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

Instructor: Professor Steven Waslander

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.

Schedule

Two 1.5 hour long weekly meeting will be held in room TBD. 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.

Prerequisites

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

Course Outline

Foundation

1. Lie Group theory for $\mathbb{SO}(3)$ and $\mathbb{SE}(3)$, parameterizations for rotations and transformations.

2. Review of Probability theory, maximum likelihood estimation, and maximum a posteriori estimation.

3. Kinematic modeling of different vehicles [1, 2].

4. Review of computer vision techniques for landmark tracking and projection [3].
5. Differential calculus of 3D orientations, representing uncertainty on $\mathbb{SO}(3)$ and $\mathbb{SE}(3)$ [4, 5].
6. Factor graph representation, solving estimation 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

1. Modeling camera residual terms using landmark re-projection and photometric error [3, 15].
2. Modeling IMU residual terms and noise characterization [16, 17, 18].
3. Modeling Absolute and Relative pose residual terms, point-cloud scan registration [19, 20].
4. Application: Bundle Adjustment [21, 22, 23].
5. Application: Sensor Calibration [24, 25, 26, 27].
6. Application: Landmark Based Visual-Inertial Odometry and SLAM [28, 29, 30, 31].
7. Application: Direct Visual-Inertial Odometry and SLAM [32, 15, 33, 34].
8. Application: Lidar Localization and SLAM [35, 36].

Grade Distribution

Presentation 1:	20%
Presentation 2:	20%
Project Report:	60%
Total:	100%

References

[1] 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.

[2] 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.

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

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

[5] 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.

[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] 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.

[16] 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.

[17] 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.

[18] 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.

[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. Sibley, C. Mei, I. Reid, and P. Newman, "Adaptive relative bundle adjustment.," in *Robotics: science and systems*, 2009.

[22] K. Konolige and M. Agrawal, "Frameslam: From bundle adjustment to real-time visual mapping," *IEEE Transactions on Robotics*, vol. 24, no. 5, pp. 1066–1077, 2008.

[23] B. Triggs, P. F. McLauchlan, R. I. Hartley, and A. W. Fitzgibbon, "Bundle adjustmenta modern synthesis," in *International workshop on vision algorithms*, pp. 298–372, Springer, 1999.

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] 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.

[32] 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.

[33] 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.

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

[35] 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.

[36] 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.