The HUGIN Real-Time Terrain Navigation System

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Abstract- **Submerged long endurance autonomous missions are a real challenge for the navigation systems of autonomous underwater vehicles (AUV). Terrain navigation is a promising technique for obtaining submerged position updates for the navigation system. This paper describes a real-time terrain navigation system developed for the HUGIN AUV, and reports of sea trials, where HUGIN 1000 HUS was navigating accurately in real-time with terrain navigation as the only source for position updates during long transit legs.**

I. INTRODUCTION

State-of-the-art autonomous underwater vehicles (AUV) have reached a high level of maturity. AUVs are however still challenged by requirements imposed by submerged long endurance autonomous missions. One of the key enabling technology areas for successfully completing such missions is underwater navigation. The navigation systems of AUVs today are typically based on an inertial navigation system (INS), aided by a Doppler velocity log (DVL) and a pressure sensor. For a high-quality aided INS (AINS) on an AUV, the errors in the heading and velocity measurements integrate to a position error in the order of 0.1-0.2% of travelled distance, mostly depending on the accuracy of the DVL.

Figure 1. HUGIN 1000 HUS recovered by HU Sverdrup II.

The main philosophy behind the HUGIN AUV navigation system is to utilize any available sensor on the AUV, together with a toolbox of aiding techniques, to either bound or limit the position error drift [1]. One of these aiding techniques is terrain navigation. Terrain navigation basically correlates bathymetric measurements with a digital terrain model (DTM), and makes estimates of the AUV's position relative to the DTM. It is an autonomous technique, but requires a pre-obtained DTM of the mission area.

Forsvarets Forskningsinstitutt (FFI, Norwegian Defence Research Establishment) has been working on terrain navigation for AUVs since the late 1990s. The first system demonstrated was based on a tightly integrated extended Kalman filter solution. It was carried out in post-processing on real data from HUGIN I equipped with an EM3000 multibeam echo sounder (MBE) [2]. During the period 2000-2002 the system was further developed, and demonstrated in post-processing on real data from a surface ship with EM3000 [3], and an AUV using its DVL [4]. The tests showed the system performed well in bathymetries that were linear and up to weakly-nonlinear, but in rough bathymetries combined with large initial position errors, the algorithm sometimes had problems with divergence. In 2003 the HUGIN real-time terrain navigation system (TerrP) was designed and implemented using a loosely coupled approach [1][5]. The system was required to operate outside the AINS, as a stand-alone system, aiding the AINS with estimated *position fixes* from terrain navigation. The algorithms implemented were a variant of TERCOM (Terrain Contour Matching)[6] for reference, and the point mass filter (PMF) [7]. Back then the system was tested off-line on playback of real HUGIN data, but never in a sea trial. In the recent years, the interest for real-time terrain navigation on the HUGIN vehicle has grown considerably. In 2009 major updates were made to TerrP to enable it to run on the payload processor on HUGIN. The HUGIN AINS was at the same time upgraded to integrate position measurements from terrain navigation, thereby providing a fully integrated terrain-aided INS solution in real-time for the HUGIN AUVs.

In late spring 2008 FFI received the HUGIN 1000 HUS in partnership with the Institute of Marine Research (IMR) and Kongsberg Maritime (KM). HUGIN 1000 HUS is usually operated from FFIs own research vessel HU Sverdrup II. For navigation the AUV is equipped with a Honeywell HG9900 inertial measurement unit (IMU), a Teledyne RDI WHN 300 DVL, a Paroscientific Digiquartz pressure sensor and acoustic transponders for HiPAP- (ultra short base line) and UTP (single underwater transponder) navigation . In addition it can carry different sets of payload sensors, such as the EM2000 multibeam echo sounder and the Edgetech 2200 side scan sonar and sub bottom profiler.

This paper describes the current TerrP system as deployed on HUGIN1000 HUS in Section II. In Section III some promising results from sea trials are reported, where HUGIN 1000 HUS is actually navigating in real-time using the integrated terrain-aided INS solution. Some applications are discussed in Section IV, before conclusions are drawn in Section V.

Work by others on real-time terrain navigation for AUVs can be found in [8][9] for the Swedish AUV62, and in [10] for the MBARI (Monterey Bay Aquarium Research Institute) Dorado mapping AUV. Both systems show promising results.

II. System Description

A. *Overall design*

A description of the basic design of the HUGIN software system is given in [11]. The system basically consists of:

- A control processor (CP) with a real-time operating system (RTOS). It handles for instance guidance and control, basic sensors, autonomous decisions and communication.
- A navigation processor (NavP) also with a RTOS. It handles the IMU, and is running the real-time AINS.
- A payload processor (PP) with a Win32 compatible OS. It handles all other payload sensors not part of the basic sensor suite.
- A top side HUGIN operator station (HOS) that handles mission planning and monitoring, and communication with HUGIN.

On HUGIN 1000 HUS, and the newer models of HUGIN, NavP is run as a subprocess on CP. All communication between the processors CP, PP and NavP is based on CORBA (Common Object Request Broker Architectrue)[11].

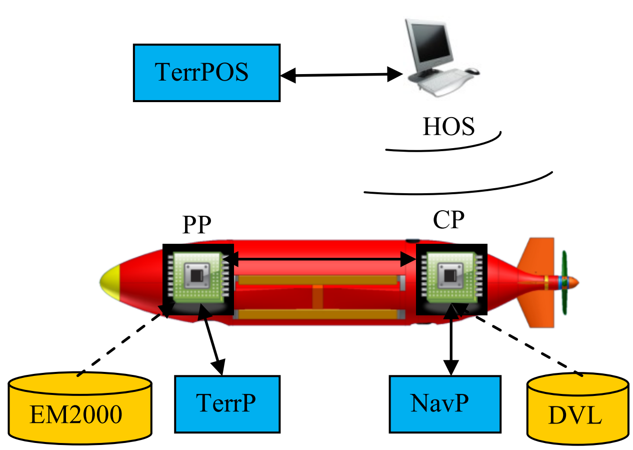

Figure 2. The deployment of the terrain navigation software components on HUGIN 1000 HUS.

The HUGIN real-time terrain navigation system (TerrP) was designed as a pure software component with CORBA interfaces which comply with the HUGIN software system. It is implemented in C++ and is currently compatible with Win32 platforms and the PharLap ETS RTOS. This makes the actual deployment of the software in the HUGIN network transparent to the rest of the system. TerrP can today run stand-alone on a dedicated processor board on the HUGIN network or as a plugin on the HUGIN payload processor, which is the way it is actually deployed on HUGIN 1000 HUS, see Fig.2. On HUGIN 1000 HUS the PP board is a Littleboard 800 with a Pentium III 1GHz processor and 256 Mb RAM. With small changes, TerrP will in the future be able to run as a subprocess on the HUGIN control processor.

Although the system is fully automatic, a top side user interface called TerrPOS has also been developed to allow for monitoring and some reconfiguration during supervised tests both in simulation and in real mission environments.

Any sensor or system data needed on the HUGIN vehicle network has a CORBA interface. TerrP may connect with the sensor and system interfaces considered part of the basic sensor suite. Today TerrP can connect to the DVL and the HUGIN inertial navigation system (NavP) in this way. In addition a generic CORBA data interface has now been defined to handle any sensors capable of bathymetric measurement outputs. The data interface handles a variable number of beams per ping, has a tag which uniquely identifies the sensor model, and a tag that uniquely identifies the coordinate system of the floating point triplets forming the actual measurements per beam, e.g. (range, azimuth, zenith) relative to a body fixed reference system, or (along track, across track, depth) relative to a local level body fixed reference system.

The map database is handled by an independent software module where all access is handled through a C++ interface. This software module is also used by the HUGIN simulator (SimP) for simulating sensors measuring bathymetry. The interface allows for depth lookup for a given horizontal position, and range lookup for a given horizontal position and a unit vector pointing in a desired beam direction, without knowledge of the actual representation of the underlying DTM. In addition a direct handle is provided for regularly gridded DTMs. This enables fast lookup for the algorithms, by bypassing the slower fully generic interface.

In a similar fashion any algorithm in TerrP must implement a C++ interface. The algorithms receive a handle to the map database interface, and for each ping, the bathymetric measurements transformed into a body-fixed local level and north aligned system. It is then the responsibility of the algorithm to compute an estimated horizontal position along with its covariance matrix, and a number (0-1) rating the uniqueness of the solution.

The integrity system is also an independent software module designed to run after the terrain correlation algorithm has converged. The integrity system will evaluate the position estimate and recommend using/not using it as a position measurement in the AINS.

Once the TerrP solution has passed through the integrity system, the solution data is published over the CORBA interface. NavP has now been extended to subscribe to position fixes from terrain navigation. The error of this position fix is modeled as a linear combination of a first order Gauss-Markov process and white noise, allowing for a possible time correlated bias in the position fix.

B. *Algorithm*

The main algorithm for terrain navigation used in TerrP today is an implementation of a 2D point mass filter (PMF) adapted for the underwater application [5][12][13][14]. The PMF is a highly versatile nonlinear Bayesian estimator capable of handling both Gaussian- and non-Gaussian distributed noise for both the measurement- and the dynamic update of the filter. In terrain navigation the 2D PMF estimates the probability density function (PDF) of the horizontal position of the AUV on a 2D grid. In our implementation the grid is actually defined in a north-aligned and horizontally level body fixed frame, and models the PDF of the position error in the AINS rather than the PDF of the global position.

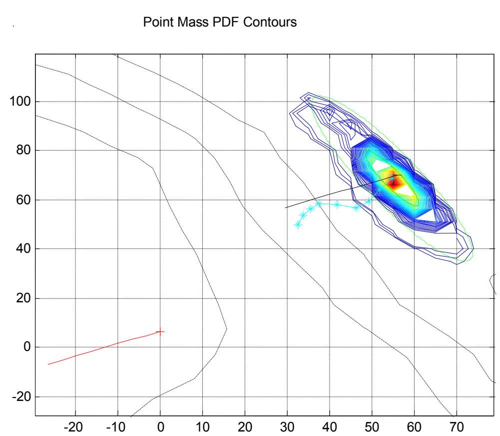

Figure 3. The contours of the PDF estimated by PMF overlaid the map contours. Simulated INS track is in red, true track is in black and the PMF estimate is in cyan.

Because of the possibly highly nonlinear nature of the DTMs that are used in the filter, the estimated PDF may very well be multimodal, or single modal but non-Gaussian. Since the AINS is running a Kalman filter, it requires Gaussian distributed errors of the position fixes. A part of the responsibility of the algorithm is therefore to compute a score (0-1) rating the single modality of the solution. This score is used in the convergence tests of the algorithm. Note that the algorithm will only find the best fitting solution within the search grid. If the true position is actually outside the search area, the algorithm will not detect this by itself. This is one of the reasons for having the integrity system described in Section II.D.

Current research and development involves making our PMF implementation even more configurable, accurate and robust for all types of scenarios, and of course making it faster as well.

C. *Digital Terrain Model*

As part of the preparation for the mission, DTMs for the mission area have to be uploaded to the vehicle. A software tool has been developed for the automatic generation of TerrP DTMs from scattered XYZ soundings. The soundings may come from official sources, recently surveyed areas by the supporting surface vessel or even HUGINs own soundings from any previous missions. The tool automatically subdivides the area according to a desirable memory footprint for TerrP.

A new feature of the system allows TerrP to be set in mapping mode. In this mode TerrP does not navigate, but rather builds a DTM within a desired bounding box using bathymetric measurements combined with position and attitude data from the AINS. After exiting the mapping mode, the constructed DTM can be used for terrain navigation, as described in Section II.E.

D. *Integrity system*

The integrity of a navigation system can be defined as its ability to provide timely warnings if and when it should not be used. It is notable that the definition hinges on the further use of the navigation data, as “when it should not be used” is application dependent. In the case of the application discussed in this paper, the position measurements from the terrain correlation system will be used to update the position estimate of the AINS by Kalman filtering. This update uses both the position estimate and its covariance, computed by the algorithm. If the true position is outside the area described by the estimate and its covariance, this may result in a position error that the navigation system is unable to recover from. The integrity of the position estimates from the terrain correlation system is thus critical to mission success. The design goal of the integrity system has therefore been to avoid Type II errors (accepting wrong measurements) even if this entails a lot of Type I errors (rejecting good measurements). It should be noted that ordinary sigma filtering of the estimates before they are used in the Kalman filter usually will not work, as the terrain correlation search area is based on the a priori estimate and covariance, and the estimate will thus always be within this area.

The integrity system uses the position estimate after convergence and the same ensemble of bottom depth measurements as was used in the correlation. The integrity system is not designed to handle estimates that have not converged, as it is almost impossible to find good criteria for rejection in such cases. The integrity tests are of two types: Suitability of terrain and goodness of fit. A terrain correlation result has to pass all the tests before it is passed on to the Kalman filter.

The suitability of terrain test is extremely simple: It just checks that the standard deviation of the bottom measurements is above a pre-selected limit. If it is below this limit, the terrain has too little variation to be suitable for terrain correlation. As this test does not depend on the result of the terrain correlation it could be moved outside the integrity test module and perhaps be performed before the terrain correlation algorithm is run. Off-line tests indicate that this test can be replaced by a maximum number of measurements used before convergence; this may also be a better way of eliminating self-similar terrain. It might also in the future be possible to select suitable terrain as a part of the mission planning.

The goodness of fit tests check how well the position estimate 'explains' the measurements. Several different possible goodness of fit criteria were tested in different scenarios to find the ones best suited for the integrity tests. These were both formal criteria from the statistical literature, and criteria developed for this specific purpose. The tests use the original bottom depth measurements (z) and the map depths (d) in the estimated position. It is worth mentioning two of the formal tests that were found wanting: The Chi-square test and the Box-Pierce test. Both these attempted to test whether z-d, the residual, was in accordance with the assumptions made in the terrain correlation algorithm. The Chi-square test checked that the standard deviation of the residual matched the assumed standard deviation, while the Box-Pierce test checked that the residuals were uncorrelated. The Chi-square test was dropped because it failed to discriminate between good and bad position estimates when there was little variation in the terrain, the Box-Pierce test was dropped because it failed in the same way when the number of measurements was small.

Two goodness of fit type criteria worked reasonably well in all scenarios, and were chosen for implementation in the real-time system. These were: The correlation between z and d, which should be close to one; and the relative standard deviation, defined as $\sigma(z-d)/\sigma(z)$; which should be a lot less than one. Both criteria make sense: There should obviously be a high correlation between the measurements and the map depths in the true position, and the relative standard deviation must be less than one in the true position, given that there is significant variation in the terrain. The terrain variation will be a part of z, but should be more or less eliminated in (z-d).

The integrity test implemented in the real-time system thus became:

Reject the position estimate if

- $\sigma(z)$ < Measurement standard deviation limit, OR
- $Corr(z,d)$ < Correlation limit, OR
- $\sigma(z-d)/\sigma(z)$ > Relative standard deviation limit

The limits were set to eliminate all Type II errors in the off line tests. This led to a high number of Type I errors, up to 60% in flat terrain. However, 66% of the rejections in the same terrain were correct, which makes the statistics for Type I error acceptable.

All the off-line tests used a MBE as the depth measuring sensor. The results from the Oslofjord 2010 [15] runs indicate that some tuning must be done to adapt the tests to other sensors. This tuning can be in the form of different rejection limits or some kind of scaling of the statistics depending on which sensor is used.

E. In situ sequential mapping and localization

TerrP also implements a concept or technique herein called *in situ* sequential mapping and localization. This is related to simultaneous localization and mapping (SLAM), but differs in its simplicity that mapping and localization are considered as uncoupled states. TerrP is always either in mapping mode or in navigating mode. The technique differs from regular terrain navigation in that no DTM has to be uploaded to TerrP before the mission.

With TerrP this can be done as follows. Before mission the operator defines a bounding box. The box may cover a particularly suitable area for terrain navigation close to the target mission area, or it may be a start line crossing over the lawn mower pattern of the target mission area. After the transit phase from the mother vessel to the target area, HUGIN will first survey the bounding box with TerrP in mapping mode. When the survey is completed, a DTM is automatically produced, and TerrP enters navigation mode. Whenever HUGIN crosses over the bounding box later in the mission, an estimate can be made from TerrP of the relative position displacement of the INS to a representative position from the time when the DTM was first surveyed. This is called a *macro delta-position measurement* in [16].

This measurement will in the future be fed back to the HUGIN INS as a macro-delta-position measurement, and will then allow HUGIN to survey the target mission area with a position error bounded to the level of the accumulated initial position error from the transit phase of the mission.

III. SEA TRIAL RESULTS

A. *Offshore test 2009*

The TerrP system has been tested at sea several times at the HUGIN test site in the Oslofjord in 2009. The first fully operational test of the whole system was however conducted far offshore in the open sea between the Norwegian coast and Bear Island in May 2009 using HUGIN 1000 HUS operated from FFI's research vessel, the HU Sverdrup II.

The purpose of the test was to demonstrate the use of terrain-aided inertial navigation to keep high real-time navigation accuracy during a transit phase to a target mission area located far away. In this mission HUGIN 1000 HUS was therefore programmed to make a straight line transit from the launch point to the mission area located about 50 km away. Soundings from the EM710 of the HU Sverdrup II in a 1.5 km wide strip along the route were used to create DTMs of 10 m resolution in TerrP's format, see Fig.4. TerrP was configured to use the PMF algorithm with absolute depth profile and connected only to the EM2000 multibeam echo sounder for bathymetric measurements.

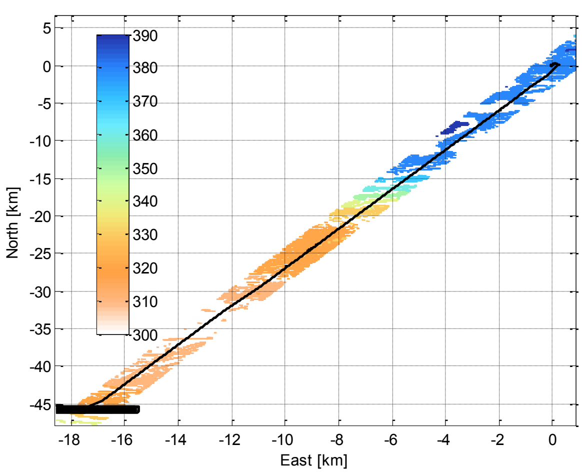

Figure 4. HUGIN's real-time AINS position (black), only aided by position updates from terrain navigation.

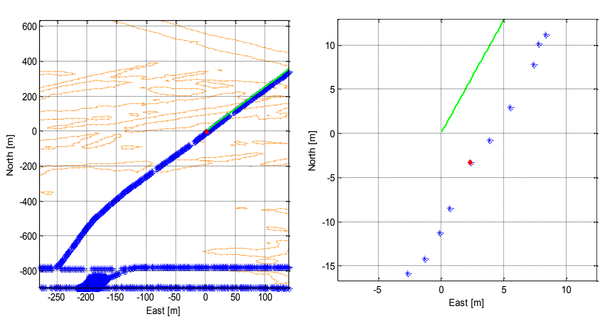

Figure 5. Left: On arrival in the target mission area: HiPAP positions (blue), and TerrP-aided NavP position (green). Right: The HiPAP position at the time of the last TerrP-aided NavP position(the origin) is marked in red, about 4 m off.

During the transit HUGIN did not receive any external position updates, but its position was monitored and logged by the HiPAP acoustic position system onboard HU Sverdrup II. HUGIN only navigated using the DVL-aided INS with position updates from the TerrP system running autonomously.

Due to an unfortunate malfunction of the hard drive on CP, the raw navigation data was not logged. The navigation could therefore not be post-processed to make a solid "ground truth" reference. The real-time navigation solution was however logged by PP, and could therefore be compared with the HiPAP positions, and so indicate the performance of the total integrated TerrP – NavP system.

On the arrival near the target mission area the difference between the HiPAP measurement and NavP's estimate was about 4 m, see Fig.5. The expected drift of the standalone DVL-aided INS in this scenario would have been 0.1-0.2% of travelled distance, which is about 50-100 m in this case.

A closer inspection of the bathymetry of the strip, see Fig.6, reveals something interesting. On the larger scale the strip must be classified as very gently sloping, dropping only 100 m in depth over a horizontal distance of 50 km. This would seem unfit for terrain navigation as the overall terrain would be almost flat within any local PMF grid. However, by looking closer at one of the DTM cells, there are clear marks of iceberg scouring on the sea floor. These are deep and wide enough to be picked up on a 10 m resolution scale. It turns out the variability in the iceberg scouring are enough to make the terrain very suitable for terrain navigation.

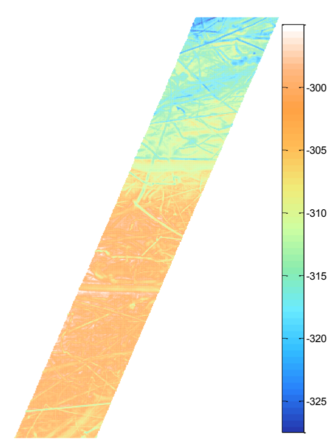

Figure 6. Clear marks of iceberg scouring are visible on the DTMs. This DTM cell is about 1.5 km wide and 12 km long.

B. *Oslo fjord 2010*

Another sea trial was conducted in the Oslofjord in May 2010. This was part of a cruise that combined tests of several HUGIN technologies at daytime with detailed bathymetric surveys done by HU Sverdrup II at nighttime, using its EM710 multibeam echo sounder. The basic idea was to use the EM710 soundings to create DTMs of 10 m resolution for TerrP, and to rerun a similar transit test as the one described in Section III.A again using HUGIN 1000 HUS. This was also the first real-time test of the integrity system described in Section II.D. Unfortunately HUGIN was not able to connect to the EM2000, due to what turned out to be a power failure. It was decided to run the mission anyway using only the DVL as bathymetric input to the TerrP system. The DVL outputs 4 ranges per ping in fixed directions referenced to a body-fixed system. The accuracy of the bathymetric measurements are poor compared to the EM2000, but adequate for use in terrain navigation in this scenario. The use of DVL for terrain navigation of AUVs has been demonstrated before [4][9][10].

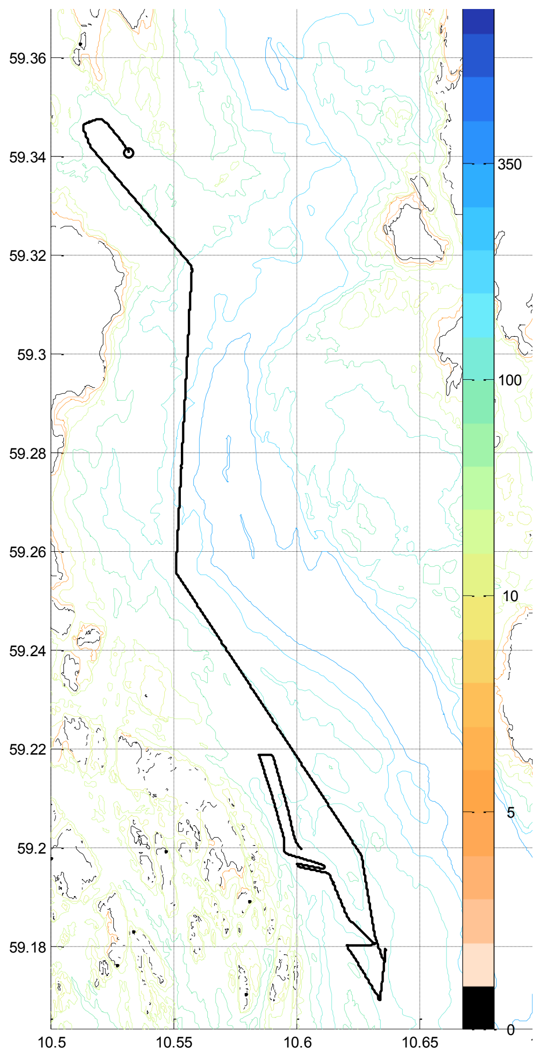

Figure 7. HUGIN's real-time INS position overlaid the S-57 charts of the mission area. HUGIN followed the fjord from north to south keeping out of the ship lane in the Oslofjord.

A mission was planned for HUGIN to launch at a northern location straight east of Åsgårdstrand, and to make a transit south to the Bolærne islands following a parallel track to the ship lane of the Oslofjord, see Fig. 7. HUGIN was programmed to follow the dramatic terrain variation about 50 m above the seafloor, not only for safety, but also for making a nice horizontal spread of the DVL beams. In the southern part of the mission HUGIN was programmed to make a pass 20 m above the seafloor, to try to get side scan images of a possible wreck. The position of the wreck was somewhat uncertain, but expected to be within range of the side scan sonar. After visiting the wreck some experimentation was planned to trigger higher drift by turning off DVL aiding in NavP (free inertial mode) for a while, still using TerrP updates.

The mission was carried out as planned with HUGIN navigating in real-time using only an IMU, a DVL and a pressure sensor. The only position updates received by NavP after initialization and before resurfacing at the end of the mission 5 hours later, was from the terrain navigation performed by TerrP. When HUGIN resurfaced the difference between NavP's position and the GPS on HUGIN was about 5 m. HUGIN's position was also monitored on the HiPAP of HU Sverdrup II, and this time the navigation could be post-processed to make an accurate "ground truth" reference solution. The analysis in [15] shows that HUGIN HUS was almost always within the grid resolution of the DTM, and that the integrity system filtered out most of the false convergences.

A side scan image of the wreck at the end of the long transit legs, shows that HUGIN passed between the wreck and the edge of a very steep underwater hill, about 70 m to the starboard side. The sonar image in Fig. 8, gives an indication of the locally rough bathymetry in the fjord.

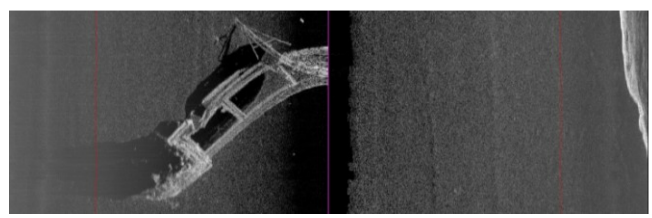

Figure 8. The Edgetech 2200 high-frequency side scan sonar image shows the wreck at the port side, and the edge of a steep underwater hill on the starboard side.

IV. Applications

The range of applications for the terrain navigation system goes beyond the use in autonomous underwater navigation that has been demonstrated in this paper. The integrity system together with a high quality DTM can be used to check a vessel's navigation system in real-time. If on the other hand the vessel navigation system can be trusted it is possible to check the integrity of the DTM in real-time, or to make a real-time estimates of depth offsets from the vertical datum caused by tidal waves.

The requirement of DTMs to be available to the AUV before the mission has been an argument against regular terrain navigation. As mentioned in Section II.E TerrP is able to create a DTM during the mission. If this is combined with an INS capable of receiving a measurement of the position difference between the AUVs current position and its position several hours ago (macro delta-position-aiding [16]), this will enable bounded navigation error in the mission area. That is if TerrP can make position updates towards the DTM created *in situ*.

Another application is to refind interesting objects detected in current or previous mine counter measures (MCM) missions. In order to find the objects again using a camera mounted on an AUV or through a diver, the position of the object must be known precisely. It is however a misconception that the *global position* must be known precisely. Consider the scenario of a MCM mission where the AUV has travelled a great distance to the target mission area without position updates, and so it arrives with a global position error of about 100 m. The AUV makes a start line DTM, and performs a lawn mower pattern search crossing this start line, keeping the position error bounded to the initial 100 m or so by running terrain navigation with the start line DTM. Interesting objects are detected in real-time from the sonar images, and their positions are registered. A DTM of the whole survey area is made from the concurrently recorded soundings from the AUV bathymetric sensor. This ensures that the DTM has the same global position error as the registered positions of the objects, i.e if you find your position relative to this DTM, you will be able to find the objects. In order to later refind the objects, the AUV simply runs regular terrain navigation using the previously constructed DTM of the whole mission area. The concept can also be used if the MCM detection & classification, and the MCM identification missions are run sequentially. The DTM and object positions of the first AUV returning from the MCM detection & classification mission is uploaded to a second AUV performing identification by camera. The second AUV transits to the mission area and runs terrain navigation with the DTM from the first AUV. It can now refind the objects, even though the global positions of the objects are actually about 100 m off.

V. CONCLUSION AND FUTURE WORK

The HUGIN real-time terrain navigation system has been described in this paper. Two sea trials demonstrate the real-time performance of the system and its ability to sustain precise navigation over long periods of transits using both the EM2000 and the DVL in different kind of bathymetries.

More real-time and simulation tests of the system components described herein are needed to increase the overall system robustness. To make the system more operationally efficient than today, the handling of the DTMs (from XYZ soundings to uploaded TerrP cells) should be made more user- friendly.

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