A General Probabilistic Framework of 3D Map Fusion for Collaborative Robots

YUE YUFENG

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirements for the degree of
Doctor of Philosophy

2018

Abstract

Utilizing a group of robots for environmental mapping, inspection or surveillance tasks have found significant attention over the last years due to the inherent advantages of robustness and efficiency. Due to limited sensing capabilities and computational power, each robot only has partial information of the surroundings. To main a comprehensive of the environment under limited communication bandwidth, fusing local 3D maps generated by individual robots to a globally consistent map is a critical challenge in multi-robot mapping missions. Most of the existing approaches are subject to certain limitations such as heterogeneous sensors, accurate matching, probabilistic merging, and inconsistency detection. This thesis proposes a systematic multi-robot mapping framework by taking those challenges into account.

First of all, the thesis proposes 3D volumetric map fusion algorithm Occupancy iterative closet point (OICP) by extending the well known iterative closest point (ICP) algorithm. The OICP algorithm combines occupancy probability in conjunction with surface information to register point cloud extracted from 3D occupancy probabilistic map, which tends to match voxels with similar occupancy probability. In addition, an environment measurement model is applied to evaluate the relative transformation and map dissimilarities are integrated using relative entropy filter. The efficiency of the proposed algorithm is evaluated using maps generated from both simulated and real environments and is shown to generate more consistent global maps.

Secondly, a hierarchical probabilistic fusion framework for matching and merging of 3D

occupancy maps is studied. Existing approaches have relied on point set registration based algorithms for map matching. However, they have not provided a comprehensive analysis of the integrated map fusion system on map uncertainty modeling, probabilistic map matching, transformation evaluation and accurate map merging. In addition, high level geometry features should be incorporated if available. The thesis addresses these issues by proposing a novel hierarchical probabilistic map fusion framework for 3D occupancy grid maps. Before the fusion of maps, the map features and their uncertainties are explicitly modeled and integrated. For map matching, a two-level Probabilistic Map Matching (PMM) algorithm is developed to include high-level structural and low-level voxel features. The relative transformation output from PMM algorithm is evaluated based on the Mahalanobis distance and the relative entropy filter is used to integrate the map dissimilarities. The results verify the accuracy and efficiency of the proposed 3D occupancy map fusion approach, and exhibit the improved convergence in these scenarios.

Finally, a distributed probabilistic framework for multi-robot mapping is proposed. There have been few works on real-time 3D map fusion with different map data type, especially merging the sparse map with the dense map. In the thesis, a general probabilistic framework is proposed to address the integrated map fusion problem, which is independent of sensor types and SLAM algorithms. The paper formulates the joint probability of the global map and the set of relative transformations between the local maps. In particular, we show that a Bayes rule based model separates the problem into an individual robot map matching problem and a multi-robot map merging problem. This makes the problem solvable for differing sensor types on the different platforms. The multiple data association method between those different types of maps provides deep insights into matching maps with the different physical and geometrical properties. The thesis also provides a distributed communication strategy to share map information among robots. The proposed approach is evaluated in real-time experiments in various environments with heterogeneous sensors, which shows its robustness and generality in 3D map fusion for multi-robot mapping missions.

Author's Publications

Journal Papers:

1. **Yufeng Yue**, Chule Yang, P. G. C. N. Senarathne, and Danwei Wang, "A General Probabilistic Framework for Dynamic Multi-Robot 3-D Map Fusion", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2018, (Under Review)

2. **Yufeng Yue**, P.G.C.N. Senarathne, Chule Yang, Jun Zhang, Mingxing Wen, and Danwei Wang, "Hierarchical Probabilistic Fusion Framework for Matching and Merging of 3D Occupancy Maps" , *IEEE Sensor Journal*, 2018, (Under Review)

3. Yuanzhe Wang, Mao Shan, **Yufeng Yue**, and Danwei Wang, "Flexible Leader-Follower Formation Analysis and Tracking Control of Multiple Nonholonomic Mobile Robots Using Relative Pose Measurements", *IEEE Transactions on Control Systems Technology*, 2018, (Under Review)

4. Chule Yang, **Yufeng Yue**, and Danwei Wang, "Probabilistic Reasoning for Unique Role Recognition Based on the Fusion of Semantic-Interaction and Spatio-Temporal Features", *IEEE Transactions On Multimedia*, 2017, (Under Review)

5. Chule Yang, Danwei Wang, Yijie Zeng, **Yufeng Yue**, Prarinya Siritanawan , and "Multimodal Information Fusion for Human-Oriented Context Awareness Using Mobile Robot", *Information Fusion*, 2017, (Under Review)

Conference Papers:

1. **Yufeng Yue**, P.G.C.N. Senarathne, Chule Yang , Jun Zhang, Mingxing Wen and Danwei Wang, "Probabilistic Fusion Framework for Collaborative Robots 3D Mapping", *21st International Conference on Information Fusion*, Cambridge, 2018. (accepted)

2. **Yufeng Yue**, Chule Yang , P.G.C.N. Senarathne, Jun Zhang, Mingxing Wen and Danwei Wang, "Online Collaborative 3D Mapping in Forest Environment", *IEEE International Conference on Robotics and Automation (ICRA) workshop*, Brisbane, 2018.

3. **Yufeng Yue**, D. Wang, P. G. C. N. Senarathne and C.Yang, " A General Framework for Distributed Multi-Robot 3-D Map Fusion," *IEEE International Conference on Robotics and Automation (ICRA) workshop*, Singapore, 2017.

4. **Yufeng Yue**, D. Wang, P. G. C. N. Senarathne and C.Yang, " Robust Submap-Based Probabilistic Inconsistency Detection for Multi-Robot Mapping," *2017 European Conference on Mobile Robotics (ECMR)*, Paris, 2017.

5. C Yang, Y Zeng, **Yufeng Yue**, J Zhang, DW Wang, Knowledge-Based Role Recognition by Using Human-Object Interaction and Spatio-Temporal Analysis, *2017 IEEE Conference on Robotics and Biomimetics (ROBIO)*, Macau, 2017. **Final List of Best Student Paper Award**

6. **Yufeng Yue**, D. Wang, P. G. C. N. Senarathne and D. Moratuwage, "A hybrid probabilistic and point set registration approach for fusion of 3D occupancy grid maps," *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Budapest, 2016.