A Cooperative Multi-Robot Team for the Surveillance of Shipwreck Survivors at Sea

Ricardo Mendonça[1], Mario Monteiro Marques[2], Francisco Marques[1], André Lourenço[1], Eduardo Pinto[1], Pedro Santana[3], Fernando Coito[1], Victor Lobo[2] and José Barata[1]

Abstract—**The sea as a very extensive area, renders difficult a pre-emptive and long-lasting search for shipwreck survivors. The operational cost for deploying manned teams with such proactive strategy is high and, thus, these teams are only reactively deployed when a disaster like a shipwreck has been communicated. To reduce the involved financial costs, unmanned robotic systems could be used instead as background surveillance teams patrolling the seas. In this sense, a robotic team for search and rescue (SAR) operations at sea is presented in this work. Composed of an Unmanned Surface Vehicle (USV) piggybacking a watertight Unmanned Aerial Vehicle (UAV) with vertical take-off and landing capabilities, the proposed cooperative system is capable of search, track and provide basic life support while reporting the position of human survivors to better prepared manned rescue teams. The USV provides long-range transportation of the UAV and basic survival kits for victims. The UAV assures an augmented perception of the environment due to its high vantage point.**

I. INTRODUCTION

The number of individuals trying to enter illegally in Europe by maritime route across the Mediterranean is growing every year. According to the International Organization for Migration, up to 3072 migrants died or disappeared in 2014 in the Mediterranean, while trying to migrate to Europe. Overall estimates are that over 22000 migrants died between 2000 and 2014. In April 2015, at least five boats carrying almost two thousand migrants to Europe sank in the Mediterranean Sea, with a combined death toll estimated at more than 1200 people [1]. Therefore, it is crucial to have autonomous systems that are able to survey and detect human beings on water, effectively helping the manned Search And Rescue (SAR) teams, specially in scenarios with low visibility as fog or night.

Mobile robots have been used in search and rescue teams on different scenarios [2], [3], [4]. Either being tele-operated or autonomous, robots can provide the required perception data of harsh and harmful environments for human search and rescue teams. For instance, aerial robots could complement the search and rescue operations by sweeping areas where victims might be, contribute for the sectorization and reduction of the search area, localizing victims, tracking them and providing real time and precise information about victim locations to maritime SAR teams.

[1]Faculty of Sciences and Technology, New University of Lisbon, (FCT-UNL), Caparica, Portugal

[2]CINAV, Portuguese Navy Research Center, Almada, Portugal

[3]ISCTE-Instituto Universitário de Lisboa, (ISCTE-IUL), Portugal

Fig. 1: *Vigil R6-WT* UAV hovering above a salient target while waiting for its partner, the *Pelagi* USV, to arrive and check if a shipwreck survivor was found.

II. RELATED WORK

Being densely populated areas, urban scenarios have become a quite common application context of search and rescue robots [5], [6], [7], [8]. Such popularity encouraged the devising of test arenas and performance metrics for robots in metropolitan SAR operations [9]. Contrariwise, only a few works had been done towards search and rescue in the maritime environments [10], [11]. In particular, Darius and ICARUS are two FP7 projects that use both Unmanned Aerial Vehicles (UAVs) and Unmanned Surface Vehicles (USVs) in SAR operations. In these projects, the heterogeneous unmanned vehicles are integrated in command and control systems [12]. Another interesting project is SEAGULL, funded by the Portuguese National Strategic Reference Framework (QREN), for the development of intelligent systems to support maritime situation awareness: tracking systems, recognizing behavioural patterns, and georeferencing oil spills [13].

The main challenge in the search of human survivors adrift at the sea is their visual detection. Observing vast regions in both ship-based or airplane-based surveillances, while looking for small targets over the highly dynamic sea background can cause vision fatigue, leading to human errors. The same also applies to the detection of lifeboats or life rafts. In this sense, Westall et al. evaluated several vision techniques applied to the aerial search of humans in maritime environments [14]. Sumimoto et al. devised a vision-based system that exploits the typical colour of these rescue vehicles [15]. However, false positives may occur if objects adrift at sea share the same colour as rescue vehicles. A more interesting approach lies in the use of visual saliency-based detection methods, as rescue vehicles are designed to be visually conspicuous on the sea background. This approach has the advantage of being robust to variations of both colour and geometry providing that these features remain salient in the visual field. In this line of approach, a saliency accumulation method between adjacent frames, in both space and frequency domains, was used to find salient targets in maritime search and rescue [16]. Nonetheless, similarity between small targets and sea clutter, in the sense of visual conspicuity, may still produce false positives. Additionally, thermal cameras play a crucial role to search for poorly conspicuous targets or to mitigate the false positives of sea clutter. Being sensible to heat radiation, these devices segment their visual field into several temperature regions that allow the distinction of human heat from other sources.

In this work, the proposed approach combines visual saliency along thermal signatures in a cooperative manner, embodied by a marsupial UAV-USV robotic team. The aerial robot rapidly covers large water regions from a high vantage point, while analysing its top-down view using visual saliency (see Fig. 1). Salient targets are then filtered out by their heat signature, using a water surface vessel equipped with a thermal camera. The latter robot is slower than the aerial one, but provides long-range transportation of the former, supports a heavier sensor payload (see Section III-A) and longer power autonomy. The goal of the proposed approach is to bring the laborious surveillance tasks to the robotic team and, only when a suitable target is found, the system requests the help of a human operator to corroborate the presence of a human survivor.

III. The Robotic Team

Similarly to [17], the proposed team for SAR operations at sea is composed of a USV piggybacking a UAV with vertical take-off and landing capabilities. However, in this work the aerial robot is a watertight version as presented in [18].

A. Unmanned Aerial Vehicle

The aerial vehicle, named *Vigil R6-WT*, is a six-rotor solution that is able to take-off and land on solid ground as well as on water surfaces (see Fig. 2). The communications are ensured using wireless radios from the Ubiquiti Networks airMAX. *Vigil R6-WT* uses the VRBRAIN hardware from VirtualRobotix as the low level control board, already equipped with GPS and IMU, and an Odroid-XU from Harkernell for high level processing. Perception is ensured by a downwards-facing RGB monocular camera. This vision system is protected inside a plastic dome for an unobstructed $150°$ view.

B. Unmanned Surface Vehicle

The water surface vehicle, named *Pelagi*, is an adapted 4.5 m Nacra catamaran (see Fig. 3). To piggyback an UAV, its deck is equipped with a docking station. Two fixed electric motors provide differential propulsion. *Pelagi*'s environment perception is ensured by a long range tilting SICK laser scanner, tilted Imagenex sonar, a $360°$ field-of-view camera from PointGrey, and a Quark2 thermal camera from FLIR. For localization purposes, the water surface robot is equipped with a 2 cm horizontal accuracy Global Positioning System (GPS) from Ashtec, and an Inertial Measurement Unit (IMU) from Phidgets. Electrical power for all this hardware is assured by two banks of 100 Ah batteries (25.6 V) with a Battery Management System (BMS) from JSC Elektromotus. The energy's distribution and the required fail-safe mechanisms are ensured using a custom board, designed specifically for *Pelagi* and capable of interfacing with the BMS. For further detail please refer to [19]. Optionally, it can be equipped with basic survival kits, if needed by the shipwreck survivors.

Fig. 2: *Vigil R6-WT* UAV airborne during a SAR mission.

Fig. 3: *Pelagi* during the field trials.

Both robots' system was developed using the Robot Operating System (ROS) [20], which is a well-known de facto standard framework for robots. ROS provides a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust software systems for robots.

IV. Cooperative Behaviour

The described robotic team cooperates to accomplish in a timely manner the assigned search and rescue mission. *Pelagi* provides an energy saving and long-range transportation of the aerial robot (when needed) and superior computational capabilities. This processing power is exploited to run crucial perceptual processes which are key for safe navigation and robust cooperative behaviours. In turn, *Vigil R6-WT* ensures an augmented and faster, although coarser, perception of the environment due to its high vantage point. All sensory data are accumulated and processed by *Pelagi* in order to build a bidimensional robot-centric cost map used for its safe navigation. The cost map is an integration of a set of partial bidimensional cost maps obtained from the different sensory modalities. The superposition of several cost maps is possible due to the rigid transformation between all sensor devices and also between both robots. The former is estimated via calibration and the latter by sharing the robots' GPS positions.

For a more accurate perception of the environment, the robotic team relies on *Pelagi* as it is equipped with more suitable sensors than its airborne partner. In particular, its own thermal camera is pivotal to corroborate the presence of shipwreck survivors and lifeboats reported by *Vigil R6*. Basic survival kits may also be available on *Pelagi* for shipwreck survivors, as well as, a communication system capable of broadcasting the location for the respective authorities.

A. Mission Control Centre

The mission control centre is a web-based application that allows the remote operator to perform off-line mission planning as well as its on-line monitoring. A sequence of mission waypoints for the robotic team are created here on top of satellite imagery, as depicted in Fig. 4. This sequence is transmitted to *Pelagi* and when the mission starts it will navigate to the first waypoint, as described in the mission work-flow.

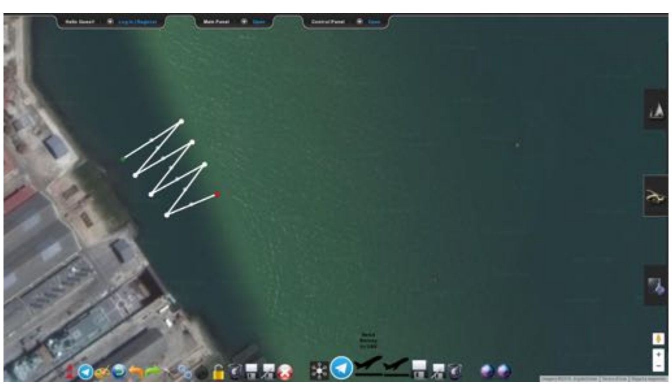


Fig. 4: Web-based mission control centre with an example of a grid-like flight pattern to be executed by *Vigil R6-WT* after its take off from *Pelagi*, when the latter arrives to its first mission waypoint.

B. Mission Work-flow

During a search and rescue mission, the robotic team executes the following work-flow:

1. While piggybacking *Vigil R6-WT*, the water surface robot navigates to a mission-defined GPS position;
2. When the robotic team arrives at the defined waypoint, *Vigil R6-WT* takes off and climbs to an altitude that allows it to cover a large water region while not hampering the visual detection of lifeboats of shipwreck survivors;
3. Exploiting the extended area coverage due to its high vantage point, the aerial robot performs its survey flight to find salient objects adrift at sea (see Section IV-C);
4. If any potential target is detected from the aerial perspective (see Section IV-D), *Vigil R6-WT* approaches and hovers around the target, while reporting its current location to *Pelagi*. The latter navigates towards those GPS coordinates to assess if the target's temperature is similar to that of a human body. To accomplish this task, thermal signatures are collected by *Pelagi*'s infrared camera. In case of a positive detection, the robotic vessel communicates its findings by sending a colour image from its *Ladybug3* camera to the mission control centre;
5. When a notification arrives at the mission control centre, a human operator inspects the image and if the target is a true positive dispatches a human search and rescue team to the reported location. Meanwhile, *Vigil R6-WT* docks in *Pelagi*'s helipad and the latter waits for the search and rescue authorities. The water surface robot may be equipped with any basic life support (e.g., food and drinking water) for the survivors;
6. If both robots do not find anything interesting, *Vigil R6-WT* docks in *Pelagi* using the procedure described in [21]. The robotic team then moves to next waypoint defined in its mission. The mission workflow repeats until no more waypoints are left to visit. Whenever *Vigil R6-WT* is low on battery or when the mission is aborted it immediately flies back to dock in *Pelagi*.

C. Aerial Search Pattern

In order to initiate the aerial search for lifeboats or human survivors, *Vigil R6-WT* takes off and climbs to a pre-defined altitude. The aerial search behaviour is performed as a grid-like flight pattern (see Fig. 4) in order to survey rapidly a large area created around the take-off coordinates.

Cartesian coordinates of each computed waypoint, coherent with the Universal Transverse Mercator (UTM) coordinate system, are converted to latitude and longitude coordinates before being sent to the UAV's control system as the next waypoint to be tracked.

D. Salient Target Detection

The sea is visually characterized by a rather monotonous texture and almost no variation in colour when observed from an aerial perspective. In this sense, floating objects are salient regions in the visual field if they contain distinct textures and colours from the ones typically observed on the water. Lifeboats and rafts are particularly designed to be such noticeable objects when they are adrift at sea (see Fig. 5). Exploiting this assumption, a bio-inspired visual attention model [22] is used to detect salient regions from aerial imagery.

A set of visual feature maps is computed from the RGB frame captured by *Vigil R6-WT*'s camera during the described search pattern. This set is composed of an intensity feature and two double-opponency colour features, red-green and blue-yellow. Each feature map is then transformed into its respective visual conspicuity map through a centre-surround operator, as described in [22]. The output is a set of centre-surround feature maps that highlight the regions of the scene that strongly differ from their surroundings. This centre-surround operator starts by computing one dyadic Gaussian image pyramid with eight levels from the intensity channel.

Two additional image pyramids, also with eight levels, are computed to account for the red-green and blue-yellow double-opponency colour feature maps. Each level corresponds to a given scale. Various scales are then used to create a set of on-off and off-on centre-surround maps per pyramid by using across-scale point-by-point subtractions. These have higher intensity on those pixels whose corresponding feature differs the most from its surroundings. Then, both on-off and off-on aggregate intensity centre-surround feature maps are scaled and averaged together to produce an intensity bottom-up conspicuity map.

The same process applies to create red-green and blue-yellow conspicuity maps, which are then averaged together to produce a single colour bottom-up conspicuity map. These centre-surround feature maps are scaled and averaged together to produce one intensity and two colour (i.e., double-opponency) bottom-up conspicuity maps. Finally, these conspicuity maps are blended in order to produce a final saliency map.

A binary threshold is applied to remove weak conspicuous regions from the saliency map. As depicted in Fig. 5, high intensity regions on the saliency map indicate the presence of a lifeboat or a human survivor.

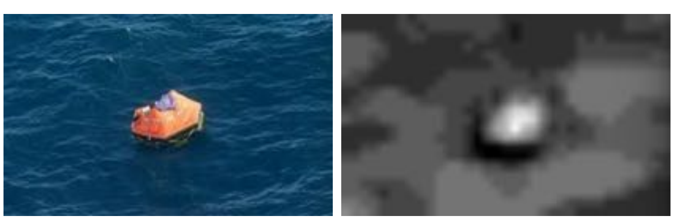


Fig. 5: Salient lifeboat adrift at sea depicted at the left image, whereas its bottom-up visual saliency is shown in the right image.

V. Experimental Results

The field experiment was performed in collaboration with the Portuguese Navy to assess the proposed cooperative robotic team's performance in pro-actively searching for possible human survivors adrift at sea.

The experimental run started with *Pelagi* navigating to a mission-defined GPS coordinates, while transporting its docked aerial partner. Upon arriving at the spot, *Vigil R6-WT* takes off from *Pelagi*'s helipad and flies around it. While this aerial search occurs, the water surface robot remains idle. After a salient object (i.e., a human survivor) was detected from the aerial perspective, as depicted in Fig. 6, *Pelagi* started moving to the current location of the UAV.

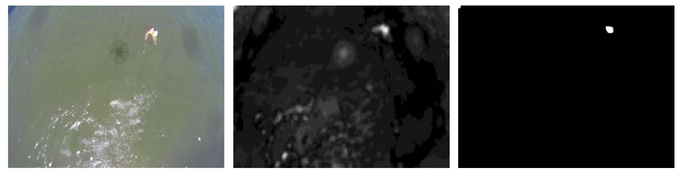


Fig. 6: Aerial detection of a shipwreck survivor. The *Vigil R6*'s aerial perspective is shown in the left image. The centre image depicts the saliency-based target detection output, whereas the right one shows the final result of the binary threshold filter.

Fig. 7 depicts the approach of *Pelagi* captured by the *Vigil R6-WT*'s camera, whereas Fig. 8 shows the UAV hovering around the target as seen by the surface vehicle.

After arriving near the reported location, the robotic surface vessel starts analysing its surroundings while the aerial robot lands on water to save battery Fig. 9.

At the water surface level, *Pelagi* detected the target's heat radiation as being similar to a human body (see Fig. 10) and notified the mission control centre by sending a message with a picture frame from its 360° colour camera (see Fig. 11).

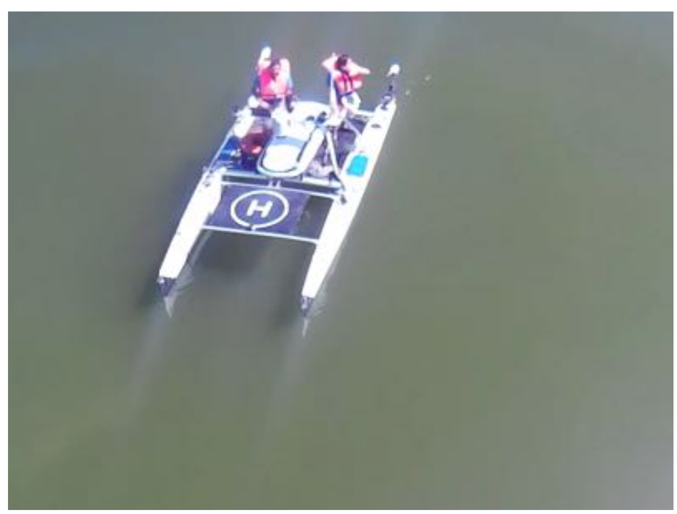
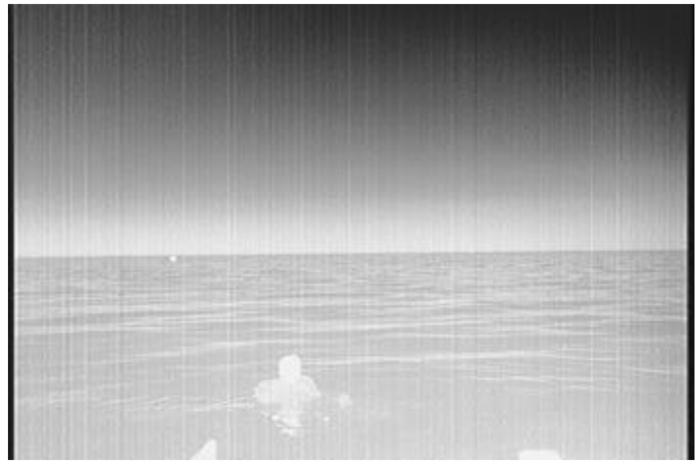


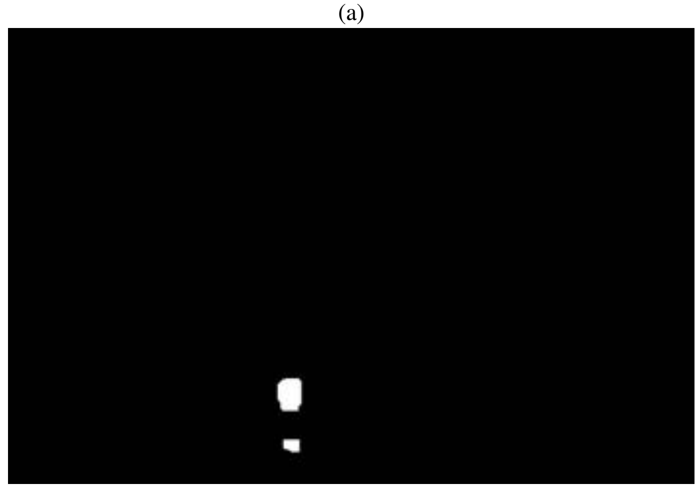
Fig. 7: *Vigil R6-WT*'s camera showing the water surface robot approaching the target's location. On board *Pelagi* there are two human operators ready to take control of the autonomous vehicle (if required) just for the sake of safety during the experimental run.

Fig. 8: *Pelagi* approaching the local of the salient target. The aerial robot can be seen hovering above that location.

Fig. 9: *Vigil R6-WT* landing on water.



(a)



(b)

Fig. 10: Heat signatures (a) captured by the thermal camera installed in *Pelagi*. A binary threshold is then applied to the thermal image, highlighting the presence of a target with a high temperature.

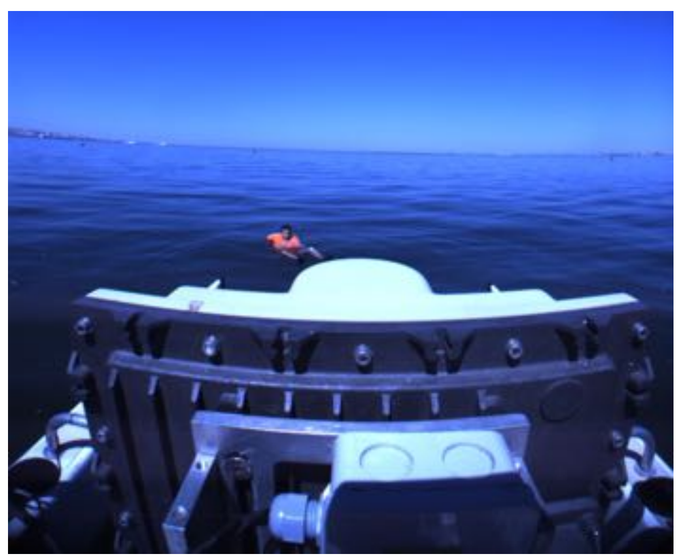


Fig. 11: Image sent to the mission control centre.

A human operator then analysed the incoming picture and decided that a shipwreck survivor was indeed found.

VI. Conclusions

A cooperative marsupial robotic team composed of an unmanned aerial vehicle and an unmanned water surface vehicle, *Vigil R6-WT* and *Pelagi* respectively, was proposed as a possible solution to reduce the operating costs of search and rescue manned teams. The heterogeneous robotic team exploits the strengths of each robot to foster an efficient search for shipwreck survivors adrift at sea. At high vantage perspectives as the ones captured by *Vigil R6-WT*'s on-board camera, the target detection was tackled by exploiting its distinctive colour and geometry that highlights it from the sea environment. Near the water surface, the target detection was performed through the heat radiation signatures captured by the thermal camera installed on *Pelagi*. An experimental scenario was performed and shown encouraging results, as the human survivor was successfully detected by both robots.

As a future development, the proposed robotic team will support the Joint Architecture for Unmanned Systems (JAUS) standard to further increase the interoperability with external systems (e.g., mission control centres). Furthermore, to increase the flight autonomy during SAR missions, *Vigil R6-WT* could recharge using an inductive charging system installed in the *Pelagi*'s helipad. Another future improvement is the development of an image filter that attenuates or removes the sun's specular lights. These reflections on the water surface can be salient from the aerial perspective, creating false positives in the visual saliency detector. Finally, the search time of the robotic team can also be improved as some lifeboats emit a signal beacon that could be used to bias the aerial search towards that source position. However, the beacon may ceases off and the lifeboat can be moved to other locations due to water currents. In this scenario, if the *Vigil R6-WT* does not find anything when it arrives to the lifeboat's last known position, a behavioural search similar to the one presented in [21] should be triggered.

A scenario that remains to be experimentally assessed and validated is the analysis of multiple hypothesis about the target's locations, i.e., several conspicuous regions. Briefly, for each high intensity region in the saliency image, its centre of mass is computed, converted from UTM to GPS coordinates and transmitted from *Vigil R6-WT* to *Pelagi*. The received coordinates are stored in a search queue that the latter robot must corroborate. If it is a false positive, the robotic team moves to the next coordinates in the queue.

Acknowledgment

This work was not possible without the support and commitment of several fellow colleagues and friends, namely: Lino Quaresma, João Carvalho, Dário Pedro, Raul Guilherme, Ricardo Pombeiro and Paulo Rodrigues.

References

[1] "The internal displacement monitoring centre." [Online]. Available: http://www.internal-displacement.org/

[2] R. R. Murphy, J. Kravitz, S. L. Stover, and R. Shoureshi, "Mobile robots in mine rescue and recovery," *IEEE Robotics Automation Magazine*, vol. 16, no. 2, pp. 91–103, 2009.

[3] Y.-W. Huang, Y. Sasaki, Y. Harakawa, E. F. Fukushima, and S. Hirose, "Operation of underwater rescue robot anchor diver iii during the 2011 tohoku earthquake and tsunami," in *OCEANS'11 MTS/IEEE Kona*, 2011, pp. 1–6.

[4] N. Ruangpayoongsak, H. Roth, and J. Chudoba, "Mobile robots for search and rescue," in *IEEE International Safety, Security and Rescue Rototics*, 2005, pp. 212–217.

[5] A. Birk, K. Pathak, S. Schwertfeger, and W. Chonnaparamutt, "The iub rugbot: an intelligent, rugged mobile robot for search and rescue operations," in *IEEE International Workshop on Safety, Security, and Rescue Robotics (SSRR). IEEE Press*, vol. 10, 2006.

[6] M. Eich, F. Grimminger, and F. Kirchner, "A versatile stair-climbing robot for search and rescue applications," in *2008 IEEE International Workshop on Safety, Security and Rescue Robotics*, 2008, pp. 35–40.

[7] F. Matsuno and S. Tadokoro, "Rescue robots and systems in japan," in *IEEE International Conference on Robotics and Biomimetics, ROBIO*, 2004, pp. 12–20.

[8] M. Bernard, K. Kondak, I. Maza, and A. Ollero, "Autonomous transportation and deployment with aerial robots for search and rescue missions," *Journal of Field Robotics*, vol. 28, no. 6, pp. 914–931, 2011. [Online]. Available: http://dx.doi.org/10.1002/rob.20401

[9] A. Jacoff, E. Messina, B. A. Weiss, S. Tadokoro, and Y. Nakagawa, "Test arenas and performance metrics for urban search and rescue robots," in *International Conference on Intelligent Robots and Systems, IROS*, vol. 4, 2003, pp. 3396–3403 vol.3.

[10] M. Lindemuth, R. Murphy, E. Steimle, W. Armitage, K. Dreger, T. Elliot, M. Hall, D. Kalyadin, J. Kramer, M. Palankar, K. Pratt, and C. Griffin, "Sea robot-assisted inspection," *IEEE Robotics Automation Magazine*, vol. 18, no. 2, pp. 96–107, 2011.

[11] R. R. Murphy, E. Steimle, C. Griffin, C. Cullins, M. Hall, and K. Pratt, "Cooperative use of unmanned sea surface and micro aerial vehicles at hurricane wilma," *Journal of Field Robotics*, vol. 25, no. 3, pp. 164–180, 2008. [Online]. Available: http://dx.doi.org/10.1002/rob.20235

[12] D. Serrano, G. De Cubber, G. Leventakis, P. Chrobocinski, D. Moore, and S. Govindaraj, "Icarus and darius approaches towards interoperability," in *IARP RISE Workshop, At Lisbon, Portugal. Proceedings of the NATO STO Lecture Series SCI-271*.

[13] M. M. Marques, P. Dias, N. P. Santos, V. Lobo, R. Batista, D. Salgueiro, A. Aguiar, M. Costa, J. E. da Silva, A. S. Ferreira *et al.*, "Unmanned aircraft systems in maritime operations: Challenges addressed in the scope of the seagull project," in *OCEANS 2015-Genova*. IEEE, 2015, pp. 1–6.

[14] P. Westall, J. J. Ford, P. O'Shea, and S. Hrabar, "Evaluation of maritime vision techniques for aerial search of humans in maritime environments," in *Digital Image Computing: Techniques and Applications (DICTA)*, 2008, pp. 176–183.

[15] T. Sumimoto, K. Kuramoto, S. Okada, H. Miyauchi, M. Imade, H. Yamamoto, and T. Kunishi, "Machine vision for detection of the rescue target in the marine casualty," in *20th International Conference on Industrial Electronics, Control and Instrumentation, IECON '94*, vol. 2, 1994, pp. 723–726 vol.2.

[16] L. Ren, C. Shi, and X. Ran, "Target detection of maritime search and rescue: saliency accumulation method," in *9th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD)*. IEEE, 2012, pp. 1972–1976.

[17] E. Pinto, F. Marques, R. Mendonça, A. Lourenço, P. Santana, and J. Barata, "An autonomous surface-aerial marsupial robotic team for riverine environmental monitoring: Benefiting from coordinated aerial, underwater, and surface level perception," in *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2014, pp. 443–450.

[18] P. Rodrigues, F. Marques, E. Pinto, R. Pombeiro, A. Loureno, R. Mendona, P. Santana, and J. Barata, "An open-source watertight unmanned aerial vehicle for water quality monitoring," in *OCEANS'15 - MTS/IEEE Washington*, 2015, pp. 1–6.

[19] E. Pinto, P. Santana, F. Marques, R. Mendonça, A. Lourenço, and J. Barata, *On the Design of a Robotic System Composed of an Unmanned Surface Vehicle and a Piggybacked VTOL*. Springer Berlin Heidelberg, 2014, pp. 193–200.

[20] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: an open-source robot operating system," in *ICRA Workshop on Open Source Software*, vol. 3, no. 3.2. Kobe, Japan, 2009, p. 5.

[21] J. Silva, R. Mendonça, F. Marques, P. Rodrigues, P. Santana, and J. Barata, "Saliency-based cooperative landing of a multirotor aerial vehicle on an autonomous surface vehicle," in *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2014, pp. 1523–1530.

[22] L. Itti, C. Koch, E. Niebur *et al.*, "A model of saliency-based visual attention for rapid scene analysis," *IEEE Transactions on pattern analysis and machine intelligence*, vol. 20, no. 11, pp. 1254–1259, 1998.