Improving Autonomous Navigation and Positioning for Commercial AUV Operations

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Abstract: **The majority of cruising Autonomous Underwater Vehicles (AUVs) rely on similar technologies for navigation and positioning solutions. This paper examines the traditional approach and some enhancements designed to improve autonomous operations that are available today. Finally it will explore some new techniques under current development. Examples of equipment and performance will be provided from Kongsberg Maritime's experience as the leading manufacturer of survey class AUVs.**

I. INTRODUCTION

The mainstream approach to navigation adopted by AUV manufacturers includes an Inertial Navigation System (INS), which consists of an Inertial Measurement Unit (IMU) and a set of navigation equations. The IMU measures the direction of movement using either fibre-optic or ring laser gyros (RLG). It also measures velocity changes through accelerometers. The INS is an autonomous system, which given some initial conditions will be able to navigate by its own. However, due to the inherent drift of any INS, additional aiding is needed, making it an aided INS (AINS). In the vertical plane the drift rate is effectively taken care of by equipping the AUV with a pressure sensor. In the horizontal plane the de-facto aiding sensor has been and still is the Doppler Velocity Log (DVL).

The typical navigation output from the DVL used for aiding is velocity relative to the sea floor. Under normal survey operations the sea floor will be within the achievable range of the DVL. When out of range, e.g. during descent to operating depth or ascent to get a GPS fix, or if bottom track for some other reason is lost, alternative velocity information is needed to retain an acceptable navigation performance. A good alternative is to combine water relative velocity information and concurrent sea current estimation [1], [2].

A clever integration of the velocity aided INS is pivotal for the overall navigation performance, particularly when position aiding is sparse. A desirable target is to be able to achieve a relative position drift of 0.1% of travelled distance (TD) when traveling between external position fixes. It should be pointed out that the % of TD specification is not complete without also describing the trajectory. A straight line trajectory is the most challenging and a further improvement in the relative drift rate is to be expected when e.g. carrying a lawn-mover survey. In either case, the velocity aided INS, at least not with the current aiding tools, will alone not typically meet the stringent requirements of the commercial survey industry, where the requirements for commercial operations often restrict the maximum position error of the geo-referenced payload data to be less than 5 meters (DRMS) throughout. Since much of this payload positioning uncertainty is attributed to the navigation performance [3], it is clear that suitable aiding must be made available. This paper provides a brief review of some of the tools and techniques available today, as well as a brief discussion on further needs.

II. KONGSBERG MARITIME AINS

One of key strengths of Kongsberg Maritime (KM) is the performance of the KM AINS employed on AUVs, ROV and underwater

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navigation solutions around the world. From an AUV perspective, the KM AINS has been utilized on the HUGIN since 1997. Since then more than 700,000 line kilometres have been completed in the commercial survey segment alone. Close to two decades of operations in the military AUV segment further add on to this, and besides being integrated in HUGIN, the KM AINS is also found in the MUNIN and REMUS vehicles.

The KM AINS was developed by KM in conjunction with FFI, the Norwegian Defence Research Establishment. It has compatibility with a large number of external aiding sensors and has a capability to add a full suite of navigation simulation and post-processing tools. The outline of the AINS is shown in *Figure 1*, where the data fusion is done using a version of the well celebrated Kalman filter (KF). The performance of the in the in-situ version of KM AINS (called NavP) with DVL aiding is 0.1% of TD (DRMS) straight line. Further improvement is possible when running the KM navigation post-processing tool named NavLab [4].

NavLab and NavP share much of the same fundamentals, and NavLab is used as extensively with all vehicles having NavP. A key difference worth mentioning when discussing in-situ navigation versus post-processing is that sensor availability may in some cases differ. For instance when tracking the AUV with GNSS-USBL (ultra short base line) then all available interrogation data are stored topside (hence being available to NavLab), while only a subset (if any) may be sent down acoustically to the AUV for aiding. For the HUGIN and MUNIN AUVs the GNSS-USBL data from the KM HiPAP system are typically transmitted to NavP every 30 seconds. NavLab also has the ability to change and tweak parameters, redo wild-point filtering or data manipulation, and it benefits from the ability to run optimal smoothing [4], [5].

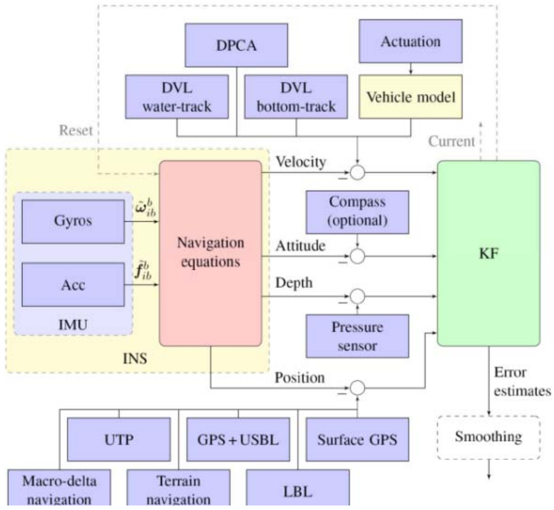

Figure 1: KM AINS Data Fusion

III. OPERATIONAL MODES AND POSITIONING

As mentioned, the successful integration of the velocity aided INS is of great importance to the overall navigation performance, and for the ability to operate autonomously. It is however inevitable that the velocity aided INS will drift of in position over time, and in order to keep the navigation position accuracy within an acceptable limit, external position aiding must be applied. Several sensor and techniques may be applied, where the application of GNSS-HiPAP for aiding the KM AINS has been mentioned already.

The majority of the commercial KM AUV customers operate their AUVs in Supervised Mode, with the support ship remaining within acoustic range of the AUV at all times. There are many advantages to operating in Supervised Mode, not least the improved in-situ navigation accuracy. All position updates, vehicle command and status communications route through the cNODE transponder on the AUV to the HiPAP. This provides the operator with real-time mission status and the ability to change vehicle and payload settings on the fly. Real-time sidescan data and bathymetry are also transmitted through the same link. Recent operations have successfully proven this methodology in depths a great at 4400 meters.

When operating a KM AUV in Supervised Mode with GNSS-HiPAP transmitted frequently to vehicle, the navigation is for practical applications drift free (a drift rate of 0.1% of TD corresponds to 6cm in 30 seconds). When set up appropriately, the in-situ navigation position accuracy of the KM AINS with GNSS-HiPAP is roughly 0.1-0.2% of depth (DRMS). Post-processing using NavLab typically improves these numbers even further.

Now, in some cases it is not possible or desirable to always have a support vessel follow the AUV. An even if one does, it may be desirable to have complementary positioning sources for improved accuracy and integrity. If autonomous missions are feasible it can free up resources.

The two main alternatives available to the KM AUVs (which enable operators to cut the acoustic tether while maintaining an accurate navigation) are Underwater Transponder Positioning (UTP) and Terrain Navigation (TerrP in-situ, and TerrLab in post-processing). Both techniques are a result of the collaboration between KM and FFI.

IV. UTP

UTP has been in existence since the early 2000s in both commercial and military operations, and it was the main positioning tool during the 2012 search for Amundsen's airplane off the northern coast of Norway.

A key feature of UTP is that only on transponder is needed to provide absolute position aiding. This minimizes logistics and cost. Of course, any numbers of transponders may be deployed and used *independently*, in a box or along a route in a chain. The transponders are boxed in at any depth within a few minutes using HiPAP on the ship.

The useful range for UTP is 1-3 kilometres from the transponder, and when placed appropriately the resulting navigation accuracy can be close to what can be obtained using GNSS-USBL [6]. For long straight-line trajectories, the maximum position error is dependent on the distance between the transponders, but when using NavLab the uncertainty between the fixes can be reduced significantly as NavLab is particularly effective when positioning is sparse.

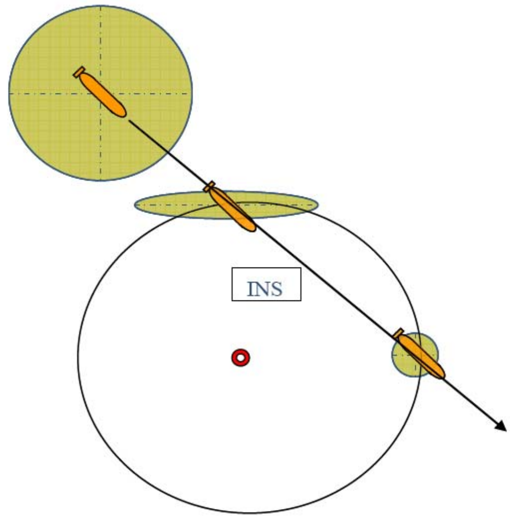

Figure 2: UTP Error Ellipse

In principle a range measurement only indicates that the AUV s somewhere on a circle with the transponder at its centre. An innovative algorithm is implemented for determining the location of the circle and for integrating UTP with the INS solution. As the AUV gets single beacon (or from multiple transponders) the navigation position error ellipse compresses both radially and tangentially, as seen in the example in *Figure 2*.

V. TERRP

Terrain navigation is a comparison of vehicle depth and a map database. TerrP (and TerrLab) requires three distinct elements: a bathymetry sensor on the AUV such as the EM2040 multibeam echosounder; a pre-existing Digital Terrain Model (DTM) of the seafloor; and, some amount of topography. The DTM is compared to the bathymetric information collected by the EM2040, altimeter or DVL. An outline is shown in *Figure 3*. Specifically the features and contours detected are compared to tie the AUV to the DTM. With an accurate, high resolution DTM, TerrP can provide autonomous navigation position accuracy on the order of 2-5 metres (DRMS). Further information can be found in [7] and references therein.

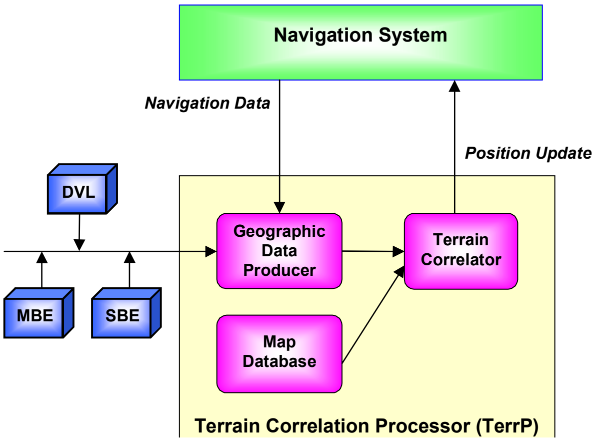

Figure 3: TerrP System

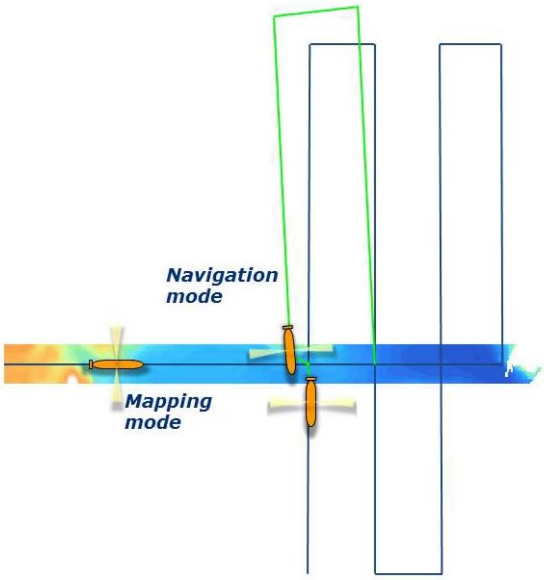

Figure 4: In-Situ Sequential Mapping and Localization

VI. In-Situ Sequential Mapping and Localization

In-situ sequential mapping and localization [8] is a new feature in TerrP. It provides the capability to conduct terrain navigation without an existing DTM. In mapping mode (possibly having GNSS-HiPAP) TerrP will create a DTM internally based on the data collected by the multibeam echosounder, altimeter or DVL. In navigation mode, this DTM is used as the comparison data set. The concept is outlined in *Figure 4*, where the position error estimate found is relative to the position error of the AUV when in mapping mode. The DTM is not estimated simultaneously as it would be in SLAM (Simultaneous Localization and Mapping).

VII. DPCA Micro-Navigation

Perhaps one of the most promising new techniques under development is DCPA micro-navigation. This uses the on-board Highly Integrated Synthetic Aperture Sonar (HISAS) as a velocity sensor in addition to being a payload sensor. If expectations are met, HISAS velocity aiding will provide a leap in velocity aided INS performance. This will again reduce the relative position error drift, which as consequence reduces the need for frequent external position updates.

VIII. Conclusion

This paper discusses the equipment and method used in the Kongsberg Maritime HUGIN and MUNIN AUVs for autonomous and supervised navigation. It demonstrates the capabilities of the system and discusses several techniques for improving autonomous navigation.

The primary aim of improving autonomous navigation is to minimize position uncertainty and maximise data relevance. The techniques demonstrated offer the opportunity for commercial operators to cut the acoustic tether and conduct concurrent revenue generation whilst retaining an acceptable standard of geolocation of the payload sensor data.

Finally, the alternative and new techniques presented, especially DPCA micro-navigation offers the potential to be a game-changer in the commercial AUV world.

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