Universitat de Girona

Doctoral Thesis

COMPACT ROUTING FOR CAYLEY GRAPHS

DANIELA AGUIRRE GUERRERO

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2018

Doctoral Program in Technology

Supervised by:
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Thesis submitted to the University of Girona in fulfillment of the requirements for the degree of Doctor of Philosophy

CERTIFICAT DE DIRECCIÓ DE TESI

Dr. Pere Vilà Talleda and Dr. Lluís Fàbrega Soler, del Departament d'Arquitectura i Tecnologia de Computadors de la Universitat de Girona,

DECLAREM:

Que el treball titulat Compact Routing for Cayley Graphs, que presenta Daniela Aguirre Guerrero per a l'obtenció del títol de doctor, ha estat realitzat sota la nostra direcció i que compleix els requisits per poder optar a Menció Internacional.

I, perquè així consti i tingui els efectes oportuns, signem aquest document.

Girona, Juliol 2018

Dr. Pere Vilà Talleda

Dr. Lluís Fàbrega Soler

PUBLICATIONS

The work developed in this thesis led to the following publications:

JOURNAL ARTICLES

[1] **D. Aguirre-Guerrero**, M. Camelo, P. Vilá and Ll. Fábrega, "WMGR: A Generic and Compact Routing Scheme for Data Center Networks," in *IEEE/ACM Transactions on Networking*, vol. 26, no. 1, pp. 356-369. Feb. 2018. DOI: 10.1109/TNET.2017.2779866

PEER-REVIEWED CONFERENCES AND WORKSHOPS

[1] **D. Aguirre-Guerrero**, M. Camelo, P. Vilá and Ll. Fábrega, "Compact Greedy Routing in Large-scale Networks using Word-metric Spaces," *1st. International Workshop on Elastic Networks Design and Optimization*, Cartagena, Spain, 2016.

OTHER CONFERENCES AND WORKSHOPS

[1] **D. Aguirre-Guerrero**, P. Vilá and Ll. Fábrega, "Encaminamiento de Información en Redes Comunicación de Gran Escala," *6to. Simposio de Becarios CONACyT en Europa*, Strasbourg, France 2017.

[1] **D. Aguirre-Guerrero**, P. Vilá and Ll. Fábrega, "Greedy Geometric in Word Metric Spaces," *1st. Conference of Pre-doctorals Researches*, Girona, Spain, 2016. ISBN: 978-8-48458-502-2

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ACRONYMS

3D	3-dimensional
OMPL	open motion planning library
DOF	degrees of freedom
ROS	robot operating system
AUV	autonomous underwater vehicle
DVL	doppler velocity log
IMU	inertial measurement unit
USBL	ultra-short baseline
CIRS	Underwater Vision and Robotics Research Center
ViCOROB	Computer Vision and Robotics Institute
COLA2	component oriented layer-based architecture for autonomy
UWSim	underwater simulator
Ifremer	French Research Institute for Exploitation of the Sea
ACE	automated control engine
ISE	International Submarine Engineering

CONTENTS

ABSTRACT

Since their beginning in the late 1950s, the capabilities and applications of autonomous underwater vehicles (AUVs) have continuously evolved. Their most common applications include imaging and inspecting different kinds of structures on the sea floor as well as collecting oceanographic information: biological, chemical, and even archaeological data.

Most of these applications require *a priori* information of the area or structure to be inspected, either to navigate at a safe and conservative altitude or to pre-calculate a survey path. However there are other applications where it's unlikely that such information is available (e.g., exploring confined natural environments like underwater caves). In these scenarios, AUVs must operate in unexplored and cluttered environments, and therefore are more exposed to collisions.

Although these AUV applications share some common requirements with other aerial and terrestrial robots (e.g., localization, mapping, vision, etc.), they are also different in significant ways. Navigating autonomously while conducting these type of tasks in underwater environments demands taking into account factors such as: the presence of external disturbances (currents), low-range visibility and limited navigation accuracy. Dealing with such constraints requires a path planner with online capabilities that can overcome the lack of environment information and the global position inaccuracy, especially when navigating in close proximity to nearby obstacles.

In this respect, this thesis presents an approach that endows an AUV with the capabilities to move through unexplored environments. To do so, it proposes a computational framework for planning feasible and safe paths online. This approach allows the vehicle to incrementally build a map of the surroundings, while simultaneously (re)plan a feasible path to a specified goal. To accomplish this, the framework takes into account motion constraints in planning feasible 2D and 3D paths, i.e., those that meet the vehicle's motion capabilities. It also incorporates a risk function to avoid navigating close to nearby obstacles.

To evaluate the proposed approach in different real-world scenarios, a series of trials were conducted with the Sparus II and the AsterX AUVs, torpedo-shaped vehicles that performed autonomous missions. These experiments include simulated and in-water trials in different environments, such as artificial marine structures, natural marine structures, and confined natural environments.

RESUMEN

Desde sus inicios a finales de los años 50, las capacidades y aplicaciones de los vehículos autónomos submarinos o AUVs (por sus siglas en inglés) han estado bajo un continuo proceso de evolución. Las aplicaciones más comunes incluyen la obtención de imágenes e inspeccción de diferentes tipos de estructuras, tales como cascos de barcos, estructuras naturales en el fondo marino, así como la recolección de información oceanográfica como datos biológicos, químicos e incluso arqueológicos.

Muchas de estas aplicaciones requieren información *a priori* del área o estructura que va a ser inspeccionada, ya sea para navegar a una altitud segura o para precalcular un camino para realizar estudios, el cual puede ser corregido o modificado en tiempo real. Sin embargo, existen aplicaciones similares o nuevas, como la exploración de entornos naturales confinados (e.g., cuevas submarinas), donde dicha información puede no estar disponible. En estos escenarios, los AUVs debe operan en entornos desconocidos, y por lo tanto los AUVs están más expuestos a colisiones.

Aunque estas aplicaciones de AUVs comparten algunos requirementos comunes con otras aplicaciones de robots aéreos y terrestres (e.g., localización, mapeo, visión, etc.), navegar autónomamente mientras se ejecutan este tipo de tareas en entornos submarinos difiere en ciertos factores, como la presencia de pertubaciones externas (corrientes), bajo rango de visibilidad y limitaciones en la precisión del sistema de navegación. Para poder abordar dichas restricciones se requiere un planificador de movimientos con capacidad de cómputo en tiempo real, el que contribuya a superar las limitaciones en la información del entorno y la falta de precisión de posicionamiento, en especial cuando se navega cerca de los obstáculos de su alrededor.

En este sentido, esta tesis presenta una método para dotar un AUV con la habilidad para moverse a través de entornos no explorados. Para ello, esta tesis propone un método para calcular en tiempo real caminos factibles y seguros. El método propuesto permite al vehículo construir incrementalmente un mapa del entorno, y al mismo tiempo replaninficar el camino factible hacia la meta u objetivo establecido. Para lograr esto, es necesario considerar las restricciones de movimiento para planificar caminos 2D y 3D que sean factibles o realizables.

Para evaluar el método propuesto, se realizaron diferentes experimentos con los AUVs Sparus II y AsterX, ambos vehículos tipo torpedo que realizaron misiones de manera autónoma en diferentes escenarios. Estos experimentos incluyen pruebas en simulación y en el agua en diferentes entornos, tales como estructuras marinas artificiales, estructuras marinas naturales, así entornos naturales confinados.

RESUM

Des dels inicis a finals dels anys 50, les capacitats i aplicacions dels vehicles autònoms submarins o AUVs (per les seves sigles en anglès) han experimentat un procés d'evolució continu. Les aplicacions més comunes són l'obtenció d'imatges i inspecció de diferents tipus d'estructures, com per exemple, cascos de vaixells o estructures naturals en el fons marí, i l'adquisició d'informació oceanogràfica com dades biològiques, químiques i arqueològiques.

Moltes d'aquestes aplicacions requereixen informació *a priori* de l'àrea o estructura que es vol inspeccionar, ja sigui per navegar a una altitud segura o per calcular en avançat un camí que permeti realitzar els estudis, el qual pot ser corregit o modificat a temps real. No obstant, existeixen aplicacions similars o noves, com l'exploració d'entorns naturals confinats (e.g., coves submarines), on aquesta informació pot ser inexistent. En aquests casos, els AUVs han d'operar en entorns desconeguts, pel que estan més exposats a col·lisions.

Tot i que aquestes aplicacions de AUVs comparteixen alguns requeriments comuns amb altres aplicacions de robots aeris i terrestres (e.g., localització, mapeig, visió, etc.), navegar autònomament al mateix temps que s'executen aquest tipus de tasques en entorns submarins difereix en certs factors, com la presencia de pertorbacions externes (corrents), baix rang de visibilitat i limitacions en la precisió del sistema de navegació. Per poder tractar les esmentades restriccions és necessari un planificador de moviments amb capacitat de processament en temps real, el que ajudi a superar les limitacions en la informació de l'entorn i la falta de precisió de posicionament, en especial quan es navega a prop dels obstacles presents en el seu voltant.

En aquest sentit, aquesta tesis presenta una alternativa per dotar un AUV amb l'habilitat de moure's a través d'entorns no explorats. Per aconseguir aquesta fita, aquesta tesis proposa un mètode per calcular en temps real camins factibles i segurs. El mètode proposat permet al vehicle construir de forma incremental un mapa de l'entorn, i al mateix temps replanificar un camí factible cap a l'objectiu establert. Per assolir això, el mètode proposat te en compte les restriccions de moviment del vehicle per planificar camins 2D i 3D que siguin factibles o realitzables.

Per avaluar el mètode proposat, s'han realitzat diferents experiments amb els AUVs Sparus II i l'AsterX, els quals són vehicles de tipus torpede que van realitzar missions de forma autònoma en diferents escenaris. Aquests experiments inclouen proves en simulació i a l'aigua en diferents entorns, tal i com estructures marines artificials, estructures marines naturals i entorns naturals confinats.

APPENDIX

A EXPERIMENTAL PLATFORMS

The experimental validation of the framework proposed in this thesis has involved two autonomous underwater vehicles (AUVs). While most of those tests were conducted with the Sparus II AUV, the experiments that proved one of the framework capabilities were done with the AsterX AUV. The following sections explain the main software and hardware aspects of both vehicles.

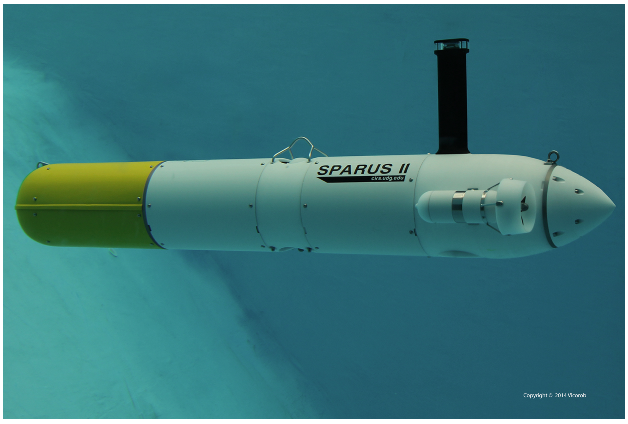
A.1 SPARUS II AUV

The Sparus II is a torpedo-shaped AUV with hovering capabilities, which has been designed and developed at the Underwater Vision and Robotics Research Center (CIRS)[1]. The vehicle is rated for depths up to 200m, and is equipped with three thrusters; two of them are located in the back, and are used for motion on the horizontal plane; the third one is located in the middle, and is dedicated to vertical motion. This implies that the AUV can be actuated in surge, heave and yaw degrees of freedom (DOF). Furthermore, the Sparus II is equipped with a navigation sensor suite that includes a pressure sensor, a doppler velocity log (DVL), an inertial measurement unit (IMU) and a GPS to receive position fixes while at surface.

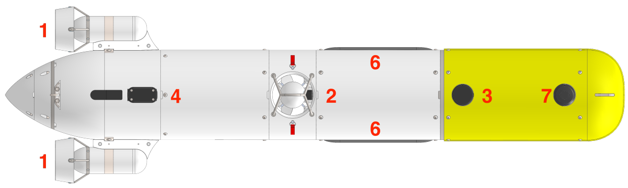
The Sparus II AUV also has communication devices such as an acoustic modem for underwater communication with other vehicles or surface stations (e.g., by using an ultra-short baseline (USBL) system), and a Wi-Fi antenna that can be used when the AUV is at surface. Moreover, the vehicle includes a configurable payload area in the front, which contains a set of exteroceptive sensors to perceive and detect the surroundings. This latter group of sensors can be modified according to the mission's requirements, and may include optical cameras, single-beam echosounders, mechanical-scanning (profiler and imaging) sonars, multibeam sonars, etc. Figure 1 depicts different views of the Sparus II AUV, including one where a possible payload configuration can be observed.

In what software concerns, the Sparus II AUV is controlled through the component oriented layer-based architecture for autonomy (COLA2) [**Palomeras2012**], which is a control architecture that is completely integrated with the robot operating system (ROS). Besides operating aboard real robots, COLA2 can interact with the underwater simulator (UWSim) [**Prats2012**], which can import 3-dimensional (3D) environment models and simulate the vehicle's sensors and dynamics with high fidelity. Furthermore, the use of ROS allows to easily integrate third party tools, such as the open motion planning library (OMPL) that offers a convenient framework that can be adapted to specific path/motion planning problems [**Sucan2012**].

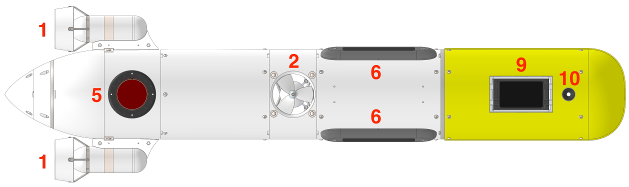
1 CIRS is part of the Computer Vision and Robotics Institute (ViCOROB) in Girona (Spain)



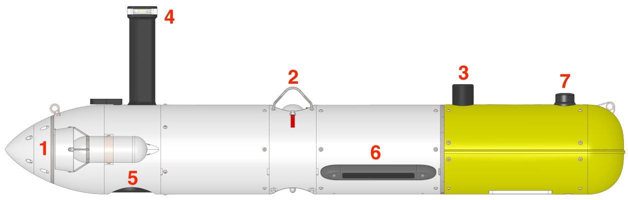
(a) Sparus II in a water tank at CIRS



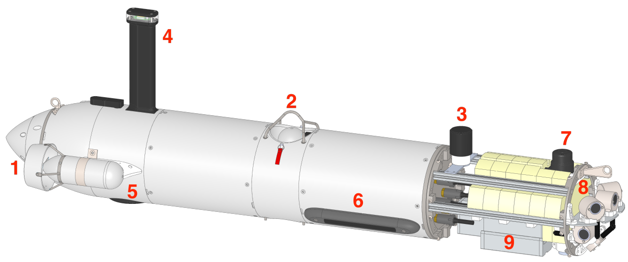
(b) Top view



(c) Bottom view



(d) Lateral view

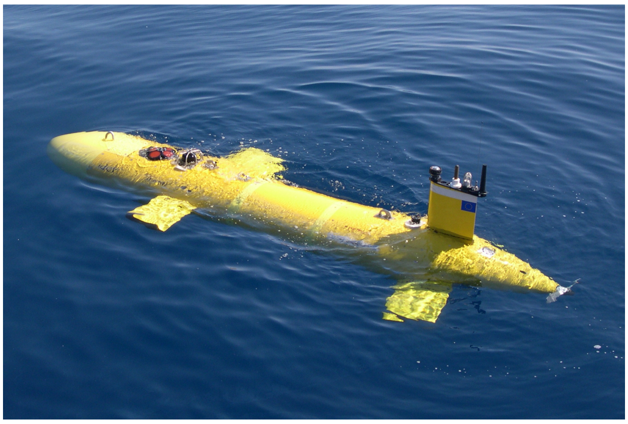


(e) 3D view

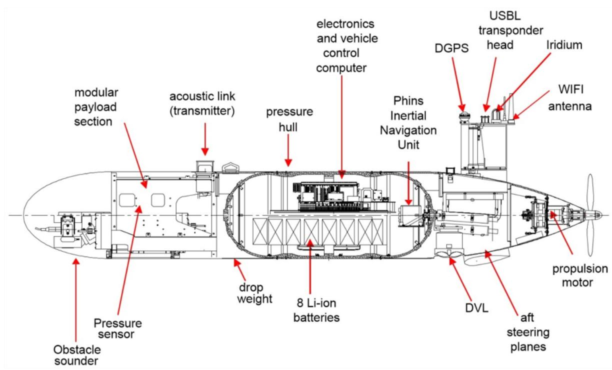
Figure 1: Sparus II AUV: top, bottom, lateral and 3D views. Different hardware parts can be observed, including the thrusters (1,2), the acoustic modem (3), the Wi-Fi and GPS (4), as well as interoceptive and exteroceptive sensors such as the DVL (5), side-scan sonar (6), mechanically-scanning imaging sonar (7), single-beam echosounders (8), multibeam sonar (9), and an optical camera (10).

A.2 ASTERX AUV

The AsterX is a torpedo-shaped AUV from the French Research Institute for Exploitation of the Sea (Ifremer). This vehicle is based on the Explorer 3000 AUV, which is built by International Submarine Engineering (ISE), from Canada. The vehicle is rated for depths up to 3000m, and is equipped with one back propulsion motor, three aft steering planes, and two fore planes. Similarly as the Sparus II, AsterX is equipped with a navigation sensor suite that includes a pressure sensor, a DVL, an IMU and a GPS to receive position fixes while at surface. It also has an acoustic modem, and a Wi-Fi antenna. This AUV also includes a modular payload area in the front, which may carry different sensors, e.g., a multibeam sonar. Figure 2 depicts the AsterX AUV at sea surface, and a schematic with its main inner hardware devices distribution.



(a) AsterX AUV at sea surface during in-water trials



(b) Lateral view

Figure 2: AsterX AUV at sea surface and its lateral view with a description of the different hardware elements.

On the other hand, the AsterX's software architecture is composed of three main functional blocks (see Fig. 3). Firstly, the AUV low-level controller, also referred as *frontseat*, guides the vehicle using the automated control engine (ACE) middleware. This controller is executed over QNX operating system, thus guaranteeing real-time computation constraints. Furthermore, this functional block also handles the vehicle's navigation and safety routines. Secondly, the *backseat* controller extends the vehicle's capabilities and applications by easing the implementation of high-level routines, such as algorithms for path/motion planning, path-tracking, and docking. These routines can directly send low-level control setpoints. This functional block has its own dedicated computer that works under the ROS (over Linux). Finally, the *payload* controller acts as a bidirectional interface between the interoceptive and exteroceptive sensors, and, on the other hand, both the *frontseat* and *backseat* controllers.

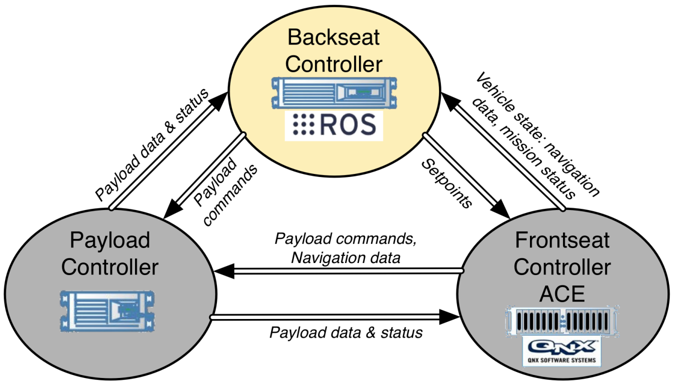


Figure 3: AsterX AUV software architecture