Terrain Referenced Navigation of AUVs and Submarines Using Multibeam Echo Sounders

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Abstract

Most AUV and submarine navigation systems are based on accurate low drift inertial navigation systems (INS) designed to sustain submerged operation for long periods of time. Regardless of velocity aiding sensor and INS quality, the position accuracy will eventually decrease necessitating position updates.

When GPS surface fixes are not allowed due to vulnerability, covertness or efficiency, terrain referenced bathymetric navigation is a well-suited method for submerged position updates. In principle terrain navigation runs on any sensor providing bathymetric data. The paper focuses on use of multibeam echo sounder (MBE), which is particularly attractive because of its wide coverage. MBEs are also ideal sensors for terrain mapping. In rapid environmental assessment (REA) and intelligence, surveillance, target acquisition and reconnaissance (ISTAR) scenarios, bathymetric mapping is an important capability. MBEs typically come with software for in-situ chart production and seabed classification.

A FFI developed terrain navigation system is integrated with the inertial navigation system on the HUGIN AUV. A Norwegian submarine is equipped with a multibeam echo sounder in an experimental set-up.

1 Introduction

Air and land navigation systems are increasingly relying on continuous GPS availability to keep high permanent position accuracy. GPS signals are blocked by water, so submarines and AUVs cannot rely on GPS as an always-available source of own ship position. Most AUV and especially submarine navigation systems are both based on low drift inertial navigation systems (INS) designed to sustain submerged operation for long periods of time. AUVs are typically equipped with a variety of acoustic sensors. Restrictions on active acoustics have limited the use of the same sensors on submarines. Thus, AUVs limit the INS position error drift utilizing acoustic Doppler velocity log (DVL) measurements, while submarines mostly use electromagnetic logs. An electromagnetic log measures speed against water, typically only in the along-ship direction. It can never measure speed over ground with an error smaller than the ocean current. In contrast, DVLs with bottom track measure speed over ground directly, and output this in three directions (forward, starboard, down). Regardless of velocity aiding sensor or INS quality, the position accuracy will eventually drift off as illustrated in Figure 1, necessitating position updates or compromising mission success.

GPS surface fix is the most obvious method for position update. However, many scenarios require submerged position updates. AUVs and submarines are increasingly being envisioned in rapid environmental assessment (REA) and intelligence, surveillance, target acquisition and reconnaissance (ISTAR) type of missions with submerged operation as a requirement. For submarine operations in general, surfacing or exposing masts should be minimized to reduce vulnerability.

High position accuracy is important to safe underwater navigation, tactical navigation through exploitation of the underwater topography and for accurate geo-referencing of payload data. Terrain referenced navigation allow for high position accuracy and submerged position updates. The multiple use of bathymetric maps including terrain navigation, mission planning and mission execution makes the cost of acquiring these maps reasonable.

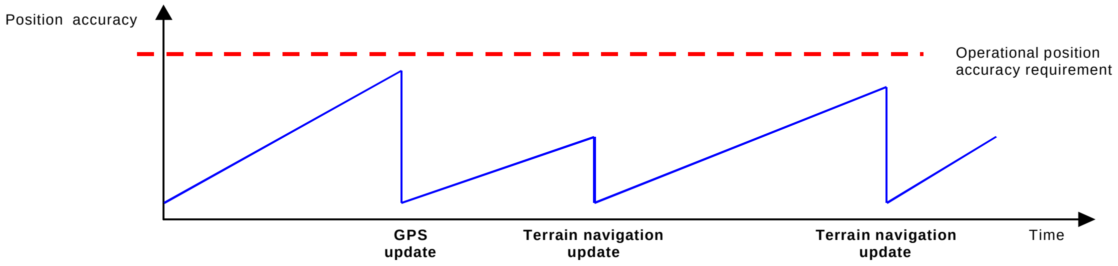

Figure 1 Illustration of navigation system position drift and effect of GPS and terrain navigation position updates.

Multibeam echo sounders (MBE) are ideal sensors for terrain mapping. In REA scenarios bathymetric mapping is an important capability. The sparse global coverage of bathymetric maps is an operational problem for both surface and underwater platforms. AUVs and submarines equipped with MBE can help this problem. MBEs typically come with software for in-situ chart production and seabed classification.

The HUGIN class of AUV have been equipped with MBEs for detailed seabed mapping since 1995, Chance et al (1), George et al (2), Jalving et al (3). The HUGIN terrain navigation system will be tested in real-time in AUV sea trials in summer 2004. A Norwegian submarine, KNM Utsira, was equipped with a multibeam echo sounder in an experimental set-up in spring 2004. FFI is actively investigating and demonstrating how MBE and terrain navigation can enhance capabilities and performance of submarines.

2 Terrain Navigation System Description

The terrain navigation system can be viewed as an independent component of the navigation system whose primary function is to provide position measurements. In an AUV or submarine the position measurements will be integrated with the inertial navigation system in similar way as GPS. In other systems it might integrate with a dead-reckoning system or serve as an independent position source. Terrain navigation can increase the total navigational integrity by providing a position estimate supplementary to INS and GPS. This is of interest for instance for surface vessels if they operate in an area where GPS can be subjected to jamming or spoofing.

In Figure 2, the HUGIN terrain navigation system is shown to illustrate a possible design of a terrain navigation system with interfaces to bathymetric sensors and a vehicle navigation system. The HUGIN Terrain Correlation Processor (TerrP) consists of the following main parts:

- *Terrain Correlator:* Runs the terrain navigation algorithms on geographically referenced depth data.
- *Geographic Data Producer:* Converts body-fixed depth sensor measurements to geographical referenced data using position and attitude data from the integrated inertial navigation system.
- *Map Database:* Readies the digital terrain model (DTM e.g. bathymetric map) for random access by the Terrain Correlator.

TerrP communicates with the integrated inertial navigation system through a well-defined interface. Thus, TerrP can in principle be interfaced to any integrated inertial navigation system that provides the necessary data set to run the terrain correlation. Calculated position fix and associated uncertainty is sent back to the navigation system to limit the position error drift, refer to illustration in Figure 1.

As shown in Figure 2, TerrP runs on any sensor providing bathymetric data, for instance multibeam echo sounder, single beam echo sounder (SBE), DVL or interferometric sonar. In this paper we will focus our discussion on MBE. The terrain correlation algorithms are described in Section 3.

TerrP uses an internal data format for storage of bathymetric maps in the Map Database. This format is optimised with respect to performance and global use. Conversion between other map formats and the internal TerrP data format is done by a data format converter, which is a separate application that runs on a standard computer and can easily be updated to provide flexibility in map formats that can be used by the terrain navigation system. The converted data is transferred to the TerrP hard disk.

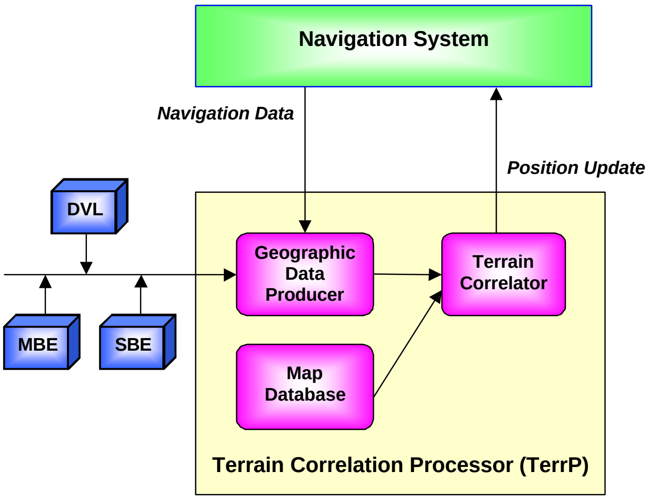

Figure 2 HUGIN terrain navigation system structure.

3 Terrain Navigation Algorithms

Terrain navigation algorithms can conceptually be divided into correlation based global search algorithms (correlation methods) and tightly integrated terrain tracking algorithms. The current HUGIN terrain navigation system is based on correlation methods.

Terrain navigation for AUVs and submarines differs from that of an aircraft with respect to sensor types and vehicle dynamics. On an aircraft typically laser or radar altimeters are used for terrain measurements, whereas acoustic sensors are typically used underwater. Aircrafts have greater speed than AUVs or submarines and are thus able to cover more ground and get a longer terrain profile to correlate with the stored map. Aircraft terrain navigation has typically performed best on maps of quality DTED 3 (digital terrain and elevation database), which has about 30 m horizontal grid resolution and world wide coverage. Underwater terrain navigation today has to depend on sparse global coverage. Available digital terrain models (DTM) often have poor resolution and accuracy, except for dedicated areas were accurate high resolution (1 – 10 m horizontal resolution) DTMs have been surveyed. Terrain navigation accuracy depends on algorithm characteristics, sensor accuracy, map accuracy, map resolution and not least terrain suitability. All terrain navigation algorithms need terrain variation to work at all. If the terrain is flat, all they can tell is that the vehicle is somewhere above the flat area.

3.1 Correlation Methods

Though the term 'Terrain Correlation' is in common usage, and is used in this paper, it is misleading. The methods do not compute correlation in a strict statistical sense, but some other matching function that shows how well a measured bottom depth profile matches a map. Terrain Contour Matching would be a better term, but this has already been used as the name of one of the several possible methods.

Terrain correlation may be done for one measurement, or for a sequence of measurements. The position is shifted around an offset area around the current position estimate, and match statistics between the measurements and the depth data in the Digital Terrain Model (DTM) is calculated in this area. The match statistics can be analysed to determine convergence, calculate a position offset, the error covariance and a position fix confidence.

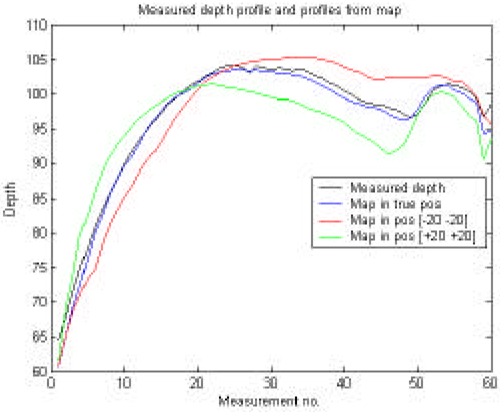

Figure 3 Terrain contour matching example: Measured depth and map depth in true and offset positions

The terrain correlation methods usually need a measured profile (several depth measurements along a line) to converge to a good position estimate. An MBE can provide a profile in a single ping, while an SBE requires several. If necessary, several pings from an MBE can be used, improving convergence by providing the depth of an area of the seabed as illustrated in Figure 7.

Two different algorithms is implemented in the HUGIN terrain navigation system

1. Terrain Contour Matching (TERCOM)
2. Point Mass Filter (PMF)

Terrain Contour Matching
TERCOM is a well-proven and robust algorithm that uses the mean absolute distance between map depth and measured depth as a matching statistic. The algorithm was originally developed by the Aeronautical Systems Division at Wright-Patterson Air Force Base in the mid seventies and successfully applied to cruise missile (Tomahawk) navigation, Golden (4). A position fix was produced by correlating a radar-altimeter-derived terrain profile with a stored topographical map, taking the best match as the position of the cruise missile.

The method implicitly assumes that the position error is constant. It can be run both as a batch algorithm and recursively. Initially a grid of possible position errors is made and then a function of the distance between measured depth and map depth in the candidate points are minimized. The original TERCOM minimizes the average distance between map depth and measured depth:

$$d\,\underline{\hat{x}} : \arg\min_{\mathrm{k,l}} \frac{1}{t}\sum_{i=1}^{t}\left|e_i(k,l)\right| \qquad (1)$$

This is known as TERCOM MAD (Minimize Average Distance). The point in the grid with lowest average distance will be chosen as the position estimate. This method can be modified in several ways, and FFI is researching several modifications for possible implementation in the HUGIN AUV. One of the goals of such modifications is to be able to compute a covariance of the measurement, both to see if the method has converged and to use in the statistical description in the Kalman Filter of the integrated inertial navigation system.

Together the computed values for each grid point form the correlation surface, giving the sum of differences for each candidate. Figure 4 shows the development of this surface as a function of the number of single depth measurements (in one special case). In the figure, we have changed the sign of the correlation value, so that the highest point is the best match.

Point Mass Filter
PMF is more sophisticated than TERCOM and actually calculates the position probability density function (PDF). The University of Linkøping has in cooperation with SAAB published several papers on terrain navigation for aircrafts, Bergman et al (5). The publications describe the application of non-linear Bayesian estimation to terrain navigation, using both simulation methods as the bootstrap filter, and deterministic integration on a mesh as in a point-mass filter (PMF).

The point mass filter is a statistical estimator that uses the a priori position distribution together with the error models of the bottom depth measurements and the map to generate an a posteriori probability density function for the position by means of

Bayes' theorem. Once a PDF for the position has been generated, an estimate of the position can be found as the expectation (mean), the median or the maximum likelihood (highest point). The covariance can also be computed from the PDF. This means that the PMF has a built-in test for convergence, something that is lacking in TERCOM. On the other hand, it is computationally more intensive and requires some knowledge of the error statistics in the sensors and the DTM.

PMF can be run both recursively, processing single measurements, or as a batch processing algorithm, processing several measurements at the time. Batch processing is the logical way to handle data from an MBE or 3D sonar, but there are advantages to processing SBE measurements this way as well. The filter can handle a changing position error when running recursively. Figure 5 shows how the PDF of the position estimate looks initially and after 1, 10 and 15 single bottom depth measurements. The figure also shows that in this case an MBE would cause convergence in one ping.

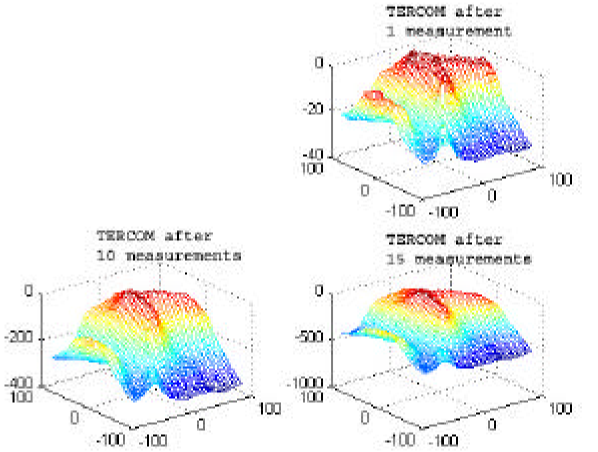

Figure 4 Example of development of a TERCOM correlation surface after 1, 10 and 15 single bottom depth measurements.

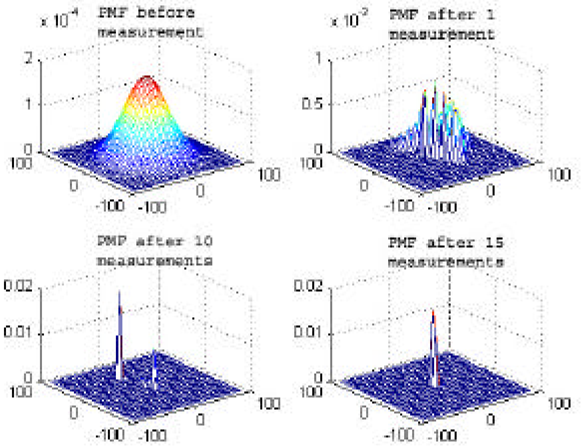

Figure 5 The Probability density function computed by the PMF algorithm after 1, 10 and 15 bottom depth measurements. Based on the same data as in Figure 4.

3.2 Tightly Integrated Terrain-Tracking Algorithms

Tightly integrated terrain-tracking algorithms are characterized by integration of the range measurements and the bathymetric map into the Kalman filter. Thus, all available information in the integrated navigation system is utilized. However, since these algorithms have less robust behavior in highly non-linear terrain, they should be considered as a supplement to terrain correlation algorithms. FFI has invested a considerable effort in developing a terrain-tracking algorithm called TRIN, Hagen and Hagen (6). This is planned for integration in HUGIN, following the completion of the work on correlation-based methods.

A precursor to TRIN was the Sandia Inertial Terrain Aided Navigation (SITAN) system that was originally used to aid helicopter navigation, Hollowell (7). SITAN uses each terrain clearance measurement from the radar-altimeter tightly integrated in an Extended Kalman Filter in an almost "continuous" way.

3.3 Concurrent Mapping and Navigation (CMN)

When no a priori data of an area exists, methods for concurrent mapping and navigation (CMN) are required. An attractive feature of TRIN (see Section 3.2) is that it includes a solution for Concurrent Mapping and Navigation (CMN). Methods and concepts for concurrent mapping and navigation based on terrain contour matching and point mass filter is an ongoing research effort. This will allow for autonomous and submerged high quality mapping of unknown areas. The general poor availability of existing DTMs makes CMN very attractive, especially in REA and ISTAR scenarios.

4 Multibeam Echo Sounders (MBE)

4.1 Principle of Operation

Multibeam echo sounders are acoustic instruments producing multiple observations of the seafloor for each transmission sequence (ping). The raw measurements are beam angles relative to the transducer array and two-way travel times for the sound pulse. The number of soundings per ping varies, but can be as high as 200 - 500. The observations are distributed along an across-track sounding line, so that a depth profile is obtained per ping, see Figure 6. The MBE data is compensated for observation platform orientation (roll, pitch, heave), as well as variations in the sound velocity profile. For submerged platforms like AUVs and submarines, a pressure sensor is required to compensate for the depth of the vehicle. While the observation platform is moving forward, new depth profiles are generated, and a swath of soundings obtained. The swath width will typically be 3 to 8 times the distance between the observation platform and the seabed. Multibeam echo sounders are nearly optimal instruments for bathymetric terrain navigation, since virtually all parts and details of the seabed is observed, see Figure 7. The figure illustrates the advantage of MBEs for terrain correlation: As the vehicle moves along it observes the depths of an area, as opposed a

SBE, which only observes depths along a line. This means that more information is available for the terrain correlation algorithms.

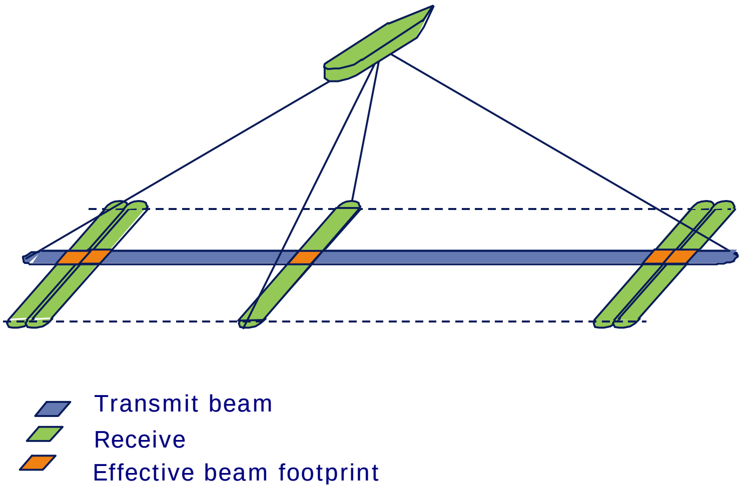

Figure 6 Illustration of the observation geometry of a multibeam echo sounder.

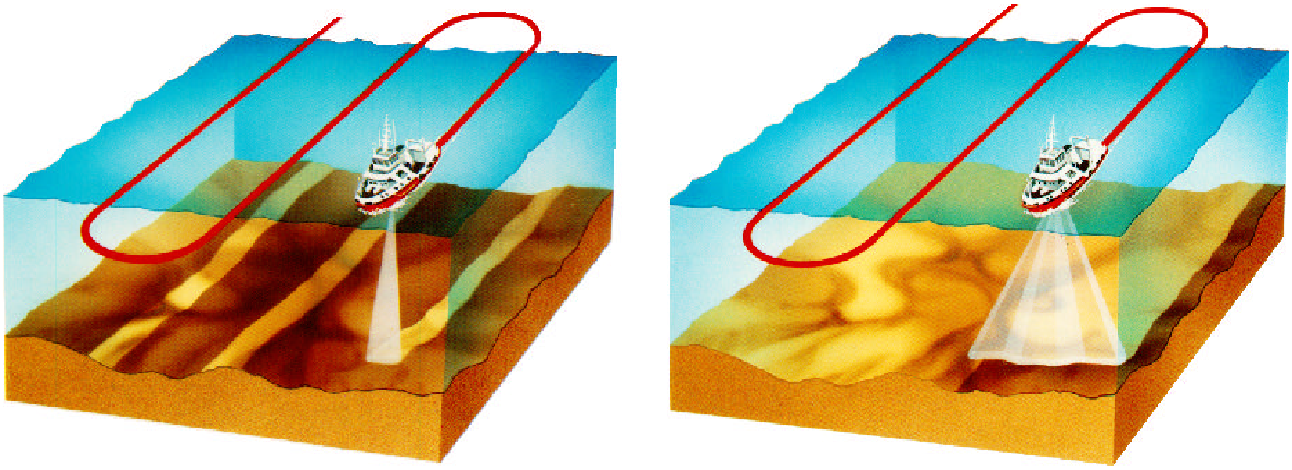

Figure 7 Illustration of the difference between observing the seafloor with a single beam echo sounder (left) and a multibeam echo sounder (right).

4.2 Terrain Modelling and Data Cleaning

A variety of post-processing systems to process acquired MBE data into digital terrain models and electronic charts exist. Recently, software systems for real-time or near real-time 2D and 3D visualization of MBE data have become available as well. Modern 3D graphical standards, typically Open-GL, enable the use of interactive 3D presentations of terrain models. The terrain model can be a regular grid of depth values, which are estimated from the most nearby soundings. In the new systems, several sets of grids with different resolutions are computed at the same time, so that a representation of suitable resolution is immediately available for visualisation at any scale.

Real-time data cleaning software is also incorporated in the systems. The principle for cleaning of MBE data is to compare soundings with other soundings located close by, and on that basis decide whether the sounding is valid or should be rejected as spurious.

4.3 Acoustic Seabed Imagery and Seabed Classification

In addition to measuring the depth, multibeam echo sounders measure the strength of signals backscattered from the seabed. Signal strengths are sampled with the full bandwidth resolution of the instrument, and can be compared to sidescan sonar images. One major difference is that signal strength is measured digitally and compensated for instrument settings as well as transducer sensitivity, to obtain a valid estimate of the true backscatter strength of the seabed.

The resulting acoustic image can be visualized to locate objects, features and clear sediment boundaries or it can be draped over the bathymetry to provide more information to the observer. Further processing of signal strength and the internal structure of the backscatter signals can result in sediment type of map used for seabed classification.

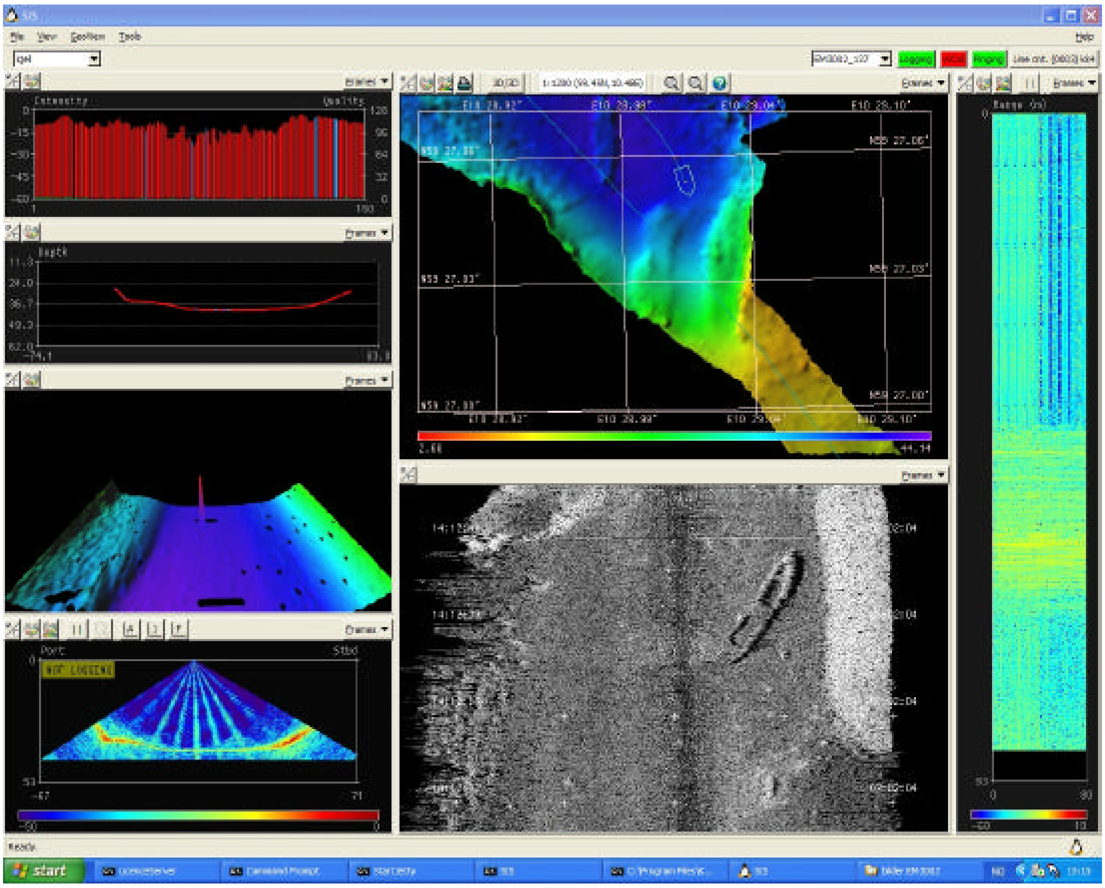

Figure 8   Real-time visualization of bathymetry (large window color scale) and seabed imagery (large window grey scale). Note the wreck on the imagery data.

4.4 Different Instrument Models for Different Platforms

Depending upon the requirements for operating depth of the instrument platform, resolution and maximum sounding range, there are different instrument models available. Typically, an AUV requires low power consumption and compact electronics, while a submarine can accept a somewhat larger transducer array and higher power consumption. Table 1 summarizes Kongsberg Maritime MBEs suitable for terrain navigation.

MBE model	**EM 3000 single/dual**	**EM 3002 single/dual**	**EM 2000**	**EM 710**
Acoustic frequency	300 kHz	300 kHz	200 kHz	70-100 kHz
Depth rating	500 m / 1500 m	500 m / 1500 m	3000 m / 6000 m	500 m
Max sounding range	150 m	150 m	350 m	>1000 m
Number of beams	127 / 254	254 / 508	111	>200
Beam spacing	0.9°	0.45°	1.5°	<0.7°
Max swath width	120° / 150°	120° / 150°	120° / 150°	140°
Transducer size	33 cm	33 cm	50 cm	50-200 cm
Electronics size	18 x 14 x 42 cm *	18 x 14 x 42 cm *	18 x 14 x 42 cm *	60 x 60 x 110 cm
Power consumption	70 – 90 W	80 – 110 W	80 W	800 W

*Table 1   Key parameters for Kongsberg Maritime multibeam echo sounders. * AUV version of processing unit.*

4.5 Use of MBEs in AUVs and Submarines

The EM 3000 and the EM 2000 multibeam echo sounders have been fitted to several AUVs, see examples in Figure 9 and Figure 10. AUVs have proven very high DTM data quality in commercial offshore operations over several years, George et al (2). The AUVs themselves are very stable platforms and the data density and the bathymetric data quality increase when the sensor is brought closer to the seabed. For AUVs and submarines engaged in rapid environmental assessment (REA) and intelligence, surveillance, target acquisition and reconnaissance (ISTAR) type of missions, bathymetric mapping is an important capability. Obviously, MBEs can be used for terrain navigation and mapping at the same time. Sections 6 discusses a number of submarine applications of MBEs.

Figure 9 EM 3000 multibeam echo sounder transducer mounted on the HUGIN 1000 AUV.

Figure 10 EM 2000 multibeam echo sounder transducers mounted on HUGIN 3000 AUV.

5 Terrain Navigation in the HUGIN AUV

5.1 HUGIN Integrated Inertial Navigation System

In Figure 11 the structure of the HUGIN integrated inertial navigation system is shown. The inertial navigation system (INS) calculates position, velocity and attitude using data from the inertial measurement unit (IMU). The IMU consists of three accelerometers measuring specific force and three gyros measuring angular rate. The Kalman filter will, in a mathematically optimal manner, utilize a wide variety of navigation sensors for aiding the INS. The Kalman filter is based on an error-state model and provides a much higher total navigation performance than is obtained from the independent navigation sensors.

With DVL aiding only, the inertial navigation system is capable of handling submerged autonomous operation for long periods of time. Depending on position accuracy requirements, the navigation system must get occasional position measurement updates, see illustration in Figure 1 and Jalving et al (8). GPS surface fixes is the preferred method for position updates when moderate water depths, mission efficiency and covertness requirements allow. Bathymetric terrain navigation allow for submerged position updates. As seen in Figure 11, the terrain navigation position fix is integrated in the inertial navigation system similarly to GPS.

HUGIN comes with a second method for submerged position update, called underwater transponder positioning (UTP), which is based on acoustic ranging and bearing to one or more underwater transponder. If HUGIN is in acoustic vicinity of its mother ship, DGPS-USBL (ultra short baseline) aiding can be used. More information on the HUGIN navigation toolbox and use of the toolbox in different applications can be found in Jalving et al (9).

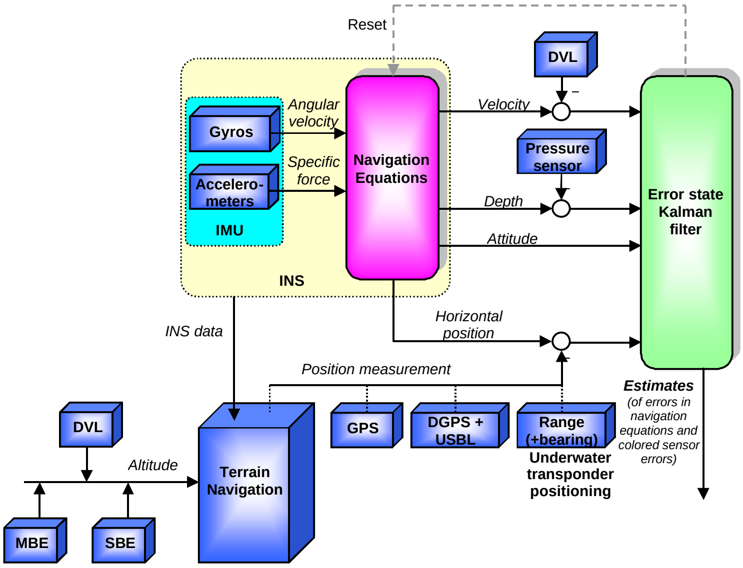

Figure 11 HUGIN integrated inertial navigation system structure. See Jalving et al (9) for further reference.

5.2 HUGIN Terrain Navigation Results

The HUGIN terrain correlation system shown in Figure 2, is currently tested on recorded data from HUGIN I missions conducted in a test area in Norway outside Horten in the Oslo fjord. The test area was surveyed by FFI's research vessel HU Sverdrup II in January 2001, with DGPS positioning and by using the EM1002 multibeam echo sounder. A high quality DTM with 10 m resolution was produced. This DTM is statistically independent of the bathymetric data collected by HUGIN I, which is very important with respect to realistic testing of terrain navigation algorithms. A data player plays the recorded real-time navigation solution and MBE and DVL bathymetric data. Except for the data player, the system is identical to the real-time version of the terrain navigation system.

Figure 12 shows the contour lines of the inverse of the resulting correlation surface of the TERCOM algorithm for a sequence of position fixes using the EM3000 measurements. Each fix is rated by a confidence value 0 (low) to 1 (high). This value indicates stability of the fix and the presence of possible multiple solutions. For each fix an estimate of position standard deviation in northern and southern direction, along with the position covariance, are calculated using the correlation surface. The figure shows how the confidence is low as long as there exists multiple solutions, but is high for the last stable and single solution. Notice also that the uncertainty of the fix is greater in the direction along the contour lines than across, indicating the importance of the position fix covariance.

The convergence time for a correlation sequence is very dependent upon the terrain, and can vary from under 5 pings for favorable areas to over 100 pings for very flat areas. A large MBE swath width is favorable to convergence time.

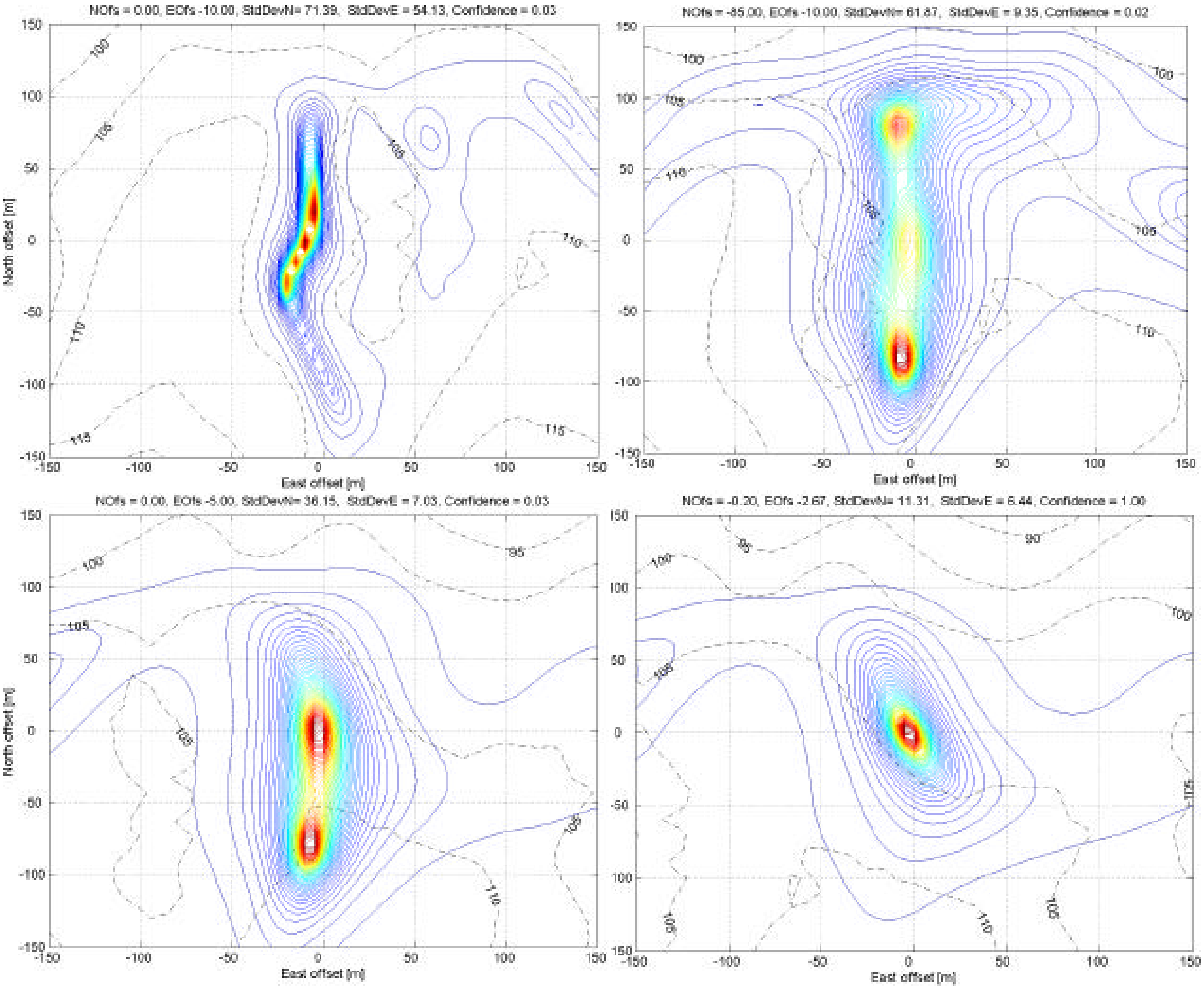

Figure 12 TERCOM correlation surface contour lines overlaid DTM contour lines for a 300m x 300m area. HUGIN I's position estimate (considered true position) is in the origin of this grid. The snapshots from top left of the correlation surface are taken at MBE ping number 1, 8, 13 and 19.

6 Terrain Navigation and Use of MBE in Submarines

6.1 Terrain Correlation in Submarines

Submariners already do a manual type of terrain correlation. They can check their position by comparing single depths or a measured profile from the single beam echo sounder with a paper chart. In addition to depth contours they can extrapolate the shape of the surface terrain to get an impression of the underwater terrain. This method is illustrated in Figure 13. WECDIS (Warship Electronic Chart Display and Information System) will support this type of terrain correlation for electronic charts.

The quality of manual terrain correlation mostly depends on the chart and the terrain. If the chart has close bottom contours (for instance <10m contour interval) or the terrain is roughly linear between contours and has unique shapes, the position fix will be good. The fix can then be sent to the integrated inertial navigation system, or used as a fix in dead reckoning. In other cases, (low resolution map or small terrain variation) one is only able to do an integrity check: The navigator can confirm that the submarine is in the area indicated by the navigation system's position and uncertainty, but cannot reduce the uncertainty. In some cases it may be possible to say where the submarine is not, and thus eliminate parts of the position uncertainty ellipse.

Figure 13 Manual Terrain Correlation: MBE data (colored with grey contours) shown in an a priori electronic map (green contours).

The methods for automatic terrain correlation against DTMs will be the same in submarines as in AUVs (refer to Section 3). A terrain correlation system for a submarine must have very high integrity, as it will be a safety critical system. High integrity can be assured by checks built into the terrain correlation system and/or having a man in the loop to accept or reject the terrain correlation result. A man in the loop will introduce delays, which must be accounted for if the measurement is to be used in the integrated inertial navigation system. The integrated navigation system should be able to accept both the position and the covariance given by the terrain correlation system, so that the shape of the uncertainty ellipsis can be taken into account.

6.2 Bathymetric Sensors

In addition to the SBE that all current submarines are equipped with, future submarines may be equipped with MBE, DVL, and a forward-looking mine avoidance/navigation sonar. All these sensors measure range to the bottom along one or more beams, and can thus be used for terrain correlation (the authors have not tested terrain correlation with a forward looking sonar). A laser can be an alternative when operating close to the bottom.

The use of active acoustics makes the submarine detectable, and perhaps identifiable, to an opponent listening at the correct frequencies. The different sensors have different beam patterns, frequencies and sound levels, thus the risk differs between sensors. To minimize the risk, all sensors should have adjustable output levels, so that they only transmit enough energy to get a bottom echo. Which sensors that can be used will depend on the tactical situation: the risk of detection must be weighed against the advantages gained by using a sensor. It might be that detailed charts and a terrain correlation system may in fact reduce the reliance on acoustic sensors, as the submarine can use the map instead of the SBE and/or forward looking sonar, and do terrain correlation with a minimum of pings when the position uncertainty becomes to large.

6.3 Tactical Navigation

Detailed bathymetric data (DTM and electronic charts) has the potential to greatly enhance the submarine's efficiency through tactical use of the underwater terrain. The submarine can hide from active sonars using bottom clutters and underwater terrain shadows. Terrain shadows can also be used to block noise radiated from the submarine itself. Areas suited for exposing masts (surface terrain shadow) can be found by combining depth charts and elevation charts. Torpedo routes can be planned to make optimal use of the terrain, the same is true for future payloads like AUVs. The detailed maps would be used both for mission planning and during the execution of the mission. This type of tactical terrain use will require high position accuracy, an accuracy that can be achieved using terrain correlation on the same bathymetric data that has been used in the charts. Thus, detailed bathymetric data will enable tactical use of the underwater terrain both directly and indirectly.

Today, few areas have bathymetry of a quality suitable for terrain correlation. One work-around is to do detailed surveys of selected areas close to or in areas of special operational interest. These areas can then be used for terrain correlation, and they can also be used as starting areas for CMN. Such surveys may be a part of REA operations, and can be done by AUVs or submarines equipped with MBEs.

6.4 Bottoming

An MBE will be of great help in one particular aspect of submarine operations: bottoming. Promising areas for bottoming of the submarine can be picked in advance. If detailed bottom characteristics are available, they can be completely determined during mission planning. In areas where there are no known bottoming areas, the submarine can do a local survey of promising areas, and bottom immediately after, if the bottom is suitable. For this to be feasible the MBE-data must allow for seabed classification in addition to bathymetry, and the bathymetry and seabed imagery must be detailed enough to reveal features (large rocks etc) that might damage the submarine (see Section 4.3 Acoustic Seabed Imagery and Seabed Classification).

7 Summary

High position accuracy is important to safe underwater navigation, tactical navigation through exploitation of the underwater topography and accurate geo-referencing of payload data. An AUV or submarine navigation system will eventually drift off in position. When GPS surface fixes are not allowed due to vulnerability, covertness or efficiency, terrain referenced bathymetric navigation is a well-suited method for submerged position updates.

Due to its wide swath, a multibeam echo sounder is an ideal sensor for terrain correlation, allowing fast conversion of the position estimate (if bottom topography permits). A MBE also provides AUVs and submarines with a bottom mapping capability, which is important to REA and ISTAR type of missions.

A detailed bathymetric map is an enabling factor for both terrain navigation and planning of tactical navigation. Concurrent mapping and navigation can be a way to deal with the general poor availability of existing DTMs.

FFI has developed and implemented a terrain navigation system for the HUGIN class of AUVs. The paper includes HUGIN results obtained by use of a data player. Real-time testing is scheduled summer 2004. A Norwegian submarine has an MBE installed in an experimental set-up, and will evaluate its use as part of the navigation system.

8 References

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