A Critical Survey On Marsupial Robotic Teams for Environmental Monitoring of Water Bodies

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***Abstract*— A robust maintenance of ecosystems demands for highly accurate and frequent monitoring of their status. The extension and remoteness of some environments renders their human-based monitoring extremely difficult. Riverine environments are a notorious example, as their sampling requires to bear into account both streams and riverbanks. The relevance of monitoring riverine environments is magnified by the intricate interactions that occur between river waters and coastal waters. This article provides a critical survey of existing solutions using robots for environmental monitoring of water bodies. Based on the survey, this article argues that autonomous robotic marsupial systems are especially adequate for the tasks at hand. Lessons learned, as well as future avenues on the application of marsupial robotic teams to environmental monitoring, are laid out in this article.**

I. INTRODUCTION

In the endeavor of maintaining our ecosystems, the ability to monitor and sample the environment is a pivotal effort. Currently, this is a human-centred activity in which complex sampling protocols are sometimes performed under extreme conditions in inhospitable settings. Technology has long been an important and crucial aid to environmental monitoring, from satellite remote sensing to widespread small and large scale sensor networks.

As in many other domains, field robots are steadily being introduced in environmental monitoring operations. This progressive acceptance stems from the fact that robots enable detailed spatiotemporal analysis and sample collection, and return, which are tasks difficult to implement with the techniques traditionally involved in environmental monitoring campaigns. These robots already monitor climate changes, measure air and water quality, monitor volcanic areas, respond to radiological disasters, among others. Refer to [1] for a survey on field robotics' environmental monitoring applications.

Robots are complex machines whose autonomous behaviour greatly depends, among many other factors, on energetic efficiency and ability to robustly perceive the surrounding environment. Hence, the use of robots is not absent of difficulties. A way of mitigating some of these difficulties is to build robotic teams, so that robots can help each other by compensating individual limitations. Marsupial robotic teams, that is, teams composed of robots that are able to carry other robots, are particularly interesting for the monitoring of water bodies. For instance, a marsupial team composed of a water surface vehicle capable of carrying an aerial vehicle allows, for instance, to join the wide field of view offered by the aerial vehicle with the endurance of the water surface vehicle [2] (see Fig. 1).

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Fig. 1. RIVERWATCH marsupial robotic team composed of an Autonomous Surface Vehicle (ASV) and an Unmanned Aerial Vehicle (UAV) [2].

This paper is organised as follows. First, an overview of current applications, techniques, and morphologies of robots applied to environmental monitoring of water bodies is provided in Section II. Then, the marsupial robotic team concept is described in Section III. Afterwards, a set of unresolved challenges are depicted in Section IV. Finally, some conclusions and future work directions are drawn in Section V.

II. ENVIRONMENTAL MONITORING OF WATER BODIES

In this section a brief overview of the techniques used in environmental monitoring focused on water bodies is provided. First, well-established approaches, such as sensor networks and remote sensing techniques, are described. Then, an analysis on the use of field robots for such applications is given. Both airborne and waterborne type of vehicles will be covered in this analysis, which will also address energy management, sensory capabilities, and real life use cases.

A. *Sensors Networks*

The conventional approach of using sensor networks for maritime environmental monitoring [3], [4] has considerable limitations when the task requires the gathering of spatiotemporally dynamic data. Static sensor networks' scalability builds on increasing the cardinality of network nodes, which limits the coverage range in large environments [5]. Despite of their usual low complexity nodes, sensor networks also suffer for energy limitations. Recent implementations use energy harvesting mechanisms to increase the network nodes' lifetime, reliability, and cost effectiveness [6]. Another limitation of sensor networks is their difficulty to assure continuous communication and data storage. In the absence of these functional requirements sensor networks have shown to be successful in water monitoring in riverine [7] and wetland [8] environments. The conventionally low complexity of these kind of sensor platforms limits their payload. Nevertheless, recent developments have shown that that multidimensional sensory data, such as image, video, and 3D profile streams, can also be provided by sensor networks [9]. Despite these advances, sensor networks suffer from two main drawbacks. First, they are (quasi-)static and, so, they have limited spatiotemporal coverage. Second, they have limited sample collection and return capabilities.

B. Airborne Environmental Monitoring

A successful and widely exploited alternative to *in situ* environmental monitoring analysis stands on remote sensing from satellite multispectral imagery [10]. A typical application of remote sensing techniques is the detection of oil spills [11]. However, the cost and spatiotemporal sparsity of satellite data hampers a fine tracking of the ecologically relevant event. This fact triggered intense research on the development of autonomous aerial vehicles for environmental monitoring.

Fixed-wing unmanned aerial vehicles have been extensively used for monitoring waterways [12]. These have been shown to endure difficult weather conditions in an energetically efficient way [13], making them most adequate for long surveys. By using seaplanes, able to land on the water body itself, extensive landing areas over ground are no longer required.

Despite their success, the low maneuverability of fixed-wings aerial vehicles impairs applications requiring precise *in situ* sampling. Moreover, fixed-wings aerial vehicles are difficult to land on surface vehicles and, thus, cannot benefit from long-range transportation by water surface mid-sized vehicles (see Section III). In recent years the use of rotary-wings unmanned aerial vehicles for environmental monitoring increased with the introduction of the now common configurations based on multiple rotors with vertical takeoff and landing abilities. Refer to [14] for a recent survey on small-sized unmanned aerial vehicles.

Multi-rotor aerial vehicles combine high manoeuvrability with low mechanical complexity. Manoeuvrability is key for precise sample retrieval in water bodies as well as in the riparian area. Low mechanical complexity fosters cost effectiveness and robustness. These assets led to a mass adaption of these multi-rotor aerial vehicles to mapping applications [15], precision water sampling [16], [17] (see Fig. 2), freshwater temperature monitoring [18], among others. Conversely, multi-rotor small-sized vehicles display limited energetic autonomy, which hinders their application to long surveys.

To increase flight range without reducing manoeuvrability, recent efforts have been made to join the multi-rotor and fixed-wing configurations [19]. However, the resulting hybrid is still unable to gather and transport large sampling volumes, neither carry complex and bulky onboard water analysis equipment.

Fig. 2. UAV water sampling [16], [17] (Image courtesy of John Paul-Ore)
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In addition to detecting and monitoring the evolution of an ecologically relevant event, it is often useful to perform an *in situ* analysis, sample collection, and sample return for subsequent studies and law enforcement. Ground-level detailed mapping of riverbanks and adjacent land is yet another relevant and infeasible task for solutions that rely solely on satellite imagery. Detailed mapping of riverbanks with trees and thick vegetation can only be properly done from a low vantage point, the one available to a water surface vehicle.

C. Waterborne Environmental Monitoring

The ability that water surface vehicles have of moving along the water body is key to overcome the drawbacks of remote sensing, namely, the inability to perform *in situ* analysis, sample collection, and detailed riverbank mapping.

Marine robotics has a long history dating from 1970's, covering numerous applications. Refer to [20], [21] for surveys on the evolution and trends of marine robotics. However, marine robots are still limited in their ability to operate robustly for long periods of time in certain situations [1] and environments such as riverine settings.

Buoyancy-driven wave gliders designed for oceanic operation have already performed long survey missions [22]. For long-lasting operation, harvesting solar energy has been used [23]. Unfortunately, glider buoyancy is unsuitable in shallow waters, rivers, and estuaries. Additional weaknesses of gliders for the monitoring of riverine and estuarine environments include low speed and low vantage point of its onboard sensors, which hampers the clear view of the far-field that is required for safe navigation and riverbank mapping.

Autonomous surface vehicles based on a traditional airboat design with flat bottom have been shown to move robustly on shallow waters [24], hence, enabling the monitoring on a wide new range of ecologically sensitive areas. The small size of these vehicles limits the water sampling volumes and onboard analytics. Conversely, larger boat-like surface vehicles do not exhibit these limitations, provided there is enough water body depth for a safe operation. Boat-like surface vehicles have been applied on a wide range of environments, such as open oceanic waters [25], inland water bodies [26], nearby man-made structures [27], and riverine environments [2], [28] (see Figs. 1,3).

Fig. 3. Roaz II [28] (Image courtesy of Hugo Ferreira).

The ability of autonomous surface vehicles to perceive the far-field is limited by the low vantage point of their sensors, which is particularly stringent for small- and mid-sized vehicles [29] (e.g. see Fig. 1 and Fig. 3). Such a limited field of view limits these vehicles' ability to robustly infer the navigation cost of the far-field with an adequate look-ahead range and, as a result, of avoiding obstacles without unnecessary energy expenditure.

III. Marsupial Robotic Systems

One way of reducing the short sightedness of water surface vehicles is to augment the vehicle's onboard sensory feedback with overhead imagery obtained by either aerial vehicles or satellites. However, solutions based on satellite imagery to aid the surface vehicle on long-range path planning despite functional [30] suffer from the images outdating problem. By using aerial vehicles rather than satellite imagery, this problem is mitigated. That is so because aerial vehicles are able to gather information on demand.

As we have seen, the lack of maneuverability of aerial vehicles with fixed wings render multi-rotor configurations more adequate to support the water surface vehicle. A multi-robot team composed of a multi-rotor aerial vehicle and a water surface vehicle was demonstrated by Murphy et al [31]. However, multi-rotor configurations are endowed with limited energetic autonomy, which imposes a small operation range to the robotic team. The operation range can be increased with a marsupial configuration, in which the water surface vehicle piggybacks the multi-rotor aerial vehicle [2], [32].

Marsupial robotic teams join the robustness and energy capacity of surface vehicles with the versatility of aerial vehicles for far-field inspection. The surface vehicle provides shelter to the aerial one, whereas the latter augments the former's perception of the environment. In this sense the overall performance of the robotic team is increased. This concept was initially validated with human operators controlling the robot-robot interactions [32] and, recently, with autonomous robots in the RIVERWATCH experiment [2] (see Fig. 1). Such autonomy is key to handle the inhospitality of riverine environments and the unreliability of communication channels linking operators to robots.

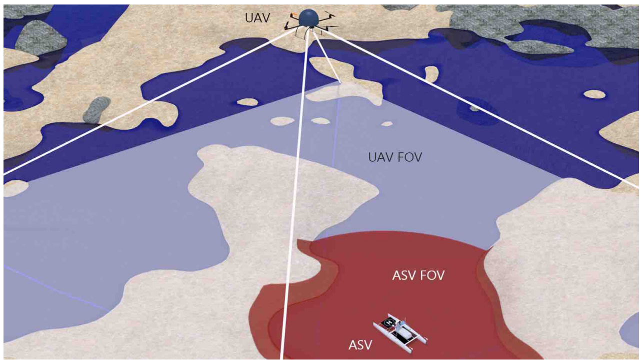


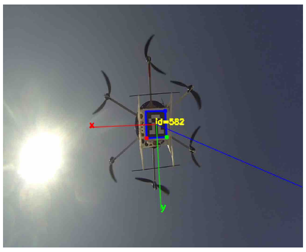
Fig. 4. RIVERWATCH's marsupial robotic team concept. The red overlay is a reference to the Autonomous Surface Vehicle (ASV) field of view (FOV), the white to the Unmanned Aerial Vehicle's (UAV's)

In the RIVERWATCH experiment[1], a $4.5\,\mathrm{m}$ catamaran-like Autonomous Surface Vehicle (ASV) carries a multi-rotor Unmanned Aerial Vehicle (UAV) (see Fig. 1). The large size of the ASV allows the retrieval of samples while at the same time provides a stable platform for the UAV docking [33]. Similarly to the work of Heidarsson and Sukhatme [34] the coordinated perception of aerial, surface, and underwater sensory feedback allows the exploitation of both robots' field of views (see Fig. 4): (1) the ASV creates local navigation cost maps based on its onboard sensor information; (2) the UAV takes off and learns an image classifier exploiting the overlap existent between both robots' field of views, and by associating its visual input with the ASV's local navigation cost maps; (3) the image classification is then applied to extend the ASV's navigation cost maps reach; (4) the UAV docks in the ASV; (5) the ASV then navigates using the augmented perception of the far field. As a result, a more energetically efficient and safer navigation is attained. A typical water-land segmentation obtained by the aforementioned method is depicted in Fig. 6.

Landing a multi-rotor UAV on an helipad is a complex vision and control problem that has been tackled by many [35], [36], [37]. To reduce the chances of failure, we have proposed a method in which both UAV and ASV cooperate throughout the landing procedure [33]. Controlled by a behavioural architecture, the UAV searches for the helipad when the latter is outside the former's field of view. For this purpose, memory of previous detections and spiral search patterns are employed. When the ASV is in the UAV's field of view, the former is tracked based on its appearance, which the UAV has learned during take-off. Moreover, visual saliency information is used to guide the detection process; note that in water environments objects are salient with respect to the somewhat homogeneous background, that is, the water surface. In the final phase of the descent, the ASV becomes responsible for tracking the UAV. For this purpose, the UAV is equipped with an augmented reality marker, which is used by the ASV to estimate the UAV's 6-DOF pose at each instant. Fig. 5 depicts typical results of the

[1] `http://riverwatchws.cloudapp.net`

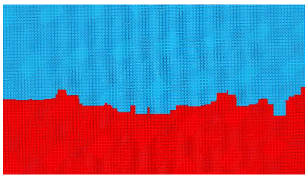
(a)



(b)

Fig. 5. Typical results obtained with the mutual detection method used for landing the UAV on the ASV [33]. (a) Detection of the helipad (red circumference) from the UAV's downwards looking camera. (b) Pose estimation of the UAV from the ASV's upwards looking camera.

(a)



(b)

(c)

Fig. 6. (a) An example of aerial shot taken by the UAV during a far field survey. (b) The input image transformed into a cost map using the technique explained in [2] with red and blue representing land and water segments, respectively. The cost map is fed into the safe navigation system of the surface vehicle. (c) Example of an image mosaic obtained during a survey on the 2014 Portuguese Navy's Robotics Exercise (REX).

UAV-ASV mutual detection method.

The augmented shared perception allows a timely detection and avoidance of usual riverine obstacles like shoals and rapids. This enhanced perception is facilitated by having the robots sharing the computational load; with its higher processing power, the ASV is able to process information sent by the aerial platform that could not be processed by the UAV alone.

The versatility of the UAV means that it is possible to sample riverbanks and margins that ASVs even with low draught cannot attain. Subsequently, the samples can be transferred to the ASV for analysis and safekeeping, thus enlarging the sampling coverage of the team.

Given the inherent multiple sensor modalities and vantage points, marsupial robotic teams are also suitable for accurate terrain modeling [38]. High resolution digital terrain modeling fed by different data acquisition methods render possible to identify the crucial morphological changes that explain water channels evolution.

IV. Open Challenges

Although the basis of the marsupial robotic team concept for environmental monitoring of water bodies has been laid down, there are still many challenges to tackle before practical applications can be fully targeted. The challenges include development or improvement of robotics simulators control and navigation methods, shared cooperative perception and docking procedures, autonomous task planning, and long-lasting operation and energy harvesting strategies.

A. *Robot Simulation in Water Bodies*

A big issue in developing multi-robot systems for natural environments is the cost of debugging. Material gets damaged easily and each testing run is too time consuming for a proper development cycle. This challenges are often overcome with the extensive use of simulators. In the case of water environments' simulators, most of the development so far has been in underwater sub-domain. Refer to [39] for a survey on underwater simulators. The choice for simulating surface vehicles is narrower; nevertheless there are a few simulators currently in development, such as MARS [40] and Kelpie [41]. While MARS allows both underwater and surface vehicles, Kelpie simulates aerial and water surface vehicles. Additionally, Kelpie is a modular and open-source multi-robot simulator fully integrated with the Robotics Operation System (ROS), which is becoming a *de facto* standard in the robotics community. One open issue with simulators like Kelpie and MARS is that wind and water currents are computed based on force vectors and simplified models. This way complex interactions among waves and wind are disregarded. To test the effects caused by such environmental factors on the vehicles' dynamics the simulation should be extended to encompass realistic wind and water flow models.

B. *Cooperative Docking*

Reliable all-weather docking mechanisms are of the highest importance for a marsupial robotic team that requires long-term power sharing between its members and the ability to provide shelter and long range transportation to the piggybacked vehicle. A possible safety measure against harsh weather conditions during the docking procedure is to use smart fixture mechanisms capable of grasping the UAV in the descent's final phase. There is some previous work in this topic [42], but it is still limited to a very small workspace. Moreover, the ability to exploit distal sensory feedback to guide the rendezvous is still missing. All these features are key if the team is to endure demanding weather conditions.

Unless the ASV is always within the UAV's reach, which would limit the behavioural autonomy of the ensemble, emergency situations may require the UAV to land in an alternative site. To avoid the inherent risks imposed by such a manoeuvre, further work is required to understand how the ensemble should handle the autonomy-safety trade-off, that is, how much both robots can be set apart to meet the task requirements without hampering safety. Even if the team is equipped with such a decision making process, there will always be situations in which landing on the least-dangerous safe site will be required.

In riverine environments, alternative landing sites can be found in vegetation-free areas on the river margins. Detecting suitable shores and selecting the one to tackle, given the vehicle's characteristics and considering the local risks and efforts the docking implies, is still an open problem. Furthermore, the actual manoeuvring that leads to the final approach, during which contact is expected in potentially vegetated terrain, is a complex problem requiring fine sensorimotor coordination. Hence the complete awareness and ability of an ASV to dock safely on land is an arduous but pressing problem to enable long-lasting autonomous surveying.

In maritime and large estuarine environments, the UAV must face the need to land on the water surface. From early on in aeronautics the exploitation of water as a landing medium proved to be a valid approach. Recently, some commercial waterproof multi-rotors were developed using this approach, which enables emergency landings on the water surface. Moreover, these new platforms will enable new applications, such as *in situ* water sampling on very shallow waters and ecologically sensitive areas. Research is also required to understand how the UAV can be detected and picked-up by the ASV after the emergency landing procedure.

Interestingly, the ability to perform emergency landings is of great use for an application-driven need, namely, inland delivery of samples collected by either UAV or ASV. This is an open problem whose solution is key to a proper fielding of these robotic systems.

C. Shared Perception

The use of marsupial robotic teams to perform cooperative traversability analysis could be further investigated. A key topic to address is the development of environment representations capable of harmoniously encompassing sensory data produced by the heterogeneous sensors spread across the multi-robot team, which includes multispectral imagery, laser scanners, underwater sonars, radars, among others.

The integration of all sensory data depends greatly on an accurate estimation of the relative pose between robots as well as on a robust registration between the heterogeneous sensory data samples. The difficulties imposed by challenging weather conditions and material degradation call for further research on robust inter-robot localisation and registration techniques.

As the volume of sensory data produced by the robots rises, issues related to compressed, progressive, and selective transmission over wireless communication channels becomes more prominent. This problem is aggravated by the heterogeneous nature of the data to be shared. Hence, normalisation efforts must be put forth so that robots can be teamed in a seamless way.

The storage of all shared data on the robots is key to enable lifetime learning and, so, to promote their autonomous behaviour. However, maintaining the high density of team-wise sensory feedback locally available in small sized and energetically limited robots may be a concern. As a result, techniques capable of handling a proper selection and compression of the data to be locally stored in each robot must be studied. In addition, techniques must be included to enable out-of-core processing.

Multi-robot sensor planning strategies must be considered to determine when and where each robot must forage for new sensory feedback. This is a particularly interesting problem as robots need to forage for data for themselves and for the other teammates.

An interesting unexplored application of shared perception in marsupial robotic teams, besides supporting safe navigation, is long-lasting non-intrusive sea wildlife monitoring. Operational costs for deploying manned teams could be reduced if such detection and tracking tasks could be supported or delegated to an autonomous marsupial robotic team. Detection and tracking of water pollutants (e.g., oil spills) are high-endurance maritime tasks that could also benefit from marsupial robotic teams. These robots could also gather considerable evidence for subsequent law enforcement, such as determining the responsible vessel's license plate from aerial imagery.

V. Conclusions

This paper provided a critical survey on several techniques employed for environmental monitoring of aquatic environments. The major techniques covered by the survey include sensor networks, remote sensing, and the more recent developments on the application of tele-operated and autonomous robots to the domain. The survey shows that robotics is gaining terrain in the environmental domain as they provide the ability to perform accurate and long-lasting spatiotemporal analysis and sampling. Multi-robot teams, in particular those implementing marsupial-like robot-robot interactions, have been shown to widen the application range of robotics in the environmental monitoring domain. Concretely, the critical literature survey shows that the marsupial configuration of multi-robot teams increases the overall robustness of systems by joining the high endurance afforded by water surface robotic systems with the far field perceptual capabilities of aerial vehicles. The survey is accompanied with a set of open problems deserving attention from the research community, such as enabling operation and docking in adverse weather conditions.

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