

第 8 讲 VINS 回顾与展望

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① 课程简单回顾

从概率到最小二乘

从最小二乘到多传感器融合

最小二乘求解方法

② VIO 拓展

综述

系统

一致性

不同视觉残差模型

多传感器融合

Section 1

课程简单回顾

从概率到最小二乘

已知一堆传感器数据，如何概率建模？

传感器测量：在某个状态发生的条件下，得到一些观测，对应似然概率 $p(\mathbf{r}_i|\boldsymbol{\xi})$ 。

利用最大后验概率估计状态量：

$$\boldsymbol{\xi}_{\text{MAP}} = \arg \max_{\boldsymbol{\xi}} \prod_i p(\mathbf{r}_i|\boldsymbol{\xi}) p(\boldsymbol{\xi}) \quad (1)$$

假设观测值服从多元高斯分布：

$$p(\mathbf{r}_i|\boldsymbol{\xi}) = \mathcal{N}(\boldsymbol{\mu}_i, \boldsymbol{\Sigma}_i), p(\boldsymbol{\xi}) = \mathcal{N}(\boldsymbol{\mu}_{\boldsymbol{\xi}}, \boldsymbol{\Sigma}_{\boldsymbol{\xi}}) \quad (2)$$

则转化为最小二乘问题：

$$\boldsymbol{\xi}_{\text{MAP}} = \arg \min_{\boldsymbol{\xi}} \sum_i \|\mathbf{r}_i - \boldsymbol{\mu}_i\|_{\boldsymbol{\Sigma}_i}^2 + \|\boldsymbol{\xi} - \boldsymbol{\mu}_{\boldsymbol{\xi}}\|_{\boldsymbol{\Sigma}_{\boldsymbol{\xi}}}^2 \quad (3)$$

最小二乘的建模关键

最小二乘问题建模的两个要素：残差函数的构建，协方差矩阵计算。

$$\xi_{\text{MAP}} = \underset{\xi}{\operatorname{argmin}} \sum_i \|\mathbf{r}_i - \boldsymbol{\mu}_i\|_{\Sigma_i}^2 + \left\| \boldsymbol{\xi} - \boldsymbol{\mu}_{\xi} \right\|_{\Sigma_{\xi}}^2 \quad (4)$$

残差函数的构建

- 视觉重投影误差：视觉特征提取，匹配，几何约束。
- IMU 预积分误差：IMU 动力模型，误差模型。
- 扩展：gps 误差，轮速计误差，uwb 等等。

协方差的计算

- 噪声方差的标定，如艾伦方差标定 IMU 随机噪声的方差。
- 协方差的传递。

最小二乘问题的求解关键

最小二乘问题求解的两个要素：求解器，雅克比。

$$\mathbf{J}^T \Sigma^{-1} \mathbf{J} \delta \xi = -\mathbf{J}^T \Sigma^{-1} \mathbf{r} \quad (5)$$

求解器

- 基础：最速下降，高斯牛顿。
- 进阶：LM, DogLeg 等等。
- 高级：Schur Complement, 鲁棒核函数的实现。

雅克比

- 链式法则，雅克比矩阵的组成。
- 对 $so3, se3$ ，四元数微小增量的导数。

Section 2

VIO 拓展

综述论文推荐

一些综述性质的工作:

- 2019, arxiv, Visual-inertial navigation: A concise review¹. 全面系统的介绍了 VIO 相关研究, 值得一读.
- 2018, ICRA, A benchmark comparison of monocular visual-inertial odometry algorithms for flying robots². 全面评测了各个 VIO 系统的精度, 有待商榷.
- 2018, IROS, Tutorial on Quantitative Trajectory Evaluation for Visual(-inertial) Odometry³. VIO 精度评估工具.

¹Guoquan Huang. "Visual-inertial navigation: A concise review". In: *arXiv preprint arXiv:1906.02650* (2019).

²Jeffrey Delmerico and Davide Scaramuzza. "A benchmark comparison of monocular visual-inertial odometry algorithms for flying robots". In: *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2018, pp. 2502-2509.

³Zichao Zhang and Davide Scaramuzza. "A tutorial on quantitative trajectory evaluation for visual (-inertial) odometry". In: *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2018, pp. 7244-7251. 🔍 🔍 🔍

一些经典的 VIO 系统

基于滤波或者优化的经典 VIO 系统: 基于滤波的 VIO:

- 2017, IJRR, Iterated extended Kalman filter based visual-inertial odometry using direct photometric feedback⁴. ROVIO, 基于 EKF 和光度误差的 VIO 系统。代码开源。
- 2007, ICRA, A multi-state constraint Kalman filter for vision-aided inertial navigation⁵. MSCKF, 经典 VIO 之作。
- 2018, RAL, Robust Stereo Visual Inertial Odometry for Fast Autonomous Flight⁶. Stereo-MSCKF, 代码开源。
- 2014, THESIS, Visual-inertial odometry on resource-constrained systems⁷. MSCKF 的各种改进和完善, li mingyang 的博士论文。

⁴Michael Bloesch et al. "Iterated extended Kalman filter based visual-inertial odometry using direct photometric feedback". In: *The International Journal of Robotics Research* 36.10 (2017), pp. 1053–1072.

⁵Anastasios I Mourikis and Stergios I Roumeliotis. "A multi-state constraint Kalman filter for vision-aided inertial navigation". In: *Proceedings 2007 IEEE International Conference on Robotics and Automation*. IEEE. 2007, pp. 3565–3572.

⁶Ke Sun et al. "Robust stereo visual inertial odometry for fast autonomous flight". In: *IEEE Robotics and Automation Letters* 3.2 (2018), pp. 965–972.

⁷Mingyang Li. "Visual-inertial odometry on resource-constrained systems". PhD thesis, UC Riverside, 2014.

基于优化的 VIO:

- 2015, IJRR, Keyframe-based visual-inertial odometry using nonlinear optimization⁸. OKVIS, 最早的基于优化的 VIO 系统, 支持双目、单目。代码开源。
- 2016, TRO, On-Manifold Preintegration for Real-Time Visual-Inertial Odometry⁹. SVO + 预积分, 非常系统的从 SO3 出发推导了预积分 VIO 系统。值得一读。
- 当然还有 VINS-Mono 的相关工作已在课程中进行推荐。

⁸Stefan Leutenegger et al. "Keyframe-based visual-inertial odometry using nonlinear optimization". In: *The International Journal of Robotics Research* 34.3 (2015), pp. 314–334.

⁹Christian Forster et al. "On-Manifold Preintegration for Real-Time Visual-Inertial Odometry". In: *IEEE Transactions on Robotics* 33.1 (2016), pp. 1–21.

VIO 一致性相关的论文

可观性:

- 2008, ICRA, Analysis and improvement of the consistency of extended Kalman filter based SLAM¹⁰. FEJ 论文.
- 2011, IROS, An observability-constrained sliding window filter for SLAM¹¹. 可观性约束, 开源的 MSCKF 代码中均有使用。

不变性:

- 2015, arxiv, An EKF-SLAM algorithm with consistency properties¹². 对理解不变性非常好的一篇论文。
- 2017, IROS, An invariant-EKF VINS algorithm for improving consistency¹³. invariant-EKF VINS。

¹⁰Guoquan P Huang, Anastasios I Mourikis, and Stergios I Roumeliotis. "Analysis and improvement of the consistency of extended Kalman filter based SLAM". In: *2008 IEEE International Conference on Robotics and Automation*. IEEE, 2008, pp. 473–479.

¹¹Guoquan P Huang, Anastasios I Mourikis, and Stergios I Roumeliotis. "An observability-constrained sliding window filter for SLAM". In: *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2011, pp. 65–72.

¹²Axel Barrau and Silvere Bonnabel. “An EKF-SLAM algorithm with consistency properties”. In: *arXiv preprint arXiv:1510.06263* (2015).

¹³Kanzhi Wu et al. "An invariant-EKF VINS algorithm for improving consistency". In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2017, pp. 1578–1585.

VIO 中利用图像数据构建不同残差模型

光度误差或者点、线、面、曲线误差：

- 2016, ICRA, Direct visual-inertial odometry with stereo cameras¹⁴. 基于直接法的 VIO。
- 2018, TRO, Observability Analysis of Aided INS with Heterogeneous Features of Points, Lines and Planes¹⁵. 基于点，线，面的 VIO 系统的可观性。
- 2017, IROS, Edge-based visual-inertial odometry¹⁶. MSCKF + Edge。
- 2018, JIRS, Realtime edge based visual inertial odometry for MAV teleoperation in indoor environments¹⁷. REBVO, 代码开源。

¹⁴Vladyslav Usenko et al. "Direct visual-inertial odometry with stereo cameras". In: *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2016, pp. 1885–1892.

¹⁵Yulin Yang and Guoquan Huang. "Observability Analysis of Aided INS with Heterogeneous Features of Points, Lines and Planes". In: *IEEE Transactions on Robotics* (Aug. 2019).

¹⁶Hongsheng Yu and Anastasios I Mourikis. "Edge-based visual-inertial odometry". In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2017, pp. 6670–6677.

¹⁷Juan José Tarrio and Sol Pedre. "Realtime edge based visual inertial odometry for MAV teleoperation in indoor environments". In: *Journal of Intelligent & Robotic Systems* 90.1-2 (2018), pp. 235–252.

VIO 和其他传感器融合

激光, 码盘, gps 等多传感器系统:

- 2019, RAL, Visual-Inertial Localization with Prior LiDAR Map Constraints¹⁸. 视觉 VIO 和激光地图。
- 2018, arxiv, A General Optimization-based Framework for Global Pose Estimation with Multiple Sensors¹⁹. VINS-Mono 的扩展版, 能融合 GPS、单目、双目等信息。
- 2017, ICRA, Vins on wheels²⁰. 系统分析了 VIO + 轮速计系统的可观性, 做机器人的小伙伴值得一读。
- 2019, ICRA, Visual-Odometric Localization and Mapping for Ground Vehicles Using SE(2)-XYZ Constraints²¹. SE2-XYZ 的模型来对地面轮速机器人进行参数化, 虽然不是 VIO 系统但是也值得一读。

¹⁸Xingxing Zuo et al. "Visual-Inertial Localization with Prior LiDAR Map Constraints". In: *IEEE Robotics and Automation Letters (RA-L)* (July 2019).

¹⁹Tong Qin et al. "A General Optimization-based Framework for Global Pose Estimation with Multiple Sensors". In: *arXiv preprint arXiv:1901.03642* (2019).

²⁰Kejian J Wu et al. "Vins on wheels". In: *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2017, pp. 5155–5162.

²¹Fan Zheng and Yun-Hui Liu. "Visual-Odometric Localization and Mapping for Ground Vehicles Using SE(2)-XYZ Constraints". In: *Proc. IEEE Int. Conf. Robot. Autom (ICRA)*. 2019.

谢谢，祝好。