

**Final Report for Period:** 08/2008 - 07/2009

**Submitted on:** 08/20/2009

**Principal Investigator:** Egerstedt, Magnus B.

**Award ID:** 0509064

**Organization:** GA Tech Res Corp - GIT

**Submitted By:**

Egerstedt, Magnus - Principal Investigator

**Title:**

CSR-EHS: Optimal, Multi-Modal Control of Complex Systems

### Project Participants

#### Senior Personnel

**Name:** Egerstedt, Magnus

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Magnus Egerstedt focuses on the issue of formulating complex control problems as hybrid, optimal control problems that are amendable to real-time timing control. Also, application domains, including autonomous robots, fall under Dr. Egerstedt's responsibilities.

**Name:** Wardi, Yorai

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Yorai Wardi's research focus lies on the issue of numerical optimization, with particular focus on algorithmic and complexity-related issues os relevance to real-time optimal control.

#### Post-doc

#### Graduate Student

**Name:** Ding, Dennis

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Mr. Ding is working on a real-time version (theory as well as numerical algorithms) of the developed optimal control algorithms for complex, multi-modal systems.

**Name:** Axelsson, Henrik

**Worked for more than 160 Hours:** Yes

**Contribution to Project:**

Dr. Axelsson (graduated with a PhD from Georgia Tech in the Spring of 2006) has been developing a computational theory for solving optimal control problems using a numerically tractable, hybrid, descent method.

#### Undergraduate Student

#### Technician, Programmer

#### Other Participant

#### Research Experience for Undergraduates

### Organizational Partners

### Other Collaborators or Contacts

Professors David Taylor and Gabriel Rincon-Mora at the Georgia Institute of Technology have been consulted regularly in order to produce convincing and realistic example problems in the general area of power electronics and power harvesting micro-electronic systems. Applications to unmanned aerial vehicle flight-mode control have been pursued in collaboration with Professor Tucker Balch at the Georgia Institute of Technology.

## Activities and Findings

### **Research and Education Activities:**

This project delivers computational tools for deciding when a supervisory-level controller should switch among different dynamic regimes. Such multi-modal systems arise in a number of applications in which the supervisor is to switch among different sensory sources, different operating points, different intermediary subtasks, or different behavioral modes of operation. In particular, by breaking down the control task into a number of subcomponents, a large part of the design complexity associated with such systems is resolved. What this project delivers is a real-time approach to the scheduling and timing issues associated with of the high-level supervisor. A numerical optimization package in Matlab has been produced for off-line as well as on-line optimal control of multi-modal systems.

At the educational side, a new undergraduate course, ECE4555 Embedded and Hybrid Control, has been introduced into the controls curriculum at the senior level and it has been taught twice in the Spring semesters of 2007 and 2008. An additional, senior-level undergraduate course on numerical methods for optimization and optimal control will be taught for the first time during the Spring of 2009 as part of the proposed educational scope of the program.

### **Findings:**

The major findings related to this project fall under three distinct areas, namely:

- (1) A descent-based algorithm has been produced for computing optimal timing-laws and schedules for complex, multi-modal systems. This numerically efficient algorithm has been implemented as part of a Matlab toolbox on optimal control of hybrid systems.
- (2) A real-time algorithm for adaptively evolving the switching laws has been produced that, at each time instant, improves the performance of the system.
- (3) The algorithms have been implemented on two robotics testbeds. the first testbed is one in which in a mobile robot is switching between different so-called behaviors in an optimal manner, in response to the changing environment. The second testbed is a simulated environment in which multiple UAVs switch between different configurations in real-time in response to dynamic changes in the environment.

### **Training and Development:**

Two graduate students have been employed through this project (Dennis Ding and Henrik Axelsson). Dr. Axelsson graduated with a PhD in the Spring of 2006 and Dennis Ding is expected to graduate with a PhD in the Fall of 2009. In order to carry out the work, these two students have been exposed to tools and techniques in areas as varied as numerical methods, optimization theory, computer science, and control theory. Through the undergraduate course, ECE4555, developed as part of this project, 50 students have so far been exposed to and involved with course material that is traditionally not seen until the graduate levels. The numerical optimization aspects of the work has been leveraged to create a new undergraduate course at the senior level on Numerical Optimal Control, which was taught for the first time during the Fall semester in 2008.

### **Outreach Activities:**

Magnus Egerstedt visited Parkside Elementary in Atlanta, GA during 2007 to talk about robotics and, in particular, how autonomous robots navigate cluttered environments by switching between different behaviors (or modes of operation). Parkside is a school populated mainly by minority students.

## Journal Publications

M. Boccadoro, Y. Wardi, M. Egerstedt, and E. Verriest, "Optimal Control of Switching Surfaces in Hybrid Dynamical Systems", *Journal of Discrete Event Dynamic Systems*, p. 433, vol. 15, (2005). Published,

M. Egerstedt, Y. Wardi, and H. Axelsson, "Transition-Time Optimization for Switched Systems", *IEEE Transactions on Automatic Control*, p. 110, vol. 51, (2006). Published,

- M. Egerstedt, S. Azuma, and Y. Wardi, "Optimal Timing Control of Switched Linear Systems Based on Partial Information", *Nonlinear Analysis: Theory, Methods and Applications*, p. 1736, vol. 65, (2006). Published,
- H. Axelsson, Y. Wardi, M. Egerstedt, and E. Verriest, "A Gradient Descent Approach to Optimal Mode Scheduling in Hybrid Dynamical Systems", *Journal of Optimization Theory and Applications*, p. 167, vol. 136, (2006). Published,
- H. Axelsson, M. Boccadoro, M. Egerstedt, P. Valigi, and Y. Wardi, "Optimal Mode-Switching for Hybrid Systems with Varying Initial States", *Journal of Nonlinear Analysis: Hybrid Systems and Applications*, p. 765, vol. 2, (2008). Published,
- X.C. Ding, Y. Wardi, and M. Egerstedt, "On-Line Optimization of Switched-Mode Dynamical Systems", *IEEE Transactions on Automatic Control*, p. , vol. , (2009). Accepted,
- V. Azhmyakov, R. Guerra, and M. Egerstedt, "Linear-Quadratic Optimal Control of Hybrid Systems: Impulsive and Non-Impulsive Models", *Automatica*, p. , vol. , (2009). Submitted,

### Books or Other One-time Publications

- H. Axelsson, M. Egerstedt, and Y. Wardi, "Reactive Robot Navigation Using Optimal Timing Control", (2005). Conference Proceedings, Published  
Collection: Proceedings of the American Control Conference  
Bibliography: 6 pages
- H. Axelsson, M. Egerstedt, G. Vachtsevanos, and Y. Wardi, "Algorithms for Switching-Time Optimization in Hybrid Systems", (2005). Conference Proceedings, Published  
Collection: Mediterranean Conference on Control and Automation  
Bibliography: 6 pages
- M. Boccadoro, M. Egerstedt, and Y. Wardi, "Obstacle Avoidance for Mobile Robots Using Switching Surface Optimization", (2005). Conference Proceedings, Published  
Collection: Proceedings of the IFAC World Congress  
Bibliography: 6 pages
- H. Axelsson, Y. Wardi, and M. Egerstedt, "Transition-Time Optimization for Switched Systems", (2005). Conference Proceedings, Published  
Collection: Proceedings of the IFAC World Congress  
Bibliography: 6 pages
- H. Axelsson, Y. Wardi, M. Egerstedt, and E. Verriest, "A Provably Convergent Algorithm for Transition-Time Optimization in Switched Systems", (2005). Conference Proceedings, Published  
Collection: Proceedings of the IEEE Conference on Decision and Control  
Bibliography: 6 pages
- H. Axelsson, M. Boccadoro, Y. Wardi, and M. Egerstedt, "Optimal Mode-Switching for Hybrid Systems with Unknown Initial State", (2006). Conference Proceedings, Published  
Collection: Proceedings of the IFAC Conference on Analysis and Design of Hybrid Systems  
Bibliography: 6 pages
- H. Axelsson, M. Egerstedt, and Y. Wardi, "Trade-Offs Between Precision and Computation Horizon in Real-Time Optimal Control of Switched Systems", (2006). Conference Proceedings, Published  
Collection: Proceedings of the American Control Conference  
Bibliography: pp. 5941-5947

- H. Axelsson, Y. wardi, and M. Egerstedt, "Convergence of Gradient-Descent Algorithms for Mode-Scheduling Problems in Hybrid Systems", (2006). Conference Proceedings, Published  
Collection: Proceedings of the Mathematical Theory of Networks and Systems  
Bibliography: 4 pages
- H. Axelsson, M. Egerstedt, and Y. Wardi, "Optimal Switching Surfaces in Behavior-Based Robotics", (2006). Conference Proceedings, Published  
Collection: Proceedings of the IEEE Conference on Decision and Control  
Bibliography: pp. 1954-1959
- S. Azuma, M. Egerstedt, and Y. Wardi, "Output-Based Optimal Timing Control of Switched Systems", (2006). Book, Published  
Collection: Hybrid Systems: Computation and Control  
Bibliography: Springer-Verlag, 14 pages
- P. Caines, M. Egerstedt, R. Malhame, and A. Schollig, "A Hybrid Bellman Equation for Bimodal Systems", (207 ). Book, Published  
Collection: Hybrid Systems: Computation and Control  
Bibliography: Springer Verlag, 4 pages
- A. Schollig, P.E. Caines, M. Egerstedt, and R. Malhame, "A Hybrid Bellman Equation for Systems with Regional Dynamics", (2007). Conference Proceedings, Published  
Collection: IEEE Conference on Decision and Control  
Bibliography: 6 pages
- Y. Wardi, X.C. Ding, M. Egerstedt, and S. Azuma, "On-Line Optimization of Switched-Mode Systems: Algorithms and Convergence Properties", (2007). Conference Proceedings, Published  
Collection: IEEE Conference on Decision and Control  
Bibliography: 6 pages
- D. Ding, Y. Wardi, and M. Egerstedt, "Adaptive Optimal Timing Control of Hybrid Systems", (2008). Conference Proceedings, Published  
Collection: Mathematical Theory of Networks and Systems  
Bibliography: 4 pages
- D. Ding, Y. Wardi, D. Taylor, and M. Egerstedt, "Optimization of Switched-Mode Systems with Switching Costs", (2008). Conference Proceedings, Published  
Collection: American Control Conference  
Bibliography: 6 pages
- A. Schild, M. Egerstedt, and J. Lunze, "Optimal Control for a Class of Planar Impulsive Hybrid Systems with Controllable Resets", (2009). Book, Published  
Collection: Hybrid Systems: Computation and Control  
Bibliography: pp. 470-474, Springer Verlag
- V. Azhmyakov, R.G. Guerra, and M. Egerstedt, "Hybrid LQ-Optimization Using Dynamic Programming", (2009). Conference Proceedings, Published  
Collection: American Control Conference  
Bibliography: 6 pages
- X.C. Ding, A. Schild, M. Egerstedt, and J. Lunze, "Real-Time Optimal feedback Control of Switched Autonomous Systems", (2009). Conference Proceedings, Accepted  
Collection: IFAC Conference on Analysis and Design of Hybrid Systems  
Bibliography: 6 pages

A. Schild, X.C. Ding, M. Egerstedt, and J. Lunze, "Design of Optimal Switching Surfaces for Switched Autonomous Systems", (2009). Conference Proceedings, Accepted  
 Collection: IEEE Conference on Decision and Control & Chinese Control Conference  
 Bibliography: 6 pages

X.C. Ding, Y. Wardi, and M. Egerstedt, "On-Line Adaptive Optimal Timing Control of Switched Systems", (2009). Conference Proceedings, Accepted  
 Collection: IEEE Conference on Decision and Control & Chinese Control Conference  
 Bibliography: 6 pages

Henrik Axelsson, "Optimal Control of Switched Autonomous Systems: Theory, Algorithms, and Robotic Applications", (2006). Thesis, Published  
 Collection: PhD Thesis  
 Bibliography: Georgia Institute of Technology

### Web/Internet Site

**URL(s):**

[http://gritslab.ece.gatech.edu/projects/projects\\_optctrl.html](http://gritslab.ece.gatech.edu/projects/projects_optctrl.html)

**Description:**

On this page, the outcomes of the award are discussed.

### Other Specific Products

**Product Type:**

Software (or netware)

**Product Description:**

A Matlab toolbox for optimal timing and scheduling control for multi-modal systems has been developed.

**Sharing Information:**

The toolbox will be made available over the Internet during 2007.

### Contributions

**Contributions within Discipline:**

Through this program, optimal control of hybrid, multi-modal systems has been put on a firm, computational footing, which thus bridges the previous gap between analytical (yet computationally cumbersome) optimality conditions, and the 'brute force' approach to the problem. In particular, a so-called insertion gradient has been produced that enables us to view the scheduling problem as a local optimization problem, thus endowing a previously intractable problem with a computationally feasible interpretation in terms of local solutions. Moreover, an on-line version of the algorithm has been developed that lends itself to fast computations in environments in which an incremental improvement is sufficient, as the system evolves.

**Contributions to Other Disciplines:**

As hybrid models are useful in a number of applications, including robotics, power electronics, real-time computer systems, and embedded computing systems, the ability to produce optimal, high-level solutions in this general area is expected to have impact beyond the controls community. In particular, work in the areas of robotics, control of multiple unmanned aerial vehicles, and power electronics, has been conducted.

**Contributions to Human Resource Development:**

**Contributions to Resources for Research and Education:**

**Contributions Beyond Science and Engineering:**

**Conference Proceedings**

**Categories for which nothing is reported:**

Organizational Partners

Contributions: To Any Human Resource Development

Contributions: To Any Resources for Research and Education

Contributions: To Any Beyond Science and Engineering

Any Conference