FORMATION CONTROL OF MULTI-ROBOT SYSTEMS IN OBSTACLE ENVIRONMENTS

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

2018

Abstract

Multi-robot system has wide applications in both civil and military fields, due to its high efficiency for task completion and robustness with respect to robot failures. Formation keeping, which is one of the main objectives for multi-robot control, has been investigated extensively in the past decade, resulting in a large variety of methodologies. However, most of the existing approaches are subject to certain limitations when implemented for addressing real formation control problems, mainly due to additional constraints introduced, such as sensor limitations, obstacle and inter-robot collision avoidance in unknown environments, connectivity maintenance, unavailability of global pose measurements and so forth. This thesis deals with formation control problem for real robot applications by taking practical constraints into account.

First of all, virtual-structure based formation tracking control is studied, where obstacle and inter-robot collision avoidance as well as connectivity maintenance are explicitly considered. To address this problem, a multi-region control scheme is proposed, where three regions, safe region, dangerous region and transition region, are defined. In different regions, priority is given to different control objectives. In safe region where trajectory tracking holds the priority, the proposed control scheme guarantees bounded reference tracking for each robot. In dangerous region where avoidance control is the main objective, a new bounded potential function is designed to formulate multiple constraints. By introducing a series of transition functions, smooth switching between trajectory tracking and avoidance control is

achieved in transition region. It has been proven that each robot can track its reference trajectory while satisfying the constraints simultaneously with a bounded controller, implying that the proposed control scheme satisfies input constraints by properly tuning parameters.

Secondly, vision-based leader-follower formation tracking control is investigated, while sensor limitations, obstacle and inter-robot collision avoidance and leader-loss situation are considered and tackled in the proposed algorithm. For leader tracking, a class of bounded barrier functions are employed to formulate distance and bearing angle constraints introduced by sensor limitations and leader-follower collision avoidance requirement. To ensure robot safety in unknown environments, a multi-region obstacle avoidance algorithm is proposed which prioritizes different control objectives in different regions. The leader-loss situation has also been studied, which may be caused by illumination variation, motion blurring or visual occlusion by obstacles. To deal with this case, a fault-tolerant strategy is designed to drive the follower to the place where the leader was lost immediately. The proposed control scheme is primarily designed for a communication-free environment where only local pose measurements are available. Furthermore, it has control input constraints explicitly taken into account.

Finally, flexible leader-follower formation tracking control is addressed, while most of formation control related work in the literature focuses on rigid formation. To illustrate the superiority of flexible formation against traditional rigid formation in terms of motion capability, a mathematically rigorous analysis is presented from the motion planning perspective on the basis of the definition of *formation flexibility*. Unlike the previous studies on flexible formation control, this work is under a more challenging assumption that global position and orientation measurements are not available. To obtain the relative pose relationships amongst robots, a stereo camera is mounted on each follower. In consideration of the fact that visual observations are noise-corrupted and intermittently available, a particle filter based relative pose estimation approach is employed to estimate the position and orientation of the leader in the local reference frame of the follower using the polluted and discontinuous information. Also, to form a flexible formation, the leader historical trajectory is reconstructed with respect to the current local frame attached on the follower, based on which a reference point is generated. In addition, the situation where robots work in unknown obstacle environments is considered. To ensure robot safety in such environments, a multi-objective control law is proposed to balance reference tracking and collision avoidance in different situations.

In summary, this thesis provides three feasible formation control strategies for multi-robot systems from the viewpoint of practical applications. All of the proposed approaches are well supported by both numerical simulations and real robot experiments.

Author's Publications

Journal Papers:

1. **Y. Wang**, D. Wang, S. Yang, and M. Shan, "A Practical Leader-Follower Tracking Control Scheme for Multiple Nonholonomic Mobile Robots in Unknown Obstacle Environments," *IEEE Transactions on Control Systems Technology*, DOI: 10.1109/TCST.2018.2825943.

2. **Y. Wang**, D. Wang, and S. Zhu, "Formation tracking of multi-vehicle systems in unknown environments using a multi-region control scheme," *International Journal of Control*, vol. 90, no. 12, 2760-2771, 2017.

3. **Y. Wang**, D. Wang, and S. Zhu, "A New Navigation Function Based Decentralized Control of Multi-Vehicle Systems in Unknown Environments," *Journal of Intelligent & Robotic Systems*, vol. 87, no. 2, 363-377, 2017.

Conference Papers:

1. **Y. Wang**, and D. Wang, "Non-singular moving path following control for an unmanned aerial vehicle under wind disturbances," *Decision and Control (CDC), 2017 IEEE 56th Annual Conference on*, Dec. 2017, pp. 6442-6447.

2. **Y. Wang**, D. Wang, and B. C. Ng, "Finite time moving target tracking using

nonholonomic vehicles with distance and bearing angle constraints," *American Control Conference (ACC)*, May 2017, pp. 2962-2967.

3. **Y. Wang**, D. Wang, and E. Mihankhah, "Navigation of multiple mobile robots in unknown environments using a new decentralized navigation function," in *Control, Automation, Robotics and Vision (ICARCV), 2016 14th International Conference on*, Nov. 2016.

Papers in Review:

1. **Y. Wang**, M. Shan, Y. Yue, and D. Wang, "Flexible Leader-Follower Formation Analysis and Tracking Control of Multiple Nonholonomic Mobile Robots Using Relative Pose Measurements," *IEEE Transactions on Control Systems Technology*, (under review).

2. **Y. Wang**, D. Wang, and S. Zhu, "Cooperative Moving Path Following for Multiple Fixed-Wing Unmanned Aerial Vehicles with Speed Constraints," *Automatica*, (under second round of review).