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Cooperative Robotics in Marine Monitoring and Exploration

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Abstract

Marine robotics play a great role in modern exploration of marine environments. The Laboratory for Underwater Systems and Technologies of the Faculty of Electrical Engineering and Computing of the University of Zagreb is involved in marine robotics research and is currently participating in a number of marine robotics related projects. This paper addressed the issue of using multiple cooperative marine robots (surface and underwater) for marine monitoring and exploration within the scope of CroMarX project. The project brings a new dimension to marine monitoring and exploration by introducing cooperative marine robots that increase operational efficiency. The main objective of the CroMarX project is to investigate and develop cooperative control algorithms in the area of marine robotics, taking into account both unmanned surface marine vehicles (USVs) and an unmanned underwater vehicle (UUV) for the purpose of marine monitoring and exploration.

Keywords: *marine robotics, cooperative robots, unmanned surface marine vehicles, unmanned underwater vehicles.*

1. Introduction

About 70% of Earth is covered in water and thus poorly accessible for exploration. As a result, we know more about the surface of the Moon and Mars than we do about our own planet. Even the Adriatic Sea with the maximum depth of around 1,200 meters remains fully unexplored. The underwater environment is harsh and under constant influence of disturbances such as sea currents, winds and waves. However, the oceans and the seas are home for a myriad of species, many of which have yet to be discovered, and a great source of resources much needed for the humankind. Human presence in the marine environment is possible only with the help of technical equipment such as SCUBA gears or manned submersibles – both approaches involve high risk for people involved.

In order to avoid direct human presence in the underwater, and still be able to monitor and explore the marine environment, unmanned marine surface vehicles (USVs) and unmanned underwater vehicles (UUVs) are successfully exploited. Unmanned marine vehicles play a large role in different application fields such as

- marine biology, for exploration and preservation of marine species and habitats,
- marine ecology, for detection of pollutants and invasive species
- underwater archaeology, for mapping and preservation of submerged cultural heritage,
- aquaculture, for maintenance of fish farms,
- marine security, for monitoring marine borders,
- offshore industry, for remote maintenance and repair of offshore infrastructure) and many more.

All maritime countries, as well as Croatia, with jurisdiction over almost half of the Adriatic Sea, have the obligation to monitor, explore and protect their marine environment.

Advances in small embedded processors, sensors and miniaturized actuators have increased interest in study and development of multi-robot systems, where a number of USVs cooperate in a common operative framework, coordinating their motion, in order to achieve a global mission goal. The fleet operation shows the potential to drastically improve the means available for ocean exploration and exploitation. The use of multiple autonomous robotic vehicles acting in cooperation will drastically increase the performance, reliability, and effectiveness of automated systems at sea. Multi-vehicle operations render possible tasks that no single vehicle can solve as well as increase operational robustness toward individual failures. This paper addresses the issues of cooperative robots used for marine monitoring and exploration.

The paper is organized as follows: the following section describes activities of the Laboratory for Underwater Systems and Technologies where research related to marine robotics is conducted; Section 2 describes state of the art in the area; while Section 3 describes CroMarX project dealing with cooperative marine robots.

1.1. Laboratory for Underwater Systems and Technologies (LABUST)

LABUST (http://labust.fer.hr) is a research laboratory of the Faculty of Electrical Engineering and Computing of the University of Zagreb that holds expertise in marine robotics: development and adaptation of marine vehicles; acoustic networks and sonars; identification, navigation, guidance and control of marine vessels; cooperative and coordinated formations of marine vehicles. LABUST has large experience in coordinating research projects (FP7 CURE, FP7 CADDY, H2020 EXCELLABUST, H2020 aPad) and participating in projects such as FP7 EUROFLEETS2, FP7 CART, H2020 subCULTron, H2020 PlaDyFleet, ECHO-DG e-URready4OS, INTERREG BLUEMED. In the last 5 years the group has also participated in other 6 international and 3 national projects related to marine robotics. LABUST have organized 10 annual field trainings “Breaking the Surface” with the purpose of conducting multidisciplinary research within marine biology, archaeology and security.

Several USVs and UUVs available in LABUST allow validation of the developed algorithms on real vehicles in real environmental conditions that are challenging and under constant influence of disturbances such as waves, sea currents and winds.

Five **USVs H2OmniX** were developed at UNIZG-FER LABUST as multipurpose vehicles with a great number of sensors, capable of executing numerous guidance and control tasks in sea state 3. Each USV (shown in Fig. 1) is a small, one man portable overactuated platform with four thrusters positioned in such a way that they form an X-shaped which allows movement in every direction while maintaining arbitrary desired heading. The dimensions of the vehicle are 707x707x450 mm and the weight is about 35 kg. The hull is made of carbon fibre which guarantees robust operation in real environmental conditions. All USVs are equipped with an Inertial Measurement Unit (IMU) and Real Time Kinematic Global Positioning System (RTK GPS) for navigation on the water surface, Ultra-Short Base Line (USBL) for acoustic localization and communication with underwater agents, e.g. divers or underwater vehicles and down looking high definition (HD) camera for diver tracking or shallow water mosaicking.

Fig. 1. The fleet of unmanned surface vehicles (USVs) H2OmniX.

UUV „BUDDY” shown in Fig. 2 was developed at LABUST with the primary purpose of assisting divers during their underwater operations, hence the name „BUDDY“. The UUV has high manoeuvring capabilities (full

Fig. 2. The unmanned underwater vehicle (UUV) BUDDY on dry land during experiments in Biograd na Moru, Croatia

actuation) due to four horizontal and two vertical thrusters and is capable of dealing effectively with underwater environment. Integrated on the UUV are proprioceptive sensor devices needed to develop a precise navigation module, i.e. IMU, DVL and USBL based positioning system. To be able to recognize postures and gestures of the diver, a set of exteroceptive sensors (stereo video system and sonar) were integrated. The frame of the autonomous underwater vehicle is made of an engineered plastic and the overall dimensions of the vehicle are 1220x700x750 mm and the weight is about 70 kg.

LUPIS UUV is torpedo shaped autonomous underwater vehicle by OceanScan, equipped with camera, forward looking sonar and sidescan sonar.

2. State of the art

2.1. Formation control

Large research interest is focused on the formation keeping. Historically different formation control frameworks were investigated such as Behavioural, Virtual Structure or Leader Follower. Distributed behavioural model suggested simple motion primitives for each group member such as collision avoidance, velocity matching and neighbour tracking, resulting in an overall complex motion behaviour resembling that found in nature, [1], [2]. The virtual structure approach is rooted in analytical mechanics for multi-body dynamics and facilitates a flexible and robust formation control scheme [3], [4].

Some works describe cooperative path following, where a group of vehicles is required to manoeuvre along pre-specified paths while keeping a desired formation pattern. In [5] work is reported in the area of absolute formation control where each vehicle is required to know its absolute position and those of the neighbouring vehicles. This is in contrast with the work in [6], where relative formation keeping is proposed where each vehicle is only required to know the position of neighbours in its own reference frame. In more recent work [7], the authors advance algorithms to coordinate the formation of vehicles when they can only measure the distances to their respective neighbours.

In Leader-Follower framework which has been extensively investigated lately, the formation consists of one or more (real or virtual) leaders to which a number of followers are assigned [8]. Paper [9] focuses on the guidance systems associated with guided motion control and presented full-scale formation control results using the coordinated target tracking functionality. The work in [10] and [11] addressed the simplified problem of maintaining an autonomous vehicle in a moving triangular formation with respect to two leader vehicles that move at the same speed and with constant separation. In [12] a control strategy for the follower vehicle is proposed that uses simple feedback laws for speed and heading commands to drive along track and cross track errors to zero. The performance of the algorithm was demonstrated in sea trials with the vehicles equipped with acoustic modems and ranging devices affected by noise, outliers and communication losses.

2.2. Collision avoidance

Another issue to be addressed, when two or more autonomous vehicles work in cooperation in the same operative area, is the problem of vehicles collision avoidance. Even if the mission is planned and cleared of any conflict between robots, vehicles can come to a collision due to external disturbances, different dynamic and kinematic characteristics, unpredicted conditions, online operation re-planning. A paper providing a general description of a multi-vehicle systems with integrated procedures and control laws to deal with the problem of inter-robot collision can be found in [13]. In [14] collision avoidance algorithm is presented based on the virtual target approach relying only on the known position of the robots in the operative frameworks. The approach offers a simple and robust methodology to achieve the collision avoidance task only on the basis of the known position of the vehicles.

2.3. USV-UUV cooperation

Cooperation between an unmanned surface vehicle (USVs) and an underwater vehicle (UUV) is of great interest to many research groups, mostly due to the fact that the USV can significantly assist the UUV in navigation through cooperation – this approach is referred to as cooperative navigation aiding (CNA). This type of scenario was applied in different research efforts. Pure CNA was utilized in the FP7 TRIDENT project [15] for aiding the navigation of an intervention AUV and in NATO project ANMCM [16] for aiding the navigation of smaller vehicles with low-quality sensors. Cooperative tracking and localization aiding of an underwater vehicle and a human diver is researched in the FP7

CADDY project [17] while the FP7 CO3AUV project [18] investigated navigation aiding of multiple UUV in parallel to cooperative movement. Different online motion planning algorithms for USVs to improve the overall quality of underwater position aiding is still an active research topic [19].

Navigation aiding and cooperative motion becomes problematic in complex underwater structures where line-of-sight acoustic communication is not possible. Multiple layers of navigation aiding by combining USV and UUVs for mapping of underwater slopes was researched in FP7 MORPH project [20].

While CNA seems to be well established in research projects during the last 6 years, different cooperation aspects between USVs and UUVs are less prominent. The H2020 subCULTron project proposes biologically inspired cooperation where interaction between USV and UUVs is not limited to navigation [21].

2.4. Mission control for multiple vehicles

It should be possible for users who are not necessarily familiar with the technical details of marine robot development to do mission programming and mission execution tasks. The development of a mission control system for single or multiple vehicles reflects the background of the developing team, the applications envisioned and the hardware available for mission control system implementation. References [22 -25] provide some background material and a historical perspective. The review of the major control architectures employed on a marine vehicle are described in [26].

The mission design layer usually provides mission map (map of the area to be covered), menu of the vehicles available to execute the mission, functionalities of each vehicle and the corresponding payload, a set of mechanisms enforcing spatial/temporal multi-vehicle synchronisation and path planning (to meet adequate spatial / temporal/energy requirements). The mission execution layer translates high-level plans into low-level primitives' execution, monitors the execution and handles the events raised for them. Popular approaches use state machines or Petri Nets to describe mission relating primitives to be executed in each state with the events that produce the transition between these states.

3. CroMarX project

"CroMarX – Cooperative robotics in marine monitoring and exploration" is a project financed by the Croatian Science Foundation. The main objective of the CroMarX project is to investigate and develop cooperative control algorithms in the area of marine robotics, taking into account both unmanned surface marine vehicles (USVs) and an unmanned underwater vehicle (UUV) for the purpose of marine monitoring and exploration. The global vision of the project is shown in Fig. 3 where a fleet of USVs is deployed at sea, exchanging information and maintaining optimal formation, while an UUV explores the underwater environment and cooperates with the USVs by taking advantage of their measurements to increase its navigation capabilities.

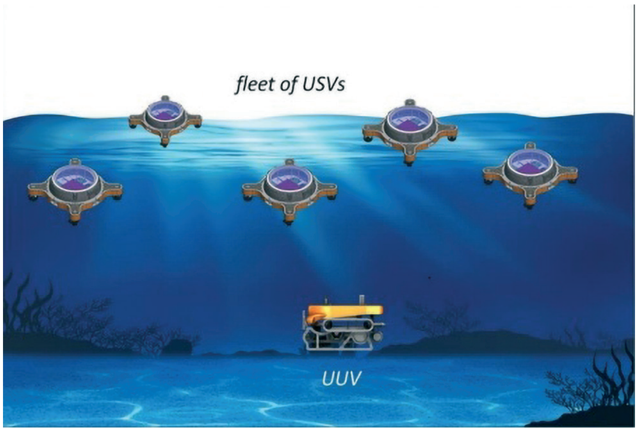

Fig. 3. The concept of the CroMarX project which includes cooperation between USVs and UUVs for the purpose of marine monitoring and exploration.

The main scientific objectives of CroMarX project are

1. Development of **cooperative control algorithms for a fleet of unmanned surface marine vehicles** for the purpose of marine monitoring

In order to achieve persistent marine monitoring (which includes monitoring marine borders, offshore structures and underwater habitats, etc.), CroMarX proposes to use a fleet of USVs that maintain a formation in order to cover a certain area. This objective includes both the development of cooperative control algorithms for controlling the formation and position of the fleet of USVs as well as formation control based on environmental inputs such as direction of sea currents.

2. Development of **cooperative control algorithms for an unmanned surface vehicle and an unmanned underwater vehicle** for the purpose of underwater exploration

In order to achieve underwater exploration, specifically seabed mapping UUVs are required to navigate precisely in order to provide georeferenced maps. Since conventional global navigation systems do not work under water, measurements from surface vehicles can be used to aid in their navigation. This objective is devoted to cooperative control algorithms for this purpose.

3. Development of the **mission control software and user interface** suitable for multiple surface and underwater marine vehicles

Controlling and monitoring multiple marine vehicles poses a challenge due to their spatial distribution and invisibility in the underwater environment. This objective is devoted to developing a mission control software that will have the function of monitoring the position of each agent involved, as well as commanding missions for individual and group of robots.

4. **Experimental validation** of the developed cooperative control algorithms applied on the fleet of unmanned surface vehicles and an unmanned underwater vehicle.

Experimental validation is of great importance in marine robotics due to the harsh nature of the environment in which the robots operate. Constant influence of external disturbances such as sea currents, waves and wind require testing of developed control algorithms in real environments. The CroMarX project is focussed around three validation scenarios that prove the functionality of the developed algorithms and show the project progress.

Scenario 1, USV fleet formation control for distributed marine monitoring, demonstrates the first USV fleet topology control. This scenario will demonstrate the functionalities of formation control with the topologies being commanded from the ground station, with special emphasis put on ensuring collision-free topology change enabled by the developed algorithm. This scenario is graphically shown in Fig. 4.

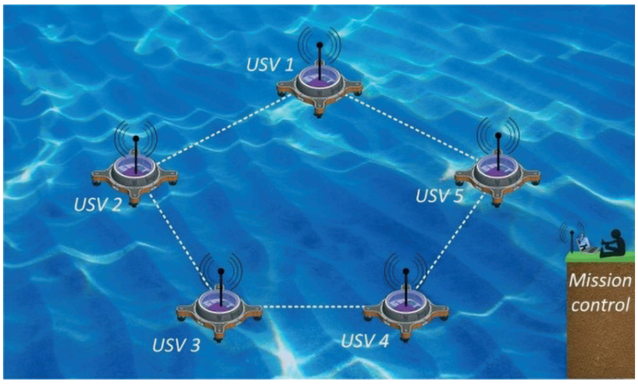

Fig. 4. The concept of Scenario 1 where the formation of the fleet of USVs is controlled from the ground station.

Scenario 2, cooperative seabed mapping using USV and UUV, demonstrates the USV-UUV cooperative control algorithms where both vehicles move in a cooperative manner while the USV is aiding the UUV in its navigation. This scenario will demonstrate the capability of seabed exploration. This scenario is graphically shown in Fig. 5.

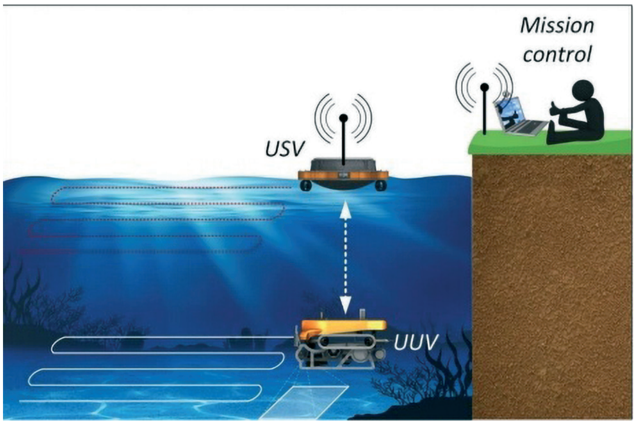

Fig. 5. The concept of Scenario 2 where a UUV and a USV cooperate in a way that the USV aids the UUV in navigation while the UUV is exploring a part of the seabed.

Scenario 3, environmentally adaptive fleet of USV formation keeping, is the final step of the USV fleet cooperative control with the addition of adaptation to environmental influences. The fleet will demonstrate how sea current can be estimated in a distributed manner, and how the fleet adapts the formation topology and orientation in order to minimize power consumption. This scenario is graphically shown in Fig. 6.

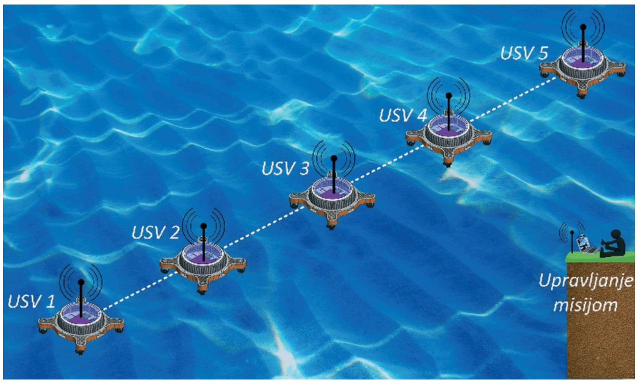

Fig. 6. The concept of Scenario 3 where a formation of the fleet of USVs autonomously adapts to the environment, i.e. so that the formation topology changes according to the direction of the current in order to minimize energy consumption.

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References

[1] Reynolds, C. W. (1987). “Flocks, Herds, and Schools: A Distributed Behavioral Model.” Computer Graphics 21(4): 25-34.

[2] Leonard, N. E. and E. Fiorelli (2001). Virtual Leaders, Artificial Potentials and Coordinated Control of Groups. Proceedings of the 40th IEEE CDC. Orlando, Florida, USA.

[3] Lewis, M. A. and K.-H. Tan (1997). “High Precision Formation Control of Mobile Robots Using Virtual Structures.” Autonomous Robots 4: 387-403.

[4] Ihle, I.-A. F., J. Jouffroy and T. I. Fossen (2006b). “Formation Control of Marine Surface Craft: A Lagrangian Approach.” IEEE Journal of Oceanic Engineering 31(4): 922-934.

[5] Ghabcheloo, R., Aguiar, A.P., Pascoal, A., Silvestre, C., Kaminer, I., and Hespanha, J. (2009). Coordinated path-following in the presence of comm. losses and time delays. SIAM Journal on Control and Optimization, 48(1), 234-265.

[6] Cao, M. and Morse, A. (2007). Station keeping in the plane with range-only measurements. In American Control Conference, 2007. ACC’07, 5419-5424. IEEE.

[7] Cao, M., Yu, C., and Anderson, B. (2011). Formation control using range-only measurements. Automatica, 47(4), 776-781.

[8] Breivik, M., V. E. Hovstein and T. I. Fossen (2008a). Ship Formation Control: A Guided Leader-Follower Approach. Proceedings of the 17th IFAC World Congress, Seoul, Korea.

[9] Breivik, M. and K. Evans (2009b). Formation Control of Unmanned Surface Vehicles, CeSOS Annual Report 2008, Centre for Ships and Ocean Structures **:** 30-31.

[10] Soares, J.M., Aguiar, A.P., Pascoal, A.M., and Gallieri, M. (2012). Triangular formation control using range measurements: An application to marine robotic vehicles. In Proceedings of the IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles, Porto, Portugal.

[11] Soares, J.M., Aguiar, A.P., Pascoal, A.M., and Martinoli, A. (2013). Joint ASV/AUV range- based formation control: Theory and experimental results. In Proceedings of the IEEE International Conf. on Robotics and Automation, Karlsruhe.

[12] Francisco Rego, Jorge M. Soares, António M. Pascoal, A. Pedro Aguiar and Colin Jones, “Flexible triangular formation keeping of marine robotic vehicles using range measurements,” in Proceedings of the 19th IFAC World Congress, IFAC WC 2014, Cape Town, South Africa, 2014.

[13] J. Kalwa, “Final results of the European Project GREX: coordination and control of cooperating marine robots,” in *Proc. of 7th IFAC Symposium on Intelligent Autonomous Vehicles*, 2010.

[14] M. Bibuli, G. Bruzzone, M. Caccia, L. Lapierre and E. Zereik, “A collision avoidance algorithm based on the virtual target approach for cooperative unmanned surface vehicles,” *Control and Automation (MED), 2014 22nd Mediterranean Conference of* , Palermo, 2014, pp. 746-751. doi:10.1109/MED.2014.6961463

[15] Pedro J. Sanz, Pere Ridao, Gabriel Oliver, Claudio Melchiorri, Giuseppe Casalino, Carlos Silvestre, Yvan Petillot, Alessio Turetta, TRIDENT: A Framework for Autonomous Underwater Intervention Missions with Dexterous Manipulation Proceedings Volumes, Volume 43, Issue 16, 2010, Pages 187-192

[16] Đ Nađ, N. Mi šković, V. Djapic and Z. Vukić, “Sonar aided navigation and control of small UUVs”, Control & Automation (MED), 2011 19th Mediterranean Conference on, Corfu, 2011, pp. 418-423.

[17] P. Abreu et al., “Cooperative control and navigation in the scope of the EC CADDY project,” OCEANS 2015 – Genova, Genoa, 2015, pp. 1-5.

[18] A. Birk et al., “The CO3AUVs (Cooperative Cognitive Control for Autonomous Underwater Vehicles) project: Overview and current progresses,” OCEANS 2011 IEEE – Spain, Santander, 2011, pp. 1-10.

[19] J. Hudson and M. L. Seto, “Underway path-planning for an unmanned surface vehicle performing cooperative navigation for UUVs at varying depths,” 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, Chicago, IL, 2014, pp. 2298-2305.

[20] J. Kalwa et al., “The MORPH concept and its application in marine research,” OCEANS – Bergen, 2013 MTS/IEEE, Bergen, 2013, pp. 1-8.

[21] Zahadat, Payam, and Thomas Schmickl. “Division of labor in a swarm of autonomous underwater robots by improved partitioning social inhibition.”Adaptive Behavior (2016): 1059712316633028.

[22] Healey, A., D. Marco, P. Oliveira, A. Pascoal, C. Silvestre, and V. Silva (1996). Strategic level mission control and evaluation of CORAL and PROLOG implementations for mission control specifications. In Proceedings of the IEEE Autonomous Underwater Vehicle (AUV) 96 Conference, Monterey, CA, USA.

[23] Healey, A., D. Marco, and R. McGhee (1996). Autonomous underwater vehicle control coordination using a tri-level hybrid software architecture. In Proceedings of the IEEE Robotics and Automation Conference, Minneapolis, USA.

[24] Oliveira P., A. Pascoal, V. Silva, and C. Silvestre (1996). Design, development, and testing of a mission control system for the MARIUS AUV. In Proceedings of the 6th International Advanced Robotics Program IARP-96, Toulon, France.

[25] Oliveira, P., A. Pascoal, V. Silva, and C. Silvestre (1998). Mission control of the MARIUS autonomous underwater vehicle: system design, implementation, and sea trials. International Journal of Systems Science, Special Issue on Underwater Robotics, 29(10), pp. 1065–1080.

[26] K. P. Valavanis, D. Gracanin, M. Matijasevic, R. Kolluru and G. A. Demetriou, “Control architectures for autonomous underwater vehicles,” in IEEE Control Systems, vol. 17, no. 6, pp. 48-64, Dec 1997. doi: 10.1109/37.642974.