

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 05-03-2016		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 26-Aug-2009 - 25-Aug-2014	
4. TITLE AND SUBTITLE Probabilistic Tracking and Trajectory Planning for Autonomous Ground Vehicles in Urban Environments			5a. CONTRACT NUMBER W911NF-09-1-0466		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS Mark E. Campbell			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Cornell University 373 Pine Tree Road Ithaca, NY 14850 -2820			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) 56043-NS.36		
12. DISTRIBUTION AVAILABILITY 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 be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT The aim of this research is to develop a unified theory for perception and planning in autonomous ground vehicles, with a specific focus on obstacle tracking/identification and trajectory planning, so as to enable reasoned, intelligent planning rather than simple reactive planning. This final report details our contributions. First, we developed a new method for anticipating obstacle motion using Gaussian Processes in order to enable contingency planning. Second, we developed three new mapping strategies including a unified terrain model based on a Markov Random Fields; soft relative maps; and fusion of stochastic maps. Third, we developed a methodology for capturing negative					
15. SUBJECT TERMS ground robots, autonomous driving, probabilistic anticipation, trajectory planning					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Mark Campbell
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 607-255-4268

Report Title

Probabilistic Tracking and Trajectory Planning for Autonomous Ground Vehicles in Urban Environments

ABSTRACT

The aim of this research is to develop a unified theory for perception and planning in autonomous ground vehicles, with a specific focus on obstacle tracking/identification and trajectory planning, so as to enable reasoned, intelligent planning rather than simple reactive planning. This final report details our contributions. First, we developed a new method for anticipating obstacle motion using Gaussian Processes in order to enable contingency planning. Second, we developed three new mapping strategies including a unified terrain model based on a Markov Random Fields; soft relative maps; and fusion of stochastic maps. Third, we developed a methodology for capturing negative information (e.g. reasoning about areas where there is no sensor data), which is then used to improve tracking of obstacles. Fourth, we developed a new smoothing method which enables real time update of complex density functions (e.g. complex maps, tracking dynamic obstacles) in the presence of sparse data. We have published /accepted 23 journal articles and conference papers.

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)

<u>Received</u>	<u>Paper</u>
03/05/2016 32.00	Daniel J. Lee, Mark E. Campbell. Smoothing Algorithm for Nonlinear Systems Using Gaussian Mixture Models, Journal of Guidance, Control, and Dynamics, (08 2015): 0. doi: 10.2514/1.G000603
03/05/2016 34.00	Nisar R. Ahmed, Mark Campbell, Rina Tse. Unified Terrain Mapping Model With Markov Random Fields, IEEE Transactions on Robotics, (04 2015): 0. doi: 10.1109/TRO.2015.2400654
03/05/2016 33.00	Kevin Wyffels, Mark Campbell. Negative Information for Occlusion Reasoning in Dynamic Extended Multiobject Tracking, IEEE Transactions on Robotics, (04 2015): 0. doi: 10.1109/TRO.2015.2409413
03/05/2016 35.00	J. Hardy, F. Havlak, M. Campbell. Multi-step prediction of nonlinear Gaussian Process dynamics models with adaptive Gaussian mixtures, The International Journal of Robotics Research, (06 2015): 0. doi: 10.1177/0278364915584007
03/05/2016 29.00	Frank Havlak, Mark Campbell. Discrete and Continuous, Probabilistic Anticipation for Autonomous Robots in Urban Environments, IEEE Transactions on Robotics, (04 2014): 0. doi: 10.1109/TRO.2013.2291620
08/27/2012 16.00	Isaac Miller, Mark Campbell. Sensitivity Analysis of a Tightly-Coupled GPS/INS System for Autonomous Navigation, IEEE Transactions on Aerospace and Electronic Systems, (04 2012): 1115. doi: 10.1109/TAES.2012.6178052
08/27/2012 19.00	Isaac Miller, Mark Campbell, Dan Huttenlocher. Map-aided localization in sparse global positioning system environments using vision and particle filtering, Journal of Field Robotics, (09 2011): 0. doi: 10.1002/rob.20395
08/27/2012 17.00	C. Rivadeneyra, M. Campbell. Probabilistic multi-level maps from LIDAR data, The International Journal of Robotics Research, (01 2011): 0. doi: 10.1177/0278364910392405
08/27/2012 18.00	Jonathan R. Schoenberg, Mark Campbell, Isaac Miller. Posterior representation with a multi-modal likelihood using the gaussian sum filter for localization in a known map, Journal of Field Robotics, (03 2012): 0. doi: 10.1002/rob.20430
09/05/2013 23.00	Jason Hardy, Mark Campbell. Contingency Planning Over Probabilistic Obstacle Predictions for Autonomous Road Vehicles, IEEE Transactions on Robotics, (08 2013): 0. doi: 10.1109/TRO.2013.2254033

TOTAL: 10

Number of Papers published in peer-reviewed journals:

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

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

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

Received Paper

TOTAL:

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

- 03/05/2016 30.00 Frank Havlak, Jason Hardy, Mark Campbell. Multiple-step prediction using a two stage Gaussian Process model,
2014 American Control Conference - ACC 2014. 04-JUN-14, Portland, OR, USA. : ,
- 08/27/2012 11.00 Daniel Lee, Mark Campbell. Iterative Smoothing Approach using Gaussian Mixture Models for Nonlinear Estimation,
IEEE/RSJ International Conference on Intelligent Robots and Systems. 20-SEP-12, . : ,
- 08/27/2012 15.00 Rina Tse, Nisar Ahmed, Mark Campbell. Unified Mixture-Model Based Terrain Estimation with Markov Random Fields,
IEEE International Conference on Multisensor Fusion and Integration. 13-SEP-12, . : ,
- 08/27/2012 14.00 Brandon Jones, Mark Campbell, Lang Tong. Bipartite Matching of Stochastic Maps,
Allerton Conference on Communication, Control, and Computing. 10-OCT-11, . : ,
- 08/27/2012 13.00 Mark Campbell, Lang Tong, Brandon Jones. Consensus of stochastic maps with nearest neighbor interactions,
SPIE Defense, Security, and Sensing. 16-APR-12, . : ,
- 08/27/2012 12.00 Nisar Ahmed, Jon Schoenberg, Mark Campbell. Fast Weighted Exponential Product Rules for Robust General Multi-Robot Data Fusion,
Robotics Science and Systems Conference. 09-JUL-12, . : ,
- 08/31/2011 7.00 J. Hardy, M. Campbell. Clustering Obstacle Predictions to Improve Contingency Planning for Autonomous Road Vehicles in Congested Environments,
IEEE/RSJ International Conference on Intelligent Robots and Systems, . 25-SEP-11, . : ,
- 09/05/2013 27.00 Mark McClelland, Mark Campbell, Tara Estlin. Qualitative Relational Mapping for Robotic Navigation, Infotech. 06-JUN-12, . : ,
- 09/05/2013 28.00 Kevin Wyffels, Mark Campbell. Modeling and Fusing Negative Information For Dynamic Extended Multi-object Tracking,
IEEE International Conference on Robotics and Automation. 06-JUN-13, . : ,
- 09/05/2013 20.00 Nisar Ahmed, Mark Campbell, Rina Tse. Unified mixture-model based terrain estimation with Markov Random Fields,
2012 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI 2012). 13-SEP-12, Hamburg, Germany. : ,
- 09/05/2013 21.00 Daniel J. Lee, Mark E. Campbell. Iterative smoothing approach using Gaussian mixture models for nonlinear estimation,
2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012). 07-OCT-12, Vilamoura-Algarve, Portugal. : ,
- 09/05/2013 22.00 Mark Campbell, Lang Tong, Brandon Jones. Consensus of stochastic maps,
SPIE Defense, Security, and Sensing. 01-APR-12, Baltimore, Maryland. : ,
- 09/05/2013 24.00 Jonathan Schoenberg, Mark Campbell, Nisar Ahmed. ast Weighted Exponential Product Rules for Robust General Multi-Robot Data Fusion,
Robotics: Science and Systems. 06-JUN-12, . : ,

TOTAL: 13

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

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
08/27/2012	8.00 Nisar Ahmed, Mark Campbell. Fast Consistent Chernoff Fusion of Gaussian Mixtures for Ad Hoc Sensor Networks, IEEE Transactions on Signal Processing (01 2012)
08/27/2012	9.00 Isaac Miller, Mark Campbell. Sensitivity Study of a Tightly-Coupled GPS / INS System for Autonomous Navigation, IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS (04 2012)
08/31/2011	1.00 I. Miller and M. Campbell and D. Huttenlocher. Particle Filtering for Map-Aided Localization in Sparse GPS Environments, Journal of Field Robotics (08 2011)
08/31/2011	6.00 J. Schoenberg, M. Campbell, I. Miller. Posterior Representation with a Multi-Modal Likelihood Using the Gaussian Sum Filter, Journal of Field Robotics (08 2011)
08/31/2011	5.00 I. Miller, M. Campbell, D. Huttenlocher. Map-Aided Localization in Sparse GPS Environments using Vision and Particle Filtering, Journal of Field Robotics (08 2011)
08/31/2011	4.00 César Rivadeneyra, Mark Campbell. Probabilistic multi-level maps from LIDAR data, The International Journal of Robotics Research (01 2011)
08/31/2011	3.00 M. Campbell. Intelligent Autonomy in Robotic Systems, The Bridge, Quarterly of the NAE (01 2010)
09/05/2013	26.00 Brandon Jones, Mark Campbell, Lang Tong. Maximum Likelihood Fusion of Stochastic Maps, IEEE Transactions on Signal Processing (12 2012)
09/05/2013	25.00 Frank Havlak, Mark Campbell. Discrete and Continuous, Probabilistic Anticipation for Autonomous Robots in Urban Environments, IEEE Transactions on Robotics (12 2012)
TOTAL:	9

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

- John A. Mellowes ‘60 Professor of Mechanical and Aerospace Engineering, 2015
 - AIAA Best Paper Award, AIAA Guidance Navigation and Control Conference, 2012
-
- Defense Sciences Study Group (DSSG), 2012-2013
 - Best Conference Poster Award, Int’l Symposium on Distributed Autonomous Robotic Systems, 2012.
 - National Academy of Sciences, Distinctive Voices Series, Irvine CA, 2012.
 - Kavli Fellow, National Academy of Science, 2011.
 - National Academy of Engineering Frontiers in Engineering Symposium, Invited Speaker, 2010.
 - Douglas Whitney Excellence in Teaching Award, Cornell University, 2010.

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Jason Hardy	0.40	
Brandon Jones	0.40	
Daniel Lee	0.20	
Mark McClelland	0.20	
Kevin Wyffels	0.40	
FTE Equivalent:	1.60	
Total Number:	5	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Mark Campbell	0.15	
FTE Equivalent:	0.15	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Scott Schlacter	0.40	Mechanical Engineering
FTE Equivalent:	0.40	
Total Number:	1	

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: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 1.00

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:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00

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

<u>NAME</u>
Total Number:

Names of personnel receiving PhDs

<u>NAME</u>	
Jason Hardy	
Frank Havlak	
Kevin Wyffels	
Mark McClelland	
Total Number:	4

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Obstacle Anticipation using Gaussian Processes

This paper presents an adaptive Gaussian Mixture Model (aGMM) formulation for performing multiple-step probabilistic state predictions using a nonparametric Gaussian Process (GP) regression model. The presented prediction algorithm is applicable to any dynamic system that is challenging to model parametrically, but where data is available. Gaussian mixture elements are propagated through the GP by analytically evaluating expectation integrals for the moments of the output distribution. Two metrics are presented and compared for adaptively splitting the initial state distribution into a sum of Gaussians to reduce the effect of nonlinearities on prediction accuracy: (1) an analytical evaluation of the excess kurtosis which measures the non-Gaussianity of the output distribution, and (2) a weighted least-squares regression model which evaluates the local nonlinearity of the GP mapping with respect to the input distribution. In addition, an on-the-fly data selection method is presented to reduce the computational complexity associated with analytically evaluating the higher-order moments of the GP output distribution. The proposed adaptive GP-aGMM formulation is applied to the case of anticipating driver behavior at road intersections using a GP driver behavior model in combination with a parametric vehicle model. Prediction performance for this scenario is evaluated using driving data collected from three human subjects navigating a standard four-way intersection. Results demonstrate that the presented prediction algorithm is capable of accurately capturing multimodal behavior in the GP training data.

Negative Information

A novel approach to utilize negative information to improve the precision and accuracy of extended multiobject tracking is presented. The parameterized probability density of object tracks undetected in sensor data is updated via inferences about the conditions necessary to result in occlusion of the undetected object. Negative information is also leveraged to inform track existence and data association, both of which contribute to a more sensible belief of the local dynamic scene. Simulation and experimental results are presented from autonomous driving scenarios, demonstrating that the use of negative information leads to a more complete, accurate, precise, and intuitive belief of the local scene, enabling high-level tasks that would otherwise be impractical.

Contingency Planning

This paper presents a novel optimization based path planner capable of planning multiple contingency paths to directly account for uncertainties in the future trajectories of dynamic obstacles. This planner addresses the particular problem of probabilistic collision avoidance for autonomous road vehicles that are required to safely interact, in close proximity, with other vehicles with unknown intentions. The presented path planner utilizes an efficient spline based trajectory representation and fast but accurate collision probability bounds to simultaneously optimize multiple continuous contingency paths in real-time. These collision probability bounds are efficient enough for real-time evaluation, yet accurate enough to allow for practical close-proximity driving behaviors such as passing an obstacle vehicle in an adjacent lane. An obstacle trajectory clustering algorithm is also presented to enable the path planner to scale to multiple-obstacle scenarios. Simulation results show that the contingency planner allows for a more aggressive driving style than non-contingency based approaches without compromising the overall safety of the robot.

Probabilistic Mapping

A terrain mapping model is proposed using a generalized Markov Random Field (MRF) representation. Unlike previous work, the proposed MRF can fully represent uncertainties due to sensor pose and measurement errors, as well as data association errors in a single model. Additionally, neither homoscedasticity nor a predefined shape of the likelihood distribution is assumed. The flexibility of an MRF model allows spatial height correlations to be incorporated. The ability to include spatial correlations not only improves the accuracy through the benefits of Bayesian prior modeling, but also serves as a basis for terrain property characterization. Maximum likelihood solutions of terrain roughness are derived. Benefits of the proposed model are demonstrated experimentally on indoor and outdoor datasets. Results show that the MRF model leads to lower height estimation errors. In addition, the capability of estimating non-Gaussian height distributions allows the information about individual terrain features to be preserved. Finally, the model is able to accurately estimate the roughness of the terrain, which is beneficial for edge detection of obstacles and non-traversable terrain regions.

Relative Mapping

This work develops a novel method for autonomous robotic navigation and mapping of large scale spaces with sparse landmarks and minimal sensing. The proposed algorithm constructs a graph-based map which encodes the relative location of landmarks in the environment. Uncertainty in these locations is captured by imposing qualitative constraints on the relationships between landmarks observed by the robot. These relationships are represented in terms of the relative geometrical layout of landmark triplets. A novel measurement method based on camera imagery is presented which extends previous work from the field of Qualitative Spatial Reasoning. Measurements are fused into the map using a deterministic approach based on iterative graph updates. Algorithm performance is evaluated using a combination of experimentally collected vision data and Monte-Carlo simulations.

Smoothing for improved perception and robustness in planning

A smoothing method for nonlinear systems using Gaussian mixture models is presented. Problems of interest include applications with highly nonlinear dynamics and/or measurement models, and sparse measurements. Two new smoothing methods are presented which incorporate adaptive Gaussian splitting in the forward path, and condensation in the backward path. A nonlinear forward-backward smoothing algorithm with Gaussian mixture models is also enabled by a novel technique to

estimate the 'backward corrector'. An experiment of a robot performing indoor navigation in a sparse featured environment demonstrates the performance of the smoothing algorithms in typical applications. Experimental results demonstrate that the new smoothing algorithms give more accurate and consistent estimates than a traditional Kalman smoother, even in the presence of a sparse featured environment and sparse measurements.

Fusion of stochastic maps

The fusion of independently obtained stochastic maps by collaborating mobile agents is considered. The proposed approach includes two parts: generalized likelihood ratio matching and maximum likelihood alignment. In particular, an affine invariant hypergraph model is constructed for each stochastic map and a bipartite matching via a linear program is used to establish landmark correspondence between stochastic maps. A maximum likelihood alignment procedure is proposed to estimate rotation, translation and scale parameters in order to construct a global map of the environment. A main feature of the proposed approach is its scalability with respect to the number of landmarks: the matching step has polynomial complexity and the maximum likelihood alignment solution is obtained in closed form. Experimental validation of the proposed fusion approach is performed using the Victoria Park experimental benchmark.

Technology Transfer

Concepts and papers from our work were regularly delivered to industry, particularly the automobile industry and the Army Research Lab, over the years of the project. This includes the probabilistic anticipation, contingency planning, and negative information work. In addition, PhD students graduated and are working for Tesla, Nissan, Bosch, and Ford.