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Registration of non-uniform density 3D laser scans for mapping with micro aerial vehicles

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HIGHLIGHTS

- We present a mapping system for non-uniform density 3D point clouds acquired by MAVs.
- To compensate for the different densities, we approximate the underlying surface.
- The extracted surface information is used to efficiently align the point clouds.
- We use the same surface-based error metric in a multi-edge pose graph optimization.
- We demonstrate 3D mapping with MAVs and superior performance to a single-edge system.

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ABSTRACT

Micro aerial vehicles (MAVs) pose specific constraints on onboard sensing, mainly limited payload and limited processing power. For accurate 3D mapping even in GPS-denied environments, we have designed a lightweight 3D laser scanner specifically for the application on MAVs. Similar to other custom-built 3D laser scanners composed of a rotating 2D laser range finder, it exhibits different point densities within and between individual scan lines. When rotated fast, such non-uniform point densities influence neighborhood searches which in turn may negatively affect local feature estimation and scan registration. We present a complete pipeline for 3D mapping including pair-wise registration and global alignment of such non-uniform density 3D point clouds acquired in-flight. For registration, we extend a state-of-the-art registration algorithm to include topological information from approximate surface reconstructions. For global alignment, we use a graph-based approach making use of the same error metric and iteratively refine the complete vehicle trajectory. In experiments, we show that our approach can compensate for the effects caused by different point densities up to very low angular resolutions and that we can build accurate and consistent 3D maps in-flight with a micro aerial vehicle.

1. Introduction

Micro aerial vehicles (MAVs) such as quadrotors have attracted much attention in the field of aerial robotics in recent years. Their size and weight limitations, however, pose a problem in designing sensory systems for environment perception. Most of today's MAVs are equipped with ultrasonic sensors and camera systems due to their minimal size and weight. While these small and lightweight sensors provide valuable information, they suffer from a limited field-of-view and cameras are sensitive to illumination conditions. Only few MAVs [1–4] are equipped with 2D laser range finders (LRF) that are used for navigation. These provide accurate distance measurements to the surroundings but are limited to the two-dimensional scanning plane of the sensor. Objects below or above that plane are not perceived.

3D laser scanners provide robots with the ability to extract spatial information about their surroundings, detect obstacles in all directions, build 3D maps, and localize. In the course of a larger project on mapping inaccessible areas with autonomous micro aerial vehicles, we have developed a lightweight 3D scanner [5] specifically suited for the application on MAVs. It consists of a Hokuyo 2D laser range scanner, a rotary actuator and a slip ring to allow continuous rotation. Just as with other rotated scanners, the acquired point clouds (aggregated over a half rotation of the scanner) show the particular characteristic of having non-uniform point densities: usually a high density within each scan line and a larger angle between scan lines (see Fig. 1). Since we use the

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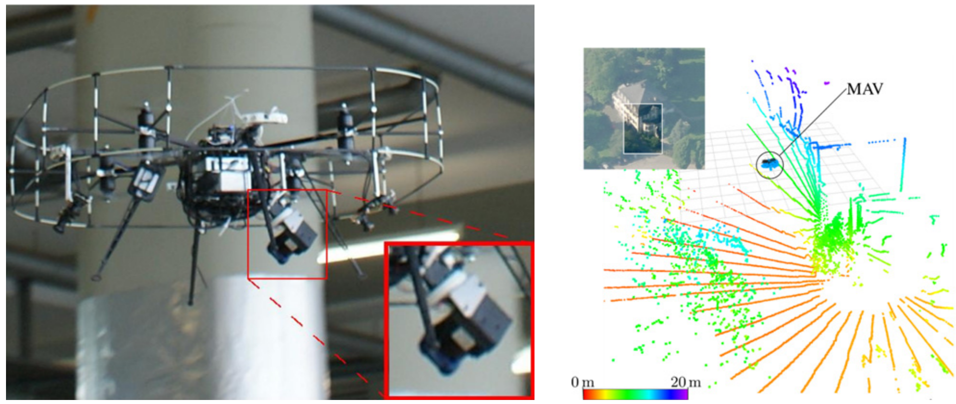

(a) Flying micro aerial vehicle with scanner.

(b) Example of a scan acquired in-flight.

Fig. 1. The laser scanner is mounted slightly below the MAV facing forwards. Continuously rotating it allows an almost omnidirectional perception of its surroundings. The resulting 3D scans (aggregated over one half rotation using visual odometry) show different point densities within and between individual scan lines.

laser scanner for omnidirectional obstacle detection and collision avoidance, we rotate it quickly with 1 Hz, resulting in a particularly low angular resolution of roughly 9° to 10°. The resulting non-uniform point densities affect neighborhood searches and cause problems in local feature estimation and registration when keeping track of the MAV movement and building allocentric 3D maps by means of simultaneous localization and mapping (SLAM).

In this paper, we present a complete processing pipeline for building globally consistent 3D maps with this sensor on a flying MAV. To compensate for the non-uniform point densities, we approximate the underlying measured surface and use this information in both initial pairwise registration of consecutive 3D scans to track the MAV movement and graph-based optimization for building a consistent and accurate 3D map. For initial registration, we extend the state-of-the-art registration algorithm Generalized-ICP (GICP) [6] to include topological surface information instead of a point's 3D neighborhood. We represent the resulting trajectory in a pose graph [7] and connect neighboring poses by edges representing point-pair correspondences between scans and encoding the same error metric using topological surface information. This graph is iteratively refined, re-estimating the point correspondences in each iteration, to build a consistent 3D map.

This paper is an extended version of our previous works on registration and mapping with such sparse 3D laser scans [8,9]. It is organized as follows. After a discussion of related work in Section 2, we present our registration approach including the approximate surface reconstruction and the approximate feature estimation in Section 3. In Section 4, we discuss the extension to a complete SLAM system: we extend the registration approach to also estimate the pose uncertainty and use this information for graph-based SLAM (single edge between connected nodes) as a baseline system. We then introduce our SLAM approach using multiple edges per connection where every edge encodes a point-to-point correspondence (in terms of the GICP error metric). In Section 5, we present the results of a thorough experimental evaluation of both the plain registration approach and the two SLAM variants. Finally, we summarize the main conclusions and discuss future work in Section 6.

2. Related work

Particularly important for the autonomous application of MAVs is the ability to perceive and avoid obstacles. Building environment maps is necessary for goal-directed navigation planning and executing the planned trajectories. In the following, we discuss related works with a focus on (1) perception, (2) registration and (3) mapping. The former two allow sensing environmental structures, keeping track of the motion of the MAV, and aggregating measurements in local egocentric maps in order to be able to reliably avoid collisions. The latter aims for building allocentric 3D environments for being able to plan paths and missions.

2.1. Perception and mapping with micro aerial vehicles

Scaramuzza et al. [10] present vision-based perception, control and mapping for a swarm of MAVs. In contrast to our work, 3D mapping is done on a ground station gathering visual keypoints from all MAVs, and dense 3D maps are reconstructed from the final trajectories off-line. Moreover, the approach is purely vision-based and restricted to downward-facing cameras whereas our approach aims at omnidirectional perception thereby allowing to map environmental structures that are not below the MAV.

For mobile ground robots, 3D laser scanning sensors are widely used due to their accurate distance measurements even in bad lighting conditions and their large field-of-view. For instance, autonomous cars often perceive obstacles by means of a rotating laser scanner with a 360° horizontal field-of-view, allowing for the detection of obstacles in every direction [11,12]. Up to now, such 3D laser scanners are rarely used on lightweight MAVs—due to payload limitations. Instead, two-dimensional laser range finders are often used [1–4,13,14]. Using a statically mounted 2D laser range finder restricts the field-of-view to the two-dimensional measurement plane of the sensor. This poses a problem especially for reliably perceiving obstacles surrounding the MAV. When moving however, and in combination with accurate pose estimation, these sensors can very well be used to build 3D maps of the measured surfaces. Fossel et al. [15], for example, use Hector SLAM [16] for registering horizontal 2D laser scans and OctoMap [17] to build a three-dimensional occupancy model of the environment at the measured heights.

Morris et al. [18] follow a similar approach and in addition use visual features to aid motion and pose estimation. Still, perceived information about environmental structures is constrained to lie on the 2D measurement planes of the moved scanner. In contrast, we use a continuously rotating laser range finder that does not only allow capturing 3D measurements without moving, but also provides omnidirectional sensing at comparably high frame rates (2 Hz in our setup by aggregating scans over one half rotation).

A similar sensor is described by Scherer et al. and Cover et al. [19,20]. Their MAV is used to autonomously explore rivers using visual localization and laser-based 3D obstacle perception. In contrast to their work, we use the 3D laser scanner for both omnidirectional obstacle perception and mapping the environment in 3D.

For building maps with a hand-held rotating 2D laser range finder, Zhang et al. [21] compute edge points and planar points