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SuperFALCON+: Complexity-Aware Global-to-Local Coordination for Resilient MAV Exploration

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Abstract

During exploration in confined environments, unknown regions often lie behind narrow turns or near walls and map boundaries. Informative global targets can be difficult to execute under local planning constraints. Our FALCON simulations exhibited obstacle-penetrating trajectories, repeated optimization failures, and premature termination, leaving regions unmapped. We present SuperFALCON+, a complexity-aware global-to-local coordination framework coupling FALCON's guidance with SUPER's local execution. Its awareness draws on prior knowledge of local-map requirements, online target span and occupancy information, and target-stream observations. Boundary-constraint coordination accounts for inflation and boundary-query requirements through a spatial reserve configured before flight. Local-constraint-aware target adjustment uses candidate distance and local occupancy to combine Target-Broker with SUPER's native free-space projection. Repeated-goal-aware handoff supervision maintains target delivery and records repeated endpoints as cues of potentially limited progress, while preserving both planners' native replanning loops. Across three confined environments, SuperFALCON+ achieves higher mean mapped volume, fewer infeasibility events, and fewer premature terminations than the evaluated baselines. Component ablations and outdoor flights further support the framework.

Keywords: Autonomous exploration, global-to-local coordination, micro aerial vehicles, target adjustment, resilient execution

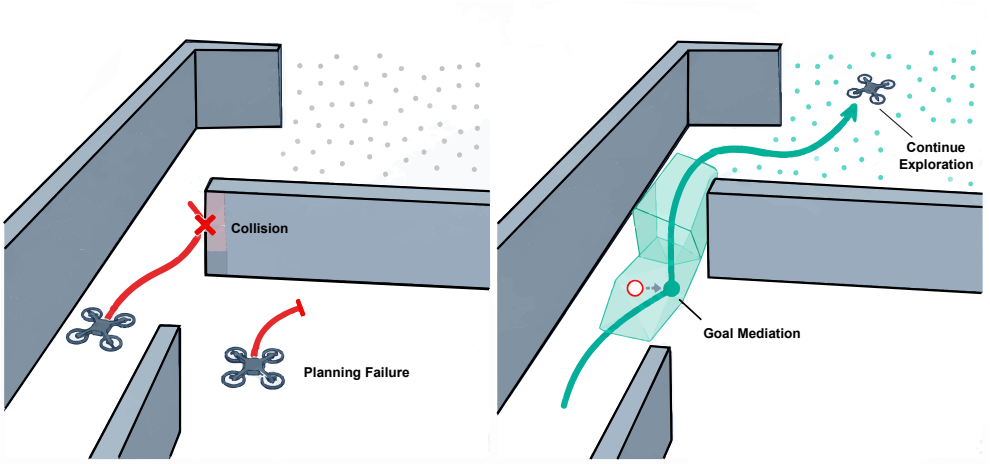


Fig. 1: Motivation for reliable exploration in confined environments. Left: Schematic illustration of two independent failure cases observed with FALCON in our simulations: obstacle penetration and planning failure. Right: SuperFALCON+ combines global exploration guidance, goal mediation, and SUPER's local trajectory planning and execution to support continued exploration through confined regions.

1 Introduction

An exploration mission must sustain executable motion until the remaining informative regions have been visited. In confined environments, this requirement becomes difficult near narrow passages, occluded corners, and restricted map boundaries. A global planner may identify a useful exploration direction while the local execution layer struggles to realize the corresponding request. Repeated planning failures or interrupted progress can then limit the mapped extent. Figure 1 illustrates two failure behaviors observed with FALCON in our simulations—obstacle penetration and planning failure—that motivate closer attention to execution reliability.

Frontier- and graph-based exploration methods organize observations into global structures that support efficient viewpoint selection and coverage guidance [1–4]. Local trajectory planners address a complementary problem: converting a requested motion into a trajectory that satisfies current map, obstacle, and vehicle constraints. These two functions operate over different spatial horizons and timescales. Global exploration requires long-range reasoning about coverage and connectivity, whereas local execution requires frequent map updates, collision checking, and kinodynamic trajectory generation.

Progress at each layer has also produced specialized spatial representations and planning abstractions. Graph-based topological exploration and dynamically expanded viewpoints improve long-range organization and rapid frontier access [5, 6]. Octree occupancy maps and onboard Euclidean distance fields provide geometric support for mapping and collision queries [7, 8], while memory-efficient boundary maps address the scaling cost of large occupancy grids [9]. At the execution layer, receding-corridor

and multi-mode hybrid planners strengthen short-horizon trajectory generation under spatial constraints [10, 11]; full-stack autonomous tail-sitter flights further demonstrate the value of carefully engineered local navigation modules [12]. These advances make the two planning levels individually capable, but they do not by themselves define how a global exploration request should be translated across mismatched map boundaries, target semantics, and replanning cycles.

This distinction motivates a modular global-to-local architecture. FALCON provides coverage-oriented global guidance through efficient frontier processing, viewpoint selection, and exploration-path planning [3]. SUPER provides safety-oriented local execution through rolling-map updates, obstacle inflation, safe-flight-corridor construction, and high-frequency trajectory replanning [13]. Their capabilities are complementary: FALCON determines which informative region should be explored next, while SUPER determines how the MAV can approach the requested region under the current local conditions. Combining them therefore provides a practical way to retain global exploration efficiency while strengthening local executability.

A unified planner could, in principle, optimize exploration decisions and vehicle trajectories within a single formulation. In practice, however, this would require frontier reasoning, global route selection, rolling-map maintenance, collision checking, and kinodynamic optimization to share a common representation and update cycle. Such tight coupling would require substantial redesign of both planning levels and would limit the reuse of independently developed exploration and navigation systems. A modular architecture preserves their specialized algorithms and allows each layer to operate at its appropriate horizon. Its central requirement is therefore a well-defined coordination interface.

Directly cascading the two planners does not satisfy this requirement. A candidate that is informative and reachable in FALCON's global representation may lie near SUPER's inflated obstacles, approach the boundary of its valid map support, or request a displacement that is difficult to realize from the current local state. Moreover, repeated delivery of a locally difficult target can interrupt progress even though both planners continue replanning. The failure is therefore not simply a weakness of either planner in isolation; it arises because exploration intent and local execution constraints are expressed through different spatial conventions and operating timescales.

We refer to the demands placed on this interface as *operational complexity*. Super-FALCON+ makes the interface aware of information available at three stages. Before flight, known requirements for obstacle inflation and boundary queries inform the configured spatial support. During target processing, candidate span and local occupancy inform target adjustment and goal validation. During execution, repeated candidate endpoints provide a cue that the target handoff may be making limited progress. These information sources are translated into configuration-, target-, and execution-level coordination responses.

Specifically, *boundary-constraint coordination* provides a scenario-calibrated reserve for local-map operations. *Local-constraint-aware target adjustment* combines Target-Broker with SUPER's native free-space projection to reconcile global requests with current local conditions. *Repeated-goal-aware handoff supervision* maintains

target delivery and records repeated endpoints while preserving the native replanning loops of both planners. Together, these mechanisms form the bridge between FALCON's global exploration capability and SUPER's local execution capability.

The resulting resilience concerns the continuity of the exploration mission. SuperFALCON+ does not seek to replace the exploration strategy of FALCON or the trajectory planner of SUPER. It coordinates their interaction so that locally difficult requests are less likely to interrupt exploration. The experiments therefore evaluate whether the coordinated system sustains mapped-space growth, reduces optimizer infeasibility events, and avoids premature mission termination. The results show higher mapped volume and more consistent mission completion than the evaluated baselines, accompanied by lower average flight speeds than FALCON.

The contributions are summarized as follows:

- We establish a modular global-to-local exploration architecture that combines FALCON's coverage-oriented global reasoning with SUPER's safety-oriented local trajectory execution. The formulation identifies the coordination interface—rather than either planning layer alone—as a critical source of execution interruption in confined environments.
- We develop a complexity-aware coordination architecture that connects each operational condition to a corresponding response: boundary-constraint coordination reserves support for local-map operations; local-constraint-aware target adjustment combines Target-Broker with SUPER's native free-space projection; and repeated-goal-aware handoff supervision maintains target delivery while recording repeated candidates.
- We integrate FALCON's coverage-oriented guidance with SUPER's local execution and evaluate the resulting exploration resilience in three confined scenarios, through component ablations, and on a physical quadrotor. The comparative results show higher mean mapped volume and fewer premature terminations than the evaluated baselines, with lower average flight speeds than FALCON.

2 Related Work

2.1 Autonomous MAV Exploration

Frontier selection, information gain, and receding-horizon planning provide established ways to select informative motions in unknown environments [14–17]. Hierarchical systems use global structures to reduce myopic decisions and organize exploration across larger regions. Representative approaches include FUEL [1], TARE [2], RACER [18], FAR Planner [19], FALCON [3], and EDEN [4]. Their map representations and route-selection strategies differ, but each must ultimately convert exploration intent into executable motion.

SuperFALCON+ retains FALCON's frontier processing and coverage guidance. It studies the interface created when that guidance is executed by an independent local planner. The design therefore complements exploration-policy improvements by addressing whether the selected requests can be delivered and processed under local execution constraints.

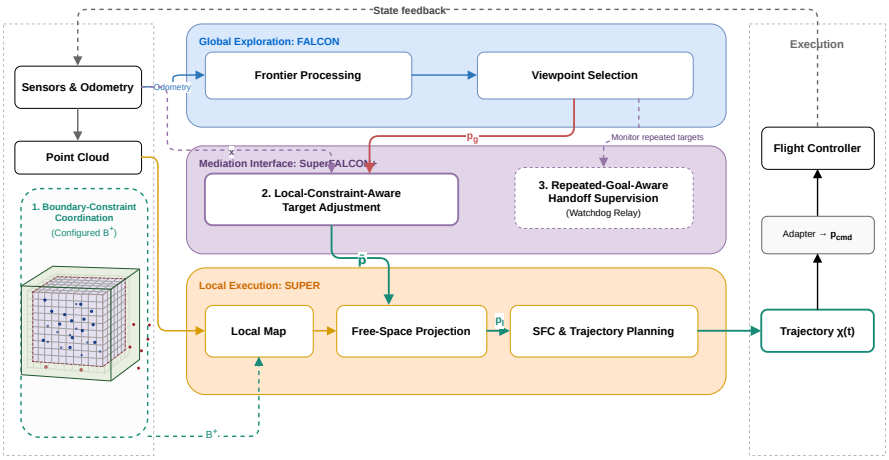


Fig. 2: SuperFALCON+ architecture. FALCON supplies exploration guidance, and SUPER generates the executed trajectory. Three mechanisms coordinate their interface: boundary-constraint coordination configures spatial reserve; local-constraint-aware target adjustment combines Target-Broker with SUPER's native free-space projection; and repeated-goal-aware handoff supervision forwards targets and records repeated endpoints. These responsibilities draw on prior map requirements, online target and occupancy information, and target-stream observations, respectively.

2.2 Local Trajectory Planning and Coordination

Local MAV planners combine map updates, path search, collision checking, and trajectory optimization under onboard computation limits. Fast-Planner [20], EGO-Planner [21], FASTER [22], and RAPTOR [23] illustrate approaches to navigation and replanning in unknown environments. Polynomial and MINCO-based formulations support efficient representations of dynamically feasible trajectories [24, 25]. SUPER [13] provides local mapping, safe-corridor construction, and trajectory execution used in the present integration.

FALCON and SUPER address complementary levels of the exploration problem. FALCON supplies long-range coverage guidance, whereas SUPER provides map-aware local trajectory generation and replanning. Their integration is therefore motivated by a functional division between exploration decision making and motion execution. The contribution of SuperFALCON+ lies in making this division operational: it coordinates spatial support, adjusts target requests using local information, and maintains their handoff across the two planning loops.

3 Methods

3.1 Complexity-Aware Coordination Principle

SuperFALCON+ treats operational complexity as a set of conditions that can disrupt the transfer of global exploration intent into locally executable motion. Rather than

assigning the environment a single complexity score, the framework uses information available at three stages of the planning process. Before flight, prior knowledge of SUPER's map-inflation and boundary-query requirements informs the spatial configuration. During target processing, candidate span and local occupancy indicate whether a global request requires adjustment. During execution, repeated target endpoints provide a cue that the global–local interface may be making limited progress.

Each information source activates a corresponding coordination response. Boundary-constraint coordination reserves spatial support for local-map operations. Local-constraint-aware target adjustment modifies the candidate request and subjects it to SUPER's occupancy-based goal projection. Repeated-goal-aware handoff supervision maintains target delivery and records repeated requests while the native replanning loops remain active. These configuration-, target-, and execution-level responses form the complexity-aware coordination principle of SuperFALCON+.

The objective of this coordination is to preserve executable exploration across conditions that can otherwise interrupt the global–local planning chain. In this work, *resilience* denotes the system's ability to maintain exploration continuity and mapped-space growth despite boundary-related faults, locally difficult target requests, and repeated planning events. It is evaluated through mapped volume, optimizer infeasibility events, and premature mission terminations. Figure 2 summarizes the division of responsibility: FALCON supplies global exploration guidance, the proposed interface coordinates the request, and SUPER retains authority over local trajectory execution.

3.2 Global Guidance and Local Execution

Let $\mathbf{x}(t)$ be the current MAV position and $\mathbf{p}_g(t)$ a candidate supplied by FALCON. In the integrated configuration, FALCON continues its frontier processing, viewpoint selection, path search, and native B-spline generation. Its trajectory endpoint supplies the target interface:

$$\mathbf{p}_g = \mathbf{m}_N, \tag{1}$$

where $\mathbf{m}_N$ is the last point of the published guidance-trajectory marker. FALCON's position-command output is not used as the final vehicle command.

The adjusted request is passed to SUPER, which consumes the point cloud and odometry, maintains its local ROG map, applies obstacle inflation, and performs local path search, safe-corridor construction, and trajectory optimization. SUPER publishes the final position command and retains its native periodic replanning and backup-trajectory mechanisms. A message translator adapts the command type to the simulator or vehicle interface.

This arrangement separates exploration guidance from execution authority while retaining both planners' update loops. The coordination mechanisms below specify how spatial support and target requests are handled between them.

3.3 Boundary-Constraint Coordination

Boundary-constraint coordination incorporates prior knowledge of the local planner's spatial requirements into the exploration configuration. SUPER's obstacle inflation

and boundary queries require spatial support that must be reconciled with FALCON's task limits. Near configured scenario boundaries, insufficient reserve can restrict these operations. We therefore configure an additional spatial envelope before flight, accounting for the selected local-map and planner configuration.

Let $\mathcal{B}$ denote the nominal task region and $\mathcal{S}(\Delta_B)$ the scenario-calibrated spatial reserve. The configured envelope is

$$\mathcal{B}^+ = \mathcal{B} \oplus \mathcal{S}(\Delta_B), \tag{2}$$

where $\oplus$ denotes the Minkowski sum. The reserve is implemented through YAML map, task, and visualization limits and remains fixed during each run. It provides additional coordinate support while preserving the configured obstacle inflation and physical obstacle geometry.

This mechanism provides configuration-level awareness of local spatial requirements. The scenario calibration supplies the reserve; the current implementation does not compute it automatically from an online complexity estimate. By accommodating known local-map operations before execution begins, the mechanism reduces one source of interruption in the global–local planning chain. Its contribution is evaluated by removing the boundary buffer in the ablation study.

3.4 Local-Constraint-Aware Target Adjustment

Near an occluded turn or a narrow passage, a candidate can retain exploration value while its position remains difficult to process under local planning constraints. The interface therefore treats the global output as a target request whose position can be adjusted before trajectory generation. Two sources of information guide this process: the candidate's span from the current vehicle state and its admissibility in SUPER's local occupancy map.

Target-Broker uses the first source to decide whether to adjust the request; SUPER uses the second to search for a locally admissible goal. This division gives target-level awareness a concrete role in the complexity-aware architecture: observed target conditions determine how exploration intent is passed to the execution layer. The mathematical rule specifies the implemented adjustment, while its numerical configuration is reported in Section 4.1.

3.4.1 Target-Broker: Candidate Target Adjustment

Let $\mathbf{x}$ denote the current vehicle position and $\mathbf{p}_g$ the global candidate. The target span is

$$d = \|\mathbf{p}_g - \mathbf{x}\|_2. \tag{3}$$

Let d_0 denote the span threshold and δ the adjustment distance. Target-Broker constructs an intermediate request as

$$\widetilde{\mathbf{p}} = \begin{cases} \mathbf{p}_g, & d \le d_0, \\ \mathbf{p}_g + \delta \dfrac{\mathbf{x} - \mathbf{p}_g}{d}, & d > d_0. \end{cases} \tag{4}$$

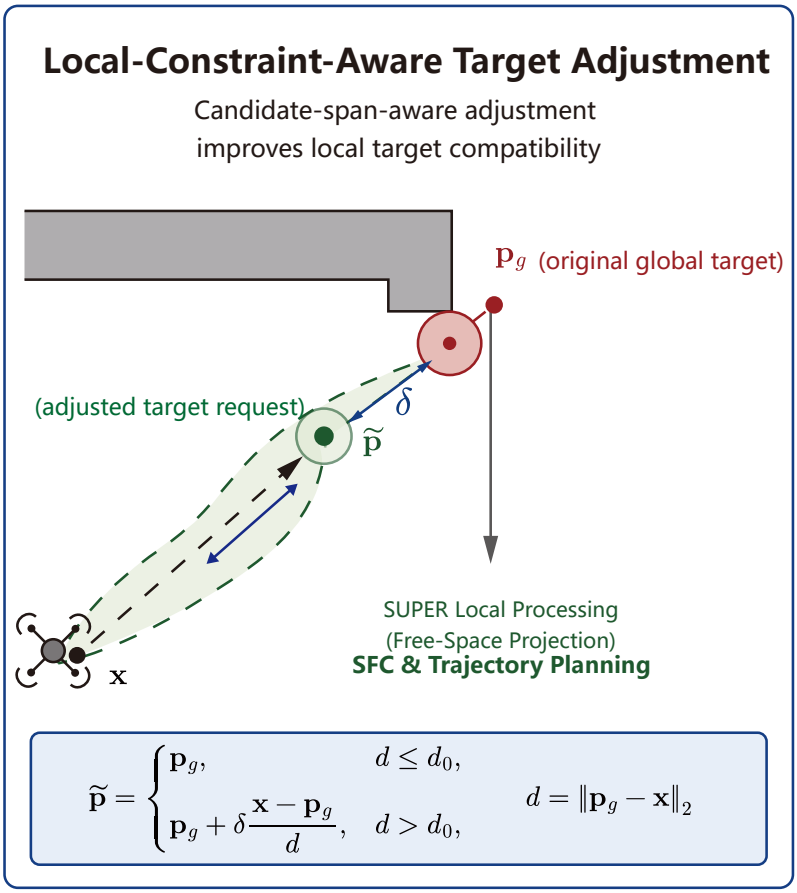


Fig. 3: Local-constraint-aware target adjustment. Target-Broker uses span d to convert FALCON's target $\mathbf{p}_g$ into the adjusted request $\widetilde{\mathbf{p}}$; SUPER then applies occupancy-based free-space projection, SFC construction, and trajectory planning. The omitted height bound $z_{\min}$ and search radius r_g are specified in Section 4.1. Target adjustment alone neither establishes obstacle clearance nor guarantees trajectory feasibility.

For a candidate exceeding the span threshold, the adjustment reduces its distance from the vehicle while retaining the original direction. Otherwise, the candidate position is retained at this stage. The request then satisfies a configured lower height bound:

$$\widetilde{p}_z \leftarrow \max(\widetilde{p}_z, z_{\min}). \tag{5}$$

Here $z_{\min}$ is expressed in the configured coordinate frame. The operation adjusts the requested target position; it does not command a backward vehicle motion.

The decision depends on the observed target span. The threshold and adjustment distance are configured parameters, and the subsequent map-based stage supplies the

obstacle information needed for local goal processing. This sequence separates the interpretation of exploration intent from validation against local occupancy.

3.4.2 SUPER Free-Space Goal Projection

After target adjustment, SUPER consults its local map and searches for a non-occupied cell in a bounded neighborhood of the request. When a suitable cell is found, the resulting local goal is represented as

$$\mathbf{p}_l = \mathcal{P}_{\text{free}}(\widetilde{\mathbf{p}}; r_g), \tag{6}$$

where r_g is the search radius. This is SUPER's native goal-processing operation: it examines precomputed neighboring grid offsets rather than solving an exact nearest-point optimization.

The two stages use different information and serve complementary purposes. Target-Broker responds to candidate span, while SUPER's projection responds to the current occupancy representation. Together they provide a locally checked request to SUPER's start/goal validation, path search, safe-corridor construction, and trajectory optimization. A locally admissible goal remains subject to the constraints of this planning pipeline, so target adjustment supports execution compatibility without guaranteeing solver success.

3.5 Repeated-Goal-Aware Handoff Supervision

Repeated-goal-aware handoff supervision uses the incoming target stream as its source of execution-level information. The watchdog-style relay forwards candidate requests and records repeated endpoints (Fig. 4). At startup, it publishes a wake-up waypoint derived from odometry. During exploration, each newly received FALCON guidance trajectory supplies an updated endpoint for the interface.

The relay couples target delivery with observation of the requests being delivered. Repeated endpoints provide a cue that can accompany limited progress, while forwarding keeps new guidance available to SUPER. These are distinct responsibilities within the same component: recording repetition does not itself initiate an escape action. The side box in Fig. 4 expands these responsibilities rather than introducing a separate recovery controller.

FALCON continues to update exploration guidance through its native loop, while SUPER independently checks and replans local trajectories. Maintaining the interface allows updated guidance to reach the execution layer as these loops operate. The relay thus supports the opportunity to continue exploration after difficult planning events without taking over either planner's recovery logic.

3.6 Integrated Complexity-Aware Coordination Process

The three mechanisms form a multi-stage complexity-aware coordination process. Prior map requirements inform boundary configuration, target distance and occupancy inform target adjustment, and target-stream observations support handoff supervision. Their shared purpose is to keep global exploration guidance compatible with

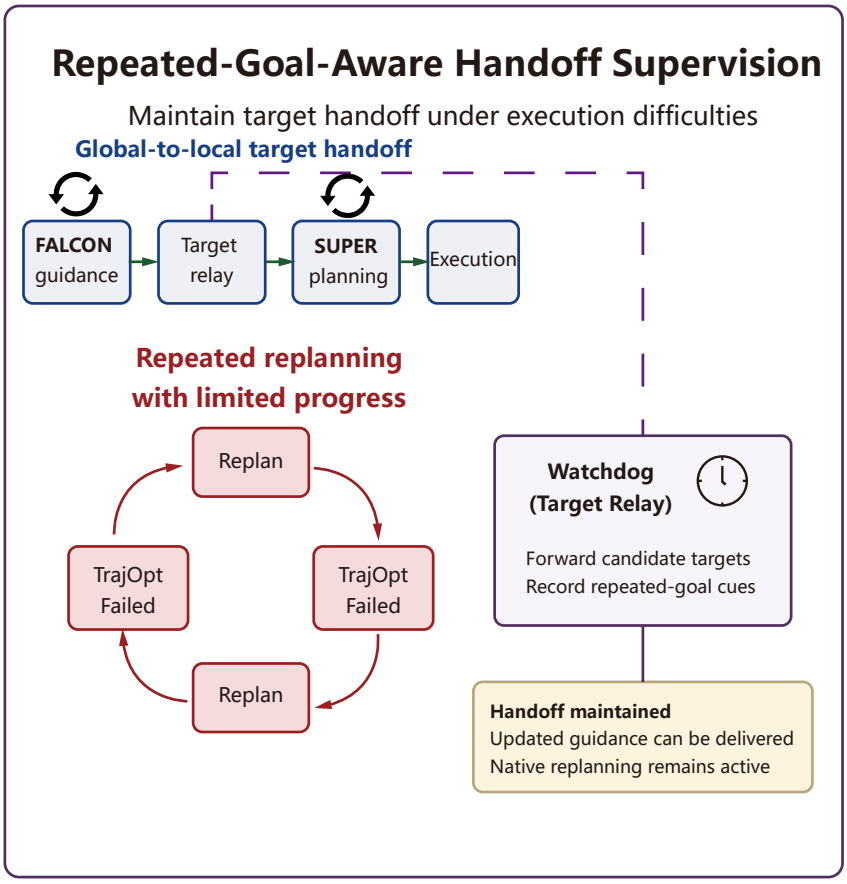


Fig. 4: Repeated-goal-aware handoff supervision. The main chain shows target transfer from FALCON through the relay to SUPER and execution. The purple dashed connection expands the relay's forwarding and repeated-goal recording functions; it does not denote a separate controller. The red cycle illustrates repeated planning failures with limited progress. Circular arrows denote the native replanning loops of FALCON and SUPER. The clock symbolizes ongoing supervision, not a timeout-triggered intervention. The relay maintains target handoff without implementing a dedicated escape maneuver.

local execution as operating conditions change. The target-to-command chain is

$$\mathbf{p}_g \xrightarrow{\text{target adjustment}} \widetilde{\mathbf{p}} \xrightarrow{\text{SUPER projection}} \mathbf{p}_l \xrightarrow{\text{SUPER planning}} \mathbf{u}_{\text{cmd}}. \tag{7}$$

Algorithm 1 summarizes the implementation responsibilities.

For example, a candidate near a confined turn first undergoes the distance rule and height correction, followed by SUPER's local-map check. Subsequent guidance updates pass through the same interface even when previous requests repeat or local execution becomes difficult. The boundary reserve supports the associated local-map operations,

Algorithm 1 Global-to-local coordination in SuperFALCON+

Require: Odometry, guidance updates, local map, configured d_0, δ, $z_{\min}$, r_g

Before flight: configuration-level awareness

Select Δ_B for local-map requirements and configure $\mathcal{B}^+$

At startup

Relay publishes a wake-up waypoint derived from odometry

Online: target processing and handoff observation

Extract endpoint $\mathbf{p}_g$ and obtain current position $\mathbf{x}$

Record repeated-candidate cues in the relay

$d \leftarrow \|\mathbf{p}_g - \mathbf{x}\|_2$, $\widetilde{\mathbf{p}} \leftarrow \mathbf{p}_g$

if $d > d_0$ **then**

    $\widetilde{\mathbf{p}} \leftarrow \mathbf{p}_g + \delta(\mathbf{x} - \mathbf{p}_g)/d$

end if

$\widetilde{p}_z \leftarrow \max(\widetilde{p}_z, z_{\min})$

Forward the adjusted request to SUPER's waypoint interface

Inside SUPER

Perform bounded free-space goal search with radius r_g

Process the result through native goal-validation and planning logic

Both planners retain their native replanning loops throughout execution

target adjustment improves request compatibility, and handoff supervision preserves the opportunity for either planner to update its solution. Their coordinated effect is the exploration continuity defined above as resilience. Its effectiveness is assessed empirically rather than through a formal completeness or deadlock-freedom guarantee.

4 Experiments and Results

The evaluation asks whether coordinating the target-execution interface helps exploration continue in confined environments. We first compare the complete system with exploration baselines, then examine the three coordination components through ablations, and finally demonstrate physical deployment. Mapped volume and premature termination are the primary mission-level outcomes; planning-event counts, speed, and duration help interpret them.

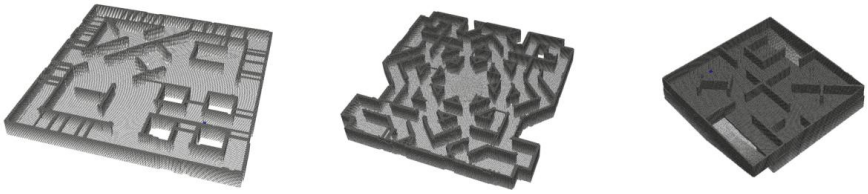
4.1 Experimental Setup and Metrics

Software-in-the-Loop simulations use the Epee benchmark framework [3]. Docker containerization with dedicated CPU core binding and memory isolation imposes processing-resource limits. Each method is evaluated over **10 independent trials per scenario** with randomized starting positions.

Implementation settings. The reported Target-Broker configuration uses the target-span threshold $d_0 = 1.5\,\mathrm{m}$, adjustment distance $\delta = 0.5\,\mathrm{m}$, and lower height bound $z_{\min} = 0.3\,\mathrm{m}$. SUPER's native free-space goal search uses $r_g = 3\,\mathrm{m}$. The boundary reserve Δ_B is calibrated through scenario configuration and remains fixed during

Table 1: Exploration performance and execution continuity across three scenarios. Volumes, durations, speeds, and infeasibility-event counts are averages over 10 trials per method and scenario; premature terminations are reported as counts out of 10.

Scenario	Method	C: Vol. (m^3)	E: Time (s)	V_{avg} (m/s)	Infeasibility Events	Premature Terminations
Complex Office	EDEN	1670.13	215.16	1.40	5.2	2 / 10
	FALCON	1692.57	142.42	**1.85**	6.4	4 / 10
	SuperFALCON+	**1804.30**	260.37	1.27	**2.2**	**0 / 10**
Octa Maze	EDEN	1990.45	330.31	1.34	13.4	4 / 10
	FALCON	3517.03	218.17	**1.80**	18.8	2 / 10
	SuperFALCON+	**3680.90**	406.94	1.05	**7.4**	**0 / 10**
Duplex Office	EDEN	1588.72	344.62	0.95	12.5	3 / 10
	FALCON	1487.90	175.22	**1.68**	17.2	3 / 10
	SuperFALCON+	**1925.69**	339.75	1.08	**8.8**	**2 / 10**



(a) (b) (c)

Fig. 5: The three highly constrained benchmark environments used in our simulated experiments: (a) **Complex Office**, (b) **Octa Maze**, and (c) **Duplex Office**.

each run. These values specify the evaluated implementation; the coordination rules are given symbolically in the method section.

The three environments introduce different constraints:

- **Complex Office** ($30\,\mathrm{m} \times 30\,\mathrm{m} \times 2\,\mathrm{m}$)**:** partitioned rooms and narrow corridors.
- **Octa Maze** ($35\,\mathrm{m} \times 35\,\mathrm{m} \times 2\,\mathrm{m}$)**:** non-orthogonal passages and repeated sharp turns.
- **Duplex Office** ($20\,\mathrm{m} \times 20\,\mathrm{m} \times 4\,\mathrm{m}$)**:** a multi-level environment with constrained staircase transitions.

We compare SuperFALCON+ with EDEN [4] and FALCON [3]. Following the reported VECO evaluation categories [3], Table 1 includes mapped volume, exploration duration, and average flight speed. We additionally report recorded optimizer infeasibility events and premature terminations to characterize execution continuity. Premature terminations denote missions ending before the intended completion condition.

Mapped volume counts accumulated free-space voxels in the operational sensor grid; it is not a normalized percentage of the nominal interior region. Because the boundary reserve changes configured spatial support, comparisons require a common counting region and voxel convention. The reported totals are interpreted as absolute mapped volumes rather than evidence of complete coverage.

4.2 Mapped Volume and Execution Continuity

SuperFALCON+ achieves the highest mean mapped volume and the fewest recorded infeasibility events in each scenario (Table 1). In the Complex Office, it maps 1804.30 m^3, compared with 1692.57 m^3 for FALCON and 1670.13 m^3 for EDEN. Its premature termination count is 0/10, compared with 4/10 and 2/10, respectively.

The Octa Maze shows a similar relationship between mapped extent and execution continuity. FALCON records 18.8 infeasibility events per trial and 2/10 premature terminations, whereas SuperFALCON+ records 7.4 events and 0/10 terminations. The corresponding mapped volumes are 3517.03 m^3 and 3680.90 m^3. Figure 6 illustrates execution difficulties and continued exploration in representative examples.

The Duplex Office remains challenging for all three methods. SuperFALCON+ maps 1925.69 m^3 and records 2/10 premature terminations, compared with 1487.90 m^3 and 3/10 for FALCON, and 1588.72 m^3 and 3/10 for EDEN. These residual failures show that the coordination interface improves the observed outcomes without eliminating every execution difficulty.

The comparison supports the complete FALCON–SUPER coordination pipeline. Because it also changes the local execution component relative to the baselines, it cannot attribute all gains to the interface alone. The component ablations below examine the contribution of the added coordination mechanisms within the integrated system.

4.3 Exploration of Remaining Confined Regions

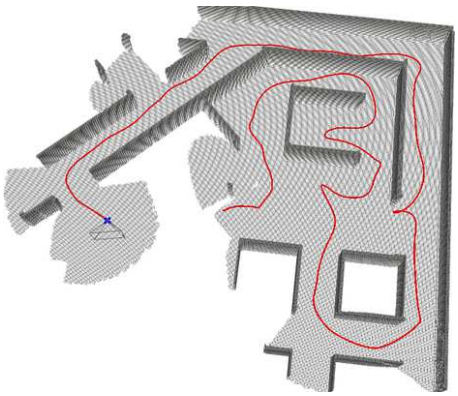
Later in a mission, remaining frontiers can lie near walls, corners, and narrow passages. Approaching these regions requires sustained local execution even when relatively little unexplored space remains. Figure 7 illustrates an Octa Maze example in which SuperFALCON+ continues through passages left unmapped in the baseline run. The larger mean mapped volume and lower termination count are consistent with this ability to sustain exploration.

Figure 8 shows a multi-level traversal example in the Duplex Office. The system combines adjusted target requests, map-based local planning, and continuing guidance updates during vertical transitions. This behavior is an outcome of the complete pipeline; the fixed target-height floor alone does not explain multi-floor traversal. The individual visualizations complement, rather than replace, the aggregate outcomes across trials.

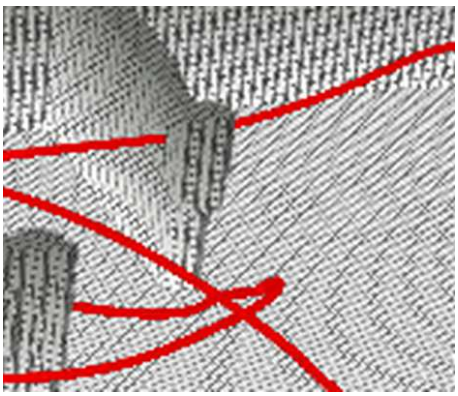
4.4 Speed and Duration Trade-off

The improved mapped volumes are accompanied by lower mean flight speeds than FALCON: 1.05–1.27 m/s for SuperFALCON+ versus 1.68–1.85 m/s for FALCON. In the Octa Maze, mean duration increases from 218.17 s to 406.94 s. The result is therefore greater explored extent and fewer interruptions, rather than faster traversal.

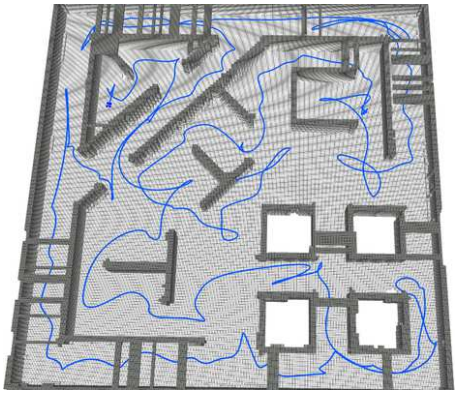
Both local trajectory behavior and mission continuation can contribute to these differences. Target adjustment changes target requests, SUPER supplies a different execution pipeline, and runs that continue into remaining regions can last longer than runs that terminate early. Aggregate durations do not separate these effects or measure



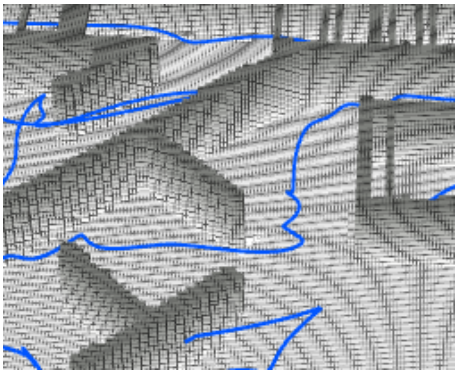
(a) Baseline:
Replanning Stagnation



(b) Baseline:
Physical clipping



(c) Ours:
Resilient Exploration



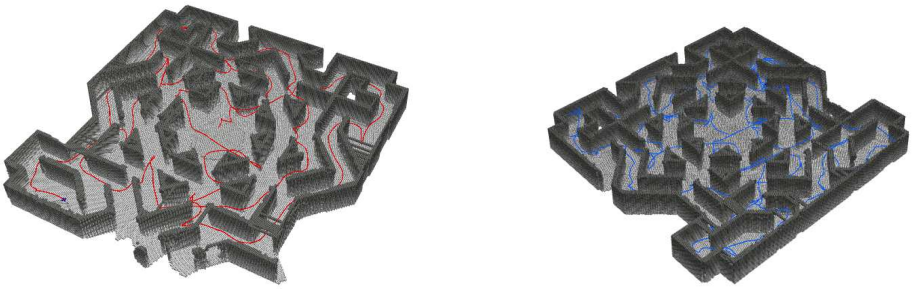
(d) Ours:
Safe Obstacle Bypassing

Fig. 6: Examples of execution behavior in confined environments. The baseline examples show (a) replanning stagnation and (b) obstacle penetration in simulation. SuperFALCON+ examples show (c) continued exploration and (d) obstacle bypassing. These views motivate coordination at the target-execution interface and illustrate outcomes of the complete pipeline.

time to equal coverage. The contribution should consequently be judged by execution continuity and mapped extent alongside speed.

4.5 Ablation of the Coordination Mechanisms

The ablation evaluates four configurations over five trials each in the Octa Maze, giving **20 trials**. The reduced configurations remove the boundary buffer, watchdog relay, or Target-Broker component while retaining the remaining configured mechanisms. The implementation names in Table 2 map directly to the three method components.



(a) FALCON (b) SuperFALCON+

Fig. 7: Exploration outcomes in the Octa Maze. The FALCON example shows remaining unmapped regions following premature termination; the SuperFALCON+ example shows continued traversal and greater mapped extent. Aggregate volumes and termination counts are reported in Table 1.

Table 2: Component ablation in the Octa Maze: mapped volume (m^3) for each trial, mean duration, and mission completion count. Four configurations are evaluated over five trials each, giving 20 trials in total.

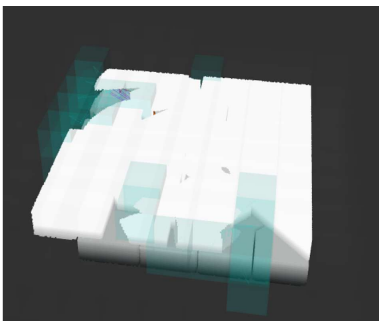
Configuration	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Avg. Time (s)	Completion
w/o Boundary Buffer	130.38†	495.58†	174.05†	127.16†	196.49†	36.68	0 / 5
w/o Watchdog Relay	61.75†	483.20†	227.48†	63.78†	197.28†	35.67	0 / 5
w/o Target-Broker	3167.08†	3681.16†	218.36†	571.84†	368.50†	149.61	0 / 5
SuperFALCON+ (Full)	**3648.53**	**3648.74**	**3664.89**	**3659.28**	**3655.61**	**406.90**	**5 / 5**

† Indicates premature termination due to a boundary fault, replanning stagnation, or local solver exception.

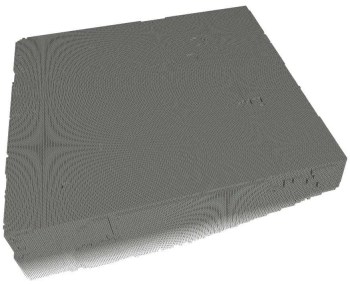
Boundary-constraint coordination. Removing the boundary buffer eliminates the additional configured support for local inflation and spatial queries. This configuration records boundary-related failures, completes 0/5 trials, and has a mean duration of 36.68 s. The result supports spatial configuration as a necessary integration consideration in the tested setup.

Repeated-goal-aware handoff supervision. Removing the watchdog relay completes 0/5 trials with a mean duration of 35.67 s and limited mapped volumes. This evaluates the relay component as a whole, including its role in target handoff. It does not separately measure the effect of logging repeated endpoints. The result links the functioning target interface to mission continuation without establishing a dedicated deadlock-escape mechanism.

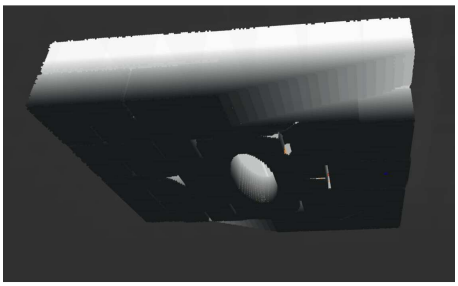
Local-constraint-aware target adjustment. The Target-Broker ablation removes target adjustment while retaining SUPER's native goal processing. It completes 0/5 trials with a mean duration of 149.61 s. Volumes vary substantially: some runs reach 3167.08 m^3 or 3681.16 m^3 before premature termination. This variability shows why volume and completion must be considered together. The comparison evaluates Target-Broker within the combined target-adjustment process, rather than independently evaluating SUPER's free-space projection.



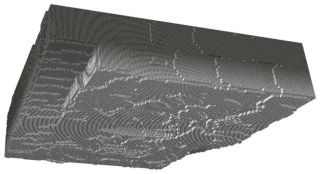
(a) EDEN
(Top/Iso View)



(b) SuperFALCON+
(Top/Iso View)



(c) EDEN
(Bottom-Up View)



(d) SuperFALCON+
(Bottom-Up View)

Fig. 8: Exploration outcomes in the Duplex Office. (a), (c) EDEN run with premature termination. (b), (d) SuperFALCON+ run with multi-level traversal. The views illustrate individual runs; aggregate outcomes are reported in Table 1.

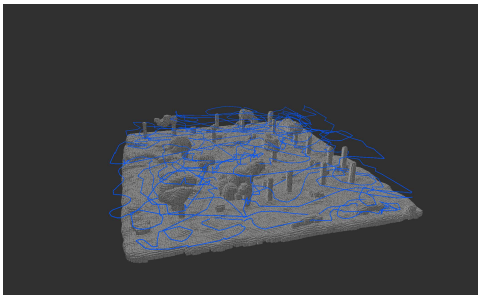
Complete coordination. With all three components enabled, the system completes 5/5 trials, with a mean volume of 3655.4 m^3 and mean duration of 406.90 s. In this ablation set, combining spatial reserve, target adjustment, and maintained handoff produces more consistent completion than any reduced configuration. The result supports the coordinated design in the tested integration; the separate Duplex Office results establish its remaining practical limits.

4.6 Real-World Validation

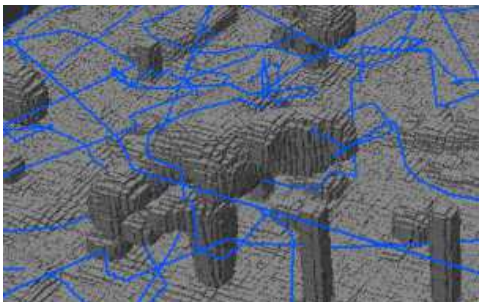
To validate the practical deployment of the proposed framework, SuperFALCON+ was implemented on a custom-built physical quadrotor. The hardware payload features a Livox Mid-360 LiDAR for omnidirectional depth sensing and an NVIDIA Jetson Orin NX 16GB onboard computer. This platform executes FAST-LIO2 [26] for real-time state estimation alongside the mapping, planning, and coordination modules. The outdoor campus test environment contained irregular tree trunks, thin branches, and



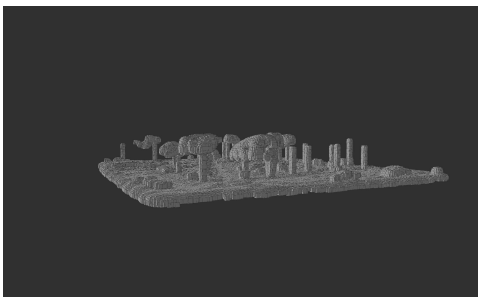
(a) Outdoor test environment



(b) Reconstructed flight trajectory



(c) Trajectory oscillations near a tree



(d) Exploration map

Fig. 9: Real-world validation of SuperFALCON+ in a campus environment. (a) The outdoor test site. (b) The reconstructed flight trajectory. (c) A close approach to a large tree produced pronounced trajectory oscillations, yet the integrated system remained operational. (d) The resulting exploration map confirms completion of the reported run.

dense foliage (Fig. 9). Wind and moving leaves introduced transient point-cloud noise and occasional mapping artifacts.

During a close approach to a large tree, the reconstructed trajectory exhibited pronounced oscillations. Despite this disturbance, the integrated system maintained the target handoff and local execution pipeline, remained operational, and completed the reported exploration run. The result demonstrates physical deployment and mission continuity in this representative trial. Controlled repeated trials and module-level outdoor ablations are still required to quantify disturbance rejection and attribute the behavior to individual coordination mechanisms.

4.7 Discussion and Scope

The three mechanisms incorporate different forms of operational awareness: known spatial requirements shape configuration, target geometry and local occupancy shape candidate processing, and repeated-target observations describe the request stream during execution. The empirical benefit is improved mapped extent and mission continuity in the tested settings. The reserve and target-adjustment parameters remain

configuration choices, while repetition recording currently supplies an observation rather than explicit recovery feedback. Future adaptation can build on these information sources by incorporating measured progress and planner feedback. A common evaluation region and explicit event and termination criteria remain necessary for interpreting the improvements.

5 Conclusion and Future Work

SuperFALCON+ addresses global–local target-execution mismatch through awareness of spatial requirements, local target conditions, and target-stream behavior. Boundary-constraint coordination incorporates prior knowledge of local-map operations into a calibrated reserve. Target-Broker and SUPER's native free-space projection use candidate distance and occupancy information to adjust exploration requests. Repeated-goal-aware supervision maintains their handoff while recording repeated endpoints. Comparative experiments show higher mean mapped volume and fewer premature terminations than the evaluated baselines, accompanied by lower speeds than FALCON. Component ablations support the coordination design, and outdoor flights demonstrate physical deployment. Future work will incorporate explicit progress and failure feedback to adapt boundary and target-adjustment parameters and extend the interface to multi-MAV exploration.

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Data availability The datasets, ROS/ROS2 configuration files, and source code generated during the current study will be made publicly available upon acceptance of this manuscript.