

# UAV backtracking home by active visual landmarks-based localization

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**Abstract.** This research statement describes how the problem of visual backtracking home for UAVs became vital for different applications: what limitations the use cases place and how it narrows the available means of solving the problem. Given constraints, the author proposes a two-stage approach to solve this task in practice. The first stage is the operation field route observation and building a navigation graph of the visual Points Of Interest (POI). As the target condition includes a GPS-denial environment with a visually ambiguous appearance, we propose to use topological mapping instead of metric. We can perform backtracking in the second phase with a constructed POI graph. The backtracking problem would need an active localization strategy to ensure a successful and safe return to the base station.

**Keywords:** Active localization · Outdoor localization · UAV · Autonomous flight · Point of interest · GPS-denied operation · Topological mapping

## 1 Introduction

Throughout technological history, breakthrough ideas initially aimed at scientific and aerospace applications later permeated wide consumer use. However, post-Cold War, the trend reversed, with consumers fostering cutting-edge advancements, spurring IoT, GPU computing, and robotics. While domestic autonomous devices like vacuum cleaners are now commonplace, translating these into scientific and aerospace fields is not seamless. Meanwhile, commercial drones have rapidly transitioned from entertainment and agriculture to the military sphere, sparking interest in adapting civil technology for broader use in aerospace research.

GPS-based navigation's reliability led to a bias and missing alternatives. In jammed GPS scenarios, UAVs depend on operators' visibility. Backup systems rely on internal sensors, while primary visual navigation falters. Developing a robust method to recover UAVs from signal loss becomes paramount in extreme conditions. This is even more crucial in the space exploration scenario, when GPS is non-existent and human operator assistance could be limited.

Navigation and mapping tasks can be approached metrically, creating an actual environment picture or, topologically, structuring it as a graph of abstract

"locations." Visual landmarks graphs have been used in some research areas [7]. This research proposal follows a topological formulation of the problem.

The proposed solution involves two phases: In the first, with active control, the agent constructs a map of the operational region, gathers route data, surveys localization uncertainty, and builds a topological map with selected POI "beacons."

In the second phase, the agent autonomously backtracks using the prepared POI map. It actively localizes based on the navigation graph, minimizing uncertainty, and plans the return route while considering battery constraints. In this problem setting, the robust UAV backtracking to a secure environment is more important than the speed of task execution.

This research statement comprises an introduction, three core sections, and a conclusion. The "Motivation" section explains the topic's selection and underlines use case constraints. The "Modern State of Research" lists foundational works for the envisioned solution. The "Approach" outlines research design and tasks, like data collection and experiments. The "Conclusion" summarizes the core parts' content.

## 2 Motivation

We have selected this research problem due to the importance and limitations of UAV technology highlighted in recent armed conflicts. From what we observe on the battlefields, solutions should migrate to the scientific and aerospace systems to give them a new push with ideas and investments.

The challenges of observed application scenarios exceed the capabilities of current methods, ensuring the novelty of any proposed solution.

From the broad public media highlights, we know that enthusiastic engineering teams are solving many problems and limitations of UAV technologies. One such topic is the "UAV recovery after control signal disruption" method. The context and challenges are such that it requires more profound principal research on a scientific level rather than engineering efforts.

This specific problem was chosen based on my background and our research institution's strategic direction:

- My background includes robotics and industrial computer vision. I also completed a research internship on autonomous navigation at the Czech Institute of Informatics, Robotics, and Cybernetics (CIIRC). Over the years, I engaged with schools at Czech Technical University on collaborative robotics and UAV topics, building connections with a renowned research laboratory on UAV autonomy challenges.

- UCU's existing 3D-aware computer vision expertise and the "Embodied AI" lab's goal of integrating 3D situational awareness in autonomous agents operations, combined with their navigation work [17], bolster my confidence. Also, the RnD collaboration between UCU and CTU UAV labs supports this topic.

From what is publicly available on this topic, the actual usage constraints include the following:

*Sensors:* Typical UAV platforms are equipped with decent-quality onboard RGB cameras. The method must mainly rely on camera visual information to be massively used. IMU, compass, and altimeter are also part of the standard sensor setup. Heavy, rare, or expensive sensors are not desirable.

*GPS:* The operation conditions include total denial of GPS signal; the proposed approach can rely on GNSS, neither mapping nor the backtracking phase. Overall, I decided to avoid all the actual metric mapping and precise localization in the operation environment. POI navigation graph should be enough to traverse it back to the home base node. Nodes could contain all required additional data about the landmarks and something about their neighboring nodes.

*Mapping constraints:* Under conditions we met in aerospace scenarios, the pilot has to control flight most of the time according to legal regulations. Therefore, the exploration phase could be done only in a passive observer manner. We must consider fuel economy and possible schedule restrictions to adapt this approach to civil aerospace needs, so there is no place for active exploration of the environment for improved mapping.

*Problem relaxation opportunities :* There are many scenarios when we have an opportunity for repeated observations of the same territory. Those are typical for the agriculture setup when a UAV travels back and forth between the operation field and the base station, patrolling some routes or repeated routes when smart platforms are used for transportation purposes. Also, we can simplify the task, looking for the cases when time constraints are not crucial: those are ones when in the mapping phase, there are weaker time constraints, a.e. missions for automated search and rescue, etc. In this setup, we could consider an active approach for POI graph creation.

*Expected restrictions :* Route has to be performed above the visually featureless areas (like uniform vegetation regions, fields, etc.). This is motivated because feature-rich locations are restricted by flight limitations or conditions specified by tasks, such as farming or forestry observations.

*Altitude :* The operation height varies from 20 to 500 meters. The limitation depends on the mission character: some require more observation field, and others call for smaller details exploration. This discourages the popular approach of satellite imagery-based navigation, as UAVs have to operate close to the ground, where the top-down representation is not appropriate.

*Setup adaptation :* With limits on active exploration during the first phase, we might need an additional camera (a.e. fisheye lens) to be added to the system, as it will give a mechanism to keep tracking/searching for POI when there are none in the main downward facing camera frame. Also, it can have an active camera on a gimbal setup, giving more degrees of freedom for active environment observation.

*Basic research questions:* 1) What is the required camera setup? 2) Effective Points Of Interest selection. 3) What should be the auxiliary information stored in POI navigation nodes? 4) What should be the update procedure for naviga-

tion graph refinement on repetitive observation? 5) Effective navigation graph creation, refinement, and traversing.

### 3 Modern state of research

Given our specific application domain and challenges, we focus on outdoor applications. However, the advancement of visual localization algorithms has primarily taken place within the context of indoor (laboratory) applications. Consequently, we are also exploring these indoor algorithms for their potential applicability to our work. [5] [16]

The domain of autonomous UAV operation has reached a level of maturity, with operational industrial systems available for specific applications, including agriculture, data collection, security, and military purposes, etc. [11].

Many platforms are equipped with onboard cameras essential for obstacle avoidance, takeoff, landing procedures, or data collection. Despite these capabilities, GNSS systems largely fulfill localization requirements, making visual localization less popular due to its complexity. Notably, only a handful of recent studies focus on pure-visual UAV localization, with the most cited work being *"No place like home"* by Warren [22]. This research addresses visual backtracking issues for UAVs, but significant differences exist in the problem setup: 1) GPS availability during the learning phase and the requirement for metric navigation; 2) Absence of guided points of interest selection and limited attention to poor localizability.

Warren addressed the GPS-denied localization problem in a different study [21], focusing on feasibility experiments with satellite data. This setup included a single down-facing camera and a teach-and-repeat approach, aligning with our problem configuration. Guru pursued a similar setup involving high-altitude fixed-wing UAVs using the same satellite data [8]. While differences exist in factors like flight altitude and the use of pre-built maps, their adaptation of Deep CNN for feature extraction presents a potential area of investigation in our research's later stages. Liu described an interesting and closely related problem setup in [14], where the approach was developed for low-altitude UAVs based on visual POIs. Notably, the urban environment they addressed is highly structured and rich in strong visual localization features. The author highlighted this environment property by utilizing text-based POIs, incorporating textual signatures visible on streets. This distinctive aspect sets it apart from our problem setup.

Unlike UAV visual-based navigation, there's an abundance of research concentrated on ground robots within indoor settings. Indoor environments lack GPS but have pervasive cameras. Also, actual metric mapping's resource demands are often excessive or unattainable for certain tasks in these situations. Well-established techniques for visual navigation have emerged [7], along with numerous robust methods for agent self-localization.

Although our active perception capabilities for building the POI graph are constrained by the limitations detailed in the Motivation paragraph, it's crucial

to highlight that active localization becomes indispensable during the backtracking phase without a precise metric map.

Our map surveying approach from the first stage involves two key aspects: reliable positioning relative to our "beacon" POIs and the localizability of local environments, as elaborated in [13]. This dual focus is essential for ensuring safe graph traversal. Furthermore, we intend to leverage established techniques to seamlessly incorporate existing solutions, particularly when addressing the challenges posed by battery life constraints in the context of the backtracking problem.

Path planning under localizability constraints has been explored in the literature, as detailed in [13]. Typically, this approach requires additional functions for localizability estimation. It is often stored in metric map form. We propose a more efficient adaptation: storing localizability data in POI nodes for safer route planning within our graph. This concept resembles the hybrid topologic-metric maps described in [20], where metric information is stored in interconnected "islands of stability," forming a global topological map.

Localization based on visual landmarks is a well-established classic problem [2] that showed its effectiveness [16] and became the classic approach. This method is an auxiliary navigation tool in ambiguous environments, where metric maps are typically constructed using specialized measurement tools like LIDAR and range measurement sensors. Although these maps accurately represent the environment, they struggle in cases with repetitive obstacle shapes, leading to reduced reliability. To overcome this, introducing a reliable visual signal source can resolve ambiguity, as highlighted in [16]. Our approach employs visual points of interest as beacons for consistent and dependable localization.

The Active Mobile Robot Localization - introduced by Bugardt [3]. As autonomous self-navigating systems have advanced, the active localization problem has garnered increasing attention, evolving into a well-established research area with diverse approaches and problem setups being investigated [6] [19]. We aim to evaluate multiple concepts in our context to determine the most effective one.

*Summary* The chosen research path addresses questions beyond current approaches. Yet, there's a solid foundation for each question. Our work will bridge previously uncombined approaches and assess their real-world efficiency. Field adaptation often reveals gaps in lab-based methods. In this project, we anticipate innovating adaptations that push the boundaries of state-of-the-art methods further.

## 4 Approach

Given its practical focus, our project will be developed incrementally, addressing partial problem solutions through effective testing and application of its components. An ablation study will be conducted to quantify and validate system effectiveness.

To begin, we need to establish a stable testing environment for comparison with a baseline method [22]. This entails designing performance metrics.

*Dataset Collection:* The initial stages involve gathering real operational recordings. Collaborative partnerships allow direct access to such data from avian reconnaissance platoons invested in this technology’s advancement. This data will serve as validation for all experiments.

*Available data:* In our gradual development approach, we will utilize existing datasets that constitute a closed-loop series of flights over the same environment, similar to the CLOUD dataset [4]. This dataset has selectively chosen pertinent data samples from past UAV outdoor localization studies, including the notable UTIAS dataset [1]. The UTIAS dataset encompasses drone imagery across repeated flight trajectories over fields and outdoor environments in varying seasons and lighting conditions.

This dataset, with its recurrent loop trajectories over the same or partially overlapping landscapes, aligns well with our research’s problem setup. It allows us to gauge localization persistence while incrementally refining the topological POI map of the environment.

*Points of Interest:* In unstructured environments, numerous visual similarities lead to localization ambiguity. Methods based on optical flow data falter over regions with dense vegetation or other visually noisy content. As humans don’t rely on such common features for navigation, the robots encounter similar challenges.

The approach for selecting Points of Interest (POIs) can be developed and tested independently. For this purpose, we can use repeated flight recordings over the same area and measure localization reliability during data playthrough. This approach isolates the POI selection element for focused evaluation.

*Localization ambiguity:* The assessment of localization ambiguity should draw from both: the overall environmental information and operation field-specific data gathered during the POI mapping. Researchers often devise their own ”localization ambiguity” criteria tailored to their problem context [12] [16].

Selection of Points of Interest (POIs) should hinge on their distinctiveness from the background, degree of similarity with other POIs in our navigation graph, and multi-angle visibility. As an initial baseline, we will employ automatic feature extraction and filtering akin to the renowned visual teach-and-repeat framework [18], which offers accessible open-source packages.

*Simulation and experiments:* The first-phase method components could be created and tested on fixed datasets. However, the backtracking phase to the home base necessitates an open environment with decision-making opportunities. Due to dataset constraints on agent positioning space, open-world simulation becomes crucial. It notably enhances the developing and testing of the ”active” navigation component, enabling route formation decisions.

We intend to develop the navigating agent using the ROS system [15], granting access to various simulators ranging from simpler ones like Gazebo [10] to more sophisticated options such as NVIDIA’s Isaac Sim with the Pegasus plugin for UAV modeling [9].

Additionally, we can explore simulations based on high-resolution satellite imagery or images taken from drones at higher altitudes, as pursued in prior research [21] [8].

Simulation provides the advantage of generating diverse scenarios for repetitive testing and designing specific corner-case experiments. This ensures that our localization system navigates effectively without getting stuck in oscillating decision situations.

*Integration:* We will commence with miniature experiments within campus facilities, focusing on an indoor setup for preliminary validation of intermediate results. Given the distinct nature of POI mapping, this approach will be more effective for actively traversing the POI graph. In the course of our research, field testing will be essential. Thus, we must develop a software package seamlessly integrated into various platforms. This package will facilitate interaction with video streams and telemetry data as inputs while receiving movement direction commands as outputs for backtracking. An autopilot interface will be necessary for executing low-level control in response to commands for UAV systems.

## 5 Conclusions

We described a design of research that aims to address cutting-edge challenges. Along this trajectory, we will confront several pivotal obstacles, generating practical solutions grounded in innovative approaches. Upon completing the envisaged research, we anticipate an outcome that, on the one hand, preserves valuable equipment and ensures its availability for important tasks while, on the other, offering a resolution for the demanding localization problem. This breakthrough will potentially expand autonomous operational capacities, minimizing risk for UAVs and broadening applications to overcome weak signal zone hindrances.

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