybersecurity agent as part of a DARPA-funded project (DARPA contract N00178-07-C-2003, $1.5 million with BBN Technologies, Inc., "Cognitive Support for Survivability Against Sophisticated Attacks", December, 2006 - June, 2008). This agent is designed to defend against inside hacker threats, e.g. someone who has already broken into the network or who is an employee. In this application, evidence cannot be trusted as it might have been fabricated by the hacker. This makes it crucial to use a reasoning method that is capable of taking a global view of the system. Our software agent uses coherence theory to reason about the inputs from the various computer and network sensors together with the set of hypotheses generated from an expert knowledge base, and find a subset that explains the observations as completely as possible. In our initial tests with this system it has produced the same conclusions as our cybersecurity expert and runs in less than a second.

Our implementation of coherence theory is a very straightforward, basic one, and is within the Soar cognitive architecture [5], which is at the core of both the cybersecurity agent and the robot. We model every piece of evidence and each hypothesis as a node in a constraint satisfaction network and search to maximize the total of satisfied constraints. This provides us with a cognitively based analytical framework for generating and evaluating hypotheses.

Previous work [9] found that both a neural net implementation and a greedy algorithm for coherence search worked very efficiently, and our implementation (a greedy algorithm) confirms this. We find our initial results very encouraging, and intend to extend both the underlying theory and our implementation.

Although the theory of coherence has been investigated extensively by philosophers and cognitive scientists, its computational properties have received attention only recently. There are important questions to be answered about coherence search, including how sensitive it is to the order in which evidence is presented, what bounds can be placed on the quality of the solutions obtained by greedy search, and whether explanation-based learning (such as exists in Soar) can speed the search significantly.

Another important issue for coherence search is the development of metrics for measuring success. In our cybersecurity project, we can measure the amount of time the system stays up and can deliver necessary combat operation functionality, but this does not quantify how much the coherence search component alone is contributing to that success. In the robotics application, measuring the contribution of coherence search is even harder. One main focus of this project will be developing and testing a number of different possible metrics. To aid in this effort, and also to provide a clear measure of success, we intend to develop a coherence theory program for a third application: poker. Poker is a game that has resisted the advance of successful game-playing programs in recent years, because poker largely depends on understanding the other players in the game, and reasoning from very incomplete information. Unlike most other games for which strong programs have been developed (chess, checkers, etc.) poker opponents can deliberately bluff and mislead a poker program, in a manner similar to cybersecurity. Poker has the advantage that online tournaments exist in which we can accurately measure the performance of the program against live opposition (without actually gambling!) and test the effectiveness of different variations of coherence search. We already possess the basic poker-playing code implemented in Soar (http://www.codeblitz.com/soarbot/soarbot.html) from a previous project.

Potential Impact on Department of Defense Capabilities

The coherence agents we have already created are autonomous reasoners that succesfully handle a large amount of sensory data in real time. We believe this approach is completely general and can be used in any decision-making setting in the military, from long-term planning to local response selection, and ranging from cybersecurity to battlefield applications. Both the applications we are already developing (robotics and cybersecurity) are important military applications. The coherence approach seems especially well suited to dealing with an adversary.

Potential Team and Management Plan

The team to carry out this work will consist of Prof. Benjamin at Pace University, Prof. Lonsdale of the linguistics department of Brigham Young University, and Prof. Lyons of the computer science department of Fordham University, together with their graduate students. This team already exists and has been working for three years on the robotics application.

Prof. Benjamin and Prof. Lyons will continue to focus on the robotics application, with Prof. Lyons concentrating on the perceptual contraints and Prof. Benjamin on the cognitive constraints. Prof. Lonsdale will contribute to the robotics application in the linguistic area (the mutual constraints between language and representation); he will also cooperate with Prof. Benjamin on the poker application. Prof. Benjamin is primarily responsible for the cybersecurity application.

The process of managing this interaction is already in place and has been successfully functioning for three years. There is a common trac/wiki system at robotlab.csis.pace.edu that includes a code repository. Weekly teleconference meetings are held. We meet in person annually, either at a conference or in a mutual lab visit.

Summary of Estimated Costs

We estimate a total project cost of $800,000 over three years. This breaks down approximately into: $190K for principal investigator support, $225K for graduate student support, $30K for supplies, software and equipment, $27K for travel to conferences, and the rest for benefits and indirect costs.

References

[1] Benjamin, D. Paul, Deryle Lonsdale and Damian Lyons, "A Cognitive Robotics Approach to Comprehending Human Language and Behaviors", Proceedings of the Human-Robot Interaction Conference 2007 (HRI2007), Washington, D.C., March, 2007.
[2] Benjamin, D. Paul, Deryle Lonsdale and Damian Lyons, "Embodying a Cognitive Model in a Mobile Robot", Proceedings of the SPIE Conference on Intelligent Robots and Computer Vision, Boston, October, 2006.
[3] Bender, J. W. (Ed.), The current state of the coherence theory. Dordrecht: Kluwer, 1989.
[4] Davidson, D., A coherence theory of truth and knowledge. In E. Lepore (Eds.), Truth and interpretation Oxford: Basil Blackwell, 1986.
[5] Laird, J.E., Newell, A. and Rosenbloom, P.S., "Soar: An Architecture for General Intelligence", *Artificial Intelligence* **33**, pp.1-64, 1987.
[6] Millgram, E., & Thagard, P. , Deliberative coherence. Synthese, 108, 63-88, 1996.
[7] Raz, J., The relevance of coherence. Boston University Law Review, 72, 273-321. 1992.
[8] Rescher, N., The coherence theory of truth. Oxford: Clarendon Press, 1973.
[9] Thagard, P., Computing coherence. In R. N. Giere (Eds.), Cognitive Models of Science, Minnesota Studies in the Philosophy of Science, vol. 15 (pp. 485-488). Minneapolis: University of Minnesota Press, 1992.

Resume of D. Paul Benjamin

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Education:

Ph.D.	Computer Science - Courant Institute, New York University, 1985
M.S.	Computer Science - Courant Institute, New York University
B.F.A.	Music - Carnegie-Mellon University
M.S.	Mathematics - Carnegie-Mellon University
B.S.	Mathematics - Carnegie-Mellon University

Research Interests:

· Design of cognitive architectures in robotics, focusing on the relationship between perception, problem solving and language
· Application of semigroup and dynamical systems theory to knowledge representation and reformulation, problem solving and learning
· Reformulation and solution of distributed constraint satisfaction problems

Professional Experience:

Pace University, School of Computer Science and Information Systems, 1997 – Present
Professor of Computer Science
Department Chair, 2000 - 2003

Rome Laboratory, Air Force Office of Scientific Research
Visiting Research Professor, 1996 - 1998

Syracuse University, Dept. of Electrical Engineering and Computer Science
Visiting Assistant Professor, 1995 - 1997

Rome Laboratory, Griffiss Air Force Base, Rome, NY
Air Force Office of Scientific Research Summer Research Fellow, 1995

Rome Laboratory, Griffiss Air Force Base, R\ome, NY
Air Force Office of Scientific Research Summer Research Fellow, 1994

Oklahoma State University, Department of Computer Science
Assistant Professor, 1992 - 1995

St. Joseph's University (Philadelphia, Pa.),
Department of Mathematics and Computer Science
Visiting Assistant Professor, 1991 - 1992

Philips Research Laboratory, Briarcliff Manor, NY
Senior Member of Research Staff, 1984 - 1990
Project Leader in Machine Learning, 1985 - 1987

Sponsored Research:

Sponsor: DARPA, “Cognitive Support for Survivability Against Sophisticated Attacks”, contract N00178-07-C-2003, $1.5 million with BBN Technologies, Inc., December, 2006 - June, 2008.

Sponsor: Department of Energy, “Integrating Perception and Action Through Local Symmetries and Invariants”, award number ER 45903, $296,079, September 2001 - August, 2005.

Sponsor: National Science Foundation, “Integrating Formal Methods Tools into the Undergraduate Curriculum”, PI: Prof. Sotorios Skevoulis, Co-PIs: Prof. P. Benjamin and Prof. D. Anderson, Award No. DUE-0126991, $73,423, September, 2002 - August, 2005.

Sponsor: Hudson Valley Center for Emerging Technologies, “Hudson Valley Intelligent Agents Laboratory”, $10,000, 2001.

Sponsor: Air Force Office of Scientific Research / Rome Laboratory, “Pragmatic Approaches to Composition and Verification of Assured Software”, $80,500, with Dr. Shiu-Kai Chin of Syracuse University and Dr. Susan Older of Syracuse University, January, 1998 - December, 1998.

Sponsor: Air Force Office of Scientific Research, “Formal Approaches to Software Design, Planning, and the Design of Secure Systems”, $105,915, Grant No. F49620-93-C-0063, October 1, 1997 - September 30, 1998.

Sponsor: National Science Foundation, “Reformulation of System Theories in Robotics”, $49,678, SGER grant 9696060, August 1, 1995 - March 31, 1998.

Sponsor: Air Force Office of Scientific Research / Rome Laboratory, “Embedding Process and Specification Descriptions within a Categorical Framework for Refinement and Composition”, $76,000, with Dr. Shiu-Kai Chin of Syracuse University, January, 1997 - September, 1997.

Sponsor: Air Force Office of Scientific Research, “Application of Decomposition and Reformulation to Transportation Scheduling”, $103,831, Grant No. F49620-93-C-0063, October 1, 1996 - September 30, 1997.

Sponsor: Air Force Office of Scientific Research / Rome Laboratory, “Application of Process Algebra and Logic'”, $82,613, with Dr. Shiu-Kai Chin of Syracuse University, May, 1996 - December, 1996.

Sponsor: Air Force Office of Scientific Research, “Reformulating Domain Theories to Improve Their Computational Usefulness”, $24,807, SREP grant, January, 1996 - December, 1996.

Sponsor: Air Force Office of Scientific Research, “Transformational Software Design by Decomposition using the Kestrel Interactive Development System”, $24,970, SREP grant, January, 1995 - December, 1995.

Patents Held:

"System for Intrusion Detection and Vulnerability Assessment in a Computer Network using Simulation and Machine Learning", (pending) U.S. provisional patent application Serial No. 60/654,415, 2005, with Pace University.

"Semantic Encoding and Compression of Database Tables", U.S. Patent 6,691,132, February, 2004, in partnership with Adrian Walker of Reengineering, LLC.

Relevant Publications:

"A Cognitive Robotics Approach to Comprehending Human Language and Behaviors", with Deryle Lonsdale and Damian Lyons, Proceedings of the Human-Robot Interaction Conference 2007 (HRI2007), Washington, D.C., March, 2007.

"ADAPT: A Cognitive Architecture for Robotics", with Damian Lyons and Deryle Lonsdale, Proceedings of the International Conference on Cognitive Modeling, (ICCM-2004), Pittsburgh, Pa., July, 2004.

"On the Emergence of Intelligent Global Behaviors from Simple Local Actions, International Journal of Systems Science, special issue: Emergent Properties of Complex Systems, Vol. 31, No. 7, pp. 861-872, 2000.

"Connecting Perception and Action by Associating Symmetries in Vision and Language", International Journal of Artificial Intelligence Tools, Vol. 8, No. 3, 1999.

"Decomposing Robotic Representations by Identifying Local Symmetries and Invariants", Proceedings of the NSF Design and Manufacturing Grantees Conference, Mexico, 1998.

"A Decomposition Approach to Solving Distributed Constraint Satisfaction Problems", Proceedings of the IEEE Seventh Annual Dual-use Technologies & Applications Conference, IEEE Computer Society Press, 1997.

"Transforming System Formulations in Robotics for Efficient Perception and Planning", Proceedings of the IEEE International Symposia on Intelligence and Systems, Washington, D.C., IEEE Computer Society Press, 1996.

"Behavior-preserving Transformations of System Formulations", Proceedings of the AAAI Spring Symposium on Learning Dynamical Systems, Stanford University, March, 1996.

"Formulating Patterns in Problem Solving", Annals of Mathematics and AI, Vol. 10, pp.1-23, 1994.

"Reformulating Path Planning Problems by Task-preserving Abstraction", Journal of Robotics and Autonomous Systems, 9, pp. 1-9, 1992.

"An Algebraic Approach to Abstraction and Representation Change", by D. Paul Benjamin, Leo Dorst, Indur Mandhyan, and Madeleine Rosar, in Proceedings of the AAAI-90 Workshop on Automatic Generation of Approximations and Abstractions, Boston, July, 1990.

Curriculum Vitae of Deryle Lonsdale

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1) Professional Preparation:

Undergrad	Faculté Saint-Jean, University of Alberta	BSc 1981	(bilingual)
Grad	Carnegie Mellon	MS (1992), PhD (1997)	Computational Linguistics

2) Appointments: (1998-present) assistant professor, BYU Linguistics; (1990-1997) research/teaching assistant, Carnegie Mellon; (1981-1990) senior computational linguist, project leader and project manager, ALPNET, Inc.

3a) Principal Publications: (ACL = Association for Computational Linguistics)

Benjamin, D. Paul, Deryle Lonsdale, Damian Lyons, "A Cognitive Robotics Approach to Comprehending Human Language and Behaviors", Proceedings of the Human-Robot Interaction Conference 2007 (HRI2007), Washington, D.C., March, 2007.

Benjamin, D. Paul, Deryle Lonsdale, Damian Lyons, "ADAPT: A Cognitive Architecture for Robotics", Proceedings of the International Conference on Cognitive Modeling, (ICCM-2004), Pittsburgh, Pa., July, 2004.

Lonsdale, Deryle (2001) An Operator-based Integration of Comprehension and Production; *LACUS Forum XXVII*; pp. 123–132; Linguistic Association of Canada and the United States.

Rytting, C.A. & D. Lonsdale (2001a) An Operator-based Account of Semantic Processing; *The Acquisition and Representation of Word Meaning*; pp. 84-92; European Summer School for Logic, Language and Information, Helsinki.

Lonsdale, D. & C. A. Rytting (2001b) Integrating WordNet with NL-Soar; *WordNet and other lexical resources: Applications, extensions, and customizations*; Proceedings of NAACL-2001; pp. 162-164; ACL.

Lonsdale, Deryle (2000) Leveraging Analysis Operators in Incremental Generation; *Analysis for Generation: Proceedings of a Workshop at the 1st International Natural Language Generation Conference*; pp. 9-13; ACL.

Lonsdale, Deryle (1997) Modeling Cognition in SI: Methodological Issues; *International journal of research and practice in interpreting*; Vol. 2, no. 1/2; pp. 91-117; John Benjamins Publishing Company, Amsterdam.

b) Selected Other Publications: (ACL = Association for Computational Linguistics)

i. Skousen. R., D. Lonsdale & D. Parkinson (Eds). (2002) Analogical Modeling: An exemplar-based approach to language; Vol. 10 of *Human Cognitive Processing Series;* 416 pp.; John Benjamins, Amsterdam.

ii. Embley, D.W., D.M. Campbell, Y.S. Jiang, S.W. Liddle, D.W. Lonsdale, Y.-K. Ng, R.D. Smith. (1999) Conceptual-Model-Based Data Extraction from Multiple-Record Web Pages; Data and Knowledge Engineering; Vol. 31; pp. 227-251; Elsevier Science, Netherlands.
iii. Lonsdale, Deryle (2003) Two-level Engines for Salish Morphology; *Proceedings of the Workshop on Finite-State Methods in Natural Language Processing*; pp. 35-42l; European ACL.
iv. (1997) U.S. Patent # 5,677,835: Integrated authoring and translation system.
v. Lonsdale, Deryle (2002) A niche at the nexus: Situating an NLP curriculum interdisciplinarily; *Effective Tools and Methodologies for teaching NLP and CL: Proceedings of the Workshop*; pp. 45-52; ACL.

4) Synergistic activities:

a) I am actively involved in linguistic research in the Native American Salishan language family, particularly Lushootseed (my ancestry includes the Upper Skagit tribe who spoke this language). My publications describe computational linguistic approaches, the first ever undertaken, for these languages: two-level, finite-state morphological engines and categorial grammar/type-logical syntax/semantics parser/generators. (See 3biii above.)

b) I have been active in the development of pedagogy for computational linguistics and natural language processing and have a peer-reviewed article in this area. (See 3bv above.)

Curriculum Vitae of Damian Lyons

DAMIAN MARTIN LYONS

Associate Professor
Department of Computer & Information Science
Fordham University

Professional Preparation:

Ph.D.	9/86	**Computer Science.** University of Massachusetts, Amherst MA.
M.S.	8/81	**Computer Science.** Trinity College, University of Dublin, Ireland.
B.A.I.	6/80	**Electrical Engineering**. Trinity College, University of Dublin, Ireland.
B.A.	6/79	**Mathematics**. Trinity College, University of Dublin, Ireland.

Appointments:

07/02 Present Associate Professor of Computer Science
Director, Robotics & Computer Vision Lab
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09/82 09/86 Research Assistant (and Ph.D. candidate)
Laboratory for Perceptual Robotics, University of Massachusetts at Amherst.

06/84 08/85 Instructor, COINS-121 Course
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1981 1982 Lecturer in Computer Science.
Waterford Regional College of Technology, Ireland

Relevant Publications:

Benjamin, D. Paul, Deryle Lonsdale, Damian Lyons, "A Cognitive Robotics Approach to Comprehending Human Language and Behaviors", Proceedings of the Human-Robot Interaction Conference 2007 (HRI2007), Washington, D.C., March, 2007.

Benjamin, D. Paul, Deryle Lonsdale, Damian Lyons, "ADAPT: A Cognitive Architecture for Robotics", Proceedings of the International Conference on Cognitive Modeling, (ICCM-2004), Pittsburgh, Pa., July, 2004.

D.M. Lyons and D. Pelletier, *A Line-Scan Computer Vision Algorithm for Identifying Human Body Features* in *Lecture Notes in AI #1739* (Eds. A. Braffart et al.)*, Springer Verlag* 2000.

D.M. Lyons, *A Schema-Theory Approach to Specifying and Analyzing the Behavior of Robotic Systems* in: Prerational Intelligence, (Eds. Ritter, Cruse & Dean) Kluwer Academic, Dordrecht/ Boston/ London 2000.

D. M. Lyons and A. J. Hendriks,*Exploiting patterns of interaction to achieve reactive behavior*, Artificial Intelligence February 1995 Volume 73 Issue 1-2.

D. M. Lyons. *Representing and analysing action plans as networks of concurrent processes.* IEEE Trans. Robotics and Automation, 9(3):241-256, June 1993.

D.M. Lyons, and A.J. Hendriks, *Reactive Planning*. Encyclopedia of Artificial Intelligence, 2nd Edition, Wiley & Sons, December, 1991.

Other Significant Publications:

D. M. Lyons. *Discrete-Event Modeling of Misrecognition for PTZ Tracking* IEEE Int. Conf. on Advanced Video and Signal Based Surveillance, Miami FL July 2003.

Brodsky, T.; Cohen, R.; Cohen-Solal, E.; Gutta, S.; Lyons, D.; Philomin, V.; Trajkovic, M. *Visual surveillance in retail stores and in the home.* Invited paper. 2nd European Workshop on Advanced Video Based Surveillance Systems, 2001, Kingston upon Thames, London, UK

Gutchess, D., Trajkovic, Cohen-Solal, E., M., Lyons, D., Jain, A., *A Background Model Initialization Algorithm for Video Surveillance* , Int. Conf. on Comp. Vision, 2001.

Lyons, D., Murphy, T., and Hendriks, A., *Deliberation and Reaction as Decoupled, Concurrent Activities*. ICRA'96 Workshop on Robotic Planning & Execution April 1996

D. M. Lyons and M. A. Arbib, "*A Formal Model of Computation for Sensory-Based Robotics*" IEEE Trans. Rob. Aut., vol. 5, no. 3 (June 1989), 280-293

Synergistic Activities:

- **Program Co-Chair** IEEE Int. Symp. on Assembly & Task Planning, Marina del Ray 1997.
- **Guest Editor** IEEE Trans. Rob. & Aut. Special Issue on Assembly & Task Planning (Feb'96).

- **Technical Committe Chairman** IEEE Rob. & Aut. Soc., Assembly and Task Planning TC, 1992-1996.
- **Chair, Organizing committee** IEEE Int. Symp. on Assembly & Task Planning, Pittsburgh 1995.
- **Program Committees:** AVBS 2003, Multi-Sensor Fusion 2003, Steering Committee IEEE Int. Symp. on Assembly and Task Planning 1998-2000; IEEE Int. Conf. Rob. & Aut. (ICRA) 1997; Intelligent Robots and Systems (IROS) 1997; Multi-sensor Fusion 1996; ISIP'97, BASYS'96, AAAI Spring Symp. on Error Det. in Manf. Sys 1994, Workshop on Comp. Theories of Interact. & Agency 1994; Workshop on Schemas and Neural Networks 1993.

Ph.D. Students Advised:
Thomas G. Murphy, 1996 (co-advisor), Sc.D. Dissertation, University of Massachusetts Lowell, Dept. of Computer Science. Thesis title: An Investigation into the Use of Deliberative Information as a Resource for Reactive System Decision Making.

Collaborators/Co-Authors in last 48 months:

Daphna Weinshall – Hebrew University
Anil Jain – Michigan State University
Eric Cohen-Solal – Philips Research USA
Tom Brodsky – ActivEye Inc.
Paul Benjamin – PACE University

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