The EU project RAMONES – continuous, long-term autonomous monitoring of underwater radioactivity

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Abstract: While radioactivity has always existed in the marine environment due to natural phenomena, artificial sources have made their way into the oceans more recently, either through low-level liquid discharges from reprocessing plants, more threatening large-scale spills due to nuclear disasters, or smaller-scale radiological events. Unchecked, radioactivity poses life-threatening risks to marine ecosystems and, ultimately, to humanity. Notwithstanding, radioactivity in the oceans is, to a very large extent, undersampled. The main goal of the RAMONES project is to offer a novel systematic solution for long-term, continuous in situ monitoring of radioactivity in the oceans, contributing also towards novel environmental intelligence policies. In this communication, an overall in-depth description of the overall robotic architecture is offered. This includes a fleet of an autonomous surface vehicle, two autonomous underwater gliders, and a static benthic laboratory, all equipped with radiological instruments: high resolution instruments installed on the fixed node and gamma-sniffers onboard the mobile nodes.

Key words: adaptive sampling, autonomous vehicles, environmental intelligence, radioactivity, underwater monitoring.

1. INTRODUCTION

Water masses, covering more than two thirds of the planet’s surface, are of vital importance to the sustainability of human life. In many ways, oceans and seas regulate our climate: they absorb heat in some regions and transport it elsewhere, effectively distributing heat across the planet. Without this planet-wide regulation system, the weather would be extreme in many regions, and some would even be uninhabitable. The oxygen/carbon dioxide balance is also largely maintained by the oceans. While it is popular belief that rainforests are the main producers of oxygen, scientists estimate that more than half of the oxygen production occurs in the oceans, with highest estimates reaching 80%. Unsurprisingly, oceans also play a key role in the carbon cycle: scientists estimate that the oceans absorb between 30 to 50% of the CO2 produced by the burning of fossil fuel. Water masses also hold an important part of the planet’s biodiversity and, in effect, are also becoming a very important source of food for the ever-increasing Earth’s population.

Radioactivity in marine environments has always been present since the formation of Earth through the so-called naturally occurring radioactivity materials. This kind of radioactivity usually refers to isotopic chains originating from long-lived uranium and thorium isotopes, posing a low but long-term risk in ecosystems. In the last century, artificial radioactivity found its way into the oceans. Common sources include low-level liquid discharges from reprocessing plants, large-scale releases due to natural disasters, and smaller-scale radiological events, such as nuclear vessels wrecks or marine disposal of nuclear material. Anthropogenic radioactivity potentially poses significant health risks. Yet, worldwide monitoring of radioactivity in marine environments is poor and limited to very few sites.

The H2020 EU project RAMONES - Radioactivity Monitoring in Ocean Ecosystems – will design, develop, and validate a novel systematic solution for long-term, continuous in situ monitoring of radioactivity in the oceans, contributing also towards novel environmental intelligence policies. Highly multidisciplinary, several key sub-objectives will be addressed, including: i) the design, development, and validation of a broad set of novel instruments for measuring underwater radioactivity; ii) the design, development, and validation of novel collaborative, adaptive, and self-aware marine robots for efficient operation and sensing using new marine radiometry instrumentation; iii) the design, development, and validation of novel environmental modelling methodologies for processing and modelling of marine radioactivity multi-modal data; iv) the introduction of novel monitoring and response channels to inform key socio-political stakeholders at regular intervals, effectively contributing to raising environmental intelligence; and v) the increase of local/citizen awareness and involvement in environmental intelligence issues, through scientific evidence and FAIR data principles.

From a macroscopic point-of-view, the RAMONES concept is composed of a set of radiological instruments installed on-board: i) a static benthic radiological laboratory, deployed on the seabed; ii) two autonomous underwater gliders (AUGs); and iii) one autonomous surface craft (ASC). These autonomous vehicles, equipped with novel radioactivity sensors, effectively constitute a disruptive and innovative concept to autonomously and adaptively monitor radioactivity in underwater environments through sensing, communication, control, and adaptation. A simplified sketch of the nodes of the proposed concept is depicted in Fig. 1. In this communication, an overview of the envisioned robotic architecture is provided.

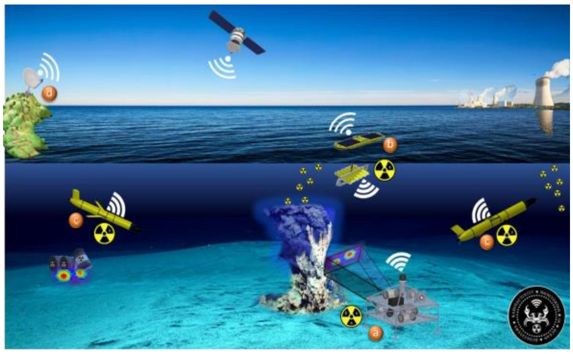

Fig. 1. A simplified sketch of the nodes of the RAMONES concept.

2. ROBOTIC ARCHITECTURE

The proposed robotic architecture consists of three mobile nodes – one autonomous surface ship and two autonomous underwater gliders – and a fixed node – a static benthic laboratory. To the purpose of fulfilling the scientific mission requirements, all these nodes are equipped with heterogeneous radiological instruments, which offer precious information to guide the system. The focus of this communication is on the robotic aspect of the system.

In the envisioned architecture, each node has well-defined objectives, as follows. The autonomous surface craft, typically an autonomous sailboat, serves as a communication relay node. Moreover, equipped with a positioning system, it is effectively part of the navigation system of the AUGs. Confined to the surface, if offers radiological measurements of the top layer of the water column. The AUGs are mobile sensing nodes that dwell on the water column, typically through yo-yo movements along the vertical plane. To georeference the acquired data, as well as to enable automatic control, navigation data is essential, hence these vehicles are also equipped with navigation aids. The benthic laboratory, in additional to sensing capabilities, is also equipped with positioning systems to aid the mobile nodes. It is important to remark that the choice of the vehicles is not innocent. Indeed, AUGs potentially offer much greater autonomy than standard propelled autonomous underwater vehicles. The same applies to autonomous sailboats.

In what concerns the robotic system, and considering high-level objectives, there are essentially two key technological challenges: i) cooperative navigation of multiple autonomous marine vehicles; and ii) adaptive motion planning and cooperative control. A simplified sketch of the commands, control and navigation network is depicted in Fig. 2.

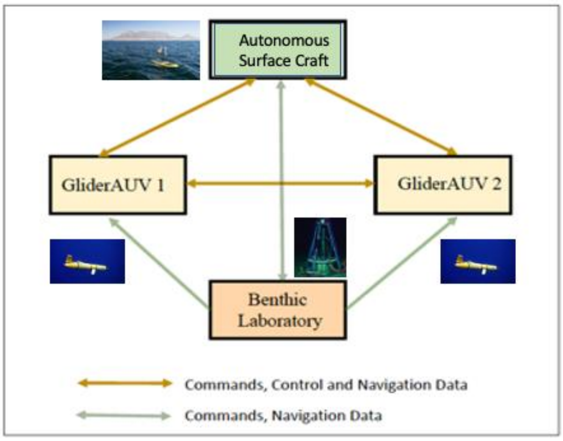

Fig. 2. The RAMONES commands, control, and navigation network

2.1. Cooperative navigation

The navigation system of a (possibly autonomous) vehicle is responsible for determining estimates of its position, attitude, and linear and angular velocities, effectively answering questions like: i) where is the vehicle? ii) where is the vehicle pointing to? iii) how fast is the vehicle moving? and iv) how fast is the vehicle turning? In certain scenarios, the navigation system also provides estimates or measurements of additional quantities, e.g. ocean and/or wind currents, relative velocity to the fluid, etc.

Global navigation satellite systems (GNSS), like the global positioning system (GPS) or GALILEO – the

European global navigation satellite system, offer precise cheap positioning, when available, and are typically the preferred choice. In this project, the navigation system of the ASC will be based on GNSS. Nevertheless, to improve its precision, other sensors will be considered, e.g. accelerometers, an attitude and heading reference system, and wind sensors. Using filtering/estimation algorithms, the information acquired by the sensor suite will be fused, in real-time, to obtain not only filtered estimates of already sensed quantities but also estimates of quantities that are not directly measured. In (Vasconcelos et al., 2011) a navigation system developed for the DELFIMx catamaran, an ASC developed at the Institute for Systems and Robotics – Lisboa / Institute Superior Técnico is experimentally evaluated. This navigation system, based on complementary filtering, fuses strapdown inertial measurements, vector observations, and GPS, providing attitude estimates in Euler angles representation and position estimates in Earth frame coordinates, while compensating for rate gyro bias.

The navigation system of the AUGs is considerably more complex due to several reasons. First, GNSS is unavailable underwater due to the attenuation of the electromagnetic waves in this medium. Thus, other positioning systems must be considered, the majority of which are based on acoustic signalling. Second, underwater acoustic positioning systems suffer from some serious bottlenecks/intricacies. Indeed, low speed of propagation of acoustic waves in water and multi-path lead to significant challenges, which usually result in low sampling rates. Third, in the particular setting of RAMONES, strict energy constraints must be met in order to empower the AUGs with greater autonomy. Thus, instead of periodic sensing, appropriate on-demand requests may be considered. Fourth, high-accuracy dead-reckoning systems are not an option due to their size, weight, cost and power characteristics.

In the envisioned scenario, a flexible setting is considered, whereby all vehicles are equipped with full ultra-short baseline (USBL) accousting positioning systems, composed of USBL heads (with USBL receiver array heads) and transponders. In optimal conditions, the USBL acoustic positioning systems are able to determine the position of the transponders with respect to the USBL heads, expressed in their reference coordinate frames. Since all vehicles are equipped with these, all vehicles will be able to determine the positions of their neighbours with respect to themselves. Through communication, and using the ASC as the inertial position provider, all vehicles are able to determine their own inertial positions. In sub-optimal conditions, the USBLs gather only inter-distance measurements between the vehicles, effectively constituting a ranging system. While this mode offers much less information, it is still of great use in improving the accuracy of the navigation system of the AUGs in the absence of position measurements.

Examples of USBL-based navigation systems for position and velocity determination with full positioning measurements can be seen in (Batista et al., 2010) and (Morgado et al., 2011), whereas in (Morgado et al., 2012) a solution for attitude estimation taking advantage of USBL position measurements is proposed. The Kalman filter is the workhorse of these solutions, all offering, under very mild assumptions, theoretical guarantees of global convergence and stability – key properties for autonomous, safe operation.

The scenario with range-only measurements is considerably more complex due to the nonlinear nature of these measurements and the fact that the system is not instantaneously observable. In fact, some persistency of excitation condition must be met, through sufficiently rich trajectories, such that the resulting estimation error dynamics are globally stable and convergent. Pioneering examples of single-range and multiple-range navigation systems for single vehicles can be found in (Batista et al., 2011) and (Batista et al., 2014), where vehicles in tandem and formations were considered in (Viegas et al., 2014) and (Viegas et al., 2016).

The envisioned cooperative navigation system for the AUGs will take advantage of the flexibility offered by the USBL positioning systems installed on-board all vehicles and will switch between different modes of operation, depending on the conditions of operation (position vs. range measurements) and energy constraints (periodic sampling vs. on-demand position/range requests). The ASC will provide inertial references through communication and simple kinematic/dynamic models will be considered for the AUGs, for dead-reckoning purposes, possibly considering the presence of inertial sensors installed on-board the AUGs. Self-driven or event-driven control techniques will be employed to balance the estimation error covariance and the energy consumption.

2.2. Adaptive motion planning and cooperative control

The RAMONES project requires the concerted operation of an ASC and 2 AUGs to detect and map the extent of radioactive sources underwater. For this purpose, besides the cooperative navigation system described previously, the RAMONES mini-fleet of vehicles will be equipped with the systems responsible for: i) generating search paths on-line (adaptive or event-driven motion planning, where the events are the occurrence of radioactivity levels above the background level) and ii) performing cooperative motion control, whereby the vehicles maneuver in synchronism to follow desired paths, based on the navigation data acquired on-line and by exchanging control-related data over the underlying acoustic communication network. The methodologies developed will build upon extensive work done at the Institute for Systems and Robotics / Instituto Superior Técnico over the years on motion planning and cooperative motion planning of autonomous air, surface, and underwater vehicles, see for example (Kaminer et al., 2017), (Rego et al., 2019), (Cichella et al., 2021) (Simetti et al., 2020), (Hung et al., 2020), (Hausler et al., 2016) and the references therein. Special emphasis will be placed on the use of event-driven cooperative motion control algorithms with a view to substantially reduce the amount of information exchanged among the heterogeneous vehicles (Hung et al., 2020).

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