Guidance and Navigation Software for Autonomous Underwater Explorer of Flooded Mines

Zorana Milošević, Ramon A. Suarez Fernandez, Sergio Dominguez, Claudio Rossi

Centre for Automation and Robotics UPM-CSIC, Universidad Politécnica de Madrid, Calle de José Gutiérrez Abascal, 2, 28006, Madrid, Spain, zorana.milosevic@upm.es

Abstract

There are a vast number of abandoned old flooded mines in Europe, with inadequate information of their current status. Exploring and surveying such mines is both unfeasible and hazardous for human divers. UX-1 is an autonomous robotic platform for survey and exploration of such mines. In this work, we present the design, implementation and testing of the guidance and navigation system of UX-1. The system has been tested using a software-in-the-loop and hardware-in-the-loop techniques, and in a real mine environment.

Keywords: underwater robots, flooded mines, mine exploration

Introduction

The total number of flooded mines in Europe is unknown. The estimations range from 5000 up to 30000. Many of such mines may still have considerable amounts of raw materials and minerals that were disregarded during the operational lifetime of the mines due to low commercial value that made their further exploitation economically unfeasible. An example of these materials is fluorite, which until recently was considered a waste mineral in many lead-zinc mines but now is on the EU list of critical raw materials (European Commission, 2017). The dependency on the import of the raw materials, geological uncertainty, growing costs of exploration, technological and economic feasibility of mine development are problems for which the EU is actively trying to find a solution.

After the discontinuance of mining activities, the maintenance systems stopped, the dewatering pumps were turned off and if there was no drainage system present, the closed mines tended to get flooded. The database developed by European Federation of Geologists (EFG) counts 8174 flooded metallic mines deeper than 50 meters, distributed in 24 different European countries. The last available information regarding the status and layout of many of those mines dates from decades (and in some cases from even more than one century) ago, resulting in a rather incomplete and imprecise data. Additionally, the depth of those mines poses severe limitations on the possibilities of their exploration, since human cave diving can be dangerous or even lethal in harsh deep mine conditions.

For the above mentioned reasons, robotics imposes itself as a good solution for a non-invasive flooded mine exploration. By using an autonomous robotic system for gathering valuable geoscientific and spatial data, the strategic decisions on re-opening abandoned mines can be supported by real data which cannot be gathered in any other way.

The serious development of autonomous underwater vehicles (AUVs) began in the 1970s. They have shown a big potential for a variety of tasks, including oceanographic surveys, sea floor mapping (Iscar et al. 2018) and air crash investigations, such as the use of AUV ABYSS and Bluefin-21 AUV in search of missing airplanes Air France Flight 447 and Malaysia Airlines Flight 370 (Geomar 2009; LeHardy 2014). Most of the mentioned applications relate to open water environment, which imposes almost no restrictions on the size and shape of the robot.

One of the first autonomous system to explore and map a subterranean cavern was DEPTHX robot. During its deployment in 2007 the vehicle explored four cenotes in Sistema Zacatón in Tamaulipas, Mexico (Gary et al. 2008). The operating environment allowed the limitation-free design with no

Figure 1 *The UX-1 robot.*

Table 1 *Characteristics of the UX-1 robot.*

Features	Specification
Hull dimension	Sphere 0.6 m diameter
Weight	≤ 106 kg
Maximum speed	0.5 m/s
Maximum operating depth	500 m
Maximum pressure	50 bar
Autonomy	≤ 5 hours

substantial restrictions on the size of the robot.

The project UNEXMIN investigates the utilization of the capabilities of a fully autonomous underwater vehicle for exploration and 3D mapping of flooded mines. Considering that the dimensions of the tunnels can be as narrow as 1.5m, the robot must be small and have high maneuverability to be able to navigate through them. The developed UX-1 is a robot specifically tailored for abandoned mine exploration, designed taking into account the aforementioned space limitations (Figure 1). The robot needs to be able to fit into small mine openings, to resist high pressure when operating at a certain depth and to avoid getting entangled with obstacles such as ropes or cables encountered during the operation. The main characteristics of the UX-1 robot are briefly outlined in Table 1.

Autonomous mapping of underwater mines is a relatively new and challenging task. The main problem is the localization and navigation due to the attenuation of Global Positioning System (GPS) and radio-frequency signals. These limitations coupled with the harsh and unstructured nature of the underwater environment are the cause of the limited number of real working robots for the case of mine exploration.

This paper describes the navigation and guidance software architecture embedded in the UX-1. This system has been tested in a controlled environment using a software-in-the-loop (SIL) and hardware-in-the-loop (HIL) techniques, and in the real mine.

Robot hardware architecture

The mechanical design of UX-1 is chosen to meet certain requirements, to wit: high maneuverability, minimum drag, reduced size, and long autonomous missions (Zavari et al. 2016). Its spherical shape of 60 cm in diameter is chosen in order to satisfy the two first requirements. Furthermore, the spherical design allows translation symmetry in all directions without changing the heading of the UV. The hull is a machined aluminum pressure hull designed to endure water pressure up to 50 bar. The robot is equipped with a ballast system for driving through long vertical shafts up to 500 m. Moreover, the robot has a pendulum system which uses batteries as weight to produce the pitching movement which is otherwise not possible with the current thruster configuration.

The instrumentation that the robot carries can be roughly divided into two categories: navigation equipment necessary for basic robotic functions and scientific instrumentation for collecting geological data. The first group includes thrusters, an inertial measurement unit (IMU), a Doppler Velocity Log (DVL), a structured light system (SLS), a multibeam profiler sonar (Kongsberg M3), pendulum and ballast systems, batteries and a computer. The second group contains a water sampler, conductivity and pH measuring units, a sub-bottom profiler, a magnetic field measuring unit, UV fluorescence imaging and multispectral imaging units. As it can be noted, only indirect geological data collection methods are included, due to the special environmental characteristics that make it impossible the direct contact with the surrounding of the probe. The detailed configuration of the sensor instrumentation is out of the scope of this paper.

Robot software architecture

The software is organized modularly into four modules: Sensor Fusion (SF), *Simultaneous Localization and Mapping* (SLAM), Low-Level Control (LLC), and Guidance, Navigation and Control (GNC), whose interactions are depicted in Fig. 2a. Each module is developed by a different team of developers, so special attention has been devoted to the interface between them to ensure a smooth integration. We refer the reader to the Deliverable 3.1 of the project[1] for further details.

The Robot Operating System[2] is chosen as a middleware (an abstraction layer between the hardware and the software) due to its modularity, good hardware support (drivers) and its messaging system which simplifies the communication between different modules of the software.

The SF module is responsible for providing pose and perception, while using the components of SLAM module. Internally, this module is composed by three submodules: Pose Estimation, Sensor Perception and Data Acquisition and Registration (acquiring the data from all the sensors).

The SLAM module receives Pose and Perception information (provided by the SF module) and provides corrected map data and global localization of a robot.

The LLC module is a simple module consisting of two monolithic programs running the two microcontrollers which, according to the low-level commands received, directly control the actuators.

The GNC module will be explained in the next section and the rest of the paper will be focused on this module, in particular, the robot autonomous guidance and navigation system.

Guidance and Navigation Software Architecture

In order for a robot to accomplish a task, it needs to "understand" the environment, i.e. what it looks like and where the robot is therein. A map is a representation of the environment and it should contain enough information for a robot to accomplish the tasks of interest.

The GNC module has four main submodules: *Mission Planner, Guidance, Navigation, and Control*. These submodules depend on the Sensor Fusion and the SLAM from which the GNC module obtains the map, robot pose, and robot global

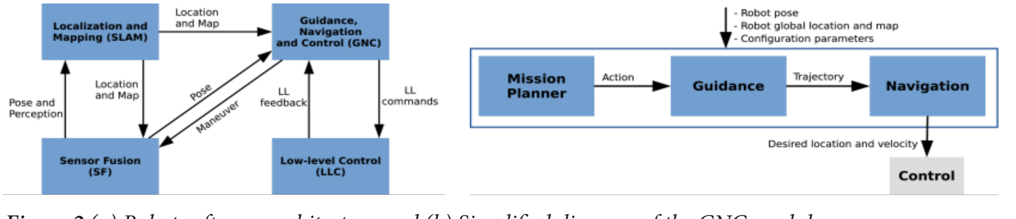

Figure 2 (a) Robot software architecture and (b) Simplified diagram of the GNC module.

1. http://www.unexmin.eu/public-deliverables/
2. ROS, https://www.ros.org/

localization. In Fig. 2b a simplified diagram of the GNC module architecture is depicted. The rest of the paper focuses on the first three submodules; the Control module is out of the scope of this paper.

The Mission Planner is the highest level submodule in charge of configuring the overall strategy. This module takes as an input a set of planned actions, which depend on whether the mine has already been explored and mapped. In the case of an unknown map, the action is explore, and if the map is known and available, the action is go to point. The go to point action is comprised of a goal location and possibly a science goal, such as water sampling or gamma-ray measuring. The actions are fed sequentially into the guidance submodule.

Guidance submodule has different behaviors depending on the action. In the case of the go to *point*, this submodule extracts the goal location from the action. If the action is *explore*, the goal location is computed taken into account constraints such as the duration of the mission and/or spatial coverage. Once the goal location is known, the submodule plans the trajectory to move the robot from the current to the goal location taking into account the kinematic restrictions of the robot and the positional requirements of the scientific data collection action. An example of a scientific data collection action imposing a specific positional requirement is multispectral image capture, which requires maintaining a certain distance to the mine wall during the operation.

The calculated trajectory in a form of waypoints is further sent to the Navigation submodule. This submodule generates velocity profiles, i.e. a waypoint and the information on how to traverse it with respect to time, which are finally transformed into low-level control commands by the Control submodule.

In Figure 3, a high level description of algorithmic steps performed by the Mission Planner, Guidance and Navigation submodules is depicted.

Results

Testing the described software architecture is challenging because of its complexity and various groups being involved in its development making the robot not always available for each group. Furthermore, real experiments can be expensive, time-consuming, dangerous, or even impossible to test under all conditions. Therefore, in order to evaluate our GNC module we have performed a series of tests gradually increasing the complexity of them. Firstly, using a Software-in-the-loop (SIL) technique, then Hardware-in-the-loop (HIL) and finally in a real mine. In Fig. 4, a visual description of the SIL and HIL is depicted.

For the SIL tests, the simulated modules are SLAM, SF, and LLC. Gazebo simulator[3] is used for modeling the dynamics of the robot and the sensor data. All the inputs to the GNC modules are simulated and its output, LL commands, is sent to the Gazebo which controls the simulated robot. The advantage of the SIL is possibility to test GNC module with various mine structures without having the real robot in our hands.

For the HIL tests, the actual robot is used and the experiments were performed in the pool with the dimensions 10×6×5 m. The simulated module is SLAM and partially SF, while the LLC is real. The real inputs to the GNC module are LL feedback and robot position. The sensors related to the map building are simulated and its readings are inputted from Gazebo. The advantage of this tests is using the real robot in the controlled environment with low risks of damaging the equipment while bypassing the readings of some sensors for map building in order to simulate different mine structures.

In Fig. 5, two examples of different mine structures are shown. The structure on Fig. 5a has been used for the HIL tests and is designed as a scaled prototype of the uranium mine Urgeirica in Portugal with the dimensions fitting the available pool for testings. The structure on the Fig. 5b has been used in the SIL tests which poses no limitations on the size of the mine structures. It represents a real sized mine Kaatiala in Finland where the first field trials took part.

In Fig. 6 an example of the trajectory planning is depicted. In Fig. 6a, a current

3 GAZEBO http://gazebosim.org/

Configuration parameters:
Set of actions
Resource constraints

Repeat:
For i = 1 to number_of_actions
Get action i from set of actions
If action is explore
Compute goal location
Else if action is go to point
Extract a goal location from action
Plan the trajectory from the current to the goal location
Send the calculated trajectory to the navigation submodule

If action has science goals
Complete a required science goal

Exception:
If there is emergency
Stop any action and solve the emergency

Figure 3 *High level description of the Mission Planner, Guidance and Navigation submodules.*

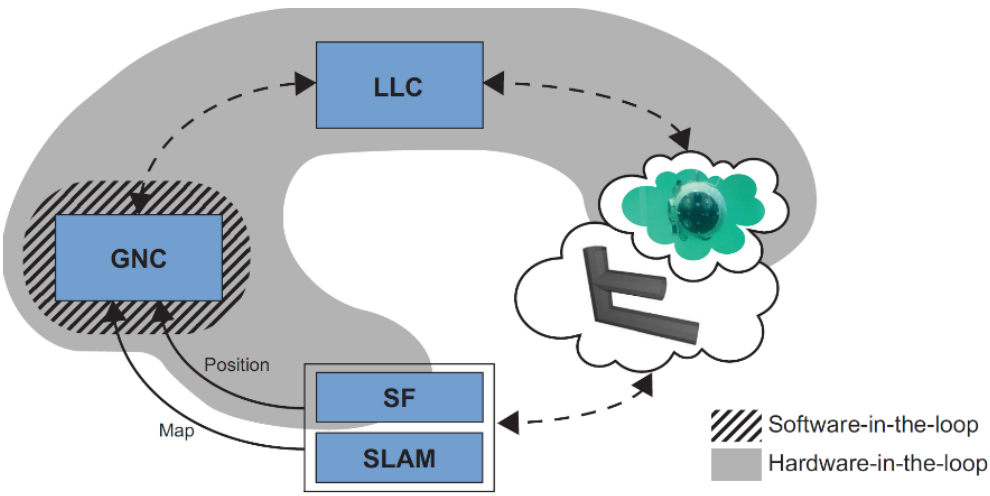

Figure 4 *SIL and HIL.*

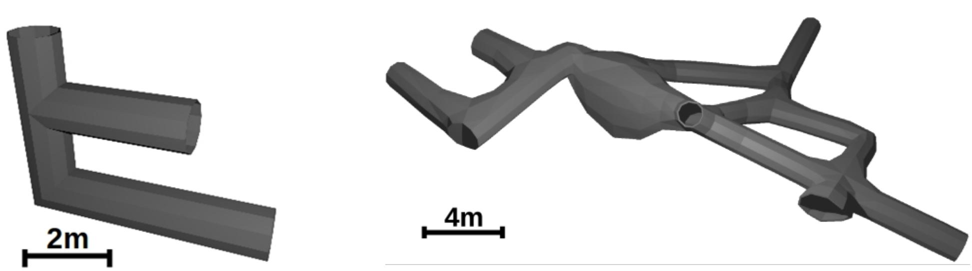

Figure 5 *Mine structures used in (a) Hardware-in-the-loop and (b) Software-in-the-loop testings*

position of the robot inside the mine is shown. In Fig. 6b, a computed map of the mine and the planned trajectory is depicted, while on the Fig. 6c the same planned trajectory is shown but without the map for easier visualization.

Conclusions and Future Work

This paper introduces the autonomous robotic platform UX-1 developed in the European project UNEXMIN for underwater exploration of flooded abandoned mines. Special emphasis is placed in the link between the stringent operational conditions that such a hostile environment represents and the decisions, regarding both the physical characteristics of the robot and its software architecture, made during its design phase.

The details provided in this paper focus on the submodules responsible for robot guidance and navigation, and on the different incremental frameworks deployed to test them. In such incremental test frameworks different parts of the of architecture of the complete robotic platform are substituted for simulations, allowing therefore to test all the

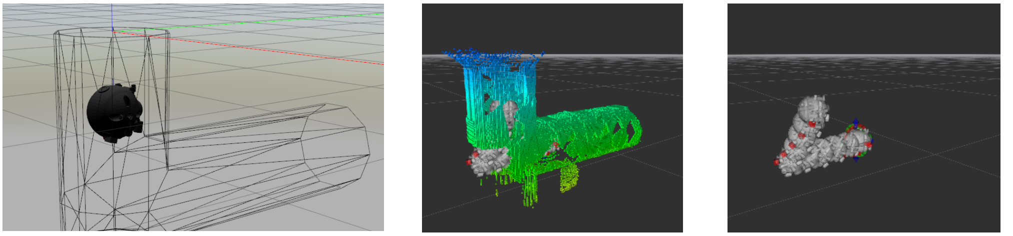

Figure 6 Example of trajectory planning (a) Current position of the robot (b) Built map and the planned trajectory (c) View without the visualization of the map.

interactions and communications between the guidance and navigation submodules and the rest of modules of the system in different development stages of the complete platform. In this way, testing at three different levels of completeness is designed and run, wherein testing the complete software and hardware platform in a real mine represents the last and final operational level in the development of UX-1. Results of partially simulated architectures and preliminary results corresponding to the complete platform level are presented in this paper. Future campaigns in several abandoned flooded mines are planned (Urgeirica uranium mine in Portugal and Ecton copper mine in UK), which will soon lead to an extensive evaluation of the complete platform in different mines with different peculiarities and specific details.

Acknowledgements

The UNEXMIN project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 690008. The authors thank M. Pici for the help with the review of the paper.

References

European Commission (2017) Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions on the 2017 list of Critical Raw Materials for the EU. COM (2017) 490 final, Brussels

Gary M, Fairfield N, Stone WC, Wettergreen D, Kantor G, Sharp JM (2008) 3-D mapping and characterization of Sistema Zacatón from DEPTHX. In: Geotechnical Special Publication. p 202-212

Geomar – AUV Abyss – www.geomar.de/en/centre/central-facilities/tlz/auv-abyss/1986/chronology-auv/ Accessed 2019-02-02

Iscar E, Barbalata C, Goumas N, Johnson-Roberson M (2018) Towards low cost, deep water AUV optical mapping. In: Oceans MTS/IEEE Charleston, SC, doi: 10.1109/OCEANS.2018.8604772

LeHardy PK, Moore C (2014) Deep ocean search for Malaysia airlines flight 370. In: Oceans – St. John's, NL, doi: 10.1109/OCEANS.2014.7003292

Thrun S, Thayer S, Whittaker W, Baker C, Burgard W, Ferguson D, Hahnel D, Montemerlo D, Morris A, Omohundro Z, Reverte C, Whittaker W (2004) Autonomous exploration and mapping of abandoned mines. IEEE Robotics Automation Magazine 11(4):79-91. doi: 10.1109/MRA.2004.1371614

Zavari S, Heininen A, Aaltonen J, Koskinen KT (2016) Early stage design of a spherical underwater robotic vehicle. In: 20th International Conference on System Theory, Control and Computing. IEEE,pp240–244