Deep-Sea AUV Navigation Using Side-scan Sonar Images and SLAM

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***Abstract*—Navigating an autonomous underwater vehicle (AUV) is a difficult task. Dead-reckoning navigation is subject to unbounded error due to sensor inaccuracies and is inapplicable for mission durations longer than a few minutes. To limit the estimation errors a global referencing method has to be used. SLAM (Simultaneous Localization And Mapping) is such a method. It uses repeated recognition of significant features of the environment to reduce the estimation error. Devices for environment sensing that are used in most land applications like cameras, laser scanners or GNSS signals cannot be used under water: GNSS signals are attenuated very strongly in water and light propagation suffers mainly from turbid water. In more than a few hundred meters water depth there is also no sunlight. Sonic waves suffer much less from these problems and therefore sonar sensors are the prevalent sensor type used under water. A main difficulty is to extract three-dimensional information from side-scan sonar images to perform SLAM as this is an ill-posed inverse problem. An overview of existing approaches to underwater SLAM using sonar data is given in this paper. A short outlook to the system that will be used in the TIETeK project is also presented.**

I. Introduction

Dead-reckoning navigation in vehicles is subject to unbounded error due to accumulation of sensor inaccuracies. The most common solution to limit the estimation errors is to use some global referencing, e.g., GNSS (global navigation satellite system) signals. Under water GNSS (or similar) signals are unavailable and therefore other means to bound the estimation error are necessary. SLAM (Simultaneous Localization And Mapping, sometimes also termed Concurrent Mapping and Localization, CML [1]) is a method that uses significant features of the environment to reduce that error and to additionally build a map of the environment which allows self-localization of the observer within that map.

The difficulties in underwater SLAM are mainly due to the fact that optical cameras do not provide valuable information in most cases as the applications are below the photic zone and/or small particles in the water scatter light and therefore limit the range of the area that could be illuminated. However most research activity on SLAM is accomplished with respect to land-based systems utilizing cameras and/or laser scanners. Due to the aforementioned reasons, sonar sensors are used in the vast majority of underwater applications. There are different kinds of sonar sensors: Multi-beam sonar sensors are able to directly give distance information while side-scan sonars only provide an echo amplitude level varying over time.

Furthermore, SLAM methods rely on features in the environment that can be repeatedly observed and can unambiguously be associated to already known features. Seafloor is often poor in features and naturally has a structure that is mostly fractal [2] what makes it rather difficult to distinguish different features that have a very similar appearance.

Section II of this paper will provide an overview of the different sensors used in deep sea environments. Section III shows the difficulties and ambiguities of interpreting side-scan sonar echo returns. Methods for extracting 3D information from side-scan sonar data are outlined and several solutions from literature which address that problem are described in Section IV. Section V shows approaches to SLAM in an underwater context. In Section VI the plans for the TIETeK project and its realization are shown. Section VII gives a short summary of the paper.

II. Sensors for Underwater Navigation and Localization

Navigation and mapping in a deep-sea environment is more difficult than on land or in air. The two main challenges are the lack of a GNSS under water and being unable to use cameras for high resolution image acquisition. An exhaustive review of the underwater acoustic image generation process is given by Murino and Trucco in [3]. Here only the most important sensors for underwater navigation are presented.

A. Dead reckoning

Applying only inertial sensors like accelerometers, gyroscopes, magnetometers, and depth sensors an estimate of the motion performed by the AUV (autonomous underwater vehicle) can be given. In most cases those sensor inputs are processed via Bayesian filter techniques such as (extended) Kalman filters or particle filters. However, over the time period of a mission the accumulation of the sensor inaccuracies leads to significant errors. Therefore, inertial sensors alone do not

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allow a robust and precise estimation of the vehicle ego-motion. Thus, these sensors need to be supported by complementary sensors that are able to reduce the estimation uncertainties.

B. Long Baseline (LBL)

The lack of a GNSS can be overcome by setting up a so-called LBL array, where additional transducers have to be placed on the seafloor at defined positions. These modules regularly send out a sonar beacon. From the delay of the signals an AUV can localize itself in the area within the transducers by means of trilateration. This approach gives quite accurate results but it is rather inflexible, complex and relatively costly as the mission area has to be marked beforehand by deploying those artificial sonar landmarks. This is a rather cumbersome process especially if the mission area is very large or chosen dynamically.

C. GNSS Aided Ultrashort Baseline

In an ultrashort baseline (USBL) configuration a surface vessel sends an acoustic beacon to the AUV and the AUV itself sends an answer beacon. From the angle of the incoming signal and the time delay, the relative position of the AUV to the surface vessel can be calculated.

Together with accurate GNSS (e.g., DGPS) information from the surface vessel global referencing of the AUV position can be achieved: The GNSS information is sent via an acoustic link down to the AUV. As the acoustic signals travel thrice the distance to the AUV ($2\times$ beacon, $1\times$ data), the position measurement arrives with several seconds of delay that has to be considered in the fusion step. A more detailed description of this approach is given in [4].

The usable range of the data link between AUV and surface vessel restricts the area where a stable communication with the AUV can be established. That narrows the mission area where such additional information can be used to the area around the surface vessel. The term *inverted USBL* is used when the roles are exchanged and instead of the surface vessel the AUV measures angle and distance to get the relative position to the ship.

D. Cameras - Gated viewing

While it is technically possible to use cameras in deep sea applications, their practical use is limited: As there is no sunlight in deep sea, passive cameras are useless and active illumination is necessary. Illumination is possible only for short distances because particles in the seawater scatter the light back to the camera – comparable to high beam headlights in a snowstorm. In very pure water the approximate viewing distance of cameras is limited to approximately 60 meters at best, much less in a real sea environment.

There is an interesting approach to alleviate that problem: a technique called gated viewing is able to partly overcome the problems of turbid water: The light scattered back from particles in short distance to the camera is responsible for the greatest amount of image disturbances. Gated viewing solves this problem by opening the camera shutter only for light that traveled over a certain distance [5]. That way reflections from proximate turbid water are not recorded. The disadvantage of gated viewing is that a powerful flashlight (typically from a laser source) is needed to illuminate the underwater scene appropriately and the camera needs to have a shutter that is able to switch extremely fast. The availability of these cameras is limited what makes that technique rather expensive. Additionally, the shutter gating needs to be selected in advance. Therefore the cameras need to cycle through different shutter gating settings to obtain a full three-dimensional impression of the surroundings.

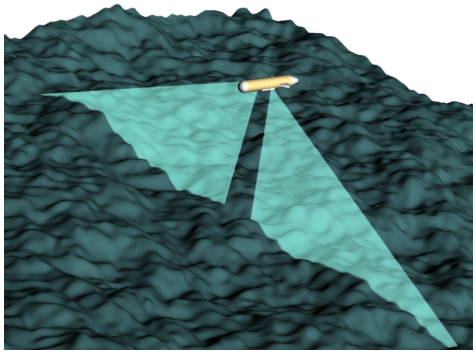

Fig. 1. Side-scan sonar beams (schematically).

In the near future, gated viewing solutions will become more widespread and affordable and they will be an important additional sensor for seafloor mapping, especially if a gated stereo camera setup is used.

E. Sonar Sensors

Sonar sensors cover far greater distances than optical sensors as sound waves are attenuated only very lightly in water. By choosing an adequate sonar wavelength the concept allows an underwater imaging resolution in the centimeter range. On the downside, sonar sensors are suffering from geometric distortions and are prone to exhibit speckle noise due to the use of coherent waves [6]. In spite of the issues, sonar-based sensors are the de facto standard for underwater applications. Many different kinds of sonar sensors are available. In [7] several configurations are shown. The most common sonar sensors are side-scan sonars and multi-beam sonars. A short overview of their working principle will be given in the following.

1) Side-scan Sonars: Side-scan (or side-looking) sonars obtain an image of the seafloor by sending out a sonar pulse (a so-called chirp) and recording the echo intensity over time. They usually have a very narrow beam ($\approx 1\,^\circ$) in the horizontal plane perpendicular to the traveling direction of the AUV and a wide beam ($\approx 50\,^\circ$) in the vertical plane (see Figure 1). The result is a one-dimensional scan line. Side-scan sonars typically have only one transducer beam per side. The sonar echo formation process is depicted in Figure 2. The received acoustic echo signal is highly ambiguous. The reconstruction of the observed three-dimensional seafloor surface shape out of the received echo intensity over time results in an ill-posed inverse problem. The ensonification process depends mainly

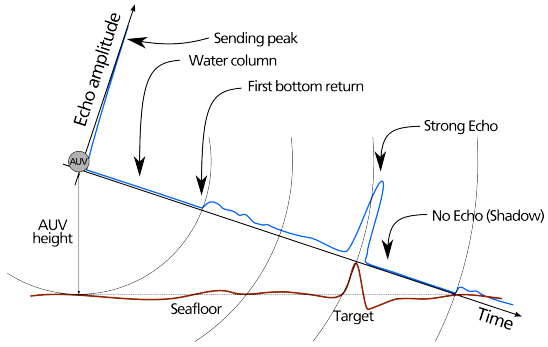

Fig. 2. Side-scan sonar echo formation (frontal view).

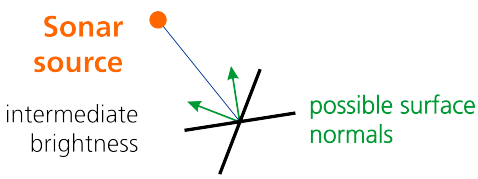

Fig. 3. Per 1D scan line sample there are two surface orientations that are a plausible explanation for a given intensity if Lambertian surface scattering is assumed. Measured surface intensity is only dependent on the angle relative to the source.

on the scattering properties of the surface, the actual sound speed distribution, the sediment type of the seafloor, the sonar beam form, the sonar frequency and volume scattering. To invert the whole ensonification process additional regularization assumptions for those parameters have to be declared. Common regularization assumptions include an isovelocity assumption for the sound wave propagation as well as Lambertian surface scattering for the seafloor (Figure 3) or the assumption that the seabed is mostly flat.

Methods that try to recover the true relief from images are called "shape-from-shading methods" (SfS). Some of these methods which are employed with side-scan sonar imagery are described in more detail in Section IV.

2) Multi-beam Sonars: A multi-beam sonar is the sonar equivalent of an optical LIDAR system. A sound pulse is emitted and the time is measured until the echo returns. Given the sound speed in water the distance in the direction of the emitted sound pulse can be calculated. Usually a multi-beam sonar uses a fan of single pencil beams with a dedicated transducer for each beam. That way it can immediately return a distance information for each beam. Compared to the side-scan sonar, the spatial resolution is lower as for each 'pixel' a separate transducer is needed. Therefore, multi-beam sonars usually are more expensive, are bulkier in size and need more power.

On the other hand, data interpretation is easier compared to side-scan data as multi-beam concepts directly provide 3D information about the environment whereas the 3D information has to be estimated from the ambiguous side-scan sonar images. Fairfield [8] investigated different multi-beam sonar geometries with respect to the suitability for underwater SLAM applications. For the considered tube-like environment he is concluding that a configuration with three mutually orthogonal great circles yields the best results. With this configuration only relatively sparse 3D information is obtained but big areas of the sensor coverage are overlapping that way.

Due to the lower resolution of multi-beam sonars sediment classification tasks are more difficult compared to a side-scan sonar whereas for SLAM tasks the immediately obtainable 3D information is more suitable.

III. Ambiguity of Side-scan Sonar Returns

Side-scan sonar echo returns contain various information besides the shape of the measured seabed. Extracting the shape information is an ill-posed inverse problem and can only be solved through regularization.

That is probably the reason why most research studies on side-scan sonar focused not on quantitative results but rather concentrate on giving qualitative correct results or classifying the seabed into regions of different types like sand ripples, rocks or flat silt areas.

What increases the complexity further is the strong illumination/ensonification directionality of the side-scan sonar [9]. The sonar beam hits the ground at a low angle of incidence for the most part of the ensonified area and that same area will have a very different appearance when being viewed from a different direction. Besides the considered limitations most of the reconstruction approaches in research do not consider dynamic objects like, e.g., fish and/or assume the seafloor to be completely static.

A. Challenges in Extracting Elevation Information

To reconstruct 3D shapes from side-scan images in a first step the problem has to be regularized which means to make assumptions about the model parameters that lead to a specific echo. The amplitude of the echo is influenced by many effects, where the most important ones are:

- angle of the seafloor surface patch relative to the source,
- distance to the source,
- sediment absorption characteristics,
- surface and volume scattering properties,
- absorption and dispersion of sound in water,
- water currents,
- varying sound speed in different depths, temperatures as well as areas of different salinity,
- multipath propagation, and
- sonar transducer beam form.

Assumptions that are common in literature are:

- Lambertian surface scattering, i.e., a surface that is rough and isotropic and reflects energy equally in all directions so that the intensity depends only on the angle to the surface normal,
- no volume scattering,
- sound wave isovelocity distribution and
- the flat seabed assumption.

Additional constraints can be given in the form of surface smoothness requirements (i.e., continuous, differentiable). Influences of sediment type, absorption and water currents are

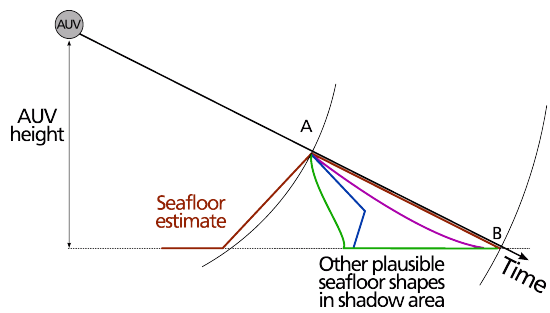

Fig. 4. Many different geometries would yield the same echo image.

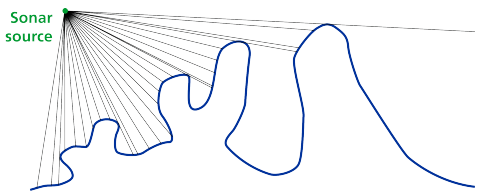

Fig. 5. Side-scan sonar ensonifying complex seafloor shape.

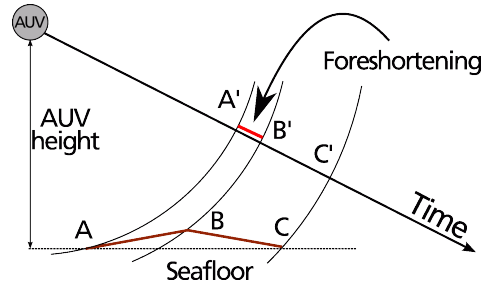

Fig. 8. Long slopes may appear shortened in the echo image.

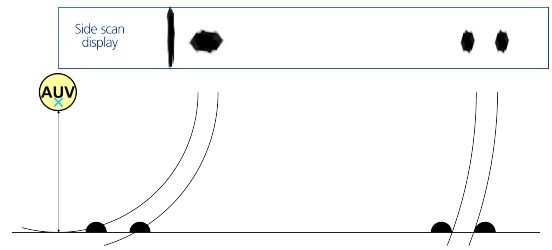

Fig. 9. Change of side-scan resolution across-track.

neglected in many cases. Multipath propagation is only of minor importance in natural environments because sonar uses time-gated pulses. The sonar transducer beam form is either known in advance or can be estimated simultaneously to the shape estimation [10].

Typically, there is no information about the shape in shadowed areas of side-scan images. Several different geometric shapes can generate the same echo (see Figure 4). Parts that are not ensonified will therefore appear covered after reconstruction (Figures 5, 6, 7).

The side-scan imaging process also introduces geometric deformations especially in short distances near to the sensor. This so-called *foreshortening* effect describes the phenomenon that a slope towards the sensor appears shortened in the sonar image [6] (Figure 8). Additionally, side-scan sonars exhibit changing spatial resolution in across-track direction. In along-track direction the resolution is also varying due to changing vehicle speed and the beam widening as the range increases (see Figures 9 and 10 adapted from [11]). The mentioned effects result from the sensor principle itself and cannot be avoided in general. *Layover* is another property of side-scan echoes that describes the effect that one may observe overlapping echoes from multiple parts of the surface that add up to a higher intensity value. This principle is shown in Figure 11 and 12.

Despite the mentioned drawbacks and ambiguities side-scan sonars are used very often as the simple construction makes them a comparably cheap and the power consumption is moderate. Side-scan sonar images can be visualized easily but

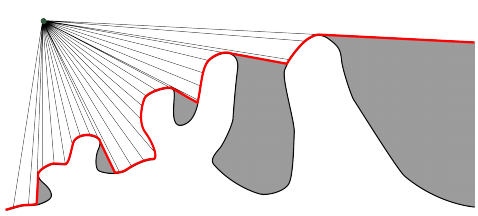

Fig. 6. Shadowed seabed areas.

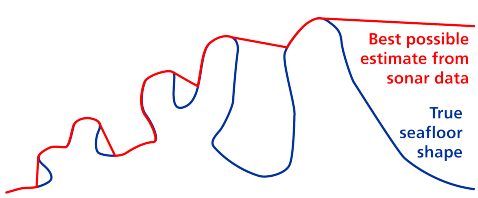

Fig. 7. Information that can be recovered from one scan.

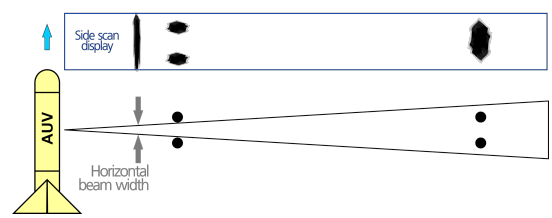

Fig. 10. Change of side-scan resolution along-track.

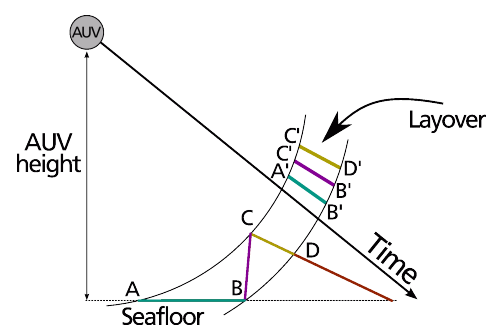

Fig. 11. Echoes from different parts of the ground may arrive simultaneously at the sensor.

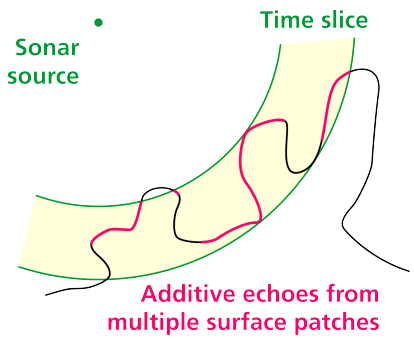

Fig. 12. Seafloor parts that are echoing simultaneously.

the interpretation is often done manually by an operator. With respect to these suppositions side-scan sonars are probably the most prevalent sensors used in deep sea applications nowadays and in the nearer future.

B. Simulator for Side-scan Imagery

J. Bell developed a sophisticated simulator for side-scan imagery based on ray-tracing that considers a stratified water column, sonar beam width, sonar beam directivity, multipath propagation, transmission losses, and ego-motion [2]. Most of the ambiguities shown in Section III-A have been taken into account. The resulting images were not only visually compared to real sonar images but the image statistics of the simulated images were also checked against real sonar images. It allows to compare shape reconstruction algorithms quantitatively with ground truth.

In the context of reconstruction of seafloor shape from side-scan sonar images, a side-scan sonar simulation can be seen as a formulation of the forward problem that needs to be inverted. The closer the simulation models the the physical properties of sound wave propagation and scattering the better are the results of the inversion. J. Bell's work lays the foundation of inverting the side-scan ensonification process.

IV. Elevation Information from Side-scan Data

To utilize side-scan sensor measurements for SLAM, it is desirable to obtain a 3D representation from the 2D sonar measurements. To reconstruct a precise 3D map of the seafloor, meaningful and robust features need to originate from the underlying seafloor geometry rather than from its image. A few methods to accomplish that goal are presented in the following section.

A. Estimating Elevation from Shadows

Reed et al. [12] use co-operative statistical snakes to detect highlight regions with neighbouring shadow regions that are facing away from the sensor. Assuming an otherwise flat seabed reconstructing object elevation information from the shadow lengths with the help of the theorem on intersecting lines is a simple and natural approach that has also been used very early by Chavez [13]. Methods processing two-dimensional images have to register the single scans lines first. The easiest approach is to just stack the scan lines. More sophisticated approaches would pre-process the scan lines considering the geometrical configuration as well as the vehicle motion prior to stacking.

B. Propagation Shape-from-Shading

Propagation SfS was pioneered by Langer and Hebert [14] and modified with a different scattering model by Durá, Bell and Lane [15]. The seafloor reconstruction uses one single scan line at a time. The reconstruction process is starting from directly beneath the sensor where a flat seabed is assumed. The vertical distance from the sensor to the seafloor is either known or can be estimated from the sonar data, assuming that the first surface echo return is resulting from perpendicular beneath the AUV. Starting from this point, the inclination angle to the surface normal is propagated towards the outer end of the sensor coverage area depending on the reflectivity. According to [15] Propagation SfS is quite robust against shadowing effects and gives good results on directional surfaces like sand ripples.

Langer and Hebert suggest additional scan line preprocessing for noise reduction. They propose median filters as a first step followed by a *graduated non-convexity filter* (GNC) which is able to maintain discontinuities. Pre-filtering is necessary due to noise of the signal which is easily corrupting the reconstruction because errors add up towards the outer ends. As every sonar line is processed individually this approach is suited for online reconstruction. However, the correct mutual registration of the processed scan lines depends on the ego-motion of the AUV which has to be estimated. As already mentioned, ego-motion estimation errors easily lead to errors in the 3D reconstruction of the seafloor surface.

C. Linear Shape-from-Shading

The Linear SfS method from Durá, Bell and Lane [15] is based on the previous work from Bell et al. on directionality effects in side-scan imaging [9]. It is a frequency domain approach which considers the fact that the sonar image is a directionally filtered version of the seabed height map. A linear transform is presented that relates the Fourier transform of the two-dimensional sonar images to the seabed height.

In [15] Linear SfS is considered not as robust as Propagation SfS when processing ripples. However, it is much more robust in the presence of noise and in processing isotropic seabeds. Processing two-dimensional sonar images makes it more difficult to employ this method as an online method. A windowed approach however may provide results with a fixed time delay.

D. Hierarchical Recovering of Shape from Side-scan Data

In the works of Coiras, Petillot and Lane ([10], [16]) an elevation map is reconstructed from side-scan sonar images. They start at a coarse resolution using an expectation-maximization approach with gradient descent to iteratively refine the most probable shape that corresponds to the echo amplitude. They assume Lambertian surface scattering and incorporate a simple forward model for ensonification which

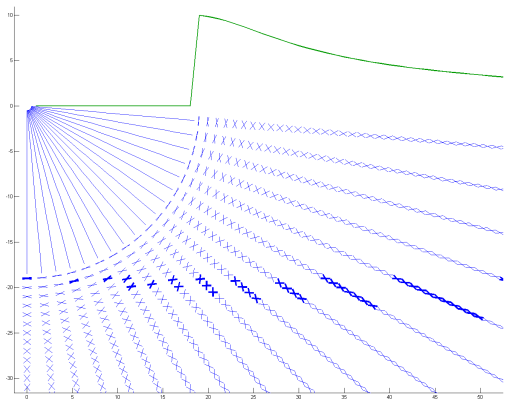

Fig. 13. Surface reconstruction ambiguity.

allows them to iteratively compare the measured echo intensity to a simulated intensity based on the current seafloor shape estimate.

Recently, Coiras and Groen formulated the inverse problem for side-scan sonars and showed some regularization approaches [17]. The basic idea is to model the physical properties of wave propagation to extract as much information as possible while still keeping the computational effort feasible. Their method works with two-dimensional side-scan images and is not designed as an online method. This has the advantage of incorporating parameter dependencies across scan lines but needs scan line registration first.

As an example, Figure 13 illustrates the solution space of possible surface patches that all explain a given backscatter intensity. Shown is a detail of a set of surface patches (blue) that may have produced the observed echo intensity (green) assuming a sonar signal with perfect time varying gain correction, isovelocity sound wave propagation and purely Lambertian surface scattering from a homogeneously sedimented seafloor as well as a knife-shaped sonar beam. Additionally, the possible angle of the received sonar signal is discretized. Although the assumptions are already quite restrictive, there are very different seafloor geometries that may serve as plausible explanations for the recorded signal. Drawn with a thick line are surface patches if a mostly flat seabed is assumed. In this example very strong regularization assumptions have been made but there is still no unique solution of the inverse problem.

V. SLAM on Sonar Data

SLAM is a method to reduce and limit uncertainty in vehicle localization and the resulting environment map through multiple re-observation of salient features (landmarks) and incorporating prior knowledge via a motion model. To ensure a robust SLAM functionality it is essential that a certain landmark can be recognized with high certainty and is not associated to a different one. By fusing the identified landmark position with the available inertial navigation sensor information localization and map errors can be reduced significantly.

Side-scan sonar images, however, do not provide 3D information directly. The sensor output is a 1D scan line that can be registered to a 2D image. Although 3D information is not strictly necessary to perform SLAM, the different appearance of features when ensonified from different angles makes it nearly impossible to robustly recognize landmarks from the 2D image alone. Therefore, it is clearly beneficial to make use of the three-dimensional reconstruction from the methods described in Section IV.

A. SLAM on Side-scan Data

An approach using side-scan sonar data for SLAM is introduced in [1] to aid mosaicing of the seafloor. The localization is done only in 2D on a vehicle model using the three parameters position $[x, y]$ and yaw angle, $[\phi]$). Not only a side-scan sonar has been investigated but also a forward-looking sonar that is able to make more frequent re-observations of landmarks. It is important to notice that to achieve re-observation of features in a side-scan image the vehicle has to turn around and re-visit the area. In their experiments the side-scan sonar observed landmarks at least twice. They employ an *Extended Kalman Filter SLAM* approach (EKF-SLAM), which is computationally unsuitable for very large numbers of landmarks and is very sensitive to wrongly assigned landmarks. The authors of [1] conclude that SLAM using a forward-looking sonar is more robust due to the multiple re-observations of landmarks and is on average two times better at estimating the vehicle's position than using SLAM with a side-scan sonar.

However, the focus of the paper lies more on the offline post-processing using a *Rauch-Tung-Striebel smoother* (RTS, explained in detail in [18]). The authors emphasize the great value of smoothing as a post-processing step.

B. SLAM in Structured Environments

Ribas et. al. describe a SLAM method for partially structured environments using a mechanically scanning imaging sonar [7]. The image generation process is similar to a side-scan sonar whereas the sensor is rotating and mounted vertically. Hence, the surrounding environment in the horizontal plane can be scanned with a single revolution. Employing the Hough transform, line-shaped features are detected and used for building a map. The SLAM functionality therefore depends on a structured environment, e.g., surrounding walls.

C. 3D SLAM on Sonar Data

Fairfield et al. [19] use multi-beam sonar information to create a map of the environment. They investigated mapping of tube-shaped water canals so-called cenotes. With respect to a single observation their sonar sensors give sparse 3D information about the shape of the surroundings which is accumulated in a map. Their SLAM method is based on *Rao-Blackwellized Particle Filters* (RBPFs) [20]. Additionally, they have developed a sophisticated data structure called *Deferred Reference Counting Octrees* (DRCO) to keep the memory requirements low as each particle has to carry the full evidence grid. They show an adaptive method where they use only as many particles as is feasible for real-time operation. They are able to stay well below 10 m of localization error even

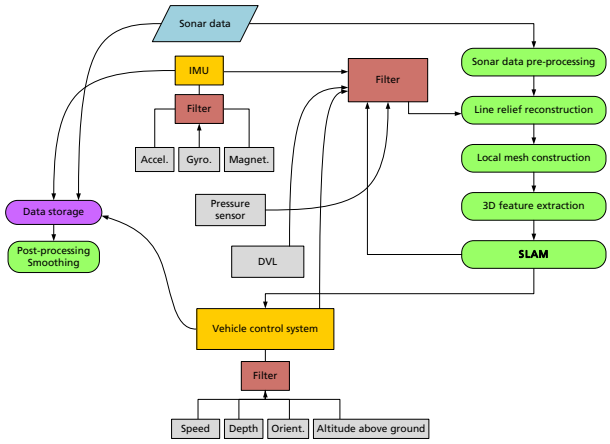

Fig. 14. Sensor fusion concept outline.

after approximately 10000 SLAM iterations. This is a very promising approach that shows how to meet such conflicting requirements as real-time operation and computational effort.

VI. Outlook – The TIETeK Project

The main goal of the joint Fraunhofer project TIETeK "Technology Concept for Inspection and Exploration of the Deep Sea" is to develop a pressure-free, cost-efficient and modular autonomous AUV for deep sea exploration [21]. Pressure free implies that all functional units (electronic components, sensors, batteries and drives) are directly exposed to the external pressure, consequently the modules will not contain pressure-resistant casings. By fusing the available sensor data with the ultrasound imaging sensors the system will provide a variety of inspection capabilities.

The TIETeK AUV will be equipped with several different exteroceptive and inertial sensors. The main exteroceptive sensor will be a high resolution side-scan sonar accompanied by a DVL (doppler velocity log), a depth sensor and IMUs (inertial measurement unit). Additionally, SLAM will be used to support navigation and to facilitate exploration. The concept is outlined in Figure 14. The proposed SLAM concept is based on an extensible fusion architecture which allows the integration of additional sensors such as multi-beam sonar or gated viewing cameras.

A. Sensor fusion

Through data fusion of the inertial sensors a dead-reckoning estimate of vehicle ego-motion is obtained. The TIETeK system holds two IMU sensors which are located both in the data fusion module and in the control system. The sensors provide data at different refresh rates and therefore the sensor fusion concept will be based on an asynchronous fusion stage as described in [22] will be used. In the first step of the data fusion process the recorded data from the inertial measurement unit will be pre-filtered by a filter stage described in [23]. In the next step the side-scan data will be exploited to extract shape information from the environment. By comparing the first surface return from the side-scan sonar sensor with the height information from the DVL a first estimation of the seafloor shape below the vehicle can be calculated. Layover situations will be detected by checking for strong echoes that are not followed by a sonar shadow. Additionally, the vehicle motion at acquisition time has to be taken into account in order to undistort and position the scan line correctly. After combining the extracted line reliefs to a local shape reconstruction, it is important to detect salient features within the relief that can be re-observed with high reliability. This is a very challenging task as the appearance of the features will change significantly when the viewing direction changes. The relief of, e.g., sand ripples may be nearly unobservable for the side-scan sonar when viewed from a certain angle. The shape of the surface ridges and the relative spacing of ridges is a feature that is likely to remain stable enough to be recognized again when ensonifying the area from a different viewing angle.

Then a SLAM method on those landmarks will be employed to obtain accurate navigation and map information. It is crucial to keep the map storage sizes low and use the computing resources efficiently as the algorithm needs to run in real time on COTS (commercial off-the-shelf) hardware inside the AUV. A hybrid SLAM solution as shown in [24] seems to be an ideal concept with respect to mission duration and the resulting map sizes. That approach is capable of preventing the filter from particle depletion which is especially important as it is expected to encounter loop closures with large loops in that scenario.

The map and the improved ego-motion information from the SLAM algorithm will then be transferred to the AUV control system to support vehicle navigation. It is also the basis for explorative actions taken autonomously by the vehicle. In an additional offline post-processing step, maps of higher quality can be achieved by incorporation of smoothing techniques.

VII. Conclusion

The side-scan sonar is a common and inexpensive sensor that delivers a high resolution image of the seafloor which can be used to aid vehicle navigation and to allow mapping. The side-scan echo return however is highly ambiguous which makes shape extraction and feature extraction from that signal a challenging task. As ground truth is unavailable in most cases, quantitative evaluation is extremely difficult. An underwater sonar simulation environment is of great help in providing a forward model to regularize the solution of the ill-posed shape extraction inverse problem. Moreover, SLAM in underwater applications is far from being as well-understood as in airborne or land applications which is partially due to the difficulty of extracting robust and meaningful features from sonar images.

SLAM has been used only very sparsely in underwater applications yet. Once computational power and gated viewing solutions become cheaper, more real-time solutions to underwater SLAM will surely emerge. Within the joint Fraunhofer project TIETeK a modular sensor fusion concept will be developed, which is capable of autonomously navigate and explore the seafloor in missions lasting up to 24 h by means of a robust SLAM functionality based on side-scan sonar data.

Furthermore, the fusion concept will be modularly expandable by incorporation of gated viewing solutions or multi-beam sonars.

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