Toward Safe and Robust Robotic Systems: Perception-Action Integration in Unstructured Environments

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I. Motivation and Vision

Advances in robotics have accelerated the deployment of intelligent systems, driving a growing demand for robots that can replace human labor in hazardous environments and improve efficiency through unmanned operations. Motivated by these academic and industrial needs, my doctoral research focuses on enabling robots to operate reliably beyond controlled laboratory in complex, unstructured environments.

One of the key challenges in real-world deployment is ensuring the safety and robustness of perception systems, which my research addresses through sensor-based planning and control. This issue becomes especially critical in safety-critical scenarios—such as the Mars helicopter mission [1]—where a visual-odometry failure over featureless terrain triggered an emergency landing. Similar challenges broadly affect applications ranging from autonomous driving to service robotics.

The central research question I pursue is: **How can we design robotic systems that are trustworthy and safe, particularly at the intersection of perception and motion?** Despite progress in spatial intelligence—such as visual SLAM—current autonomous systems still lack the robustness needed for long-term operation in unstructured environments. A core challenge lies in the traditional modular architecture of autonomy, where perception is treated as an independent, passive module, isolated from downstream components such as planning and control. To address this, my goal is to develop a framework for the safe, closed-loop integration of perception and action (Fig. 1), enabling robots to adapt their behavior dynamically to maintain perceptual reliability and ensure system-level safety. To this end, my previous and ongoing research has focused on improving the robustness of vision-based systems, particularly for state estimation and target localization.

II. Research To Date

This section highlights selected research supporting my doctoral objective: developing a planning and control framework for robust vision-based perception systems.

A. *Planning and Control for Reliable Visual Navigation*

A key challenge in vision-based navigation, particularly for odometry and SLAM, is ensuring sufficient visual information. Maintaining salient features helps avoid degenerate solutions and reduces drift—both essential for safe operation.

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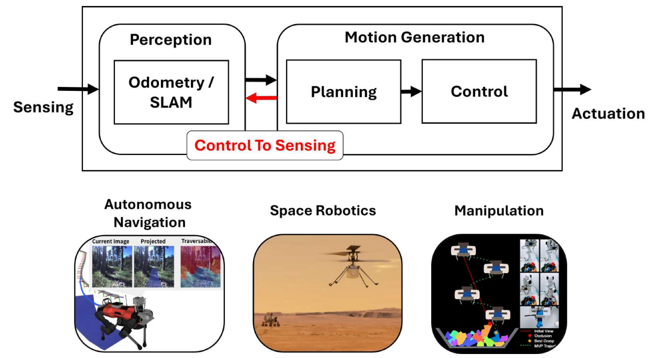

Fig. 1: The diagram illustrates a closed-loop system linking perception and action. Unlike conventional passive perception pipelines that feed sensory data downstream, my research explores a *control-to-sensing* strategy—actively selecting actions to enhance perceptual quality. This feedback-driven approach enables more robust and reliable perception, with broad applications in autonomous navigation, space robotics, and manipulation. (Image sources, from left to right: [2], [3], [4])

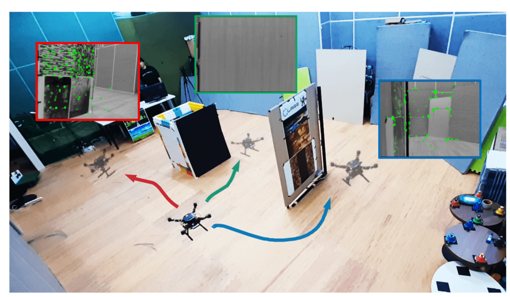

Fig. 2: For robust visual navigation, an aerial vehicle should decide on a path that can guarantee enough visible features from multiple path candidates.(Source: [5], ©2021 IEEE.)

In visually sparse environments (e.g., plain walls), SLAM performance degrades. To address this, we proposed a topology-aware global planner (Fig. 2) that classifies paths by visual saliency and topological structure. This enables selection of feature-rich paths to improve localization robustness for aerial robots.

To extend perception-aware planning into the control layer, we developed a safe visual feature-constrained controller (Fig. 3) ensures that a sufficient number of features are tracked online. This work leverages Control Barrier Functions (CBFs) [6], a method from constrained control theory,

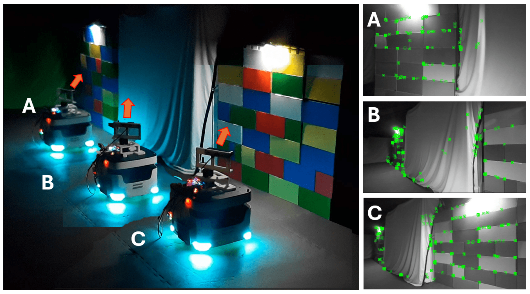

Fig. 3: Robots at three timestamps (A, B, C) are shown with onboard images and ORB-SLAM2 feature tracks [7], controlled by the safe controller from [8]. The proposed safety filter adaptively adjusts control inputs to maintain feature tracking. (Source: [8], ©2025 IEEE.)

to enforce set invariance in visual feature space. The resulting safety filter guarantees stable feature tracking, thereby enhancing the reliability of SLAM in real-time applications. This work bridges formal safety guarantees with the practical requirements of perception-driven autonomy.

B. Visibility Constrained Control

Another research focus involves enforcing visibility constraints to keep critical landmarks within view—important for tasks like perching, docking, or inspection.

To address this, we first developed a control-theoretic framework based on the Reference Governor approach [9]. This method ensures that the visibility constraint—keeping a landmark within the onboard camera's field of view—is satisfied while the robot tracks a given trajectory.

Building on this, we extended the method to handle more realistic scenarios involving occlusions, recursive feasibility, and goal convergence. This enhanced visibility-constrained controller allows for robust performance in cluttered environments and is being prepared for submission to an IEEE Transactions journal (Fig. 4).

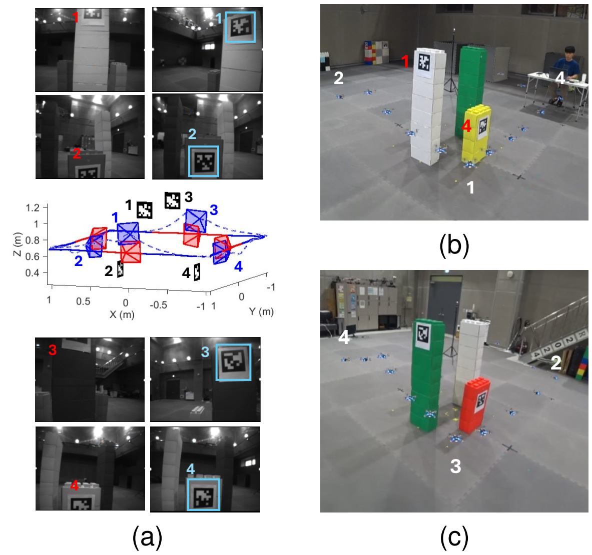

Fig. 4: Quadrotor flight experiment demonstrating visibility maintenance of central landmarks while following a rectangular trajectory. (a) First-person-view images at moments where field-of-view (FoV) violations may occur, comparing the baseline controller (left) and the proposed controller (right). (b–c) The proposed controller adjusts vertical trajectories to satisfy FoV constraints and ensure continuous visibility.

III. Future Research Directions

My prior work has primarily focused on reliable visual navigation and landmark tracking, closely tied to traditional robotics topics in computer vision and control. Looking ahead, my research aims to broaden the scope of safety assurance in robotic perception.

One key direction is the integration of modern perception systems, such as deep-learning-based SLAM and spatial understanding enabled by foundation models, into planning and control frameworks. These systems offer powerful semantic reasoning and generalization, but often lack formal safety guarantees. My goal is to bridge this gap by embedding such learning-based perception modules within control-theoretic safety frameworks, enabling robust and certifiable autonomy in complex environments (Fig. 5 (a)).

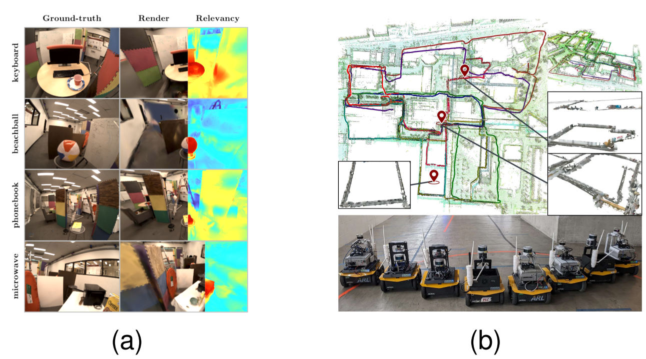

Fig. 5: (a) Safe navigation with Gaussian Splatting map (Source: [10] ©2025 IEEE.) (b) Multi-robot distributed SLAM (Source: [11] ©2023 IEEE.)

Another promising direction is to develop active perception strategies for large-scale multi-agent systems. Multi-agent collaboration plays a vital role in distributed spatial understanding, as robots can exchange observations, share spatial information, and enhance robustness through cooperative localization and environment mapping. Building on my experience in distributed multi-agent planning [12], [13], I aim to design frameworks where information-aware planning and cooperative sensing improve system-wide perception reliability. Recent work in resilient and collaborative mapping [11], [14] demonstrates the potential of such systems to improve robustness via shared situational awareness and relative localization (Fig. 5 (b)).

These directions are unified under the broader goal of enabling safe, scalable, and intelligent autonomy, where perception is no longer passive but actively integrated with control and coordination.

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