POSITIONING ACCURACY FOR THE HUGIN DETAILED SEABED MAPPING UUV

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Abstract - **HUGIN is an untethered underwater vehicle (UUV) intended for bathymetric data collection for detailed seabed surveying. The HUGIN sensor suit, consisting of standard commercially available navigation sensors and a multibeam echosounder, is reviewed with respect to accuracy and important characteristics. A Kalman filter for post processing integration of UUV sensors and survey vessel sensors is described. We present a complete error budget and discuss the resulting positioning accuracy of the digital terrain model (DTM) that has been achieved with the HUGIN UUV. Finally we show how the claimed positioning accuracy has been verified.**

I. INTRODUCTION

Untethered underwater vehicle (UUV) technology has in recent years been recognized as a potential area for providing the offshore survey market with cost-effective and high data quality solutions for detailed seabed mapping of possible subsea construction sites and pipeline routes.

In the HUGIN development program two untethered underwater vehicles have been produced. The vehicles are fitted with a Kongsberg Simrad EM3000 multibeam echosounder for underwater surveys to depths of 600 m. HUGIN I had its first sea trial in summer 1996 and has been used as a test and demonstration platform. HUGIN II was in spring 1998 put into commercial operation, offering services to the survey market. The HUGIN development program is a co-operation between Norwegian Defence Research Establishment (FFI), Kongsberg Simrad AS, Norwegian Underwater Intervention AS (NUI) and Statoil, Størkersen et. al. [1].

HUGIN has a low drag hull in order to minimize power losses. The vehicle has a length of 4.8 m, nominal cruise speed of 4 knots, volume of 1.2 m^3 and battery power for 36 h continuos operation before recharging.

The Kalman filter described in this paper will be integrated in the Kongsberg Simrad Neptune/Merlin ROV/AUV data processing package.

II. NAVIGATION CONCEPT

Fig. 1 shows the navigation systems and sensors necessary for positioning of multibeam echosounder data in global coordinates. A commercial survey vessel will typically have its surface position provided Differential Global Positioning System (DGPS) or Real-Time Kinematic Global Positioning System (RTK GPS).

HUGIN's position relative to the survey vessel is measured by means of Kongsberg Simrad's High Precision Acoustic Positioning system (HiPAP). In order to determine EM3000's orientation, which is necessary for determining the EM3000 footprint relative to the UUV, HUGIN is equipped with Seatex Motion Reference Unit (MRU-5), which among several data, outputs the vehicle's roll and pitch angle. Heading is measured by Leica Digital Magnetic Compass (DMC). Depth is measured with Digiquartz 8DP700-I.

The above mentioned measurements are sufficient to position the EM3000 footprint in global coordinates, provided sufficient care has been taken to ensure accurate

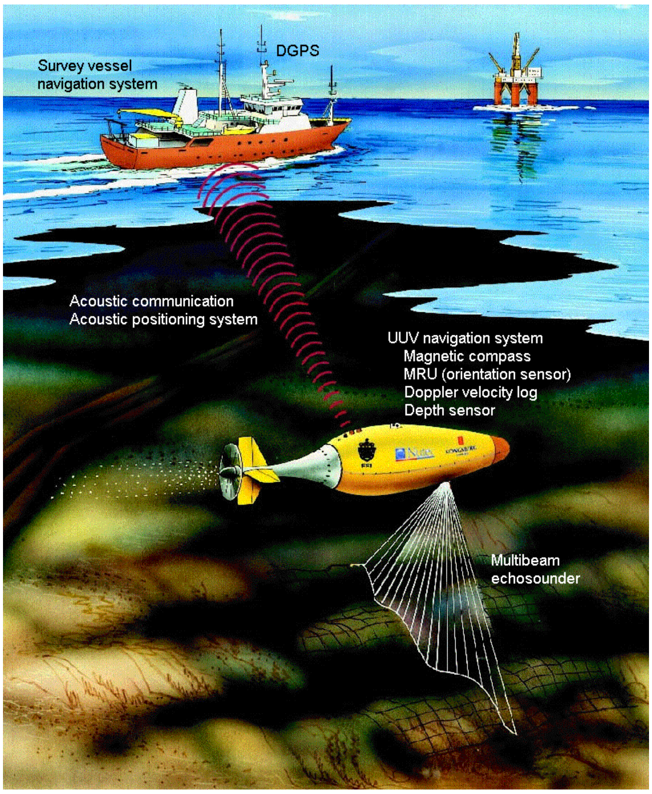

Fig. 1. A seabed mapping scenario with the HUGIN system

time tagging. However, increased accuracy can be achieved by post processing the measurements in a Kalman filter. For improved performance, the Kalman filter utilizes measurements from the doppler velocity log and angular rate measurements from the MRU as well.

III. KALMAN FILTER FOR POST PROCESSING OF HEADING AND POSITION

A. Kalman filter structure

Modeling of sensor errors form the basis of an *error-state* Kalman filter. In Fig. 2 a block diagram of the Kalman filter is shown. Heading difference (computed heading – measured heading) and the position error difference (dead reckoned position – measured position) is fed into the Kalman filter. The Kalman filter outputs error estimates of the dead reckoned position and the computed heading. These are used to produce filtered heading and position estimates. An in-depth description of the Kalman filter is given in [2].

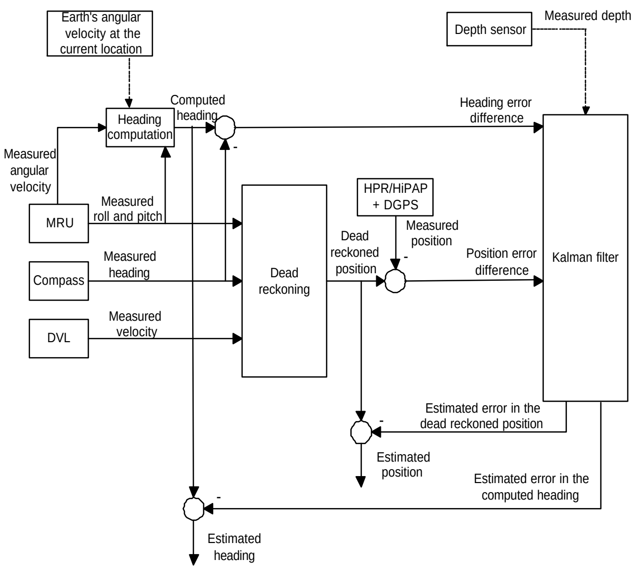

Fig. 2. Kalman filter structure

B. Smoothing

The accuracy of the heading and position estimates are enhanced by a smoothing process, [3]. First the conventional (real time) Kalman filter is run, saving all a priori and a posteriori estimates with their error covariance matrices. Then an optimal recursive smoothing algorithm adjusts all the estimates, starting at the last estimate and running backwards in time.

When making smoothed state estimates, all measurements in past and future are available, and consequently there is no delay in the estimates. Further, it is possible to make estimates in accordance with the process model. Contrasting this with the conventional Kalman filter (filtered estimate), where the process model is used only in the prediction part. Thus, producing a posteriori estimates, unexpected measurements lead to steps in the filtered estimate.

IV. SENSOR QUALITY

A. Position

Typically DGPS systems have an accuracy of 2 m (2σ) whereas RTK GPS is in the sub-meter region.

HiPAP produces its position estimates based on measurements of horizontal bearing, vertical bearing and distance, [4]. For moderate vertical angles, the bearing accuracy is 0.3º (1σ) and the distance accuracy better than 0.2 m (1σ). Clearly, the HiPAP position error increases with depth.

Provided correct sound velocity profile estimate, the HiPAP position error is as the DGPS error believed to have no bias. Biased position errors can not be estimated. The combined DGPS/HiPAP position error is in the Kalman filter modeled as a sum of colored noise and white noise.

A prerequisite for good HiPAP position estimate is that the survey vessel's attitude is well known. For instance, the Seatex Seapath system has an attitude accuracy of 0.05º (1σ), [5]. This specification is six times better than the HiPAP bearing accuracy, though attitude errors in the survey vessel's navigation system do not contribute significantly to the HiPAP position error.

B. Heading

The main magnetic compass error sources are lack of compensation for declination and the UUV's magnetic signature. Declination can easily be compensated for. The Leica DMC measures the total three dimensional magnetic field vector of its environment, composed of the earth's magnetic field vector and the magnetic disturbances created by the UUV itself, [6]. The DMC has software for detection and compensation of both softmagnetic disturbances (field distortions caused by magnetic materials) and hardmagnetic disturbances (magnetic fields caused by magnets or electric currents).

The Leica DMC is located as close to HUGIN's nose as possible in order to reduce the effects of the vehicle's battery and electronics. A Leica DMC accuracy of 1º should be feasible, an accuracy of 2-3º is relatively easy obtainable. After Kalman filter post processing, a heading accuracy better than 0.5º (1σ) is achievable, according to the Kalman filter variance. Thus, the contribution of the heading error to the position error for the EM3000's outer beams is less than 0.8 m (1σ) for 175 m swath width (175 m is maximum

EM3000 swath width obtainable at 50 m UUV height). For comparison, a heading error of 3.0º would have contributed to a position error of 4.6 m.

C. MRU

Seatex MRU specifications state that static accuracy in roll and pitch is 0.04º (1σ) and that dynamic accuracy is 0.05º (1σ), [7]. This implies that MRU's contribution to the total position error is less than 0.1 m at an UUV height of 50 m.

D. Doppler velocity log (DVL)

The 287.5 kHz version of the EDO 3050 doppler velocity log has a bottom reference velocity precision specification of 0.01 m/s (1σ), [8]. The accurate velocity measurements are vital for the Kalman filter post processing.

E. Depth sensor

The Digiquartz 8DP700-I has a specified accuracy of 0.01% of full scale (700 m), [9]. In the post processing, the measurements must be compensated for tidal water, atmospheric pressure and water density.

F. EM3000 multibeam echosounder

Provided sufficient signal to noise ratio, the main factors contributing to multibeam echosounder depth and position errors are variations in sound of speed and beam width. According to [10], typical along track and across track position errors are less than 1% of the distance to seabed. Thus, for an UUV height of 50 m, the EM3000 caused position error is in the order of 0.5 m (1σ).

V. Post processing and time synchronization scheme

During a survey, DGPS and/or RTK GPS and HiPAP position measurements are stored onboard the survey vessel. The vessel's orientation in roll, pitch and azimuth must also be known, for stabilization of the GPS antennas and for relating the HiPAP bearings to the North East Down coordinate frame (“local level”). The position data is time tagged in UTC (Universal Time Coordinate) provided by GPS.

The HUGIN vehicle data (Leica DMC, MRU, EDO 3050 and Digiquartz 8DP700-I) is stored on the same hard disk as the EM3000 range data is stored. Proper time tagging is ensured by first synchronizing HUGIN's operator station with GPS UTC. Then the HUGIN control processor is synchronized to GPS UTC (synchronization is managed by the operator station). The HUGIN control processor is equipped with a crystal oscillator with drift specification better than 1 PPM (parts per million). Thus, for a HUGIN mission typically lasting 36 h, the total time drift will be less than 130 ms. This corresponds to a position error less than 0.30 m.

After a survey mission the HUGIN hard disk is simply dismounted from the vehicle and connected to the post processing computer.

VI. Positioning accuracy

The contributions of the individual error sources to the resulting multibeam echosounder footprint position uncertainty are summed up in Table 1. The position uncertainty predictions assume an UUV depth of 300 m, that the survey vessel is 141 m off the vehicle in the horizontal plane and that the UUV is 50 m above the seabed. Increased depth, horizontal vessel to vehicle distance and height above the seabed will cause increased positioning errors.

The different error sources are grouped in three categories denoted “Survey vessel”, “UUV” and “Time synchronization”. For the Survey vessel group, the effects of DGPS, HiPAP and attitude accuracy of the vessel’s navigation system are calculated separately. The survey vessel’s navigation system combines these sensors and produces a combined DGPS/HiPAP position estimate whose error is estimated in the Kalman filter post processing. This error estimate is used in the making of the Digital Terrain Model (DTM). Contributing to the resulting DTM position uncertainty is thus the uncertainty in the DGPS/HiPAP error estimate. According to the Kalman filter, this uncertainty is for the given example approximately 1 m (1σ).

For the survey vessel, GPS antenna and HiPAP transducer mounting axis misalignment also contribute to the position error. These error sources are assumed negligible. In the UUV group we see the effect of the Kalman filtering of the Leica heading, outer beam position error is reduced from 4.6 m to 0.8 m (1σ). MRU roll and pitch errors are not estimated. Leica DMC, MRU, EDO 3050 DVL and EM3000 mounting axis misalignment should be less than 0.06° due to proper mechanic design and careful assembling. Fixed angular or linear offset errors can be detected and compensated for in standard procedures.

Considering the Time synchronization group, we see that synchronization uncertainty is negligible. Positioning error contribution originating from the time drift is insignificant.

Under the assumptions of statistical independent error sources, the total DTM position uncertainty can be calculated by root-square-summing all the figures emphasized in bold. This amounts to 1.4 m. The validity of this positioning uncertainty estimate relies on the dubious assumption that no slowly varying bias are present in the combined DGPS/HiPAP position estimate. Increased depth will as discussed in Section IV.A cause increased HiPAP position uncertainty. This will to a certain extent affect the post processing of position and heading.

Table 1: Contributing error sources for resulting multibeam echosounder footprint position uncertainty. In the calculations we have assumed that the UUV is at 300 m depth, 50 m above sea bed and 141 m off the survey vessel in the horizontal plane.

Error source	**Resulting EM3000 footprint position uncertainty (circular error)**	**Basis for position uncertainty calculations**
Survey vessel		
DGPS	2 m (2σ)	Technical specifications (Section IV.A)
HiPAP	1.7 m (1σ)	Technical specifications (Section IV.A)
Vessel attitude	0.4 m (1σ)	Technical specifications, Seapath attitude uncertainty = 0.05º (Section IV.A)
Combined DGPS/HiPAP estimate from the vessel's navigation system	~ 2.3 m (1σ) (a seemingly time varying and non-ergodic statistical process)	Kalman filter estimate
Kalman filtered position	**1.0 m (1s)**	Kalman filter variance (text above table)
UUV		
Leica DMC heading	4.6 m (outer beam) (1σ)	Kalman filter estimate, heading uncertainty = 3.0° (Section IV.B)
Kalman filtered heading	**0.8 m (outer beam) (1s)**	Kalman filter variance, heading uncertainty = 0.5° (Section IV.B)
MRU level (roll and pitch)	**0.08 m (1s)**	Technical specifications, level uncertainty = 0.065° (Section IV.C)
Leica mounting axis misalignment	0.11 m (outer beam) (1σ)	Assumptions, attitude uncertainty = 0.06º
MRU mounting axis misalignment	**0.07 m (1s)**	Assumptions, attitude uncertainty = 0.06º
EM3000 mounting axis misalignment	**0.15 m (outer beam) (1s)**	Assumptions, attitude uncertainty = 0.06º
EDO 3050 DVL mounting axis misalignment	**0.1 m (outer beam) (1s)**	Assumptions, attitude uncertainty = 0.06º
EM3000 accuracy	**0.5 m (1s)**	Technical specifications (Section IV.F)
Time synchronization		
Synchronization accuracy	**0.02 m**	Technical specifications
Time drift	**0.30 m**	Measured value (Section V)
Resulting DTM uncertainty		
Bold figures root-square-summed	**1.4 m (1s)**	

VII. VERIFICATION OF RESULTING DTM POSITION ACCURACY

HUGIN I was used in a commercial survey operation for a projected pipeline route (Åsgard Transport). For several reasons no marker was placed on the bottom, and the calibration run in an area with several pipelines was not successful due to a temporarily echosounder failure. Thus, the positioning accuracy has been verified by comparing multiple object observations.

Natural features, for instance rocks, are visible on the sonar data and can be classified as objects. In cases where we have overlapping sonar data and can identify the same object on two footprints, the horizontal (and vertical) distance between the two observations can be found. A large position offset between the two observations obviously indicate considerable DTM position uncertainty. Establishing the distance between the observations prior to and after the filtering, gives an idea of the improvement achieved in the post processing. According to Table 1, the filtered heading and the filtered UUV position are the main contributors to the DTM position error.

To compare the distance between two object observations with the uncertainty in heading and position, we derived the mathematical relation between these quantities. The found position offset between two observations can be compared with the theoretical standard deviations. The theoretical standard deviations of the object observations in the unfiltered data set are calculated using the Leica DMC heading uncertainty and the combined DGPS/HiPAP position uncertainty listed in Table 1. For the observations in the filtered data set, the theoretical value is based on the Kalman filter standard deviation of heading error and position error estimate (due to a temporarily invidious installation of a magnetic valve, we used a heading uncertainty of 0.8° instead of 0.5º as indicated in Table 1). Table 2 summarizes these

Table 2: Comparison of object observation position offset in filtered data set (filtered heading and position) and unfiltered data set (Leica DMC heading and combined DGPS/HiPAP position). Theoretical uncertainty of the two data sets are also calculated.

Object no.	Observation position offset prior to filtering (m) North	East	Observation position offset after filtering (m) North	East	Theoretical uncertainty prior to filtering (1σ) (m) North	East	Theoretical uncertainty after filtering (1σ) (m) North	East
1	**7.5**	2.0	< 0.5	< 0.5	5.12	3.40	1.17	1.00
2	4.6	2.3	< 0.5	< 0.5	5.06	3.40	1.16	1.00
3	1.8	**4.5**	< 0.5	0.8	4.92	3.39	1.15	1.00
4	3.0	1.2	< 0.5	**2.0**	4.92	3.38	1.15	1.00
5	**6.2**	2.0	< 0.5	< 0.5	5.43	3.42	1.21	1.00
6	4.2	1.3	**1.6**	< 0.5	5.59	3.41	1.22	1.00
7	**7.0**	**5.0**	**1.5**	**1.2**	5.48	3.32	1.21	0.99
8	**8.0**	< 0.5	**1.7**	0.6	4.64	3.32	1.12	0.99
9	**8.5**	0.7	**2.0**	0.5	4.26	3.32	1.08	0.99
10	3.6	2.2	**1.7**	0.5	4.82	3.31	1.14	0.99
11	0.7	2.0	**1.3**	**2.0**	3.28	3.24	1.13	1.27
12	2.9	1.1	0.3	< 0.2	3.24	3.24	1.13	1.27
13	0.1	0.8	0.1	0.3	3.30	3.24	1.14	1.27
14	3.3	2.3	< 0.5	< 0.5	4.17	3.76	0.84	0.79
Average:	4.39	1.98	0.84	0.66	4.59	3.37	1.13	1.04

comparisons for all the objects we found in the runs we investigated.

In Table 2 we notice a significant improvement in the filtered data. Furthermore, we can compare the observation position offset after filtering with its theoretical standard deviation. Assuming normally distributed errors, 68% of the observed position offsets should be within its standard deviation. The bold figures indicate an offset exceeding the standard deviation, and we have 19 of 28 inside, which is exactly 68%! However, this test only compares each value with a boundary, not taking into account how far from the boundary they are. Investigating the average actually indicates a better performance than anticipated. This may suggest that the filtered heading uncertainty of 0.8° used in the theoretical standard deviation calculations is too conservative.

VIII. Conclusions

UUVs with standard commercially available navigation sensors and multibeam echosounder have the potential of collecting data for high quality seabed mapping.

The HUGIN sensor suit functions satisfactorily and in accordance with specifications. Magnetic compass heading errors in the order of 3º (1σ) can be reduced to 0.5º (1σ) by proper post processing in an error-state Kalman filter and a smoothing algorithm. Combined DGPS/HiPAP position uncertainty can be reduced to approximately 1.0 m (1σ) for an UUV operating at 300 m depth.

A complete error budget consists of survey vessel sensor accuracy, UUV sensor accuracy, sensor axis mounting misalignment, Kalman filter estimates and time synchronization uncertainties. A resulting DTM (seabed map) position accuracy of 1.5 m (1σ) is achievable (HUGIN UUV at 300m depth, 50 m above seabed and 141 m off the survey vessel in the horizontal plane).

The DTM position accuracy estimates have been verified by a thorough examination of objects on the seabed observed in the multibeam echosounder data.

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