20 Years of Vehicles at CDS
in twenty-five minutes and zero formulas

Andrea Censi ('12)
Geometric Control of Mechanical Systems
Geometric Control of Mechanical Systems
Geometric Control of Mechanical Systems
Geometric Control of Mechanical Systems
Geometric modeling of mechanical systems

Differential geometry essential:

**Advantages**

1. Prevents artificial reliance on specific coordinate systems.
2. Identifies key elements of system model.
3. Suggests methods of analysis and design.

**Disadvantages**

1. Need to know differential geometry.

*Bullo, Lewis*
Geometric Control of Mechanical Systems
Geometric Control of Mechanical Systems

Nonlinear Control of Mechanical Systems: A Riemannian Geometry Approach

1999
Thesis by Francesco Bullo
now: UCSB
Geometric Control of Mechanical Systems

Nonlinear Control of Mechanical Systems: A Riemannian Geometry Approach

1999

Thesis by Francesco Bullo

now: UCSB
Geometric Control of Mechanical Systems

Nonlinear Control of Mechanical Systems: A Riemannian Geometry Approach
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now: UCSB

Aspects of Geometric Mechanics and Control of Mechanical Systems
1995, AM
Thesis by Andrew David Lewis
now: Queens University Kingston (CA)
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Everything is the Same: Modeling Engineered Systems
Geometric Control of Mechanical Systems

Nonlinear Control of Mechanical Systems: A Riemannian Geometry Approach
1999
Thesis by Francesco Bullo
now: UCSB

Control of Multiple Model Systems
2002
Thesis by Todd Murphy
now: Northwestern

Foundations of Computational Geometric Mechanics
2004
Thesis by Melvin Leok
now: UCSD

Aspects of Geometric Mechanics and Control of Mechanical Systems
1995, AM
Thesis by Andrew David Lewis
now: Queens University Kingston (CA)

Everything is the Same: Modeling Engineered Systems

modeling
Connecting Constructing Predicting
Trajectory Generation and Optimal Control
Trajectory Generation and Optimal Control
Trajectory Generation and Optimal Control
Exponential Stabilization of Driftless Nonlinear Control Systems

Thesis by
Robert Thomas M’Closkey III

1995, ME

now: UCLA
Trajectory Generation and Optimal Control

Exponential Stabilization of Driftless Nonlinear Control Systems
1995, ME
Thesis by Robert Thomas M’Closkey III
now: UCLA

Trajectory Generation for Nonlinear Control Systems
1996, ME
Thesis by Michiel J. van Nieuwstadt
now: Ford

now: UCLA
Trajectory Generation and Optimal Control

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now: Ford

Differentially Flat Nonlinear Control Systems
1997, AM
Thesis by Muruhan Rathinam
now: UMBC
Trajectory Generation and Optimal Control

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1997, AM
Thesis by Muruhan Rathinam
now: UMBC

Trajectory Generation for Nonlinear Control Systems

1996, ME
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now: Ford

Real-Time Optimal Trajectory Generation for Constrained Dynamical Systems

2003
Thesis by Mark B. Milam
now: Northrop Grumman
<table>
<thead>
<tr>
<th>Title</th>
<th>Year</th>
<th>Student</th>
<th>Current Institution</th>
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<td>Ashley Moore</td>
<td>The Aerospace Corporation</td>
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Thesis by Robert Thomas M’Closkey III
now: UCLA

Differentially Flat Nonlinear Control Systems
1997, AM
Thesis by Muruhan Rathinam
now: UMBC

Efficient Methods for Stochastic Optimal Control
2014
Thesis by Matanya B. Horowitz
now: Cognitive Robotics (startup)

Real-Time Optimal Trajectory Generation for Constrained Dynamical Systems
2003
Thesis by Mark B. Milam
now: Northrop Grumman

Trajectory Generation for Nonlinear Control Systems
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Thesis by Michiel J. van Nieuwstadt
now: Ford

Discrete Mechanics and Optimal Control for Space Trajectory Design
2011
Thesis by Ashley Moore
now: The Aerospace Corporation
Control of Mechanical Systems
Control of Mechanical Systems

Distributed Control
Control of Mechanical Systems ➤ Distributed Control ➤ Dynamics and Control of Information Flows
Control of Mechanical Systems

Distributed Control

Dynamics and Control of Information Flows

Receding Horizon Control of Nonlinear Systems:
A Control Lyapunov Function Approach

Thesis by
Ali Jadabaie

now: UPenn

2001
Receding Horizon Control of Nonlinear Systems:
A Control Lyapunov Function Approach

Thesis by
Ali Jadabaie

now: UPenn

Collaborative scalar-gain estimators for potentially unstable social dynamics with limited communication

Usman A. Khan\textsuperscript{a,1}, Ali Jadabaie\textsuperscript{b}

\textsuperscript{a} Electrical and Computer Engineering Department, Tufts University, 161 College Ave., Medford, MA 02155, USA
\textsuperscript{b} Electrical and Systems Engineering Department, University of Pennsylvania, 3501 Walnut St., Philadelphia, PA 19104, USA
Receding Horizon Control of Nonlinear Systems:
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2001
Thesis by
Ali Jadbabaie
now: UPenn

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\textsuperscript{b} Electrical and Systems Engineering Department, University of Pennsylvania, 3510 Walnut St., Philadelphia, PA 19104, USA
Receding Horizon Control of Nonlinear Systems: A Control Lyapunov Function Approach

Thesis by
Ali Jadababaie

now: UPenn

Collaborative scalar-gain estimators for potentially unstable social dynamics with limited communication*

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¹ Electrical and Computer Engineering Department, Tufts University, 161 College Ave., Medford, MA 02155, USA
² Electrical and Systems Engineering Department, University of Pennsylvania, 3501 Walnut St., Philadelphia, PA 19104, USA

Eulerian Opinion Dynamics with Bounded Confidence and Exogenous Inputs*

Anahita Mirtabatabaei¹, Peng Jia¹, and Francesco Bullo³

¹ University of Texas at Austin, Department of Electrical and Computer Engineering
² University of California, Los Angeles, Department of Electrical Engineering
³ University of California, Los Angeles, Department of Mechanical and Aerospace Engineering
Receding Horizon Control of Nonlinear Systems: 
A Control Lyapunov Function Approach

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now: UPenn

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\textsuperscript{b} Electrical and Systems Engineering Department, University of Pennsylvania, 3518 Walnuk St., Philadelphia, PA 19104, USA

Optimal and Cooperative Control of Vehicle Formations

Thesis by
J. Alexander Fax

now: Northrop Grumman

Eulerian Opinion Dynamics with Bounded Confidence and Exogenous Inputs\textsuperscript{c}

Anahita Mirtabatabaei\textsuperscript{1}, Peng Jia\textsuperscript{1}, and Francesco Bullo\textsuperscript{1}

\textsuperscript{c} Distributed Control of Robotic Networks: A Mathematical Approach, Society for Industrial and Applied Mathematics
Control of Mechanical Systems

Distributed Control

Dynamics and Control of Information Flows

Receding Horizon Control of Nonlinear Systems:

A Control Lyapunov Function Approach

Thesis by

Ali Jadabaie

2001

now: UPenn

Collaborative scalar-gain estimators for potentially unstable social dynamics with limited communication*

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a Electrical and Computer Engineering Department, Tufts University, 161 College Ave., Medford, MA 02155, USA
b Electrical and Systems Engineering Department, University of Pennsylvania, 3501 Walnut St., Philadelphia, PA 19104, USA

Optimal and Cooperative Control of Vehicle Formations

2002

now: Northrop Grumman

Eulerian Opinion Dynamics with Bounded Confidence and Exogenous Inputs*

Anahita Mirtabatabaei a, Peng Jia b, and Francesco Bullo c

a Francesco Bullo
b Jorge Cortés
San Francisco, USA

b Sergio Martínez
San Francisco, USA

a Francisco Bullo
b Jorge Cortés
San Francisco, USA
Receding Horizon Control of Nonlinear Systems: A Control Lyapunov Function Approach

2001

Thesis by
Ali Jadbabaie

Collaborative scalar-gain estimators for potentially unstable social dynamics with limited communication

Usman A. Khan a, *, Ali Jadbabaie b

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b Electrical and Systems Engineering Department, University of Pennsylvania, 3544 Walnut St., Philadelphia, PA 19104, USA

Eulerian Opinion Dynamics with Bounded Confidence and Exogenous Inputs

2004

Thesis by
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Optimal and Cooperative Control of Vehicle Formations

2002

now: UCSC

Distributed Receding Horizon Control of Multiagent Systems

2004

Thesis by
William B. Dunbar

now: UCSC
Control of Mechanical Systems

Distributed Control

Dynamics and Control of Information Flows
Control of Mechanical Systems  ➔  Distributed Control  ➔  Dynamics and Control of Information Flows

Distributed Estimation and Control in Networked Systems

2007, EE
Thesis by
Vijay Gupta
now: U. Notre Dame
Control of Mechanical Systems

Distributed Control

Dynamics and Control of Information Flows

Distributed Estimation and Control in Networked Systems

Thesis by Vijay Gupta
now: U. Notre Dame

Coordinated Control for Networked Multi-Agent Systems

Thesis by Zhipu Jin
now: Shape Security
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Distributed Control

Dynamics and Control of Information Flows

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Coordinated Control for Networked Multi-Agent Systems

2007, EE

Thesis by Zhipu Jin

now: Shape Security

Geometrical analysis of spatio-temporal planning problems

2007, EE

Thesis by Abhishek Tiwari

now: Silvus Technologies
Control of Mechanical Systems

Distributed Control

Dynamics and Control of Information Flows

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  - now: U. Notre Dame

Geometrical analysis of spatio-temporal planning problems

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  - now: Silvus Technologies

MANAGING INFORMATION IN NETWORKED AND MULTI-AGENT CONTROL SYSTEMS

- Thesis by Michael S. Epstein, 2008, ME
  - now: McKinsey

Coordinated Control for Networked Multi-Agent Systems

- Thesis by Zhipu Jin, 2007, EE
  - now: Shape Security

STATE ESTIMATION IN MULTI-AGENT DECISION AND CONTROL SYSTEMS

- Thesis by Domitilla Del Vecchio, 2007
  - now: MIT
Distributed Estimation and Control in Networked Systems
2007, EE
Thesis by Vijay Gupta
now: U. Notre Dame

Coordinated Control for Networked Multi-Agent Systems
2007, EE
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MANAGING INFORMATION IN NETWORKED AND MULTI-AGENT CONTROL SYSTEMS
2008, ME
Thesis by Michael S. Epstein
now: McKinsey

Resource Optimization for Networked Estimator with Guaranteed Estimation Quality
2009
Thesis by Ling Shi
now: HKUST
Generalizations of H-Infinity Optimization / Control of Rotating Stall

Thesis by
Raffaello D’Andrea

now: ETHZ
Generalizations of H-Infinity Optimization / Control of Rotating Stall

Thesis by
Raffaello D’Andrea

now: ETHZ

(1997, EE)
Generalizations of H-Infinity Optimization / Control of Rotating Stall

Thesis by
Raffaello D’Andrea

now: ETHZ

2006

2014
A Geometric Framework for Dynamic Vision

Thesis by
Stefano Soatto

1996

now: UCLA
A Geometric Framework for Dynamic Vision
(SLAM)

Thesis by
Stefano Soatto

now: UCLA

1996
Perception as a Dynamic Process

A Geometric Framework for Dynamic Vision (SLAM)

Thesis by
Stefano Soatto
now: UCLA
Perception as a Dynamic Process

A Geometric Framework for Dynamic Vision (SLAM)

Thesis by
Stefano Soatto

now: UCLA

An Invitation to 3-D Vision
From Images to Geometric Models

Yi Ma
Stefano Soatto
Jana Noeske
Sharif S. Sainz
Perception as a Dynamic Process

A Geometric Framework for Dynamic Vision (SLAM)

Thesis by
Stefano Soatto

1996
now: UCLA

Averaging and Control of Nonlinear Systems
(with Application to Biomimetic Locomotion)

Thesis by
Patricio Antonio Vela

2003
now: GATECH
Perception as a Dynamic Process

A Geometric Framework for Dynamic Vision (SLAM)

1996
Thesis by Stefano Soatto
now: UCLA

Averaging and Control of Nonlinear Systems (with Application to Biomimetic Locomotion)

2003
Thesis by Patricio Antonio Vela
now: GATECH

Optimized selection of key frames for monocular videogrammetric surveying of civil infrastructure

2013
Abbas Rashidi, Fei Dai, Ioannis Brilakis, Patricio Vela

Controlled Recognition Bounds for Visual Learning and Exploration

2013
A Geometric Framework for Dynamic Vision (SLAM)

Thesis by
Stefano Soatto
1996
now: UCLA

Controlled Recognition Bounds for Visual Learning and Exploration

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Thesis by
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2003
now: GATECH

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Abbas Rashidi\textsuperscript{a}, Fei Dai\textsuperscript{b}, Ioannis Brilakis\textsuperscript{c}, Patricio Vela\textsuperscript{c}

2013
Perception as a Dynamic Process

Control of Perception Process

A Geometric Framework for Dynamic Vision (SLAM)
Thesis by Stefano Soatto
1996
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Controlled Recognition Bounds for Visual Learning and Exploration
2013

INTELLIGENT INFORMATION GATHERING: USING CONTROL FOR SENSING AND DECISION MAKING
Thesis by Timothy H. Chung
2007, ME
now: NPS
Stefano Soatto (Tim Chung)

Inference
Patricio Vela
Vijay Gupta Ling Shi
Abhishek Tiwari Networks (Zhipu Jin)

Control
D. Del Vecchio Alex Fax
Mark Milan Ali Jadabaie
(M. van Nieuwstadt)
William Dunbar

Francesco Bullo (Andrew Lewis)
Muruhan Rathinam (Raff. D’Andrea)
Melvin Leok
Robert M’Closkey Ashley Moore Matanya Horovitz
(Scott Kelly)
Legend


CDS degree  (non CDS)

Inference
Stefano Soatto  (Tim Chung)
Patricio Vela
Vijay Gupta
Abhishek Tiwari
Networks
D. Del Vecchio  (Michael Epstein)
Alex Fax
Ling Shi
Files
Francesco Bullo  (Andrew Lewis)
Muruhan Rathinam  (Raff. D’Andrea)
Todd Murphey
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Robert M’Closkey  (Scott Kelly)

Networks
Vijay Gupta  (Michael Epstein)
Ling Shi
(Andrew Lewis)
Alex Fax

Formal methods

Bio-inspired control

Autonomy

Biology

1994-2000
2000-2008
2009-2014

CDS degree  (non CDS)
Neuroethology and Biomechanics
Neuroethology and Biomechanics
Neuroethology and Biomechanics
Neuroethology and Biomechanics

Michael Dickinson
Neuroethology and Biomechanics

Michael Dickinson

Floris Van Bruegel
Neuroethology and Biomechanics

Michael Dickinson
Neuroethology and Biomechanics

Michael Dickinson

Andrew Straw
Neuroethology and Biomechanics

stimulus → brain → decisions

Andrew Straw

Michael Dickinson
Neuroethology and Biomechanics

stimulus → brain → decisions

tracked trajectories

Michael Dickinson

Andrew Straw
Neuroethology and Biomechanics

Michael Dickinson

Andrew Straw

stimulus \rightarrow \text{brain} \rightarrow \text{decisions}

tracked trajectories
Neuroethology and Biomechanics
Steady as She Goes: Visual Autocorrelators and Antenna-mediated Airspeed Feedback in the Control of Flight Dynamics in Fruit Flies and Robotics

Thesis by
Sawyer Buckminster Fuller

now: Harvard
Steady as She Goes: Visual Autocorrelators and Antenna-mediated Airspeed Feedback in the Control of Flight Dynamics in Fruit Flies and Robotics

Thesis by
Sawyer Buckminster Fuller
now: Harvard

Complex behavior and perception in *Drosophila* emerges from iterative feedback-regulated reflexes

Thesis by
Floris van Breugel
now: UW
Steady as She Goes: Visual Autocorrelators and Antenna-mediated Airspeed Feedback in the Control of Flight Dynamics in Fruit Flies and Robotics

2011, BE
Sawyer Buckminster Fuller
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Complex behavior and perception in *Drosophila* emerges from iterative feedback-regulated reflexes

2014
Floris van Breugel
now: UW
Neuroethology and Biomechanics

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Winner, 2008 “Art in Science” competition
Neuroethology and Biomechanics

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Thesis by
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now: Harvard

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2014

Thesis by
Floris van Breugel
now: UW

Winner, 2008 “Art in Science” competition

Fuller SB, Straw AD, Peek MY, Murray RM and Dickinson MH, PNAS 2014
Bio-inspired Control
Bio-inspired Control
Bio-inspired Control

The Mechanics and Control of Robotic Locomotion with Applications to Aquatic Vehicles

1998, ME

Thesis by Scott D. Kelly

now: UNCC
Bio-inspired Control

The Mechanics and Control of Robotic Locomotion with Applications to Aquatic Vehicles

1998, ME

Thesis by Scott D. Kelly

now: UNCC

Figure 5. Simple model for an inchworm robot
Bio-inspired Control

The Mechanics and Control of Robotic Locomotion with Applications to Aquatic Vehicles

1998, ME
Thesis by Scott D. Kelly
now: UNCC

Bio-Inspired Visuomotor Convergence in Navigation and Flight Control Systems

2006, ME
Thesis by James Sean Humbert
now: UMD

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Bio-inspired Control
Bio-inspired Control

Hierarchies, Spikes, and Hybrid Systems: Physiologically Inspired Control Problems

Thesis by
Andrew Lamperski

2012
Bio-inspired Control

Hierarchies, Spikes, and Hybrid Systems: Physiologically Inspired Control Problems
2012
Thesis by
Andrew Lamperski

Optimal Uncertainty Quantification via Convex Optimization and Relaxation
2014, EE
Thesis by
Shuo Han
now: UPenn
Bio-inspired Control

Hierarchies, Spikes, and Hybrid Systems: Physiologically Inspired Control Problems

2012
Thesis by
Andrew Lamperski

Optimal Uncertainty Quantification via Convex Optimization and Relaxation

2014, EE
Thesis by
Shuo Han
now: UPenn

5 years earlier, in a Caltech basement...
Bio-inspired Control

Hierarchies, Spikes, and Hybrid Systems: Physiologically Inspired Control Problems
2012
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Optimal Uncertainty Quantification via Convex Optimization and Relaxation
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Bio-inspired Control

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2012
Thesis by Andrew Lamperski

Optimal Uncertainty Quantification via Convex Optimization and Relaxation

2014, EE
Thesis by Shuo Han
now: UPenn

CONTROLLING FREE FLIGHT OF A ROBOTIC FLY USING AN ONBOARD VISION SENSOR INSPIRED BY INSECT OCELLI
SAWYER B FULLER, MICHAEL KARPELSON, ANDREA CENSI, KEVIN Y MA, AND ROBERT J WOOD
Autonomous Vehicles
Autonomous Vehicles
Autonomous Vehicles
Autonomous Vehicles

Figure 2: Systems architecture for operation of Alice in the 2007 Challenge. The sensing subsystem is responsible for building a representation of the local environment and passing this to the navigation subsystems, which computes and commands the motion of the vehicle. Additional functionality is provided for process and health management, along with data logging and simulation.
Autonomous Vehicles
Autonomous Vehicles

System Architectures and Environment Modeling for High-Speed Autonomous Navigation

Thesis by
Lars B. Cremean

now: Aerovironment

2006, ME
Autonomous Vehicles

System Architectures and Environment Modeling for High-Speed Autonomous Navigation

2006, ME
Lars B. Cremeen
now: Aerovironment

Real-Time Trajectory Generation for Constrained Nonlinear Dynamical Systems Using Non-Uniform Rational B-spline Basis Functions

2008
Melvin E. Flores
now: JPL
Autonomous Vehicles

System Architectures and Environment Modeling for High-Speed Autonomous Navigation

2006, ME
Lars B. Cremeen
now: Aerovironment

Real-Time Trajectory Generation for Constrained Nonlinear Dynamical Systems Using Non-Uniform Rational B-spline Basis Functions

2008
Melvin E. Flores
now: JPL

Robust Model Predictive Control with a Reactive Safety Mode

2008, ME
John M. Carson III
now: JPL

now: JPL
Robot Navigation in Dense Crowds: Statistical Models and Experimental Studies of Human Robot Cooperation

2012

Thesis by
Pete Trautman

now: Matrix Research
Robot Navigation in Dense Crowds: Statistical Models and Experimental Studies of Human Robot Cooperation

Thesis by
Pete Trautman

now: Matrix Research

Bootstrapping Vehicles: a Formal Approach to Unsupervised Sensorimotor Learning Based on Invariance

Thesis by
Andrea Censi

now: MIT
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Robot Learning

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Bootstrapping Vehicles: a Formal Approach to Unsupervised Sensorimotor Learning Based on Invariance

2012

Thesis by Andrea Censi

now: MIT
Formal Methods
Formal Methods
Formal Methods
Formal Methods

safe

◊ goal

unsafe

unsafe

goal
Formal Methods

Safety Verification and Failure Analysis of Goal-Based Hybrid Control Systems

2009, ME
Thesis by
Julia M. B. Braman
now: NASA JSC (Houston)
Formal Methods

☐ safe
◊ goal

Formal Methods for Design and Verification of Embedded Control Systems: Application to an Autonomous Vehicle

2010, ME
Tichakorn Wongpiromsarn
now: Ministry of Science, Thailand

Safety Verification and Failure Analysis of Goal-Based Hybrid Control Systems

2009, ME
Thesis by
Julia M. B. Braman
now: NASA JSC (Houston)
Formal Methods

- □ safe
- ◊ goal

Unsafe goal

Formal Methods for Design and Verification of Embedded Control Systems: Application to an Autonomous Vehicle

2010, ME
Tichakorn Wongpiromsarn
now: Ministry of Science, Thailand

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Formal Methods

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Control of Dynamical Systems with Temporal Logic Specifications

2014
Thesis by Eric M. Wolff
now: Nutonomy (startup, Boston)


2013, ME
Thesis by Huan Xu
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Thesis by
Eric M. Wolff


2013, ME

now: UMD

Thesis by
Huan Xu

Formal Methods for Control Synthesis in Partially Observed Environments: Application to Autonomous Robotic Manipulation

2014

now: Humin (startup, SF)

Thesis by
Rangoli Sharan

Formal Methods for Design and Verification of Embedded Control Systems: Application to an Autonomous Vehicle

2010, ME

now: Ministry of Science, Thailand

Thesis by
Tichakorn Wongpiromsarn
Legend


CDS degree  (non CDS)

Eric Wolff  (Mumu Xu)
Rangoli Sharan  (Julia Braman)  (John Carson)
(Tim Chung)
Ling Shi  (Lars Cremeans)  Andrea Censi  (Zhipu Jin)
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Mark Milan  (M. van Nieuwstadt)  Ali Jadbabaie
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Robert M’Closkey  Ashley Moore  (Scott Kelly)
Matanya Horovitz

Muruhan Rathinam  (Raff. D’Andrea)

Floris Van Bruegel  (Shuo Han)  (Sawyer Fuller)
CDS: The Power of Theory