Chapter

A System for Continuous Underground Site Mapping and Exploration

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Abstract

3D mapping becomes ever more important not only in industrial mobile robotic applications for AGV and production vehicles but also for search and rescue scenarios. In this chapter we report on our work of mapping and exploring underground mines. Our contribution is two-fold: First, we present our custom-built 3D laser range platform SWAP and compare it against an architectural laser scanner. The advantages are that the mapping vehicle can scan in a continuous mode and does not have to do stop-and-go scanning. The second contribution is the mapping tool mapit which supports and automates the registration of large sets of point clouds. The idea behind mapit is to keep the raw point cloud data as a basis for any map generation and only store all operations executed on the point clouds. This way the initial data do not get lost, and improvements on low-level date (e.g. improved transforms through loop closure) will automatically improve the final maps. Finally, we also present methods for visualization and interactive exploration of such maps.

Keywords: 3D mapping, continuous mapping, large underground site mapping, mapping tools, point cloud registration, map exploration, map visualization

1. Introduction

An important environment information in urban search and rescue applications is 3D map data of the site. First responders usually have 2D map material of buildings, tunnels and street sites, while a concise overview in 3D would possibly give them further and new important information about the situation at hand. Kruijff et al. [1, 2], for instance, report from mapping an earthquake site in Mirandola, Italy, in July 2012. There, an unmanned guided vehicle (UGV) together with unmanned aerial vehicle (UAV) acquired 3D environment information to help judge if partly destroyed structures are safe for first responders to move in. Also, robotic technology may help reveal information that is inaccessible otherwise. For example, [3] present an approach for UAV-based mapping of underground tunnels in darkness. While more works focus on disaster management with UAVs (e.g. [4]), many others build upon ground-based USAR robots with the capability to map the disaster site in 3D (see, for instance [5, 6]). Many other related research works including our own previous research [7–9] focus on investigating SLAM algorithms best suited for mapping disaster sites. How large outdoor environments can be mapped in a fast manner is investigated in [10]. A general overview on robotics in disaster scenarios can be found, for example, in [11]. Again other work looks at sensor systems [12] that are appropriate for generating feasible maps. As shown in [13], for first responders it is important to get a reliable overview of the disaster site and the damages and hazards in order to react correctly. This motivates the work presented in this paper. It is very important to get a map quite quickly in order to judge the operation on-site. The operation may be inspecting a disaster site, mapping a building site or, as in our case, mapping an underground mining operation: in each of these examples, the operator needs to quickly get an overview of the site. The operator then either learns where further sensor information needs to be acquired or what measures need to be taken for the operation. In this paper, we report on our 3D mapping system which offers exactly this. In a slightly different but comparable setting in underground mines, we developed a mapping system in hardware and software which allows to quickly integrate new laser scans into a 3D map.

1.1 The project UPNS4D+

The results presented in this paper are part of the project "Underground 4D+ Positioning, Navigation and Mapping System for Highly Selective, Efficient and Highly-secure Exploitation of Important Resources" (UPNS4D+) which was funded by the German Federal Ministry of Education and Research within the programme of "R4–Innovative Technologies for Resource Efficiency – Research for the Provision of Raw Materials of Strategic Economic Importance".

The overall project aimed at exploiting mineral resources of rare earths in a highly selective, efficient and highly secure way from local deposits as well as detecting new ones. This required innovative mining technologies which integrate dynamic change of the mine. The interdisciplinary research project UPNS4D+ aimed at developing an underground deposit positioning, navigation and mapping system for a mobile robot platform. For more details on the overall project, we refer to [14, 15].

The consortium consisted of the following partners: (1) indurad GmbH, Aachen; (2) Fachhochschule Aachen, MASCOR Institute; (3) MILAN Geoservice GmbH, Spremberg; (4) RWTH Aachen University, Institute for Advanced Mining Technology; (5) XGraphic Ingenieurgesellschaft mbH, Aachen; (6) Technische Universität Bergakademie Freiberg; (7) Fritz Rensmann, Maschinenfabrik, Diesellokomotiven, Getriebe GmbH & Co. KG, Dortmund; and (8) GHH Fahrzeuge GmbH, Gelsenkirchen. The project started in April 2015 and ended in December 2018.

The goal of our subproject "6D mapping" was to develop a prototype robot system that is able to map underground mining sites. To this end, a suitable robot platform had to be equipped with the right sensor equipment (radar, cameras, LiDARs, IMU). The data coming from the sensors needed to be integrated into consistent high-dimensional maps deploying known SLAM approaches. High-dimensional means that besides the 3D point clouds, also key frames from the vision or radar data were stored in the map. New approaches had to be developed to grant easy access to the data in order to process and visualize them.

1.2 Contribution

In the following, we present results from that research project that are highly relevant also for urban search and rescue robotics and will find useful applications there. In particular, we present:

1. A novel sensor platform [16] which allows for continuous high-resolution scans

2. A novel registration tool for checking point clouds on-site

3. The sensor data registration tool mapit which facilitates the processing of large-scale point cloud data.

1.3 Outline

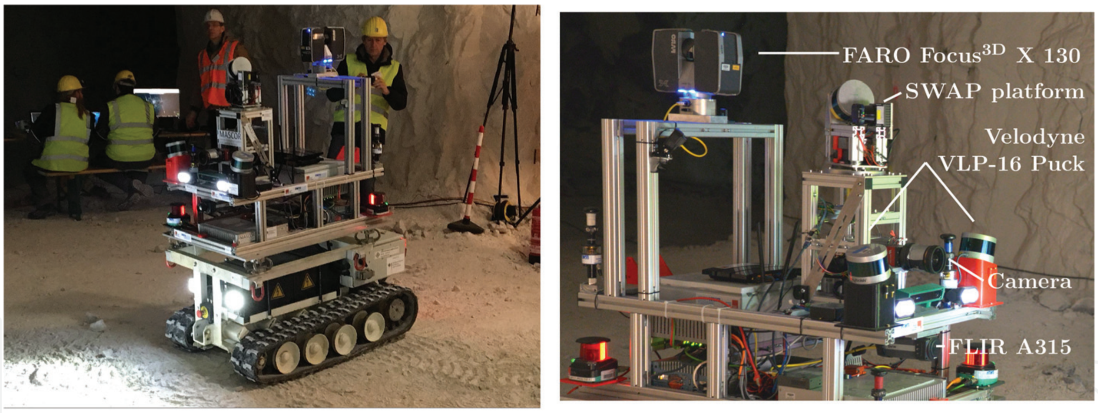
The paper is organized as follows. In the next section (Section 2), we present the exploration vehicle that was developed during the project and used in our experiments. We introduce the overall platform design and the sensor setup which was used for exploration runs at underground mining site. Our exploration robot is equipped with a revolving 3D LiDAR for acquiring map data, several further 3D and 2D laser range finders used for navigation and terrain classification, a thermal imaging camera for detecting mine workers even in unilluminated areas and a high-resolution wide-angle camera for teleoperation. Additionally, we mounted a FARO 3D LiDAR as a reference system.

Section 3 is devoted to our novel 3D LiDAR platform SWAP. SWAP allows to continuously acquire 3D point cloud data of the environment while the robot is slowly moving forwards. This highly reduces the time needed to acquire a section of the underground mine, compared with the FARO scanner also mounted on the exploration vehicle. Such architectural scanners are usually meant to acquire the scene from a fixed position taking up to 10 minutes for scanning a single (but very dense) point cloud. An important development of this project is the mapping and registration tool mapit, which facilitates the registration and manipulation of point cloud and map data. We will outline the idea of mapit in Section 4. In Section 5 we present a number of visualization tools that were developed with mapit. In Section 6 we conclude.

2. Exploring and mapping underground mines

The underlying idea in the UPNS4D+ project is to deploy two kinds of vehicles in an underground mining facility. There is an exploration vehicle that periodically drives around in the underground mine when no regular work is taking place to initially record and then update a map. The second vehicle is a regular processing vehicle that is performing the daily work in the mine. It used the map that is periodically updated by the exploration vehicle. While the exploration vehicle needs to have more sophisticated sensory equipment for recording the map, for the processing vehicle, a stripped-down equipment suffices, since it only needs to localize within a given map.

With our project partners, we developed the exploration robot shown in **Figure 1a**. It is a skid-steered tracked robot based on a mini excavator platform. It carries the modular sensor platform shown in **Figure 1b**. The robot can drive up to 3 ms^{-1} and is controlled via the ROS [17] Movebase. For navigation, collision avoidance and terrain classification, two Velodyne VLP-16 Puck LiDARs are mounted at the front. They acquire environment information with 16 scan lines with an opening angle of 30° and with 20 Hz. They are mounted on a 20° slope to be able to get information in the close vicinity of the robot. With a horizontal opening angle of 360°, they can acquire 3D data from the front and the sides of the robot. For safety reasons, additional 2D laser range finders have been mounted at two corners of the sensor platform which are also used for collision avoidance.



(a) (b)

Figure 1.
Exploration robot developed for mapping underground mining sites. (a) Exploration vehicle and (b) Sensor setup of the exploration robot.

	SWAP platform	FARO Focus^{3D} X 130
Measuring range	0.1–100 m	0.6–130
Horizontal resolution	2°	0.035°
Vertical resolution	0.4°	0.07°
Sphere coverage	80.27%	83.33%
Scan time	0.3–30 s	1–30 min

Table 1.
Comparison between SWAP and FARO Focus^{3D} X 130.

The mapping operation is not run autonomously in the mine environment for now. At the front of the robot, an Allied Vision GT6600C high-resolution camera with a wide-angle lens is mounted. The camera can be used for teleoperation.

As an additional safety feature, we mounted a FLIR A315 thermal camera at the front of the robot in order to be able to detect persons even when not sufficient light is available.

For mapping the mine, the platform is equipped with a rotating 3D LiDAR system, the SWAP platform, which we will describe in detail in the next section. For reference, we mounted a FARO Focus^{3D} X 130 LiDAR, which can be used in a stop-and-go fashion. Scanning times of the Focus LiDAR lie between 1 and 30 min. To remotely operate the LiDAR, we developed a ROS driver based on the FARO SDK.

As part of our project contribution, we developed a rotating sensor platform for the swift acquisition of dense point clouds as reported in [16]. The main goal was to find a compromise between acquiring accurate and dense point clouds which usually takes much time and having available data for online use in a robotic system for tasks such as localization which has to be updated more frequently. For instance, taking the FARO LiDAR with an angular resolution of 0.0035°, very dense and accurate point clouds can be recorded. However, the robot needs to stand still, and the scanning time of a single scan can take up to 30 min. **Table 1** shows a comparison of the two scanners.

3. The 3D LiDAR system SWAP

In this section, following previous work in [16], we present the 3D LiDAR platform SWAP which was developed during the mine mapping project. The SWAP platform consists of a Velodyne VLP-16 PUCK LiDAR and a Hokuyo UTM-30LX-EW range scanner which are both mounted opposite to each other on a disk which rotates both scanning devices around the centre of the disk. The disk and the upper part of the scanner are driven by a motor which is equipped with absolute encoders. Both scanners transfer their data via Ethernet which is connected by a slip ring which connects the revolving part to the rest of the scanning device. The combination of motor and gear head provides us with 3 Nm of torque and allows for a maximum rotation speed of 2.6 Hz. However, a reasonable azimuth resolution can only be achieved with a scanning speed of up to 1.67 Hz, while the full-sphere point clouds are then captured with a half revolution which equals 3.34 Hz for this. We deploy a 14 bit industrial grade absolute SSI encoder which is mounted on the drive shaft. The resolution provides a maximum error of 1.32