Permanent Ocean Presence With Autonomous Sailing Robots

Wind-Propelled Vessels Foster Missions With Precise Maneuvering

By José C. Alves • Nuno A. Cruz

The demand for accurate ocean sampling is continuously growing to provide a better understanding of the complex sea environment. Current economic and social activity is strongly dictated by knowledge built on data collected from thousands of sensors around the world, ranging from space-borne remote sensors to underwater devices transported by profilers. Although the most widespread data are weather forecasts and early warnings for hurricanes or tsunamis, another sensible domain that relies on data gathered from the ocean environment is the security of maritime frontiers against illegal activities such as trafficking drugs and people, and terrorism threats.

Potential Benefits of Autonomous Sailboats

Recent advances in the comprehension of several oceanographic phenomena have been fostered by the development of key technologies, including modeling capabilities and the ability to feed those models with real field data. Such data has been obtained using several types of innovative sensors, both on traditional science cruises and integrated in more complex systems, such as drifting buoys, ASVs or AUVs. For a given application or challenge in data acquisition, the combination of assets is chosen according to the tradeoff between estimated performance and operational cost. With the expansion of the suite of available robotic devices, other scenarios are envisaged for their operation, with an increasing demand for a longer mission duration. In recent years, there has been a strong effort to develop devices that target a permanent presence in the ocean, with notable achievements by long-term AUVs, underwater gliders and wave gliders. However, their limited speed precludes the ability to beat the ocean currents and limits the scope of utilization.

Autonomous sailboats are a relatively new robotic technology that may complement existing efforts toward a permanent, sustainable presence in the ocean. They rely on wind to provide propulsion and only need electrical energy for onboard electronics and rudder/sail adjustments, which only require a few watts. If we combine this low consumption with the energy provided by current solar panels and the energy densities of existing batteries, it is feasible to devise an energy management system that provides a continuous supply of power to the onboard electronics. The absence of electrical propulsion has an additional benefit, the silent nature of operations, which is extremely important in all sorts of missions involving underwater acoustic detection.

Autonomous sailboats can transport a wide variety of sensors in the hull and mast, or towed/winched several meters below the sea surface. Data from these sensors can be stored onboard or transmitted to shore via radio or satellite. The exact position of the device can be tracked so that all data can be geolocated. All this information can be interpreted by a mission supervisor in real time, changing mission parameters, sensor settings or taking other actions. The cost of operating a fleet of autonomous sailboats is associated with the support infrastructure, such as communications, backing personnel and hypothetical emergency rescue equipment.

Applications

Autonomous sailboats have great potential to gather long-term data to understand multiple aspects of the ocean environment. In terms of oceanography, they can be used to study many processes occurring at the surface, like the energy exchange between the ocean and the atmosphere and how it affects the climate. They can also be a valuable tool to understand the dynamics of episodic events that evolve on a timescale of weeks or months, like harmful algae blooms or the evolution of pollution plumes. Even though these incidents can already be tracked by satellite, the ability to capture in-situ data for the full cycle can provide valuable data about the phenomena.

The silent nature of the operation of sailboats makes them an ideal platform for acoustic measurements in the ocean, such as the detection of mammal sounds or the localization of moving vessels with specific acoustic signatures. Ocean surveillance can also be complemented with more conventional technologies like imaging or radar, taking advantage of the mast height for increased range of sight. The dynamic reconfiguration of a coordinated fleet of such crafts can be arranged for tackling specific surveillance objectives.

Technology Status

One important point to address regarding permanent ocean presence is the ability to withstand the harsh conditions at sea during long periods of time. Up to the present, there have been some successful demonstrations of high-endurance capability with small autonomous wind-propelled crafts, with different proposals resembling conventional sailing boats or more customized and sophisticated designs. Success stories include the French Vaimos from ENSTA Bretagne (Brest, France), the Norwegian Sailbuoy vessel from CMR Instrumentation (Bergen, Norway) and the Saildrone project, a 19-foot-long trimaran rigging a wing sail that recently completed a 34-day trip from San Francisco, California, to Hawaii.

In some applications, other features are needed to complement the endurance capabilities, such as maneuverability, accuracy of course and station keeping. Examples include monitoring pollution plumes, performing scans of the seafloor ~~and~~ continuously sampling the near-surface environment.

All these developments have benefited from the active sharing of knowledge and field experience among various groups from universities, research and development centers, and industry. Since 2006, two annual events, one mainly in Europe and another in North America, have offered opportunities for joining the international community active in robotic sailing to discuss achievements through technical meetings and performance evaluations with field exercises. These are excellent opportunities to assess the results of practical developments, while attempting to accomplish increasingly complex tasks, thus encouraging the community to invest in new improvements. Such challenges are planned to evaluate the accuracy of course control, speed along different points of sailing, the ability to perform a station-keeping navigation pattern and an endurance task to verify the aptitude for long-term missions.

The FASt Sailboat

The FASt autonomous sailboat is a 2.5-meter-long, 50-kilogram unmanned mono hull capable of fully autonomous navigation under sail through a set of waypoints. The sailboat was designed and built during 2007 in the school of engineering of the University of Porto, Portugal, and since then has been evolving to include additional features. The latest developments have focused on complementing endurance with trajectory accuracy and the precise execution of sailing maneuvers like gibing and tacking.

A small solar panel is the only source of electric energy that proved to be sufficient for long-term missions due to a low-power computing system and the ability to adapt the frequency of sail and rudder actuation for adjusting the navigation performance as a tradeoff of accuracy of route, speed and usage of the available power for the electric motors.

The boat has a payload capability of a few kilograms, distributed along the interior of the hull, on the deck, or even attached to the mast or the 1.2-meter-deep keel. The interior free volume for installing equipment can also reach a few liters, depending on the form factor of the items. The sailboat can thus be configured to transport instrumentation devices required for a specific mission. Naturally, adding weight, altering the hull's hydrodynamics or the sail plan aerodynamics may negatively impact speed, stability and maneuverability.

Although the main ~~mission~~ of its embedded internal computer is to perform all the navigation tasks—route planning, obstacle avoidance, course control, maneuvering—it can also be programmed to acquire data from additional sensors, ~~stored locally~~ in its solid-state hard disk, or even transmit relevant information via satellite data links. An internal Ethernet network running standard network protocols eases the interconnection of additional computers or network-enabled devices.

The option for a conventional two-sail configuration (Marconi rig) enabled the capability of upwind navigation, aided by a 1.2-meter-long keel and a 20-kilogram lead ballast bulb (40 percent of the total displacement). Both sails are controlled by a single electric actuator, pulling the sails against the wind as in normal sail boats. Although in the current configuration the inability to reduce the sail area hinders the operation with strong winds, particularly in upwind legs, the navigation along the other points of sailing has been successfully verified in 20 knots wind. A top speed of 9.6 knots has been registered during a downwind trial in open sea with wind in excess of 20 knots and 2.5-meter swells.

Mission Management

From the navigation point of view, a typical autonomous mission consists of visiting a preprogrammed sequence of waypoints. The coordinates of these waypoints can be provided as a simple static text file or created interactively using a convenient graphical user interface. Prior to the mission, it is possible to predict the behavior of the vessel by running the onboard code in a kinematic simulation model that also includes suitable wind patterns. During a mission, the same interface software displays the status of the vehicle subsystems, transmitted via radio by the telemetry system, using Wi-Fi, RS-232 radio or Iridium. In the event of an unexpected behavior, it is also possible to take manual control of the boat using a radio command. While maneuvering, the vehicle records a log file with multiple data about internal subsystems. Such a file can be played back in the same console to visualize the behavior during the mission, or translated into Matlab, for a quantitative, systematic analysis of the vehicle performance.

Along with the coordinates of the mission waypoints, there are also some configuration parameters that may be adjusted before or during a mission. One example is the definition of the width of the upwind corridor, whenever the vehicle needs to navigate against the wind to reach a given target. In addition to setting up a list of static or dynamic waypoints, a mission may also have programmed tasks to be performed at given locations, for example activating equipment for recording or transmitting data or performing a station-keeping navigation pattern.

Sea Trials

A series of five upwind passages between two virtual buoys was part of a 2.5-hour trial course around three waypoints **[location of testing? what month and year was it conducted?]**, where the upwind navigation was constrained to a 50-meter-wide virtual corridor. The wind changed significantly during the various upwind passages, with a direct impact on the average velocity to the target (VMG). These results showed that even with a light, 6-knot wind observed during the last leg, the autonomous sailboat was capable of approaching the upwind objective faster than 1.3 knots.

When the wind direction permits a direct course to the target waypoint, the navigation path can be maintained in a much narrower passage by enabling a route-control mechanism based on the cross-track error relative to the ideal path. ~~A~~ test run was completed around a triangular course, where the recorded track was kept within a 10-meter-wide lane with an average cross-track error of 2.9 meters. The recorded positions were obtained with a conventional GPS receiver, and thus the paths suffered from the intrinsic GPS position error.

One important feature for ocean data acquisition was the ability to maintain a position within a small area, thus acting as a virtual moored buoy, irrespective of the wind or sea current. Although the ~~course~~ already demonstrated the ability to stay inside of a few-hundred-meter square, a more aggressive strategy would reduce the station-keeping region even further. The recorded track around a set of virtual buoys placed conveniently with the objective to minimize the deviation from the target point was represented by the center of a 20-meter-radius red circle. We observed that all the GPS positions were within this circle, and 95 percent stayed below the 15-meter range.

Conclusions

Autonomous sailboats have ~~moved out of~~ a state of research and development, and are already being used in a series of field operations that take advantage of their exclusive characteristics, not only related to their inherent endurance but also in terms of maneuvering accuracy. The performance demonstrated in such operations serves to reveal the benefits of this new technology as compared to existing alternatives for long-term ocean presence. ~~The~~ vessels are therefore on the rise of the acceptance curve and starting to shape the future of ocean presence, where wind-powered vehicles will have a prominent role.

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References

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Figure 1

The FASt autonomous sailboat during a 25-nanometer trial near Sesimbra, Portugal: LOA, LWL 2.5 meters, displacement 50 kilograms.

Figure 2

The graphical user interface used to program, simulate, supervise and play back a sailboat mission. The track presented was recorded during a 2.5-hour trial in Cardiff Bay, Wales, and shows five laps around three virtual buoys.

Figure 3

Plot of the sailboat track during five upwind passages between two virtual buoys.

Figure 4

Summary of the performance results for the five tracks: instantaneous boat speed, average VMG to the upwind target, average wind direction and speed.

Figure 5

Trajectory accuracy while performing a triangular course, allowing a direct navigation to a target waypoint, recorded near Brest, France. The ~~distance between~~ the two red lines ~~enclosing the route during each leg~~ is 10 meters.

Figure 6

Example of sailboat performance during a station-keeping trial near Brest, France. The goal was to maintain a navigation pattern as close as possible to the center of the red circle.

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