MSCKF系列算法的由来与研究现状

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2019.12.01

MSCKF是什么？

- Multi-State Constraint Kalman Filter
- 本质上是一个EKF，是一种视觉惯性里程计（VIO）方案
- 视觉前端分类：特征点法（basically）
- 信息融合层次：紧耦合

MSCKF试图解决的问题

- 传统的基于EKF的VIO中，状态一般为当前位姿和地图点，地图点很多，造成系统维数很大，计算量大。

- MSCKF为了降低计算量，其特殊之处在于：

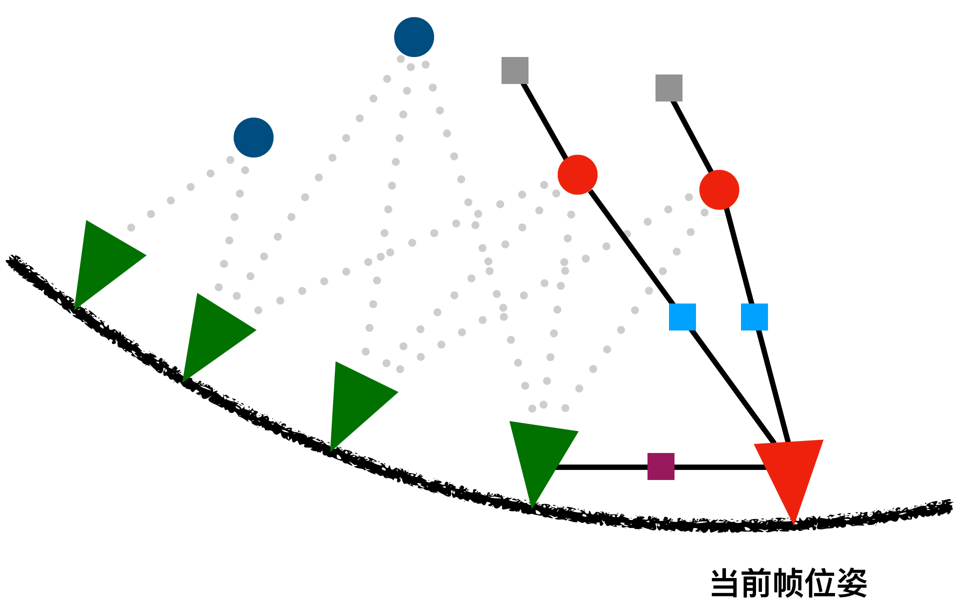
1）采用历史位姿状态增广的方式构建滤波器状态，状态中不再包括地标点；

2）利用零空间投影，从测量残差中消去不属于滤波器状态的地标点误差；

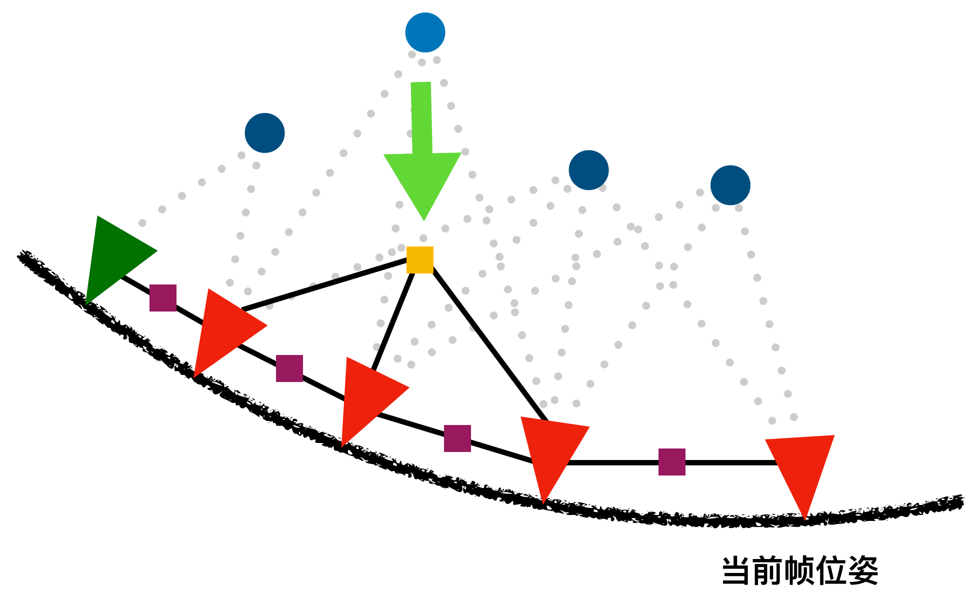
3）再次利用零空间投影，浓缩测量残差，进一步降低计算开销。

MSCKF试图解决的问题

EKF-VIO因子图示意



MSCKF因子图示意



红色图形：属于状态的节点

■ ：reprojection factor

■ ：INS propagation correlation

■ ：prior factor for landmarks

■ ：covisibility factor

SC-KF (2002)

Stergios I. Roumeliotis

MSCKF (2007)

Anastasios I. Mourikis

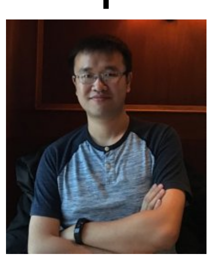
FEJ (2008)
OC-KF (2010)

Guoquan (Paul) Huang

MARS LAB

SR-ISWF (2015)
etc...

Hybrid SLAM (2013)
MSCKF 2.0 (2013)



Mingyang Li

RPNG

RVIO (2018)
Open_VINS (2019)
etc...

枯燥的论文总结开始

- [1] Mourikis, Anastasios I., and Stergios I. Roumeliotis. "A multi-state constraint Kalman filter for vision-aided inertial navigation." Proceedings 2007 IEEE International Conference on Robotics and Automation. IEEE, 2007.

MSCKF开山之作

完整的误差状态EKF模型，基于JPL四元数

active状态为当前帧对应的IMU位姿，增广状态为当前帧对应的相机位姿

误差四元数基础

- [2] Trawny, Nikolas, and Stergios I. Roumeliotis. "Indirect Kalman filter for 3D attitude estimation." University of Minnesota, Dept. of Comp. Sci. & Eng., Tech. Rep 2 (2005): 2005.

JPL四元数基础，姿态误差方程的完整推导，看过都说好

罗马不是一天建成的

- [3] Roumeliotis, Stergios I., and Joel W. Burdick. "Stochastic cloning: A generalized framework for processing relative state measurements." Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292). Vol. 2. IEEE, 2002.
- [4] Mourikis, Anastasios I., and Stergios I. Roumeliotis. "On the treatment of relative-pose measurements for mobile robot localization." Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.. IEEE, 2006.

使用状态增广/stochastic cloning以利用帧间约束的思想来源

可观性修正

- [5] Huang, Guoquan P., Anastasios I. Mourikis, and Stergios I. Roumeliotis. "Analysis and improvement of the consistency of extended Kalman filter based SLAM." 2008 IEEE International Conference on Robotics and Automation. IEEE, 2008.

提出FEJ（First Estimate Jacobian）

- [6] Huang, Guoquan P., Anastasios I. Mourikis, and Stergios I. Roumeliotis. "Observability-based rules for designing consistent EKF SLAM estimators." The International Journal of Robotics Research 29.5 (2010): 502-528.

提出OC-EKF（Observability Constrained EKF）

MSCKF 2.0

- [7] Li, Mingyang, and Anastasios I. Mourikis. "High-precision, consistent EKF-based visual-inertial odometry." The International Journal of Robotics Research 32.6 (2013): 690-711.

MSCKF 2.0：增广状态采用历史帧对应的IMU位姿；采用global的误差四元数扰动；利用FEJ修正可观性；IMU-CAM外参在线标定

Hybrid SLAM

- [8] Li, Mingyang, and Anastasios I. Mourikis. "Optimization-based estimator design for vision-aided inertial navigation." Robotics: Science and Systems. 2013.

Hybrid SLAM，将观测时间较长的地标点作为状态进行估计，传统EKF-VIO和MSCKF的混合体

传感器参数在线标定

- [9] Li, Mingyang, et al. "High-fidelity sensor modeling and self-calibration in vision-aided inertial navigation." 2014 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2014.

基于Hybrid SLAM，引入传感器在线标定，包括：

1）相机内参（内参矩阵、畸变系数）

2）Rolling Shutter效应（readout time）

3）IMU内参（非正交误差、标度因数、g-sensitivity）

4）IMU-CAM spatial and temporal calibration

适配计算量受限平台

- [10] Wu, Kejian, et al. "A Square Root Inverse Filter for Efficient Vision-aided Inertial Navigation on Mobile Devices." Robotics: Science and Systems. Vol. 2. 2015.

SR-ISWF，用平方根滤波重构Hybrid SLAM，提高算法效率

优雅的引入回环校正

- [11] DuToit, Ryan C., et al. "Consistent map-based 3D localization on mobile devices." 2017 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2017.
- [12] Geneva, Patrick, James Maley, and Guoquan Huang. "An Efficient Schmidt-EKF for 3D Visual-Inertial SLAM." Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. 2019.
- [13] Geneva, Patrick, Kevin Eckenhoff, and Guoquan Huang. "A Linear-Complexity EKF for Visual-Inertial Navigation with Loop Closures." 2019 International Conference on Robotics and Automation (ICRA). IEEE, 2019.

利用Schmidt-EKF，使得MSCKF/Hybrid SLAM具有重定位和回环功能

RPNG持续输出

- [14] Huai, Zheng, and Guoquan Huang. "Robocentric visual-inertial odometry." 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018.

R-VIO，https://github.com/rpng/R-VIO

- [15] P. Geneva, K. Eckenhoff, W. Lee, Y. Yang, and G. Huang, “Openvins: A research platform for visual-inertial estimation,” in IROS 2019 Workshop on Visual-Inertial Navigation: Challenges and Applications, Macau, China, Nov. 2019.

Open_VINS，https://github.com/rpng/open_vins

- [其他] 多IMU、多Camera、动态目标跟踪、高级特征、运动退化、多传感器融合、etc…

线特征引入

- [16] Zheng, Feng, et al. "Trifo-VIO: Robust and Efficient Stereo Visual Inertial Odometry using Points and Lines." 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018.

双目、点线特征

- [17] Yulin, Yang, et al. "Visual-Inertial Odometry with Point and Line Features." 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2019.

rpng出品，非常详尽的分析造成线特征三角化失败的退化运动、参数化方式比较

利用人造建筑的结构化特征

- [18] Zou, Danping, et al. "StructVIO: visual-inertial odometry with structural regularity of man-made environments." IEEE Transactions on Robotics 35.4 (2019): 999-1013.

Struct VIO，检测并利用人造结构中水平和垂直的线辅助VIO，基于MSCKF实现

视觉前端处理

- [19] Zheng, Xing, et al. "Photometric patch-based visual-inertial odometry." 2017 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2017.

测量残差采用光度误差而非重投影几何误差

- [20] Zhu, Alex Zihao, Nikolay Atanasov, and Kostas Daniilidis. "Event-based visual inertial odometry." 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). IEEE, 2017.

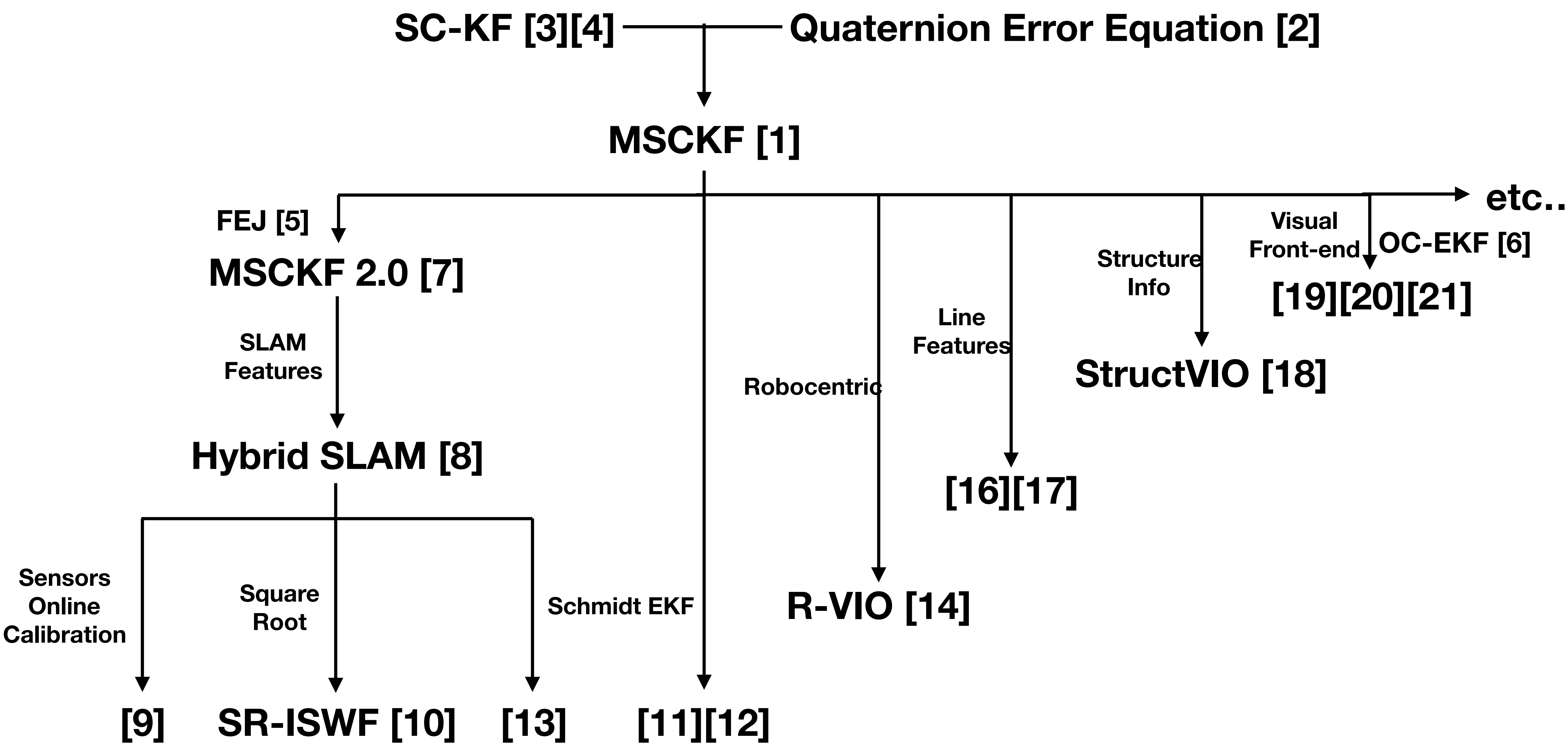
前端引入事件相机，开源了一个它所基于的单目MSCKF实现:https://github.com/daniilidis-group/msckf_mono

双目MSCKF

- [21] Sun, Ke, et al. "Robust stereo visual inertial odometry for fast autonomous flight." *IEEE Robotics and Automation Letters* 3.2 (2018): 965-972.

双目MSCKF实现，利用OC-EKF修正可观性：https://github.com/KumarRobotics/msckf_vio

简略MSCKF族谱


SC-KF [3][4]
Quaternion Error Equation [2]
MSCKF [1]
etc…
FEJ [5]
MSCKF 2.0 [7]
Visual
Front-end
OC-EKF [6]
Structure
Info
[19][20][21]
Line
Features
SLAM
Features
StructVIO [18]
Robocentric
Hybrid SLAM [8]
[16][17]
Sensors
Online
Calibration
Square
Root
Schmidt EKF
R-VIO [14]
[9]
SR-ISWF [10]
[13]
[11][12]

开源代码汇总

- MSCKF_MONO: https://github.com/daniilidis-group/msckf_mono
- MSCKF_VIO: https://github.com/KumarRobotics/msckf_vio
- R-VIO: https://github.com/rpng/R-VIO
- Open_VINS: https://github.com/rpng/open_vins

谢谢！