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Continuous mapping and localization for autonomous navigation in rough terrain using a 3D laser scanner

David Droeschel *, Max Schwarz, Sven Behnke

Autonomous Intelligent Systems Group, Computer Science Institute VI, University of Bonn, Friedrich-Ebert-Allee 144, 53113 Bonn, Germany

HIGHLIGHTS

- A complete system for continuous mapping and localization fully integrated.
- Allocentric mapping system to allow for continuous mapping and localization.
- Experiments from the DARPA Robotics Challenge Finals and DLR SpaceBot Camp 2015.

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ABSTRACT

For autonomous navigation in difficult terrain, such as degraded environments in disaster response scenarios, robots are required to create a map of an unknown environment and to localize within this map. In this paper, we describe our approach to simultaneous localization and mapping that is based on the measurements of a 3D laser-range finder. We aggregate laser-range measurements by registering sparse 3D scans with a local multiresolution surfel map that has high resolution in the vicinity of the robot and coarser resolutions with increasing distance, which corresponds well to measurement density and accuracy of our sensor. By modeling measurements by surface elements, our approach allows for efficient and accurate registration and leverages online mapping and localization. The incrementally built local dense 3D maps of nearby key poses are registered against each other. Graph optimization yields a globally consistent dense 3D map of the environment. Continuous registration of local maps with the global map allows for tracking the 6D robot pose in real time. We assess the drivability of the terrain by analyzing height differences in an allocentric height map and plan cost-optimal paths. The system has been successfully demonstrated during the DARPA Robotics Challenge and the DLR SpaceBot Camp. In experiments, we evaluate accuracy and efficiency of our approach.

1. Introduction

In order to enable robot systems to enter areas inaccessible to humans, e.g., in disaster scenarios or for planetary exploration, autonomous navigation is key. It necessitates the capability to simultaneously build maps of unknown environments and to localize within. These environments can be cluttered or degraded and pose a challenge for perception algorithms. To enable autonomous navigation, the perceived map of the environment has to be accurate enough to allow for analyzing whether a particular region is drivable or not. Besides that, the efficiency of the perception system is important since the operation in these environments often requires online mapping and localization in real time with limited onboard computers.

In this paper we describe our system for mapping and localization on our mobile manipulation robot Momaro. The robot has been developed according to the requirements of the DARPA Robotics Challenge[1] (DRC). The goal of the DRC was to foster research for robots that are able assist humans in responding to catastrophic situations, such as the nuclear disaster at Fukushima in 2011. Being teleoperated over a limited network connection, the robots had to solve eight tasks relevant to disaster response. While the DRC showed the potential of robots for tasks found in disaster response scenarios, it also showed that fully autonomous navigation and manipulation in unstructured environments—also

* Corresponding author.
E-mail addresses: droeschel@ais.uni-bonn.de (D. Droeschel), max.schwarz@uni-bonn.de (M. Schwarz), behnke@cs.uni-bonn.de (S. Behnke).

[1] http://www.theroboticschallenge.org/.

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0921-8890/

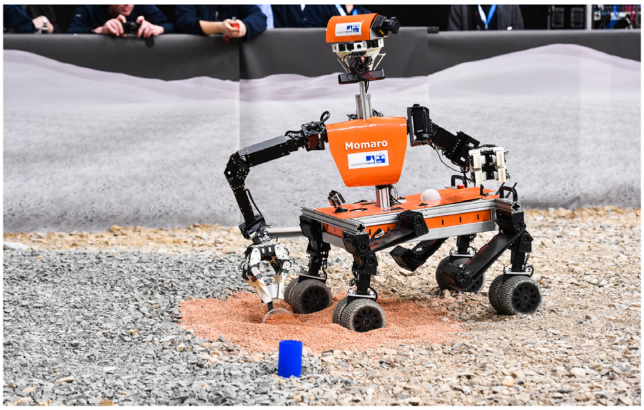

Fig. 1. The mobile manipulation robot Momaro taking a soil sample during the DLR SpaceBot Camp. Without intervention of an operator, the robot learned a map of the previously unknown environment, localized within this map, and autonomously navigated to the goal pose that has been specified in a coarse environment map beforehand.

due to the lack of applicable perception methods—is still beyond the state of the art.

In contrast to the DRC, where robots could be teleoperated for navigation, the DLR SpaceBot Camp 2015 focused on autonomy. Based on a coarse map of the environment, the robot had to explore a previously unknown planetary-like environment and to perform a set of mobile manipulation tasks. Fig. 1 shows our robot Momaro taking a soil sample. By means of a 3D continuously rotating laser scanner, Momaro acquires range measurements in all spatial directions. The 3D scans of the environment are aggregated in a robot-centric local multiresolution map. The 6D sensor motion is estimated by registering the 3D scan to the map using our efficient surfel-based registration method [1]. In order to obtain an allocentric map of the environment—and to localize in it—individual local maps are aligned to each other using the same surfel-based registration method. A pose graph that connects the maps of neighboring key poses is constructed and optimized globally. By localizing the robot with respect to the optimized pose graph, we gain an accurate estimate also in larger environments with big loops, where filter-based approaches would obtain an inaccurate estimate. The graph-based formulation allows to globally minimize accumulated errors, resulting in an accurate map of the environment and localization pose.

The remainder of the paper describes our laser perception system that was used during the DRC Finals and the DLR SpaceBot Camp. During the DRC, only the local mapping components where used to build a egocentric map of the robot's direct vicinity. This map was used by the manipulation operator when planning motions and to correct odometry drift of the robot, when aligning to a previously acquired local map. This part of the system is described in Sections 4 and 5 and is based on our previous work in [1]. Apart from the local mapping, our allocentric mapping component [2] was used to allow for fully autonomous navigation during DLR SpaceBot Camp and is described in Section 6.

In this article, we present a complete system for continuous mapping and localization, fully integrated in our navigation system and extensively tested. Building a fully integrated system with the given requirements led to the following advances over our previous work:

1. We extended our local multiresolution map to address for dynamics in the environment. By efficiently maintaining occupancy information we increase the quality of the maps and the robustness of the registration.
2. We extended our allocentric mapping system to allow for fully continuous mapping and localization during mission, without the necessity to map the environment beforehand or to stop for acquiring new 3D scans and to process them.
3. In the evaluation section, we show data acquired during the DARPA Robotics Challenge Finals and the DLR SpaceBot Camp 2015.

Our mapping pipeline is published open-source,[2] making it available to other researchers in order to facilitate developing robotic applications, contributing to the system, and for comparing and reproducing results.

2. Related work

For mobile ground robots that operate in cluttered and degraded environments, 3D laser scanners are the preferred sensor for mapping and localization. They provide accurate distance measurements, are almost independent on lighting conditions, and have a large field-of-view.

Mapping with 3D laser scanners has been investigated by many groups [3–6]. A common research topic in laser-based simultaneous localization and mapping (SLAM) is efficiency and scalability, i.e. maintaining high run-time performance and low memory consumption. To gain both memory and runtime efficiency, we build local multiresolution surfel grid maps with a high resolution close to the sensor and a coarser resolution farther away. Local multiresolution corresponds well to the sensor measurement characteristics. Measurements are aggregated in grid cells and summarized in surface elements (surfels) that are used for registration. Our registration method matches 3D scans on all resolutions concurrently, utilizing the finest common resolution available between both maps, which also makes registration efficient. In previous own work [7,8], we used this concept within an octree voxel representation.

For aligning newly acquired 3D scans with the so far aggregated map, we use our surfel-based registration method [1]. In contrast to many methods for point set registration—mostly based on the Iterative Closest Point (ICP) algorithm [9]—our method recovers the transformation between two points sets through probabilistic assignments of surfels. Probabilistic methods for point set registration are becoming more and more popular recently and show promising results [10–12].

Hornung et al. [13] implement a multiresolution map based on octrees (OctoMap). Ryde et al. [14] use voxel lists for efficient neighbor queries. Both of these approaches consider mapping in 3D with a voxel being the smallest map element. The 3D-NDT [15] discretizes point clouds in 3D grids and aligns Gaussian statistics within grid cells to perform scan registration.

Belter et al. [16] also propose to use local grid maps with different resolutions. In contrast to our approach, different map resolutions are used for different sensors, resulting in an uniform grid map for each sensor. Herbert et al. propose elevation maps [17], extending 2D grid maps by adding a height for every grid cell. While elevation maps only model a single surface, multi-level surface maps [18] store multiple heights in each grid cell, allowing to model environments with more than on surface, such as bridges for example. Pfaff et al. [19] propose a method for detecting loop closures in elevation maps. Fankhauser et al. [20] use local elevation maps and handle drift by propagating uncertainties of the robot pose through the map.

Our mapping system has been successfully applied on micro aerial vehicles (MAV) to allow for fully autonomous navigation [21]. In contrast to this work, we do not rely on accurate

2 https://github.com/AIS-Bonn/mrs_laser_map.