Robotics and Autonomous Systems 67 (2015) 61–71

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Experiments on sampling/patrolling with two Autonomous Underwater Vehicles

Alessandro Marino [a,*], Gianluca Antonelli [b]

[a] Dipartimento di Ingegneria dell'Informazione, Ingegneria Elettrica e Matematica Applicata, Università degli Studi di Salerno, Via Giovanni Paolo II, 132, 84084, Fisciano (SA), Italy

[b] Dipartimento di Ingegneria Elettrica e dell'Informazione, Università degli Studi di Cassino e del Lazio Meridionale, Via Di Biasio 43, 03043, Cassino, Italy

HIGHLIGHTS

- A patrolling/sampling strategy for cooperative AUVs is developed.
- Gaussian Processes and Voronoi tessellations are used as main tools.
- Realistic constraints, decentralization and robustness are main features.
- Experiments on a two underwater vehicles setup.

ARTICLE INFO

Article history:
Available online 16 October 2014

Keywords:
Underwater robotics
Autonomous Underwater Vehicles
Patrolling
Surveillance
Robot cooperation
Monitoring

ABSTRACT

In this paper, an experimental investigation of the sampling/patrolling tasks by means of cooperative underwater vehicles is presented. Both in the case of sampling and patrolling, the mission consists in periodically visiting proper locations of the environment in order to estimate the field of interest or check for unexpected events. In previous work of the same authors, it has been shown that these tasks can be addressed by a proper combination of Gaussian Processes and Voronoi tessellation tools. The Gaussian Processes allow to put these tasks in a probabilistic framework, while the Voronoi tessellation allows to distribute the overall strategy as well as the handling of asynchronous communication or possible loss or adjunct of vehicles. The approach was already tested in simulation by varying all the parameters of interest as well as on a set-up composed by three marine surface vehicles. In this paper, experiments are extended to the still challenging scenario of Autonomous Underwater Vehicles (AUVs) communicating by acoustic modems and moving in the 3D space. The experiments were run in the La Spezia harbour, in Italy, as demo of the European project Co^{3}AUVs.

1. Introduction

The application of autonomous mobile networks of robots and sensors to the underwater domain could have great potential for monitoring the marine environments. Here, monitoring is used as general term including applications as, for example, temperature or salinity field reconstruction or surveillance [1,2]. All these activities are extremely difficult, costly and potentially dangerous for humans. For these reasons, underwater applications would receive great benefit from the use of multi-robot systems able to perform the mission for a long time and over a large area. However, performing cooperative underwater mission is still a challenge due to the technological limits mainly related to the underwater localization and inter-vehicle communication. Beyond the theoretical issues, this aspect poses additional constraints in the algorithm design phase that need to be handled in a comprehensive way.

Sampling spans the fields of ecology, earth science, statistics, diagnosis, and robotics. The general aim of sampling is to determine the minimum set of sampling locations to characterize a given phenomenon. It consists in acquiring samples of a given field (e.g., salinity, temperature) at proper locations in order to estimate the overall field also in locations where no samples were taken. The particular field and the locations from where these samples are acquired determine the reconstruction error. If the field is time-varying, then, it is necessary to repeatedly sample the environment. In the underwater scenario, this problem has increasingly

* Corresponding author.
E-mail addresses: almarino@unisa.it (A. Marino), antonelli@unicas.it (G. Antonelli).

http://dx.doi.org/10.1016/j.robot.2014.09.030
0921-8890/

gained interest in the last decades mainly due to the recent improvements in the autonomy of the underwater vehicles.

On the other hand, the patrolling task consists in travelling around an area, at regular intervals, in order to protect or supervise it [3]. Patrolling, thus, involves repeatedly visiting key locations within the working area, to assess environmental state with respect the presence of eventual intruders or any unexpected event. Sampling and patrolling, thus, share several common aspects. In both cases, the vehicles need to properly choose locations to sample/visit inside the working area. As a consequence, both tasks can be handled under the same mathematical framework.

Despite the fact that the sampling and patrolling tasks have been widely faced in literature from a theoretical point of view, only a few experiments have been carried out, especially in an underwater scenario, without simplistic assumptions due to the existing technical problems. The marine environment exhibits additional challenges due to the extremely harsh conditions in which the robots need to operate. For this reason, the problem at hand has been afforded with a list of realistic constraints:

- Decentralized algorithm;
- Anonymity among robots;
- Robustness to a wide range of failures such as communications, robot loss or still;
- Scalable with the number of robots;
- Possibility to tailor the algorithm with respect to the communication capabilities;
- Not optimality seek but benchmarking required;
- Implementation on a real resource-limited set-up.

The rational is described in detail in Section 4.1.

To the purpose, the strategy proposed in this paper merges together two useful mathematical tools: Gaussian Processes and Voronoi tessellation. Given acquired samples, the Gaussian Processes [4] allow to predict the field at unknown location and to compute the uncertainty involved in that prediction [5]. Gaussian Processes allow us to address in an elegant fashion the time and space variability, i.e., both a forgetting factor and the need to patrol more often certain regions. Ground breaking work on ocean sampling is described in [6], where autonomous robots carrying environmental sensors are coordinated in order to efficiently sample an ocean region. The Voronoi tessellation represents a subdivision of a set given a finite number of points [7,8]. One of their main features is that they can be calculated in a distributed way. Each robot, thus, is able to compute its Voronoi cell relying only on its exteroceptive sensors and/or communication capabilities.

The paper is organized as follows. Section 2 contains a bibliography review. In Section 3, the underwater vehicles used in the experiments are described in order to highlight the strong constraints imposed by the underwater scenarios. In Section 4, the problem addressed is described together with the designed strategy. Finally, in Section 5 the experimental tests are shown. The latter were run in the La Spezia harbour, in Italy, as demo of the European project Co^{3}AUVs in the facilities of the NATO CMRE (Centre for Maritime Research and Experimentation), formerly known as NURC.

The theoretical background for this paper has been presented in [9]. An experimental implementation with three marine surface vehicles has been detailed in [10,11]. A compact description of this work has been presented in [12]. This paper aims at collecting the results obtained in the papers above, and at showing, in an extensive way, how the designed sampling/patrolling strategy is suitable also for a challenging scenario as the underwater environment.

2. Literature analysis

Tasks such as patrolling or sampling have been widely studied in the past decades, mainly from a theoretical point of view or under *scale* experiments such as laboratory set-up. Few experiments on cooperative underwater vehicles have been performed.

In [13], an analysis of the main patrolling task issues and some multi-agent-based solutions are presented; a very careful analysis was carried out by taking into consideration aspects such as agents type, communication, coordination scheme, perception, decision-making, etc. In [14,15], graph-theory is used to find the optimal solution of a mathematical problem expressing a multi-robot surveillance problem. In [16], the authors analyse non-deterministic paths for a group of homogeneous mobile robots patrolling a frontier, under the assumption of an hostile agent trying to enter the area, where the latter has full knowledge of the algorithm. Recently, in [17] a polynomial time algorithm for the minimum refresh time problem was developed. In [18], a patrolling strategy of a linear border based on a Finite State Automata approach is designed and experimented. To the best of authors' knowledge no patrolling solution for cooperative underwater vehicles was proposed so far.

As mentioned earlier, sampling problems benefit from the use of the Gaussian Processes theory. Within this framework, significant contribution is given by [19] where a proper scalar index function is proposed and optimized by a gradient-based, distributed, discrete-time approach in the case of static fields. The above cited papers exploit the mathematical properties of the centroidal Voronoi partitions [20]. In [21] a series of algorithms for adaptive sampling with communication constraints expressed in terms of connectivity of the graph of the vehicles is proposed.

Concerning underwater experiments, however, most of the work done involve only one vehicle or, when several are into play, the coordination among vehicles is not fully exploited. The main reason behind that lies in the difficulties arising in underwater communication. In [22], a fleet of underwater gliders is coordinated for sampling purposes. A virtual bodies and artificial potentials (VBAP) based strategy is adopted. In their implementation, way-points are generated from the discretization of continuous trajectories that represent the VBAP algorithm output running on a centralized unit, which assumes vehicles moving at constant speed. The vehicles do not communicate between them and need to surface to acquire the new way-point list. In [23], a metric is defined for adaptive sampling and the strategy is applied to a fleet of gliders that can move along particular path properly parametrized. Communication among gliders for feedback control law calculation is done above the surface via a central data hub. In [24], a glider coordinated control system is designed. Gliders periodically surface to connect via satellite or radio frequency communication to a ground station. While on the surface, gliders transmit measured data and receive new way-points, which are the coordinates of their next destinations. Vehicles move along a predefined path template. Experiments are carried out on a set-up of 6 gliders moving in a 2D scenario. In [25], a cooperative control algorithm for heterogeneous underwater vehicles and static sensor nodes in an underwater environment is shown. The elements are mainly networked optically, and the focus is on the algorithmic and systems issues related to an effective vehicles' cooperation. Experiments are conducted with two AUVs for robot rescue, cooperative motion and cooperative data collection tasks. In [26], an algorithm to determine relevant points of interest for a chosen oceanographic feature was presented for a 2D scenario. Also in this case, the proposed solution is tested on a single glider set-up. In [27], the relevant information about the underwater environment is not collected based an a priori defined path, but an adaptive sampling paradigm is defined. The AUV is able to interpret some of the payload data in order to change the sampling pattern and concentrate measurements in the regions of interest. Experiments involving a small AUV in a thermocline tracking manoeuvre is shown. In [28], an ocean sampling network of 10 gliders was deployed in the Monterey Bay,