Ultra-wideband-based Navigation for Unmanned Aerial Vehicles

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Abstract

Micro unmanned aerial vehicles (UAVs) play more and more important roles in both civilian and military applications. Currently, the navigation and control of UAVs is critically dependent on the localization service provided by the Global Positioning System (GPS), which suffers from the multipath effect and blockage of line-of-sight, and fails to work in an indoor, forest or urban environment. Therefore, how to achieve positioning in a spatially restricted area or dense environment, say woods, multi-functional office or urban canyons, with sufficient localization accuracy which can support autonomous flight is a worthy research topic. This thesis concentrates on GPS-denied localization for UAVs by leveraging a radio frequency (RF) technology- ultra-wideband (UWB) signal. We shall devise algorithms and develop systems for localization and apply the estimates to multi-UAV formation control.

In the first part of this thesis, we establish a localization system for UAVs based on UWB ranging measurements, and each UAV is able to estimate its own global positions in a customized reference frame. To achieve the localization, a UWB module is installed on the UAV to actively send ranging requests to some fixed UWB modules at known positions (a.k.a. anchor nodes). Once a distance is obtained, it is calibrated first and then goes through outlier detection before being fed to a localization algorithm. The localization algorithm is initialized by trilateration and sustained by the ex-

tended Kalman filter (EKF). Afterwards, the position and velocity estimates produced by the algorithm will be further fed to the control loop to aid the navigation of the UAV. Flight tests in different environments have been conducted to validate the performance of our UWB based localization system with anchor nodes.

However, in many operation environments, it is impractical to have fixed anchor nodes due to large operational scale and area. Moreover, the accuracy of anchors' positions will greatly affect the positioning accuracy of UAV. To reduce human labor and human-induced errors, in the second part of this thesis, we study the active relative localization (RL) problem of a mobile UAV on 2D plane to a static UAV (beacon) under motion constraint, using the self-displacement and UWB ranging measurements. In practice, due to the environment or task constraint, a UAV may only be allowed to travel a small distance to fulfill the RL. We find a lower bound of mean square error in terms of this small distance and the sample size. As revealed from the lower bound, it only needs to enlarge the ranging span from the starting point to the ending point and increase the number of rangings to reduce the estimation error of initial relative position, which is related to and extends the existing results of unconstrained optimal sensor placement. In this light, we design an algorithm to actively reduce the localization error along the ranging path by incrementally enlarging the ranging span, and apply EKF to account for the noise in the displacement measurements. Simulations and flight experiments have been conducted to validate our proposed RL strategy.

With the booming development of low-cost micro UAV such as quadcopter, multi-UAV systems and relevant applications have been extensively studied recently, and most of the proposed multi-agent controllers rely on inter-agent relative positions which are assumed to be measurable. However, in practice, the relative position is difficult to obtain and so far there exists no comerial product for UAV to measure this information. In addition, most of existing formation experiment results including both simulation and actual flight still depend on some external infrastructure for positioning. Therefore, the third part of this thesis puts forth a simultaneous infrastructure-free cooperative RL and distributed formation control strategy for UAVs in GPS-denied environments. Instead of estimating relative coordinates by detecting specific patterns using image processing methods, an onboard UWB ranging and communication (RCM) network is adopted to sense both the inter-UAV distance and exchange information for RL estimation. Without any external infrastructures prepositioned, each agent cooperatively performs the proposed consensus-based fusion method, which fuses the developed direct and indirect RL estimates, to generate the relative positions to its neighbours in real time despite the fact that some UAVs may not have direct range measurements to their neighbours. The RL estimates together with the relative velocity and inter-UAV distance measurements are used to control a UAV swarm. Both the cooperative RL and the formation control are implemented in a distributed fashion. Extensive real-world flight tests corroborate the merits of the developed simultaneous RL and formation control system.

Author's Publications

Journal papers:

1. **K. Guo**, Z. Qiu, C. Miao, A. H. Zaini, C.-L. Chen, W. Meng, and L. Xie, "Ultra-wideband-based Localization for Quadcopter Navigation," *Unmanned Systems*, vol. 4, no. 01, pp. 23-34, 2016.

2. **K. Guo**, Z. Qiu, W. Meng, L. Xie, and R. Teo, "Ultra-wideband Based Cooperative Relative Localization Algorithm and Experiments for Multiple UAVs in GPS-denied Environments," *International Journal of Micro Air Vehicles*, vol. 9, no. 3, pp. 169-186, 2017.

3. **K. Guo** and L. Xie, "Infrastructure-free Cooperative Relative Localization for Unmanned Aerial Vehicles in GPS-denied Environments," *International Journal of Robotics and Automation*, accepted, 2017.

4. **K. Guo**, X. Li and L. Xie, "Ultra-wideband-based Cooperative Relative Localization and Distributed Formation Control for UAVs," to be submitted.

5. Z. Han, **K. Guo**, L. Xie and Z. Lin, "Integrated Relative Localization & Leader-Follower Formation Control," *IEEE Transactions on Automatic Control*, regular paper, 2018.

Conference papers:

1. **K. Guo**, D. Han, and L. Xie, "Range-Based Cooperative Localization with Single Landmark," in Proceedings of *the 13th IEEE International Conference on Control and Automation (ICCA)*, July 3-6, Ohrid, Macedonia, 2017, pp. 588-593.

2. **K. Guo**, Z. Qiu, W. Meng, and L. Xie, "Relative Localization for Quadcopters using Ultra-wideband Sensors," *International Micro Air Vechicle Competition and Conference (IMAV)*, Beijing, China, Oct. 2016, pp. 243-248. Best paper finalist.

3. **K. Guo** and L. Xie, "Infrastructure-free Cooperative Relative Localization for Unmanned Aerial Vehicles in GPS-denied Environments," *IEEE International Conference on Unmanned Systems (ICUS)*, Beijing, China, Oct. 2017. Best paper award.

4. T. M. Nguyen, A. H. Zaini, **K. Guo**, and L. Xie, "An Ultra-wideband based Multi-UAV Localization System in GPS-denied Environments," *International Micro Air Vechicle Competition and Conference (IMAV)*, Beijing, China, Oct. 2016, pp. 56-61. Best paper finalist.

5. T. M. Nguyen, A. H. Zaini, C. Wang, **K. Guo**, and L. Xie, "Robust Target-relative Localization with Ultra-Wideband Ranging and Communication," *IEEE International Conference on Robotics and Automation (ICRA)*, accepted, 2018.