

An Open-Source System for Vision-Based Micro-Aerial Vehicle Mapping, Planning, and Flight in Cluttered Environments

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Abstract

We present an open-source system for Micro-Aerial Vehicle autonomous navigation from vision-based sensing. Our system focuses on dense mapping, safe local planning, and global trajectory generation, especially when using narrow field of view sensors in very cluttered environments. In addition, details about other necessary parts of the system and special considerations for applications in real-world scenarios are presented. We focus our experiments on evaluating global planning, path smoothing, and local planning methods on real maps made on MAVs in realistic search and rescue and industrial inspection scenarios. We also perform thousands of simulations in cluttered synthetic environments, and finally validate the complete system in real-world experiments.

1 Introduction

Autonomous navigation from on-board sensing is essential for Micro-Aerial Vehicles (MAVs) in many applications. In this work, we specifically target applications where MAVs can assist human operators in difficult tasks, such as search and rescue (S&R) and industrial applications. Core challenges in these areas include lack of GPS or other external sensing, unreliable communication (forcing the MAV to be self-sufficient without off-board porcessing), and having to operate close to structure with comparatively small platforms, limiting payload and sensing capabilities.

Aiming to present solutions for those challenges, this paper introduces an open-source system capable of performing autonomous online planning and mapping. Our previous work proposes dense mapping [1] and online replanning [2, 3] methods for safe navigation of previously-unexplored spaces. We focus on explicitly mapping free space in very cluttered environments, and exploring planning strategies that are inherently conservative: that is, they only allow traversal of space that is confirmed to be free. Here we aim to extend our local planning work to also cover global planning scenarios, where a map is already available (either on the return route of the current mission or from a previous mission), and explore interactions between local and global planning frameworks.

Furthermore, we compare various global planning methods, including improving on our previously-proposed topological graphs built from Euclidean Signed Distance Fields (ESDFs) [4]. We also extend our local

*Work peformed while at ETH, now with Oculus Zürich.



Figure 1: The platform used for collecting the test datasets, a custom-built drone using the DJI FlameWheel F550 frame, an Intel NUC for on-board processing, Pixhawk for flight control, VI Sensor for monocular state estimation and stereo depth, and an Intel Realsense D415 for RGB-D input.

replanner to be used as a path-smoothing method for converting lists of waypoints from global planners to dynamically-feasible timed trajectories. All global planning methods are evaluated on three realistic scenarios, two from a search and rescue training area, and one from an industrial environment with large machinery, recorded with the MAV system described in this paper.

We additionally improve our local planning architecture, and discuss how it fits in from a system perspective. We unify how global plans and single waypoints are handled and tracked, improve the performance of the local planner when goals are in unknown space, and validate the complete framework both in thousands of simulated scenarios and in real-world experiments.

The aim of this work is to introduce an open-source *complete system* dealing with the aforementioned challenges. This set-up allows the robot to be robust to loss of communication (which is typical in for example S&R scenarios), and behave intelligently and safely even when not under direct control of a human. We discuss the control, state estimation, sensor, and hardware concerns and requirements for such systems, and make the software for all parts available open-source.

In summary, the main contributions of this work are as follows:

- A complete open-source system for autonomous GPS-denied navigation.
- A thorough treatment of considerations in 3D mapping for planning applications, expanding on our previous work [1] with regards to unknown space and generation methods.
- We extend our previous work on topological sparse graph generation [4] to create more useful graphs, faster.
- A discussion and comparison of various global planning methods on real maps.
- We extend our previous work in local planning [2, 3] to also be usable for path smoothing and compare several methods.
- Finally, we unify our previously-proposed local planner architecture to create a system that can both smooth global trajectories, locally explore in unknown space, and deal with changes in a map by actively replanning.

2 Related Work

In this section we will mostly focus in reviewing previous work presenting similar complete systems. For a more thorough discussion of state of the art in the individual components we refer the reader to our previous work [2, 1, 3, 4], and more detailed comparisons to other works are offered in each individual section of the system.

We aim to show a complete system for mapping and planning on-board an autonomous UAV, using vision-based sensing. Lin *et al.* [5] presented a similar complete system, spanning visual-inertial state estimation, local replanning, and control. However, there are a few key differences between the frameworks proposed: ours focuses strongly on the map representation we use and exploiting all the information within, while theirs uses a standard occupancy map. More importantly, our planning is *conservative*, meaning we will only traverse known free space, while theirs assumes unknown space is free. Therefore, we must make more considerations about the contents of our map with our restrictive assumptions. We also offer an evaluation of global and path smoothing planning methods.

Mohta *et al.* [6] also propose an autonomous system for fast UAV flight through cluttered environments. There are also a few key differences with their work, especially on mapping and planning. They use a LIDAR as the main sensor, which gives 360° field of view to collision detection, removing many of the issues with narrow field of view sensors which we attempt to address in this work. They also only keep a small local 3D map, and use a global 2D map to escape local minima, whereas we use a full global 3D approach at comparable computation speeds. For how the mapping is used, they attempt to break the world into overlapping convex free-space regions, which grows in complexity and is increasingly more limited as the space gets more cluttered, while we always plan directly in our map representation. They also make no considerations for how drift will affect the map other than to keep only a local 3D map.

Finally, the system we propose is conceptually similar to the original system in our previous work [7]. The core differences are that we improved every individual component, designed and evaluated a custom mapping system, and proposed a way to do local replanning as well (whereas the previous work was only global planning). This makes the system proposed in this work much more robust and able to deal with changes in the environment. Additionally, in this work we discuss practical requirements for real-world applications and make every part of the system available open-source.

3 System Overview

We describe a complete MAV hardware and software system capable of supporting autonomous flight with only on-board vision-based sensing. All of the software described in the system has available open-source with provided links.

3.1 Overall Architecture

We show an overview of the complete system in Fig. 2, focusing on the data flow between mapping and planning processes. Stereo and depth images can be used interchangeably for the mapping, combined with a pose estimate from visual-inertial monocular odometry. The odometry is then fused with the body IMU of the MAV to create a high-rate pose estimate used for control. Position control runs on the on-board computer, and gives roll, pitch, and yaw-rate commands to the attitude controller on the flight controller. The output of the planning stack are timed trajectories, sampled at the position controller rate (typically 100 Hz). Since we use a model-predictive controller (described in more detail below), this allows us to have a much higher trajectory tracking accuracy due to the long prediction horizon.

The diagram shows operation set up over two stages: the first is online flight through completely or partially

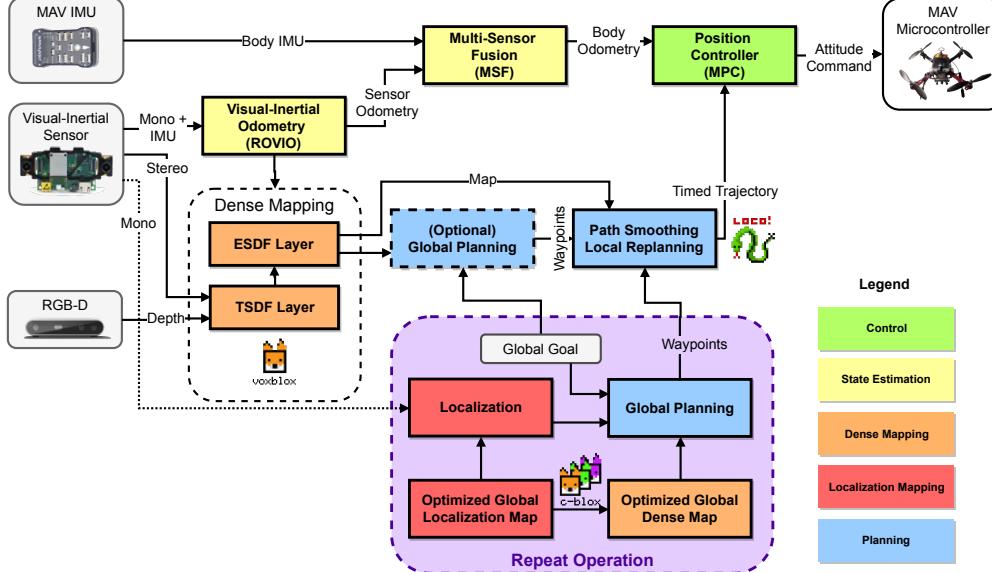


Figure 2: Overall system architecture, showing most key components of the system, and the data flow between especially global and local components. The initial inspection of an environment takes place using local replanning and avoidance through unknown space, and repeated missions use mostly the global planning framework. Though to allow our system to deal with dynamic obstacles, changes in the environment, and potentially drifting maps, the local planner will always collision-check and re-plan any trajectories before execution.

unexplored space, in white, and in purple global planning in previously-built maps. This system allows us to do an initial flight, optimize a map using off-line tools, then perform repeat inspections in the same area. Using a local planner on the output of the global planners guarantees that even if the environment changes between missions, we are able to safely navigate through it by replanning locally. Likewise, we can use the same tools without stopping to optimize a map – for instance, using a global planner to return home at the end of a mission.

3.2 Hardware

Fig. 1 shows the MAV used to collect the evaluation datasets and test the overall system. It is built around a DJI FlameWheel F550, with 6 motors for actuation. The low-level control is performed with a pixhawk¹, using custom firmware that accepts attitude and yaw-rate commands ². This is necessary as we do not use GPS and fly indoors and in other environments where magnetometer readings are unreliable, therefore giving an absolute yaw reference is both undesirable and meaningless in our local coordinate frame.

On-board processing, which runs everything shown in Fig. 2, is performed on an Intel NUC. The main sensor is a custom-made visual-inertial sensor [8], with two monochromatic cameras in a stereo configuration, hardware-synced to an ADIS448 IMU. It is used for mono visual-inertial state estimation, and also for stereo depth for mapping. Optionally, we also use an Intel Realsense D415 for an additional source of RGB-D depth.

Though a dedicated visual-inertial sensor is a nice-to-have for such platforms, there is currently not one available off the shelf that is suitable for MAV flight. Instead, we recommend using a USB machine vision camera, and hardware time-synchronizing it to a flight controller. We make a sample driver implementing

¹<http://pixhawk.org>

²http://github.com/ethz-asl/ethzasl_mav_px4

this for the FLIR Blackfly or Chameleon 3³ and the pixhawk available⁴. We make our instructions for setting up such a system and considerations with regard to timing accuracy available online⁵. This set-up is also extendable to multi-camera systems, as multiple cameras can be triggered from the same pulse.

3.3 Control

We use a cascaded control architecture, with an inner loop that controls attitude and runs at a minimum of 100 Hz on the MAV autopilot, and an outer position control loop that runs on the on-board computer at 100 Hz. For the outer loop, we use a non-linear Model Predictive Control (MPC), proposed by Kamel *et al.* [9] and available open-source⁶.

The MPC takes in the body odometry estimates from Multi-Sensor Fusion (MSF, described in Section 3.4) and a timed full state trajectory to track. We exploit the properties of the flat state for MAVs to only need to specify position, yaw, and their derivatives [10].

One of the advantages of using an MPC over a PID loop for trajectory tracking is that the MPC is able to look ahead at future trajectory points, and minimize tracking error over the complete prediction horizon. This means that overall trajectory tracking performance is improved significantly, and there are advantages to planning high-fidelity, dynamically-feasible trajectories, as they will be executed almost perfectly.

The non-linear MPC also has a *very* long horizon of 3 seconds, or 300 timesteps. While this is very convenient for executing long complex global trajectories, special care must be taken when using it for online replanning. Namely, we need to timestamp our entire trajectory to be monotonically increasing, and trajectory updates must be inserted into the correct place in the MPC queue. The queue is cleared if a trajectory with a time before the current execution time is sent, and the new trajectory replaces the complete queue. Fig. 3 shows an example of a replan cycle, happening for the purposes of the illustration at 50 Hz. The MPC queue is initialized with a starting trajectory. The local replanning “locks” the beginning of the initial trajectory, including the first 20 ms which is when the controller will receive the updated trajectory, and also another 30 ms look-ahead so that the reference does not change too quickly, then replans starting at 50 ms. A 3 second chunk, starting at the 50 ms, is then sent to the controller queue, which inserts the updated trajectory at the correct time, even though it has only executed up to 20 ms.

This queueing scheme allows us to replan at any given rate, while making sure that the controller always has a reasonable trajectory within its time horizon.

3.4 State Estimation

All state estimation is done on-board and not using external sensing (i.e., no vicon or GPS). This gives our system flexibility to be used in complex GPS-denied environments. Our main state estimator is Rovio⁷, which is a robust visual-inertial odometry framework [11], [12]. Rovio is a filter-based estimator, which uses direct photometric error on a small number of patch features in the image. For our application, this design has a few distinct advantages over more traditional, keypoint-based methods like Okvis [13]: a filter with a small state-space (using only 25 features) is fast to compute, even on the on-board CPU, and using direct photometric error makes the method resistant to motion blur. In our experience, Rovio is comparably accurate to other methods such as Okvis and VINS-mono [14], but more robust under real conditions.

However, Rovio only gives us the odometry in the *sensor* frame, which for our system is usually the IMU that is part of the visual-inertial (VI) sensor. Rovio also only outputs updated poses at the camera frame

³<http://ptgrey.com/blackfly-usb3-vision-cameras>

⁴http://github.com/ethz-asl/flir_camera_driver

⁵http://github.com/ethz-asl/mav_tools_public/wiki/Visual-Inertial-Sensors

⁶http://github.com/ethz-asl/mav_control_rw

⁷<http://github.com/ethz-asl/rovio>

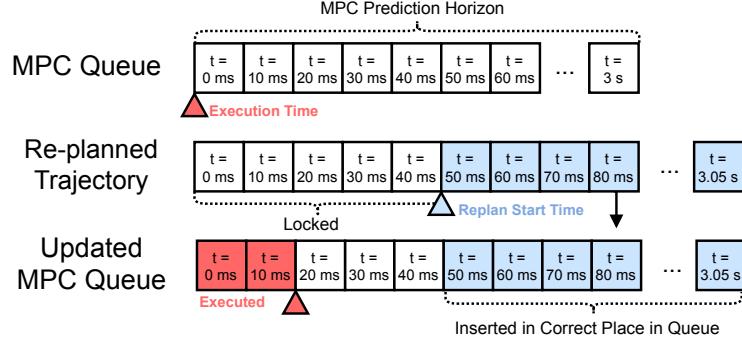


Figure 3: Diagram showing the MPC queue, and how it is updated when a section of the trajectory is replanned. Note that slightly more of the trajectory is locked down than is executed during the planning time. This allows the MPC to not have very abrupt changes in reference. For illustration purposes, the MPC is shown here running at 50 Hz, while it normally runs at 100 Hz on the real platform.

rate. Depending on the hardware set-up, we have two solutions to receive body-IMU-frame odometry at 100 Hz.

If using a separate VI sensor, then the odometry estimate from Rovio must be transformed into the body frame and fused with the body IMU. This is done using Multi-Sensor Fusion (MSF) [15], which is a highly-configurable filter capable of taking multiple sensors and pose sources⁸.

In another configuration, where the only IMU on the system is hardware time-synchronized to a camera, no transformation or fusion needs to be done. We only need to use the estimated Rovio IMU biases to propagate the odometry estimate using incoming IMU measurements. This is done using a package called `odom_predictor`, which queues incoming IMU measurements and re-applies them when new (delayed) estimates are available from Rovio. It is also available open-source⁹.

3.5 Localization

This paper aims to address issues with creating dynamically-feasible global plans. However, global planning requires *global localization*. Since all visual- and visual-inertial odometry frameworks drift, no matter how little, long-term operation or operation in previously-explored environments requires the ability to perform loop-closures.

To localize against a global map, we use `maplab` [16], an open-source¹⁰ framework for creating, storing, optimizing, and localizing in visual-inertial maps.

To create global maps, we first generate a sparse pose-graph of landmarks in the observed scene. This is done by using `Rovoli` [16], a front-end for Rovio that also does feature tracking and extraction (independently of Rovio’s 25 tracked patch features).

This sparse graph can then be loop-closed and optimized using bundle adjustment in an offline process, giving optimized, globally-consistent poses for all keyframes. To generate the global map, we can then replay all pointclouds from the initial flight and integrate them into a dense map using optimized poses. Localization in the matching sparse map will then line up correctly with the optimized dense map.

If using ORB-SLAM [17] as the SLAM system, a better approach is to build up a dense map using submaps,

⁸http://github.com/ethz-asl/ethzasl_ms

⁹http://github.com/ethz-asl/odom_predictor

¹⁰<http://github.com/ethz-asl/maplab>

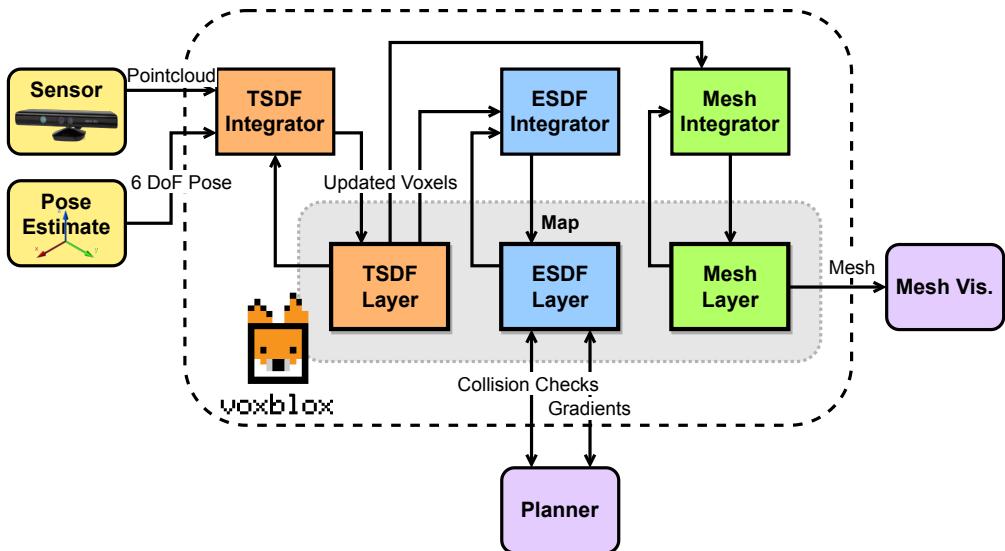


Figure 4: Voxblox system diagram, showing how the TSDF and ESDF layers are interconnected through integrators.

and only fuse them when the covariance between their relative poses is small enough, as presented in our previous work [18]. This allows us to get a globally-optimal dense map in a single step, without having to run a recorded dataset through an offline framework. However, since ORB-SLAM does not support localization against a previous map, this limits us to global localization within a single mission.

4 Dense Mapping

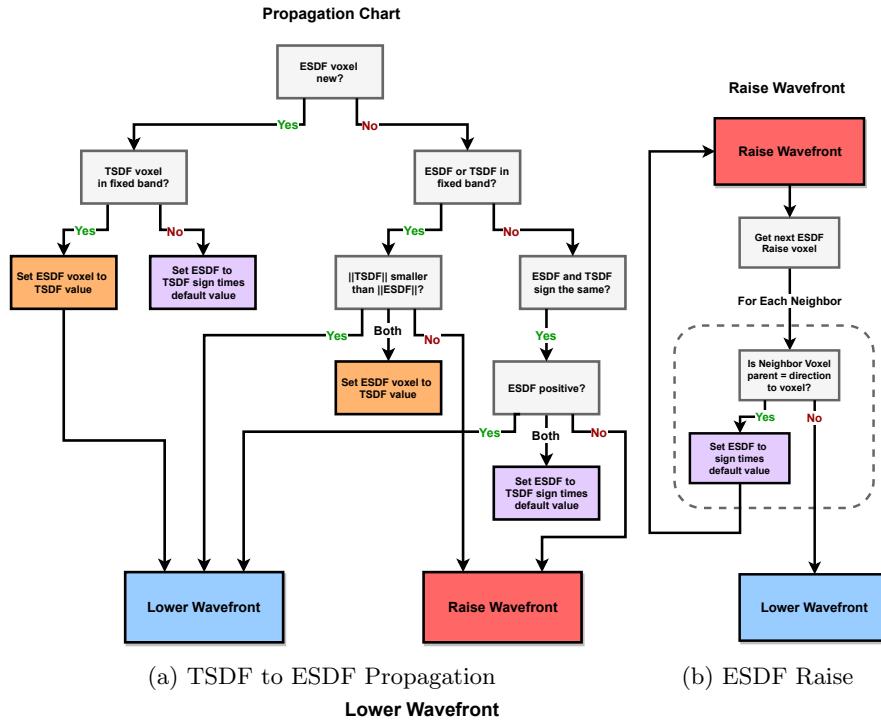
Dense mapping is key to planning performance, as a plan can only be as good as the map. We use a flexible mapping framework called *voxblox*¹¹, introduced in our previous work [1]. The framework is centered around using Signed Distance Fields (SDFs), or voxel grids of distance values to surfaces. We use two different types of SDFs: Truncated Signed Distance Fields (TSDFs), based on Curless and Levoy [19] and KinectFusion [20] for integrating point cloud data, in a method that gives a more accurate surface estimate than occupancy-based methods, but uses projective distances and truncates the value to a small band around surface crossings. The second type of field is a Euclidean Signed Distance Field (ESDF), which store Euclidean, rather than projective distance to each obstacle, and are not truncated to a specific range. These ESDFs are then the representation we use for planning, as they contain collision information for the entire map, and can also be used to quickly get obstacle gradients, which will be essential for some of the planning methods below. A system diagram showing inputs, outputs, and data flow is shown in Fig. 4.

4.1 Euclidean Signed Distance Fields

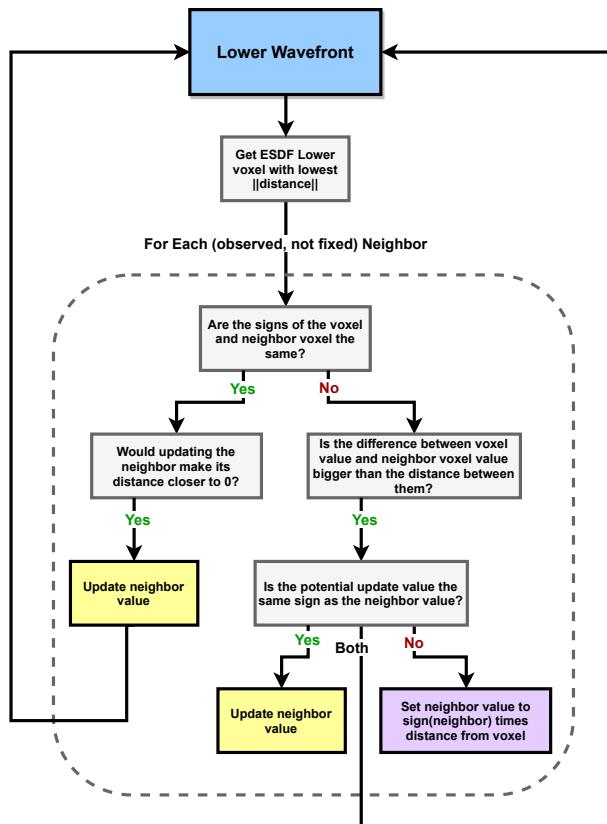
This section will discuss how an ESDF is computed from a TSDF. A more thorough analysis, including upper bounds on error introduced by various assumptions and a comparison with occupancy-based methods is offered in our previous work [1].

While it might seem unintuitive that there is a non-trivial process to convert from a TSDF to an ESDF, this is because the distances in both representations are computed differently. TSDFs use projective distance, or distance along the ray cast from the sensor to the surface. These distances are fairly accurate near surface

¹¹<http://github.com/ethz-asl/voxblox>



Lower Wavefront



(c) ESDF Lower

Figure 5: Diagrams explaining how the ESDF is constructed in three stages.

crossings, but quickly accumulate large errors [21]. In contrast, an ESDF needs true Euclidean distances, which can only be calculated in a global fashion. Luckily, incremental algorithms exist for computing ESDFs from occupancy maps [22], and our work extends these methods to also work from TSDFs.

Generating the ESDF is done in three stages, detailed in Fig. 5: propagation (a), raise (b), and lower (c). The first, and most different from occupancy-based methods such as [22], is the TSDF to ESDF propagation. Due to the inaccuracy of TSDF distance estimates, we define a radius called a “fixed band” around the surface, which must be at least one voxel size and at most equal to the truncation distance. TSDF values that fall within this band are considered fixed, copied into the ESDF, and can not be altered in the ESDF update. Next, updated voxels may simply retain their value, or be put into the “lower” wavefront (when their updated distance values are closer to the surface than before) or the “raise” wavefront (when their values become farther from the surface). If performing a batch update (i.e., the entire layer at once), all voxels will go to the lower wavefront.

After propagating all updated values from the TSDF into the ESDF, we then process the raise wavefront. This consists of simply invalidating all voxels in the wavefront and their children. Since each voxel stores its “parent” (if the voxel is in the fixed band from the TSDF, it is its own parent), this is then an incremental brushfire operation. All voxels cleared from the raise wavefront have their still-valid neighbors added to the lower wavefront, to guarantee that their values get updated.

The lower wavefront behaves similarly to the occupancy case: iterate over all voxels in the lower wavefront, if their neighbor’s distance to the surface can be lowered through the current voxel, then update the neighbor and add it to the lower wavefront. Special distinctions must be made when implicit zero-crossings exist: i.e., two voxels are neighbors with opposite signs, and neither is fixed. This case is further explained in Fig. 5c.

4.2 Unknown Space

A key problem with mapping for collision avoidance is deciding how unknown space is handled. There are two options: treating all unknown space as free (optimistic), and treating all unknown space as occupied (pessimistic or conservative).

While many local collision avoidance works treat unknown space as free and have a high replan rate to avoid collisions [23], this is inherently unsafe. While it works well in uncluttered environments, where most unknown space *is* free, this assumption gets progressively worse as obstacle density in the environment increases and sensor field of view decreases.

Since our work aims to deal with the worst possible case, which is very obstacle-dense environments and a narrow field-of-view sensor, we cannot adopt the optimistic strategy. In fact, we always plan to stop in known free space, to guarantee safety in partially-unexplored environments.

However, it is a challenge to encode unknown space information in the ESDF, as the ESDF integration requires TSDF distances to build on, and those are either positive or negative. There is the additional problem that the MAV has no knowledge of the state of its current position at start-up or take-off, as it has never observed the space it occupies at the start. Furthermore, if the sensor has a very narrow field of view, the space it perceives in front of the sensor may not be wide enough to fit the entire robot body, essentially paralyzing the robot to never move. Finally, it is not clear how to correctly treat voxels bordering unknown space in ESDF computation.

We propose a simple strategy to resolve these issues, originally proposed in our previous work [3]. The idea is to have two overlapping “spheres” centered around the current robot pose that are applied in the ESDF, shown in Fig. 6. The inner sphere is small and only slightly larger than the robot radius and is called the “clear sphere”, which sets unknown space within it to free in the ESDF. The outer sphere affects all points not within the clear sphere and sets all unknown voxels to occupied. Any voxels that receive distances from

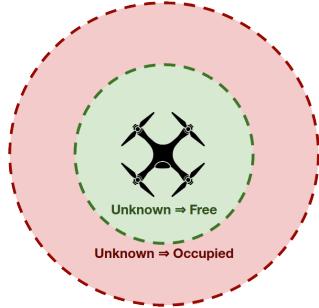


Figure 6: Diagram showing the two radii around the current robot pose: a small clear sphere, which should be only slightly larger than the robot, and an occupied sphere, which should be roughly the size of the planning radius.

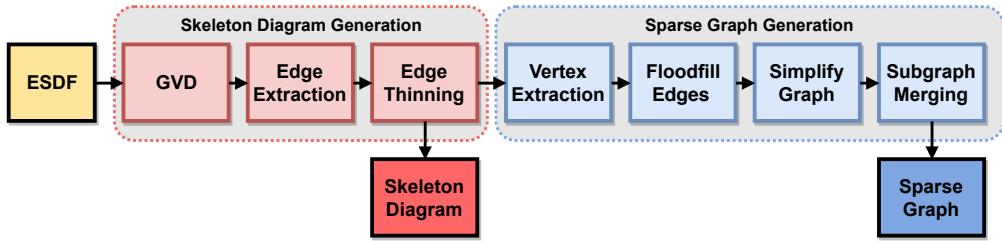


Figure 7: Steps in generating a sparse topological graph, also referred to as a skeleton graph.

this operation are marked as hallucinated in the map, so that as soon as real distance measurements are available from the TSDF, their values are overwritten.

5 Sparse Topology

In this section, we extend our work on generating sparse topological skeletons from [4]. We describe a complete method to extract a sparse graph of the traversable free space in an ESDF from only ESDF map data. This sparse graph is then used for very fast global planning later sections of this work.

Our main contributions over our previous work in this section include:

- Switching to a simpler definition of the Generalized Voronoi Diagram (GVD), using 26-connectivity.
- Extending the method to work for both full and quasi-Euclidean distance.
- Speeding up sparse graph construction through use of flood-fill operations on the edges.
- Proposing a new sparse graph simplification and sub-graph re-connection methods, which produce more usable graphs significantly faster.

Fig. 7 shows the stages in the process, illustrated at key points with Fig. 8.

First, the generalized voronoi diagram (GVD) is constructed. This is done by iterating all voxels in the ESDF to attempt to find “ridges” or “basis points”. A point is considered a basis point if its neighbors have parent vectors that are at least some angle apart. The angle differs depending on whether quasi-Euclidean or full Euclidean distance is employed, as quasi-Euclidean has a lower resolution in parent directions. For full Euclidean distance, the separation angle is 45° , and for quasi-Euclidean it is 90° .

We use a different definition of what belongs on the GVD from our previous work, making the definition

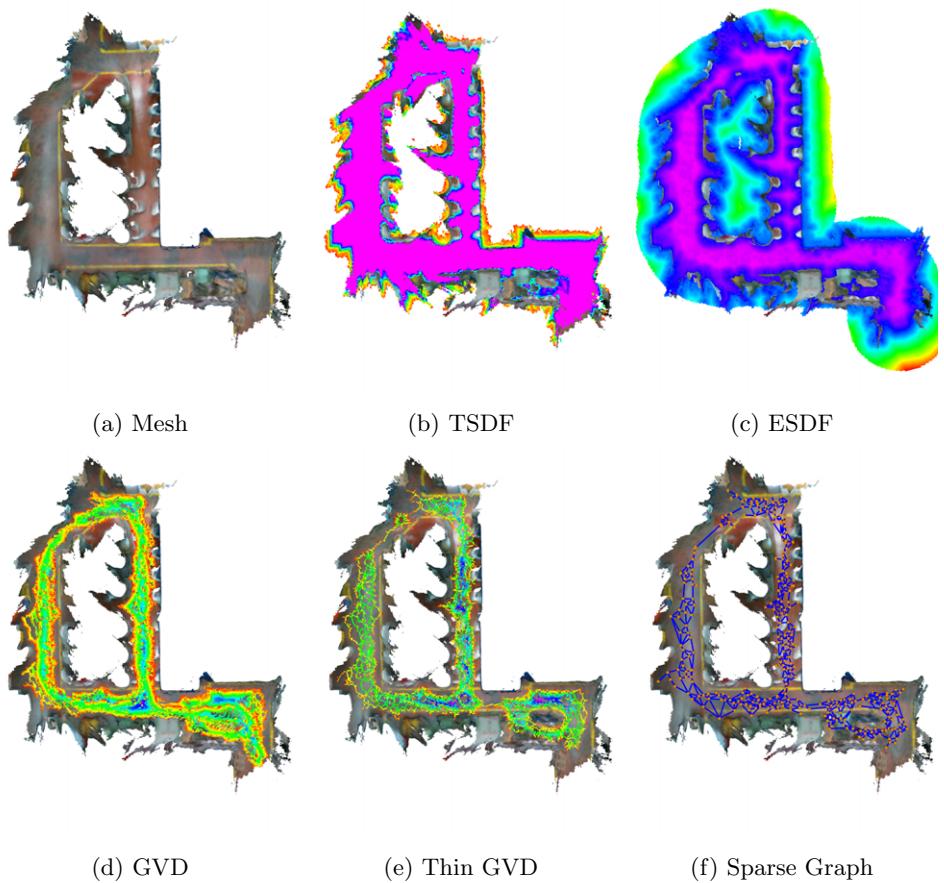


Figure 8: Different stages of sparse topology skeleton computation, shown on the machine hall realsense dataset. Colors represent distances from obstacles.

simpler and more physically meaningful. Before we used 6-connectivity when evaluating belonging on the GVD, but now we use full 26-connectivity for all parts of the process. A point is considered a GVD face if it has 9 or more neighbors that are basis points, an edge if it has 12 or more, and a vertex at 16 or more. For the purposes of the remaining method, we do not consider faces, as the goal is to build as sparse of a diagram as possible.

Finally, to create a sparse diagram (which is simply a voxel layer containing number of basis point neighbors and whether the point is an edge or vertex or not), we apply a series of thinning operations described in more detail in [4]. Fig. 8d and e show the difference before and after thinning: after the operation is applied, all that is left is a one voxel-thick skeleton diagram.

To be more useful for planning, we want to further sparsify this diagram into a graph, removing the notion of discrete voxel sizes. We propose a different method of generating the sparse graph from the skeleton diagram here, which does not follow the underlying diagram exactly (as our previous work did) but greatly simplifies it. The downside to this is that edges no longer follow the maximum-clearance edges, but may now pass through intraversable space. However, they will always be *very near* traversable space, therefore as long as a flexible smoothing method is employed afterwards, a feasible path will be found.

We take all vertices in the skeleton diagram, assign them unique vertex IDs, and perform a flood-fill in all directions that contain edges, labelling the edges with the two nearest vertex IDs. This is a speed improvement and simplification over our previous “edge-following” algorithm, and does not suffer from edge cases where edge connections are missed.

To simplify this graph, we attempt to remove all vertices that are not adding information to the graph – essentially, vertices that are on straight lines or nearly-straight lines between other vertices. The filter consists of removing vertices that have exactly two edges, and whose removal will not displace the edges more than 2 voxels.

As a final step, we attempt to find any way to reconnect disconnected subgraphs. We label each self-contained subgraph in the sparse graph with another flood-fill operation, and assign subgraph IDs. We then iteratively search for connections from all subgraphs to all other subgraphs: if a connection is found, one of the subgraphs is relabelled. To see if two sub-graphs can be connected, we first search along the skeleton diagram using A*: if a connection exists, we insert a new edge between the two closest vertices. If no connection exists in the diagram (which very occasionally happens due to discretization error), we search in the traversable space of the ESDF, again using A*. If a path exists there, then we attempt to verify that ESDF path is valid and close to straight-line.

Both of these methods are much faster and more reliable at producing usable sparse planning graphs than our previous approach.

6 Global Planning

In this section we will discuss different global planning strategies and their advantages and disadvantages. It is assumed that a complete global map is available for these methods. We plan only in position space, assuming the MAV is a sphere for collision-checking purposes (as this makes it rotationally-invariant), and the output of all the global planners is a list of position waypoints from start to goal. All methods described here are available open-source¹².

¹²http://github.com/ethz-asl/mav_voxblox_planning

6.1 Sampling-based Methods

The first class of methods we will consider are sampling-based methods. They are very well suited for large 3D problems, as they do not suffer from the same scaling problem as search-based methods. One of the most commonly-used classes of methods is Rapidly-exploring Random Trees (RRT) [24], where random points are sampled in the planning space (in our case, just 3D position space) and iteratively connected to a tree. Once the goal point is sampled, there exists a path from the start point (the root of the tree) to the goal.

One key advantage of this class of methods is that all that is required is a way to determine if a randomly-sampled state is valid or not, and a way to determine whether connections between states are valid. We propose two different methods to do this: one in the ESDF, which is pessimistic (assuming unknown space is occupied) and on the TSDF, which is optimistic (assuming unknown space is free). As long as they are coupled with a conservative/pessimistic local planner, either method can be used.

The look-up in the ESDF requires only a single point per pose (as the ESDF already stores the distance to the nearest obstacle, and therefore as long as that distance is larger than the robot radius, the point is feasible), while the TSDF look-up requires looking up an entire sphere and every voxel within. Additionally, for determining if motions between two states are valid, we use a ray-cast operation to not miss any potentially occupied voxels.

Here we briefly review a few of the methods that we benchmark in the evaluations.

RRT-Connect is a very fast variant of the original RRT algorithm, which does a bi-directional search: growing a tree from both the start and the goal points [25]. One the downside, it does not optimize the paths (the algorithm terminates once a path is found), so they are often much longer than necessary in complex environments. For the purposes of our benchmarks, we treat this as the “first solution” time and solution length for RRT-based algorithms.

RRT* combines the best of both A* (which is an optimal planning algorithm) and random sampling to create a probabilistically-optimal planning solution [26]. This method samples new points and rewrites the graph for shorter solutions, up until a time-limit is reached. There are other variants, such as Informed RRT* [27], which iteratively shrink the sampling space after an initial solution is found, similar to how the admissible heuristic is used in A*.

In general, this is the class of methods we prefer to use, as they give short, nearly-optimal paths, and it is possible to decide how to trade-off computation time versus optimality depending on application.

For planning in a changing map, RRT-based methods are a very powerful tool, as they do not store any information between planning queries. However, for global planning in a static map, this discards and replicates a large amount of sampling effort. Therefore, Probabilistic Roadmaps (PRMs) are suitable for many applications where the map remains fixed.

These approaches are similar to the topological graphs described below, in that they usually consist of two stages: building the roadmap, and then searching the roadmap for a solution. However, they suffer the same drawbacks as all probabilistically-optimal methods: it is not clear how much sampling is “enough” sampling, so it can only be decided by heuristics, and small openings or narrow corridors pose huge problems for PRM-based methods (as the chances of samples landing within them are small).

6.2 Topological Graphs

Our proposed method is a search through the sparse topological graph generated in Section 5. Unlike PRM-based methods, ours is deterministic and has a fixed computation time. Additionally, since the graph is based on the structure of the ESDF, which already encodes the geometry of the scene, it does not suffer from

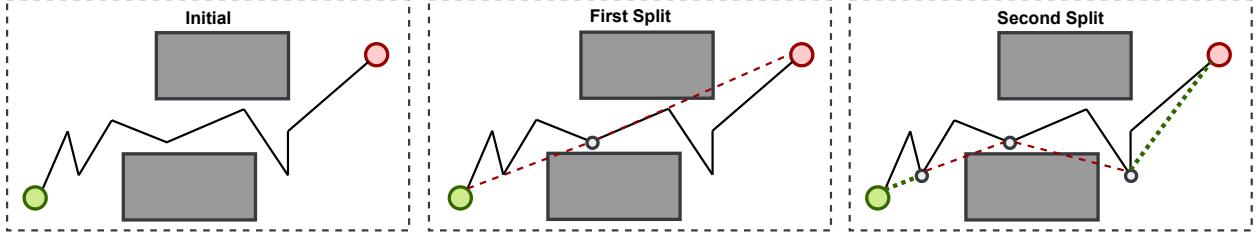


Figure 9: First three steps of binary-search graph shortening. The path is iteratively split in half, until sub-paths are able to be shortened or no more splits are possible. Green shows successful shortened paths, while red shows invalid shorten attempts.

narrow corridor openings. The downside to this fixed execution and search time is that while the graph will contain all topologically-distinct homotopies of the space, it is not guaranteed that the path length in the graph is the same as the shortest path length through the space. We perform graph shortening (described below) to attempt to overcome this issue, but it is possible that an incorrect homotope will be selected (though this can also be a problem in PRMs, depending on how the point distributions are sampled).

The method works as a two-stage search, starting from the sparse graph from Section 5. We first find the nearest sparse graph vertex to the start and goal by using a pre-computed k-D tree of vertices. Then we find a path through the graph using A*. Due to the small size of the graph, this is a very fast operation, so it is possible to solve the problem for multiple start and goal vertices from the k-D tree to attempt to find a better solution. Finally, we plan from the start pose to the start vertex using A* in the ESDF, and likewise for the goal. Since these distances are always short, this is also not an expensive process.

6.2.1 Graph Shortening

While planning through the sparse topological graph is extremely fast, the waypoints it produces aim to maximize clearance, not necessarily minimize absolute path length (path length on the *graph* is minimized) through all traversable space. For instance, even a straight-line path from A to B would zig-zag along the maximum clearance lines in the graph.

To overcome this, we use iterative path shortening in the ESDF. We attempt to short-cut between pairs of waypoints on the initial graph path in a binary search manner, checking for traversability in the ESDF map, shown in Fig. 9.

We first try to shortcut directly from start to goal; if the straight-line path is not traversable, we then split the waypoint list into two halves: front to middle and middle to back. Each half is then iteratively checked, whether the intermediate vertices can simply be removed; if not, it is further split into two halves.

We perform this full splitting procedure multiple times to ensure that no further shortening is possible. This is similar to what the OMPL library [28] does with the RRT-planned paths, with the important distinction that our method is deterministic, while theirs randomly tries to connect pairs of waypoints. This means that ours does not need heuristics to know when it is terminated: once no more changes are made, the waypoint list is as shortened as possible. The randomized approach requires options such as maximum steps and maximum empty steps (steps that do not shorten) before terminating, which means that it may still be possible to shorten the graph at termination.

7 Path Smoothing

Path smoothing deals with taking a set of waypoints and converting them to a smooth, dynamically-feasible path. We present three methods we compare for these purposes: velocity ramp, polynomial, and our approach named Loco. We enforce dynamic constraints in the form of maximum velocity and acceleration limits.

7.1 Velocity Ramp

The simplest method is velocity ramp. A straight-line path is drawn between consecutive pairs of waypoints, and maximum acceleration is applied until the velocity limit is reached, at which point the acceleration is zero. The same principle is applied on decelerating toward the next point.

The total time between two waypoints is described as:

$$t = \frac{v_{max}}{a_{max}} + \frac{\|\mathbf{x}_{goal} - \mathbf{x}_{start}\|}{v_{max}} \quad (1)$$

where t is the time in seconds, v_{max} and a_{max} are the velocity and acceleration constraints, respectively, and \mathbf{x}_{start} and \mathbf{x}_{goal} are the 3 DoF positions of the start and goal.

7.2 Polynomial

High-degree polynomial splines are a common representation for MAV trajectories, as they are easy to compute, can be smooth and continuous up to high derivatives, and are shown to be dynamically feasible as long as velocity and acceleration constraints are met [10], [29].

We implement a path smoothing method from Richter *et al.* [29], where a polynomial spline is fit to the waypoints and then iteratively split at collisions.

First, we discuss the optimization problem. We formulate it to minimize a high derivative such as jerk or snap, as shown to be desirable by Mellinger *et al.* [10].

We will consider a polynomial spline in K dimensions, with S segments, and each segment of order N . Each segment has K dimensions, each of which is described by an N th order polynomial:

$$f_k(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \dots a_N t^N \quad (2)$$

with the polynomial coefficients:

$$\mathbf{p}_k = [a_0 \ a_1 \ a_2 \ \dots \ a_N]^\top. \quad (3)$$

Rather than optimizing over the polynomial coefficients directly, which has numerical issues at high N s, we instead optimize over the end-derivatives of segments within the spline [29]. We distinguish between fixed derivatives \mathbf{d}_F (such as end-constraints) and free derivatives \mathbf{d}_P (such as intermediate spline connections):

$$\mathbf{p} = \mathbf{A}^{-1} \mathbf{M} \begin{bmatrix} \mathbf{d}_F \\ \mathbf{d}_P \end{bmatrix}. \quad (4)$$

Where \mathbf{A} is a mapping matrix from polynomial coefficients to end-derivatives, and \mathbf{M} is a reordering matrix to separate \mathbf{d}_F and \mathbf{d}_P .

We aim to minimize the derivative cost, J_d , which represents a certain derivative (often jerk or snap) of the position [10], with \mathbf{R} as the augmented cost matrix.

$$\begin{aligned} J_d &= \mathbf{d}_F^\top \mathbf{R}_{FF} \mathbf{d}_F + \mathbf{d}_F^\top \mathbf{R}_{FP} \mathbf{d}_P + \\ &\quad \mathbf{d}_P^\top \mathbf{R}_{PF} \mathbf{d}_F + \mathbf{d}_P^\top \mathbf{R}_{PP} \mathbf{d}_P \end{aligned} \quad (5)$$

Finding the \mathbf{d}_P^* that minimized J_d is possible to do in closed-form [29]:

$$\mathbf{d}_P^* = -\mathbf{R}_{PP}^{-1} \mathbf{R}_{FP}^\top \mathbf{d}_F \quad (6)$$

This method allows us to fit a smooth polynomial spline to a series of waypoints, by using the positions of the waypoints as vertex constraints.

However, since waypoint trajectories are planned such that the *straight-line* path (visibility graph) between them is collision-free, the smoothed path often runs into collision. To remedy this, any time a collision is detected, this method adds a new waypoint on the visibility graph closest to its projection onto the straight-line path, and the optimization is re-run.

While this is fast and easy to implement, this method suffers from occasionally not being able to escape collisions, and in difficult cases, creates many extra waypoints. The optimization problem does not scale well numerically when there are many waypoints, especially close together in time, as the segment times get very short (and must be raised to high powers). Furthermore, adding these additional waypoints often perturbs the trajectory in unexpected ways, causing the robot to take large detours.

7.3 Local Continuous Optimization (Loco)

To overcome these issues, we propose our own method, Local Continuous Optimization method, Loco [2]. Rather than iteratively collision-checking and splitting the trajectories, we introduce the collisions as soft costs in the optimization, following the general structure that Ratliff *et al.* [30] proposed in their CHOMP method.

Introducing this soft cost leads to the following optimization problem, where w terms are constant weights:

$$\mathbf{d}_P^* = \underset{\mathbf{d}_P}{\operatorname{argmin}} \ w_d J_d + w_c J_c \quad (7)$$

J_d remains as in (5) above, and we introduce a new term, J_c represents a soft collision cost:

$$J_c = \sum_{t=0}^{t_m} c(\mathbf{f}(t)) \|\mathbf{v}(t)\| \Delta t \quad (8)$$

which approximates the line integral of costs along the path, where $c(\mathbf{x})$ is the collision cost from the map, $\mathbf{f}(t)$ is the position along the trajectory at time t , and $\mathbf{v}(t)$ is the velocity at time t .

For the collision cost in the map, we use a smooth gradually decreasing function proposed in CHOMP[30], where ϵ is a tuning value for how far outside the robot radius we care about collisions, \mathbf{x} is a position in the map, and $d(\mathbf{x})$ is the ESDF distance at that point:

$$c(\mathbf{x}) = \begin{cases} -d(\mathbf{x}) + \frac{1}{2}\epsilon & \text{if } d(\mathbf{x}) < 0 \\ \frac{1}{2\epsilon}(d(\mathbf{x}) - \epsilon)^2 & \text{if } 0 \leq d(\mathbf{x}) \leq \epsilon \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

In practice our robot radius is rarely 0, so we subtract the robot radius r from $d(\mathbf{x})$.

Now that we have a method of locally optimizing trajectories to be collision-free, evaluated at length in our previous work [2], the question is how to best make it fit through a series of waypoints.

We can use the starting method described above, where each waypoint simply becomes a control point/vertex in the spline. This means that for every waypoint, we have another segment in the spline. This has various downsides, most notably that for long, complex trajectories, the problem gets significantly slower computationally, and can have numerical scaling issues.

We found in practice that the optimization works best with a small (3-5) number of segments, therefore we explored methods to fit a visibility graph to these segments. The first solution was to generate an initial polynomial solution passing through all waypoints, and then re-sample it down to S segments, by selecting $S - 1$ evenly-spaced times to sample the trajectory at. These then become the new waypoints. We will refer to this strategy as “polynomial resampling” in the results in Section 9.3.

The second method is to instead sample directly on the visibility graph. Rather than sampling evenly-spaced ts on a polynomial trajectory, we instead fit a velocity ramp straight-line trajectory to a visibility graph, and sample the ts on this trajectory. This method is referred to as “visibility resampling” in the results.

As shown in Section 9.3, both of these methods create better, higher-quality paths faster than simple waypoint fitting.

8 Local Replanning

The system components we have described so far allow us to plan efficiently in a known map. However, in order to build the map to begin with, the MAV needs to autonomously navigate in an initially unknown environment, while remaining safe. Similarly, to deal with changes in the environment between then the global map was constructed and in repeated missions, we want to use the local planner to re-plan any path that may have become in collision.

Therefore, we propose a local planner that is able to handle both a single general goal that may be in unknown or occupied space (for initial map building missions), and a more complex series of waypoints from a global planner, and ensure safety of any trajectory sent to the controller. While the underlying optimization we use for generating the trajectories is Loco and already described in Section 7.3 above, here we describe how to handle the different cases described above in analogous ways, especially in partially unknown or changing environments. A diagram of our system is shown in Fig. 10.

It is worth mentioning that after our introduction of continuous-time local trajectory optimization methods in [2], this has become a popular approach to solving local replanning problems. The system presented by Lin *et al.* [5] uses the same general form of optimization problem, while seeding the optimization with an initial guess from a search-based algorithm. Usenko *et al.* [31] speed up the optimization significantly by switching to B-splines rather than Hermetian splines and better exploiting the structure of the optimization problem. Morell *et al.* [32] also propose a similar method, with the additional options to constrain the optimization within free-space corridors or respect other hard constraints in the optimization.

However, in contrast all these works, this section focuses on the system-level considerations of how a local planner utilizing such a local trajectory optimization planner can be used with tracking waypoints which may not be in free space, attempting to follow global plans which may no longer be valid, and guarantee safety even in unknown or slowly changing environments.

In Fig. 10, we show that all user inputs, whether an entire waypoint trajectory from a global planner or a single waypoint to track, are treated similarly in a waypoint queue. If there are multiple waypoints in free space in the queue, we attempt to smooth a path through them directly using the path smoothing strategy described in Section 7.3. Otherwise, we attempt track the next waypoint in the queue using the local replanning directly. While the underlying optimization is the same, the difficult component is selecting the goal point of the initial condition of the optimization. Even if we have a soft cost (rather than a hard

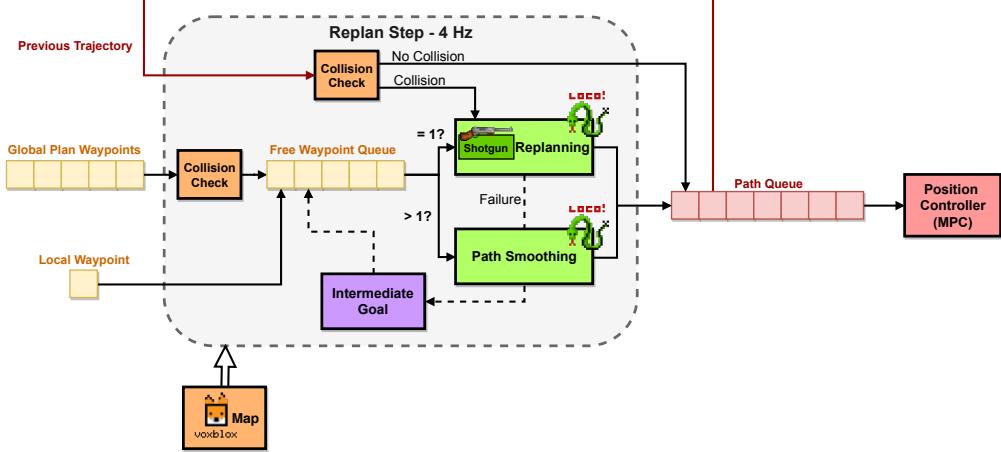


Figure 10: Details of the local planner. This architecture is designed to track both single waypoints and a global waypoint path, and constantly check the executed trajectory for new collisions. This allows our system to be safe even in the presence of new dynamic obstacles, drifting coordinate frames, or if the global map used is different from the current state of the environment.

constraint) on the goal point, it is still necessary that the initial goal is in or very near free space. We propose a shotgun goal selection strategy, described in Section 8.1 below, to intelligently select a free-space goal when the first waypoint is in collision or unknown space.

Another issue is that the planner will not always reach a waypoint even with a valid goal, for a variety of reasons – too narrow corridors, lack of connectivity in regions, and especially narrow field of view in vision-based sensors. In cluttered scenarios, local optimization alone may not lead to observing enough free space to reach a global goal. To overcome these further issues, we introduce intermediate goal points which are inserted into the waypoint queue when the local replanning fails. This idea was originally introduced in our previous work [3] and reviewed in Section 8.2 below.

8.1 Shotgun Goal Selection

Shotgun goal selection deals with the issue of what happens if the currently-tracked waypoint is in unknown or occupied space. In our previous work [3], we explored finding an intermediate goal along a straight-line path from the start to the goal, or following the gradient back from the goal. However, this is often quite limiting and may not lead to connected space. We propose a method of selecting an intermediate goal by performing a randomized search around the start point. The idea is to do something like a reverse particle filter, combining goal-seeking behavior, exploration through a random walk, and trying to maximize clearance to obstacles.

Every time we attempt to plan to a waypoint, we generate a number of shotgun particles, each of which is allowed to run for a fixed number of iterations. At each iteration, a particle randomly decides between 3 options:

- take the direction closest to the goal,
- take the direction maximizing obstacle distance,
- or take a random direction (other than where the particle came from).

By trading off between the probabilities of these 3 outcomes, the shotgun particles may explore, seek the goal, or maximize clearance more. The first shotgun particle generated will always do 100% goal-seeking behavior, to cover the trivial case, and any shotgun particle that reaches the goal will terminate the process. The path

of the shotgun particle is then subsampled and shortened using the approach described in Section 6.2.1, and then optionally fed as the initial solution to the optimization problem in Section 7.3.

8.2 Intermediate Goal Points

Especially when seeking to navigate through unexplored cluttered environments, local path-planning alone may not be sufficient. As shown in our previous work [3], adding a strategy to select intermediate goal points when local path planning fails substantially increases chances of success, especially in very cluttered scenes. Our previous work introduced two main strategies to find intermediate goal points: random and local exploration.

In the random strategy, whenever the optimization would fail to find a viable solution toward the goal, we would select a random intermediate goal within a fixed radius of the MAV’s current pose. This random goal does not need to be in free space, as the replanning strategy can deal with waypoints in collision or unknown space safely.

The local strategy combines goal-seeking with maximizing an exploration gain. First, we select a number of candidate points in *free space*. Note that the position may not be feasible for the entire MAV to fit, the single point at the center needs to simply be free. We then select the best point to use as the intermediate goal by evaluating all points on a combination of two metrics: exploration gain and goal-seeking.

Using knowledge of the model of the MAV’s depth sensor (assuming it is a normal pinhole camera whose field of view can be modeled with a frustum), we can evaluate the exploration gain of a randomly-selected pose as follows, where \mathbf{x} is the position of the MAV in space and γ is its yaw angle:

$$l(\mathbf{x}, \gamma) = \#\{v | v \in \text{frustum}(\mathbf{x}, \gamma) \cap v \in \text{unknown}(v)\} \quad (10)$$

Which essentially counts the unknown voxels v in the view of the camera frustum.

While this will select points that have the possibility of exploring the most unknown space, it is also essential to make progress toward the global goal (\mathbf{g}) (or the next “real” waypoint). The goal-seeking gain d_g is a function of the sampled position \mathbf{x}_n , the trajectory start point \mathbf{x}_s , and maximum sampling radius r .

$$d_g = \|\mathbf{g} - \mathbf{x}_s\| + r \quad (11)$$

$$R(\mathbf{x}_n, \gamma, \mathbf{g}) = w_e l(\mathbf{x}, \gamma) + w_g \frac{d_g - \|\mathbf{g} - \mathbf{x}_n\|}{d_g} \quad (12)$$

w_e and w_g are hand-tuned weights trading off between exploration gain and goal-seeking behavior.

However, whether these strategies make sense to use depends heavily on the application. One main downside is that they make the behavior of the robot unpredictable: the location of the next most promising point for exploration is difficult for a safety pilot to predict, and the robot will often go into parts of the environment that may not be desirable to explore. These downsides are shared by all sampling-based exploration algorithms, such as Next Best View planners [33]: while performing excellently in simulation, they are often scary to do real experiments with. For this reason, while we also evaluate these methods in the results section, in many applications employing these intermediate goal point strategies is not a great practical choice. This is why we developed the Shotgun Goal Selection in Section 8.1: to capture some of the benefits of these methods while maintaining predictable behavior from the MAV.

9 Evaluation and Experiments

We aim to validate our complete system, spanning from quantitative global planning on multiple real-world scenarios and maps, to evaluating a variety of path smoothers in comparison to one another, to thousands

Name	Location	Duration	Volume	Contents
Shed	Wangen a. A, BE, CH	217 sec	38 x 35 x 12 m	Mixed indoor and outdoor dataset with narrow openings
Rubble	Wangen a. A, BE, CH	159 sec	28 x 27 x 12 m	Outdoor dataset, over earthquake damaged buildings
Machine Hall	ETH Zürich, ZH, CH	251 sec	24 x 30 x 8 m	Indoor area, with large industrial machinery

Table 1: Dataset statistics and descriptions.

of local planning simulation scenarios and finally fully integrated system tests in closed loop on-board the platform.

9.1 Evaluation Datasets

We focus our evaluations on real datasets, collected in typical scenarios for search and rescue and industrial inspection. We performed three inspection flights, two at a military search-and-rescue training ground at Wangen an der Aare, and one in the ETH Zürich Machine Hall. Photos of the three areas, named “Shed”, “Rubble”, and “Machine Hall” respectively, are shown in Fig. 11 and described in Table 1. All datasets were collected with the MAV and sensor set-up described in Section 3.2, using both stereo and RGB-D (Intel Realsense D415) sensors.

We make six global maps available: two per dataset, one using the stereo cameras and one using the RGB-D sensor (RS). All the maps are available for download ¹³.

The provided maps were generated with 10 cm voxels, 1 meter clear and 4 meter occupied spheres (described in Section 4.2), 8 meter maximum ray distance for TSDF construction, and 4 meter maximum ESDF computation distance.

We provide both a stereo and an RS map of all environments due to the narrow field of view (FoV) of the realsense camera, but superior depth measurements (and color information). Fig. 13 shows the difference in traversability between the stereo and the RGB-D version of the shed dataset, assuming an 0.5 meter robot radius. For other datasets, such as machine hall, this is less important because the structure is much closer and therefore the narrow FoV makes little difference.

9.2 Sparse Topology Generation

To show that our sparse topology graph (or skeleton) is a feasible global planning strategy, we analyze the amount of time it takes to generate the sparse graph from an ESDF for each dataset. The results are shown in Fig. 14.

There is a large difference in the generation time between stereo and realsense for the machine hall and rubble datasets, due to how much more space is traversable in the stereo datasets. However, most datasets are generated in 2 seconds or less, and the worst-case is 10 seconds. We consider this very feasible for a pre-processing step for global planning, as the actual planning times are orders of magnitude faster than other methods.

¹³http://github.com/ethz-asl/mav_voxblox_planning



(a) Shed, outdoors



(b) Shed, indoors



(c) Rubble

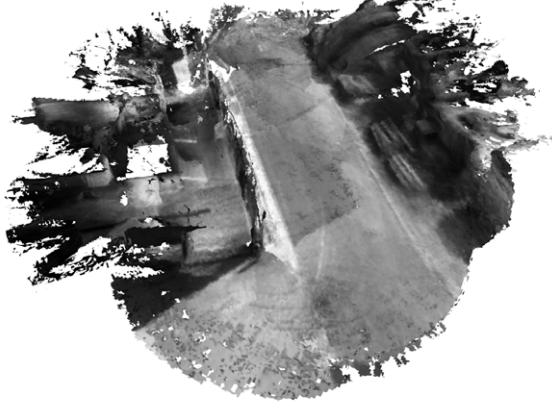


(d) Machine Hall

Figure 11: Photos of the three scenarios from the benchmark dataset. Top (left and right): outdoor and indoor parts of the shed scene. Bottom left: rubble scene. Bottom right: machine hall scene.



(a) Shed (RS)



(b) Shed (Stereo)



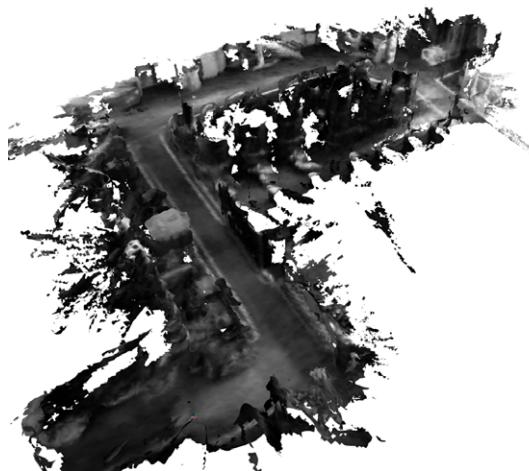
(c) Rubble (RS)



(d) Rubble (Stereo)



(e) Machine Hall (RS)



(f) Machine Hall (Stereo)

Figure 12: Colored meshes of the realsense (RS) and stereo versions of the three maps used for benchmarking. Our stereo system is based on grayscale cameras, so no color data is available.

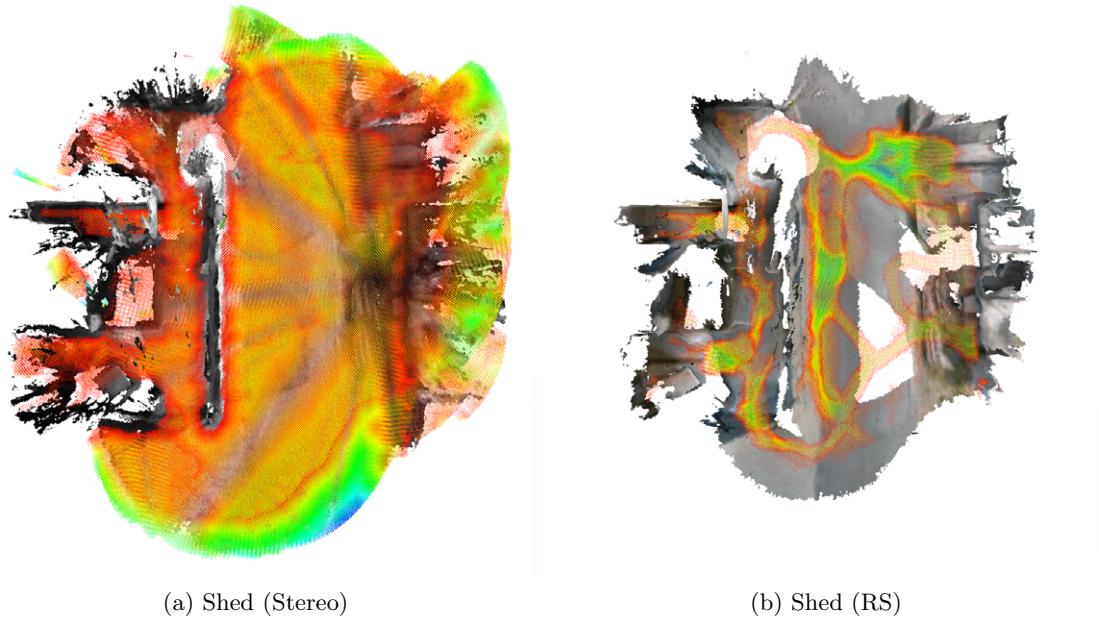


Figure 13: Traversability differences between stereo datasets and realsense datasets. Traversable space (given an 0.5 meter robot radius) is shown as colored points. As can be seen, much more space is considered traversable with stereo data.

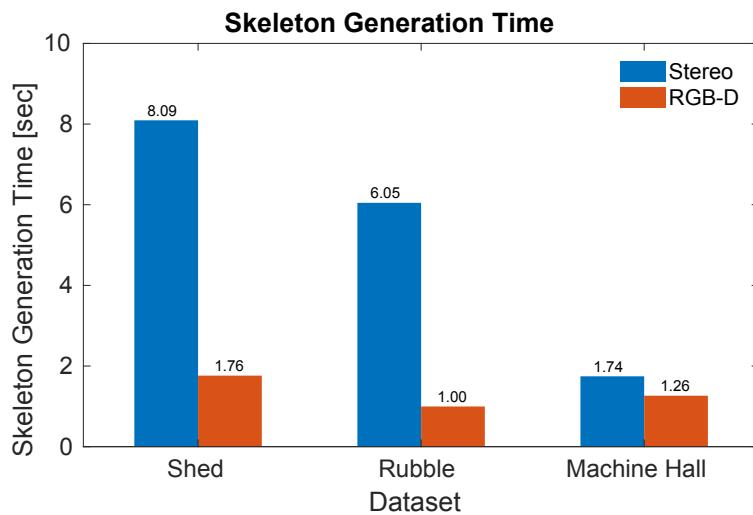


Figure 14: Sparse topological (skeleton) graph generation timings for the test datasets. The stereo datasets generally take longer because there is more traversable space.

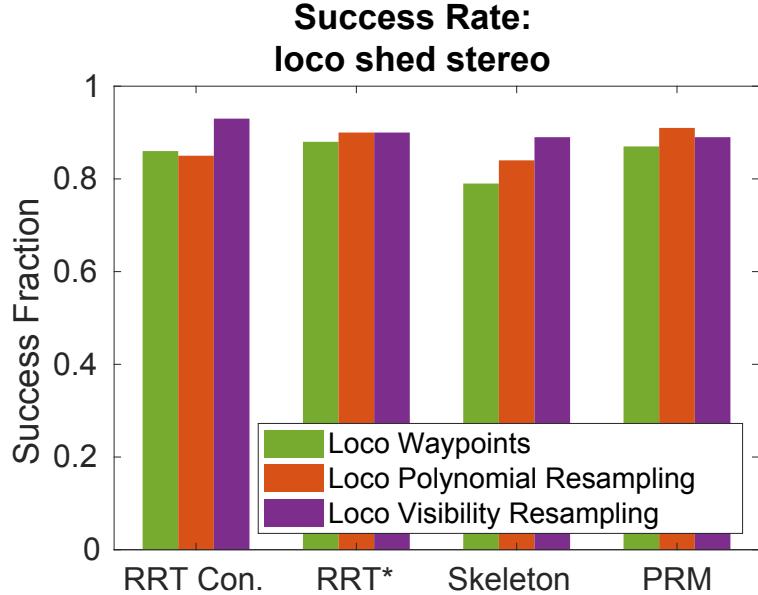


Figure 15: A comparison of different waypoint fitting methods for Loco, and their success rate on the shed stereo dataset given different global planning methods. In general, visibility resampling has the highest success rate.

9.3 Loco

We analyze the effect of different waypoint fitting methods for Loco, as described in Section 7.3. We compare three methods: waypoint fitting (where each pair of waypoints has a segment between them), polynomial resampling (where an initial polynomial trajectory is fit with one segment through each waypoint, then resampled to a fixed number of waypoints), and visibility graph resampling (where intermediate waypoints are sampled directly off the visibility graph). The results are shown in Fig. 15, evaluated on the stereo shed dataset.

The visibility graph resampling has the highest success rate, and we use that variant as ‘Loco’ for the remaining evaluations.

9.4 Global Planning Benchmarks

To demonstrate the differences between different global planning methods, and how choice of path smoother affects the final result, we run 100 trials on all provided datasets. Each trial starts and ends at a random location, a minimum of 2 meters apart. The robot radius is 0.5 meters for all planners.

We use multiple global planning methods, summarized below:

None Straight-line path between start and goal, no planning, meant to give an estimate of how many of the test cases have trivial solutions.

RRT Conn. RRT-Connect, which grows a bi-directional tree from and toward the goal. Very fast, ran with an upper time bound of 1.0 sec (though terminates when first solution is found).

RRT* Probabilistically-optimal random planner, ran for 2.0 seconds.

Skeleton Our sparse topological planner, using path shortening on the output path.

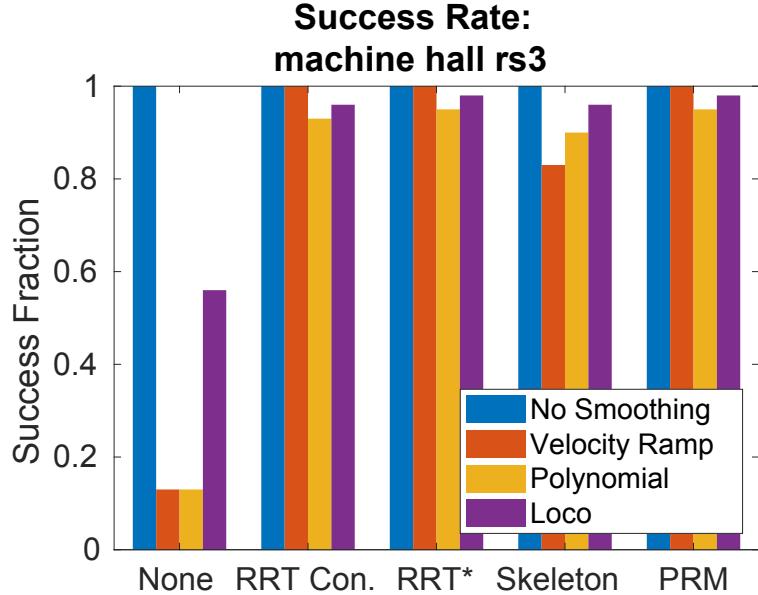


Figure 16: Success rate of various global planner and path smoothing methods on the Machine Hall Realsense dataset, showing our method (Loco) is able to give smooth dynamically-feasible paths for more test cases than competing methods.

PRM Probabilistic roadmap, aimed to compare versus our skeleton-based method. The pre-planning stage is run for 2.0 seconds (to mirror the average dataset processing time of the sparse topology), and each planning query is given an additional 0.1 seconds.

Likewise, we test a variety of path smoothing methods:

No Smoothing Not an actual path smoothing method, just an indicator showing whether the global planner succeeded or not.

Velocity Ramp Velocity ramp method, always applying maximum or no acceleration. Follows straight-line paths between waypoints.

Polynomial The polynomial splitting approach of [29], described in sections above.

Loco Our local continuous trajectory optimizaton algorithm, run with visibility waypoint re-sampling, as determined from the previous sections to be the best.

Fig. 16 shows a comparison of all described methods on the Machine Hall Realsense dataset. There are a number of take-aways from these results. When not using a global planner (i.e., attempting to draw a straight-line path between start and goal), only 13% of the test cases have trivial solutions, but Loco is able to solve 56% of problems with no global plan. In general, the success rate of Loco is also slightly higher, as it is able to better utilize the information in the map.

All the global planners are able to solve all of the planning problems. One key point to note is that the velocity ramp method does not work very well with the topological skeleton planner: this is because our graph simplification method contains some edges that do not lie perfectly on the straight-line. However, the Loco planner has a comparable success rate with the skeleton planner as other planners, again because it can follow gradient information in the map and slightly perturb the waypoints to produce a collision-free path.

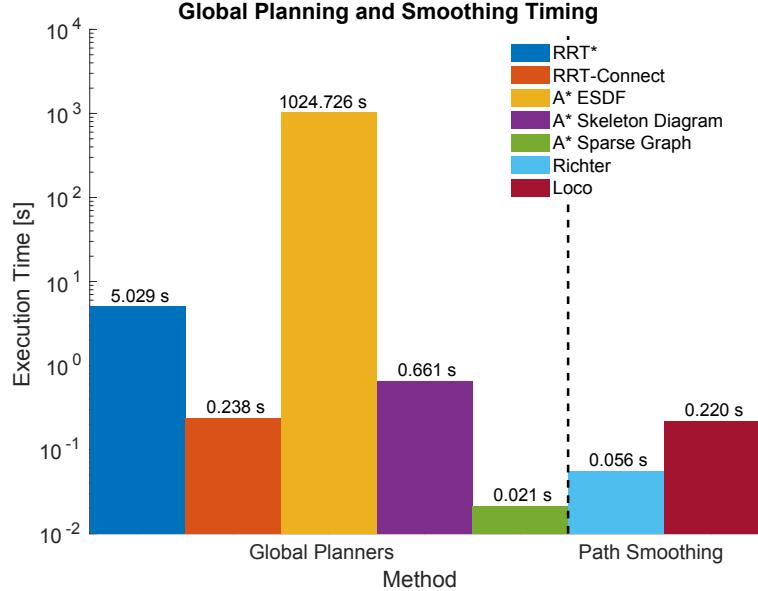


Figure 17: Timings for various global and local planning methods. Note the log scale. As can be seen, skeleton planning is at least one order of magnitude faster than other global planning methods, and while loco timing is slightly slower than polynomial, it is still within bounds for fast global planning applications.

The timings for a single typical trajectory on the Shed stereo dataset are shown in Fig. 17 (note the log scale). The topological skeleton planning method is 10x faster than even RRT Connect (and produces much shorter path lengths). Both the polynomial and loco smoothing methods are acceptable for fast global planning, though the polynomial method is approximately 2x faster.

9.5 Local Planning Benchmarks

In order to evaluate the complete local planning approach, we repeat a series of simulated evaluations similar to those in [3]. We focus specifically on extremely cluttered environments, such as the random Poisson forests introduced by Karaman *et al.* [34].

We generate a map that is $15m \times 15m \times 5m$ with a random distribution of cylindrical obstacles. The density of the obstacles varies between 0.1 objects per square meter to 0.5 objects per square meter, which corresponds approximately to 10% of the volume being occupied to 50%. To simplify the testing procedure, a 2 meter long section on the left and right side of the map is always left obstacle-free, allowing us to set the start and goal positions in the same location in each trial.

Each trial consists of a maximum of 60 simulated steps, each corresponding to a simulated second of flight. At the beginning of each iteration, the simulated MAV observes its environment once, with a forward-facing sensor with a 320×240 pixel resolution and a 90° horizontal field of view. This data is then incorporated into a voxblox map, and we run one step of the local planner described in Section 8. A sample test environment, as explored by the MAV, and a path between the start and goal is shown in Fig. 18.

We ran the evaluations for a total of 1000 trials per method, amounting to 100 trials per density. The aggregated results are shown in Fig. 19. The “Naive” method presented is the raw Loco method from Section 7.3, which as can be seen performs the worst. Using the Shotgun goal selection described in Section 8.1 substantially improves performance, though if the Shotgun path is not used for hotstarting the optimization (in the Shotgun No Path method), the performance is slightly worse than when using the path.

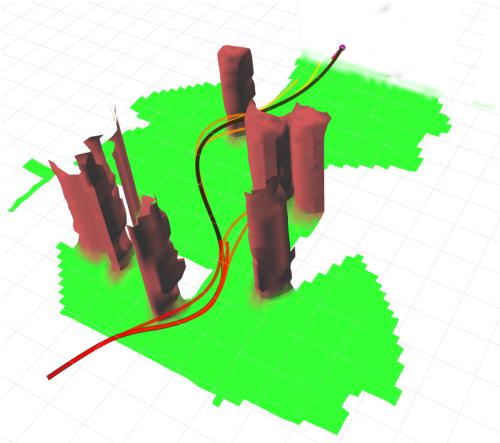


Figure 18: An example of the environment used by the local benchmark, with an obstacle density of $0.2 \text{ objects}/m$, which roughly corresponds to 20% of the volume being occupied. The incremental plans of the MAV are shown in color, from red to yellow over time, and the final executed path is shown in black.

What is interesting to note, however, is that the last four methods, combining Shotgun and Naive with the intermediate goal strategies described in Section 8.2, all perform similarly. In our previous work [3], we saw the same effect between the random and local exploration strategies, but the local exploration had significantly shorter path lengths. However, the similar performance between the Shotgun strategies and the Naive strategies when augmented with intermediate goal selection suggests that they perform largely the same role as the Shotgun goal selection. This suggests that in scenarios where a randomized goal selection strategy such as random or local exploration is suitable (such as exploring empty environments without people, or where the entire space is safe to enter), the Shotgun strategy is not necessary. On the other hand, in cases where an operator would like to have more high-level control over the motion of the drone and less unpredictability, the Shotgun strategy has most of the same advantages while having the robot behave predictably.

9.6 Platform Experiments

While most of the evaluations in the previous sections are on real datasets collected with the MAV, allowing us to quantitatively test the performance of global planning and local smoothing, in this section we aim to show full closed-loop on-board experiments, showcasing the complete system.

The tests were performed on a platform similar to the hexacopter described in Section 3.2 and shown in Fig. 1. For these experiments, we used a quadcopter based on the DJI F450 frame (as we have lower payload requirements due to the minimal sensor setup), a Pixhawk flight controller, an Intel NUC for on-board processing, and a stereo visual-inertial sensor [8] for both state estimation and depth data. The system is shown flying in a lab environment in Fig. 20. Instructions, part files, and a description and links to the complete software stack are available online¹⁴.

The experimental validation consisted of 6 experiments, focusing on show-casing the local planner and its interaction with a global planner. Experiments were done in two scenes; one in a cluttered robotics office, shown in Fig. 21a and a machine hall, similar section to what was showcased in the Machine Hall evaluation dataset in Section 9.1 and shown in Fig. 21c.

In every experimental set-up, the MAV starts out with an empty local map. Optionally, it may either build its own global map (i.e., use the same map for both the local and the global planner), or use a previously-built

¹⁴github.com/ethz-asl/mav_tools_public

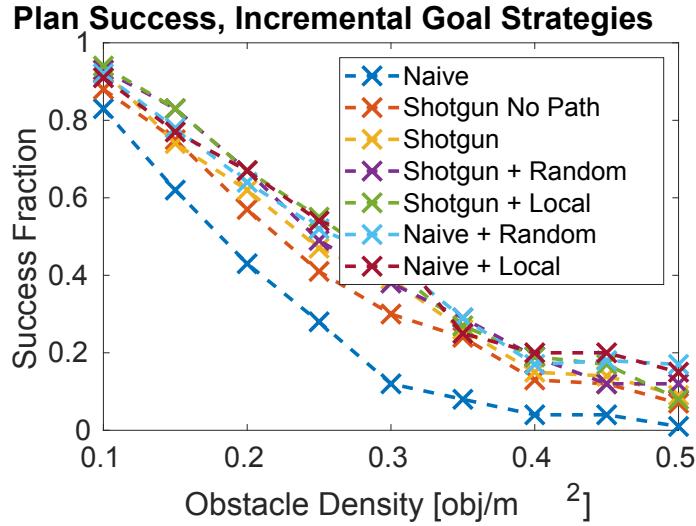


Figure 19: Success rate of multiple variants of our local planner. Naive is the original Loco method presented in Section 7.3, Shotgun No Path Section 8.1 uses the shotgun goal selection but without using its path to hotstart the optimization, Shotgun uses the hotstarts, and the other methods use the intermediate goal strategies described in Section 8.2. As can be seen, using the Shotgun selection significantly increases the success rate of the naive planner, but its advantages are cancelled out by intermediate goal strategies.

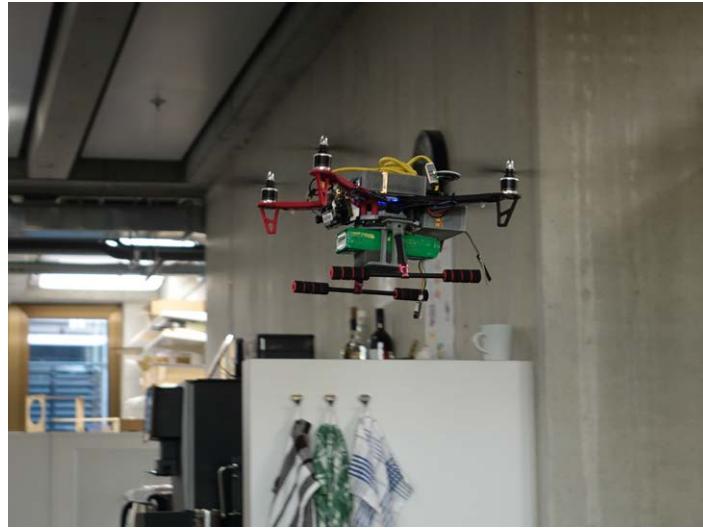


Figure 20: The platform used for the closed-loop experiments, a smaller quadcopter based on a DJI F450 frame with a stereo visual-inertial sensor [8] mounted to the front for both state estimation and depth measurements. Here it is shown flying through a cluttered office space in Experiment 1.



(a) Office

(b) Office + Obstacle

(c) Machine Hall

(d) Machine Hall + Obs.

Figure 21: Photos of scenes that the local planner experiments were performed in, with and without the added obstacle. The obstacles were used in trials where the global planner uses a previously-built map, to verify that the local planner is able to cope with changes to the global plan in the presence of obstacles.

Step	Time [ms]
TSDF Integration	2.0
ESDF Clear Radius	5.2
ESDF Integration	97.5
Shotgun Goal Search	9.8
Loco Solve Time	28.3

Table 2: Average timings for each step in mapping and planning in Experiment 1 on-board the platform.

global map. In the latter case, we always add some obstacles that are not present in the original global map to show that the local planner always verifies any global trajectories against the current state of its local map. The obstacles we add to both scenes are shown in Fig. 21b and Fig. 21d, and are placed directly in the line the planner normally took to the goal. If we use the same map for local and global planning, since we do not do any online localization, the odometry may have drifted during flight. Being able to return safely even in a drifting map again showcases the safety of our local planner framework.

A table describing all of the experiments is shown in Table 3, and screenshots of the final paths flown are shown in Fig. 22. As with all live experiments, they are best viewed on video at <http://youtu.be/xQTokwr1le0>. The timings for each component in Experiment 1 are given in Table 2, averaged over the entire experiment. Note that we use 15 cm voxels a 4 meter clear sphere, which contributes to the long update time of the ESDF integration.

In the spirit of complete honesty with the reader, while most of the experiments presented worked on the first attempt, a few did not. Some did not succeed due to bugs in the planner (which have since been fixed),

#	Location	Local Map	Global Map	Planner Forward	Planner Back	Obstacles
1	Office	New	None	Local	None	None
2	Office	New	From Exp. 1	Global	None	Pallet
3	Office	New	New	Local	Global	None
4	Machine Hall	New	None	Local	None	None
5	Machine Hall	New	None	Local	Global	New
6	Machine Hall	New	From Exp. 5	Global	Global	Trash bin

Table 3: Summary of experimental setup, and which maps were used for local and global planning, and what obstacles were added.

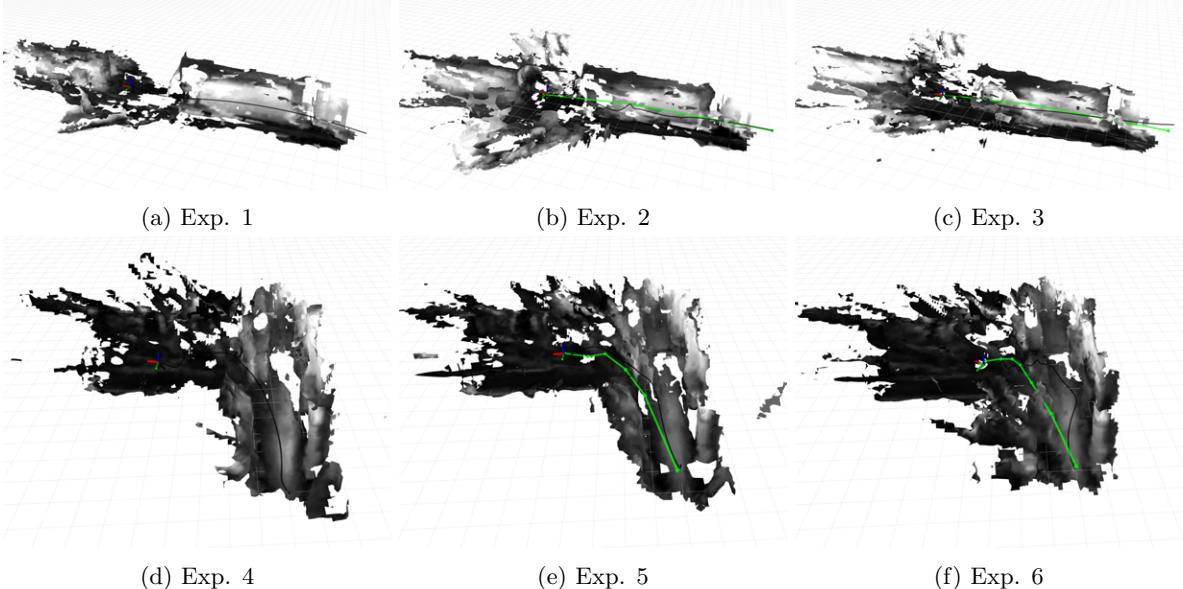


Figure 22: Screenshots of the on-board map and planned paths (the local planner in black, global planner in green). The start and end locations are the same for all 3 experiments in each location. Note how in experiments 2 and 6, the global planner path goes directly through an obstacle, but the local planner is able to replan and recover.

but a number failed for other reasons. Of the 3 experiments that we ran after removing the last bugs, all of which were in the machine hall, 1 failed on the return flight due to the planner being too conservative around the added trash bin obstacle, and not being able to find its way back (stopping next to the trash bin). 2 succeeded but with “loops” or 360° turns in the trajectory. Of all the failures, including those while debugging edge cases in the local planner, there were no collisions.

10 Conclusions

In this paper we have presented a complete system for mapping and planning with MAVs. The system was designed and implemented with a focus on GPS-denied environments and assuming no communication and therefore suitable for online processing. In particular, we have presented our findings on performing dense mapping and both local and global planning on-board Micro-Aerial Vehicles with narrow field-of-view vision sensors. Our contributions focused on discussing practical problems and solutions to issues encountered while attempting to navigate such systems safely in real environments. We extended our previous work by improving a global planning sparse topology generation algorithm, suggest methods in which our local replanning algorithm can also function for path smoothing, improved the success rate of our local planning, provided a full framework for local replanning that is able to handle both global paths and local waypoints in unknown space, and benchmark a variety of global and local planning methods, both on real and simulated data. Most importantly, we described not only our mapping and planning approaches, but considerations that must be taken in other parts of the system for this approach to work, such as state estimation and controls, and made all of our code available online and open-source. Finally, we validated the complete system in a series of platform experiments.

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