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Plane-Based Registration of Sonar Data for Underwater 3D Mapping

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***Abstract*— Surface-patches based 3D mapping in a real world underwater scenario is presented. It is based on a 6 degrees of freedom registration of sonar data. Planar surfaces are fitted into the sonar data and the subsequent registration method maximizes the overall geometric consistency within a search-space to determine correspondences between the planes. This approach has previously only been used on high quality range data from sensors on land robots like laser range finders. It is shown here that the algorithm is also applicable to very noisy, coarse sonar data. The 3D map presented is of a large underwater structure, namely the Lesumer Sperrwerk, a flood gate north of the city of Bremen, Germany. It is generated from 18 scans collected using a Tritech Eclipse sonar.**

I. INTRODUCTION

Maps are the core world models for autonomous mobile robots engaging in complex mission tasks. While many successful solutions exist for 2D mapping by land robots - some even consider this as a more or less solved problem [1][2] - it is still a major challenge for the underwater domain [3]. There are two main reasons for this. First, high quality, high resolution range sensors - especially laser range finders - are available for land robots, whereas underwater range sensors produce much coarser, noisier data at lower update frequencies. Second, land robots operate in environments where many obstacles exist that provide a basis for rich sets of natural landmarks for mapping, whereas this is rarely the case for underwater environments [4].

As a consequence, many underwater approaches to mapping rely on artificial markers, i.e., beacons at stationary positions, which have to be exactly known [5][6][7] or at least constrained, e.g. by the known depth of the ocean floor [8][9]. When natural landmarks are used in the underwater domain, then they are usually highly environment specific. Examples for application specific landmarks are bubble plumes in shallow vent areas [10][11], complex floor topographies e.g. along ridges [12], or visual features on visually rich ocean floors [13], especially at reefs [14] like the Great Barrier Reef [15][16].

Previous work on underwater mapping predominantly dealt with 2D representations, which is sufficient for a wide range of applications. For underwater systems, one may argue that ground elevation as represented in classic bathymetric maps may be sufficient [17]. But underwater robots are increasingly used not only in open sea applications but also in more complex environments like marinas, harbors or at dams. 2D mapping in these environments may be sufficient for aiding a remote operator or for most simple tasks [18][19], but it is far from sufficient for any intelligent operation of AUVs. The work on 3D underwater mapping so far has mainly concentrated on vision based approaches and significant efforts to localize the vehicle [20], [13].

Here, up to our knowledge for the first time, registration of sonar data is used to generate a 3D underwater surface-patches based map. The registration method was introduced by ourselves in [21], where typical land robot sensors were used for its validation. Sonar data is, in contrast, much more coarse and noisy.

II. PLANE-SEGMENT EXTRACTION AND MATCHING

The scan-matching based on plane-segments consists of the following three steps:

1) **Planes extraction from raw point-clouds**: This procedure is based on region-growing in a range-image scan followed by a least-squares estimation of the parameters of planes. The covariances of the plane-parameters are computed as well. The details may be found in the previously published work of the authors [22].
2) **Pose-registration by plane-matching**: This step consists of two substeps:
   a) Finding the correspondences between plane-segments in the two scans to be matched. These two scans may be successive samples for normal registration or may be non-successive, if a loop is being closed.
   b) After the correspondences have been decided on, finding the optimal rotation and translation which aligns the corresponding set of planes. This gives the pose change of the robot between the scans.
3) **Polygonization**: This step consists of polygonizing each plane-segment by finding the boundary of each surface-patch so that the surface can be compactly described. This step is crucial for visualization of the result, however, if only pose registration is desired, it may be omitted. It is also described in [22].

The registration method in the second step above uses planar patches extracted from the range data and maximizes the overall geometric consistency within a search-space to determine correspondences between planes. This method, named Minimum Uncertainty Maximum Consensus (MUMC) was introduced by the authors in [21]. The search-space is pruned using criteria such as overlap, and size-similarity. For all these tests, only the plane parameter covariance matrix is employed, without the need to refer back to the original point-cloud. This approach is fast and

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its reliability. Its computation-time increases with the number of planes. Finally, the covariance matrix of the solution is computed which identifies the principal uncertainty directions. This information is indispensable for subsequent refinement processing like pose-graph-SLAM [23], although this is outside the scope of this paper.

III. EXPERIMENTS AND RESULTS

A. The Tritech Eclipse Sonar

The device used in the experiments presented here is a Tritech Eclipse sonar. It is a multi-beam sonar with time-delay beam-forming and electronic beam steering. Its core acoustic sensing parameters are:

- Operating Frequency: 240 kHz
- Beam Width: 120°
- Number of Beams: 256
- Acoustic Angular Resolution: 1.5°
- Effective Angular Resolution: 0.5°
- Depth/Range Resolution: 2.5 cm
- Maximum Range: 120 m
- Minimum Focus Distance: 0.4 m
- Scan Rate: 140 Hz at 5 m, 7 Hz at 100 m

Please note that the scan rate is dependent on the resolution with which the scan is taken and that high resolution scans take longer.

The core hardware parameters are:

- Width: 342 mm
- Height: 361 mm
- Depth: 115 mm
- Weight Wet / Dry: 9 kg /19 kg
- Depth Rating: 2500 m
- Power Consumption: 60 W
- Supply Voltage Nominal: 20-28 VDC

B. A 3D Map of the Lesumer Sperrwerk

The device was used to generate 18 scans of the Lesumer Sperrwerk, a river flood gate in the north of Bremen, Germany (figure 1). The overall area covered is approximately 110 m by 70 m. The sonar data is quite noisy and error-prone. Hence, a pre-filtering using a threshold on the intensity values was done, i.e., readings with a weak echo were discarded. In addition to a reduction in noise and in the overall amount of data, it led to a significant reduction of the field of view of the sonar to about 90° opening angle - instead of 120° - as the center is most illuminated by sound; an effect which is also described in the device's manual. Despite this simple pre-processing, the data is still quite noisy. Example point clouds from the scans are shown in figure 2. The scans have varying amount of overlap, ranging from about 90 to 50 percent between consecutive scans.

Planes are fitted in the 18 scans with the previously described method [22]. One interesting side-effect of the plane based representation is the compression of the data. The effect is even stronger in this experiment where pre-processed, sub-sampled point cloud data is used. The average point cloud size is here 126 KB whereas the planar patches are only 24 KB on the average, i.e., smaller by a factor of more than 5 (figure 3).

TABLE I

MUMC PARAMETERS (UNITS MM AND RADIANS). COMPARE WITH [21, TABLE II].

Parameter	**Value**
$F_t\%$	50
$\epsilon_1, \bar{c}$	$10^{-7}, 5$
$\bar{L}_{\text{det}}$	15
$\bar{\chi}^2_{\text{ovlp}}$	2
$\bar{\chi}^2_{\times}$	5×10^5
$\bar{\chi}^2_{\delta}$	10
$\bar{\chi}^2_{t,e}$	$\chi^2_{1,1.5\%} = 3.84$
κ	6

The data is then turned into a 3D map with our plane-registration method MUMC. During the extraction-phase, the uncertainties in the planes' parameters (normal and distance to the origin) were also computed as covariance matrices. For this, a key requirement is the availability of a sensor uncertainty model. Since a sonar's measurement error depends on a wide array of effects which are hard to model, we opted for assuming a constant standard deviation of $\sigma = 1$ meter for all beams. A more accurate model will definitely improve the covariance estimates for the extracted planes. Most of the consistency tests in MUMC [21] are based on χ^2-tests in which these plane-covariances are used in a central way. Interestingly, we hardly changed the default thresholds in [21, Table II] for the sonar, although the defaults were computed based on sensors commonly used on land-robots. This parameter table is reproduced here in Table I to show the exact values used for the Tritech Eclipse sonar. The lack of any substantial change in these values compared to other sensors shows that the method is robust as long as the sensor error model used is reasonable.

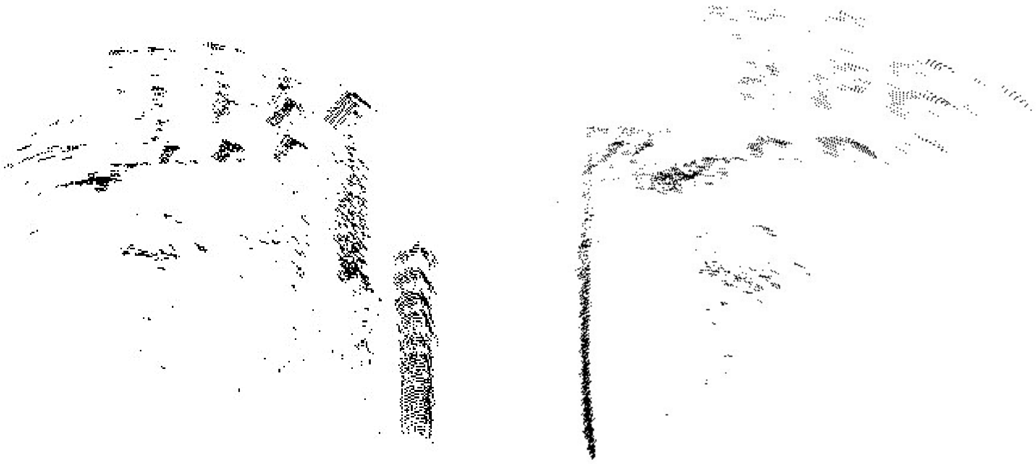
Please note that no motion sensors like a Inertial Navigation System (INS) or even an attitude sensor like a gyro where required. The resulting 3D map is shown in figure 5. It has a very reasonable correspondence with the real structure as shown in an overlay of a top view with Google earth (figure 4). The map is at least suited to be used for some rough path-planning on an AUV.

The plane extraction takes about 0.9 to 1.4 seconds and the polygonization of the patches - useful mainly for visualization or path-planning - takes 0.87 to 1.5 seconds. The actual registration, i.e., the plane matching takes 8 to 56 seconds with an average of 31 seconds on a standard PC with a AMD Turion 64 X2 processor and 1 Gb of RAM. Though this has not been the main focus of this paper, these run-times are still suitable for online computations on the vehicle, especially to occasionally map larger areas for online path-planning.

IV. CONCLUSIONS

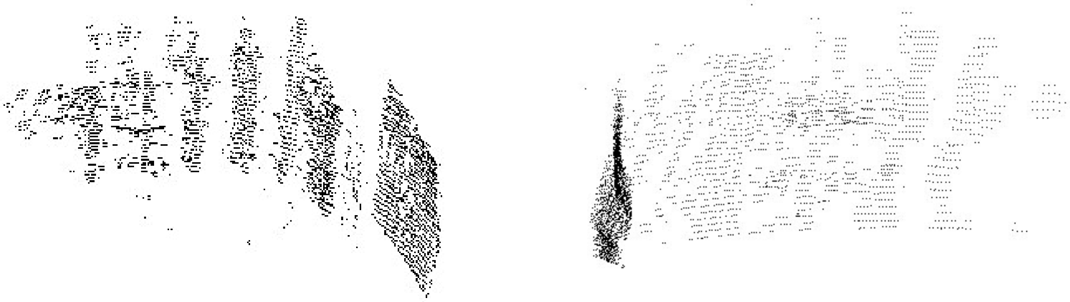
We presented the registration of sonar data to generate a 3D map in a real world underwater scenario. We employ plane-based registration, which was previously introduced by

Fig. 1. An overview of the Lesumer Sperrwerk as seen from the river's surface.



(a) scan 4, top view

(b) scan 17, top view



(c) scan 4, perspective view

(d) scan 17, perspective view

Fig. 2. Examples of sonar scans as point clouds. As can be seen, the data is quite noisy.

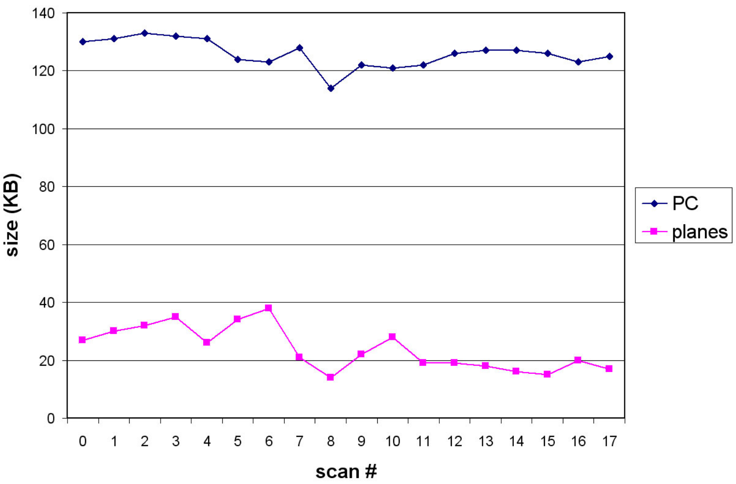


Fig. 3. One important fringe benefit of the plane extraction is the significant compression of the data.

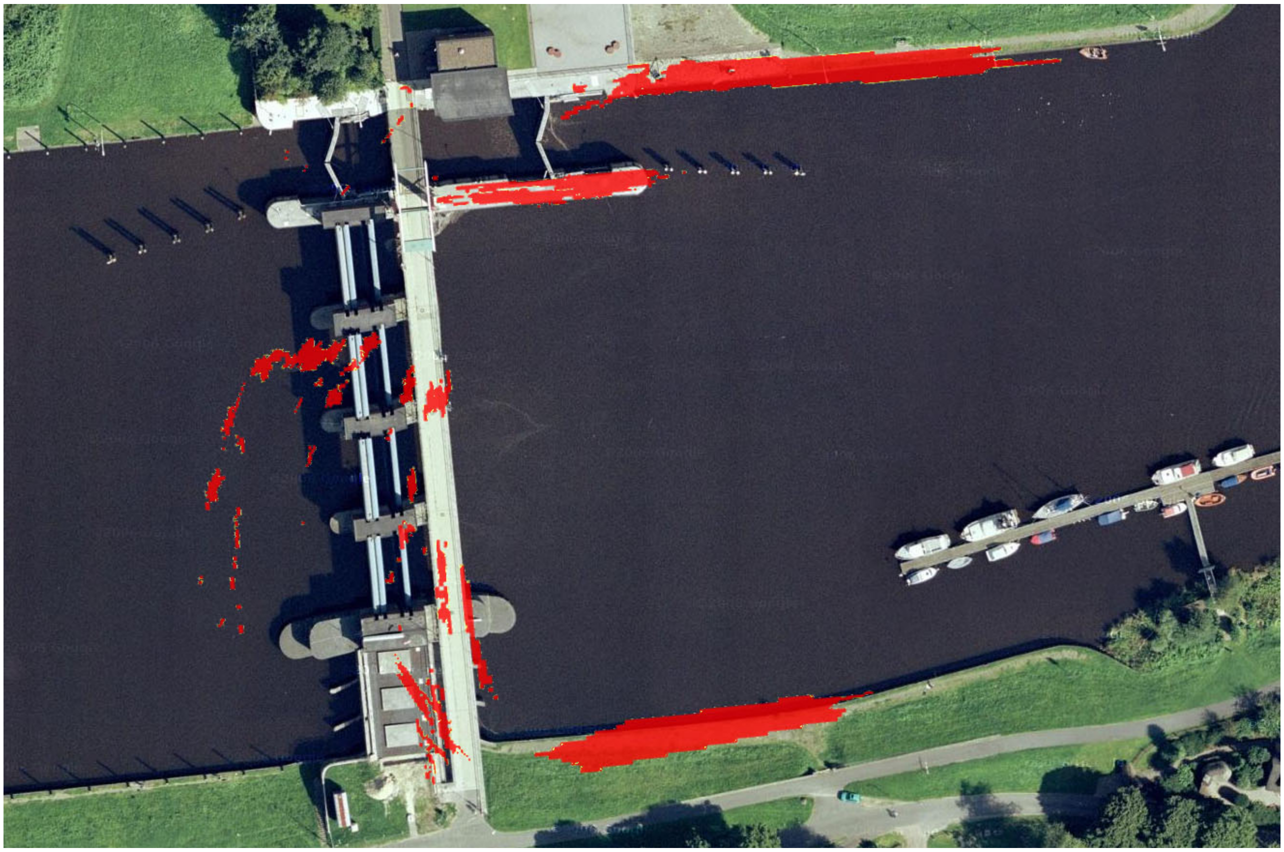


Fig. 4. An overlay of the top-view of the 3D map of the Sperrwerk on an image from Google maps. It can be seen that the map captures the real structure quite well.

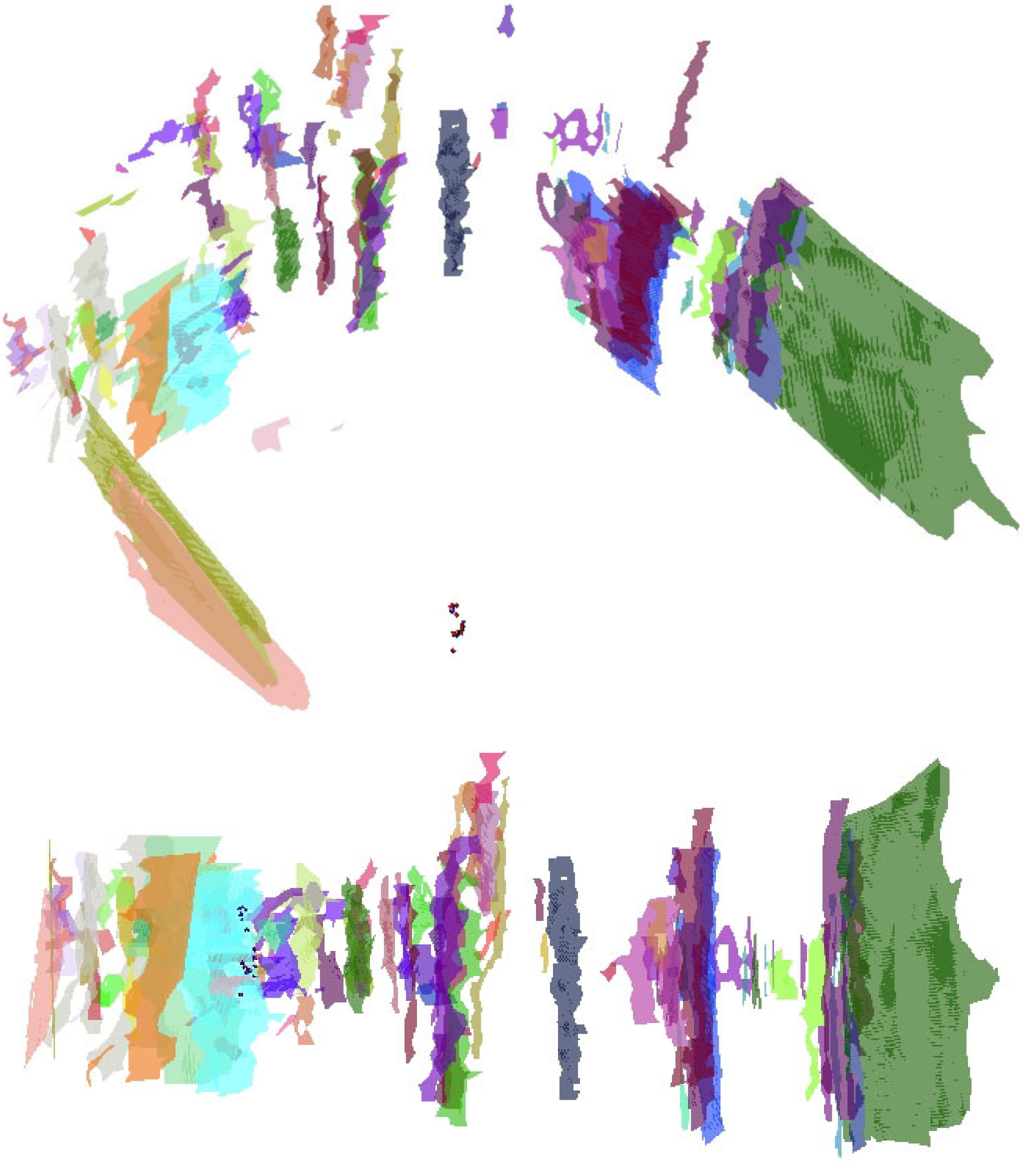


Fig. 5. Perspective views of the 3D map generated from the 18 registered scans. A comparison with ground truth is shown in figure 4. Corresponding planar patches matched across two or more scans are shown in the same color.

ourselves and so far had only been tested on quite high quality range data from sensors on land robots. The plane-based registration decouples rotation and translation determination, and it is able to compute the uncertainty in pose-registration using the uncertainties in the plane parameters.

It was shown that this recently introduced algorithm can even cope with the coarse and noisy data from a sonar. Concretely, the generation of a 3D map of a larger underwater structure in form of a flood gate was presented. A Tritech Eclipse sonar was used to acquire 18 scans of the environment, which got successfully registered into one 3D map that corresponds well with the real structure.

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