RANGING-BASED ADAPTIVE NAVIGATION FOR AUTONOMOUS MICRO AERIAL VEHICLES

THESIS ABSTRACT

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Recent decade has witnessed a surge in popularity of Micro Aerial Vehicles (MAVs) with applications in many civilian, industrial and military applications. Essentially, for successful maneuver of MAVs, or mobile robots in general, two problems need to be adequately addressed: localization and navigation, or estimation and control in a more general sense. Most commonly we find that these two problems are addressed in separate manner, whereas localization capability is usually the primal assumption, upon which different navigation strategies can be developed. While this approach may facilitate convenient solution and analysis, it also brings about several limitations. On one hand, for long-range operations of MAVs, or cooperative operations involving a large number of MAVs, while the most viable option for localization would be some artificially installed localization infrastructure, applications based on these system have low adaptability to different and complex environments. On the other hand, by employing only onboard sensors, visual navigation techniques can offer a much more flexible method for MAV localization in GPS-denied environments. However, vision-based techniques tend to suffer from long-term estimation drift. Moreover, they are only effective for single MAV application. In multi-MAVs operations, since each visual localization system uses a different frame of reference, collaborative operations between the MAVs wouldn't be possible if there is no prior knowledge to convert the position information from one frame to another. These imitations motivate the research in this thesis to seek new methods for operation of MAVs with minimal deployment cost and adequate flexibility.

Inspired by the aforementioned issues, the objective of this thesis is to develop an integrated estimation-control scheme that can achieve a high level of flexibility, portability and practicality for autonomous navigational tasks of MAVs in GPS-denied environment. As a first expedition into this direction, a sensor fusion scheme is proposed to achieve relative positioning and tracking of a target by MAV using Ultra-wideband (UWB) ranging sensors strategically installed on both the MAV and the target. To achieve robust localization for autonomous flight even with uncertainty in the speed of the target, two main features are developed. First, an estimator based on Extended Kalman Filter (EKF) is developed to fuse UWB ranging measurements with data from onboard sensors including inertial measurement unit (IMU), altimeters and optical flow. Second, to properly handle the coupling of the target's orientation with the range measurements, UWB based communication capability is utilized to transfer the target's orientation to the quadcopter. Experiment results demonstrate the ability of the quadcopter to control its position relative to the target autonomously in both cases when the target is static and moving.

While the aforementioned sensor fusion scheme can offer reliable and robust target tracking capability, it may not be effective for long range navigation task. Thus a new problem with the objective of navigating a MAV to desired location while estimating its position relative to a single static landmark is studied. In this investigation a relative localization algorithm was developed to estimate the position of the MAV relative to the landmark by using only distance and displacement measurements. Since these measurements can be easily obtained from generic but efficient

ranging and vision-based self-localization techniques, the estimation-control scheme can achieve independence from extensive external localization system, thus can be adopted in many environments (portability) without incurring high setup and maintenance cost (flexibility). Based on this estimation, a control scheme is delicately designed to ensure asymptotic convergence of the estimation as well as the docking objectives. Regarding practicality, to ensure maximal compatibility with real-world implementation, all dynamics, estimation and control processses are directly formulated and analysed under a discrete-time framework. Moreover, to avoid overburdening the physical system, constraint on bounded control input is also considered in the design of the control law. By employing discrete-time LaSalle's invariance principle, asymptotic convergence of the navigation task can be established in the noise-free case, and the stability under distance measurement noise is also investigated. Comprehensive simulation and real-world experiments are conducted to demonstrate the efficiency of our method.

Based on the investigations on sensor fusion for target tracking and single landmark navigation, the two ranging-based relative localization scheme is further extended and combined in an autonomous docking of MAV on moving target. Though vision-based techniques have become quite popular for autonomous docking of MAVs, due to limited field of view (FOV), the MAV must rely on other methods to detect and approach the target before vision can be used. A method combining sequential ranging of Ultra-wideband sensor with vision-based techniques is developed to achieve both autonomous approaching and landing capabilities in GPS-denied environments. In the approaching phase, an exponentially convergent recursive least-square optimization algorithm is proposed to estimate the position of the MAV relative to the target by using the distance and relative displacement measurements. Using this estimate, MAV is able to efficiently approach the target until the landing pad is detected by an onboard vision system, then UWB measurements and vision-derived poses are fused with onboard sensor of MAV to facilitate an accurate landing maneuver. Real-world experiments are conducted to demonstrate the efficiency of our method.

So far the aforementioned problems only focus on navigation of single MAV. However, compared with a single MAV, a team of MAVs will increase the efficiency in carrying out cooperative tasks such as mapping, inspection or coverage. In logistics, a MAV team can also be used to transport a payload to some locations that ground robots cannot access. While there are many works discussing multi-UAV navigation and coordination strategies using relative position or bearing measurements, the practicality of these strategies is uncertain as direct measurement of relative states is a strong assumption from a technological point of view. This motivated us to apply the distance-displacement based relative localization technique to such cooperative multi-robot schemes. Specifically, we investigate the problem of controlling a multi-robot team to follow a leader in formation, supported by relative position estimate derived from distance and self-displacement measurements. The main challenge of the problem, which is to simultaneous fulfill both relative localization and control tasks, is efficiently resolved by embedding a distance-based *persistently excited adaptive relative localization* technique into a *time-varying formation* with bounded control input (PEARL-TVF). By assuming that the leader is globally reachable and selecting proper parameters, it is shown that PEARL-TVF ensures exponentially convergent localization, which leads to exponentially convergent formation when the leader's behavior is deterministic, and bounded formation error for a non-deterministic leader. Extensive numerical simulations and real-world implementations are carried out to verify the theoretical results and demonstrate the efficacy as well as effectiveness of the proposed method.

Publications

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