ME 780
Nonlinear State Estimation for Robotics and Computer Vision Applications
SPRING 2017

Instructor: Professor Steven Waslander (stevenw@uwaterloo.ca)

Course Coordinator: Arun Das (adas@uwaterloo.ca)

Overview and Objectives

The course will be addressing two concepts:

1. **Nonlinear State Estimation**: Present a mathematical foundation which is required to solve state estimation problems using nonlinear models.

2. **State-of-the-art Applications**: Review the latest work within the areas of Simultaneous Localization and Mapping (SLAM), sensor calibration, visual odometry, and other robotics and computer vision applications.

Prerequisites

Students are expected to have good knowledge on linear algebra, probability theory, calculus, numerical computation, and basic knowledge of computer vision techniques.

Class Schedule

Two 1.5 hour long weekly meetings will be held in room E5-3101. Students in the class will alternate in presenting formal talks on the mathematical foundation for nonlinear state estimation and applications of said estimation to robotics, well as their own findings in simulation using real data sets. Topics for each week of lecture will be agreed upon in the first week of class, and the class is expected to take the standard 12 weeks.

Homework

Every few weeks, we will take one session to work through some homework questions. Each presenter is expected to prepare one homework problem, and will present it to the class as the end of their talk. On each homework day (see presentation schedule), the class will work through and discuss the problems for the topics covered between the previous and current homework days.

Course Outline

Foundation

1. Lie Group theory for $\mathbb{SO}(3)$ and $\mathbb{SE}(3)$, parameterizations for rotations and transformations.
2. Differential calculus of 3D orientations, representing uncertainty on $\mathbb{SO}(3)$ and $\mathbb{SE}(3)$ [1, 2].
3. Review of computer vision techniques for landmark tracking and projection [3].
4. Kinematic modeling of different vehicles [4, 5].
5. Review of probability theory, maximum likelihood estimation, maximum a posteriori estimation, linear least-squares, properties of estimators.
6. Factor graph representation, nonlinear least-squares problems on manifolds [6, 7].
7. Batch estimation, solving sparse linear systems in information and square root form [8, 9, 10].
8. Marginalization and sliding window estimation [11, 12, 13, 14].

Applications for Robotics and Computer Vision

9. Modeling IMU residual terms and noise characterization [15, 16, 17].
10. Modeling camera residual terms using landmark re-projection and photometric error [3, 18].
11. Modeling Absolute and Relative pose residual terms, point-cloud scan registration [19, 20].
12. Application: Sensor Calibration [21, 22, 23, 24].
13. Application: Landmark Based Visual-Inertial Odometry and SLAM [25, 26, 27, 28].
14. Application: Direct Visual-Inertial Odometry and SLAM [29, 18, 30, 31].
15. Application: Lidar Localization and SLAM [32, 33].

Presentation Schedule

Date	**Presenter**	**Topic Number**
May 8	Steve	1
May 9	Arun	Overview
May 15	Arun	2
May 16	Jason	3
May 22	Holiday (CAN)	
May 23	Homework	
May 29	Holiday (USA)	
May 30	WISE Lab	4
June 5	Jason + Arun	5
June 6	Nav	6
June 12	Ben	7
June 13	Leo	8
June 19	Homework	
June 20	Chris	9
June 26	Nav	10
June 27	Ben	11
July 3	Holiday (CAN)	
July 4	Jason	12
July 10	Homework	
July 11	Leo	13
July 17	Chris	14
July 18	Wise Lab	15
July 24	Homework	
July 25	Extra	

Grade Distribution

Presentation 1:	20%
Presentation 2:	20%
Conference/Journal Paper:	60%
Total:	100%

References

[1] T. Barfoot, *State Estimation for Robotics*.

[2] M. Bloesch, H. Sommer, T. Laidlow, M. Burri, G. Nuetzi, P. Fankhauser, D. Bellicoso, C. Gehring, S. Leutenegger, M. Hutter, *et al.*, “A primer on the differential calculus of 3d orientations,” *arXiv preprint arXiv:1606.05285*, 2016.

[3] R. Hartley and A. Zisserman, *Multiple view geometry in computer vision*. Cambridge university press, 2003.

[4] A. Kelly , "A vector algebra formulation of kinematics of wheeled mobile robots," Tech. Rep. CMU-RI-TR-10-33, Robotics Institute, Pittsburgh, PA, August 2010.

[5] G. Hoffmann, H. Huang, S. Waslander, and C. Tomlin, "Quadrotor helicopter flight dynamics and control: Theory and experiment," in *AIAA Guidance, Navigation and Control Conference and Exhibit*, p. 6461, 2007.

[6] F. Dellaert, "Factor graphs and gtsam: A hands-on introduction," tech. rep., Georgia Institute of Technology, 2012.

[7] R. Kümmerle, G. Grisetti, H. Strasdat, K. Konolige, and W. Burgard, "g 2 o: A general framework for graph optimization," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pp. 3607–3613, IEEE, 2011.

[8] K. Wu, A. Ahmed, G. A. Georgiou, and S. I. Roumeliotis, "A square root inverse filter for efficient vision-aided inertial navigation on mobile devices.," in *Robotics: Science and Systems*, 2015.

[9] M. Kaess, A. Ranganathan, and F. Dellaert, "isam: Incremental smoothing and mapping," *IEEE Transactions on Robotics*, vol. 24, no. 6, pp. 1365–1378, 2008.

[10] M. Kaess, H. Johannsson, R. Roberts, V. Ila, J. J. Leonard, and F. Dellaert, "isam2: Incremental smoothing and mapping using the bayes tree," *The International Journal of Robotics Research*, vol. 31, no. 2, pp. 216–235, 2012.

[11] G. Sibley, L. Matthies, and G. Sukhatme, "Sliding window filter with application to planetary landing," *Journal of Field Robotics*, vol. 27, no. 5, pp. 587–608, 2010.

[12] G. Sibley, L. Matthies, and G. Sukhatme, "A window filter for incremental slam," in *Unifying perspectives in computational and robot vision*, pp. 103–112, Springer US, 2008.

[13] G. Sibley, "Sliding window filters for slam," *University of Southern California, Tech. Rep.*, 2006.

[14] H.-P. Chiu, S. Williams, F. Dellaert, S. Samarasekera, and R. Kumar, "Robust vision-aided navigation using sliding-window factor graphs," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pp. 46–53, IEEE, 2013.

[15] J. Nikolic, P. Furgale, A. Melzer, and R. Siegwart, "Maximum likelihood identification of inertial sensor noise model parameters," *IEEE Sensors Journal*, vol. 16, no. 1, pp. 163–176, 2016.

[16] C. Forster, L. Carlone, F. Dellaert, and D. Scaramuzza, "Imu preintegration on manifold for efficient visual-inertial maximum-a-posteriori estimation," Georgia Institute of Technology, 2015.

[17] C. Forster, L. Carlone, F. Dellaert, and D. Scaramuzza, "Supplementary material to: Imu preintegration on manifold for efficient visual-inertial maximum-a-posteriori estimation," tech. rep., Technical Report GT-IRIM-CP&R-2015-001, Georgia Institute of Technology, 2015.

[18] C. Forster, M. Pizzoli, and D. Scaramuzza, "Svo: Fast semi-direct monocular visual odometry," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, pp. 15–22, IEEE, 2014.

[19] G. Sibley, "Relative bundle adjustment," 2009.

[20] A. Das, "Scan registration using the normal distributions transform and point cloud clustering techniques," 2013.

[21] G. Atanacio-Jiménez, J.-J. González-Barbosa, J. B. Hurtado-Ramos, F. J. Ornelas-Rodríguez, H. Jiménez-Hernández, T. García-Ramirez, and R. González-Barbosa, "Lidar velodyne hdl-64e calibration using pattern planes," *International Journal of Advanced Robotic Systems*, vol. 8, no. 5, p. 59, 2011.

[22] G. Pandey, J. R. McBride, S. Savarese, and R. M. Eustice, "Automatic targetless extrinsic calibration of a 3d lidar and camera by maximizing mutual information.," in *AAAI*, 2012.

[23] L. Heng, B. Li, and M. Pollefeys, "Camodocal: Automatic intrinsic and extrinsic calibration of a rig with multiple generic cameras and odometry," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pp. 1793–1800, IEEE, 2013.

[24] J. Rehder, J. Nikolic, T. Schneider, T. Hinzmann, and R. Siegwart, "Extending kalibr: Calibrating the extrinsics of multiple imus and of individual axes," in *Robotics and Automation (ICRA), 2016 IEEE International Conference on*, pp. 4304–4311, IEEE, 2016.

[25] A. I. Mourikis, N. Trawny, S. I. Roumeliotis, A. E. Johnson, A. Ansar, and L. Matthies, "Vision-aided inertial navigation for spacecraft entry, descent, and landing," *IEEE Transactions on Robotics*, vol. 25, pp. 264–280, April 2009.

[26] S. Leutenegger, S. Lynen, M. Bosse, R. Siegwart, and P. Furgale, "Keyframe-based visual–inertial odometry using nonlinear optimization," *The International Journal of Robotics Research*, vol. 34, no. 3, pp. 314–334, 2015.

[27] A. I. Mourikis and S. I. Roumeliotis, "A multi-state constraint kalman filter for vision-aided inertial navigation," in *Robotics and automation, 2007 IEEE international conference on*, pp. 3565–3572, IEEE, 2007.

[28] J. Kelly and G. S. Sukhatme, "Visual-inertial sensor fusion: Localization, mapping and sensor-to-sensor self-calibration," *The International Journal of Robotics Research*, vol. 30, no. 1, pp. 56–79, 2011.

[29] C. Forster, Z. Zhang, M. Gassner, M. Werlberger, and D. Scaramuzza, "Svo: Semidirect visual odometry for monocular and multicamera systems," *IEEE Transactions on Robotics*, 2016.

[30] J. Engel, T. Schöps, and D. Cremers, "Lsd-slam: Large-scale direct monocular slam," in *European Conference on Computer Vision*, pp. 834–849, Springer, 2014.

[31] J. Engel, V. Koltun, and D. Cremers, "Direct sparse odometry," *arXiv preprint arXiv:1607.02565*, 2016.

[32] I. Baldwin and P. Newman, "Road vehicle localization with 2d push-broom lidar and 3d priors," in *Robotics and automation (ICRA), 2012 IEEE international conference on*, pp. 2611–2617, IEEE, 2012.

[33] R. W. Wolcott and R. M. Eustice, "Fast lidar localization using multiresolution gaussian mixture maps," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, pp. 2814–2821, IEEE, 2015.