

# Randal W. Beard

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## Professional Experience

### Brigham Young University, Provo, Utah

Professor, Electrical and Computer Engineering Department, 2007—Present

Associate Professor, Electrical and Computer Engineering Department, 2002—2007

Assistant Professor, Electrical and Computer Engineering Department, 1996—2002

### Air Force Research Lab, Munitions Directorate, Eglin Air Force Base, Florida

National Research Council Fellow, 2006-2007

### Jet Propulsion Laboratory, Pasadena, California

Summer Faculty Fellow in the Spacecraft Guidance and Control Division, 1997-1998

### Rensselaer Polytechnic Institute, Troy, New York

Research Assistant, Center for Intelligent Robotic Systems for Space Exploration, 1992-1995

## Education

**Rensselaer Polytechnic Institute**, Electrical Engineering, PhD, 1995

**Rensselaer Polytechnic Institute**, Mathematics, MS, 1994

**Rensselaer Polytechnic Institute**, Electrical Engineering, MS, 1993

**University of Utah**, Electrical Engineering, BS (Magna Cum Laude), 1991

## Research Focus

**Unmanned Air Vehicles.** Developing autonomous control technologies for real-time navigation, guidance, and control of unmanned air vehicles (UAVs). Developed path planning, trajectory generation, and trajectory tracking algorithms that require minimal computational resources. Directed the development of a light-weight, low-power autopilot for small (1-6 foot wingspan) UAVs. Developed an experimental testbed for small UAVs that has logged thousands of hours of successful flight tests.

**Multiple Vehicle Coordination and Control.** Developing coordination strategies for heterogeneous collections of autonomous vehicles. Platforms include uninhabited aerial vehicles, mobile robots, and spacecraft, with a particular emphasis on UAVs. Applications include coordinated formation maneuvers, coordinated rendezvous, coordinated timing, trajectory generation and autonomous landing. Developed a multiple UAV testbed capable of deploying five UAVs simultaneously. Also developed a multiple vehicle testbed including five differential drive mobile robots and ten omni-directional mobile robots.

**Nonlinear Control.** Developed practical algorithms to generate and improve the performance of feedback control laws for general classes of nonlinear systems. The Galerkin spectral method has been used to successively approximate the Hamilton-Jacobi-Bellman equation, which is at the foundation of nonlinear optimal control. The results also generate practical algorithms for solving nonlinear H-infinity (robust) control problems. Numerous application of the method have been explored including hydraulic actuators, underwater vehicles, power systems, and robotics.

## Books

[3] Randal W. Beard, Timothy W. McLain, *Small Unmanned Aircraft: Theory and Practice*, Princeton University Press, 2012, ISBN: 978-06-911-4921-9.

[2] Kimon P. Valavanis, Randal W. Beard, Paul Oh, Anibal Ollero, Leslie Piegl, Hyunchul Shim, *Selected Papers from the 2<sup>nd</sup> International Symposium on UAVs*, Springer, 2010, ISBN: 978-90-481-8763-8.

[1] Wei Ren, Randal W. Beard, *Distributed Consensus in Multi-Vehicle Cooperative Control*, Communication and Control Engineering Series, Springer Verlag, New York, 2007, ISBN: 978-1-84800-014-8.

- Over 21,000 chapter downloads.

## Journal Publications and Book Chapters

- Google Scholar h-index is 52, with 18,087 total citations.

- [78] Peter C. Niedfeldt, Randal W. Beard, "A Comparison and Parameter Analysis of Recursive-RANSAC," *IEEE Transactions on Aerospace and Electronic Systems*, (in review).
- [77] Laith R. Sahawneh, Matthew O. Duffield, Randal W. Beard, Timothy W. McLain, "Detect and Avoid for Small Unmanned Aircraft Systems using ADS-B," *Air Traffic Control – Quarterly*, (to appear).
- [76] David O. Wheeler, Paul W. Nyholm, Daniel P. Koch, Gary J. Ellington, Benjamin J. Lewis, Timothy W. McLain, Randal W. Beard, "Relative Navigation in GPS-Degraded Environments," *Wiley Encyclopedia on Aerospace Engineering*, (to appear)
- [75] Eric Quist, Peter Neidfeldt, Randal W. Beard, "Radar Odometry with Recursive-RANSAC," *IEEE Transactions on Aerospace and Electronic Systems*, (to appear).
- [74] Laith R. Sahawneh, James Mackie, Jonathan Spencer, Randal W. Beard, Karl F. Warnick, "Airborne Radar-Based Collision Detection and Risk Estimation for Small Unmanned Aircraft Systems," *AIAA Journal of Aerospace Information Systems*, (to appear).
- [73] Robert Mahony, Randal W. Beard, Vijay Kumar, "Modeling and Control of Aerial Robots," *Springer Handbook of Robotics*, 2<sup>nd</sup> Edition, ed. Siciliano, Khatib, (to appear).
- [72] Eric Quist and Randal W. Beard, "Radar Odometry on Small Unmanned Aircraft," *IEEE Transactions on Aerospace and Electronic Systems*, (to appear-Feb 2016).
- [71] Peter C. Niedfeldt, Randal W. Beard, "Convergence and Complexity Analysis of Recursive-RANSAC: A New Multiple Target Tracking Algorithm," *IEEE Transactions on Automatic Control*, vol. 61, no. 2, p. 456-461, February, 2016.
- [70] Huili Yu, Randal W. Beard, "A Vision-based Three-tiered Path Planning and Collision Avoidance Scheme for Miniature Air Vehicles," *International Journal of Robotics and Automation*, vol. 30, no. 5, doi: 10.2316/Journal.206.2015.5.206-4182, 2015
- [69] Liang Sun, Jeremy Castagno, John Hedengren, Randal W. Beard, "Real-Time Parameter Estimation for Towed Cable Systems Using Moving Horizon Estimation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 2, p. 1432-1446, April, 2015.
- [68] Huili Yu, Keven Meier, Matt Argyle, Randal W Beard, Probabilistic Path Planning for Cooperative Target Tracking Using Aerial and Ground Vehicles, *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 2, p. 541-552, April, 2015.
- [67] Randal W. Beard, Jeff Ferrin, Jeff Humpherys, "Fixed Wing UAV Path Following in Wind with Input Constraints," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 6, p. 2103-2117, November, 2014.
- [66] John Macdonald, Robert Leishman, Randal W. Beard Timothy McLain, "Analysis of an Improved IMU-Based Observer for Multirotor Helicopters," *Journal of Intelligent & Robotic Systems*, vol. 74, no. 3-4, p. 1049-1061, June, 2014.
- [65] Robert C. Leishman, Timothy W. McLain, Randal W. Beard, "Relative Navigation Approach for Vision-Based Aerial GPS-Denied Navigation," *Journal of Intelligent and Robotic Systems*, vol. 74, no. 1-2, p. 97-111, April, 2014.
- [64] Liang Sun, John D. Hedengren, Randal W. Beard, "Optimal Trajectory Generation using Model Predictive Control for Aerially Towed Cable Systems," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 37, no. 2, p. 525-539, March, 2014.
- [63] Joseph W. Nichols, Liang Sun, Randal W. Beard, Timothy McLain, "Aerial Rendezvous of Small Unmanned Aircraft Using a Passive Towed Cable System," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 37, no. 4, p. 1131-1142, July, 2014.
- [62] Kevin Cook, Everett Bryan, Huili Yu, He Bai, Kevin Seppi, Randal Beard, "Intelligent Cooperative Control for Urban Tracking," *Journal of Intelligent and Robotic Systems*, vol. 74, no. 1-2, p 251-267, 2014.
- [61] Mark Owen, Randal W. Beard, Timothy W. McLain, "Implementing Dubins Airplane Paths on Fixed-wing UAVs," *Handbook of Unmanned Aerial Vehicles*, ed. Kimon P. Valavanis, George J. Vachtsevanos, Springer Verlag, Section XII, Chapter 68, p. 1677-1702, 2014.
- [60] Matthew E. Argyle, Randal W. Beard, David W. Casbeer, "A Multi-Team Consensus Bundle Algorithm," *Handbook of Unmanned Aerial Vehicles*, ed. Kimon P. Valavanis, George J. Vachtsevanos, Springer Verlag, Section XII, Chapter 61, p. 1491-1508, 2014.
- [59] Robert Leishman, John Macdonald, Randal W. Beard, Timothy W. McLain, "Quadrotors and Accelerometers: State Estimation with an Improved Dynamic Model," *IEEE Control Systems Magazine*, vol. 34, no. 1, p. 28-41, February, 2014.
- [58] Peter Niedfeldt, Brandon Carroll, Joel Howard, Randal W. Beard, Bryan Morse, Stephen Pledgie, , "Enhanced UAS Surveillance Using a Video Utility Metric," *International Journal for Unmanned Systems*, vol. 1, no 2., p. 277-296, 2013.
- [57] Huili Yu, Rajnikant Sharma, Randal W. Beard, Clark N. Taylor, "Observability-based Local Path Planning and Collision Avoidance using Bearing-only Measurements," *Robotics and Autonomous Systems*, vol. 61, no. 12, p 1392-1405, December, 2013.
- [56] Rajnikant Sharma, Stephen Quebe, Randy Beard, Clark Taylor, "Bearing-only Cooperative Localization," *Journal of Intelligent and Robotic Systems*, vol. 72, no. 3-4, p. 429-440, December, 2013.

- [55] Mangal Kothari, Rajnikant Sharma, Ian Postlethwaite, Randal W. Beard, Daniel Pack, "Cooperative Target-capturing with Incomplete Target Information," *Journal of Intelligent and Robotic Systems*, vol. 72, no. 3-4, p. 373-384, December, 2013.
- [54] Huili Yu, Randal W. Beard, "Vision-based Local-level Frame Mapping and Planning in Spherical Coordinates for Micro Air Vehicles using Bearing-only Camera," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 3, p. 695-703, 2013.
- [53] Huili Yu, Randal W. Beard, "A Vision-based Collision Avoidance Technique for Micro Air Vehicles Using Local-level Frame Mapping and Path Planning," *Autonomous Robots*, Vol 34, Issue 1-2, p. 93-109, 2013.
- [52] Rajnikant Sharma, Randal W. Beard, Clark N. Taylor, Stephen Quebe, "Graph-based Observability Analysis of Bearing-only Cooperative Localization," *IEEE Transactions on Robotics*, Vol. 28, No. 2, p. 522-529, April, 2012.
- [51] Rajnikant Sharma, Jeffery B. Saunders, Randal W. Beard, "Reactive Path Planning for Micro Air Vehicles Using Bearing-Only Measurements," *Journal of Intelligent and Robotic Systems*, vol. 65, no. 1-4, p 409-416, 2012.
- [50] Jeffery Saunders, Randal W. Beard, "Visual Tracking in Wind with Field of View Constraints," *International Journal of Micro Air Vehicles*, vol. 3, no. 3, September, p. 169-182, 2011.
- [49] Joel G. Manathara, P. B. Sujit, Randal W. Beard, "Multiple UAV Coalitions for a Search and Prosecute Mission," *Journal of Intelligent and Robotic Systems*, Vol. 62, No. 1, p. 125-158, 2011.
- [48] Mark Colton, Liang Sun, Daniel Carlson, Randal Beard, "Multi-vehicle Dynamics and Control for Aerial Recovery of Micro Air Vehicles," *International Journal of Vehicle Autonomous Systems*, Vol. 9, Nos. 1/2, p. 78-107, 2011.
- [47] Joseph Egbert, Randal W. Beard, "Low-Altitude Road Following Using Strap-down Cameras on Miniature Air Vehicles" *Mechatronics (Special Issue on Development of Autonomous Unmanned Aerial Vehicles)*, vol 21, no. 5, p. 831-843, August, 2011.
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- [45] Randal W. Beard, "Embedded UAS Autopilot and Sensor Systems," in *Encyclopedia of Aerospace Engineering*, R. Blockley and W. Shyy (eds). John Wiley & Sons Ltd, Chichester, UK, p. 4799-4814, 2010.
- [44] Ryan S. Holt, Randal W. Beard, "Vision-Based Road-Following Using Proportional Navigation" *Journal of Intelligent Robotic Systems*, Vol. 57, No. 1, p.193-216, December, 2009.
- [43] Jeff Saunders, Randal W. Beard, "UAV Flight Simulation with Hardware-in-the-loop Testing and Vision Generation" *Journal of Intelligent Robotic Systems*, Vol. 57, No. 1, p.407-415, December 2009.
- [42] P. B. Sujit, Derek B. Kingston, Randal W. Beard, "Autonomous Forest Fire Monitoring System Using Multiple UAVs" in *Autonomous Robots Research*, Nova Publishers, (to appear).
- [41] Derek B. Kingston, Randal W. Beard, Ryan Holt, "Decentralized Perimeter Surveillance Using a Team of UAVs" *IEEE Transactions on Robotics*, vol. 24, no. 6, December, 2008, p. 1394-1404.
- [40] David L. Johansen, James K. Hall, Clark N. Taylor, Randal W. Beard, "Stabilization of Video from Miniature Air Vehicles for Target Localization," *AIAA Journal of Aerospace Computing, Information, and Communication*, vol. 5, no. 8, p. 251-273, August, 2008.
- [39] Derek B. Kingston, Randal W. Beard, "UAV Splay State Configuration for Moving Targets in Wind," in *Advances in Cooperative Control and Optimization*, edited by Michael J. Hirsch, Lecture Notes in Computer Science, Springer Verlag, 2008.
- [38] Wei Ren, Ji-Sang Sun, Randal Beard, Timothy McLain, "Experimental Validation of an Autonomous Control System on a Mobile Robot Platform," *IET Control Theory & Applications*, vol. 1, no. 6, 2007, p. 1621-1629.
- [37] Randal W. Beard, "State Estimation for Micro Air Vehicles," in *Innovations in Intelligent Machines I*, edited by Jovaan S. Chahl, Lakhmi C. Jain, Akiki Mizutani, Mika Sato-Ilic, Studies in Computational Intelligence (SCI), vol. 70, Springer Verlag, Berlin Heidelberg, 2007, p. 173-199.
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- [35] Derek R. Nelson, Blake Barber, Timothy W. McLain, Randal W. Beard, "Vector Field Path Following for Miniature Air Vehicles," *IEEE Transactions on Robotics*, vol. 23, no. 3, June, 2007, p 519-529.
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- [33] D. Blake Barber, Stephen Griffiths, Timothy W. McLain, Randal W. Beard, "Autonomous Landing of Miniature Aerial Vehicles," *AIAA Journal of Aerospace Computing, Information, and Communication*, vol. 4, no. 5 May, 2007, p. 770-784.
- [32] Wei Ren, Randal W. Beard, Ella Atkins, "Information Consensus and its Applications in Multi-vehicle Cooperative Control," *IEEE Control Systems Magazine*, vol. 27, no. 2, April, 2007, p.71-82.
- [31] D. Blake Barber, Joshua D. Redding, Timothy W. McLain, Randal W. Beard, Clark N. Taylor, "Vision-based Target Geo-location using a Fixed-wing Miniature Air Vehicle," *Journal of Intelligent and Robotic Systems*, vol. 47, no. 4, December, 2006, p. 361-382.

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- [29] Stephen Griffiths, Jeff Saunders, Andrew Curtis, D. Blake Barber, Timothy W. McLain, Randal W. Beard, "Maximizing miniature aerial vehicles," *IEEE Robotics and Automation Magazine*, vol. 13, no. 3, 2006 p. 34-43.
- [28] David W. Casbeer, Derek B. Kingston, Randal W. Beard, Timothy W. McLain, Sai-Ming Li, Raman Mehra, "Cooperative Forest Fire Surveillance Using a Team of Small Unmanned Air Vehicles," *International Journal of Systems Science*, vol. 37, no. 6, May, 2006, p. 351-360.
- [27] Randal W. Beard, D.J. Lee, Morgan Quigley, Sarita Thakoor, Steve Zornetzer, "A New Approach to Observation of Descent and Landing of Future Mars Mission Using Bioinspired Technology Innovations," *AIAA Journal of Aerospace Computing, Information, and Communication*, vol. 2, no. 1, January, 2005, p. 65-91.
- [26] Randal Beard, Derek Kingston, Morgan Quigley, Deryl Snyder, Reed Christiansen, Walt Johnson, Timothy McLain, Mike Goodrich, "Autonomous Vehicle Technologies for Small Fixed Wing UAVs," *AIAA Journal of Aerospace Computing, Information, and Communication*, vol. 2, no. 1, January, 2005, p. 92-108.
- [25] Wei Ren, Randal W. Beard, "Consensus Seeking in Multi-agent Systems Using Dynamically Changing Interaction Topologies," *IEEE Transactions on Automatic Control*, vol. 50, no. 5, May, 2005, p. 655-661.
- [24] Erik P. Anderson, Randal W. Beard, Timothy W. McLain, "Real Time Dynamic Trajectory Smoothing for Uninhabited Aerial Vehicles," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 3, May, 2005, p. 471-477.
- [23] Timothy W. McLain, Randal W. Beard, "Coordination Variables, Coordination Functions, and Cooperative Timing Missions," *AIAA Journal of Guidance, Control, & Dynamics*, vol. 28, no. 1., January, 2005, p. 150-161.
- [22] J. Willard Curtis, Randal W. Beard, "A Complete Parameterization of CLF-Based Input-to-State Stabilizing Control Laws," *International Journal of Robust and Nonlinear Control*, vol. 14, 2004, p. 1393-1420.
- [21] Wei Ren, Randal W. Beard, "Trajectory Tracking for Unmanned Air Vehicles with Velocity and Heading Rate Constraints," *IEEE Transactions on Control Systems Technology*, vol. 12, no. 5, September, 2004, p. 706-716.
- [20] J. Willard Curtis, Randal W. Beard, "Satisficing: A New Approach to Constructive Nonlinear Control," *IEEE Transactions on Automatic Control*, vol. 49, no. 7, July, 2004, p. 1090-1102.
- [19] Wei Ren, Randal W. Beard, "Formation Feedback Control for Multiple Spacecraft via Virtual Structures," *IEE Proceedings-Control Theory and Applications*, vol. 151, no. 3, May, 2004, p. 357-368.
- [18] James K. Archibald, Randal W. Beard, "Robot Soccer for Undergraduate Students," *IEEE Robotics and Automation Magazine*, vol. 11, no. 1, March, 2004, p. 70-75.
- [17] Wei Ren, Randal W. Beard, "A Decentralized Scheme for Spacecraft Formation Flying via the Virtual Structure Approach," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 27, no. 1, January, 2004, p. 73-82.
- [16] Wei Ren, Randal W. Beard, Timothy W. McLain, "Coordination Variables and Consensus Building in Multiple Vehicle Systems," *Block Island Workshop on Cooperative Control*, Editors Vijay Kumar, Naomi Leonard, A. Stephen Morse, Lecture Notes in Control and Information Systems, vol. 309, Springer-Verlag, p. 171-188, 2004.
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- [14] Jonathan Lawton, Randal W. Beard, "Attitude Regulation About a Fixed Rotation Axis," *AIAA Journal of Guidance, Control, and Dynamics*, vol. 26, no. 2, March, 2003, p. 253-258.
- [13] Randal W. Beard, Timothy W. McLain, Michael Goodrich, Erik P. Anderson, "Coordinated Target Assignment and Intercept for Unmanned Air Vehicles," *IEEE Transactions on Robotics and Automation*, vol. 18, no. 6, December, 2002, p. 911-922.
- [12] Jonathan Lawton, Randal W. Beard, "Synchronized Multiple Spacecraft Rotations," *Automatica*, vol. 38, no. 8, August 2002, p. 1359-1364.
- [11] Randal W. Beard, "Linear Operators with Application in Control and Signal Processing," *IEEE Control Systems Magazine*, vol. 22, no. 2, April 2002, p. 69-79.
- [10] Randal W. Beard, Jonathan Lawton, Fred Y. Hadaegh, "A Coordination Architecture for Spacecraft Formation Control," *IEEE Transactions on Control Systems Technology*, vol. 9, no. 6, November 2001, p. 777-790.
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### Peer-Reviewed Conference Articles

- [156] Laith Sahawneh, Matthew Argyle, Randal W. Beard, "3D Path Planning for Small UAS Operating in Low-Altitude Airspace," *Proceedings of the International Conference on Unmanned Air Systems*, Washington DC, 2016 (in review).
- [155] Benjamin Lewis, Randal W. Beard, "A Framework for Visual Return-to-Home Capability in GPS-Denied Environments," *Proceedings of the International Conference on Unmanned Air Systems*, Washington DC, 2016 (in review).
- [154] Joshua Y. Sakamaki, Randal W. Beard, Michael Rice, "Cooperative Estimation for a Vision-Based Target Tracking System," *Proceedings of the International Conference on Unmanned Air Systems*, Washington DC, 2016 (in review).
- [153] He Bai, Randal W. Beard, "Relative Pose Estimation for Target Handoff in GPS-Denied Environments," *Proceedings of the American Control Conference*, Boston, MA, 2016 (to appear).
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- [151] Laith R. Sahawneh, Jonathan Spencer, Randal W. Beard, Karl F. Warnick, "Minimum Required Sensing Range for UAS Sense and Avoid Systems," *Proceedings of the AIAA Infotech@Aerospace, AIAA Science and Technology Forum and Exposition*, San Diego, CA, paper no. AIAA-2016-1982, January, 2016.
- [150] Maziar Izadi, Amit Sanyal, Randal W. Beard, He Bai, "GPS-Denied Relative Motion Estimation for Fixed-Wing UAV Using the Variational Pose Estimator," *IEEE Conference on Decision and Control*, p. 2152-2157, IzadOsaka, Japan, December 2015.
- [149] He Bai, Kevin Cook, Huili Yu, Kyle Ingersoll, Randal W. Beard, Kevin Seppi, "Improving Cooperative Tracking of an Urban Target with Target Motion Model Learning," *IEEE Conference on Decision and Control*, p. 2347-2352, Osaka, Japan, December 2015.
- [148] Kyle Ingersoll, Peter C. Niedfeldt, Randal W. Beard, "Multiple Target Tracking and Stationary Object Detection with Recursive-RANSAC and Tracker-Sensor Feedback," *Proceedings of the International Conference on Unmanned Air Vehicles*, Denver, CO, 2015.
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- [146] Laith Sahawneh, Randal W. Beard, "A Probabilistic Framework for Unmanned Aircraft Systems Collision Detection and Risk Estimation," *IEEE Conference on Decision and Control*, Los Angeles, CA, p. 242-247, December, 2014.
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- [144] Peter C. Niedfeldt, Eric Quist, Randal W. Beard, "Characterizing Range Progression of SAR Point Scatters with Recursive RANSAC," *Proceedings of the IEEE Radar Conference*, Cincinnati, OH, OR, p. 712-717, 2014.
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- [142] Jason M. Beach, Matthew Argyle, Randal W. Beard, Timothy W. McLain, "Tailsitter Heading Estimation using a Magnetometer," *Proceedings of the American Control Conference*, Portland, OR, p. 91-96, June, 2014.
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- [133] Matthew Argyle, Randal W. Beard, "The Vertical Bat Tail-sitter: Dynamic Model and Control Architecture," *American Control Conference*, Washington DC, p. 806-811, June, 2013.
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- [130] John C. Macdonald, Randal W. Beard, "Efficient Estimation for Indoor Navigation," *JSDE/ION Joint Navigation Conference*, Colorado Springs, CO, June, 2012.
- [129] Robert Leishman, John Macdonald, Timothy W. McLain, Randal W. Beard, "A Relative Navigation and Mapping Framework for Indoor Aerial Flight," *IEEE Conference on Robotics and Automation*, Saint Paul, Minnesota, p. 4937-4942, May 2012.
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- [1] Randal Beard, George N. Saridis, "A Cost Measure for Efficient Scheduling in Intelligent Machines," *Proceedings of the IEEE 8th International Symposium on Intelligent Control*, Chicago, Illinois, p. 52-57, August, 1993.

### **Peer Reviewed Video Presentations**

- [3] Joseph A. Jackson, Andrew M. Eldredge, Stephen R. Griffiths, Jeffrey B. Saunders, Timothy W. McLain, Randal W. Beard, "Miniature Air Vehicle Obstacle Avoidance," *IEEE International Conference on Robotics and Automation*, Orlando, FL, May, 2006.
- [2] Joseph A. Jackson, Andrew M. Eldredge, Derek R. Nelson, Stephen R. Griffiths, Timothy W. McLain, Randal W. Beard, "Miniature Air Vehicle Cooperative Timing Missions," *IEEE International Conference on Robotics and Automation*, Orlando, FL, May, 2006.
- [1] Andrew M. Eldredge, Stephen R. Griffiths, Timothy W. McLain, Randal W. Beard, "Recent Research Results using Miniature Air Vehicles," *AIAA Infotech@Aerospace Conference*, Arlington, VA, 2005. (Winner of grand prize for best overall video.)

### **Book Reviews**

- [1] R. W. Beard, "Soccer Robotics by Jong-Hwan Kim, Dong-Han Kim, Yong-Jae Kim, and Kiam-Tian Seow," *IEEE Control Systems Magazine*, vol. 25, no. 5, p. 93-95, October, 2005.

### **Research Contracts and Grants**

- [40] Randal Beard (PI), "A Novel Algorithm for Tracking Multiple Targets with Significant Background Clutter," *Air Force Research Laboratory (RWK)*, \$230,000, 2013-2016.
- [39] Randal Beard (PI), Tim McLain, "Long Endurance Vertical Takeoff and Landing Tier 2 Size UAV," *AFOSR SBIR Phase I & II with MLB Corporation*, \$228,998, 2011-2015.
- [38] Tim McLain (PI), Randal Beard, "Veracity Evaluation of non-Redundant Information in Flight Systems (VERACITY)," *AFOSR SBIR Phase I & II with SSCI*, \$254,346, 2011-2013.
- [37] Randal Beard (PI), Kevin Seppi, "Intelligent Controller Development for Cooperative UAV Missions," *AFOSR SBIR Phase I & II with Utopia Compression Corporation*, \$185,000, 2012-2015.
- [36] Randal Beard (PI), "Passive Collision Detection for UAV Sense and Avoid System," *DARPA SBIR Phase II with Utopia Compression Corporation*, \$70,000, 2011-2012.
- [35] Karl Warnick (PI), Randal Beard, "Non-GPS Dependent Method for Accurate UAS Navigation and Orientation Determination," *AFOSR, SBIR Phase I & II with ImSAR Technology*, \$159,260, 2011-2013.
- [34] Randal Beard (PI), "Miniature Self-Deploying Systems in Cluttered/Confined Environments," *AFRL Campus Challenge*, \$150,000, 2011.
- [33] Tim McLain (PI), Randal Beard, "Swarm/Agent Technology for Small Unit Scalable Effects," *Army, SBIR Phase I with Procerus Technology*, \$38,537, 2009-2010.
- [32] Tim McLain (PI), Randal Beard, "Robust Autonomous Maneuvering of Unmanned Air Systems in Challenging Environmental/Weather Conditions," *Navy, SBIR Phase I with Mosaic ATM*, \$21,000, 2009-2010.

- [31] Randal Beard (PI), Timothy W. McLain, Mark Colton, "Aerial Recovery of Micro Air Vehicles," *AFOSR, STTR Phase I & II with Procerus*, \$509,987, 2008-2012.
- [30] Randal Beard (PI), Timothy W. McLain, Bryan Morse, "Persistent Tactical Seeability through Integrated Sensor Guidance," *ARMY, SBIR Phase I & II with Mosaic ATM*, \$251,755, 2008-2011.
- [29] Randal Beard (PI), "Human Assisted UAV/UGV Cooperative Tracking of Urban Dismounts," *Air Force Research Laboratory, SBIR Phase II with SET Corporation*, \$218,701, 2008-2010.
- [28] Randal Beard (PI), "UAV/UGV Urban Tracking," *Air Force Research Laboratory, SBIR Phase I with SET Corporation*, \$33,333, 2007.
- [27] Tim McLain (PI), Randy Beard, Jerry Bowman, Michael Goodrich, Deryl Snyder, Clark Taylor, and Jim Archibald, "Miniature Air Vehicles Center of Excellence," *State of Utah*, \$130,000, 2007-2008.
- [26] Randal W. Beard (PI), Timothy W. McLain, "VAMAV: Visual Collision Detection and Avoidance for a Micro Air Vehicle," *Air Force Research Laboratory, SBIR with Scientific Systems Company Inc., Phase I & II*, \$166,000, 2006-2008.
- [25] Timothy W. McLain (PI), Randal W. Beard, "Rapid Deployment and Target Tracking for Micro Air Vehicles," *Idaho National Laboratory*, \$75,984, 2006-2007.
- [24] Deryl Snyder (PI), Randal W. Beard, Timothy W. McLain, "Aerodynamics and Control of Autonomous VTOL Micro-Air-Vehicles," *AFRL/MN*, \$149,924, 2005-2006.
- [23] Timothy W. McLain (PI), Randal W. Beard, "Center of Excellence in Unmanned Air Vehicle," *Utah Centers of Excellence Program*, \$422,400, 2005-2007.
- [22] Randal W. Beard (PI), Timothy W. McLain, "Coordinated Control of Multi-Agent Systems in Rapidly Varying Environments," *NASA (STTR Phase II)*, \$329,681, 2005-2007.
- [21] A. Lee Swindlehurst (PI), Randal W. Beard, Michael A. Jensen, Timothy W. McLain, Todd, K. Moon, "Distributed Communication and Control for Multiple Miniature Unmanned Air Vehicles," \$1,124,191, *NSF*, \$, 2004-2009.
- [20] Randal W. Beard (PI), D.J. Lee, "Biologically Inspired Navigation and Control for Small Unmanned Air Vehicles," *NASA-Ames/JPL*, \$66,068, 2004.
- [19] Timothy W. McLain (PI), Randal W. Beard, "Cooperation and Consensus Seeking for Teams of Unmanned Air Vehicles," *AFOSR*, \$342,043, 2004-2007.
- [18] Randal W. Beard (PI), Timothy W. McLain, "Real-Time Trajectory Generation for Autonomous Nonlinear Flight Systems," *AFOSR (STTR Phase II)*, \$299,799, 2004-2006.
- [17] Randal W. Beard (PI), Timothy W. McLain, "Coordinated Control of Multi-Agent Systems in Rapidly Varying Environments," *NASA (STTR Phase I)*, \$49,174, 2004.
- [16] Randal W. Beard (PI), Timothy W. McLain, "Navigation and Control Technologies for Autonomous Micro Vehicles," *AFRL/MN*, \$196,487, 2003-2004.
- [15] Randal W. Beard (PI), "Development, Integration, and Testing of an Autopilot System for BATCAM," *AFRL/MN*, \$38,250, 2003.
- [14] Timothy W. McLain (PI), Randal W. Beard, "Automated Landing of an Unmanned Air Vehicle in a Non-Cooperative Environment," *NASA Ames Research Center*, \$162,748, 2003-2006.
- [13] Randal W. Beard (PI), Timothy W. McLain, "A Low Cost Autopilot for Small Autonomous Air Vehicles," *BYU Technology Transfer Office*, \$20,000, Jan. 2003-Dec. 2003.
- [12] Michael A. Goodrich (PI), Dan R. Olson, Randal W. Beard, Timothy W. McLain, "Neglect Tolerant Interaction: Integrating Multi-Platform Interface Technology with Multiple Autonomy Levels," *DARPA*, \$1.1 M, Sept. 2002-Aug. 2004.
- [11] Randal W. Beard (PI), Timothy W. McLain, "Fast, Robust, Real-Time Trajectory Generation for Autonomous and Semi-Autonomous Nonlinear Flight Systems," *AFOSR (STTR Phase I)*, \$49,850, Oct. 2002-Sept. 2003.
- [10] Randal W. Beard (PI), "Precision Formation Flying for Deep Space Interferometry," *NASA/JPL*, \$60,000, Sept. 2000-Nov. 2002.
- [9] Randal W. Beard (PI), James K. Archibald, "Monitoring Hazardous Materials using Coordinated Control of Multiple Vehicles," *INEEL*, \$20,000, Jan. 2001-Dec. 2004.
- [8] Timothy W. McLain (PI), Randal W. Beard, "Coordinated Control of Unmanned Air Vehicles," *AFOSR*, \$172,956, Jan. 2001-Dec. 2004.
- [7] Randal W. Beard (PI), "A Practical Approach to Nonlinear Robust Control," *NSF*, \$155,212, Sept. 1998-Aug. 2001.
- [6] Randal W. Beard (PI), "Multiple Spacecraft Coordination and Control," *NASA/JPL*, \$100,000, Sept. 1997-Aug. 2000.
- [5] David Long (PI), Randal Beard, Kevin Smith, "QuikSCAT Calibration Ground Station Study," *NASA/JPL*, \$25,959, Sept. 1998-Nov. 1998.
- [4] Randal W. Beard (PI), Timothy W. McLain, "Coordinated Control of UAVs," *BYU College of Engineering and Technology*, \$19,000, Jan. 2000-Dec. 2001.
- [3] Randal W. Beard (PI), Wynn Stirling, Kevin Smith, James Archibald, Rick Frost, "The MAGICC Laboratory," *BYU College of Engineering and Technology*, \$35,000, Jan. 1999-Aug. 2000.
- [2] Rick Frost (PI), Jim Archibald, Randal Beard, Kevin Smith, Wynn Stirling, "Intelligent Autonomous Agents," *BYU College of Engineering and Technology*, \$50,000, May 1998-May 1999.

- [1] Randal W. Beard (PI), Timothy W. McLain, "A New Design Technique for Nonlinear Dynamic Systems," *BYU College of Engineering and Technology*, \$35,285, Sept. 1996-Aug. 1997.

## PhD Students

- [13] Laith Sahawneh, "Airborne Collision Detection and Avoidance for Small UAS Sense and Avoid Systems," PhD, 2016.
- [12] Eric B. Quist, "UAV Navigation and Radar Odometry," PhD, 2015.
- [11] Peter C. Niedfeldt, "Recursive-RANSAC: A Novel Algorithm for Tracking Multiple Targets in Clutter," PhD 2014.
- [10] Liang Sun, "Dynamic Modeling, Trajectory Generation and Tracking, Simulations and Experiments of Aerially Towed Cable Systems for Aerial Recovery of Miniature Aerial Vehicles," PhD 2012.
- [9] John C. Macdonald Jr., "Efficient Estimation for Small Multi-Rotor Air Vehicles Operating in Unknown, Indoor Environments," PhD 2012.
- [8] Rajnikant Sharma, "Bearing-only Cooperative Localization and Path Planning for Ground and Aerial Robots," PhD 2011.
- [7] Huili Yu, "Vision-based Path Planning, Collision Avoidance, and Target Tracking for Unmanned Air and Ground Vehicles in Urban Environments," PhD, 2011.
- [6] Jeff Saunders, "Obstacle Avoidance, Visual Automatic Target Tracking, and Task Allocation for Small Unmanned Air Vehicles," PhD, 2009.
- [5] David Casbeer, "Decentralized Estimation Using Information Consensus Filters with a Multi-Static UAV Radar Tracking System," PhD, 2009.
- [4] Derek Kingston, "Decentralized Control of Multiple UAVs for Perimeter and Target Surveillance," PhD, 2007.
- [3] Wei Ren, "Consensus Seeking, Formation Keeping, and Trajectory Tracking in Multiple Vehicle Cooperative Control," PhD, 2004.
- [2] J. Willard Curtis, "Satisficing Control for Nonlinear Systems," PhD, 2002.
- [1] Jonathan Lawton, "A behavior-based approach for spacecraft formation flying," PhD, 2000.

## MS Students

- [23] Patrick C. DeFranco, "Detecting and Tracking Moving Objects from a Small Unmanned Air Vehicle," MS, 2015.
- [22] James K. Ingersoll, "Vision Based Multiple Target Tracking Using Recursive RANSAC," MS, 2015.
- [21] Everett Bryan, "Cooperative Target Tracking Enhanced with the Sequence Memoizer," MS, 2013.
- [20] Stephen Quebe, "Modeling, Parameter Estimation, and Gaze Control of Unmanned Indoor Quadrotor," MS, 2013.
- [19] Kevin Meier, "Developing a Guidance Law for a Small-Scale Controllable Projectile Using Backstepping and Adaptive Control Techniques and a Hardware System Implementation for a UAV and a UGV to Track a Moving Ground Target," MS, 2012.
- [18] Brandon Carroll, "Using Motion Fields to Estimate Video Utility and Detect GPS Spoofing," MS, 2012.
- [17] Bryce S. Pincock, "Real-Time Target Following Using an Unmanned Rotorcraft with a Laser Rangefinder," MS, 2012.
- [16] Caleb Chamberlain, "System Identification, State Estimation, and Control of Unmanned Aerial Robots," MS, 2011.
- [15] Andrew Curtis, "Path Planning for Unmanned Air and Ground Vehicles in Urban Environments," MS, 2008.
- [14] Joe Egbert, "Low-Altitude Road Following Using Strap-Down Cameras on Miniature Aerial Vehicles," MS, 2007.
- [13] Stephen Osborne, "Transition Between Hover and Level Flight for a Tailsitter UAV," MS, 2007.
- [12] Ryan Holt, "Three Enabling Technologies for Vision-Based Forest-Fire Perimeter Surveillance Using Multiple Unmanned Aerial Systems," MS, 2007.
- [11] Brandon Call, "Obstacle Avoidance for Unmanned Air Vehicles," MS, 2006.
- [10] David Johansen, "Video Stabilization and Object Localization using Feature Tracking with Small UAV Video," MS, 2006.
- [9] Joshua Matthews, "Adaptive Control of Micro Unmanned Air Vehicles," MS, 2006.
- [8] Walter H. Johnson, "Design and Implementation of the Kestrel Autopilot," MS, 2005.
- [7] Reed Christiansen, "Design of an Autopilot for Small Unmanned Aerial Vehicles," MS, 2004.
- [6] Joshua Hintze, "Autonomous Landing of a Rotary Unmanned Aerial Vehicle in a Non-cooperative Environment Using Machine Vision," MS, 2004.
- [5] Derek B. Kingston, "Implementation Issues of Real-Time Trajectory Generation of Small UAVs," MS, 2003.
- [4] Erik Anderson, "Extremal Control and Unmanned Air Vehicle Trajectory Generation," MS, 2002.
- [3] Jed Kelsey, "The MAGICC Mobile Robot Toolbox (MMRT): A Simulink-based Control and Coordination Toolbox for Multiple Robotic Agents," MS, 2001.
- [2] J. Willard Curtis, "Nonlinear controller comparison on a benchmark system," MS, 2000.
- [1] Brett Young, "Mobile robots: coordination and control," MS, 2000.

## Technology Transfer

### NSF I/UCRC Center for Unmanned Air Systems (C-UAS)

*BYU Site Director, 2012-Present.*

### Utah State Center of Excellence

*Co-Director, Center of Excellence for Small Unmanned Air Vehicles, 2004-2010.*

### Spin-off Companies

*Co-Founder, Procerus Technologies, January 2004.*

Procerus has licensed BYU's autopilot and video processing technologies. They manufacture the Kestrel autopilot, which is the smallest commercially available UAV autopilot. The Kestrel autopilot is currently used in the Air Force BATCAM and Night Hawk programs and the Army TAC-MAV program. It has been deployed for testing in Afghanistan and Iraq. In 2012 Procerus was acquired by Lockheed Martin.

*Technical Advisory Board, Flying Sensors, January 2006*

Flying Sensors utilizes BYU's UAV technology to provide aerial surveillance, videography, and mapping services in industrial and commercial applications. Since beginning operations, Flying Sensors has demonstrated their capabilities to numerous potential customers in a variety of applications. They recently secured a long-term surveillance contract as well as start-up funding from the State of Utah.

### Patents

*Programmable Autopilot System for Autonomous Flight of Unmanned Aerial Vehicles, Randal W. Beard, Reid Christensen, Walter Johnson, and Timothy McLain, Patent no. 7,302,316, issued November 27, 2007.*

*Aerial Recovery of Small and Micro Air Vehicles, Randal W. Beard, Patent No. 8,973,860. Issued March 10, 2015.*

## Invited Presentations

- Norwegian University of Science and Technology/AMOS, May, 2015.
- University of Washington, January, 2015.
- Naval Postgraduate School, November, 2014.
- University of Texas at Dallas, October, 2014.
- University of Illinois, Urbana-Champaign, March, 2014.
- Iowa State University, February, 2014.
- Missouri University of Science and Technology, November, 2013.
- Semi-Plenary Address, IFAC Symposium on Nonlinear Control Systems (NOLCOS), Toulouse, France, September, 2013.
- Texas A&M, Aerospace Engineering Department, November, 2012.
- Keynote speaker at the UAS Video Tracking Workshop and Challenge, Texas A&M, October, 2011.
- Plenary speaker at the International Conference on Unmanned Air Systems, Denver, CO, May, 2011.
- Harbin Institute of Technology, Harbin, China, April, 2011.
- University of California at Santa Barbara, January 2011.
- University of Porto, Porto, Portugal, May 2010.
- Short Course on Guidance and Control of MAVs, University of Porto, Portugal, May, 2010.
- Plenary speaker at the Seventh International Symposium on Mechatronics and its Applications, Sharjah, UAE, April, 2010.
- Short Course on Guidance and Control of MAVs, American University of Sharjah, UAE, April, 2010.
- Plenary speaker at the IFAC Workshop on Networked Robotics, Golden, Colorado, October, 2009.
- Royal Institute of Technology, Stockholm Sweden, March, 2009
- Plenary speaker at IEEE-Boeing Technologies Conference, Seal Beach, California, August, 2008.
- Plenary speaker at the Seventh International Conference on Autonomous Agents and Multiagent Systems (AAMAS), Estoril, Portugal, May, 2008.
- University of New Mexico, Albuquerque, New Mexico, November, 2007.
- University of Florida, Gainesville, Florida, October, 2007.
- Georgia Tech, Robotics Institute, Atlanta, GA, September, 2007.
- Georgia Tech, Aerospace Engineering Departments, Atlanta, GA, March, 2007.
- "Collision Detection and Avoidance Techniques for Micro Air Vehicles," Three hour invited workshop presentation at the Institute for Defense and Government Advancement, UAV Summit, February, 2007.
- Panel discussing future directions of Cooperative Control at the 2007 Conference on Cooperative Control and Optimization, Gainesville, Florida, January, 2007.

- University of Florida, REEF, Fort Walton Beach, Florida, January, 2007.
- University of Washington, Seattle, WA, January, 2006.
- Virginia Polytechnic and State University, Blacksburg, VA, November 2005.
- University of Wyoming, Laramie, WY, November, 2005.
- Rensselaer Polytechnic Institute, Troy, NY, October, 2005.
- GRASP Lab, University of Pennsylvania, Philadelphia, PA, October, 2004.
- Raytheon, Tucson, AZ, March 2004.
- Utah State University, October 2003.
- Ohio State University, August 2003.
- AFRL/VA, WP AFB, Dayton, Ohio, August, 2003.
- INEEL, Idaho Falls, ID, August, 2003.
- AFRL/MN, Eglin AFB, Ft. Walton Beach, FL, June, 2003.
- UC Santa Barbara, May 2003.
- University of Nevada, Reno, 2002.
- Jet Propulsion Laboratory, 1998.
- INEEL, Idaho Falls, ID, 1997.
- Idaho State University, 1997.

## **Professional Activities**

- Fellow of IEEE
- Associate Fellow of AIAA.
- AIAA Unmanned Systems Program Committee, 2016-Present.
- Associate Editor, International Conference on Robotics and Automation, 2016.
- Scientific Advisory Board, Centre for Autonomous Marine Operations and Systems (AMOS), Norwegian University of Science and Technology, Trondheim, Norway, 2015-2016.
- Advisory Board, International Symposium on Mechatronics and Its Applications (ISMA), 2015.
- Program Committee, IEEE International Conference on Multisensor Fusion and Integration, 2015.
- Associate Editor, International Conference on Robotics and Automation, 2015.
- Exhibits Chair, American Control Conference, 2015.
- Awards Committee, IEEE Control Systems Society, 2015.
- Program Committee, Robotics and Science Systems, 2014.
- Associate Editor, International Conference on Robotics and Automation, 2014.
- Associate Editor, IEEE Transactions on Automatic Control, 2011-2013.
- IEEE Control Systems Society Conference Publication Chair, 2010-2013
- Publications Chair, American Control Conference, 2013.
- General co-Chair, International Conference on Unmanned Aircraft Systems, 2012.
- Publications Chair IEEE Conference on Decision and Control, 2012.
- Publications Chair, IEEE Conference on Decision and Control, 2011.
- Program Committee, Robotics: Science and Systems, 2011.
- Chair, IEEE Technical Committee on Aerospace Controls, 2011-Present.
- Program Committee, IEEE Conference on Decision and Control, 2010.
- Program Committee, Unmanned Vehicle Workshop, Istanbul, Turkey, 2010.
- Associate Editor, Journal of Intelligent and Robotic Systems, 2006-2010.
- Associate Editor, IEEE Control Systems Magazine, 2004-2009.
- Member of IEEE Technical Committee on Aerospace Controls, 2009-Present.
- Member of IEEE Technical Committee on Aerial Robotics, 2009-Present.
- Program Chair, Second International Symposium on Unmanned Aerial Vehicles, 2009.
- Program Committee, IFAC Workshop on Networked Robotics, 2009.
- Organizing Committee, First International Symposium on Unmanned Aerial Vehicles, 2008.
- Associate Editor, IEEE Control Systems Society Conference Editorial Board, 1999-2007.
- Vice Chair for Student Affairs, American Control Conference, 2007.
- Program Vice Chair, Mediterranean Conference on Control and Automation, 2007.
- Program Committee, IASTED International Conference on Control and Applications, 2005.
- Program Committee, American Control Conference, 2005.
- Program Committee, American Control Conference, 2004.
- Program Committee, IEEE Conference on Control Applications, 2002.

## University Responsibilities

- University awards committee, 2015-present.
- Chair, ECE undergraduate committee, 2012-present.
- ECE rank and status committee, 2007-present.
- University rank and status appeals committee, 2011-2014.
- Chair, ECE curriculum re-design committee, 2011-2013.
- Chair, ECE graduate committee, 2010-2011.
- Chair, ECE external relations committee, 2006-2010.
- ECE External relations committee, 2003-2006.
- ECE Undergraduate committee, 2001-2003.
- Chair, ECE faculty search committee, 2000-2001.
- ECE Faculty search committee, 1999-2000.
- High School liason, 1995-2001.

## Courses Taught

- ECEn 212 Introduction to Circuits
- ECEn 370 Probability Theory
- ECEn 380 Signals and Systems
- ECEn 483 Introduction to Feedback Control
- ECEn 490 Senior Design / Capstone (robot soccer, UAVs, quadrotors, laser guided munition)
- ECEn 671 Mathematics of Signals and Systems
- ECEn 674 Flight Control Systems
- ECEn 773 Linear Systems Theory
- ECEn 774 Nonlinear Systems Theory

## Awards

- Cozzins Teaching and Learning Fellowship, Brigham Young University, 2012.
- Karl G. Maeser Research and Creative Arts Award, Brigham Young University, 2009.
- Outstanding Researcher, College of Engineering and Technology, Brigham Young University, 2008.
- National Research Council Fellowship, 2006-2007.
- Advised a student team that took first place at the 2<sup>nd</sup> US-European Competition for Micro Air Vehicles, November, 2006.
- Advised a student team that took second place at the AUVERSI Undergraduate Student Competition for Autonomous Fixed Wing Aircraft, June, 2006.
- Technology Transfer Award, Brigham Young University, 2006
- Advised a student team that won the Grand Prize for Best Overall Video at the Infotech@Aerospace Conference, 2005
- Young Scholar Award, Brigham Young University, 2004
- Finalist, Stoel Rives Innovation Award, 2004
- Voted Outstanding Teacher by graduating seniors, BYU Electrical and Computer Engineering Department, 2004
- Outstanding Faculty Award, BYU Electrical and Computer Engineering Department, 2002
- Advised an undergraduate student who won the best undergraduate student paper award at the 2002 International Telemetry Conference.
- Advised a graduate student who won the best graduate student paper award at the 2002 International Telemetry Conference.
- Advised a graduate student who was a finalist in the Best Student Paper Competition at the 2001 American Control Conference.
- Voted Outstanding Teacher by graduating seniors, BYU Electrical and Computer Engineering Department, 1998
- Outstanding Senior, University of Utah Electrical Engineering Department, 1991.