Aquatic Surface Robots: the State of the Art, Challenges and Possibilities*

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***Abstract*— In this paper, a survey of the state of the art, challenges, and possibilities for aquatic surface robots is presented. To this end, a survey and classification of aquatic surface robots is first outlined. Then, different levels of autonomy are identified for this typology of robots and categorised into environmental complexity, mission complexity, and external system independence. From this perspective, a step-wise approach is adopted on how to increment aquatic surface robots abilities within guidance, navigation, and control in order to target the different levels of autonomy. Possibilities and challenges for designing aquatic surface robots as carriers for conducting research activities are discussed. The main goal of this paper is to further increase global efforts to realise the wide range of possible applications offered by aquatic surface robots and to provide an up-to-date reference as a benchmark for new research and development in this field.**

***Index Terms*— aquatic surface robots, unmanned surface vehicles, robotics.**

I. INTRODUCTION

Collecting environmental data in aquatic ecosystems is challenging [1]–[3]. It typically requires human-operated research vessels, which are time and cost-inefficient, and it can be dangerous (e.g. scuba diving for sample collection). Unmanned Surface Vehicles (USVs), however, start to make their appearance, predominantly for military and marine purposes [4]. USVs are remotely controlled rafts that can be equipped with various cameras and sensors to collect environmental data [5]. Commercially available USVs are relatively large and heavy (typically 1-10 m, 30 kg - several tons), and costs of purchase are very high [5]. Hence, they are currently unavailable for a broad public, and they are not practical to transport and operate in ecosystems with difficult access (e.g. most rivers and lakes).

The objective of this paper is to further raise awareness of the potential outcomes with aquatic surface robots and provide an up-to-date stepping stone for continued research and development within this field. In this work, we review the state of the art within aquatic surface robots, and give an outline of the current challenges and possibilities within this research area. The identification of various levels of autonomy, such as environmental complexity (EC), mission complexity (MC), and external system independence (ESI), is proposed. To target the different levels of autonomy, we present a step-wise approach on how to increase aquatic surface robot abilities within guidance, navigation, and control (GNC). The underlying idea is shown in Figure 1.

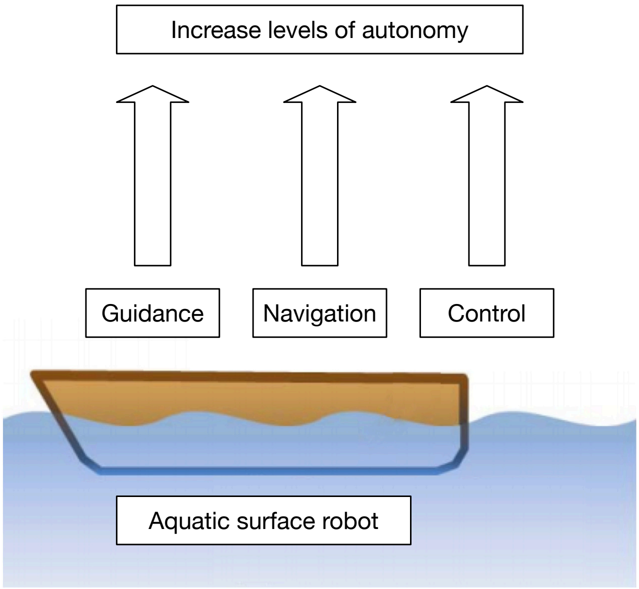

Fig. 1: The underlying idea of applying a step-wise approach on how to increase aquatic surface robot autonomy levels within guidance, navigation, and control (GNC).

The paper is organised as follows. A survey and classification of aquatic surface robots is given in Section II. In Section III, challenges and possibilities in the context of autonomy levels for aquatic surface robots are discussed. In Section IV, we focus on exploring possibilities for designing aquatic surface robots as carriers for conducting research activities. Finally, conclusions and remarks are discussed in Section V.

II. SURVEY AND CLASSIFICATION OF AQUATIC SURFACE ROBOTS

There is a wide range of aquatic surface robots with different size [6]–[11]. The focus of this paper is on reviewing aquatic surface robots that can easily being transported and operated to conduct research activities in ecosystems with difficult access. Therefore, we review small size USVs with no more than 2 m length. The reviewed USVs are shown in Figure 2 and listed in Table I, which in spite of our best effort may not constitute an exhaustive list.

For the considered small size of aquatic surface robots, there are two types of hull generally adopted - catamaran

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type, as shown in Figure 2-a-b-c; - single hull type, as shown in Figure 2-d-e-f. Both of these different types of hull are portable and easy for deploy by one man. The most common actuation system for driving the vehicles is with electric actuators, i.e. thrusters. These systems are used for shallow water surveillance, bathymetric survey and water monitoring, by remote control with telemetry [12]–[17].

The Otter USV is shown in Figure 2-a. It is developed by Maritime Robotics [12] and it is a hydrographic survey tool for mapping of sheltered and enclosed waters. With tight integration between the on-board control system that enables autonomy and the multibeam echo-sounder, a bathymetric survey can be executed with a simple, streamlined workflow. The hull of Otter is a robust catamaran design and the tightly integrated bathymetric survey system makes it a cost-efficient turn-key solution for bathymetric surveys in sheltered waters such as small lakes, canals, rivers, ponds, and harbor areas.

The SR-Surveyor M1.8 USV is shown in Figure 2-b. It is developed by Sea Robotics [13] and it is a highly capable man-portable autonomous hydrographic survey vessel. It is tightly integrated with multiple high-resolution hydrographic sensors and a topographical mapping LiDAR. Its unique sensor suite makes it a versatile system for collecting a wide range of hydrographic data in inland and coastal waters. Its small form factor, light weight, and extremely shallow draft allow it to be rapidly deployed to difficult to access areas.

The Heron USV is shown in Figure 2-c. It is developed by Clearpath Robotics [14] and it is a portable, mid-sized surface vessel. The catamaran design includes anti-fouling thrusters, an incredibly shallow profile, and built in GPS for easy access positioning data. This USV features a payload bay for mounting submerged sensors or equipment on deck. Heron's folding pontoons and quick swappable battery make transport, launch and retrieval a quick and easy process.

The GeoSwath 4R USV is shown in Figure 2-d. It is developed by Kongsberg Maritime [15] and it offers efficient simultaneous swath bathymetry and side scan mapping. The market leading wide swath sonar system - GeoSwath Plus, has been closely integrated with 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.

The SL20 USV is shown in Figure 2-e. It is developed by OceanAlpha [16] and it is a compact and portable USV for hydrographic and bathymetry surveying. Its 177cm moon pool 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 weights 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.

The Z-Boat 1800 RP USV is shown in Figure 2-f. It is developed by Teledyne Marine [17] and it is a high performance portable remotely-operated hydrographic survey boat. It offers 8kt maximum operating speed, an ADCP, a side scan, multibeam sonar payloads, and autonomous waypoint navigation.

Table I summarises the characteristics of these vehicles. The hull lengths are in the range from 1 to 2 m, while their weights differ much, from 10kg to 55kg. Weights above 20kg could be a challenge for one man to deploy and recover the USVs, even though they are portable. They use radio frequency for telemetry communication and navigation, and remote operation range is between 1200 and 6200 m. Their endurance and maximum speeds are also quite different. Minimum endurance for operation is 2 hours at a nominal speed, while batteries can be replaced with standby ones, and charged to full within one day. These two parameters mainly depend on the battery packs and hull design. The information of cost of each USV is limited, while it is reasonable to assume that cost depends on the system performance, including hardware like hull materials, sensors used, batteries, motors, and software for integration and operation level.

Commercial applications of these USVs provides evidence that most of the required technology is mature and available, including sensors, communication and control principals. High-speed with acceptable endurance could be achieved at relatively low cost. However, to the best of our knowledge, a low-cost and open framework for aquatic surface robots is still missing.

III. Challenges and Possibilities in the Context of Autonomy Levels for Aquatic Surface Robots

When designing aquatic surface robots, different levels of autonomy can be identified from an operational point of view. The The Autonomy Levels for Unmanned Systems (ALFUS) group defines autonomy as "A unmanned systems (UMS)'s own ability of sensing, perceiving, analysing, communicating, planning, decision-making, and acting/executing to achieve its goals as assigned by its human operator(s) through designed human–robot interaction (HRI) or assigned through another system that the UMS interacts with" [18]. Various levels of autonomy can be distinguished. Based on this idea, the autonomy and technology readiness assessment (ATRA) framework [19], [20] is adopted and presented to better understand the design of these systems. This choice is motivated by the fact that the ATRA framework is universally recognised by the robotic research community as a standard approach to unify autonomy and technology and therefore it can be used to measure the maturity and robustness of a system. The ATRA framework combines both autonomy levels (AL) and technology readiness level (TRL) metrics. The concepts of environmental complexity (EC) and mission complexity (MC) are also considered to better identify the different levels of autonomy. Additionally, the external system independence (ESI) metric, which represents the independence of snake robots from other external systems


(a) (b) (c) (d) (e) (f)

Fig. 2: Small size USVs with no more than 2 m length: (a) Otter, (b) SR-Surveyor M1.8, (c) Heron, (d) GeoSwath 4R, (e) SL20, (f) Z-Boat 1800 RP.

TABLE I: Existing USVs with smaller length than 2 m

USV name	Manufacturer	L [m]	W [m]	H [m]	Weight [Kg]	Range [m]	Endurance [h]	Max speed [knots]
Otter	Maritime Robotics	2.00	1.08	0.81	55	2500	20.0	5.5
SR-Surveyor M1.8	Sea Robotics	1.80	0.91	1.00	49	6200	5.5	4.0
Heron	Clearpath Robotics	1.35	0.98	0.32	28		2.5	3.3
GeoSwath 4R	Kongsberg Maritime	1.80	0.90		55	1500	6.0	6.0
SL20	Ocean Alpha	1.05	0.55	0.3-	10	2000	2.0	10.0
Z-Boat 1800-RP	Teledyne Marine	1.80	1.00	1.10	38	1200	4	10.0

or from human operators, is adopted. The proposed application of the ATRA framework to aquatic surface robots is shown in Figure 3. When considering aquatic surface robots, identifying and differentiating between consecutive autonomy levels is very challenging from a design point of view. Nevertheless, it is crucial to clearly distinguish autonomy levels during the design process in order to provide the research community with a useful evaluation and comparison tool. Inspired by similarly demanding systems [19], [21], a nine-level scale is proposed based on gradual increase (autonomy as a gradual property) of guidance, navigation, and control (GNC) functions and capabilities. Referring to Figure 3, the key GNC functions that enable each autonomy level are verbally described along with their correspondences with mission complexity (MC), environmental complexity (EC), and external system independence (ESI) metrics (illustrated with a colour gradient).

IV. POSSIBILITIES FOR DESIGNING AQUATIC SURFACE ROBOTS FOR RESEARCH ACTIVITIES

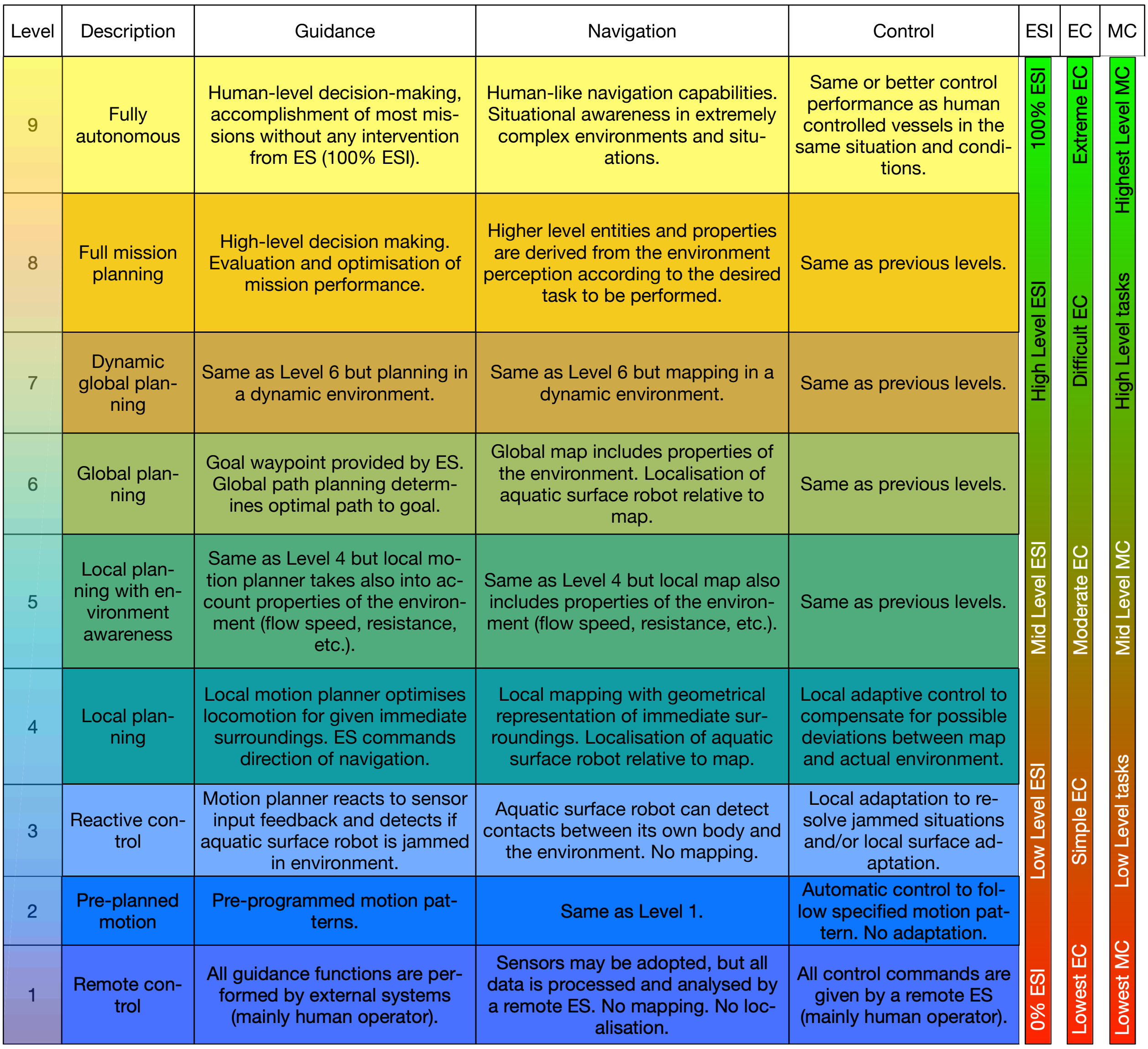
When considering the possibility of designing aquatic surface robots for conducting research activities, a unified design approach is still missing to the best of our knowledge. To contribute towards this direction, a universal framework architecture is proposed in this section.

The following criteria were taken into account when considering the design guidelines for the proposed framework:

- flexibility: the framework must offer the possibility of performing different research activities;
- reliability: the system must be easy to maintain, change and extend as a research tool, by adding new components and features;
- integrability: the framework must allow for future transparent integration with both real robots as well as simulated robots [22].

The proposed framework is shown in Figure 4. A hierarchically organised structure is proposed. The following abstraction levels are defined and listed with a bottom up approach:

- Physical/virtual layer. The framework must be designed to support the physical robot and interact with the real world scenario. Furthermore, the possibility of rapid-prototyping the system throughout simulation must be also considered. In particular, a promising approach consists in developing a digital twin with hardware-in-loop (HIL) simulation [23] to develop the



Level	Description	Guidance	Navigation	Control	ESI	EC	MC
9	Fully autonomous	Human-level decision-making, accomplishment of most missions without any intervention from ES (100% ESI).	Human-like navigation capabilities. Situational awareness in extremely complex environments and situations.	Same or better control performance as human controlled vessels in the same situation and conditions.	100% ESI	Extreme EC	Highest Level MC
8	Full mission planning	High-level decision making. Evaluation and optimisation of mission performance.	Higher level entities and properties are derived from the environment perception according to the desired task to be performed.	Same as previous levels.			
7	Dynamic global planning	Same as Level 6 but planning in a dynamic environment.	Same as Level 6 but mapping in a dynamic environment.	Same as previous levels.	High Level ESI	Difficult EC	High Level tasks
6	Global planning	Goal waypoint provided by ES. Global path planning determines optimal path to goal.	Global map includes properties of the environment. Localisation of aquatic surface robot relative to map.	Same as previous levels.			
5	Local planning with environment awareness	Same as Level 4 but local motion planner takes also into account properties of the environment (flow speed, resistance, etc.).	Same as Level 4 but local map also includes properties of the environment (flow speed, resistance, etc.).	Same as previous levels.	Mid Level ESI	Moderate EC	Mid Level MC
4	Local planning	Local motion planner optimises locomotion for given immediate surroundings. ES commands direction of navigation.	Local mapping with geometrical representation of immediate surroundings. Localisation of aquatic surface robot relative to map.	Local adaptive control to compensate for possible deviations between map and actual environment.			
3	Reactive control	Motion planner reacts to sensor input feedback and detects if aquatic surface robot is jammed in environment.	Aquatic surface robot can detect contacts between its own body and the environment. No mapping.	Local adaptation to resolve jammed situations and/or local surface adaptation.	Low Level ESI	Simple EC	Low Level tasks
2	Pre-planned motion	Pre-programmed motion patterns.	Same as Level 1.	Automatic control to follow specified motion pattern. No adaptation.			
1	Remote control	All guidance functions are performed by external systems (mainly human operator).	Sensors may be adopted, but all data is processed and analysed by a remote ES. No mapping. No localisation.	All control commands are given by a remote ES (mainly human operator).	0% ESI	Lowest EC	Lowest MC

Fig. 3: The ATRA framework [19], [20] applied to aquatic surface robots with the different levels of external system independence (ESI), of environmental complexity (EC) and of mission complexity (MC). ES refers to “External System”.

system more safely, rapidly and efficiently [24];

- Carrier layer. It is the layer that is strictly needed for guidance, navigation and control (GNC). This layer is normally designed by robotics experts. This layer include the following components:
  - Mechanical interface. A modular approach must allow for selecting different typologies of hull;
  - Hardware interface. This includes all sensors and actuators that are absolutely necessary for achieving the GNC functions;
  - Software interface. This includes the control software that make it possible to achieve the GNC functions;
- Add-on layer. This layer is specifically designed to make it possible to use the aquatic surface robot for a variety or research activities. This layer makes it possible to add extra sensors, actuators and software apps that are not 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;
- Application layer. This is an additional layer that

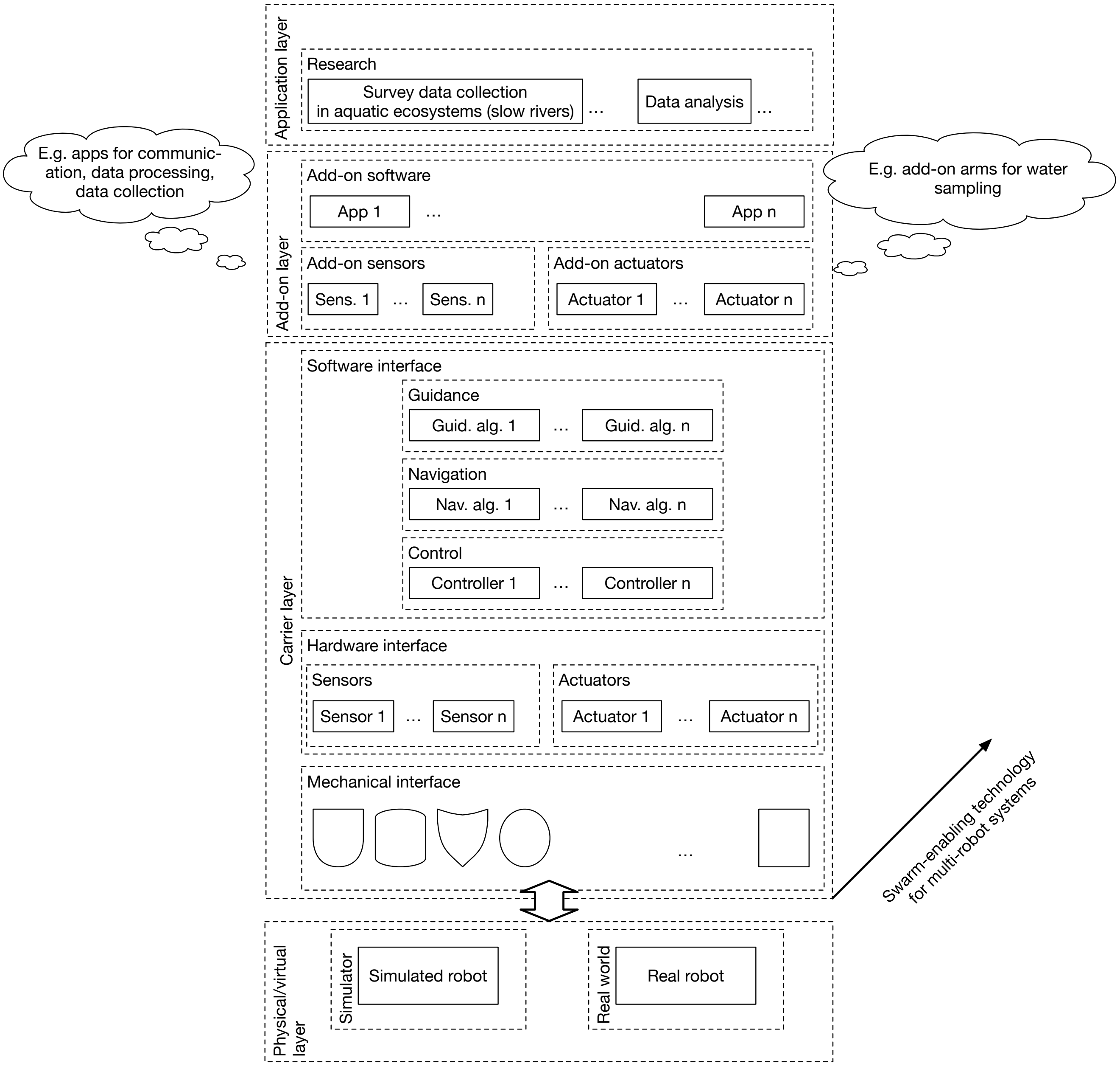


Fig. 4: The proposed universal framework for designing aquatic surface robots.

can be used 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 [25]–[27]. The framework address some of the challenges and open possibilities in this domain by providing a universal design approach.

V. Concluding Remarks

In this work we surveyed and discussed the state-of-the-art, challenges, and possibilities with aquatic surface robots. We reviewed existing literature relevant for aquatic surface robots with length smaller than 2 m. Furthermore, we proposed a division of levels of autonomy inspired to the traditional robotic design standards and suggested a step-wise approach to increasing the level of autonomy within three main robot technology areas: guidance, navigation, and control (GNC). We also discussed possibilities for designing such systems as carriers for conducting research experiments. In particular, a modular architecture was proposed.

Aquatic surface robots have potential for being adopted in a variety of applications [28]. One of the fundamental targets of this paper is to further increase global efforts to realise the large variety of application possibilities offered by these systems and to provide an up-to-date reference as a stepping-stone for new research and development within this field.

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