The Aquatic Surface Robot (AnSweR), a lightweight, low cost, multipurpose unmanned research vessel

Sanfilippo, F., Tang, M. & Steyaert, S.

Published in: Communications in Computer and Information Science
DOI: 10.1007/978-3-030-71711-7

Citation:
Sanfilippo, F., Tang, M. & Steyaert, S. (2021). The Aquatic Surface Robot (AnSweR), a lightweight, low cost, multipurpose unmanned research vessel. In S. Y. Yayilgan, I. S. Bajwa & F. Sanfilippo (Eds.), Intelligent Technologies and Applications (p. 251-265). Communications in Computer and Information Science. Springer. doi: 10.1007/978-3-030-71711-7

The Aquatic Surface Robot (AnSweR), a lightweight, low cost, multipurpose unmanned research vessel*

Filippo Sanfilippo[1,2][0000−0002−1437−8368], Min Tang[3], and Sam Steyaert[4]

[1] Dept. of Engineering Sciences, University of Agder (UiA), Jon Lilletuns vei 9, 4879, Grimstad, Norway
filippo.sanfilippo@uia.no
[2] Dept. of Mechanical, Electronic and Chemical Engineering, Oslo Metropolitan University (OsloMet), PO box 4 St. Olavs plass, 0130, Oslo, Norway
[3] Dept. of Science and Industry systems, University of South-Eastern Norway (USN), Post box 235, 3603 Kongsberg, Norway
[4] Faculty of Biosciences and Aquaculture, Nord University, Universitetsalléen 11, 8026, Bodø, Norway

Abstract. Even though a few examples of aquatic surface robots exist, they are generally expensive, relatively large and heavy and tailored to custom-made hardware/software components that are not openly available to a broad public. In this work, the Aquatic Surface Robot (*AnSweR*), a newly-designed, lightweight, low cost, open-source, multipurpose unmanned research vessel is presented. The *AnSweR* features a lightweight and compact design that makes it fit in a backpack. Low-noise operation (in and above the surface) is achieved with a propulsion system based on two water-jets. Only affordable commercial-off-the-shelf (COTS) components are adopted. The primary goal of the *AnSweR* is to map underwater landscapes and to collect bathymetry data in lakes, rivers, and coastal ecosystems. A modular hardware and software architecture is adopted. This architecture allows the *AnSweR* to be equipped with a customisable add-on set of sensors and actuators to enable a variety of research activities, such as measuring environmental variables (e.g., salinity, oxygen, temperature) and sampling operations (e.g., sediment, vegetation, microplastics). The software architecture is based on the Robot Operating System (ROS). This paper describes the design of *AnSweR* as the main scientific contribution and presents preliminary simulation and experimental results which illustrate its potential.

Keywords: Aquatic surface robots · Unmanned surface vehicles · Robotics.

1 Introduction

The monitoring of ambient environmental conditions in aquatic ecosystems is essential to ecological management and regulation. However, collecting environmental data in such aquatic environments is a challenging process [1]. It typically requires human-operated research vessels or equipment, which are time and cost-inefficient, and can

---

* This work is supported by the Top Research Centre Mechatronics, University of Agder (UiA), Jon Lilletuns vei 9, 4879, Grimstad, Norway.

expose operators to dangerous situations (i.e., scuba diving for sample collection). Unmanned surface vehicles (USVs), which started to make their appearance predominantly for military and marine purposes [25], are also becoming increasingly relevant for research purposes. USVs are remotely controlled rafts that can be equipped with various cameras and sensors to collect environmental data [2]. Commercially available USVs are fairly large, heavy (usually 1-10 m, 30 kg - several tons) and considerably expensive [2]. As a result, they are generally inaccessible to a broad public and are not practical to transport and operate in difficult to reach environments (e.g., most rivers and lakes).

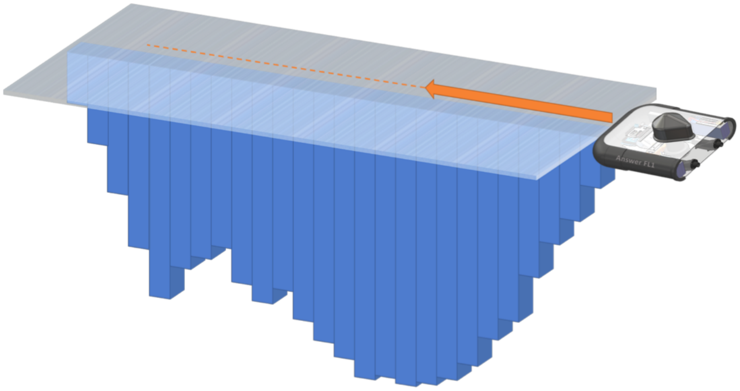

Fig. 1: The Aquatic Surface Robot (*AnSweR*) is a newly-designed, lightweight, low cost, open-source, multipurpose unmanned research vessel. The primary goal of the *AnSweR* is to map underwater landscapes and to collect bathymetry data in lakes, rivers, and coastal ecosystems. A modular hardware architecture is adopted.

Nowadays, different commercial off-the-shelf (COTS) aquatic surface robots exist [5, 11, 13, 16, 20, 22]. However, most of the existing robots are typically costly, relatively large and heavy and custom-built to specific hardware/software modules that are not openly available. Moreover, they are typically not easy to maintain, change or extend as research tools, by adding new hardware/software components and features. Therefore, the integration of these robots with other research tools still requires a significant effort. Consequently, this process can often be a tedious and time-consuming task, which may prevent researchers from fully focusing on the tasks necessary to achieve the core experimental objectives.

To give researchers and other users a robotic solution that is inexpensive, easily customisable, and fast to fabricate, a newly-designed, lightweight, low cost, open-source, multipurpose unmanned research vessel is introduced in this work. The presented robot is named Aquatic Surface Robot (*AnSweR*) and is shown in Fig. 1. The *AnSweR* is characterised by a lightweight and compact design that makes it fit in a backpack. Exclusively low-cost commercially available components are employed. The robot mechanical components can be easily manufactured, thus making the rapid-prototyping process very economical and fast. The robot's primary purpose is to map underwater environments and to gather data on bathymetry in lakes, rivers and coastal habitats. A modular hardware architecture is adopted. In particular, the (*AnSweR* is equipped with a hardware interface that includes all sensors and actuators which are absolutely necessary for achieving guidance, navigation, and control (GNC) functions [9]. A propulsion system with two water-jet thrusters, a depth camera, a global positioning system (GPS), and a sonar are adopted to enable the robot's external system independence (ESI), adaption to environmental complexity (EC) and to mission complexity (MC). Furthermore, the *AnSweR* may be fitted with a versatile collection of sensors and actuators to allow for a range of research activities, such as measuring environmental variables (e.g., salinity, oxygen, temperature), sampling and monitoring operations (e.g., sediment, vegetation, microplastics). The concept of modularity is also applied to the software architecture. The *AnSweR* is equipped with a core control software that make it possible to achieve the required GNC functions. Moreover, an add-on software layer makes it possible to integrate extra software functionalities that can be developed/added on-demand to perform the desired research activities. The software architecture is based upon the Robot Operating System (ROS) [18]. The design of the *AnSweR* is presented as the main scientific contribution of this work. Preliminary simulation and experimental results are outlined to demonstrate potential applications.

The paper is organised as follows. A review of the related research work is given in Section 2. In Section 3, we focus on the description of the mechanical overview. A hardware/software overview is described in Section 4. In Section 5, some preliminary simulation and experimental results are outlined. Finally, conclusions and future works are discussed in Section 6.

2 Related Research Work

A diverse range of aquatic surface robots exist [12, 15, 17, 21, 23, 24]. The focus of this paper is on introducing the (*AnSweR*) robot that can easily be transported and operated to conduct research activities in ecosystems with difficult access. Therefore, small size USVs with no more than 2 m length are briefly reviewed in this section. A more detailed review is described in [19]. For the investigated small size USVs, two types of hull are generally adopted: catamaran type or single hull type. Both of these different types of hull are easily carried and deployed by one man. Electric actuators, such as thrusters represent the most prevalent actuation systems for propelling these vehicles. These systems are used for shallow water surveillance, bathymetric survey and water monitoring, by remote control with telemetry [5, 11, 13, 16, 20, 22].

Regarding catamaran type hulls, different USVs are available. For instance, Maritime Robotics produces the Otter USV [13], which is a hydrographic survey tool for mapping of sheltered and enclosed waters. With close integration between the on-board control system that enables autonomy and the multibeam echo-sounder, a bathymetric survey can be carried out with a quick, seamless workflow. The closely integrated bathymetric survey system makes the Otter a cost-effective solution for bathymetric surveys in sheltered waters such as small lakes, canals, rivers, ponds, and harbour areas. Another example with similar hull typology is the SR-Surveyor M1.8 USV, which is a highly capable man-portable autonomous hydrographic survey vessel developed by

Sea Robotics [20]. It is tightly integrated with multiple high-resolution hydrographic sensors and a topographical mapping LiDAR. Thanks to its unique sensor suite, it is very suitable for collecting a wide range of hydrographic data in inland and coastal waters. Its small form factor, light weight, and shallow draft enable the SR-Surveyor M1.8 to be rapidly deployed in difficult to access areas. One more example with catamaran type hull is the Heron USV, which is a portable, mid-sized surface vessel developed by Clearpath Robotics [5]. Its design comprises anti-fouling thrusters, a remarkably shallow profile, and built-in GPS. Submerged sensors or equipment on deck can be mounted on a specifically designed payload bay. Folding pontoons and a quick swappable battery make transport, launch and retrieval a quick and easy process.

Regarding single type hulls, various example exist. For instance, the GeoSwath 4R USV is developed by Kongsberg Maritime [11]. It offers efficient simultaneous swath bathymetry and side scan mapping. It features closely integrated ancillary sensors and communication links into a proven remote-controlled platform for quick and easy deployment and operation. This remote hydrographic survey boat allows surveying in locations and situations in which deployment of conventional platforms is not practicable or hazardous. Another example with similar hull typology is the SL20 USV, which is developed by OceanAlpha [16]. Its compact and portable form factor makes it suitable for hydrographic and bathymetry surveying. It supports flexible deployment of different instruments like an Acoustic Doppler Current Profiler (ADCP) and an echo sounder. With the size of 1 m long and weight of 17 kg, it is easy for one man to operate and transport. Its powerful battery and low power consumption provide 6 hours of endurance at 3 knots. One more example with single type hull is the Z-Boat 1800 RP USV. It is developed by Teledyne Marine [22] and it is a high performance portable remotely-operated hydrographic survey boat. It offers 8kt maximum operating speed, an ADCP, a side scan, and multibeam sonar payloads, with autonomous waypoint navigation.

Commercial applications of these USVs provides an indication that most of the necessary technology is mature and available, including sensors, communication and control principals. However, a robotic solution that is inexpensive, easily customisable, and fast to fabricate is still missing to the best of our knowledge.

3 Mechanical Overview

In this section, the modular mechanical design of the *AnSweR* is presented.

3.1 Hull design

A monohull-shaped design is adopted, as shown in Figure 2. The *AnSweR* is extremely compact in size (L 360 mm x W 285 mm x H 135 mm), and lightweight (3 Kg). The draft or draught of the robot's hull is 50 mm, with the thickness of the hull included. While computerised numeric cut (CNC) and 3D-printing fabrication processes and materials could be employed for the fabrication process, low-cost COTS components are used to fast-prototyping the *AnSweR*. In particular, polyvinyl chloride (PVC) pipes are adopted to build the hull frame. PVC pipes are non-toxic and are most commonly used for plumbing and drainage. PVC has many benefits for fast-prototyping processes. Its

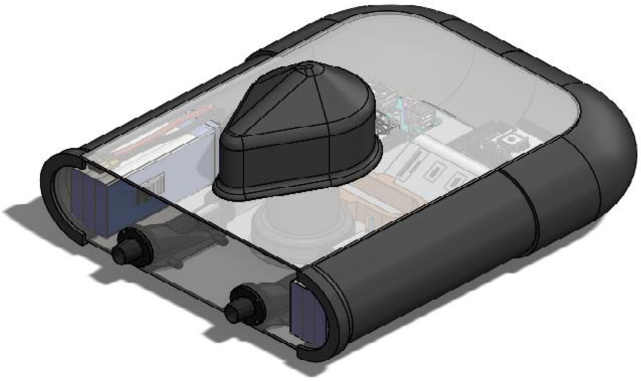

Fig. 2: The *AnSweR* is extremely compact in size (L 360 mm x W 285 mm x H 135 mm), and lightweight (3 Kg).

strength, waterproofness and durability along with low cost and easy availability make it the go to material for the fast construction of the hull. Moreover, the smooth surface of PVC material results in an efficient flow rate and reduces energy use. PVC is easy to machine, cut and connect allowing close tolerances to be achieved with either push fit or threaded compression style fittings. Leak-free PVC fittings are adopted for eliminating water loss and obtaining round corners at the front of the hull. The hull provides room for the hardware interface that includes all sensors and actuators which are strictly required to achieve all the vital GNC functions. Moreover, the hull modular design provides additional room for a payload that may be fitted with a versatile set of sensors and actuators to allow for a variety of research activities, such as measuring environmental variables (e.g., salinity, oxygen, temperature), sampling and monitoring operations (e.g., sediment, vegetation, microplastics). The payload is limited to 1 Kg.

To enable a see-through capability, the bottom, rear and top of the hull are fitted with transparent plexiglass sheets. Compared to tempered glass, plexiglass holds up better in harsh weather conditions and is more shatter resistant while still allowing 90% of light to pass through it and reach sensors that might require it. One of the biggest advantages of plexiglass panels is the ability to easily cut and form them. This is especially relevant for speeding up the prototyping process. The inner side of the bottom panel provides specifically designed slots to enclose all internal electronic components. The rear panel is set up with the needed cut-outs to enclose the propulsion system. The top panel is equipped with a specifically designed cut-out to enable the fitting of a thru-hull sensor. A 3D-printed top cup encapsulates the thru-hull sensor. The top panel is provided with a custom-made edge profile that makes it possible to easily remove it to access the inner compartment and reach all internal electronic components. Silicon-based glue is adopted to ensure seal that maintains a strong hold against harsh weather conditions. The design of all components will be made publicly available.

3.2 Propulsion

The *AnSweR* is actuated by two water-jets that are simmetrically allocated onto the rear panel of the hull. Water-jets operate differently than propellers. Propeller attempt to minimise the velocity change and rely on generating pressure differences. Alternatively, water-jets designedly increase the velocity change between inlet and outlet. That change in momentum creates thrust. By multiplying the thrust with a consistent flow rate, propulsion is achieved [4]. A water-jet is fundamentally a pump inside a very short pipe. Pumps have some advantages over propellers. Pump efficiencies around 90% or more are regularly attainable. In comparison, conventional propellers are limited to 60%-72% efficiency. Each water-jet is embedded inside the hull, with just one outlet. At speed, the exit nozzles completely clear the water. This reduces the total resistance on the robot. The absence of a propeller shaft or shaft brackets makes it possible to reduce drag through the water. Moreover, water-jets do not require a rudder, because they direct the thrust through changing the direction of the outlet stream. These characteristics make it possible for the *AnSweR* to achieve low-noise operationn (in and above the water surface). Finally, water-jets also provide great manoeuvring control and enable the *AnSweR* for avoiding getting stuck with floating debris or vegetation. Two brushless waterproof motors (*Racerstar 2440*) run the two water-jet thrusters. The *AnSweR* can reach a max speed of 2 m/s.

4 Hardware/Software Overview

In this section, the modular hardware/software design of the *AnSweR* is presented.

4.1 Computation and communications

An *Arduino Mega 2560* micro-controller is embedded in the *AnSweR* to enable an efficient low-level interface with the propulsion system and the sensors. Moreover, on-board computation is provided by an *Odroid XU4*. The *Odroid XU4* is a powerful single-board computer (SBC) that features an energy-efficient hardware and a small form-factor. In particular, the *Odroid XU4* is composed of an octa-core ARM Cortex-A7 CPU clocked at 2Ghz, 2GB RAM, 2 Universal Serial Bus (USB) 3.0 ports, 1 USB 2.0 port, and 30-pin general purpose input/output (GPIO) expansion header supporting diverse protocols such as universal asynchronous receiver/transmitter (UART), inter-integrated circuit (I2C), serial peripheral interface (SPI) and One-Wire, which facilitates integration with different electronic components and modules. The form-factor of the *Odroid XU4* (83 mm x 58 mm x 20 mm) is a crucial parameter for the selection of this specific micro-controller for the *AnSweR*, given the limited physical space. The *Odroid XU4* offers open source support and runs *Ubuntu MATE 16.04*, a *Linux* distribution based on *Debian*. The *Odroid XU4* is located in the main electronics enclosure. To enable data communication between the *Arduino Mega 2560* micro-controller and the *Odroid XU4*, an *Arduino* USB 2 Serial converter is adopted. To enable communication between the *AnSweR* and the ground/control station, a USB wireless fidelity (Wi-Fi) module for the *Odroid XU4* is used. Alternatively, a radio communication (RC) controller can be interfaced with the *Arduino Mega 2560* micro-controller for long range communication (operating range of up to 1000 m).

4.2 Sensors required to achieve all the GNC functions

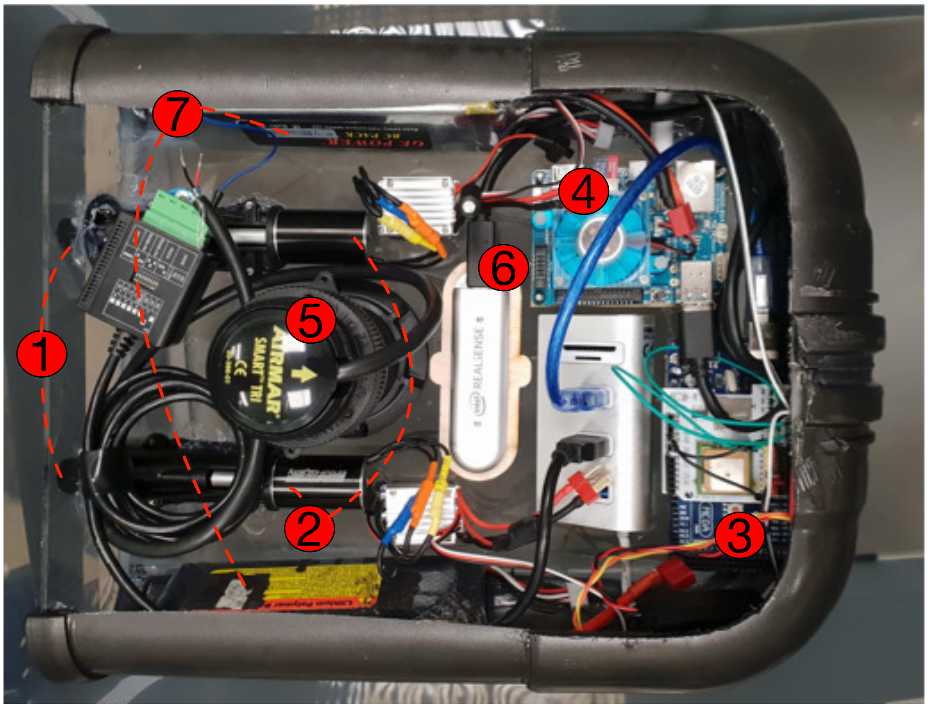

Fig. 3: The most relevant *AnSweR* hardware components: 1) two water-jets; 2) two brushless waterproof motors; 3) an *Arduino Mega 2560* micro-controller; 4) an *Odroid XU4* single-board computer (SBC); 5) a *DST800* smart transducer multisensor; 6) an *Intel RealSense D435 RGBD* camera; 7) two battery packs.

As shown in Figure 3, various sensors are included in in the *AnSweR*. To achieve all the vital GNC functions the following sensors are considered:

- a *STMicroelectronics LSM303D* magnetometer, which is a system-in-package featuring a 3D digital linear acceleration sensor and a 3D digital magnetic sensor. It includes an I2C serial bus interface that supports standard and fast mode (100 and 400kHz) and an SPI serial standard interface. The sensor can be configured to generate an interrupt signal for free-fall, motion detection and magnetic field detection;
- a *DST800*, which is a smart transducer multisensor that offers depth, speed, and temperature functions in one compact thru-hull fitting. This is a low-profile, retractable sensor. The signals from the sensors are processed right inside the housing itself. The sensor is integrated into the system thanks to a specifically designed cut-out of the hull top panel;
- an *Intel RealSense D435 RGBD* camera, which is a stereo tracking device that offers quality depth for a variety of applications. It provides a wide field of view

and a range up to 10 m. Thanks to its small form-factor, the camera is integrated into the inner side of the hull bottom panel, with the lens facing down to the water;
- an *Adafruit Ultimate* GPS breakout, which provides GPS signals. The breakout is built around the *MTK3339* chipset, a high-quality GPS module that can track up to 22 satellites on 66 channels, has an excellent high-sensitivity receiver, and a built in antenna. It can do up to 10 location updates a second for high speed, high sensitivity logging or tracking. Power usage is remarkably low, only 20 mA during navigation.

4.3 Battery packs

Two battery packs are fitted into the hull enabling the *AnSweR* for an operating time of up to 6 hours.

4.4 Open-source software

In line with the overall low-cost approach of the *AnSweR*, an open-source software framework is designed for the low-level control. To design the software architecture, the Robot Operating System (ROS) [18] is selected. ROS is a meta-operating system designed for robotic applications. The primary aim of ROS is to provide a generic interface for quicker and simpler design of capable robotic applications. Some of the ROS features comprise hardware abstraction, device drivers, message-passing and package management. The Gazebo 3D simulator [10] can be adopted in combination with ROS to simulate robots accurately and efficiently in complex indoor and outdoor settings. Gazebo also offers a robust physics engine, high-quality graphics, and convenient programmatic and graphical interfaces. In this perspective, ROS serves as the interface for the robot model of the *AnSweR*, while Gazebo is used to simulate both the robot and its operational environment. In addition to ROS and Gazebo, the RViz (ROS visualisation) [8] tool can be adopted to visualise and monitor sensor information retrieved in real-time from both the simulated scenario as well as from the real world. Other advantages for developers are the ROS community-driven support and the stable release-cycle of distributions (a new version is released every year, while a new long-term support (LTS) version is released every second year). In addition, ROS offers an excellent interface for hardware modules, such as various micro-controllers and other peripheral devices, such as actuators and sensors. The choice of ROS for the design of the control architecture makes it possible to extend the modular concept to both the hardware as well as the software of the *AnSweR*.

4.5 Framework architecture

The proposed control framework is hierarchically organised, as shown in Fig. 4. The carrier layer is the layer that is strictly needed for achieving the standard functions and capabilities of guidance, navigation, and control (GNC) [9]:

- guidance: this level is responsible for performing the functions of sensing, mapping and localisation. The *AnSweR*'s sensor data are used to produce a representation of the surrounding environment. This level performs parsing or segmenting

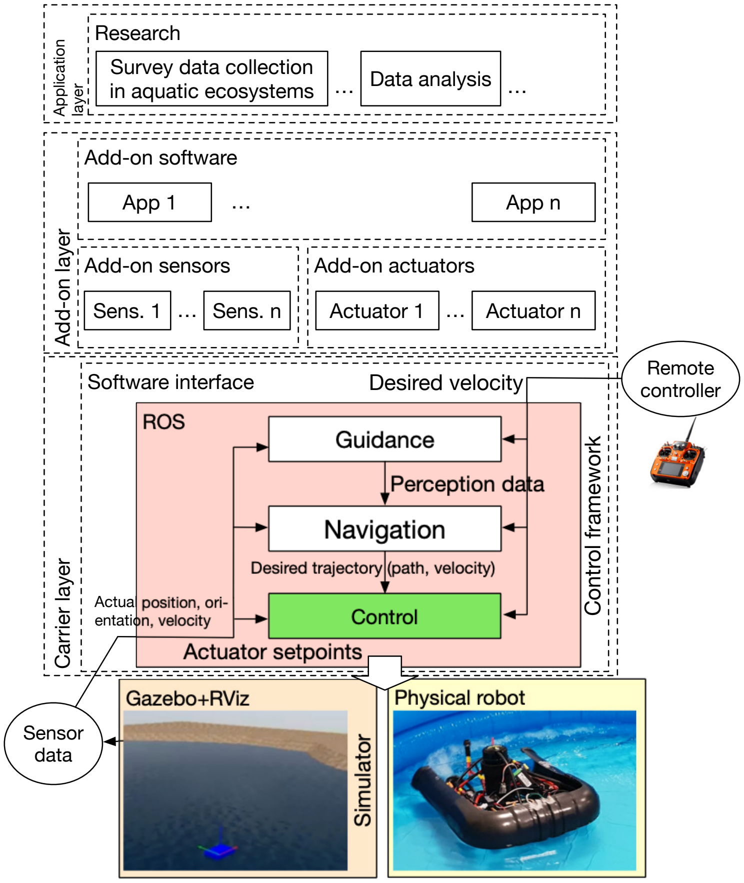

Fig. 4: The proposed framework architecture for the *AnSweR*.

of low-level sensor data (e.g., point-clouds) into higher-level and more manageable information;
- navigation: this level is responsible for decision making in terms of where, when and how the robot should ideally move. External system commands (e.g., a remote controller operated by a human operator or an external system) and the *AnSweR*'s perception data represent the input to this level. The expected output from this level is the robot's desired trajectory (e.g., path and velocity information);
- control: this level is the core of the proposed control framework. It allows researchers for developing their own alternative control methods. The level does not enforce any limitations with respect to its internal implementation. Each possible control method, however, must comply with the framework's given interfaces. The inputs to this level are the desired trajectory, as well as any relevant information from the above guidance level (perception data). The goal of the control level is to obtain the required setpoints for the robot actuators in order to follow the desired trajectory. This control action will preferably be based on the high-level information from the guidance level, but lower-level information like the actual position might be necessary depending on the actual algorithm employed in the control level.

Note that only the control layer is currently implemented, while the navigation and guidance levels will be implemented in the future.

The add-on layer makes it is possible to add extra sensors, actuators and software apps that are not strictly needed for achieving the GNC functions but are rather used for performing different research activities, i.e. water sampling, data collection and data processing. This layer includes the following components:

- Add-on sensors. These are extra sensors that can be added on-demand according to the specific research activity to be performed;
- Add-on actuators. These are extra actuators that can be added on-demand according to the specific task to be achieved. For instance, a gripper or a robotic arm could be connected to the robot to collect water samples;
- Add-on software. These are extra software apps that can be developed/added on-demand to perform the desired operations.

An application layer is a supplementary abstraction level that makes it possible to develop additional and more complex research tasks, such as survey data collection, data analysis and other activities.

The proposed framework can be extended to the possibility of controlling multiple cooperative aquatic surface robots [6, 7, 14].

5 Simulations and Experimental Results

As depicted in Fig. 4, the proposed control framework is implemented in ROS, while Gazebo is used to provide seamless simulations, and RViz is selected to visualise and monitor sensor information retrieved in real-time from the simulated scenario. The *AnSweR* is implemented as a digital twin according to the Universal Robotic Description Format (URDF) into a model with a basic box-shaped hull and two thrusters, as shown

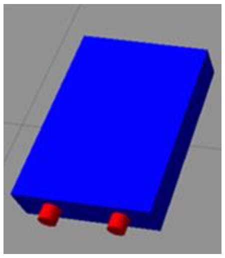

Fig. 5: The *AnSweR* model with a basic box-shaped hull and two thrusters.

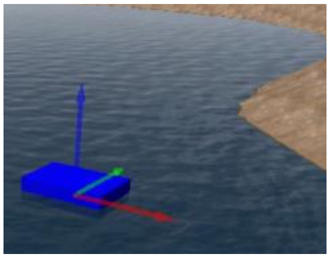

Fig. 6: A simulation scenario is built in Gazebo reproducing an aquatic environment.

in Fig. 5. The rigid body dynamics implemented in Gazebo are augmented with environmental forces via a set of *Gazebo USV Plugins* [3]. These plugins simulate the effects of dynamics (e.g., manoeuvring - added mass, drag, etc, ave field - motion of the water surface), thrust (e.g., vehicle propulsion) and wind (e.g., windage). A simulation scenario is built in Gazebo reproducing an aquatic environment, as shown in Fig. 6.

In this preliminary study, the *AnSweR* is teleoperated from the ground station by adopting the standard ROS teleoperation package, *teleop_twist_keyboard*. The corresponding ROS topic graph is shown in Fig. 7. The node *teleop_twist_keyboard* reads keyboard inputs and publishes commands to the topic *cmd_vel*. Then the node *twist2drive* subscribes to the topic *cmd_vel* and publishes commands in topic *cmd_drive*. Finally, the node gazebo (simulator) subscribes to the topic *cmd_drive* and sets throttle commands to the left and right thrusters accordingly. A graphical user interface is also implemented to control linear and angular velocities, as shown in Fig. 8. A time plot of the *AnSweR* linear velocity is shown in Fig. 9. A preliminary in-water teleoperation test for the *AnSweR* is shown in Fig. 10.

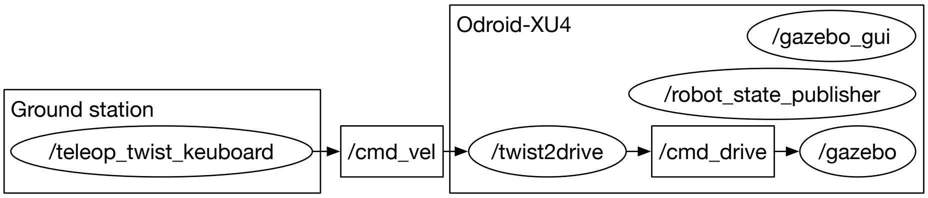

Fig. 7: The ROS topic graph for teleoperating the *AnSweR*.

6 Conclusions and Future Work

The Aquatic Surface Robot (*AnSweR*), a newly-designed, lightweight, low cost, open-source, multipurpose unmanned research vessel was introduced in this work. The *AnSweR* is characterised by a lightweight and compact design that makes it transportable inside a backpack. With its ultra-low draught, the *AnSweR* can operate in very shallow

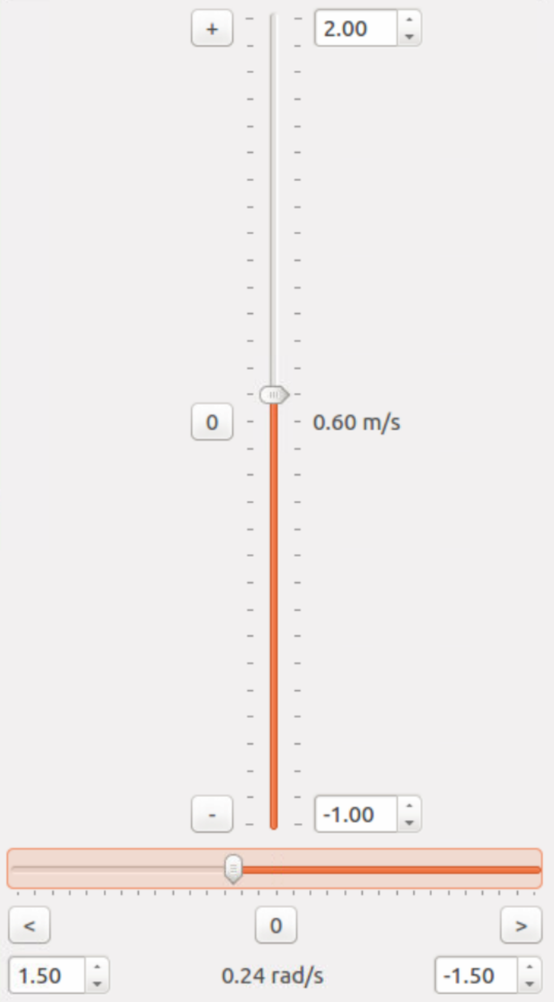

Fig. 8: A graphical user interface is implemented for the *AnSweR* to control linear and angular velocities.

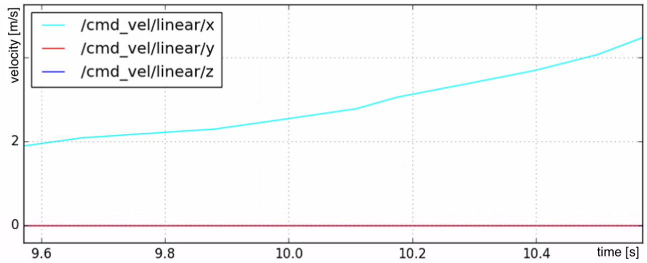

Fig. 9: A time plot of the *AnSweR* linear velocity.

Fig. 10: A preliminary in-water teleoperation test for the *AnSweR*.

waters. Thanks to its water-jet propulsion, the *AnSweR* is characterised by low-noise operation (in and above the surface). The design of the robot relies exclusively on low-cost commercial-off-the-shelf (COTS) components. The robot's primary purpose is to monitor aquatic environments and to gather data on bathymetry in lakes, oceans, and coastal habitats. A modular hardware and software architecture is adopted, which makes it possible for the *AnSweR* to be customised with a payload of sensors and actuators for enabling a range of research activities, such as measuring environmental variables (e.g., salinity, oxygen, temperature) and sampling operations (e.g., sediment, vegetation, microplastics). The principle of modularity is also adopted for the software architecture. The robot is fitted with a core control software, which allows the necessary guidance, navigation and control (GNC) functions to be accomplished. In addition, an add-on software layer enables the incorporation of additional software functionalities which can be developed/added on-demand to conduct the desired research activities. The software architecture is based on the Robot Operating System (ROS) [18]. The choice of ROS for the implementation of the control framework enables researchers to develop different control algorithms in a simulated environment with the Gazebo 3D simulator [10]. This integration makes the development of control algorithms more safe, rapid and efficient. Preliminary simulations and experimental results were presented to illustrate the potential of the proposed design.

As future work, the design of reliable control algorithms for navigation and guidance will be investigated. Moreover, the possibility of gradually increment the autonomy levels of the *AnSweR* in terms of external system independence (ESI), adaption to environmental complexity (EC) and to mission complexity (MC). The possibility of advancing the *AnSweR* from being a simple stand-alone aquatic surface robot to becoming part of a swarm of cobots will also be considered in the future.

7 Acknowledgements

The authors gratefully acknowledge the contribution of Erlend Helgerud, Sondre Lieblein Aronsen and John Mulholland.

References

1. Bayat, B., Crasta, N., Crespi, A., Pascoal, A.M., Ijspeert, A.: Environmental monitoring using autonomous vehicles: a survey of recent searching techniques. Current opinion in biotechnology **45**, 76–84 (2017)
2. Bertram, V.: Unmanned surface vehicles-a survey. Skibsteknisk Selskab, Copenhagen, Denmark **1**, 1–14 (2008)
3. Bingham, B.: Gazebo USV plugins, theory of operation, `https://github.com/bsb808/robotx_docs/blob/master/theoryofoperation/theory_of_operation.pdf`, last accessed May 2020
4. Carlton, J.: Marine propellers and propulsion. Butterworth-Heinemann (2018)
5. Clearpath Robotics Inc.: Heron, `https://clearpathrobotics.com/heron-unmanned-surface-vessel/`, last accessed January 2020
6. Curcio, J., Leonard, J., Patrikalakis, A.: Scout-a low cost autonomous surface platform for research in cooperative autonomy. In: Proc. of OCEANS 2005 MTS/IEEE. pp. 725–729 (2005)
7. Duarte, M., Costa, V., Gomes, J., Rodrigues, T., Silva, F., Oliveira, S.M., Christensen, A.L.: Evolution of collective behaviors for a real swarm of aquatic surface robots. PloS one **11**(3) (2016)
8. Kam, H.R., Lee, S.H., Park, T., Kim, C.H.: Rviz: a toolkit for real domain data visualization. Telecommunication Systems **60**(2), 337–345 (2015)
9. Kendoul, F.: Towards a Unified Framework for UAS Autonomy and Technology Readiness Assessment (ATRA). In: Nonami, K., Kartidjo, M., Yoon, K.J., Budiyono, A. (eds.) Autonomous Control Systems and Vehicles, pp. 55–71. No. 65 in Intelligent Systems, Control and Automation: Science and Engineering, Springer Japan (2013), `http://link.springer.com/chapter/10.1007/978-4-431-54276-6_4`, dOI: 10.1007/978-4-431-54276-6_4
10. Koenig, N., Howard, A.: Design and use paradigms for gazebo, an open-source multi-robot simulator. In: Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). vol. 3, pp. 2149–2154 (2004)
11. KONGSBERG: GeoSwath 4R USV, `https://www.kongsberg.com/maritime/products/marine-robotics/autonomous-surface-vehicles/geoswath-4r-USV/`, last accessed January 2020
12. Liu, Z., Zhang, Y., Yu, X., Yuan, C.: Unmanned surface vehicles: An overview of developments and challenges. Annual Reviews in Control **41**, 71–93 (2016)
13. Maritime Robotics AS: The Otter, `https://www.maritimerobotics.com/otter`, last accessed January 2020
14. Mendonça, R., Marques, M.M., Marques, F., Lourenco, A., Pinto, E., Santana, P., Coito, F., Lobo, V., Barata, J.: A cooperative multi-robot team for the surveillance of shipwreck survivors at sea. In: Proc. of OCEANS 2016 MTS/IEEE Monterey. pp. 1–6 (2016)
15. Metcalfe, B., Thomas, B., Treloar, A., Rymansaib, Z., Hunter, A., Wilson, P.: A compact, low-cost unmanned surface vehicle for shallow inshore applications. In: Proc. of the IEEE Intelligent Systems Conference (IntelliSys). pp. 961–968 (2017)
16. OceanAlpha: SL20, `https://www.oceanalpha.com/product-item/sl20/`, last accessed January 2020
17. Park, J., Kang, M., Kim, T., Kwon, S., Han, J., Wang, J., Yoon, S., Yoo, B., Hong, S., Shim, Y., et al.: Development of an unmanned surface vehicle system for the 2014 maritime robotx challenge. Journal of Field Robotics **34**(4), 644–665 (2017)
18. Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R., Ng, A.Y.: ROS: an open-source robot operating system. In: Proc. of the IEEE International Conference on Robotics and Automation (ICRA), workshop on open source software. vol. 3, p. 5 (2009)

19. Sanfilippo, F., Tang, M., Steyaert, S.: Aquatic surface robots: the state of the art, challenges and possibilities. In: Proc. of the IEEE International Conference on Human-Machine Systems (ICHMS), Rome, Italy (2020)
20. SeaRobotics Corporation: SR-Surveyor M1.8, `https://www.searobotics.com/products/autonomous-surface-vehicles/sr-surveyor-m1-8`, last accessed January 2020
21. Tanakitkorn, K., Wilson, P.: A new design concept for a fully actuated unmanned surface vehicle. Ocean Engineering (2019)
22. Teledyne Marine: Z-BOAT 1800RP, `http://www.teledynemarine.com/z-boat-1800rp`, last accessed January 2020
23. Villa, J., Paez, J., Quintero, C., Yime, E., Cabrera, J.: Design and control of an unmanned surface vehicle for environmental monitoring applications. In: Proc. of the IEEE Colombian Conference on Robotics and Automation (CCRA). pp. 1–5 (2016)
24. Wang, G., Shi, F., Xiang, X.: Unmanned boat design for challenges and verification of unmanned surface ship intelligent navigation. In: Proc. of the IEEE 8th International Conference on Underwater System Technology: Theory and Applications (USYS). pp. 1–5 (2018)
25. Yan, R.j., Pang, S., Sun, H.b., Pang, Y.j.: Development and missions of unmanned surface vehicle. Journal of Marine Science and Application **9**(4), 451–457 (2010)