Swarming tight interactions for achieving resistibility of large robotic systems in real-world conditions

Jiri Horyna[1*], Martin Saska[1]

Abstract— **This paper presents an autonomous swarm system designed to be an enabling technology for achieving resilience to both partial and complete dropouts of localization of individual vehicles in large teams. The challenge of creating a resilient swarm system across diverse mission types is closely tied to maintaining accurate state awareness, regardless of changing environmental conditions and external threats like jamming and spoofing of primary localization data. Leveraging purely relative measurements and onboard sensor data to ensure accurate state awareness despite intermittent localization failures is extremely important for enhancing security, resilience, and safety of cooperating systems including edge autonomous devices. By combining approaches increasing resilience during both partial and complete localization dropouts, the paper bridges the gap in enhancing the resilience of drone swarm operations, allowing them to adapt dynamically across a wide range of mission types. Herein, we introduce and discuss the description and results of these state-of-the-art distributed state estimation techniques, which significantly strengthen swarm system security against vulnerabilities posed by emerging threats.**

I. Introduction

Achieving secure state estimation in aerial autonomous systems across a variety of mission types and real-world environmental conditions is a challenging task. It involves designing a system that is both versatile and adaptive, as well as responsive to external threats. External localization architectures, such as the Global Navigation Satellite System (GNSS), may be unavailable or unsuitable due to issues like low accuracy and unreliability in urban environments. Moreover, without proactive security algorithms, these techniques are vulnerable to interference, jamming, or spoofing. In UAV research, various self-localization approaches, such as Simultaneous Localization and Mapping (SLAM) [1] algorithms and Visual-Inertial Odometry (VIO) [2], have been developed to stabilize and navigate robots in GNSS-denied environments. However, regardless of the primary localization source, onboard state estimation accuracy can temporarily decrease due to factors like computational singularities, environmental characteristics, or unexpected sensor malfunctions. For instance, the accuracy of methods relying on optical cameras can be significantly compromised by homogeneity in the camera image (Fig. 1).

Our solution to these bottlenecks that prevent direct use of these techniques in zero trust multi-robot architectures is based on decentralized and distributed state estimation frameworks that combine the primary localization source with onboard observations of surrounding agents. This approach ensures stable flight even when confidence in the primary localization decreases, such as when an external threat is detected. These independent frameworks enhance the swarm system's resilience against undesirable and uncontrollable negative effects, whether they impact only a subset of agents or the entire swarm.

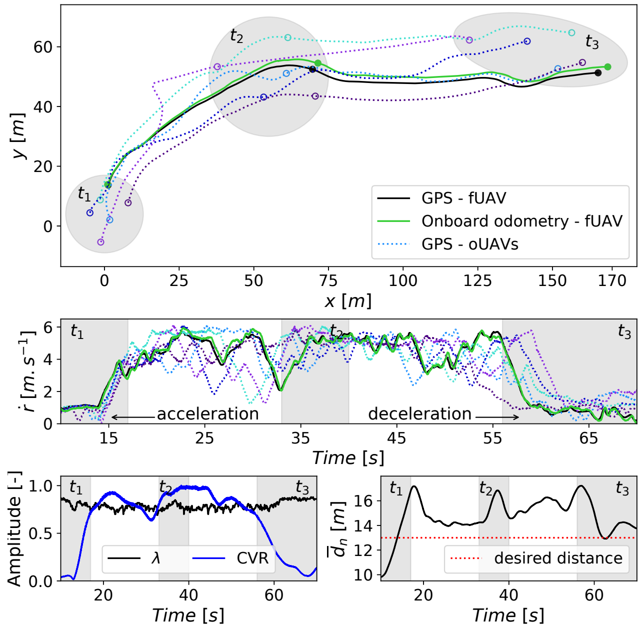
[1] are with Multi-Robot Systems Group, Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, Prague, Czech Republic
*corresponding author, horynjir@fel.cvut.cz

Fig. 1: In a feature-poor environment, a multi-UAV system faces challenges since onboard visual or LiDAR localization may not be feasible as an alternative to GNSS localization. This scenario requires innovative approaches to maintain accurate positioning and state estimation despite the lack of environmental features to aid in navigation.

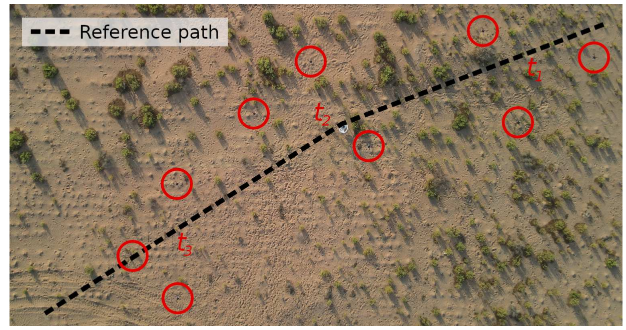
II. Partial degradation of primary localization performance

Herein, we focus on a system designed to resist partial localization dropouts of individual robots or even subgroup of robots due to spatial unavailability of localization modalities. This system integrates robust mutual perception mechanisms and shared measurements into the closed-loop primary state estimation pipeline. Such an approach enables the swarm to continue its mission even when localization dropouts occur among a subset of edge drone agents.

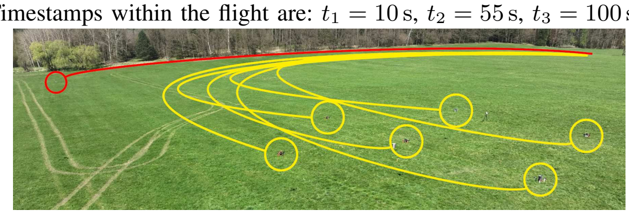
Specifically, our Multi-robot State Estimation (MRSE) during partial degradation of primary localization performance relies on fusing primary localization data (e.g., GNSS, VIO) with Inertial Measurement Unit (IMU) readings and a robust onboard mutual perception system that estimates the distance and bearing of surrounding agents. Building on previous studies [3], [4], our work presents a comprehensive distributed state estimator architecture integrated into the closed-loop state estimation and control pipelines. This architecture is grounded in modeling the movements of surrounding agents. The model-based estimated positions of these agents serve as floating localization anchors for the focal UAV when it faces emerging threats or singularity in



(a) Swarm approaching a static goal. Swarm UAVs' positions, velocities, and qualitative parameters are displayed. $\overline{d}_n = 15.12\,\mathrm{m}$ with standard deviation $5.07\,\mathrm{m}$. GNSS is used as a ground truth, only.



(b) Flocking of three UAVs with the proposed lateral estimator. Fusion coefficients are determined onboard according to the confidence in the accuracy of the optical flow velocity of a particular UAV. Timestamps within the flight are: $t_1 = 10\,\mathrm{s}$, $t_2 = 55\,\mathrm{s}$, $t_3 = 100\,\mathrm{s}$.



(c) A swarm of six UAVs (yellow) using the proposed approach. The group velocity of $5\,\mathrm{m\,s^{-1}}$ was reached, while the swarm stayed coherent without reliance on GNSS and communication.

Fig. 2: Demonstration of multi-robot state estimation approach in GNSS-denied feature-poor environments.

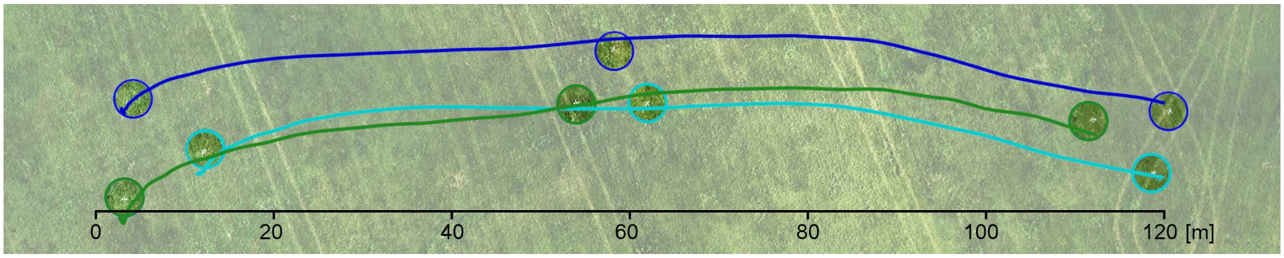
onboard state estimate. The focal UAV uses these floating anchors and an onboard mutual visual perception system to estimate its state. The multi-robot state estimate is further enhanced by fusing it with IMU data, ensuring robustness during agile maneuvers. Final resilience of the UAV state estimate is achieved by adaptively fusing the multi-robot state estimate with the primary state estimator, based on the monitored confidence in the primary state estimate. By integrating and refining collective measurements, the system compensates for individual inaccuracies, thereby enhancing overall performance. To further improve the robustness of surrounding agents' model, we incorporate an approach for estimating the immeasurable velocities of surrounding UAVs based on observed swarming behavior, making communication an optional modality.

III. Global loss of primary localization performance

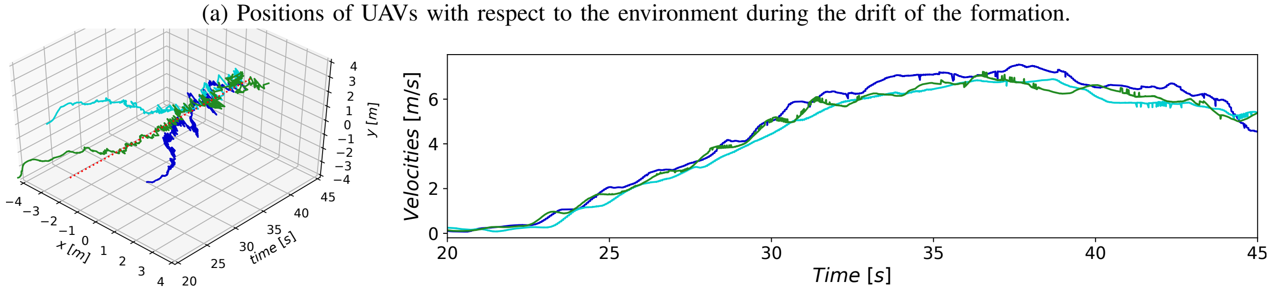
The second part of the paper examines state-of-the-art techniques aiming at achieving state estimation during global loss of primary localization performance. It is designed to enhance the resilience of swarm systems by proactively responding to known or emerging threats, relying solely on relative measurements. Our method integrates decentralized state estimation techniques with robust mutual perception mechanisms and onboard sensor data to maintain accurate state awareness despite intermittent localization failures. It employs an onboard mutual perception system to determine the relative positions of neighboring agents, which are used to define an unambiguous reference frame within the local constellation. This unambiguous definition of a floating reference frame enables precise estimation of the focal UAV's state relative to the local constellation. Disturbances affecting individual drones are mitigated through a distributed high-level control law, ensuring stability among surrounding agents. Our solution demonstrates how a robot swarm adapts more effectively to localization dropouts than a single agent, which is particularly crucial in GNSS-denied environments lacking significant localization features, as shown in Fig. 3b. Compared to a single-drone scenario, the proposed purely relative state estimation and control strategy allows a team of UAVs to continue their mission even during global localization dropouts or during external attempt to break through state estimation security. Although the overall multi-robot system is not jointly observable with respect to the environment, leading to formation drift, any drift other than uniform translation of the swarm as a whole is attenuated. This behavior facilitates velocity consensus among the UAVs, effectively addressing the double integrator synchronization problem.

IV. Experimental results

The experiments were designed to validate the system's functionality in realistic GNSS-denied, feature-poor environments, a critical step for identifying and addressing system bottlenecks in future development. A F4F F450 quadcopter equipped with a Pixhawk autopilot, a rangefinder for precise altitude control, and a downward-facing camera for VIO was used (for more details on the UAV setup, see [5]). The system also featured an onboard relative perception system to estimate the positions of surrounding agents relative to the focal agent. In Fig. **??**, UVDAR [6], [7] was employed for



(a) Positions of UAVs with respect to the environment during the drift of the formation.



(b) Left: positions of UAVs converge to the origin of their control frames. Right: ground velocities of UAVs.

Fig. 3: Experiment with 3 UAVs during a global localization dropout. Despite the swarm drifting, the constellation is maintained through state estimation using relative measurements.

mutual perception; however, any onboard mutual perception system can be integrated with the introduced state estimation approaches. All control [8], estimation, and planning computations were conducted onboard an Intel NUC-i7 with embedded WiFi for optional communication, utilizing the Robot Operating System (ROS).

The introduced multi-robot state estimation strategy was successfully tested in feature-poor environments, such as a desert and plain grass field, under conditions of partial state estimation performance degradation caused by uniformity in the VIO camera image. Specifically, as shown in Fig. 2c and Fig. 2a, the UAVs used VIO fused with the multi-robot state estimator for self-localization and UVDAR for mutual perception and collision avoidance. The swarm covered over 200 meters with an average velocity of $5.0, \mathrm{m.s}^{-1}$. The rapid movement above the grass surface made VIO feature tracking more challenging, reducing confidence in VIO localization and leading to increased reliance on the multi-robot state estimator (MRSE), as indicated by a lower coefficient λ. Videos: `http://mrs.felk.cvut.cz/iros-2022-estimation`, `https://mrs.fel.cvut.cz/ral-2023-demo`.

The resilience against the entire global localization loss was tested using three UAVs hovering at a desired height (see Fig. 3a). Initially, the UAVs relied on GNSS for self-localization. Then, all onboard state estimators were switched to the introduced state estimation method, which uses only relative measurements. This setup simulated the emerging threat of GNSS jamming, leaving the UAVs without world frame position and velocity data. Despite this, the swarm flew over 100 meters (Fig. 3a), with drift velocity increasing to $7\,\mathrm{m.s}^{-1}$ (Fig. 3b), and successfully completed the experiment without collisions, maintaining cohesion through relative measurements alone. The UAVs' relative positions converged to the origin of their floating frames (Fig. 3b), in line with the intended design of the state estimator and feedback control approach. Video: `https://youtu.be/kPiOdsPKh-U?si=HHr9xecnXYJaZM2S`.

V. CONCLUSION AND FUTURE WORK

This paper has presented an autonomous swarm system designed to enhance resilience in large teams of UAVs, particularly in scenarios where individual vehicle localization is partially or completely lost. By focusing on the use of purely relative measurements and onboard sensor data, we have demonstrated a robust approach to maintaining accurate state awareness, even in the face of environmental challenges and external threats such as jamming and spoofing. The combination of state-of-the-art distributed state estimation techniques introduced here significantly improves the security, resilience, and safety of cooperating systems, making them better suited to dynamically adapt across a wide range of mission types.

Our future work will focus on integrating this resilient state estimation system into a fully secured multi-UAV framework, with particular attention to edge cases where no sensory information is available. This will include incorporating AI algorithms for enhanced threat detection and mitigation, as well as designing coordinated mechanisms that enable a collective swarm response to emerging threats. Additionally, the system will be generalized to support heterogeneous multi-robot teams with varying dynamics, further broadening its applicability. Secure communication protocols will also be developed to ensure that data integrity is maintained, and information is utilized only when it is both available and trustworthy. This ongoing research will continue to push the boundaries of resilience and security in autonomous swarm operations, addressing the ever-evolving challenges posed by complex environments and adversarial threats.

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