9th IFAC Conference on Control Applications in Marine Systems
The International Federation of Automatic Control
September 17-20, 2013. Osaka, Japan

Magnetic Navigation and Tracking of Underwater Vehicles ⋆

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Abstract: This paper proposes novel methods with the potential to improve the performance of navigation and tracking systems in underwater environments. The work relies on well-established methods of potential field inversion and introduces a new analytic formulation designed to stabilize the solution of the inverse problem in real-time applications. The navigation method proposed exploits the terrain information associated with geomagnetic field anomalies, without the need of a priori maps. The procedure can also be applied to track a moving vehicle based on its associated disturbance of the environmental magnetic field. We envision the integration of theses methods in terrain-aided navigation systems, simultaneous localization and mapping algorithms, and tracking applications.

Keywords: Navigation; tracking; magnetic methods; inverse problems; particle filters.

1. INTRODUCTION AND MAIN CONTRIBUTION OF THE PAPER

The execution of long-range and long-term missions by robotic underwater vehicles in a fully autonomous mode is still a challenging problem. Without the aid of external references, the position error of high-grade inertial navigation systems (INS) grows at a minimum rate of 0.1 percent of the distance traveled. Even with the integration of Doppler velocity loggers (DVL) with INS to improve the performance of dead-reckoning navigation systems, the positioning error grows unbounded at a considerable rate. Hence, efficient and affordable navigation methods are under development to afford underwater robotic vehicles the capacity of executing long-range missions with minimum human intervention. Among the novel methods proposed, the terrain aided navigation (TAN) and the Simultaneous localization and mapping (SLAM) approaches have great potential for the implementation of a new generation of reliable and affordable navigation systems. However, a fair assessment of the state of the art shows that TAN and SLAM implementations in the marine environment are still in a experimental phase. SLAM is a method rooted in the mobile robotics community where navigation problems have been solved relying on the extraction of geometric features and prominent landmarks or based on the utilization of artificial beacons. Normally, these conditions cannot be ensured in marine environments. On the other hand, TAN has already proved its efficacy in natural, unstructured environments but requires the existence of prior maps for navigation, a requirement that cannot be fulfilled easily in most applications. The terrain-based approach also assumes that the terrain is sufficiently rich in terms of topography to permit the estimation of position. It is well-known that this assumption is not valid in vast areas of the ocean floor. To solve this problem we proposed in prior works to complement the topographic information with geomagnetic data extracted from the terrain; Teixeira (2007); Teixeira and Pascoal (2008).

It is against this backdrop of ideas that this paper proposes the combination of different analytic methods of geopotential field inversion to implement 3D localization algorithms that can be employed in navigation and tracking. We propose its integration in TAN and SLAM to improve the navigation capabilities of autonomous underwater vehicles. Based on the same methods, we present a tracking procedure that may find applications in civilian and military applications.

2. MAGNETIC METHODS IN NAVIGATION AND TRACKING PROBLEMS

The magnetic field of the Earth is a vector field characterized by very slow variations in its intensity and orientation due to geophysical phenomena in the interior of the planet and by higher frequency fluctuations caused by external influences such as the solar activity. In addition to these large-scale variations, there are local anomalies in terms of magnitude and orientation of the geomagnetic field that are introduced by natural and artificial objects with induced and remanent magnetization. The exploitation of

⋆ The first author holds a post-doc grant of the Portuguese Foundation for Science and Technology (FCT). This research was supported in part by the FCT project ATLAS [PTDC/EEA-ELC/111095/2009] which includes FEDER funds and also by the EU FP7 Project MORPH under grant agreement No.288704.

these geomagnetic anomalies as a source of information for the navigation of AUVs has been proposed many years ago but the concept still requires practical demonstration.

Implementation issues One of the advantages of magnetic navigation consists in being passive and economical in terms of energy. Magnetic sensors do not emit signals that can be detected and tracked remotely and their typical power consumption is orders of magnitude lower than that required by active sonar systems employed in bathymetric TAN.

The main problem to solve in magnetic-based navigation is the suppression of electromagnetic noise or the mitigation of its effects on the measured data used for localization. A global source of magnetic noise is the solar activity that affects the magnetosphere of our planet and manifests in the form of periodic diurnal variations of the Earth's magnetic field, superimposed by random components of higher frequency. This which noise affects equally any measurements obtained in a given region, can be filtered out by taking differential measurements of the magnetic field using magnetic gradiometers instead of single magnetometers. In robotic platforms, the electrical thrusters and other components of the vehicle constitute important sources of electromagnetic noise. This issue assumes special relevance in applications like the present one, that require magnetic measurements with very high precision. A typical solution to this problem consists in the placement of magnetic sensors as far away as possible from the sources of noise but this may not be practical to implement in small robotic vehicles. We are currently studying solutions that involve well-known calibration techniques to compensate the disturbances introduced by the vehicle and its payload, combined with methods based on temporal correlation, spectral analysis, and band-pass filtering to mitigate the electrical noise induced by the thrusters/actuators.

Besides underwater navigation, we envision tracking of underwater objects or vehicles as another interesting application of the methods proposed here. The tracking system proposed consists basically in a vector gradiometer which senses the anomalous magnetic field vector caused by a passing vehicle. The corresponding gradient measurements are processed by an inversion algorithm to estimate its position and velocity vector. In these conditions, the tracking problem can be solved with a relatively simplified sensor set-up since the magnetic observer may be deployed at a fixed location thus eliminating the need for the continuous acquisition of its relative localization and orientation parameters. In this type of application, local sources of electromagnetic noise can be easily avoided.

2.1 Alternative methods of magnetic navigation

A survey of the literature reveals that two main methods have been proposed in the last decades for magnetic navigation of underwater vehicles. The first approach is basically an extension of the terrain-aided navigation concept with exploitation of geopotential fields. It consists in matching a set of scalar or vectorial field measurements performed by a moving platform with a magnetic signature of the terrain. A different approach that has emerged more recently consists in the application of inverse methods to localize the sources of the local magnetic anomalies and estimate the position of the vehicle relative to these sources; see e.g. Kumar et al. (2005); Pei and Yeo (2006); Nara et al. (2006); Birsan (2011). This method can be used in the context of TAN but shows considerable promise for integration in SLAM algorithms due to its ability to localize accurately point-like features that do not have to be mapped a priori. The increasing interest in this class of methods may be attributed in part to the emergence in the last few years of sensors such as superconducting quantum interference devices (SQUID) and spin exchange relaxation-free (SERF) magnetometers. These ultra-high sensitivity devices open the possibility of exploring in practice some concepts that could not be tested with the technologies previously available.

A few reports on the utilization of magnetic inversion methods for underwater vehicle tracking have been published recently; however, to the best of our knowledge no experimental results are available; see e.g. Birsan (2006).

3. THEORETICAL FOUNDATIONS AND IMPLEMENTATION OF THE PROPOSED APPROACH

The approach to magnetic navigation proposed here borrows from the theories of classical electrodynamics and geopotential field inversion; see Jackson (1975) and Blakely (1995). It is also inspired by related studies in the geophysics and navigation domains; see, e.g. Wynn et al. (1975); Pedersen and Rasmussen (1990); Reid et al. (1990); Zhang et al. (2000); Schmidt et al. (2004); Kumar et al. (2005); Allen et al. (2005); Heath (2007). This class of methods assumes the existence of anomalous magnetic dipoles in the environment whose sources can be localized using a set of very precise measurements of the magnetic field vector and its gradients. Its potential in terms of navigation is justified by the fact that many geological features in the ocean floor generate magnetic dipoles of large magnitude that can be treated as landmarks and processed by navigation methods such as TAN and SLAM.

3.1 Analytic inversion of magnetic field anomalies

To introduce the method, we consider the problem of localizing a magnetic object characterized by a dipole moment $\mathbf{m} = m_x\hat{\mathbf{x}} + m_y\hat{\mathbf{y}} + m_z\hat{\mathbf{z}}$. See Telford et al. (1998) and the references therein for an introduction to basic concepts in geomagnetism. The magnetic field observed at a point P localized relatively to the dipole center by the vector $\mathbf{r} = r_x\hat{\mathbf{x}} + r_y\hat{\mathbf{y}} + r_z\hat{\mathbf{z}}$ with modulus $r = |\mathbf{r}|$, is

$$B_i = \frac{\mu_0}{4\pi}\left[\frac{3(\mathbf{m} \bullet \mathbf{r})}{r^5} r_i - \frac{m_i}{r^3}\right], \quad (i = x, y, z) \ . \qquad (1)$$

The gradient of the vector field is a tensor defined by

$$\mathbf{T} = \begin{bmatrix} \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial y} \\ \dfrac{\partial}{\partial z} \end{bmatrix} [\, B_x \ B_y \ B_z \,] = \begin{bmatrix} B_{xx} & B_{xy} & B_{xz} \\ B_{yx} & B_{yy} & B_{yz} \\ B_{zx} & B_{zy} & B_{zz} \end{bmatrix} \qquad (2)$$

and using (1), each element B_{ij} of $\mathbf{T}$ has the form (see Heath (2007))