Sumário da Lição

Inertial Navigation Systems Aided by Positioning Systems: Applications in Ocean Robotics

Paulo Jorge Coelho Ramalho Oliveira

Professor Associado

na

Área Científica de Controlo, Automação e Informática Industrial

Departamento de Engenharia Mecânica

Instituto Superior Técnico

Universidade de Lisboa

fevereiro de 2016

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1. Introduction

The last decade has witnessed a tremendous progress in the development of marine technologies that afforded scientists with advanced equipment and methods for ocean exploration and exploitation. Recent advances in marine robotics, sensors, computers, communications, and information systems are being applied to develop sophisticated technologies that will lead to safer, faster and more efficient ways of exploring and exploiting the ocean, in potentially harsh and hazardous conditions. There has been also worldwide a surge of interest in the development of autonomous marine robotic platforms able of collecting data at the surface of the ocean and underwater, at an unprecedented scale. Representative examples are autonomous surface craft (ASC) and autonomous underwater vehicles (AUVs). The envisioned mission scenarios, call for the decentralized navigation, guidance, and control (NGC) of single or multiple vehicles acting in cooperation to execute challenging tasks without close supervision of human operators, see [1] and the references therein for details.

The final goal of this endeavor will be to make possible for users, who are not familiar with technical details of marine robotics, to program the robots and accomplish nontrivial missions. To tackle this issue, more accurate and less demanding navigation and positioning systems need to be developed, to support reliable decentralized mission control systems for single and multiple autonomous marine robots.

1.1 Oceanic Robotic Platforms

Figure 1.a – The AUV Infante (on the left), the SIRENE underwater shuttle (on the middle) and the ASC Delfim$_X$ (on the right).

Instituto Superior Técnico, through the Laboratory for Robotics and Systems in Engineering and Science, has been involved in an oceanic robotic platforms research and development program. Under this framework, lead by the Dynamic Systems and Ocean Robotics Laboratory of ISR, several platforms have been developed, as depicted in Fig. 1.a. On the left panel, the Infante AUV is presented, equipped with two stern thrusters for propulsion and six fully moving control surfaces (two stern rudders, two bow planes and two stern planes) for vehicle steering and diving in the horizontal and vertical planes, respectively. This AUV is an evolution from MARIUS, the first civilian AUV developed in Europe, during the nineties. Infante has a maximum rated speed, with respect to the water, of 2.5 m/s. At a cruising speed of 1.3 m/s, the estimated mission duration and range are 18 h and 83 km, respectively, with a maximum depth of operation of 500 m. Its current scientific sensor suite includes a Doppler velocity log, a sidescan SONAR (Sound Navigation and Ranging), a mechanically scanning pencil beam SONAR, a conductivity–temperature–depth (CTD) logger, a fluorometer, a Plankton sampler, and a video camera. In a representative mission, the vehicle performs lawn mowing maneuvers at different depths to collect scientific data in the water column or bathymetric data from the sea floor. In order to geo-referencing data of major interest for the scientists, low cost, highly accurate inertial navigation systems are needed.

The Sirene AUV, depicted in the middle panel of Fig. 1, is an underwater shuttle designed to automatically position a large range of benthic stations on the seabed, down to depths of 4000 m. The vehicle was developed by a team of European partners coordinated by IFREMER, in the scope of the MAST-II European project DESIBEL (New Methods for Deep Sea Intervention on Future Benthic Laboratories) that aimed to compare different methods for deploying and servicing benthic stations, as discussed in [4]. The need for the Sirene AUV to return to the same location at the sea bottom, with a positioning error not exceeding 2 meters, triggered the need for the development of high performance aided inertial navigation systems.

The autonomous catamaran Delfim$_X$, displayed in the right panel of Fig. 1.a, was designed for automatic marine data acquisition for risk assessment, in semi-submerged structures [20]. Its use allows for the access to remote and confined locations in a systematic way, provided by precise SONAR and LIDAR (Light Detection And Ranging) data acquisition systems. To successfully execute its mission, the catamaran is required to have a reliable on-board navigation system based on low-power consumption, inexpensive hardware, capable of efficiently integrating the information from inertial and aiding sensor suites. The partial availability of NAVSTAR-GPS signals on the mission scenarios lead to the inclusion of an all weather global positioning system (GPS) receiver and the fusion of its data with the Delfim$_X$ motion data, provided by accelerometers, rate-gyros, magnetometers, and Doppler velocity data relative to the fluid and to the sea bottom, in shallow areas.

2. Positioning Systems for Underwater Applications

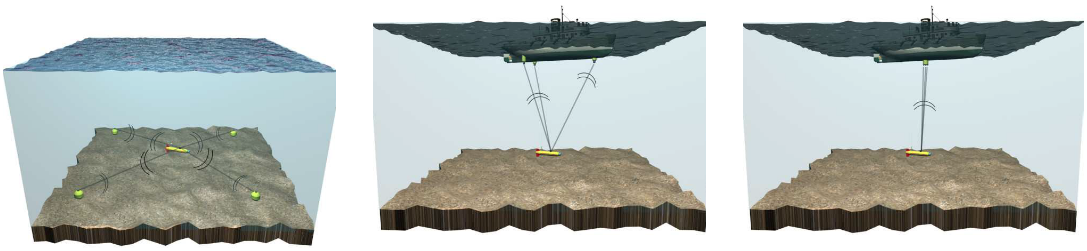


Figure 2.a – Underwater acoustic positioning systems: a) Long Baseline LBL (left), b) Short Baseline SBL (middle), and c) Ultra-Short Baseline USBL (right).

Free from the constraints of an umbilical cable, AUVs are steadily becoming the tool *par excellence* to acquire marine data on an unprecedented scale and to carry out interventions in undersea structures. As previously described, central to the operation of these vehicles is the availability of accurate navigation and positioning systems. The former provides high data rate measurements of the angular and linear positions of a vehicle and velocity and are therefore crucial to platform stabilization and control. The latter are often used to complement, at low data rate, the information provided by the navigation system, as it is not generally corrupted by persistent disturbances (e.g. biases) that degrades the overall performance when integrated in open loop for long periods. The classical approaches to tackle the problem of underwater vehicle positioning include Long Baseline (LBL), Short Baseline (SBL), and Ultra-Short Baseline (USBL) systems, as depicted in Fig. 2.a. An introduction to this challenging area can be found in [11, 17, 20] and in the references therein.

More recently, triggered by the fast development of GPS technology, new underwater acoustic positioning systems have arisen, based on buoys equipped with GPS receivers and acoustic communication capabilities. One such system is the commercially available GPS Intelligent Buoys (GIB), as depicted in Fig. 2.b.

Figure 2.b – The GIB system: a) example of configuration at sea (left), b) buoys on the peer (middle), and c) pinger to instal onboard the underwater vehicle (right).

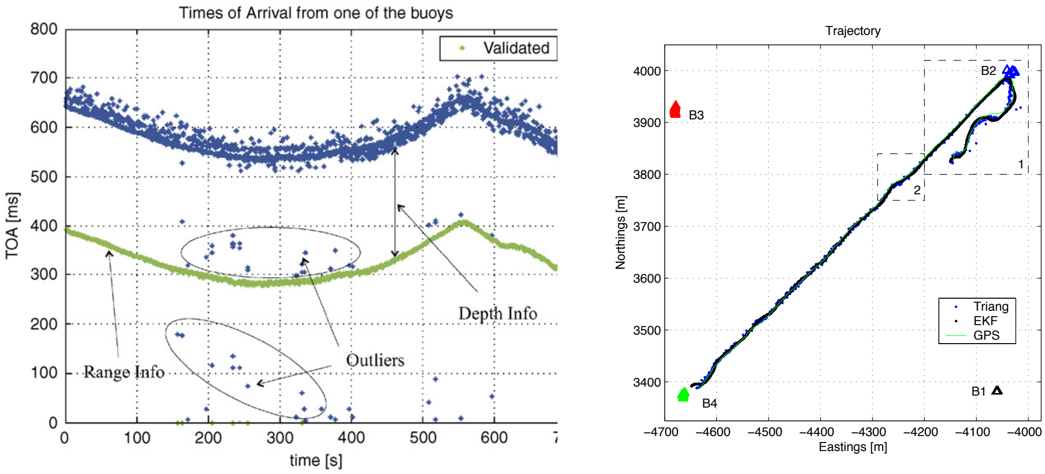
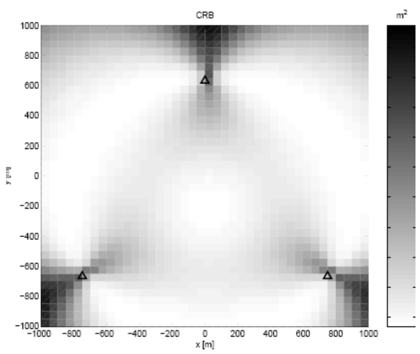
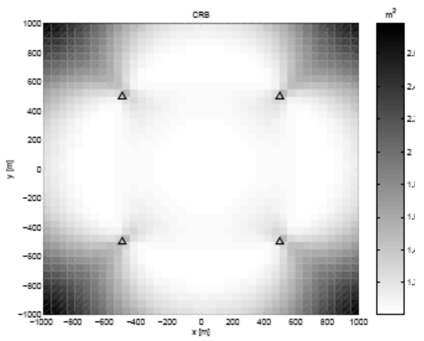


Figure 2.c – Data from pinger to buoy (left panel) and vehicle trajectory at sea (right).

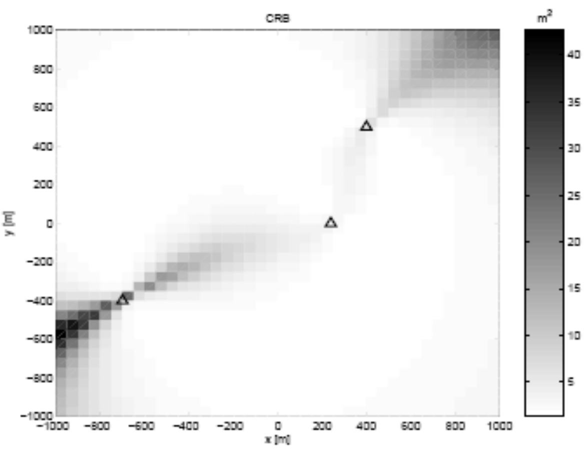
In the scenario adopted, the target carries a pinger (in the right panel of Fig. 2.b) that emits acoustic signals periodically, as determined by a very high precision clock that is synchronized with GPS, prior to system deployment. The target is tracked from the surface by using a system of four buoys (left and middle panels of Fig. 2.b), equipped with hydrophones and electronic circuitry that measures the times of arrival of the acoustic signals emitted by the pinger or, equivalently, the four target-to-buoy range measurements. Due to the finite speed of propagation of sound in water, these



3 buoys



4 buoys



3

buoys asymmetric

Figure 2.d – GIB system: Cramér Rao lower bound for several buoys' configurations.

measurements are obtained with different latencies. Moreover, dropouts and outliers on the measurements occur due to acoustic path screening, partial system failure, and multipath effects. as is the case of the data from one buoy depicted in Fig. 2.c, left panel.

In [2], a detailed description of this system and a target tracker for underwater vehicles, based on extended Kalman filtering (EKF) can be found. The results of a validation experiment at sea are depicted in Fig. 2.c, right panel. Resorting to estimation techniques, an analytical lower bound on the accuracy of the position estimates can be obtained using the Cramér-Rao lower bound (CRB), see [3] and the references therein for a theoretical introduction and for the detailed study on the buoys configuration on the GIB system performance, respectively.

An interesting conclusion is that some configurations, as the one with the results presented in the right panel of Fig. 2.d, can degrade severely the performance of the GIB positioning system. The study of theoretical performance bounds has proven to be a flexible tool that can provide insight on the correct procedures to deploy the systems at sea, in order to optimize the overall performance. Also, this bound provides limits for the attainable performance, helping on the choice of favorable buoy geometries or system reconfiguration requirements, for specific mission scenarios.

3. Inertial Navigation Systems

The inertial navigation system (INS) is the backbone architecture that performs attitude, velocity and position numerical integration from data acquired from rate gyro and accelerometer triads, rigidly mounted on the vehicle structure, in the so-called strapdown configuration (to differentiate from gimbaled configurations).

3.1 Classical approach

For highly maneuverable vehicles, the INS numerical integration must properly address the fast dynamics of inertial sensors output, to avoid estimation errors buildup. The INS computations that are usually adopted, account for the high frequency attitude, velocity and position motions (denoted as coning, sculling, and scrolling, respectively), and are based on the algorithms developed by Paul Savage, as presented in the seminal works [18, 19]. The pure INS algorithm integrates the inertial sensor readings, and hence the results are corrupted by disturbances such as bias and noise, among other error sources.

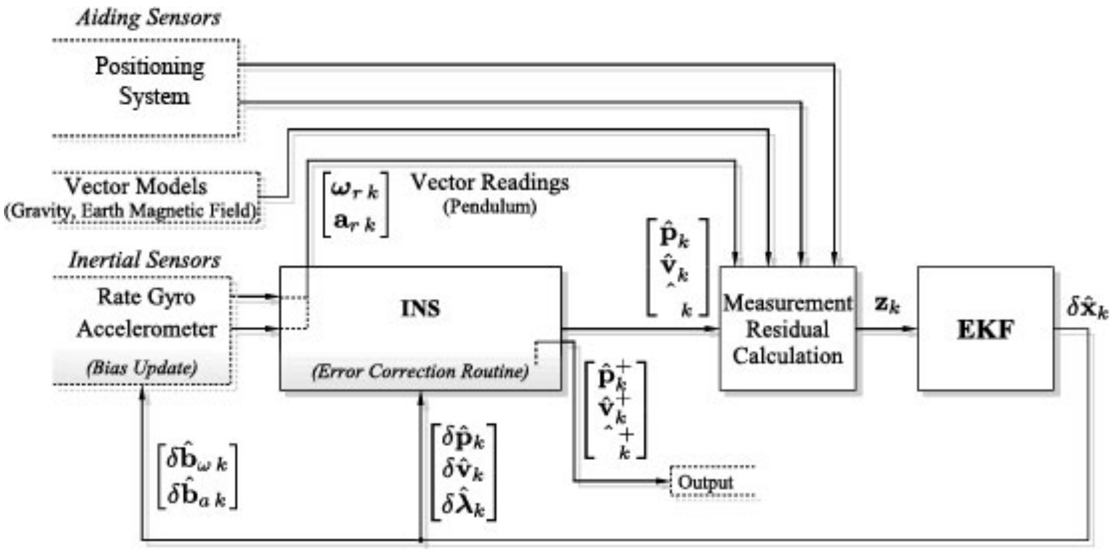


Figure 3.a – Inertial navigation system with estimation error compensation. The estimates of the sensor biases are dynamically updated using the filter results.

The classical solution is based on an EKF that exploits the aiding information from the positioning systems described in section 2. Interestingly, it is also possible to dynamically compensate for the non-ideal sensor characteristics that otherwise would yield unbounded inertial integration errors, as in the case of tightly coupled architecture that is depicted in Fig. 3.a. Rate gyro and accelerometer biases compensation enhancements are obtained, using magnetometer measurements and selective frequency contents from gravity information, provided by the accelerometer triad readings.

A solution to integrate vector observations such as magnetometer and gravity measurements, or positioning data in the EKF is proposed in [21]. The proposed vector aiding technique decomposes and optimally integrates gravitational observations in the EKF, taking into account the vehicle dynamics bandwidth information to properly trace inertial motion. Gravity readings are provided by the accelerometer triad, and hence distorted in the presence of linear and angular accelerations. A dynamic compensation of external accelerations is performed using the INS information to estimate angular acceleration, while linear acceleration is characterized in the frequency domain using the filter state space. Thus the proposed approach exploits the low frequency contents of the gravity readings to compute the attitude estimation error in the EKF.

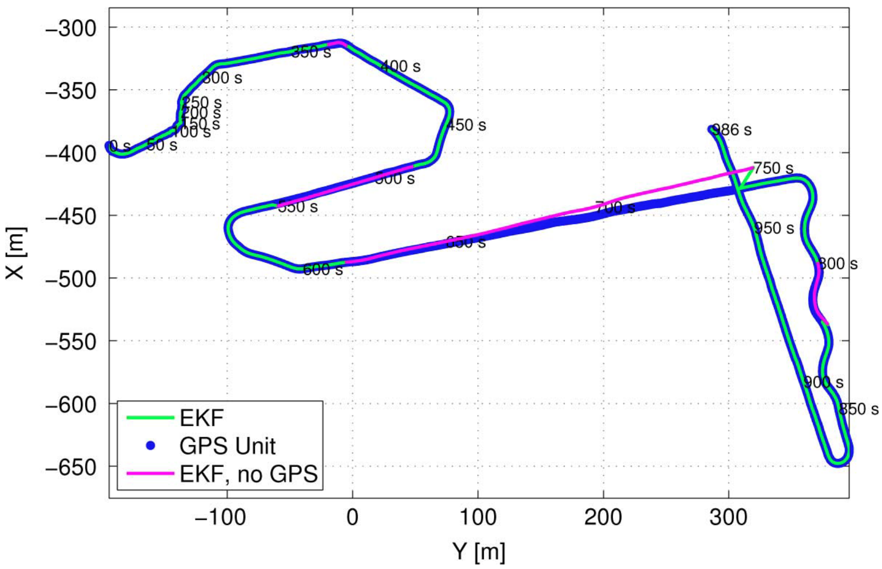


Figure 3.b – Delfim$_X$ trajectories with GPS outage: although the GPS is disabled at t ∈ [370, 380] s, t ∈ [480, 550] s, t ∈ [615, 750] s, and t ∈ [800, 820] s, the position estimates track the nominal trajectory.

The experimental results obtained at sea with the Delfim$_X$ ASC showed that the proposed navigation system accurately estimates position (and attitude), as depicted in Fig. 3.b. The compensation of sensor non-idealities such as bias and noise effects, and the autonomy with respect to outages of the GPS aiding signals can be tackled by exploiting the vector measurements directly in the filter, as verified in the sea trials.

3.2 New Synthesis and Analysis Tools

Despite the good performance results in robotic and manned vehicles obtained with the aforementioned architectures, i.e. with filtering solutions supported in the EKF, no general analysis results on stability or observability exist in the literature. This lack of knowledge triggered our interest on the design and performance evaluation of globally asymptotically stable time-varying kinematic filters. In the first stage, the estimation of linear motion quantities of mobile platforms (position, linear velocity, and acceleration) in three dimensions was addressed. A solution, assuming access to precise attitude information, is reported in [5], where Kalman and H_∞ optimal filters for linear time-varying systems and the explicit optimal filtering solutions are obtained through the use of an appropriate *Lyapunov* coordinate transformation. Several examples of application in the field of ocean robotics were provided to demonstrate the potential and usefulness of the proposed design methodology, namely: i) the estimation of unknown ocean currents and ii) the joint estimation of the robotic platform velocity and the acceleration of gravity.

Moreover a systematic methodology for the observability analysis of the class of systems that can provide linear motion estimates in mobile platforms, assuming also exact angular measurements, is reported in [6]. The analysis is rooted on systems theory and do not require any linearization or approximation. Interestingly, it was proved that not all trajectories yield the system observable. In fact the trajectories should be rich enough in what concerns the evolution of the direction of the angular velocity and, for uniform complete observability to be attained, the direction of the angular velocity cannot stay indefinitely arbitrarily close to a constant vector. Thus the system is uniformly completely observable if and only if a persistent change in the direction of the angular velocity occurs.

4. Inertial Navigation Systems Aided by USBL Positioning System

The synthesis, design, and implementation of an ultra-short baseline (USBL) system have been pursued at ISR in the last six years. The first prototype was recently completed, to allow the performance assessment of the new filters and observers developed, with special focus on tightly coupled methods. This integrated USBL/INS solution will be used in the future as a low-cost navigation system in underwater applications.

At the core of the system there is an acoustic array of four hydrophones, sampled by 18 bit effective Sigma-Delta Analog to Digital converters, into a Digital Signal Processor (DSP) as well as Micro Electro-Mechanical Systems (MEMS) triads of rate-gyros, accelerometers, and magnetometers, as depicted in Fig. 4.a. A transponder that replies to the interrogations sent out by the integrated USBL/INS system was also implemented as a byproduct of this technological development. Special attention was given to the signals to be used in the acoustic positioning system. Given its immunity to the ambient noise and the possibility of simultaneous use by multiple agents, direct spread-spectrum sequence (DSSS) coded signals were selected.

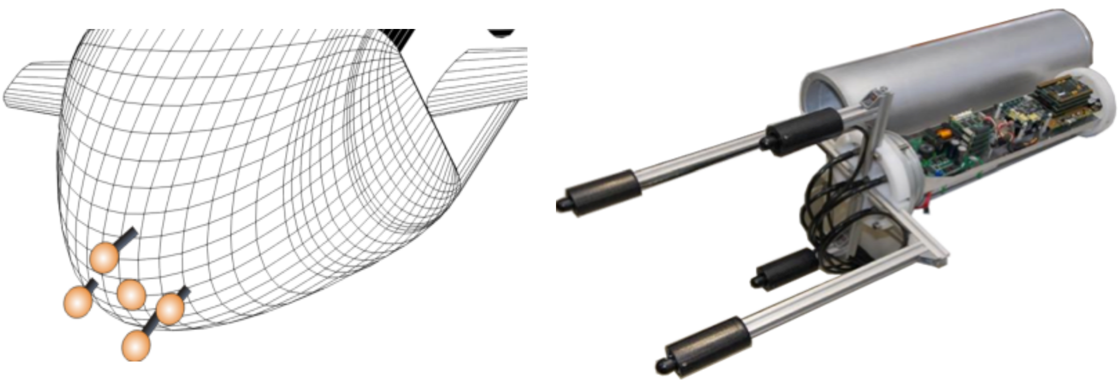


Figure 4.a – Inverted USBL planned instalation at Infante AUV, on the left panel.
USBL prototype developed, on the right panel.

Given the successful results on the study of navigation systems for the estimation of linear quantities, outlined in section 3, a novel approach for the design of globally asymptotically stable

(GAS) position and velocity filters for Autonomous Underwater Vehicles (AUVs) was addressed. This approach is based directly on the available Ultra-short Baseline (USBL) acoustic positioning system readings, complemented with data from a Doppler Velocity Log (DVL). The methodology adopted exploits an equivalent linear time-varying (LTV) system that fully captures the dynamics of the nonlinear system, allowing for the use of powerful linear system analysis and filtering design tools that yield GAS filter error dynamics [12]. For this system, observability is proven, under the assumption that there exists an array with at least four non-coplanar receivers. In terms of performance assessment, numerical results using Monte Carlo simulations and a comparison with the Bayesian Cramér-Rao Bound (BCRB) reveal that the proposed filter performance is tight to this theoretical lower bound estimation error.

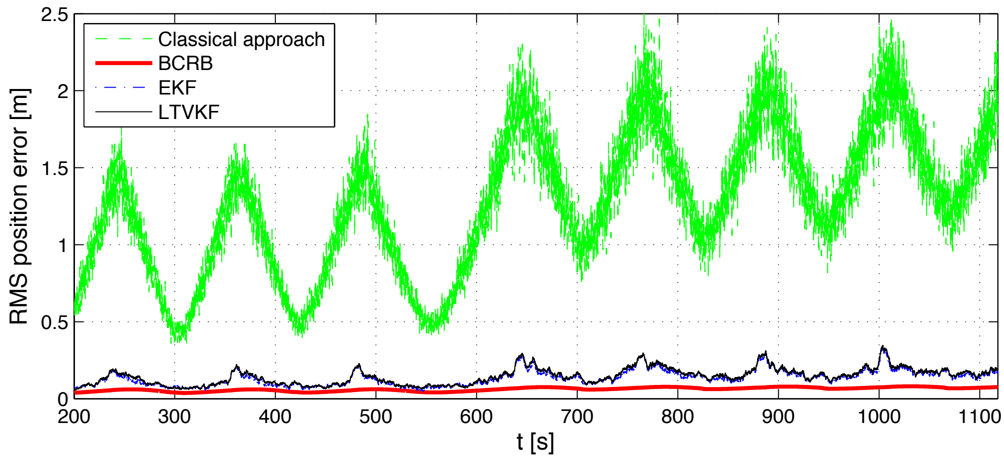


Figure 4.b – USBL performance with low grade heading system.

In comparison with other approaches considered as the state of the art, the proposed solution, designed in the body-fixed coordinate frame (LTVKF), achieves the same level of performance as the one obtained resorting to the EKF, which does not offer GAS guarantees and it outperforms other classical filters (e.g. loosely coupled), as depicted in Fig. 4.b. Moreover, inclusion of the kinematics of the ranges in the proposed solution allows for a better description of the disturbances on acoustic sensor readings. The design framework adopted also enables the filter to easily tackle individual range measurements outages, by simply bypassing corrections from problematic receivers. It is important to remark that in the classical solution a position fix might not even be available if one receiver fails to detect the acoustic signal.

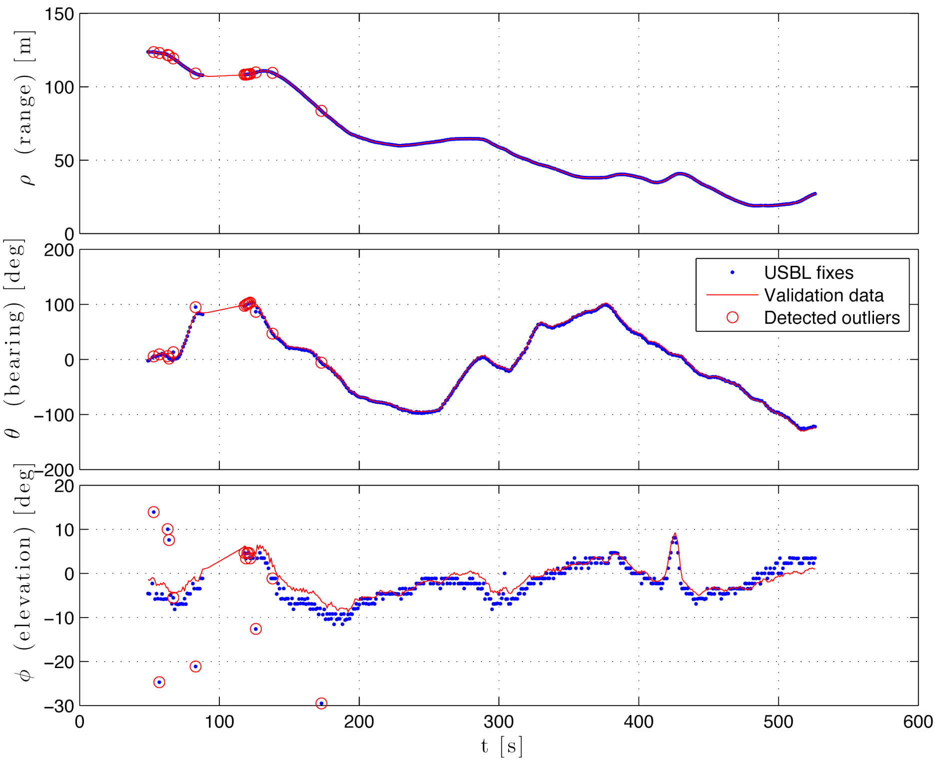


Figure 4.c – USBL/INS results at sea, with the presence of outliers.

The implementation of the overall acoustic positioning system includes an on-line heuristic outlier detector and classifier, yielding satisfactory results even in shallow water applications, as depicted in Fig. 4.c. Note that the correct classification of outliers in the positioning data is of utmost importance, as it would otherwise cause significant disturbances in the subsequent filtering stages. The assessment of the overall performance enhancement was further evidenced [13] by enforcing an USBL data outage for a period of 30 s, in which the tightly-coupled revealed to drift much less from the nominal trajectory when compared to the traditional loosely-coupled solution.

4.1 USBL/INS Applications

The promising features of the USBL/INS tool under development revealed to be a good solution in a number of underwater applications. One example for the use of the resulting navigation systems was proposed and approved in late 2010 under the framework of the FCT project MAST/AM [16]. At the core of this collaborative work is the possibility of tracking fishes tagged with VEMCO commercially available acoustic markers, as depicted in the left panel of Fig. 4.d. The signals emitted by these acoustic tags could be easily detected by USBL acoustic arrays located at surface in drifting buoys, with a GPS and an INS, or by an underwater portable unit carried by a scuba diver. The data acquired can then be processed and fused with the INS data to obtain relative directions to the marker. The directional information can be geo-referenced through a surface vessel or serve as a guidance tool for divers. The interchange of data with an USBL/INS installed on a

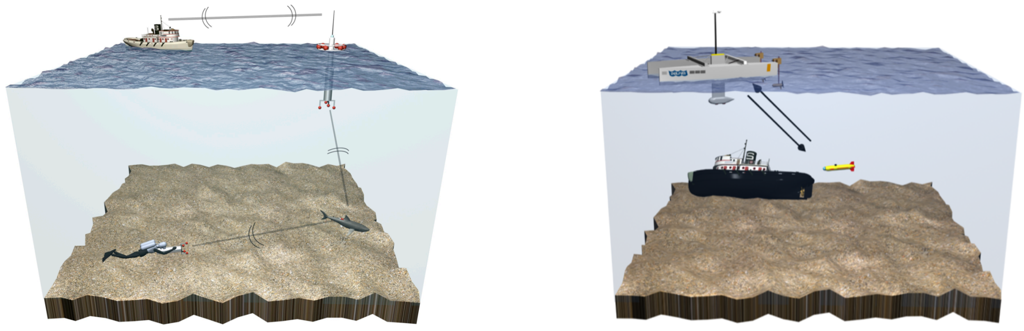


Figure 4.d – Artist's concepts for the FCT MAST/AM project, on the left panel and for the TRIDENT EU project on underwater intervention, on the right panel.

buoy at surface allows the 3D trajectory estimation of the tagged animal in real time, at unprecedented accuracy.

Under the framework of the European project TRIDENT focusing on underwater intervention tasks, the use of an inverted-USBL positioning system is also being instrumental, in a configuration depicted in the right panel of Fig.4.d. The strategy pursued is to install such devices on-board intervention AUVs (I-AUVs), to allow their localization relative to a surface craft at a known position, as depicted on the left panel of Fig. 4.d, as detailed in [14]. Resorting to the same techniques, a solution for the problem of finding black boxes of crashed airplanes has been pursued. The flight and voice data recorders have a built-in acoustic beacon that emits pulses when in contact with water. That source can be localized and the position information can then be fed into the homing vehicle controller that steers the vehicle towards the pinging target.

The exploitation of these solutions revealed that we are pushing the use of these systems to the limit. Due to noise, attenuation of the acoustic signals used, or multipath phenomena, sometimes only a sub-set or just one range is available. A similar situation occurs when several vector measurements are required to tackle a positioning or attitude estimation problem but under practical conditions of operations only a subset (or even just one) is available.

5. **Inertial Navigation Systems Under Limited Aiding**

In the cases where only limited aiding data is available to help the navigation systems, only a few works can be found in the literature, see [10] and the references therein. This lack of knowledge for the analysis of these extreme situations triggered also our interest towards the study of observability, stability, and the relation with the trajectories that the underwater vehicles are required to perform. Two situations were studied in detail: i) single range aided navigation and source localization and ii) source localization and navigation aided by one bearing.

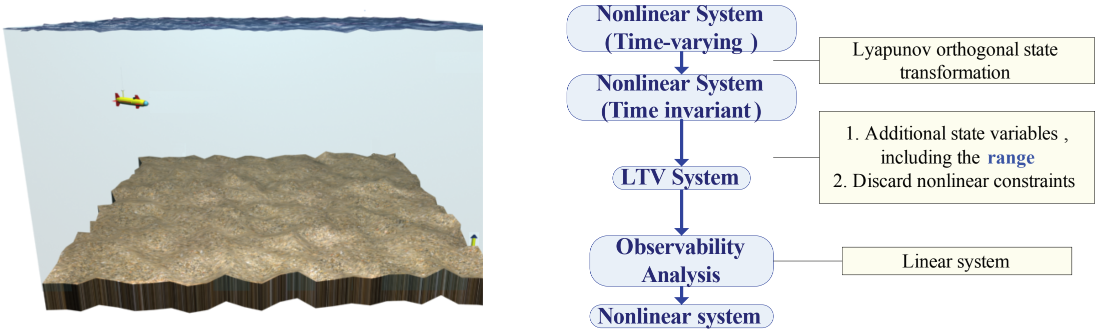


Figure 5.a –Single beacon navigation, relative to a known landmark on the left panel. Systems' theory logical steps for observability analysis, on the right.

5.1 Single range aided navigation and source localization

The problem of navigation system design and the dual problem of source localization by mobile agents, based on only one range to a single external source in addition to relative velocity readings (as depicted on the left panel of Fig. 5.a), has been addressed and a sub-optimal solution was proposed (see [7]). The original contributions were: i) the necessary and sufficient conditions on the observability of the nonlinear systems at hand, which are useful for trajectory planning and motion control of the agent; and (ii) a nonlinear system is advanced such that, given the input and output of the system, can be regarded as linear time-varying, for which a Kalman filter can be applied to successfully estimate the system state, as depicted in the right panel of Fig. 5.a. Simulation results, in the presence of realistic measurement noise, provided the confirmation to the consistence of the proposed solution. The validation of these methodologies has been successfully pursued under the framework of the EU project TRIDENT, introduced above.

5.2 Single direction aided navigation and source localization

The problem of source localization has been subject of intensive research in recent years. Roughly speaking, an agent has access to a set of measurements and aims to estimate the position of a source. The set of measurements depends on the environment in which the operation occurs and the mission scenario itself. Recent results for this problem were obtained, resulting in a set of globally asymptotically stable Kalman filters for the problems of source localization and navigation based on direction measurements to a single source [8]. The observability of the systems was fully characterized, which draw to the conclusion on the asymptotic stability of the Kalman filters. The observability conditions that were derived are directly related to the motion of the agent/vehicle and as such they are useful for motion planning and control. Simulation results were presented that illustrates the good performance for the proposed solutions. When compared with the EKF, they achieve similar performance but with global asymptotic stability guarantees. Future work will be carried out, under the framework on the FCT project MAST/AM, to validate at sea these results. Extensions of the present work to the case where directions to multiple sources are available will also be considered.

6. **Underwater Environmental Measurements with Missing Data**

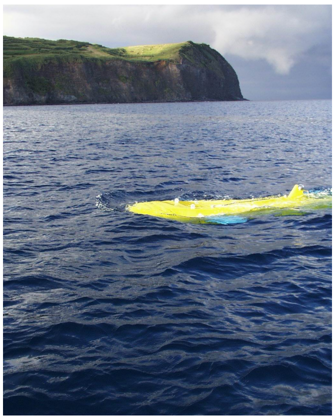
The widespread use of ASCs, Remotely Operated Vehicles (ROVs), and AUVs carrying powerful computers, mass storage media, and state-of-the-art sensors and transducers, have endowed the scientists with tools that can collect massive quantities of data on relevant marine quantities. Sensor fusion problems such as outlier detection and removal, signals interpolation, extrapolation, and reconstruction, data geo-referencing, and data mining, to name a few, can only be accomplished resorting to advanced estimation and signal processing techniques.

The central problem of geo-referencing the information acquired during the survey missions, is therefore tackled resorting to the navigation systems outlined previously and installed and operated onboard. However it must be pointed out that data is not available at uniform temporal and spatial rates. Other domains where this phenomenon occurs are remote sensing, digital communications (subject to bursts of destructive interferences), estimation and control in networked systems, and computer vision (when occlusions occur), just to name a few. Thus, the problem of interpolating multidimensional sampled signals with missing data is central in a series of applications.

A non-iterative methodology based on Principal Component Analysis (PCA) has been proposed, that corresponds to the sub-optimal solution to a regulated weighted least mean square minimization problem, based on estimates for the mean and covariance of signals corrupted by zero-mean noise, see [15] for details. Additionally, estimates for the mean square interpolation error, with upper and lower bounds have also been deduced. Some refinements are used to improve the solution proposed, namely: i) mean substitution for covariance estimation, ii) Tikhonov regularization and, iii) dynamic principal components selection.

6.1 Bathymetric Data Fusion

The proposed methodology for the interpolation and regularization of multidimensional sampled signals with missing data, that departs from the classical approaches, have been applied to bathymetric data fusion in [9].



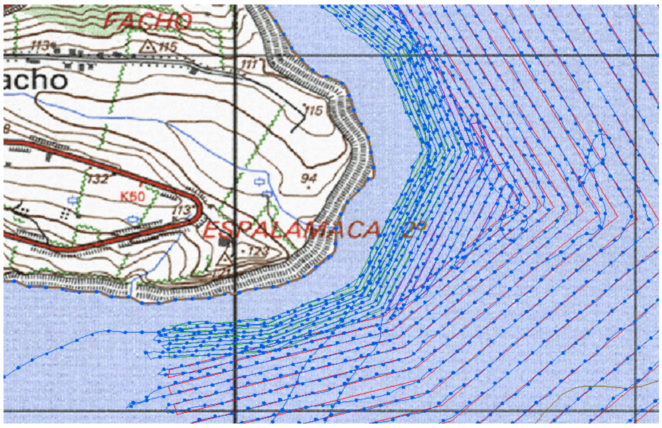


Figure 6.a – Infante AUV at sea, with Espalamaca hill in the horizon, at left panel. Planned (red line) and executed trajectories (blue), in the right panel.

The passage between the islands of Faial and Pico is probably the best-known shallow-water area in the Azores. A number of studies using mechanically scan and sidescan and multibeam SONARs have already covered the main aspects of seabed morphology and character, resulting in a good knowledge of the general distribution of the different bottom types and features. The Espalamaca-Madalena ridge, on the left panel of Fig. 6.a, is one of those structures of great interest for the marine geologists and was selected to assess the performance and flexibility of the new sensor fusion technique.

A careful planned survey at sea was carried out, as detailed in the right panel of Fig. 6.b, near Espalamaca hill in Horta, Faial Island, Azores, during August 2004. The non-iterative methodology for the interpolation and regularization of multidimensional sampled signals with missing data, based on PCA, was applied to bathymetric data acquired during tests at sea. Based on unbiased estimators for the mean and covariance of signals corrupted by zero-mean noise, the PCA decomposition is performed and the signal is interpolated and regularized. The (sub-)optimal solution was obtained from a weighted least mean square minimization problem, and upper and lower bounds were provided for the mean square interpolation error, as depicted in the right panel of Fig. 6.b. The results obtained pave the way to the use of the proposed framework in a number of sensor fusion problems, in the presence of missing data. Ultimately, this method aims at overcoming the limitations faced today in marine data fusion problems.

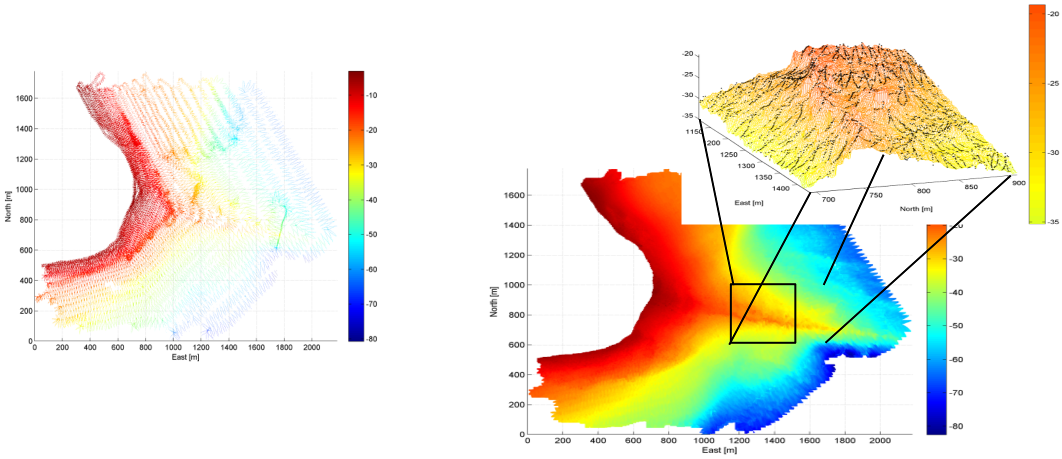


Figure 6.b – Geo-referenced survey data acquired in Espalamaca, on the left and data fusion results, on the right.

Acknowledgments

A word of appreciation goes to my previous supervisors Prof. João Lemos, Prof. João Sentieiro, and Prof. António Pascoal, that along my career have always shown me, with their examples and wise words, how to make choices and proceed in this difficult trail that is the scientific research. The theoretical work briefly mentioned in this summary was mainly developed with the contributions of Pedro Batista, Marco Morgado, José Vasconcelos, and Alex Penas. A special thanks goes to my good friend Carlos Silvestre, for all our long and fruitful discussions and joint collaborative work. The practical validation of work previously outlined would never had been possible without the help of Bruno Cardeira, Manuel Rufino, Luís Sebastião, and João Alves, from the DSOR lab.

The work accomplished along these last 20 years would also have not been possible without the support from European Union (MAST, Marie Curie, and FP programmes), Fundação para a Ciência e a Tecnologia (Plurianual and Estratégico Projects and PhD funding Programs), and Agência de Inovação (AdI) that funded the projects where I had the pleasure to participate. The ambience at Institute for Systems and Robotics, in the Scientific Area of Systems, Decision, and Control of DEEC, and more recently in the Scientific Area of Control, Automation, and Industrial Informatics of DEM, were the right ingredients that seasoned the work developed so far. Thank you all.

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IST, 29 de fevereiro de 2016