

Final Report for Period: 03/2010 - 08/2010

Submitted on: 05/27/2011

Principal Investigator: Balch, Tucker .

Award ID: 0347743

Organization: Georgia Tech Research Corp

Submitted By:

Balch, Tucker - Principal Investigator

Title:

CAREER: Learning Executable Models of Physical Social Agent Behavior

Project Participants

Senior Personnel

Name: Balch, Tucker

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Wallen, Kim

Worked for more than 160 Hours: No

Contribution to Project:

Professor Wallen is a collaborator at Yerkes Primate Center. We are jointly working on an application of this work to animal behavior research.

Name: Pratt, Stephen

Worked for more than 160 Hours: No

Contribution to Project:

Stephen is an assistant professor at Arizona State University. He is providing access to ant colonies for our study. We are investigating, together with him, the behavior of *A. Cockerelli* in cooperative carrying tasks.

Name: Donaldson-Mat, Matina

Worked for more than 160 Hours: No

Contribution to Project:

Matina is a postdoc at the University of Arizona. We are working with her on the study of honey bee behavior.

Post-doc

Graduate Student

Name: Khan, Zia

Worked for more than 160 Hours: Yes

Contribution to Project:

Zia is a PhD student. He is developing algorithms for tracking animals in video and using other sensors.

Name: Feldman, Adam

Worked for more than 160 Hours: Yes

Contribution to Project:

Adam is a PhD student. He is developing algorithms for recognizing social animal behavior from the trajectories we generate. He has also worked with Summer Adams to develop detection based tracking algorithms using multiple laser range finders or video input.

Name: Adams, Summer

Worked for more than 160 Hours: Yes

Contribution to Project:

Developed software for detection based tracking of people, monkeys and ants.

Name: Nguyen, Hai

Worked for more than 160 Hours: Yes

Contribution to Project:

Developed agent-based model learning algorithms. Researching new behavior modeling and tracking methods.

Name: Lee, Jin

Worked for more than 160 Hours: Yes

Contribution to Project:

Jin conducted research in computer vision tracking and developed software for tracking fish in an aquarium.

Name: Quitmeyer, Andrew

Worked for more than 160 Hours: Yes

Contribution to Project:

Andrew is joining the project to assist with video capture of honey bee behavior and tracking their movements. He's in charge of animal care of our insect colonies.

Undergraduate Student

Name: Scherer, Jesse

Worked for more than 160 Hours: Yes

Contribution to Project:

Jesse helps us gather animal data by viewing and validating tracks gathered from video analysis.

Name: Guillory, Andrew

Worked for more than 160 Hours: Yes

Contribution to Project:

Developed agent-based model learning algorithms.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Culpepper, Stephen

Worked for more than 160 Hours: Yes

Contribution to Project:

Stephen helps keep our animals healthy. He also builds and manages their habitats.

Years of schooling completed: Sophomore

Home Institution: Same as Research Site

Home Institution if Other:

Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree

Fiscal year(s) REU Participant supported: 2005

REU Funding: REU supplement

Organizational Partners

Emory University, Yerkes Regional Primate Research Center

We work with Kim Wallen at Yerkes to track and analyze the behavior of rhesus monkeys.

PRINCETON UNIVERSITY

We collaborate with Stephen Pratt in Biology at Princeton. We are helping him gather quantitative information from ant tracks.

CORNELL UNIVERSITY INC

sportvision

We are investigating the possibility of technology transfer to use our tracking algorithms in sportvision's work with video augmentation of sport broadcasts.

EPPS Aviation

We are investigating the possibility of using our tracking software to improve safety and security at airports.

Arizona State University

We collaborate with Stephen Pratt in Biology at ASU. We are helping him gather quantitative information from ant tracks.

Other Collaborators or Contacts

I work with Magnus Egerstedt, Bruce Walker and Frank Dellaert at Georgia Tech.

Activities and Findings**Research and Education Activities:**

We have gathered and processed volumes of social animal behavior in video form. I believe our experiments represent more data than has ever been gathered for these types of behavior. In particular, we have:

Recorded and tracked 500 hours of rhesus monkey behavior at Yerkes Primate Research Center. The quantitative data from these tracks supports the PhD research of Rebecca Herman.

Recorded and tracked 3 hours of interaction behavior of the ant *Aphaenogaster cockerelli*.

Recorded (but not yet tracked) 7 days of honey bee activity inside an observation hive.

Reconstructed behavioral controllers of simulated robots using only tracking data.

Recorded and tracked a full basketball game.

I have presented the results of this work at a number of conferences and workshops over the last five years.

Over the year 2009, the PI was on sabbatical investigating the use of Machine Learning in finance. A result of that work has been the development of a new course on Machine Learning for finance that was taught in spring 2010 at Georgia Tech, and that we expect to teach annually.

In 2010, the PI continued development of the new course CS 7646: Machine Learning for Finance. In concert with that, we developed, with students, a new open source toolkit for quantitative finance. The toolkit is called QSTK (Quantitative Software Tool Kit). It is available online at wiki.quantsoftware.org.

We continued outreach and collaboration with biologists including Stephen Pratt at ASU and Martina Donaldson at University of Arizona, and Kim Wallen at Emory. These collaborations resulted in new proposals and awards from NSF, NIH and ONR in which we are using the algorithms developed in this work.

Findings:

The key finding is that computer vision technologies really can accelerate research in the biological sciences. We have enabled research at Yerkes that would not otherwise be possible.

We have developed new algorithms capable of tracking many 10s of animals at once, and algorithms that can automatically interpret their behavior. We have also demonstrated algorithms that can reconstruct behaviors from only tracking data.

A significant recent result (2009) was a new multi-target model-based tracker that uses Iterative Closest Point (ICP) we call Multi ICP. As of 2011 work has been submitted and is in revision.

There were no new findings in 2010.

Training and Development:

My two PhD students have learned how to devise and conduct animal behavior experiments, and how to validate the accuracy of new methods of measuring behavior.

Our undergraduates are actively participating in our research, and learning firsthand how research is conducted in computer science and the biological sciences.

Two PhD students funded under this work graduated in 2009: Adam Feldman (now at Google) and Matt Powers (now at CMU NREC).

A number of graduate students have joined my research group to contribute to the development of the open source QSTK system. In addition to the research we conduct in this area, they are also learning open source software development practices.

Outreach Activities:

Our lab provides frequent tours for local and regional students. In September 2004, for example, we hosted 500 high school students over two days. In November 2006, we hosted 50 gifted 4th graders, in April 2010 we hosted 200 high school students.

I have twice visited elementary schools to lecture on honey bee behavior.

I have been interviewed on CNN about our work 3 times.

We created an educational video concerning the honey bee waggle dance. It has received thousands of views. You can view it here: <http://www.youtube.com/watch?v=bFDGPgXtK-U>

Journal Publications

Z. Khan, R. Herman, K. Wallen, T. Balch, "A 3-d Visual Tracking System for the Study of Spatial Navigation and Memory in Rhesus Monkeys", Behavior Research Methods, Instruments & Computers, p. 112, vol. , (2004). Published,

P. Ulam, T. Balch, "Niche Selection in Foraging Tasks in Multi-Robot Teams Using Reinforcement Learning", Adaptive Behavior, p. 112, vol. 12, (2004). Published,

A. Feldman, and T. Balch, "A Human Trainable System for Automated Social Insect Behavior Recognition", Adaptive Behavior, p. 112, vol. 12, (2004). Published,

Z. Khan, T. Balch, F. Dellaert, "MCMC-Based Particle Filtering for Tracking a Variable Number of Interacting Targets", IEEE Transactions on Pattern Analysis and Machine Intelligence, p. 112, vol. , (). Submitted,

- Balch, Dellaert, Feldman, Guillory, Isbell, Khan, Prtatt, Stein, Wilde, "How multi-robot systems research will accelerate our understanding of social animal behavior", Proceedings of the IEEE, p. , vol. , (2006). Accepted,
- Z. Khan, T. Balch, and F. Dellaert, "MCMC Data Association and Sparse Factorization Updating for Real Time Multitarget Tracking with Merged and Multiple Measurements", IEEE Transactions on Pattern Analysis and Machine Intelligence, p. 1960, vol. 28, (2006). Published,
- Z. Khan, T. Balch, and F. Dellaert,, "Multitarget Tracking with Split and Merged Measurements", IEEE Computer Society Conference on Computer Vision and Pattern Recognition, p. 605, vol. 1, (2005). Published,
- M. Egerstedt, T. Balch, F. Dellaert, F. Delmotte, and Z. Khan, "What Are the Ants Doing? Vision-Based Tracking and Reconstruction of Control Programs", IEEE Conference on Robotics and Automation, p. 4182, vol. , (2005). Published,
- A. Feldman, T. Balch, "Representing Honey Bee Behavior for Recognition Using Human Trainable Models", Adaptive Behavior, p. 241, vol. , (2004). Published,
- Sang Min Oh, James M. Rehg, Tucker Balch, Frank Dellaert, "Learning and Inference in Parametric Switching Linear Dynamical Systems", IEEE International Conference on Computer Vision, p. 1161, vol. , (2005). Published,
- Sang Min Oh, James M. Rehg, Tucker Balch, Frank Dellaert, "Data-Driven MCMC for Learning and Inference in Switching Linear Dynamic Systems", Proceedings of the Twentieth National Conference on Artificial Intelligence, p. 944, vol. , (2005). Published,
- Andrew Guillory, Hai Nguyen, Tucker R. Balch, Charles Lee Isbell Jr., "Learning executable agent behaviors from observation", Autonomous Agents and Multi-agent Systems, p. 795, vol. , (2006). Published,
- Ding, XC; Powers, M; Egerstedt, M; Young, SY; Balch, T, "Executive Decision Support Single-Agent Control of Multiple UAVs", IEEE ROBOTICS & AUTOMATION MAGAZINE, p. 73, vol. 16, (2009). Published, 10.1109/MRA.2009.93252
- O'Hara, KJ; Walker, DB; Balch, TR, "Physical path planning using a pervasive embedded network", IEEE TRANSACTIONS ON ROBOTICS, p. 741, vol. 24, (2008). Published, 10.1109/TRO.2008.91930
- Balch, T; Summet, J; Blank, D; Kumar, D; Guzdial, M; O'Hara, K; Walker, D; Sweat, M; Gupta, G; Tonsley, S; Jackson, J; Gupta, M; Muhammad, MN; Proshod, S; Eilbert, N; Gavin, A, "Designing personal robots for education: Hardware, software, and curriculum", IEEE PERVASIVE COMPUTING, p. 5, vol. 7, (2008). Published,
- Oh, SM; Rehg, JM; Balch, T; Dellaert, F, "Learning and inferring motion patterns using parametric segmental Switching Linear Dynamic Systems", INTERNATIONAL JOURNAL OF COMPUTER VISION, p. 103, vol. 77, (2008). Published, 10.1007/s11263-007-0062-
- Khan, Z; Balch, T; Dellaert, F, "MCMC data association and sparse factorization updating for real time multitarget tracking with merged and multiple measurements", IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, p. 1960, vol. 28, (2006). Published,
- Balch, T; Dellaert, F; Feldman, A; Guillory, A; Isbell, CL; Khan, Z; Pratt, SC; Stein, AN; Wilde, H, "How multirobot systems research will accelerate our understanding of social animal behavior", PROCEEDINGS OF THE IEEE, p. 1445, vol. 94, (2006). Published, 10.1109/JPROC.2006.87696
- Khan, Z; Herman, RA; Wallen, K; Balch, T, "An outdoor 3-D visual tracking system for the study of spatial navigation and memory in rhesus monkeys", BEHAVIOR RESEARCH METHODS, p. 453, vol. 37, (2005). Published,
- Khan, Z; Balch, T; Dellaert, F, "MCMC-based particle filtering for tracking a variable number of interacting targets", IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, p. 1805, vol. 27, (2005). Published,
- Herman, RA; Khan, Z; Balch, T; Wallen, K, "Rhesus monkey spatial cognition: Sex differences and effects of prenatal androgen exposure.", HORMONES AND BEHAVIOR, p. 91, vol. 46, (2004). Published,

Anderson, C; Balch, T, "Special issue on Mathematics and Algorithms of Social Interactions - With papers arising from The Second International Workshop on the Mathematics and Algorithms of Social Insects", ADAPTIVE BEHAVIOR, p. 145, vol. 12, (2004). Published,

Sariel-Talay, S; Balch, TR; Erdogan, N, "Multiple Traveling Robot Problem: A Solution Based on Dynamic Task Selection and Robust Execution", IEEE-ASME TRANSACTIONS ON MECHATRONICS, p. 198, vol. 14, (2009). Published, 10.1109/TMECH.2009.201415

Roberts, R; Pippin, C; Balch, T, "Learning Outdoor Mobile Robot Behaviors by Example", JOURNAL OF FIELD ROBOTICS, p. 176, vol. 26, (2009). Published, 10.1002/rob.2027

Sariel, S; Balch, T; Erdogan, N, "Naval mine countermeasure missions - A distributed, incremental multirobot task selection scheme", IEEE ROBOTICS & AUTOMATION MAGAZINE, p. 45, vol. 15, (2008). Published, 10.1109/M-RA.2007.91492

Books or Other One-time Publications

Web/Internet Site

URL(s):

<http://www.kinetrack.org>

Description:

Our publications, results and demonstration videos are added to this site when they occur.

Other Specific Products

Product Type:

Software (or netware)

Product Description:

We have created several easy to use software products for tracking animals by vision and by laser trackers. Our software is used at Arizona State University by Stephen Pratt, by Emory University by Kim Wallen, and also in other projects at Georgia Tech.

Sharing Information:

The software is available for download on our website:

<http://www.kinetrack.org/software.html>

Product Type:

Software (or netware)

Product Description:

We have created a software toolkit for quantitative investing and machine learning called QSTK. It is provided under an open source license.

Sharing Information:

<http://www.quantsoftware.org>

Contributions

Contributions within Discipline:

We have contributed new approaches to the problem of tracking multiple interacting targets in video.

We have contributed new approaches to the problem of tracking multiple interacting targets using laser scanners.

We created a new algorithm for combining information from multiple sensor types (vision, laser, RFID) into complete tracks with correct ID association.

We have contributed new approaches to the problem of recognizing the behavior of interacting animals.

We have developed new approaches for the reconstruction of agent behavior from tracking data.

Contributions to Other Disciplines:

Our work enables new quantitative assessments of the behavior of monkeys, fishes, ants and bees. In particular, we can provide orders of magnitude more data and more accuracy than could be provided before.

We are directly impacting research with monkeys at Yerkes and ants at Arizona State and bees at the University of Arizona.

Our approaches are now being used in a new effort to make animal displays (e.g. aquaria) more accessible to those with vision impairments. In particular we are building a system in which animals are tracked using our computer vision system. The output of our tracker is fed to a system that generates music automatically. The music reflects the motions of the animals and provides a more comprehensive experience.

We have contributed new approaches and algorithms for computational analysis of equities, and offer the approaches in an open source toolkit.

Contributions to Human Resource Development:

I am most proud of how well our undergrads are responding to their experiences in our lab.

They make a big difference in our research, and they realize that they do.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Our approaches are now being used in a new effort to make animal displays (e.g. aquaria) more accessible to those with vision impairments. In particular we are building a system in which animals are tracked using our computer vision system. The output of our tracker is fed to a system that generates music automatically. The music reflects the motions of the animals and provides a more comprehensive experience.

Our latest work is now becoming visible in Finance (the quantitative software toolkit).

Conference Proceedings

Lee, JH;Mottaghi, R;Pippin, C;Balch, T, Graph-based Planning Using Local Information for Unknown Outdoor Environments, "MAY 12-17, 2009", ICRA: 2009 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, VOLS 1-7, : 4122-4127 2009

Lee, J;Pippin, C;Balch, T, Cost Based Planning with RRT in Outdoor Environments, "SEP 22-26, 2008", 2008 IEEE/RSJ INTERNATIONAL CONFERENCE ON ROBOTS AND INTELLIGENT SYSTEMS, VOLS 1-3, CONFERENCE PROCEEDINGS, : 684-689 2008

Roberts, R;Nguyen, H;Krishnamurthi, N;Balch, T, Memory-based learning for visual odometry, "MAY 19-23, 2008", 2008 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, VOLS 1-9, : 47-52 2008

Sariel, S;Balch, T;Erdogan, N, Incremental multi-robot task selection for resource constrained and interrelated tasks, "OCT 29-NOV 02, 2007", 2007 IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS, VOLS 1-9, : 2320-2325 2007

- Wooden, D;Powers, M;MacKenzie, DC;Balch, T;Egerstedt, M, Control-driven mapping and planning, "OCT 29-NOV 02, 2007", 2007 IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS, VOLS 1-9, : 3062-3067 2007
- Feldman, A;Adams, S;Hybinette, M;Balch, T, A tracker for multiple dynamic targets using multiple sensors, "APR 10-14, 2007", PROCEEDINGS OF THE 2007 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION, VOLS 1-10, : 3140-3141 2007
- Nathuji, R;O'Hara, KJ;Schwan, K;Balch, T, CompatPM: Enabling energy efficient multimedia workloads for distributed mobile platforms - art. no. 65040I, "JAN 31-FEB 01, 2007", Multimedia Computing and Networking 2007, 6504: I5040-I5040 2007
- O'Hara, KJ;Balch, TR, Pervasive Sensor-less networks for cooperative multi-robot tasks, "JUN 23-25, 2004", Distributed Autonomous Robotic Systems 6, : 305-314 2007
- Powers, M;Balch, T, Value-based communication preservation for mobile robots, "JUN 23-25, 2004", Distributed Autonomous Robotic Systems 6, : 327-336 2007
- Sun, J;Mehta, T;Wooden, D;Powers, M;Rehg, J;Balch, T;Egerstedt, M, Learning from examples in unstructured, outdoor environments, "DEC, 2005", JOURNAL OF FIELD ROBOTICS, 23 (11-12): 1019-1036 NOV-DEC 2006
- O'Hara, KJ;Bigio, VL;Dodson, ER;Irani, AJ;Walker, DB;Balch, TR, Physical path planning using the GNATs, "APR 18-22, 2005", 2005 IEEE International Conference on Robotics and Automation (ICRA), Vols 1-4, : 709-714 2005
- Egerstedt, M;Balch, T;Dellaert, F;Delmotte, F;Khan, Z, What are the ants doing? vision-based tracking and reconstruction of control programs, "APR 18-22, 2005", 2005 IEEE International Conference on Robotics and Automation (ICRA), Vols 1-4, : 4182-4187 2005
- Sariel, S;Balch, T, A distributed multi-robot cooperation framework for real time task achievement, "JUL 12-14, 2006", Distributed Autonomous Robotic Systems 7, : 187-196 2006
- Sariel, S;Balch, T;Stack, J, Empirical evaluation of auction-based coordination of AUVs in a realistic simulated mine countermeasure task, "JUL 12-14, 2006", Distributed Autonomous Robotic Systems 7, : 197-206 2006
- Sariel, S;Balch, T;Erdogan, N, Robust multi-robot cooperation through dynamic task allocation and precaution routines, "AUG 01-05, 2006", ICINCO 2006: Proceedings of the Third International Conference on Informatics in Control, Automation and Robotics, : 196-201 2006
- O'Hara, KJ;Bigio, V;Whitt, S;Walker, D;Balch, T, Evaluation of a large scale pervasive embedded network for robot path planning, "MAY 15-19, 2006", 2006 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION (ICRA), VOLS 1-10, : 2072-2077 2006
- O'Hara, KJ;Nathuji, R;Raj, H;Schwan, K;Balch, T, AutoPower: Toward energy-aware software systems for distributed mobile robots, "MAY 15-19, 2006", 2006 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION (ICRA), VOLS 1-10, : 2757-2762 2006
- Raj, H;Seshasayee, B;O'Hara, KJ;Nathuji, R;Schwan, K;Balch, T, Spirits: Using virtualization and pervasiveness to manage mobile robot software systems, "JUN 16, 2006", SELF-MANAGED NETWORKS, SYSTEMS, AND SERVICES, PROCEEDINGS, 3996: 116-129 2006
- Powers, M;Balch, T, A Learning Approach to Integration of Layers of a Hybrid Control Architecture, "OCT 10-15, 2009", 2009 IEEE-RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS, : 893-898 2009
- Powers, M;Balch, T, Incremental Adaptive Integration of Layers of a Hybrid Control Architecture, "OCT 18-22, 2010", IEEE/RSJ 2010 INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS (IROS 2010), : - 2010

Categories for which nothing is reported:

Any Book

Contributions: To Any Resources for Research and Education

May 24, 2010

To Whom It May Concern:

I am writing this letter to certify that the School of Interactive Computing continues to support the research efforts of Dr. Tucker Balch and that he continues to be eligible to receive support under the CAREER program. Dr. Balch began his full-time tenure-track position here at Georgia Tech in August, 2001 and was promoted to Associate Professor in July, 2006.

All faculty members are supported by the School to devote two-thirds of their academic year time to research. The regular teaching load for research active faculty is two courses per academic year, or one per semester. These courses typically include a graduate level class in the area of research expertise. We also include a provision for reduced load in recognition of course development activities. Dr. Balch received start-up funding in the amount of \$275,000 to support equipment, travel and student stipends. In addition, the School and the Robotics and Intelligent Machine Center assist in funding a robotics technician to help build the robotics research infrastructure.

In closing, I continue to monitor the career development of Dr. Balch and it is proceeding quite well. I attest that the PI's career development plan is supported by and integrated into the educational and research goals of the School and the organization. And, finally, I personally commit to the support and professional development of the Dr. Balch.

Sincerely,



Aaron Bobick, Chair
School of Interactive Computing