INTEGRATED INERTIAL NAVIGATION SYSTEMS FOR AUVS FOR REA APPLICATIONS

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AUVs have an important role to play in preparing the littoral undersea battlespace. This capability addresses all aspects of the environment, including the acquisition of hydrographic and oceanographic data and the detection of threats, wrecks, pipelines, cables, and other objects in all ocean environments and particularly in denied areas. This paper defines three Rapid Environmental Assessment (REA) missions and their requirements with respect to navigational accuracy and covertness, and shows practical navigation solutions based on system components that are either commercially available or will become available in a short time frame.

1 Introduction

AUVs have an important role to play in preparing the littoral undersea battlespace. This capability addresses all aspects of the environment, including the acquisition of hydrographic and oceanographic data and the detection of wrecks, pipelines, cables, and other objects in all ocean environments and particularly in denied areas. The acquisition of oceanographic data is of key importance for strategic and tactical operations. Accurate knowledge of the ocean bottom, its characteristics and environmental conditions is a vital prerequisite for mission planning.

AUVs are well suited for many oceanographic tasks as they can independently acquire high quality information for later delivery or transmission. Conventional oceanographic data acquisition is largely dependent on hull mounted or towed systems that require extensive surface ship support and suffer speed limitations imposed by the tow cable. AUVs permit collection of significantly greater quantities of data at less cost by multiplying the effectiveness of existing platforms. AUV technology allows acquisition of affordable, near real time data at the required temporal and spatial sampling densities and provides maritime commanders with critical knowledge such as bathymetry, tides, waves, currents, winds, presence of mines, wrecks and obstructions, bottom composition and acoustic propagation.

In this paper, three Rapid Environmental Assessment (REA) missions and their requirements with respect to navigation accuracy and covertness are defined. Solutions to how these requirements can be met by the AUV integrated inertial navigation system are presented. The proposed integrated inertial navigation system components are either commercially available (Section 3.2 DVL aided INS, Section 3.4 Standard Position Aiding, Section 3.5.1 Underwater Transponder Positioning, Section 3.7 Navigation Post-Processing), operationally available today (Section 3.5.2 Bathymetric Terrain Navigation: Correlation Methods, 3.5.3 Bathymetric Terrain Navigation: Gradient Methods) or will become available in a 1 – 2 years time frame (Section 3.3 SAS Velocity Aiding). Concepts and techniques for Concurrent Mapping and Navigation (CMN), Section 3.6 will probably need development on a longer time scale before maturing in integrated inertial navigation systems for REA operations.

2 REA Scenarios

2.1 Definitions of REA Scenarios

Data to be acquired in REA missions, to provide maritime commanders with critical information for planning strategic and tactical operations, include:

- Bathymetry and bottom imagery
- Thermal and acoustic properties
- Ocean currents and tides
- Chemical, nuclear, and biological sampling
- Bottom structure and composition
- Meteorological data

The utilisation of AUVs ranges from surveying large littoral undersea zones to detailed characterization of specific areas. It is required to perform these missions covertly (or with minimum visibility) where battlespace dominance has not been achieved. The focus is on the littoral but a deep-water survey capability is also required for oceanographic characterization.

Essential to the success of these missions is the capability to accurately position the acquired data to a pre-determined level of precision. For the purpose of characterizing the navigation performance required, three types of missions have been defined in Table 1. Position accuracy specifications are assumed 1σ Gaussian normal distribution.

It is assumed that the transit is in deep water where bottom contact with Doppler velocity log is not possible, however a limited number of GPS fixes can be obtained by the AUV to reduce the navigation error. Surfacing of the AUV in the area of operation, which is deemed to be under enemy surveillance, should be avoided or minimized. The Doppler velocity log and every other acoustic sensor are allowed to ping continuously. It is acceptable to achieve the required navigational precision in post-processing. In localisation missions it is necessary to estimate the position accuracy in real-time and plan the tracks accordingly to ensure 100% coverage of the area.

REA mission	***Survey***	***Explore***	***Localize***
Purpose	Ocean survey to determine the suitability of an area for military operations	Determine presence of threats and obstructions and collect bathymetry to optimize subsequent transit routes	Map position of threats and obstructions accurately for subsequent avoidance or clearance
Data collected	- Sea floor composition - Environmental data - Bathymetry - Low resolution sonar imagery	- Sonar imagery - Bathymetry - Sea floor composition	- Sonar imagery
Transit to area	50 km	20 km	10 km
Area parameters	10×10 km^2	10×2 km^2	10×1 km^2
Water depth	>1000 m to 20 m	100 m to 10 m	50 m to 3 m
Position accuracy in operational area	100 m (1σ)	10 m (1 σ)	5 m (1σ)
Position accuracy in transit	100 m (1σ)	100 m (1σ)	100 m (1σ)

Table 1 Definition of three REA missions: Survey, Explore and Localize

Figure 1 illustrates the three different REA missions defined in Table 1:

- Step 1, Survey:

  A large area is initially surveyed to determine its general characteristics in preparation for an amphibious landing. Two beaches are considered suitable. The survey shows that the sea floor in front of one of them is covered with vegetation that can conceal mines.

- Step 2, Explore:

  The approach to the second beach is explored to determine the presence of mines and obstructions. The mission reveals the presence of a minefield and sparse vegetation.

- Step 3, Localize:

  The localization mission maps the minefield and the sea floor accurately to identify a clear channel to the beach.

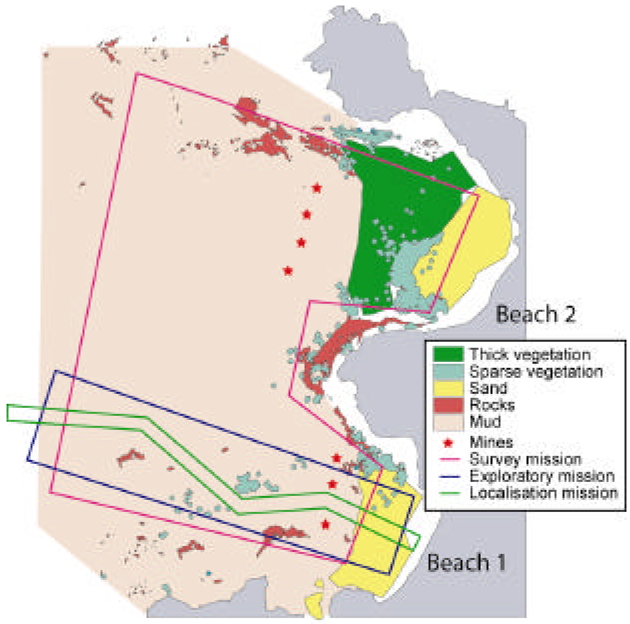

Figure 1 Illustration of AUV REA m issions defined in Table 1

2.2 Track Lines and Altitude

Important mission parameters such as altitude and line spacing are dependent on the mission objective, navigation accuracy and not least payload sensors characteristics. For instance, bathymetric mapping with a multi-beam echo sounder is typically done at a higher altitude than collection of sonar imagery. For the Survey and Explore missions, highest priority is sonar imagery to establish the presence of a mine threat. Especially in the Survey mission, targets should be insonified at low AUV altitudes to obtain shadows suitable for detection and classification. As Side Scan Sonar (SSS) and Synthetic Aperture Sonar (SAS) resolution and swath width vary from sensor to sensor, the line spacing defined in Table 2 should only be regarded as an example. The line spacing are input parameters to the mission plans used to investigate navigation accuracy in Section 4. Generally, less advanced SSS and SAS require higher navigation system performance due to tighter line spacing and thus longer distances traveled.

Mission	***Survey***	***Explore***	***Localize***
Altitude	15 m	5 m	2-3 m
Line spacing	300 m	100 m	75 m

Table 2 Sample altitude and line spacing for the REA missions defined in Table 1

The AUV will run track lines parallel to the beach. As discussed in Section 3.2.3, survey lines normal to the main axis of a corridor is favorable in terms of accuracy due to canceling of the body-fixed errors of the DVL aided INS. Parallel lines will also reduce the requirements for the forward looking collision avoidance sonar when approaching the beach and make it possible to plan in advance when detecting obstacles with the SSS / SAS.

3 AUV Integrated Inertial Navigation Systems

3.1 Integrated Inertial Navigation System Structure

In Figure 2, typical structure of an integrated inertial navigation system is shown. The Inertial Navigation System (INS) calculates position, velocity and attitude using high frequency data from an Inertial Measurement Unit (IMU). An IMU consists of three accelerometers measuring specific force and three gyros measuring angular rate. A Kalman filter will, in a mathematically optimal manner, utilize a wide variety of navigation sensors for aiding the INS. The Kalman filter is normally based on an error-state model and provides a much higher total navigation performance than is obtained from the independent navigation sensors.

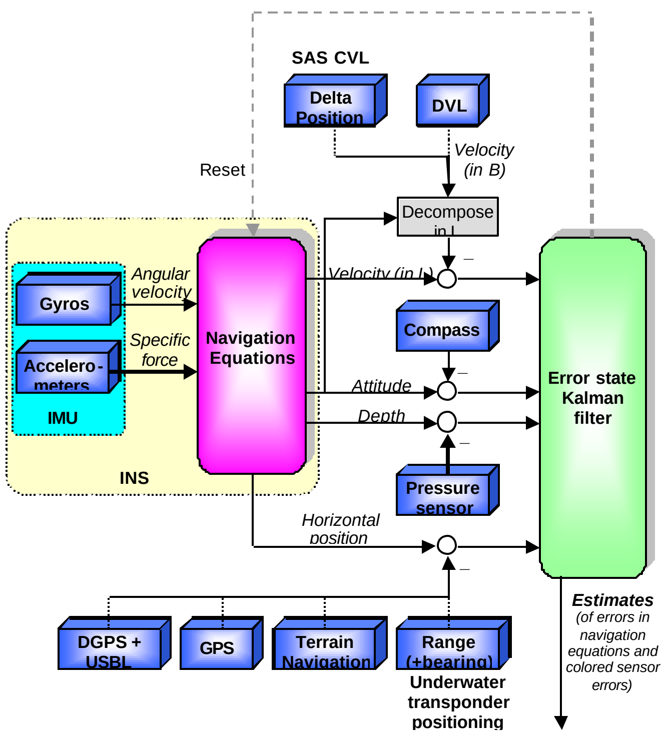

Figure 2 Integrated inertial navigation system structure

3.2 DVL aided INS

3.2.1 DVL Aided INS - Core Navigation System

AUVs for REA applications should handle submerged autonomous operation for long periods of time. The solution for modern AUVs is a Doppler velocity log (DVL) aided inertial navigation system that can integrate various forms of position measurement updates. For most REA applications, position measurements are only available in limited periods of time or space, thus the core velocity aided inertial navigation system must exhibit high accuracy. In Figure 2, the core DVL aided INS system consists of the IMU and the navigation equations, the DVL, the compass (optional), the pressure sensor and the error state Kalman filter.

Inertial navigation systems are usually classified by the standard deviation of the positional error growth of their free inertial (unaided) performance (see Table 3). A free inertial INS will, after a short period of time, have unacceptable position errors. IMUs for REA applications should be in the 1 nmi/h class.

Class	***Gyro technology***	***Gyro bias***	***Accelerometer bias***
>10 nmi/h	RLG, FOG[1]	1°/h	1 milli g
1 nmi/h	RLG, FOG	0.005°/h	30 micro g

Table 3 INS classes. Notes 1: RLG – Ring Laser Gyro, FOG – Fiber Optic Gyro

DVL accuracy is dependent on frequency. Higher frequency yields better accuracy at the sacrifice of decreased range as illustrated in Table 4. In REA applications in littoral waters accuracy is main priority.

Frequency	***Long term accuracy***	***Range***
150 kHz	±0.5% of speed ± 2 mm/s	425 – 500 m
300 kHz	±0.4% of speed ± 2 mm/s	200 m
600 kHz	±0.2% of speed ± 1 mm/s	90 m
1200 kHz	±0.2% of speed ± 1 mm/s	30 m

Table 4 RDI Workhorse Navigator Doppler Velocity Log accuracy and range specifications [1]

3.2.2 Simplified Error Analysis Straight Trajectories

The simplified error analysis presented in this section is useful for understanding the basic mechanisms of a DVL aided INS and assessing how IMU and DVL sensor accuracy is determining the overall position accuracy.

The horizontal position drift of a DVL-aided INS is determined by the error in the estimated Earth-fixed velocity (i.e. North and East velocity). The main contributors to this error are:

- Error in body-fixed velocity
- Error in heading

The error in estimated body fixed velocity, is mainly determined by the low-frequency error of the DVL itself (without position aiding this error is not observable when going at a straight line). High frequency velocity errors are estimated by means of the accelerometers. Even the most accurate INS will without aiding after a short period of time have a velocity uncertainty larger than the DVL accuracy. The fact that the DVL accuracy is thus strongly determining how accurate a good quality navigation class INS with DVL navigates, is often not recognized in navigation accuracy reports. Referring to Table 4, a 300 kHz DVL typically have a scale factor type of error of 0.4% of speed contributing to an along track error drift of 0.4% of traveled distance, or 28.8 m/hour for an AUV traveling at 2 m/s (4 knots). However, there are ways to improve the DVL accuracy. Sacrificing range, the 1200 kHz version from the same vendor has an accuracy specification of 0.2% of speed corresponding to 0.2% of traveled distance, or 14.4 m/hour (AUV speed 2 m/s). The scale factor error is observable by the Kalman filter when position measurements are available or when the AUV is turning. Thus, the Kalman filter can compensate for part of the scale factor error when running more complex missions than a straight line. This is explained in Section 3.2.3 and taken advantage of in Section 4.

The error in heading is determined by the gyrocompassing capability of the integrated system. The heading estimation error will typically be of low frequency, corresponding to non-observable gyro bias dynamics. Referring to Table 3, a 1 nmi/h navigation class IMU typically gyrocompass to an accuracy of $s(dy)$ = 0.02 deg sec latitude. This corresponds to an error drift of $s(dy)\cdot 100$ % of traveled distance ($s(dy)$ in radians). At 45° latitude this equals 0.05% of traveled distance, or 3.4 m/hour at 2 m/s AUV speed.

In Figure 6 position accuracy for an AUV with a 1 nmi/h IMU and 1200 kHz DVL running a straight line in East direction has been simulated (green graph) using NavLab (see Appendix A and [13]). Along track position error drift is in the order of 8 m/hour while cross track position error drift is in the order of 2.5 m/hour. This is a somewhat smaller drift than predicted by the simplified error analysis. There are two main reasons; the Kalman filter compensates for a scale factor error estimated when position measurements were available and the actual scale factor error is modeled as a first order Markov process and not a constant error. Choosing time constants that realistically reflect the physical error process is very important when estimating DVL aided INS error drift and when tuning the Kalman filter for real applications. It is the time constants which largely influence the simulation results in Section 4.

As 1 nmi/h navigation class INS are relatively easily obtainable in the marketplace and the DVL induced position error is close to an order of magnitude larger than the IMU induced position error for straight-line trajectories, most focus should be on how to improve the velocity accuracy. This explains the importance of the work presented in Section 3.3.

3.2.3 Countering DVL Aided INS Position Error Growth

For a submerged AUV without position updates, there are several ways to counter the position error growth of a DVL aided INS:

1. Cancel error growth with a geometric mission plan pattern
2. Estimate DVL scale factor error in real-time and compensate

3. Estimate constant part of scale factor error in post-processing and later compensate in real-time

The accuracy estimates in Section 3.2.2 are valid for straight-line trajectories. As the main error contributors of a DVL aided INS are body fixed velocity and heading, a canceling effect of the error growth is obtained when for instance running a lawn mower pattern. The canceling effect increases with the stability of the body fixed velocity error and heading error. Also the canceling effect increases with shorter line lengths. When simulating a DVL aided inertial navigation system in a lawn mower pattern, best results are obtained when large time constants are set for the DVL, gyro and accelerometer errors.

A second important effect of maneuvering is that the velocity error becomes observable by comparing expected centripetal acceleration with measured acceleration from the IMU. If the velocity error is the same during the maneuver (i.e. when it is observed) as it is in the following line, this estimation and compensation will significantly reduce the position error drift. However real DVL-data from RDI Workhorse Navigator 300 kHz suggests that during the maneuver, the error might be different, and in such cases this effect will have limited importance for the overall position drift. This real data problem can be countered by a sophisticated compensation method, but other sensors or frequencies might not exhibit this error characteristic. When the mechanism works, the error growth when running long straight lines can be significantly reduced by adding 360° turns at regular intervals, see Figure 7.

The effect of canceling error growth by a mission pattern and estimation and compensation of DVL error by maneuvering is illustrated in Table 5. Position error drift for a straight-line trajectory (no mechanisms working) is compared with a straight-line trajectory with 360° turns at regular intervals (estimation and compensation of DVL error) and a lawn mower pattern (both mechanisms working). For the straight line with regular turns, the accuracy increases with decreased intervals between the 360° turn. The effect of a lawn mower pattern is strong and heavily exploited in Section 4.

Position error drift (% of traveled distance)	***Straight line***	***Straight line with 360° turns every 5 km***	***Lawn mower pattern with 1 km lines***
Along track	0.11%	0.05%	0.01%
Across track	0.03%	0.02%	0.001%

Table 5 Typical reduction in position error drift of a DVL aided INS when comparing a straight-line trajectory with a straight line with 360° turns and a lawn mower pattern. The table has been compiled by analyzing simulated real-time position accuracy estimates (green graphs) in Figure 6 (straight-line trajectory), Figure 7 (straight-line trajectory with 360° turns) and Figure 8 (lawn mower pattern (position drift between GPS updates analyzed)). Note that when modeling DVL errors as Markov processes (Appendix A), the calculated error drift in percent of traveled distance decreases somewhat with increased distances used for measuring.

The DVL scale factor error has a time varying component and a constant and repeatable component. The constant component can be estimated in post-processing comparing a number of missions and compensated for in real-time in following missions. However, this requires effort and a competent user and consequently the procedure has not been applied when designing the navigation system strategies in Section 4.

3.3 SAS Velocity Aiding

In Section 3.2.2 it was shown that for an AUV equipped with a 1 nmi/h type of IMU or better, the DVL accuracy is the limiting factor to the position accuracy during submerged navigation with no position updates.

Modern MCM and REA AUVs are likely to be equipped with Synthetic Aperture Sonar due to the improved resolution and image quality offered compared to SSS. SAS requires very good relative navigation to obtain focused images. Relative navigation in SAS is often referred to as micro-navigation. One method of micro-navigation called Displaced Phase Center Array (DPCA) generates, as a by-product, a revolutionary good velocity (or more precisely, *displacement*) measurement. This complex displacement measurement needs to be integrated in the Kalman filter in a non-traditional way, which is an on-going research effort, [2].

The DPCA velocity measurement technique, based on expensive and sophisticated sonar hardware and advanced signal processing, is in fact very similar to the technique used in a correlation velocity log (CVL). If expectations are proved true and the DPCA velocity measurement is an order of magnitude more accurate than DVL, along track error contribution will be in the same order as across track error contribution (0.02% of traveled distance). Consequently a leap in performance of velocity aided inertial navigation systems could be achieved, allowing longer time intervals between position updates.

3.4 Standard Position Aiding

As seen in Figure 2, there are several alternatives for providing the integrated inertial navigation systems with position updates. Standard position measurements include:

- GPS surface fix
- Combined DGPS-USBL (Ultra Short Base Line)
- LBL (Long Base Line)
- GPS buoys

The following GPS services can be used for obtaining surface position fixes:

- GPS Standard Positioning Service (SPS)
- GPS Precise Positioning Service (PPS)
- Differential GPS (DGPS)
- Real-Time Kinematic GPS (RTKGPS)

GPS SPS is available to all users worldwide. GPS PPS is available only to authorized users and primarily intended for military purposes. Authorization is determined by the US Department of Defence (DoD). Authorized users include US and NATO military and other selected military and government agencies. GPS PPS receivers should be the choice for military REA AUVs. Compared to GPS SPS, GPS PPS is more resistant to jamming and deception. Links that transmits differential signals for DGPS and RTKGPS are vulnerable to jamming and less feasible in military AUV REA scenarios. GPS SPS and GPS PPS have comparable accuracy. Table 7 shows expected GPS PPS accuracy used in the simulations in this paper. Note that these are typical values, not specifications. Specifications on GPS SPS state 13 m 95% horizontal error, see [3]. Performance is subject to GPS system characteristics, ionospheric and tropospheric conditions, satellite geometry, baseline length (for differential systems) and multipath effects. A dual-frequency system has better accuracy than a single frequency system due to cancellation of ionospheric errors.

DGPS-USBL position updates necessitate that a mother ship close to the AUV combines DGPS and USBL data, and transmits the data to the AUV on an acoustic link. In [4] the position accuracies obtainable in offshore mapping operations with a mother ship in water depths down to 3000 m have been thoroughly analyzed. See [5] for operational results.

LBL systems provide accurate AUV position measurements once a network of four LBL transponders have been deployed and calibrated. LBL systems in AUV applications will probably become obsolete with the advent of underwater transponder positioning described in Section 3.5.1, where only one underwater transponder is necessary to bound the INS position drift, drastically reducing the operational efforts involved in deployment and calibration.

An interesting alternative to LBL systems is offered by GPS buoys that float on the surface and provide navigation information to the vehicles by means of acoustic communication. An example of this approach is the GIB buoy manufactured by ORCA Instrumentation, [6].

3.5 Advanced Techniques for Position Aiding

A number of advanced techniques for providing alternative position measurement updates have been developed. These include various forms of bathymetric terrain navigation, feature based navigation and range and bearing measurements to one or more underwater transponders.

3.5.1 Underwater Transponder Positioning (UTP)

Pinging a transponder on the seafloor and measuring range and bearing is the traditional approach to acoustic navigation. From range and bearing measurements, position has been computed in commercial Ultra Short Base Line (USBL) and Short Base Line (SBL) systems for decades. Instead of integrating a complex USBL system in an AUV, the AUV could be fitted with two transducers separated by as long baseline as possible – this is basically a SBL system.

This principle has been implemented in the NavP UTP navigation system, which is commercially available for the HUGIN class of AUVs. The range and bearing measurements are tightly integrated as position measurements in the Kalman filter of the inertial navigation system (actually position measurements can be produced with only range measurements available as well). The system works with only one underwater transponder, but can utilize any number of transponders in an optimal way. Compared to a traditional LBL system, NavP UTP has improved accuracy due to tight coupling with the INS, increased operating area and significantly less deployment costs, since only one transponder is necessary to bind the position drift.

A number of UTP sea trials were performed outside Horten, Norway, March 2003, with very good results. In Figure 3 the HUGIN trajectory is shown. HUGIN navigated at 180 m water depth with UTP as the only source for position updates. Post-mission, the navigation data was compared to independent DGPS-USBL data stored on the survey vessel. The average difference between the two data sets in North and East was 2.2 m and 2.6 m (1σ, RMS). When NavLab post-processing (smoothing) was applied (see Section 3.7), the difference was reduced to 1.2 m in North and 1.5 m in East (1σ, RMS). This is very close to the accuracy of the DGPS-USBL system. Figure 4 shows the difference between DGPS-USBL position estimate and the UTP post-processed navigation solution.

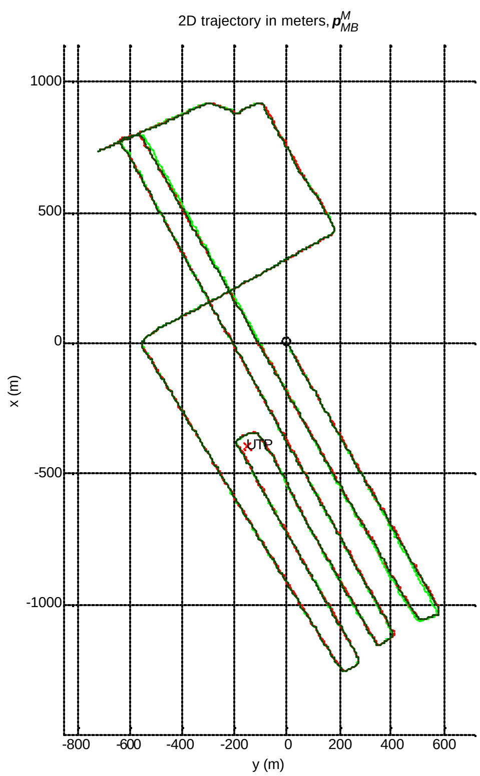

Figure 3 HUGIN 2D trajectory in UTP sea trial. UTP was deployed at x = -396 m, y =151 m (relative coordinates).

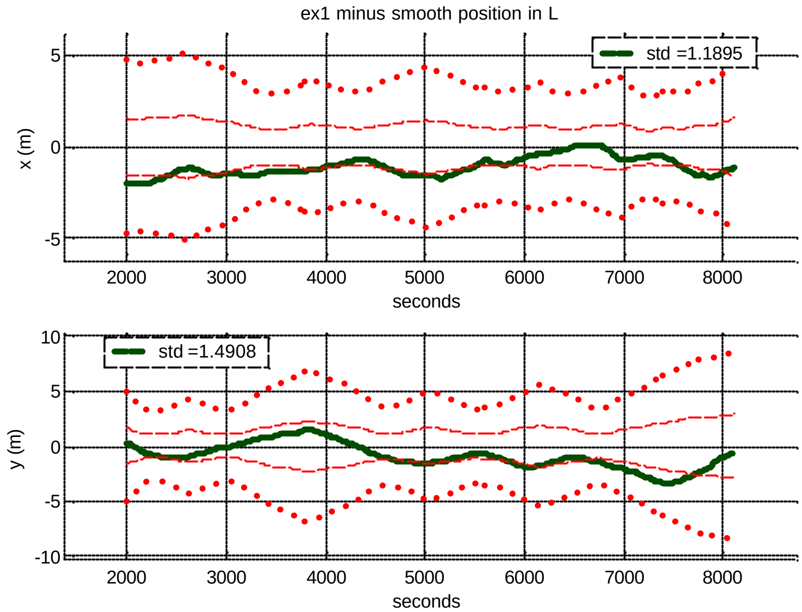

Figure 4 Results from UTP sea trial. Dark graph: difference between UTP post-processed navigation solution and independent DGPS-USBL position estimates. Red dashed and red dotted graphs are 1σ and 3σ estimated uncertainty of the difference.

3.5.2 Bathymetric Terrain Navigation: Correlation Methods

Conceptually there is a difference between correlation based global search methods discussed in this section and tightly integrated terrain tracking algorithms discussed in Section 3.5.3. Terrain correlation may be done for one measurement, or on a sequence of measurements. The measured water depths are shifted around an offset area around current position, and a correlation between the measurements and the depth data in the Digital Terrain Model (DTM) is calculated in this area. The calculated correlation is called the correlation surface. The correlation surface is analysed to determine convergence, calculating a position offset, the error covariance and a position fix confidence.

Terrain correlation runs on any sensor providing bathymetric data, for instance MBE, SBE, altimeter, DVL or interferometric sonar. In Figure 5 the HUGIN terrain correlation system is illustrated. The *Geographic Data Producer* converts AUV depth + bathymetric sensor data in AUV body-fixed coordinates to geographical referenced data, using the current navigation solution. The *Terrain Correlator* runs the terrain correlation algorithms on one measurement or iteratively on a sequence of measurements. *Map Database* readies the DTMs for random access by the Terrain Correlator. Position updates are sent to the integrated inertial navigation system Kalman filter to bind the INS position drift.

The actual correlation can be done selecting different algorithms:

- *Terrain Contour Matching*, [7]
  A well-proven and robust algorithm that uses the mean absolute distance as a correlation measurement. Models for sensor and map noise may be included. The covariance matrix of the position fix is found through the correlation surface.
- *Point Mass Filter*, [8]
  A more sophisticated algorithm that actually calculates the position Probability Density Function (PDF) using Bayesian estimation. Enables the use of advanced models for sensor and map noise. Enables a statistically sound use of the navigation system accuracy as an input. The covariance matrix of the position fix is found directly from the PDF.

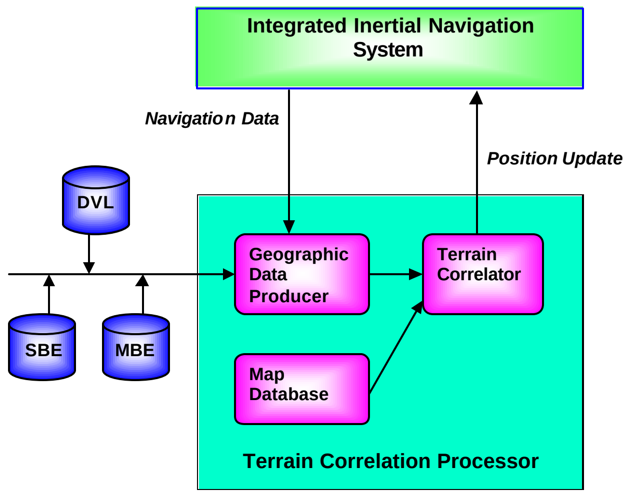

Figure 5 Structure of the HUGIN terrain correlation system

3.5.3 Bathymetric Terrain Navigation: Tightly Integrated Terrain-Tracking Algorithms

Tightly integrated terrain-tracking algorithms are characterized by integration of range measurements and the bathymetric map into the Kalman filter. Thus, all available information in the integrated navigation system is utilized, potentially providing increased accuracy. Compared to correlation methods, the algorithms have less robust behavior in highly non-linear terrain. More on tightly integrated terrain-tracking algorithms can be found in [9] and [10].

3.5.4 Feature-Based Navigation

In feature-based navigation, an imaging sensor is used to sense the environment. The raw image data is fed into an image-processing algorithm whose output is a set of recognizable features or landmarks. Features can be natural or man made. The vehicle can navigate using an existing map of features. Alternatively, the vehicle can concurrently build a map and navigate using this map (concurrent mapping and navigation, see Section 3.6). In both cases repeated observations of landmarks and perfect data association are of vital importance.

When re-observing a landmark, the integrated navigation system uses its position and attitude estimates to predict the position of the landmark. This predicted position is compared with the mapped position of the landmark and the difference is used to estimate the navigation errors. See for example the paper by Tena Ruiz in this book. The paper by Hafskjold [11], though for an aerial application, is a good description on how a feature based navigation system can be used in an integrated inertial navigation system.

3.6 Concurrent Mapping and Navigation

Concurrent Mapping and Navigation (CMN) is important to covert REA missions in unknown areas. As outlined in this section, concurrent mapping and navigation can be achieved using different techniques, sensors and data. In literature, CMN is often referred to as Concurrent Mapping and Localization (CML). For a real-time integrated inertial navigation system in an AUV, we consider CMN a better description.

3.6.1 Concurrent Mapping and Navigation with Underwater Transponder Positioning

The easiest way to operate an UTP system is to estimate accurately the position of the underwater transponders with a USBL equipped mother ship. The transponder position coordinates are sent to the navigation system prior to UTP navigation.

In a more advanced concept, the integrated navigation system is able to estimate the position of an underwater transponder while navigating with another. In this way, the AUV will be able to deploy a trail of underwater acoustic buoys for UTP navigation and acoustic communication. This concept can be denoted Concurrent Deployment and Navigation (CDN) or UTP CDN.

3.6.2 Concurrent Mapping and Navigation with Bathymetric Data

An attractive feature of tightly integrated terrain-tracking algorithms is that a solution for concurrent mapping and navigation follows inherently. Solutions to CMN, considering both tightly integrated terrain-tracking algorithms and correlation algorithms, is an ongoing research effort [9].

3.6.3 Concurrent Mapping and Navigation with Features

Feature based navigation requires re-observation of recognizable features and comparison of predicted landmark position with a mapped landmark position. When mapping and navigating at the same time, the imaging sonar or the mission pattern must permit re-observation of landmarks in the same mission. The areas covered by a forward looking sonar overlap and landmarks re-observations can be used for concurrent mapping and localization, [12]. A side-scan sonar on the other hand, has little or no overlap, consequently the same sea floor area must be passed several times. This is the case for narrow lawn mower patterns or patterns specifically designed for concurrent mapping and navigation. The paper by Tena Ruiz in this book is a good description of concurrent mapping and localization using a side scan sonar.

3.7 Navigation Post-Processing

Whenever time constraints allow, navigation post-processing should be applied to increase the position accuracy. Navigation post-processing is especially effective when position updates are scarce. This is the case with GPS surface fixes, terrain navigation in a few reference areas and scattered underwater transponders. In Figure 6 the effect of navigation post-processing when running a 15 km straight-line trajectory with GPS fix at the end is shown. The effect is less, but still substantial when running a lawn mower pattern, see Figure 8 where GPS fix every 15th line has been simulated (1 km line length).

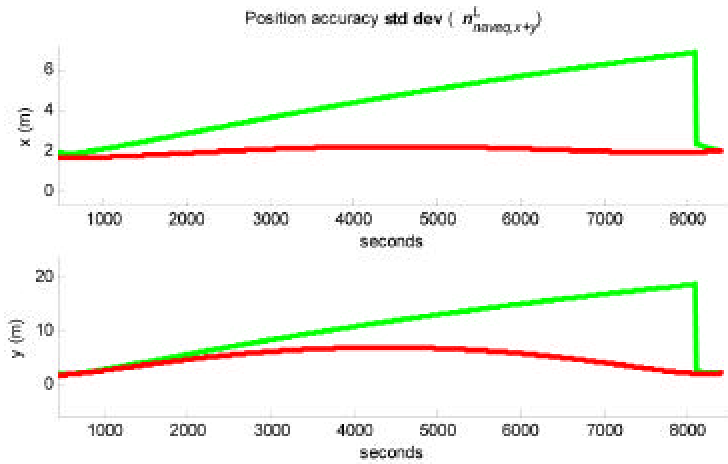

Figure 6 The effect of navigation post-processing when running a straight line with GPS fix after 15 km. Green graph: real-time position accuracy (1σ). Red graph: post-processed position accuracy (1σ). x and y in local level (L) corresponds approximately to position uncertainty in across track and along track direction for this particular mission.

Integrated inertial navigation system comes with extensive systems for integrity check. This is of crucial importance to safeguard against jamming, multipath effects, internal sensor failures etc. However, if the integrity mechanisms should fail to detect a navigation sensor wild point or degraded sensor performance, the real-time navigation estimates can be seriously affected. An important feature of navigation post-processing is increased navigational integrity and the ability to recover faulty data sets with undetected wild-points or degraded sensor performance.

Navigation post-processing tools for AUVs have been commercially available since 2000, [13], [5].

4 Navigation System Design for REA Applications

The proposed navigation system design for REA applications is based on extensive navigation accuracy simulations. In the simulations we have assumed a basic navigation suite consisting of a 1 nmi/h IMU (Table 3), a 1200 kHz DVL (Table 4) and a good performance GPS PPS receiver (Section 3.4). All simulations are made using the

NavLab navigation package [13]. In Appendix A, the navigation sensors simulation parameters are summarized.

4.1 Transit Phase in Deep Water Area

Deep waters can be transited in two ways (refer to Table 4 for typical DVL ranges):

1. The AUV has sufficient depth rating to run close to the seabed with DVL bottom lock.
2. AUV is running in the water column with water column velocity aiding only.

For a bottom following AUV in deep water, GPS fixes can be impractical because of the time required to surface and dive. Another implication is that DVL bottom track is lost for a period of time when the AUV makes a GPS fix. Consequently, some of the effect of the position update is lost, even though position error drift is strongly correlated with velocity error and thus partly compensated for when DVL bottom track velocity is established after diving. In Figure 7 a 50 km transit with DVL bottom track and no GPS position updates is simulated. In order to reduce the position error drift, the AUV makes 360° turns every 5 km to estimate and compensate for DVL error (see Section 3.2.3). The position accuracy in transit is well below the 100 m (1σ) specification stated in Table 1. Better accuracy is obtained with smaller intervals between each 360° turn.

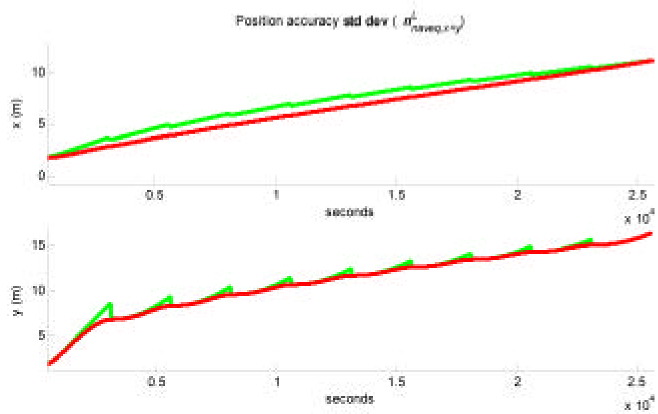

Figure 7 Position accuracy for a 50 km straight-line transit. The AUV makes 360° turns every 5 km to enable estimation and compensation of DVL error and thus increased position accuracy. Since no position measurements are available, the difference between real-time (green graph) and post-processed (red graph) position accuracy is small.

In Section 2.1 it is assumed that the large water depth in the transit area allows neither DVL bottom track nor AUV bottom following. An AUV navigating with water velocity aiding only has substantially larger position error drift than an AUV with DVL bottom lock. However, as GPS surface fixes are allowed in the transit phase, maintaining 100 m (1σ) position accuracy does not present any problem.

4.2 Low Visibility REA Missions

When operational requirements allow surfacing, navigation accuracy specifications as stated in Table 1, are met by running the AUV in a lawn mower pattern and making GPS fixes at regular intervals. If time constraints allow, navigation post-processing offers increased intervals between GPS fixes and increased navigation accuracy. In Figure 8 predicted position accuracy for the Localize mission with 1 km line lengths and GPS fixes every 15^{th} line (every 2 h and 11 min) is shown. Effective cancellation of the error drift with the lawn mower pattern show up as ripples on the real-time postion accuracy estimate graph. GPS fixes show up as larger resets. Navigation post-processing improves accuracy conside rably, especially before a position update.

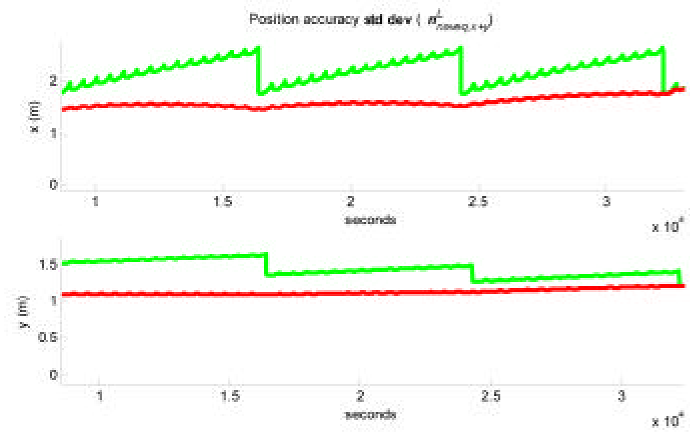

Figure 8 Position accuracy for the Localize mission with GPS fixes every 15^{th} line. Line length is 1 km. Green graph: real-time position accuracy (1σ). Red graph: post-processed position accuracy (1σ). x and y in local level (L) correspond approximately to North and East direction. A North East aligned mission plan was simulated for simplicity.

4.3 Covert REA Missions

In this section, navigation strategies to meet the navigation requirements defined in Section 2.1 are presented. The accuracy estimates for the Survey and Explore missions are based on simulation results. The accuracy estimates for the Localize mission is based on HUGIN sea trial data (Section 3.5.1). The position error uncertainty is elliptical due to different strength of the two major error sources, error in body-fixed velocity and error in heading (Section 3.2.2). Thus, estimated position uncertainty in Table 6 is given in two axes, x and y.

The navigation strategies to meet the requirements for the Survey and Explore missions are similar:

1. The operational area is divided into smaller parts to increase the error cancellation effect of the lawn mower pattern with DVL aiding only. Figure 9 shows the mission plan for one of the four parts that make up the area for the Survey mission.

2. The AUV surfaces for GPS fixes when entering and exiting the operational area.
3. Navigation post-processing is applied to increase navigational accuracy and integrity.

Figure 10 shows the position accuracy for the Survey mission. The position accuracy requirements for both the Survey and the Explore mission are met, compare Table 1 and Table 6.

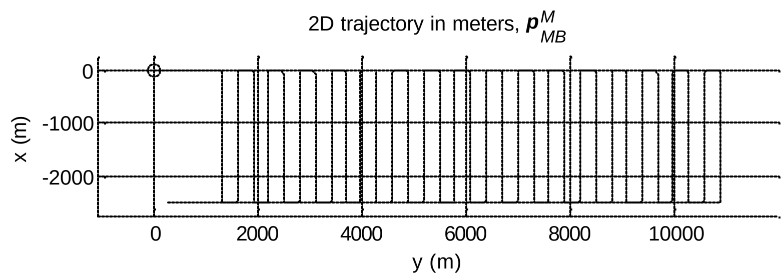

Figure 9 The 10×10 km^2 Survey area was divided into four areas of 2.5×10 km^2. The figure shows simulated mission plan for one of the parts. Position accuracy increases with reduced line lengths. The Explore area was similarly divided into two 1×10 km^2 areas. Division of the operational area into smaller parts also allows for operation of multiple AUVs and reduced requirements on battery endurance.

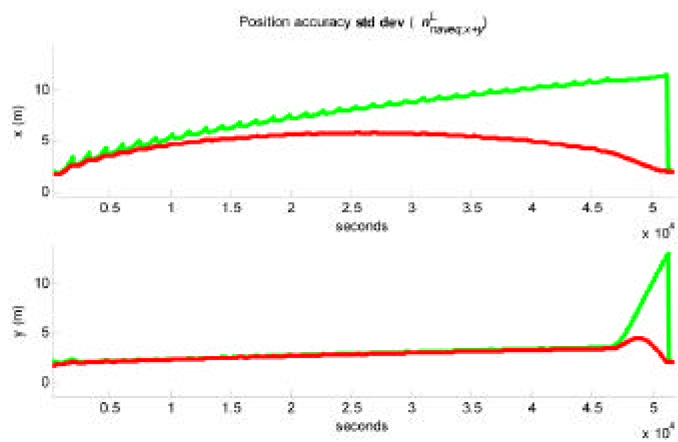

Figure 10 Position accuracy for a 2.5×10 km^2 part of the Survey area. The mission plan is shown in Figure 9. The AUV surfaced for GPS fixes when entering and exiting the operational area. Green graph: real-time position accuracy (1σ). Red graph: post-processed position accuracy (1 σ). The increase in y position uncertainty at the end of the mission is due to the 10 km straight-line transit out of the operational area.

To meet the navigation requirements for the Localize mission without GPS fixes in the operational area, underwater transponder positioning, terrain navigation or feature-based navigation must be applied, see Table 6. To meet the requirements in a single mission, techniques for concurrent mapping and navigation (Section 3.6) must be utilized. Alternatively, one could build a map (bathymetry, features and / or underwater transponders) using post-processed navigation data (for maximum accuracy) and use the mapped reference areas for binding the position error drift in consecutive missions.

Mission	***Survey***	***Explore***	***Localize***
Area parameters Navigation strategy	10×10 km^2 Divide area into 4 pieces of 2.5×10 km^2 Lawn mower pattern GPS surface fix when entering and exiting the operational area. Navigation post-processing	10×2 km^2 Divide area into 2 pieces of 1×10 km^2 Lawn mower pattern GPS surface fix when entering and exiting the operational area. Navigation post-processing	10×1 km^2 area Lawn mower pattern GPS surface fix when entering and exiting the operational area. Concurrent mapping and navigation: - UTP CDN - Terrain navigation - Feature based navigation Navigation post-processing
Line spacing	300 m	100 m	75 m
Number of lines	33	100	133
Line length	2.5 km	1 km	1 km
Mission length	102.5 km $\times 4$	120 km $\times 2$	153 km
Mission duration	14.2 hour $\times 4$	16.7 hour $\times 2$	21.2 hour
Max real-time uncertainty	x: 11 m (1σ) y: 4 m (1σ)	x: 5.5 m (1σ) y: 2.5 m (1σ)	UTP: x: 3 m (1σ) y: 3 m (1σ)
Max post-processed uncertainty	x: 6 m (1σ) y: 4 m (1σ)	x: 3.5 m (1σ) y: 2.5 m (1σ)	UTP: x: 2 m (1σ) y: 2 m (1σ)
Figures / illustrations	In Figure 9 simulated mission plan for one of the 2.5×10 km^2 pieces is shown. Figure 10 shows position accuracy.	Mission plan and error trends are similar as in Figure 9 and 10, but position accuracy is better because of shorter line lengths.	Figure 3 and Figure 4 demonstrates UTP concept and capability.

Table 6 Navigation strategies to meet the navigation requirements defined in Table 1

5 Summary

The main purpose of this paper has been to demonstrate how a toolbox of navigation techniques should be applied to meet the navigation requirements for AUVs intended for rapid environmental assessment.

A REA scenario consisting of three AUV mission types were defined. A large area is initially *surveyed* to determine general characteristics and pick the right beach for an amphibious landing. The beach is *explored* to determine presence of mines or obstacles and a *localization* mission maps the minefield accurately to identify a clear channel to the beach. Navigation accuracy requirements for each mission type were specified. The missions were required to be performed covertly in areas where battlespace dominance had not been achieved. Thus, surfacing for GPS fixes should be minimized.

The core navigation system should consist of a low drift velocity aided inertial navigation system based on a 1 nmi/h class IMU and an accurate DVL. There are several ways to counter the position error growth. In this paper the technique of cancelling error growth with a lawn mower pattern was used extensively. When available, a SAS velocity measurement will potentially increase the accuracy of integrated inertial navigation systems significantly.

Whenever time constraints allow, navigation post-processing should be applied to increase the position accuracy. Post-processing is especially effective when position fixes are scarce, making it very attractive for covert REA applications.

The navigational requirements for the Survey and Explore missions were met by dividing the operational area into smaller parts, applying a lawn mower pattern with relatively short line lengths, surfacing for GPS fixes when entering and exiting the operational area and post-processing the navigation data.

To position mines with an accuracy of 5 m (1σ) throughout the operational area without surfacing for GPS fixes, as defined for the Localize mission, advanced techniques for submerged position updates should be applied:

- Underwater transponder positioning
- Terrain navigation.
- Feature-based navigation

More research and development is needed for SAS velocity aiding and the various techniques for concurrent mapping and navigation. Future research must also focus on increasing robustness and integrity of integrated inertial navigation system. However, most systems and techniques described in this paper are either commercially or operational available, [14]. The biggest task ahead is actually demonstrating robust and accurate REA navigation in realistic sea trials and military exercises.

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Appendix A: Navigation Sensor Parameters

Table 7 summarizes the navigation sensor parameters used in the navigation accuracy simulations in this paper. All simulations are made in the NavLab navigation package. NavLab (Navigation Laboratory) is a powerful and versatile tool intended for navigation system research and development, navigation system accuracy analysis and navigation data post-processing, [13], [15].

A sensor error typically consists of several components and different parameters are necessary to describe each part. NavLab models the following error components:

- *White noise*
  This error is uncorrelated from one measurement to the next, and is described by its standard deviation.
  For gyros and accelerometers, a parameter describing *continuous* white noise is used. These parameters are called angular and velocity random walk coefficients, and have different units than the measurements.
- *Colored noise*
  A colored error (also called bias) is modelled as a first order Markov process:

  $$\dot{x} = -\frac{1}{T}x + g$$

  where x is the colored error, T is the time-constant, and g is white-noise. Such a process is described by its standard deviation (of x) and its time-constant. The standard deviation describes the magnitude of the colored noise, and the time-constant describes how fast it changes.
- *Scale factor error*
  This error depends on the value to be measured, and the error is a constant times the measurement. The scale factor error parameters used in the simulations were less than the colored noise, thus this parameter is omitted from Table 7 for simplicity. Note that the DVL scale factor error was modelled as colored noise, assuming a constant AUV speed of 2.0 m/s.

Sensor	***Standard deviation white noise***	***Standard deviation Markov process***	***Time constant Markov process***
Gyro	Angular random walk: 0.0025 °/√h	0.0035 °/h	3600 s
Accelerometer	Velocity random walk: 10 µg/√Hz	30 µg	3600 s
DVL	0.004 m/s	x: 0.0041 m/s y, z: 0.001 m/s	1800 s
GPS PPS	0.21 m	3.5 m	300 s
Pressure sensor	0.02 m	0.3 m	200 s

Table 7 Dominating navigation sensor parameters used in accuracy simulations. Scale factor error parameters have been omitted from the table for clarity.

IMU: 1 nmi/h class, refer to Table 3

DVL: 1200 kHz accuracy class, refer to Table 4. The DVL is assumed to have bottom lock throughout the operational area. DVL scale factor error was modeled as colored noise, assuming a constant AUV speed of 2.0 m/s.

GPS PPS: Typical values for horizontal accuracy are used. These differ from the specification in [3].

Pressure sensor: Sensor accuracy 0.01% Full Scale (FS). FS = 3000 m.