Design and development of a cost-effective quadcopter for rapid underground mine mapping

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Abstract. Mine surveying and mapping is a time-consuming and hazardous task that is critical to most underground mining operations. The introduction of robotics for underground mine mapping can reduce these safety risks for humans. This project aims to develop a cost-effective quadcopter equipped with dedicated sensors capable of performing SLAM (Simultaneous Localization and Mapping) in GNSS (Global Navigation Satellite System)-denied environments, such as underground mine sites. Various localization and mapping algorithms were compared and tested, and the SpectacularAI package proved to be a computationally efficient SLAM method that can run on the quadcopter’s onboard computer, creating dense and detailed point cloud maps.

1. Introduction

Mine surveying is critical to ensuring worker safety, efficient resource management, and monitoring the structural integrity of underground mining operations. Precise measurements enable project planning and post-extraction assessments that yield valuable insights, such as the direction of the stope face, the volume of extracted material, and the locations and sizes of underground support pillars [1]. Traditional surveying methods rely on geodetic instruments like total stations and levels, but these techniques often suffer from omission errors due to surface unevenness and tend to be time-consuming [2]. Given the significant human safety and health hazards in underground mines—including fires, rock falls, gas leaks, and floods [3]—robots have recently been deployed to assist with surveying, environmental monitoring, and exploration.

Such robotic platforms include autonomous rovers for underground 3D mapping using rotating lidar sensors [4] and composite systems like the Rhino, which utilize lidar and RGB-D fusion for underground localization and mapping [5]. More recent approaches extend these capabilities through multi-robot exploration, mapping, and terrain perception by networking platforms such as quadrupeds, rovers, and UAVs (Unmanned Aerial Vehicles) [6]. UAVs, in particular, serve as rapid exploration tools that provide fast data collection and extensive coverage, with most of these platforms relying on lidars to perform SLAM algorithms [7]. Additionally, UAVs can navigate challenging terrain conditions—such as extreme slopes, water pools, tight spaces, and vertical shafts—where quadrupeds and rovers often struggle [7]. The aim of this project is to design and develop a cost-effective, small-scale quadcopter that performs onboard SLAM in underground mines, delivering a comprehensive 3D representation of the environment.

1. Methodology and Results

The developed platform, called Void Raven, consists of a custom-built 5-inch quadcopter with components specifically chosen for performance and efficiency to maximize the UAV’s permittable payload and exploration time. Additionally, the quadcopter is equipped with a Pixhawk 6C Mini Flight Controller running PX4, which handles low-level flight control and facilitates processes such as position estimate calculations.

Additional components integrated into the platform include a Khadas Vim4 running Ubuntu 22.04 and ROS2 for onboard computing, a Here Flow optical flow sensor to aid with position control in the absence of GNSS in underground environments, and an OAK-D Pro W RGB-D (Red, Green, Blue-Depth) camera that provides depth information and generates a point cloud for SLAM. An RGB-D camera was chosen over the commonly used lidar because it is significantly lower in cost, provides more visual information—including surface texture and colour—and has lower power consumption. A detailed image of the platform is shown in Figure 1.

A room with a building and a window

AI-generated content may be incorrect.Careful considerations were required when selecting SLAM algorithms due to the Vim4's limited computational power and its arm64 architecture, while most SLAM solutions are developed for powerful AMD64 platforms. After thorough evaluation and testing, it was decided to employ the SpectacularAI package for SLAM. This package uses HybVIO, which fuses visual odometry and IMU (Inertial Measurement Unit) data to track the camera's position [8]. Additionally, it incorporates OpenVSLAM—a re-implementation of ORB-SLAM2—that introduces local bundle adjustment for mapping as well as pose-graph optimization and global bundle adjustment for loop closure optimization [9]. Figure 2 shows a point cloud map created by the system while being teleoperated up a flight of stairs, through a foyer, and into a passageway.

Fig. 2. Point Cloud Map created using the developed platform

Fig. 1. Detailed Picture of the Platform

From this map, it is evident that the dense point cloud contains a high level of detail, providing valuable information about the environment. However, a drift in the point cloud is also visible, likely due to the absence of visual odometry when the UAV faced a featureless wall while rotating. This issue could be mitigated by fusing the VIO output into the flight controller’s extended Kalman filter to obtain a more robust global position estimate. **(Do I mention how I want to introduce VIO into EKF and use that as position estimate? Or not for now?)**

1. Conclusion

A quadcopter capable of mapping GNSS-denied environments, such as underground mines, was successfully developed using cost-effective and energy-efficient components. The deployed software suite was tested and proved to generate a point cloud map of its environment with detailed features. Finally, the platform could be further improved by incorporating additional sensor fusion and potentially automating its operation.

References

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