REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
08-02-2017	Final Report	10-Jan-2011 - 9-Sep-2016

4. TITLE AND SUBTITLE
Final Report: MURI: Neuro-Inspired Adaptive Perception and Control for Agile Mobility of Autonomous Vehicles in Uncertain and Hostile Environments

5a. CONTRACT NUMBER
W911NF-11-1-0046

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS
Panagiotis Tsiotras, Eric Feron, Frank Dellaert, Jim Rehg, Karl Iagnemma, Emilio Frazzoli, Laurent Itti

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Georgia Tech Research Corporation
505 Tenth Street NW
Atlanta, GA 30332 -0420

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
58144-NS-MUR.158

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
This final report summarizes the results of the work performed between for the period beginning August 1, 2015 and ending July 31, 2016, under the support of ARO MURI grant no. W911NF1110046.

During the last year, we made significant progress in several areas. First, we continued our investigation into the semi-autonomous and autonomous vehicle control, which has application to driver assistance scenarios (i.e., manned vehicles), teleoperated scenarios, or unmanned and autonomous vehicles. This year, a major focus was on

15. SUBJECT TERMS
autonomous systems, perception, control, planning, validation and verification, agility, mobile vehicles, autocode

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Panagiotis Tsiotras
UU	UU	UU	UU		19b. TELEPHONE NUMBER 404-894-9526

Report Title

Final Report: MURI: Neuro-Inspired Adaptive Perception and Control for Agile Mobility of Autonomous Vehicles in Uncertain and Hostile Environments

ABSTRACT

This final report summarizes the results of the work performed between for the period beginning August 1, 2015 and ending July 31, 2016, under the support of ARO MURI grant no. W911NF1110046.

During the last year, we made significant progress in several areas. First, we continued our investigation into the semi-autonomous and autonomous vehicle control, which has application to driver assistance scenarios (i.e., manned vehicles), teleoperated scenarios, or unmanned and autonomous vehicles. This year, a major focus was on conducting large-scale experimental analyses with human subjects in the loop, to study the engagement of humans with semi-autonomous and autonomous driving technologies (which were developed under this MURI program). We have also continued our work on improving the convergence rates of randomized, sampling-based planners, which have been recently shown to be capable for solving problems in high dimensional search spaces. We introduced three new algorithms, the PI-RRT# (that utilizes policy iteration updates), the DRRT (that combines gradient descent with randomized sampling to increase convergence) and the CL-RRT# (that uses closed-loop predictions for kinodynamic motion planning). We also investigated generalized label correcting (GLC) algorithms for kinodynamic motion planners and we found a very efficient scheme to generate, in a principled manner, the control primitives. In terms of perception, this last year we finalized the development of a new visual attention model which learns from human eye movements and continued our work on deciphering driver state and intentions beyond eye movements. Our perception work also focused on developing a SLAM-type of algorithm to support the MPPI controller described in last year's report. Last but not least, we continued our work on developing credible autocoders to simplify the validation and verification of autonomous embedded systems. This past year we have focused on autocoders for semi-definite programs, a very important class of on-line optimization algorithms that recently proved their worth with the autonomous landing of a SpaceX Falcon 9 rocket on a barge in the middle of the ocean.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/08/2017	132	T. Wang, R. Jobredeaux, M. Pantel, P.-L. Garoche, E. Feron and D. Henrion. Credible Autocoding of Convex Optimization Algorithms, Journal of Optimization and Engineering, (08 2015): 0. doi:
02/08/2017	151	Park, J., Reimer, B. and Iagnemma, K.. A User Study of Semi-Autonomous and Autonomous Highway Driving: An Interactive Simulation Study, IEEE Pervasive Computing, ( ): . doi:
02/08/2017	149	Brian Paden, Valerio Varricchio, and Emilio Frazzoli. Design of Admissible Heuristics for Kinodynamic Motion Planning via Sum of Squares Programming, Robotics Letters, ( ): . doi:
02/08/2017	148	Emmanuel Boidot. Aude Marzuoli, and Eric Feron. Optimal players policies for discrete and continuous ambush games, IEEE Transactions on Intelligent Transportation Systems, ( ): . doi:
09/02/2014	85	Raghvendra V. Cowlagi, Panagiotis Tsiotras. Curvature-Bounded Traversability Analysis in Motion Planning for Mobile Robots, IEEE Transactions on Robotics, (08 2014): 1011. doi: 10.1109/TRO.2014.2315711
09/02/2014	86	A. Borji, L. Itti. Defending Yarbus: Eye movements reveal observers' task, Journal of Vision, (03 2014): 1. doi: 10.1167/14.3.29
09/02/2014	87	Laurent Itti, Ali Borji. Optimal attentional modulation of a neural population, Frontiers in Computational Neuroscience, (03 2014): 1. doi: 10.3389/fncom.2014.00034
09/02/2014	88	D.-N. Ta, K. Ok, F. Dellaert. Vistas and parallel tracking and mapping with Wall–Floor Features: Enabling autonomous flight in man-made environments, Robotics and Autonomous Systems, (11 2014): 1657. doi: 10.1016/j.robot.2014.03.010
09/06/2015	121	Junghee Park, Sisir Karumanchi, Karl Iagnemma. Homotopy-Based Divide-and-Conquer Strategy for Optimal Trajectory Planning via Mixed-Integer Programming, IEEE Transactions on Robotics, (12 2015): 0. doi: 10.1109/TRO.2015.2459373
09/06/2015	133	Sterling J. Anderson, James M. Walker, Karl Iagnemma. Experimental Performance Analysis of a Homotopy-Based Shared Autonomy Framework, IEEE Transactions on Human-Machine Systems, (04 2014): 190. doi: 10.1109/TSMC.2014.2298383
09/06/2015	122	A. Borji, D. Parks, L. Itti. Complementary effects of gaze direction and early saliency in guiding fixations during free viewing, Journal of Vision, (11 2014): 0. doi: 10.1167/14.13.3
09/06/2015	123	Ali Borji, Laurent Itti, Daniel Parks. Augmented saliency model using automatic 3D head pose detection and learned gaze following in natural scenes, Vision Research, (11 2014): 0. doi: 10.1016/j.visres.2014.10.027
09/06/2015	124	Ali Borji, Laurent Itti. Optimal Attentional Modulation of a Neural Population, Frontiers in Computational Neuroscience, (03 2014): 0. doi:

09/06/2015 125 Ali Borji, Dicky N. Sihite, Laurent Itti. What/Where to Look Next?Modeling Top-Down Visual Attention inComplex Interactive Environments,
EEE Transactions on Systems, Man, and Cybernetics, Part A - Systems and Humans, (05 2014): 523. doi:

09/08/2015 131 Jiaping Zhao, Laurent Itti. Classifying Time Series: a Local Descriptor Perspective,
IEEE Transactions on Knowledge and Data Engineering, (12 2015): 0. doi:

TOTAL: 15

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL: 5

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1) Arslan, O. and Tsiotras, P., "Dynamic Programming Principles for Sampling-Based Motion Planners," Optimal Robot Motion Planning Workshop in the IEEE International Conference on Robotics and Automation, Seattle, WA, May 30, 2015.

2) Arslan, O. and Tsiotras, P., "Machine Learning and Dynamic Programming Algorithms for Motion Planning and Control," New England Machine Learning Day, Microsoft Corporation, Cambridge, MA, May 18, 2015.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper	
02/08/2017	155	Arslan, O., Berntorp, K., and Tsiotras, P.. Sampling-based Algorithms for Optimal Motion Planning Using Closed-loop Prediction, International Conference on Robotics and Automation. 30-MAY-17, Singapore. : ,
02/08/2017	153	Arslan, O., and Tsiotras, P.. Incremental sampling-based motion planners using policy iteration methods, 2016 IEEE 55th Conference on Decision and Control (CDC). 12-DEC-16, Las Vegas, NV, USA. : ,
02/08/2017	154	Sun, W., Theodorou, E., and Tsiotras, P.. Stochastic Game Theoretic trajectory optimization in continuous time, 2016 IEEE 55th Conference on Decision and Control (CDC). 12-DEC-16, Las Vegas, NV, USA. : ,
02/08/2017	143	Reimer, B., Pettinato, A., Fridman, L., Lee, J., Mehler, B., Seppelt, B., Park, J., and Iagnemma, K.. Behavioral Impact of Drivers' Roles in Automated Driving, the 8th International Conference on Automotive User Interfaces and Interactive Vehicle Applications. 24-OCT-16, Ann Arbor, MI, USA. : ,
02/08/2017	144	G. Williams, N. Wagener, B. Goldfain, P. Drews, J. M. Rehg, B. Boots, and E. A. Theodorou. Information theoretic MPC using neural network dynamics, Conference on Neural Information Processing Systems. 14-DEC-16, Barcelona, Spain. : ,
02/08/2017	140	Brian Paden and Emilio Frazzoli. Selection of Control Input Primitives for the Generalized Label Correcting Method, American Control Conference. 09-JUL-16, Boston, MA. : ,
02/08/2017	141	Brian Paden and Emilio Frazzoli. A Generalized Label Correcting Method for Optimal Kinodynamic Motion Planning, Workshop on Algorithmic Foundations of Robotics. 09-FEB-17, San Francisco. : ,
02/08/2017	142	Valerio Varricchio, Brian Paden, Dmitry Yershov, and Emilio Frazzoli. Effcient Nearest-Neighbor Search for Dynamical Systems with Nonholonomic Constraints, Workshop on Algorithmic Foundations of Robotics. 19-DEC-16, San Francisco. : ,
02/08/2017	145	G. Williams, N. Wagener, B. Goldfain, P. Drews, J. M. Rehg, B. Boots, and E. A. Theodorou. Information theoretic MPC for model-based reinforcement learning, International Conference on Robotics and Automation. 30-MAY-17, Singapore. : ,
02/08/2017	146	Grady Williams, Paul Drews, Brian Goldfain, James M. Rehg, and Evangelos A. Theodorou. Aggressive Driving with Model Predictive Path Integral Control, International Conference on Robotics and Automation. 17-MAY-16, Stockholm, Sweden. : ,
02/08/2017	147	E Boidot, A Marzuoli, E Feron.. Optimal navigation policy for an autonomous agent operating in adversarial environments, International Conference on Robotics and Automation. 17-MAY-16, Stockholm, Sweden. : ,
02/08/2017	150	Hauer, F., and Tsiotras, P.. Deformable Rapidly-Exploring Random Trees, Robotics: Science and Systems. 17-JUL-17, Cambridge, MA. : ,
02/08/2017	152	Hauer, F., Tsiotras, P.. Reduced complexity multi-scale path-planning on probabilistic maps, 2016 IEEE International Conference on Robotics and Automation (ICRA). 16-MAY-16, Stockholm, Sweden. : ,

TOTAL: **13**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
02/08/2017	13.00	Hauer, F., Kundu, A., Rehg, J., and Tsiotras, P.,. Multi-scale perception and path planning on probabilistic obstacle maps, 2015 IEEE International Conference on Robotics and Automation (ICRA). 26-MAY-15, Seattle, WA, USA. : ,
02/08/2017	29.00	T. Wang, R. Jobredeaux, M. Pakmher, M. Vivies, and E. Feron. Credible autocoding and verification of a gas turbine engine FADEC, 2014 IEEE/AIAA 33rd Digital Avionics Systems Conference (DASC). 05-OCT-14, Colorado Springs, CO, USA. : ,
02/08/2017	28.00	P. Roux, R. Jobredeaux, E. Feron and P.-L. Garoche. Closed loop analysis of control command software, the 18th International Conference on Hybrid Systems: Computation and Control (HSCC '15). 14-APR-15, Seattle, Washington. : ,
02/08/2017	27.00	E. Boidot, A. Marzuoli, and E. Feron. Optimal Planning Strategy for Ambush Avoidance, AAAI Conference on Artificial Intelligence. 28-JAN-15, Austin, TX. : ,
02/08/2017	18.00	S.-Z. Yong, B. Paden, and E. Frazzoli. Computational methods for MIMO flat linear systems: Flat output characterization, test and tracking control, 2015 American Control Conference (ACC). 01-JUL-15, Chicago, IL, USA. : ,
02/08/2017	17.00	J.-h. Jeon, S. Karaman, and E. Frazzoli. Optimal sampling-based Feedback Motion Trees among obstacles for controllable linear systems with linear constraints, 2015 IEEE International Conference on Robotics and Automation (ICRA). 26-MAY-15, Seattle, WA, USA. : ,
02/08/2017	16.00	Kobilarov, M., Ta, D.-N., and Dellaert, F.. Differential dynamic programming for optimal estimation, 2015 IEEE International Conference on Robotics and Automation (ICRA). 26-MAY-15, Seattle, WA, USA. : ,
02/08/2017	15.00	Arslan, O. and Tsiotras, P.. Machine Learning Guided Exploration for Sampling-based Motion Planning Algorithms, International Conference on Intelligent Robots and Systems. 28-SEP-15, Hamburg, Germany. : ,
08/30/2011	6.00	Steve Peters, Emilio Frazzoli, Karl Iagnemma. Differential Flatness of a Front-Steered Vehicle with Tire Force Control, 2011 International Conference on Intelligent Robotics and Systems (IROS). 25-SEP-11, . : ,
08/30/2011	14.00	Alejandro Perez, Sertac Karaman, Alexander Shkolnik, Emilio Frazzoli, Seth Teller, Matthew Walter. Asymptotically-optimal Path Planning for Manipulationusing Incremental Sampling-based Algorithms, 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011). 25-SEP-11, . : ,
08/30/2011	13.00	Joshua Bialkowski, Sertac Karaman, Emilio Frazzoli. Massively Parallelizing the RRT and the RRT^{L}, 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011). 25-SEP-11, . : ,
08/30/2011	12.00	Romain Jobredeaux, Timothy Wang, Eric Feron. Autocoding Control Software with Proofs I: Annotation Translation, 30th Digital Avionics Systems Conference. 16-OCT-11, . : ,

08/30/2011 10.00 Imon Chakraborty, Panagiotis Tsiotras. Mitigation of Unavoidable T-bone Collisions at Intersections Through Aggressive Maneuvering,
50th IEEE Conference on Decision and Control and European Control Conference (ECC/CDC 2011). 12-DEC-11, . : ,

08/30/2011 9.00 Oktay Arslan, Panagiotis Tsiotras. Solving Shortest Path Problems with Curvature Constraints Using Beamlets,
2011 EEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011). 25-SEP-11, . : ,

08/30/2011 8.00 Yibiao Lu, Oktay Arslan, Xiaoming Huo, Panagiotis Tsiotras. Multi-Scale LPA* with Low Worst-Case Complexity Guarantees,
2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011). 25-SEP-11, . : ,

08/30/2011 7.00 Raghvendra Cowlagi, Panagiotis Tsiotras. `Multiresolution H-Cost Motion Planning: A New Framework for Hierarchical Motion Planning for Autonomous Mobile Vehicles,
2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011). 25-SEP-11, . : ,

08/30/2012 43.00 A. Borji , D. N. Sihite , L. Itti. An Object-based Bayesian Framework for Top-down Visual Attention,
Twenty-Sixth AAAI Conference on Artificial Intelligence. , . : ,

08/30/2012 47.00 Kyel Ok, Duy-Nguyen Ta, Frank Dellaert. Vistas and Wall-Floor Intersection Features: Enabling Autonomous Flight in Man-made Environments,
2nd Workshop on Visual Control of Mobile Robots (ViCoMor). , . : ,

08/30/2012 46.00 Chris Beall, Duy-Nguyen Ta, Kyel Ok, Frank Dellaert. Attitude Heading Reference System with Rotation-Aiding Visual Landmarks,
International Conference on Information Fusion. , . : ,

08/30/2012 45.00 Ali Borji, Dicky N. Sihite, Laurent Itti. Salient Object Detection: A Benchmark,
European Conference on Computer Vision. , . : ,

08/30/2012 41.00 Yin Li, Jiaya Jia, Jian Sun, Liwei Wang, David Wipf, James M. Rehg. Learning sparse covariance patterns for natural scenes,
2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 16-JUN-12, Providence, RI, USA. : ,

08/30/2012 40.00 Alircza Fathi, Jessica K. Hodgins, James M. Rehg. Social interactions: A first-person perspective,
2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 16-JUN-12, Providence, RI, USA. : ,

08/30/2012 42.00 Herencia-Zapana, H. , Jobredeaux, R. , Owre, S. , Garoche, P.-L. , Feron, E. , Perez, G. , Ascariz, P..
PVS Linear Algebra Libraries for Verification of Control Software Algorithms in C/ACSL,
Proceedings of the Fourth NASA Formal Methods Symposium (NFM 2012). , . : ,

08/30/2012 38.00 Laurent Itti, Ali Borji. Exploiting local and global patch rarities for saliency detection,
2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 16-JUN-12, Providence, RI, USA. : ,

08/30/2012 37.00 Ali Borji, Dicky N. Sihite, Laurent Itti. Probabilistic learning of task-specific visual attention,
2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 16-JUN-12, Providence, RI, USA. : ,

08/30/2012 36.00 Ali Borji, Dicky Sihite, Laurent Itti. Computational Modeling of Top-down Visual Attention in Interactive Environments,
British Machine Vision Conference 2011. , Dundee. : ,

08/30/2012 35.00 Sterling J Anderson, Sisir B. Karumanchi, Karl Iagnemma. Constraint-based planning and control for safe, semi-autonomous operation of vehicles,
2012 IEEE Intelligent Vehicles Symposium (IV). 03-JUN-12, Alcal de Henares , Madrid, Spain. : ,

08/30/2012 34.00 Sterling J. Anderson, Sisir B. Karumanchi, Bryan Johnson, Victor Perlin, Mitchell Rohde, Karl Iagnemma. Constraint-based semi-autonomy for unmanned ground vehicles using local sensing,
Unmanned Systems Technology XIV. , Baltimore, Maryland, USA. : ,

08/30/2012 33.00 Jeong hwan Jeon, Sertac Karaman, Emilio Frazzoli. Anytime computation of time-optimal off-road vehicle maneuvers using the RRT*,
2011 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC 2011). 12-DEC-11, Orlando, FL, USA. : ,

08/30/2012 32.00 Richard Roberts, Duy-Nguyen Ta, Julian Straub, Kyel Ok, Frank Dellaert. Saliency detection and model-based tracking: a two part vision system for small robot navigation in forested environment,
Unmanned Systems Technology XIV. , Baltimore, Maryland, USA. : ,

08/30/2012 31.00 Panagiotis Tsiotras, Raghvendra V. Cowlagi. Hierarchical motion planning with kinodynamic feasibility guarantees: Local trajectory planning via model predictive control,
2012 IEEE International Conference on Robotics and Automation (ICRA). 14-MAY-12, St Paul, MN, USA. : ,

08/30/2012 30.00 Imon Chakraborty, Panagiotis Tsiotras, Jianbo Lu. Vehicle posture control through aggressive maneuvering for mitigation of T-bone collisions,
2011 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC 2011). 12-DEC-11, Orlando, FL, USA. : ,

08/30/2012 44.00 Shane Grant, Laurent Itti. Saliency Mapping Enhanced by Symmetry from Local Phase,
IEEE International Conference on Image Processing. , . : ,

08/31/2011 15.00 Ali Borji, Dicky N. Sihite, Laurent Itti. Computational Modeling of Top-down Visual Attention in Interactive Environments,
The 22nd British Machine Vision Conference. 29-AUG-11, . : ,

08/31/2011 18.00 Xiaofeng Ren, James M. Rehg, Alireza Fathi. Learning to recognize objects in egocentric activities,
2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 20-JUN-11, Colorado Springs, CO, USA. : ,

08/31/2011 17.00 Alireza Fathi, Maria Florina Balcan, Xiaofeng Ren, James M. Rehg. Combining Self Training and Active Learningfor Video Segmentation,
22nd British Machine Vision Conference (BMVC 2011). 29-AUG-11, . : ,

08/31/2011 16.00 Alireza Fathi, Ali Farhadi, James M. Rehg. Understanding Egocentric Activities,
13th International Conference on Computer Vision (ICCV 2011). 06-NOV-11, . : ,

08/31/2012 50.00 Vu Anh Huynh , Emilio Frazzoli. Probabilistically-Sound and Asymptotically-Optimal Algorithm for Stochastic Control with Trajectory Constraints,
51st IEEE Conference on Decision and Control. , . : ,

09/01/2013 54.00 Richard Roberts, Duy-Nguyen Ta, Julian Straub, Kyel Ok, Frank Dellaert. Saliency detection and model-based tracking: a two part vision system for small robot navigation in forested environment,
SPIE Defense, Security, and Sensing. 23-JUN-12, Baltimore, Maryland. : ,

09/01/2013 55.00 Emmanuel Boidot, Eric Feron. Planning random path distributions for ambush games in unstructured environments,
2012 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR). 05-NOV-12, College Station, TX, USA. : ,

09/01/2013 63.00 Oktay Arslan, Panagiotis Tsiotras. Use of Relaxation Methods in Sampling-Based Algorithms for Optimal Motion Planning,
IEEE International Conference on Robotics and Automation. 06-MAY-13, . : ,

09/01/2013 64.00 I. Chakraborty, P. Tsiotras, R. Sanz-Diaz . Time-Optimal Vehicle Posture Control to Mitigate Unavoidable Collisions Using Conventional Control Inputs,
American Control Conference. 17-JUN-13, . : ,

09/01/2013 65.00 R. Roberts, F. Dellaert . Optical Flow Templates for Superpixel Labeling in Autonomous Robot Navigation,
5th Workshop on Planning, Perception and Navigation for Intelligent Vehicles (PPNIV13). 03-NOV-13, . : ,

09/01/2013 66.00 J. Bialkowski, S. Karaman, M. Otte, E. Frazzoli. fficient Collision Checking inSampling-based Motion Planning,
International Workshop on Algorithmic Foundations of Robotics . 13-JUN-12, . : ,

09/01/2013 67.00 J. Bialkowski, M. W. Otte, E. Frazzoli. Free-configuration Biased Sampling for Motion Planning,
IEEE/RSJ Int. Conf. on Intelligent Robots and Systems. 03-NOV-13, . : ,

09/01/2013 68.00 S. Karaman, E. Frazzoli. Sampling-based Optimal Motion Planning for Non-holonomic Dynamical Systems,
IEEE International Conference on Robotics and Automation. 06-MAY-13, . : ,

09/01/2013 69.00 P. Chaudhari, S. Karaman, D. Hsu, E. Frazzoli. Sampling-based Algorithms for Continuous-time POMDPs,
American Control Conference. 17-JUN-13, . : ,

09/01/2013 70.00 J. Jeon, R. Cowlagi, S. Peters, S. Karaman, E. Frazzoli, P. Tsiotras, K. Iagnemma. Optimal Motion Planning with the Half-Car Dynamical Model for Autonomous High-Speed Driving,
American Control Conference}. 17-JUN-13, . : ,

09/01/2013 71.00 P. Chaudhari, S. Karaman, E. Frazzoli. Sampling-based Algorithm for Filtering using Markov Chain Approximations,
51th IEEE Conference on Decision and Control Conference. 10-DEC-12, . : ,

09/01/2013 72.00 C. Siagian, C. K. Chang, L. Itti. Mobile Robot Navigation System in Outdoor Pedestrian Environment Using Vision-Based Road Recognition,
IEEE International Conference on Robotics and Automation. 06-MAY-13, . : ,

09/01/2013 73.00 J. Windau, L. Itti. Situation Awareness via Sensor-equipped Eyeglasses,
IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,

09/01/2013 74.00 C. K. Chang, C. Siagian, L. Itti. Beobot 2.0: Autonomous Mobile Robot Localization and Navigation in OutdoorPedestrian Environment,
IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,

09/01/2013 75.00 W. S. Grant, R. C. Voorhies, L. Itti. Finding Planes in LiDAR Point Clouds for Real-Time Registration,
IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,

09/01/2013 76.00 N. Noori, L. Itti. Traces of Intellectual Working Memory Tasks on Visual-Spatial Short-Term Memory,
35th Annual Conference of the Cognitive Science Society. , . : ,

09/01/2013 77.00 N. Noori, L. Itti. Schema-Driven, Space-Supported Random Accessible Memory Systems for Manipulation of Symbolic Working Memory,
35th Annual Conference of the Cognitive Science Society. , . : ,

09/01/2013 78.00 N. Noori, L. Itti. Where What You Count is What Really Counts,
35th Annual Conference of the Cognitive Science Society. , . : ,

09/01/2013 80.00 A. Fathi, Y. Li, J. Rehg. Learning to Recognize Daily Actions using Gaze,
European Conference on Computer Vision. 07-OCT-12, . : ,

09/02/2014 94.00 Timothy E. Wang, Alireza Esna Ashari, Romain J. Jobredeaux, Eric M. Feron. Credible autocoding of fault detection observers,
2014 American Control Conference - ACC 2014. 04-JUN-14, Portland, OR, USA. : ,

09/02/2014 93.00 Fuxin Li, Taeyoung Kim, Ahmad Humayun, David Tsai, James M. Rehg. Video Segmentation by Tracking Many Figure-Ground Segments,
2013 IEEE International Conference on Computer Vision (ICCV). 01-DEC-13, Sydney, Australia. : ,

09/02/2014 92.00 Yin Li, Alireza Fathi, James M. Rehg. Learning to Predict Gaze in Egocentric Video,
2013 IEEE International Conference on Computer Vision (ICCV). 01-DEC-13, Sydney, Australia. : ,

09/02/2014 91.00 Ali Borji, Hamed R. Tavakoli, Dicky N. Sihite, Laurent Itti. Analysis of Scores, Datasets, and Models in Visual Saliency Prediction,
2013 IEEE International Conference on Computer Vision (ICCV). 01-DEC-13, Sydney, Australia. : ,

09/02/2014 90.00 Alexandre Constantin, Junghee Park, Karl Iagnemma. A margin-based approach to threat assessment for autonomous highway navigation,
2014 IEEE Intelligent Vehicles Symposium (IV). 08-JUN-14, MI, USA. : ,

09/02/2014 89.00 Duy-Nguyen Ta, Marin Kobilarov, Frank Dellaert. A factor graph approach to estimation and model predictive control on Unmanned Aerial Vehicles,
2014 International Conference on Unmanned Aircraft Systems (ICUAS). 27-MAY-14, Orlando, FL, USA. : ,

09/03/2014 98.00 Kunda, A., Li, Y., Dellaert, F., Li, F. , Rehg, J.M.. Joint Semantic Segmentation and 3D Reconstruction for Monocular Video,
European Conference on Computer Vision. 06-SEP-14, . : ,

09/03/2014 06.00 D.-N. Ta, F. Dellaert. Linear-Time Estimation with Tree Assumed Density Filtering and Low-Rank Approximation,
IEEE/RSJ Int. Conf. on Intelligent Robots and Systems. 14-SEP-14, . : ,

09/03/2014 05.00 Richard Roberts, Frank Dellaert. Direct Superpixel Labeling for Mobile Robot Navigation Using Learned General Optical Flow Templates,
IEEE/RSJ Int. Conference on Intelligent Robots and Systems. 14-SEP-14, . : ,

09/03/2014 04.00 . Bayesian Optimization Explains Human Active Search,
Advances in Neural Information Processing Systems. 05-DEC-13, . : ,

09/03/2014 03.00 A. Borji , L. Itti. Human vs. Computer in Scene and Object Recognition,
IEEE Conference on Computer Vision and Pattern Recognition. 24-JUN-04, . : ,

09/03/2014 02.00 Vu Anh Huynh, Leonid Kogan , Emilio Frazzoli. A Martingale Approach and time-consistent Sampling-based Algorithms for Risk Management in stochastic optimal control,
EEE Conference on Decision and Control. 15-DEC-14, . : ,

09/03/2014 99.00 Li, Y. , Hou, X. , Koch, C. , Rehg, J. M., Yuille, A.. The Secrets of Salient Object Segmentation,
Computer Vision and Pattern Recognition. 24-JUL-14, . : ,

09/05/2015 11.00 Oktay Arslan, Evangelos A. Theodorou, Panagiotis Tsiotras. Information-theoretic stochastic optimal control via incremental sampling-based algorithms,
2014 IEEE Symposium on Adaptive Dynamic Programming and Reinforcement Learning (ADPRL). 09-DEC-14, Orlando, FL, USA. : ,

09/05/2015 12.00 Wei Sun, Evangelos A. Theodorou, Panagiotis Tsiotras. Continuous-time differential dynamic programming with terminal constraints,
2014 IEEE Symposium on Adaptive Dynamic Programming and Reinforcement Learning (ADPRL). 09-DEC-14, Orlando, FL, USA. : ,

09/05/2015 14.00 Oktay Arslan, Panagiotis Tsiotras. Dynamic programming guided exploration for sampling-based motion planning algorithms,
2015 IEEE International Conference on Robotics and Automation (ICRA). 26-MAY-15, Seattle, WA, USA. : ,

09/06/2015 19.00 Brian Paden, Sze Zheng Yong, Emilio Frazzoli. Asymptotically reachable states and related symmetry in systems theory,
2015 American Control Conference (ACC). 01-JUL-15, Chicago, IL, USA. : ,

09/06/2015 20.00 Junghee Park, Karl Iagnemma. Sampling-based Planning for Maximum Margin Input Space Obstacle Avoidance,
EEE/RSJ International Conference on Intelligent Robots and Systems. 28-SEP-15, . : ,

09/06/2015 26.00 Jiaping Zhao, Christian Siagian, Laurent Itti. Fixation Bank: Learning to Reweight Fixation Candidates,
IEEE Conference on Computer Vision and Pattern Recognition. 08-JUN-15, . : ,

TOTAL: **76**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

08/30/2012 27.00 Ali Borji, Dicky N. Sihite, Laurent Itti. Where to look next? Modeling Top-down VisualAttention in Complex Interactive Environments,
IEEE Transactions on Systems, Man, and Cybernetics, Part A - Systems and Humans (01 2012)

TOTAL: **1**

Number of Manuscripts:

Books

Received Book

08/30/2012 28.00 Laurent Itti, Ali Borji. Computational Models: Bottom-Up and Top-Down Aspects, Oxford : Oxford University Press, (03 2012)

TOTAL: **1**

Received	Book Chapter	
09/01/2013	79.00	L. Itti, A. Borji. Computational Models of Attention, New York: W.W. Norton , (03 2014)
09/03/2014	97.00	P. Tsiotras, R. Sanz-Diaz. Real-Time Near-Optimal Feedback Control of Aggressive Vehicle Maneuvers, Switzerland: Springer Lecture Notes in Control and Information Sciences, (03 2014)
TOTAL:	**2**	

Patents Submitted

"AutoRally". Brian Goldfain, Paul Drews, James Rehg, Evangelos Theodorou, Panagiotis Tsiotras, Grady Williams, U.S. Patent Application No: 62/335,121, May 12, 2016.

Patents Awarded

Awards

1) 2015 Axelby Award for paper "Robust Distributed Routing in Dynamical Networks?Part II: Strong Resilience, Equilibrium Selection and Cascaded Failures,? IEEE Transactions on Automatic Control, Vol. 58, No. 2, pp. 333-348, February 2013, co-authored by Emilio Frazzoli, Kevan Sala, Giacomo Como, Munzer Dahleh, and Daron Acemoglu. The Axelby award is given "To recognize outstanding papers published in the IEEE Transactions on Automatic Control."

2) Emilio Frazzoli received the 2017 IEEE Kiyo Tomiyasu award "for contributions to planning, control, and fleet operation algorithms for autonomous vehicles."

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Junghee Park	1.00	
Paul Drews	0.50	
Brian Paden	0.50	
Brian Goldfain	0.80	
Rorry Brenner	1.00	
Chen Zhang	1.00	
Florian Hauer	1.00	
FTE Equivalent:	**5.80**	
Total Number:	**7**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Karl Iagnemma	0.20	
Frank Dellaert	0.05	
Emilio Frazzoli	0.83	
Eric Feron	0.10	
Laurent Itti	0.25	
Panagiotis Tsiotras	0.08	
Jim Rehg	0.08	
FTE Equivalent:	**1.59**	
Total Number:	**7**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Park, J.	
Arslan, O.	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Our work during the last year can be broadly divided into the following areas:

(a) development of semi-autonomous and autonomous vehicle control with application to driver assistance scenarios;
(b) deciphering driver state and intentions beyond eye movements to predict and understand human attention mechanisms;
(c) improvement of the MSPP algorithm that merges sensing/perception with control/planning algorithms using multiscale probabilistic obstacle maps;
(d) development of several new sampling-based algorithms for kinodynamic motion planning and investigation of their convergence properties;
(e) utilization of stochastic and information-theoretic ideas (path integral) to develop new, sampling-based, and completely parallelizable algorithms, for on-line optimal trajectory generation of a general class of nonlinear systems;
(f) experimental testing of these algorithms on a scaled high-speed AGV platform; and finally,
(g) continued our work on credible autocoding of advanced, real-time optimization algorithms, specifically, interior-point optimization algorithms that are essential for convex optimizers.

SEMI-AUTONOMOUS AND AUTONOMOUS VEHICLE CONTROL % IAGNEMMA

We have continued our investigation into the semi-autonomous and autonomous vehicle control framework, which has application to driver assistance scenarios (i.e., manned vehicles), teleoperated scenarios, or unmanned and autonomous vehicles. The method relies on planning of constraints that approximately bound homotopic path classes, thus identifying and evaluating "fields of safe travel" that an operator can travel within. This paradigm promises to enable more efficient approaches to both planning and perception, since an initial analysis of candidate fields of travel can serve as a filtering step to determine how to best allocate attention and computational resources.

In this year, a major focus has been on conducting large-scale experimental analyses with human subjects in the loop, to study the engagement of humans with semi-autonomous and autonomous driving technologies (which were developed under this MURI program). These studies were conducted in collaboration with experts in human-vehicle interaction at the MIT Age Lab. The overall purpose of the studies was to measure driving performance, measured by a variety of metrics such as collision ratio and desirableness of vehicle behavior, and driver's response measured by the level of comfort and trust on the system and attentiveness to the driving task, with various levels of driver assistance system in place. Numerous factors have been selected to measure for comparing different assistance systems in terms of user's response, in particular, perceived usefulness, perceived ease of use, perceived safety, anxiety, sense of control, fun, and likability. These measures are selected from well-established models of technology acceptance and usability in the fields of human factors and human computer interaction. These studies showed a relationship between level of automation, driving performance, driver attentiveness, and other factors.

VERIFICATION AND VALIDATION OF CONTROL SOFTWARE OF AUTONOMOUS SYSTEMS % FERON

Our work in V\&V for software for autonomous systems have continued and has extended the concept of credible autocoding to encompass credible autocoding of advanced, real-time optimization algorithms. Namely, our research has established the theoretical basis upon which interior-point optimization algorithms can be autocoded from high-level specifications to proof-carrying code, where the proof concentrates on code execution time and effective convergence towards optimality. This effort got comforted in terms of relevance by the recent autonomous landing of a SpaceX Falcon 9 rocket on a barge, which precisely used online convex optimization to perform this mission-critical task.

NEUROMORPHIC ALGORITHMS FOR ATTENTION % ITTI

During this last period of performance, we finalized developing a new visual attention model which learns from human eye movements, the ¿fixation bank¿ attention model. The model was described in the previous annual report. We also continued our work on deciphering driver state and intentions beyond eye movements. We focused on the analysis of low-dimensional time-series, as can be obtained from inertial measurement units (IMUs, which integrate accelerometer and gyroscope information in three dimensions). Given such data, one core algorithm to develop is one of classification of a time series (sequences of motions over time, as measured by IMUs placed on the head or limbs) into different activities, which may then help evaluate driver state. Time series classification (TSC), more generally, arises in many fields and has a wide range of applications. Here, we adopt the bag-of- words (BoW) framework to classify time series. Our algorithm first samples local subsequences from time series at feature-point locations when available. It then builds local descriptors, and models their distribution by Gaussian mixture models (GMM), and at last it computes a Fisher Vector (FV) to encode each time series. The encoded FV representations of time series are readily used by existing classifiers, e.g., SVM, for training and prediction. In our work, we focused on detecting better feature points and crafting better local representations, while using existing techniques to learn codebook and encode time series. Specifically, we developed an efficient and effective peak and valley detection algorithm from real-case time series data. Subsequences are sampled from these peaks and valleys, instead of sampled randomly or uniformly as was done previously. Then, two local descriptors, Histogram of Oriented Gradients (HOG-1D) and Dynamic time warping-Multidimensional scaling (DTW-MDS), are designed to represent sampled subsequences. Both descriptors complement each other, and their fused representation is shown to be more descriptive than individual ones. We tested our approach extensively on 43 UCR time series datasets, and obtain significantly improved classification accuracies

over existing approaches, including NNDTW and shapelet transform.

INTEGRATED HIERARCHICAL MAP BUILDING AND PLANNING

During this year, we developed several modifications to the previously proposed multi-scale path-planning algorithm (MSPP) we described in last year annual report, in order to speed-up its execution. Recall that the MSPP algorithm leverages a multi-scale representation of the environment in n dimensions encoded in a tree structure constructed by recursive dyadic partitioning of the search space and it was designed to operate smoothly with multi-scale representation of the environment obtained from similar multi-resolution perception algorithms. We developed a new method to compute the graph neighbors in order to reduce the complexity of each iteration, from O(|V| 2) to O(|V | log |V |) where |V| is the number of the vertices in the search graph. We then showed how to delay expensive intermediate computations until we know that new information will be required, hence saving time by not operating on information that is never used during the search. Finally, we designed a way to remove the very expensive need to calculate a full multi-scale map with the use of sampling and derive an theoretical upper bound of the probability of failure as a function of the number of samples.

SAMPLING BASED ALGORITHMS FOR PATH AND MOTION PLANNING % TSIOTRAS & FRAZZOLI

This year we continued our work on sampling-based motion planners. We have shown that the recently developed RRT* algorithm by our group hinges on dynamic programming ideas. These ideas have been explored to introduce new sampling-based planners that utilize value iteration principles from dynamic programming. The recently proposed RRT# algorithm utilizes such dynamic programming ideas (namely, asynchronous value iteration) and implements them incrementally on randomly generated graphs to improve on the rates of convergence over the original RRT* algorithm. A C/C++ implementation of RRR\# has been uploaded on OMPL library and is now publicly available. Once the connection with dynamic programing is made, other algorithms are possible, beyond methods based on value-iteration. We have proposed the PI-RRT# algorithm that utilizes policy iteration instead of value iteration and which is better suited for massive parallelization.

In another stream of research we investigate the convergence properties of sampling-based path planning algorithms in terms of the dimensionality of the search space. Using the Hypercube Diagonal Experiment, we showed that the probability of sampling a point that improves the solution decreases exponentially with the dimension of the problem. We then analyzed how the samples can be repositioned in the search space in order to minimize the approximation error. Based on this observation, we have developed the DRRT (Deformable Rapidly Exploring Random Tree) algorithm that utilizes optimization of sample location in the framework of RRT algorithms to improve convergence. It is shown that the DRRT algorithm significantly outperforms all current sampling-based algorithms in terms of convergence.

KINODYNAMIC MOTION PLANNING

Motion planning under differential constraints is one of the canonical problems in robotics and autonomous systems, and still remains a major challenge. State-of-the-art methods evolve around kinodynamic variants of popular sampling-based algorithms, such as Rapidly-exploring Random Trees (RRTs). However, there are still challenges remaining, for example, how to include complex dynamics, while guaranteeing optimality. If the open-loop dynamics are unstable, exploration by random sampling in control space becomes inefficient. We describe a new sampling-based algorithm, called CL-RRT#, which leverages ideas from the RRT\# algorithm and a variant of the RRT algorithm that generates trajectories using closed-loop prediction. The idea of planning with closed-loop prediction allows us to handle complex unstable dynamics and avoids the need to find computationally hard steering procedures. The search technique presented in the RRT# algorithm allows us to improve the solution quality by searching over alternative reference trajectories. Using an autonomous-driving scenario, we show the benefits of the proposed approach.

Within the class of optimal kinodynamic motion planning problems, the generalized label correcting (GLC) method is an efficient search-based approach that relies on a finite set of control primitives that are concatenated into candidate control signals. Advantages of the technique include a simple implementation, convergence to the optimal cost with increasing resolution, and no requirement for a point-to-point local planning subroutine. We have investigated the principled selection of this set of control primitives. Emphasis is placed on a particularly challenging input space geometry, the n-dimensional sphere. We have proposed using controls which minimize a generalized energy function and discuss the optimization technique used to obtain these control primitives. A numerical experiment is presented showing a factor of two improvement in running time when using the optimized control primitives over a random sampling strategy.

Admissible heuristics can help with the kinodynamic motion planning problem. But how does one obtain an admissible heuristic for a kinodynamic motion planning problem? To answer this question, we have developed a sufficient condition for the admissibility of a heuristic which can be checked directly from the problem data. This condition is also used to formulate an infinite dimensional linear program to optimize an admissible heuristic to be a close underestimate of the optimal cost to reach the goal. This optimization is then approximated and solved in polynomial time using sum of squares programming techniques.

Nearest-neighbor search dominates the asymptotic complexity of sampling-based motion planning algorithms and is often addressed with k-d tree data structures. While it is generally believed that the expected complexity of nearest-neighbor queries is O(log(N)) in the size of the tree, in our recent work it is reveals that when a classic k-d tree approach is used with sub-Riemannian metrics, the expected query complexity is in fact (Np log(N)) where p is determined by the degree of nonholonomy of the system These metrics arise naturally in nonholonomic mechanical systems, including classic wheeled robot models. To address this negative result, we propose novel k-d tree build and query strategies tailored to sub-Riemannian metrics and demonstrate significant improvements in the running time of nearest-neighbor search queries.

HIGH SPEED DRIVING USING STOCHASTIC OPTIMAL CONTROL % DELLAERT / REHG

Aggressive driving still remains a challenging task for most autonomous vehicles, owing to the inherent nonlinearity of the problem, the uncertainty in the environment and the friction dynamics, and the short time scales for perception, planning and action. We have investigated the use of stochastic optimal control ideas based on sampling to develop aggressive driving maneuvers and test them on a dirt track. A model predictive control algorithm has been designed for optimizing non-linear systems subject to complex cost criteria. The algorithm is based on a stochastic optimal control framework using a fundamental relationship between the information theoretic notions of free energy and relative entropy. The optimal controls in this setting take the form of a path integral, which we approximate using an efficient importance sampling scheme. The proposed Model Predictive Path Integral (MPPI) control has been experimentally verified by implementing it on a Graphics Processing Unit (GPU) and has been applied it to the problem of controlling a fifth-scale Auto-Rally vehicle in an aggressive driving task.

Research this year has also focused on driving using visual information to inform the cost function of the MPPI controller. A first attempt was made using SLAM based approaches, but it was quickly discarded because the objective of generalization was not met. Several approaches were tried using neural networks. Initially, we attempted to directly predict the position and orientation of the vehicle using neural networks. This approach would allow us to remove the GPS from the system and drive using visual information only. This did not prove fruitful, and was not sufficiently refined to work with our current control architecture (MPPI). Finally, we attempted to train a neural network to produce a costmap image (labeling pixels near the center of our track as low cost and pixels near the edge or off the track high cost). To do this, we used data collected over the past several years combined with position data gathered from previous efforts in GPS/IMU fusion on this platform to provide ground truth data for collected images. We were then able to successfully train a neural network to produce cost maps that the MPPI algorithm could successfully use to traverse our track at high speed using only visual information (no absolute position sensing). In addition to driving using visual information, the MPPI control system was refined and improved to allow more aggressive and robust driving behaviors.

Technology Transfer

1) Timothy Wang has moved to become a research engineer at United Technologies Research Center, specifically for his expertise on the verification of vehicle autonomy such as that used on SpaceX's rocket recovery.

2) Oktay Arslan has become a member of the JPL robotics group where his primary responsibility is to implement and evaluate sampling-based path-planning algorithms (such as RRRT#) to the next 2020 Mars rover.

3) Karl Iagnemma and Emilio Frazzoli have established nuTonomy that has become one of the major players in self-driving vehicle technology.