Ocean sampling and surveillance using autonomous sailboats

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Abstract

In this paper, we discuss some of the potential applications of small scale autonomous sailboats. The use of autonomous sailboats for ocean sampling has been tentatively proposed before, with little or no attention from the scientific community. There have also been minor efforts towards the development and deployment of actual prototypes, due to a number of technical limitations and significant risks of operation. We show that, currently, most of the limitations have been surpassed, with the existing availability of extremely low power electronics, flexible computational systems and high performance renewable power sources. At the same time, some of the major risks have been mitigated, allowing this emerging technology to become an effective tool for a wide range of applications in real scenarios. We illustrate some of these scenarios and we describe the status of the current efforts being made to develop operational prototypes, with some promising results already being achieved.

1. Introduction

Sailing is a relatively complex task, highly dependant on environmental conditions, such as wind and sea state. In conventional sailing boats, the sailor controls the rudder according to the desired course and uses the sail sheet to maximize velocity. For a given course, boat speed, wind speed and wind direction, there is an optimum angle between the sail and direction of the wind that maximizes the speed of the boat.

Autonomous sailboats are robotic boats that use wind energy for propulsion and have the capability to control the sails and rudders without human intervention. The use of autonomous sailboats for ocean sampling has been tentatively proposed before, but there have been minor efforts towards the development and deployment of actual prototypes, due to a number of technical limitations and significant risks of operation. In this paper, we show that currently, most of the limitations have been surpassed, with the existing availability of extremely low power electronics, flexible computational systems and high performance renewable power sources. At the same time, some of the major risks have been mitigated, allowing this emerging technology to become an effective tool for a wide range of applications in real scenarios, complementing the other technologies available for ocean sampling.

This paper is organized as follows. Section 2 provides some background regarding ocean sampling, briefly introducing the other technologies available. In Section 3 we provide a typical SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) relative to the potential utilization of autonomous sailboats in the ocean. Next, in Section 4, we describe a set of applications where autonomous sailboats may be effectively used. In Section 5 we analyze the status of the current efforts being made to develop operational prototypes, and finally, Section 6 presents the main conclusions and the plans for future evolutions.

2. Motivation

2.1 The importance of ocean data

The ocean has been a subject of study since man started to depend on it for various reasons, from early sailors willing to understand the prevailing currents as they influenced the course of the ships, to fishermen seeking the best fishing grounds.

Over the last decades, there has been a dramatic broadening on the knowledge about the physical processes behind the ocean dynamics. This has allowed for the development of various mathematical models that attempt to reproduce the real conditions found in the oceans. Although these models require calibration with real multi-scale data, the fact is that the data available has always been relatively scarce, particularly what concerns *in-situ* measurements (Legrand et al., 2003).

2.2 Technology for ocean sampling – a survey

Ships of opportunity – One of the easiest (and possibly the oldest) way to get ocean measurements is the installation of *in-situ* instruments on ships of opportunity, such as cargo ships or ferry-boats (Petersen et al., 2004). Typical sensors include temperature and conductivity recorders, current profilers, etc. In these systems, data is stored internally and it is only retrieved when the ship reaches the final destination.

Moored Instrumentation and Ocean Observatories – In-situ long term observatories are important tools for monitoring time-variations of oceanic processes. Ocean observatories are unmanned systems located at a fixed site, providing information regarding the seafloor, the water column and the surface. They have been installed all over the world, particularly in the last decade (Soreide et al., 2001). Arrays of moored, and therefore static, instrumentation can provide simultaneous time series, but spatial resolution is typically poor due to the high cost. Current developments try to get the most out of the moored instrumentation by combining a profiling mechanism to a moored based system (Brown et al., 2001).

Towed Systems – Towed bodies can provide quasi-synoptic two-dimensional sections of the evolving ocean fields. They are controlled from a ship via an umbilical cord, providing power and communications. They have limited maneuverability and can follow simple trajectories, using deflection surfaces for changing depth and orientation. Some undulating versions allow for complex vertical patterns, such as *yo-yo's*.

Remotely Operated Vehicles – Remotely Operated Vehicles (or ROVs) are underwater robotic machines that operate with a physical link with the surface. Nonetheless all technological advances, the mobility of these vehicles remain severely constrained by the umbilical, and the drag associated to the frame and the cable prevent high velocities, so that the major application for these vehicles is to perform close inspections in environments with low currents, in shallow waters.

Drifters, Profilers and Gliders – Drifters are instrumented floats dropped from a support vessel, which then drift horizontally with the local currents for long periods of time (Soreide et al., 2001). Present profilers are similar to the drifters, but they use variable buoyancy to move vertically through the ocean. Gliders not only use variable buoyancy to move vertically, but they have also wings and control foils designed to allow steerable gliding, thus providing for some limited control on horizontal propulsion (Eriksen et al., 2001). Some of these vehicles can surface from time to time and fix position via GPS and communicate via appropriate satellite links. Nonetheless, the amount of information that can be transmitted is very limited and the scientists need to wait for recovery to get full data. For a long time, there have been suggestions for the harvest of propulsion energy from the environment to allow for very long range operations, and recently a heat engine that draws energy from the ocean thermocline has been tested. The work required to change buoyancy results from heat flow from warm surface to cooler deep water, so that the vehicle can cycle thousands of times between the surface and some programmed depth (Webb et al., 2001).

Autonomous Surface Vehicles – Autonomous Surface Vehicles (or ASVs) are robotic boats that typically use electric power for propulsion and operate without any physical link with the operator. ASVs have usually a large capacity in terms of payload volume and weight, but the limited amount of energy stored on board prevents their use in long range missions. Although there has been some effort regarding the deployment of ASVs for operation in coastal waters, the fact is that the prototypes being developed are mainly intended for calm inland waters (Cruz et al., 2007).

Autonomous Underwater Vehicles – In the last decade, some important technological advances, together with new ideas for efficient ocean sampling, forested the development of Autonomous Underwater Vehicles (AUVs) (Griffiths, 2003). AUVs constitute powerful and effective tools for underwater data gathering. These vehicles operate with no physical link with the surface, carrying a set of relevant sensors to characterize the underwater environment. AUV utilization is still quite limited as far as routine ocean sampling is concerned, but some very interesting results have aroused from their use in challenging environments, such as under Arctic ice-sheets, in deep water, in very shallow waters, and in extreme environments.

Remote Sensing – Due to their global coverage and sophisticated instrumentation, environmental satellites are playing an expanding role in monitoring ocean conditions, namely in sea-surface temperature and chlorophyll concentration. The contributions of satellites are fundamental to measuring variations on time scales ranging from seasonal-interannual to decadal. However, they lack in detail and have poor vertical information.

2.3 The AOSN Concept

The concept of Autonomous Ocean Sampling Networks (AOSN) was first described in (Curtin et al., 1993), in a novel approach to provide a framework to encompass a set of cooperative efforts taking place, integrating multiple information sources about the oceans.

The fundamental idea behind this paradigm is the cooperative utilization of the complementary technology available for ocean sampling, in order to provide a synergetic observation system for a given region. Curtin *et al.* envisaged the installation of moored instrumentation linked to shore via radio or satellite communications, providing oceanographic and atmospheric data in real time. At the same time, a set of small, high-performance vehicles (gliders and AUVs) would be navigating in the area to provide intensive 4-D data about the region.

2.4 Why autonomous sailboats?

One of the characteristics of autonomous robotic systems is the absence of physical connections with any operator, therefore they have to carry all required energy or/and harvest some energy from the environment. For any moving system, the fraction of energy necessary to provide motion is usually significant. Autonomous sailboats rely on wind to provide propulsion and so they only need electrical energy for the onboard electronics and rudder adjustments. With current reduction in power consumption from electronic circuits and sensors, it is possible to trim down the energy requirement to a few tens of Watt-hour per day. At the same time, there have been major developments in technology associated with renewable energy sources for micro-generation, such as miniature wind turbines and solar panels, and it is now possible to have high performance commercial-off-the-shelf energy generators at very reasonable costs (Maycock and Bradford, 2007). If we combine this with the energy densities provided by new battery technologies, such as Lithium-Ion, then it is clear that it is feasible to devise an energy management system that can provide a continuous supply of power to the onboard electronics.

Autonomous sailboats can transport a wide variety of sensors and store the incoming data internally or transmit it to shore via radio or satellite. Even the smallest autonomous sailboats have some space available for sensors, either in the hull, the mast or in the form of an underwater towed system. With the ability to travel for long distances, even though it may be at modest velocities, it is clear that these systems may provide valuable ocean data in spacial and temporal scales complementary to the other technologies already in use.

2.5 Dimensions of autonomous sailboats

The size of a recreational yacht varies from the most modest single person "dinghy" to the long luxury models. Besides personal preferences (wether aesthetics, social impact, or other), size is mainly dictated by a tradeoff between size/comfort and price. When it comes to autonomous sailboats, there are no limitations regarding people transportation and surely comfort is not an issue. Many other aspects have to be contemplated instead, and usually the driving factors are safety and performance. Sailing performance results from a complex tradeoff between various design factors, such as sail area, sail shape, hull size and hull shape (Marchaj, 1996).

When determining the size of an autonomous sailboat, it is important to contemplate both the permanent hardware that needs to be installed (electronics and mechanical systems) and also the extra payload that may be transported for particular applications. Even with these constraints, there is usually some degree of flexibility on the overall size of the sailboat, providing the scaling process is taken according to the principles of yacht design (Marchaj, 1996, Skene, 2001).

There are some advantages of building a larger sailboat, such as:

- **More velocity** – Theoretically, the maximum velocity of a sailboat is proportional to the square-root of the length on the water line (LWL);
- **More payload capacity** – The available volume inside the hull increases with the cube of the scaling factor. A bigger sailboat will also have a higher mast and a larger deck space for sensor placement;
- **More stability** – As the dimensions increase, it is possible to improve the ratio between the ballast and the total weight, increasing stability.

A larger sailboat has also some disadvantages, such as:

- **Cost increase** – The cost of hull construction naturally increases for a larger scale;
- **More complex logistics** – An increase in size and weight impair storage, transportation and operational logistics;
- **More power required for steering** – A larger, heavier sailboat demands more power for steering.

Another consequence of increasing the size of a sailboat is to augment the visibility as seen from other ships. This may be an advantage when the priority goes to equipment safety (diminishing the risks of ship collision), and/or when a surveillance operation also relies on the deterrence ability. In other surveillance scenarios, however, it may be preferable to have an *invisible* sailboat.

3. The Role of Autonomous Sailboats - A SWOT Approach

3.1 Strengths

Long mission ranges – Assuming that every autonomous sailboat has an energy management system capable of charging a set of internal batteries, then these vehicles have practically no limitations in range and so they can be used for long term, large scale *in-situ* data sampling.

Negligible operational costs – The costs of operating an autonomous sailboat are essentially those associated with the support infrastructure, such as communications, backing personnel and hypothetical emergency rescue equipment.

Potential for towing sensors – Autonomous sailboats have no underwater moving parts, apart from the small rudders in the stern, which have a slow and only occasional activity. Thus, it is extremely easy to tow external sensors and/or arrays without the risk of the sensor cables getting tangled. With some clever design it is even possible to conceive a winch-driven system that can be lowered in the water column in calm regions.

Real time data transmission – Autonomous sailboats can use a radio or satellite link to transmit sensor data to a control station. This information may be interpreted by a mission coordinator to periodically assess the quality of the sensor data or to alter the trajectory.

Real time localization – Using standard (and inexpensive) commercial off-the-shelf technology, it is possible for an on-board computer to know the *exact* location anywhere in the world, and relay this information back to a control station via radio. It is also relatively easy to use redundant tracking devices, such as Argos satellites, for example, to know the position of the sailboat.

Very low noise generation – Autonomous sailboats generate a minor amount of acoustic noise as compared to motorized vessels, with virtually no noise produced by propulsion and only a small amount originated in the interaction between the hull and the sea surface. As far as underwater sound is concerned, with a proper mechanical design, the other sources of noise may be neglected, such as sail and cable vibration, small rudder corrections, etc. Thus, with respect to sound detection, these sailboats are comparable in performance to gliders and drifters.

3.2 Weaknesses

Risk of collision – The smallest sailboats may be hard to detect from a large ship radar and they will surely not respond to any tentative of contact by radio, so there is a serious risk of ship collision, particularly when crossing regions with large ship traffic. There is also a great number of floating debris in the ocean and is possible that an hypothetical collision with a large fragment cause serious damage to the hull of a small sailboat.

Vulnerability to bad weather – When a vessel is programmed to travel hundreds or even thousands of miles, it is very likely to find high seas and bad weather at any moment during the journey. With the current capabilities of weather forecasting, it is usually possible to predict an incoming storm several days in advance, which may be useful to change the course of the sailboat using satellite communications. Nonetheless, if the wind does not help, it may be impossible to run away from an incoming storm.

Limited access to the ocean – Autonomous sailboats travel at the surface of the ocean, and so they are best suited to measure surface or sub-surface data. Even with towed or winch-driven systems, it is not expected that these vehicles can sample more than the very top layer of the ocean.

Degradation of sensor accuracy over time – Biofouling is a nuisance associated with any system subject to long term deployments, and it is particularly severe in the ocean. In the case of oceanographic optic sensors, there are already a few products with a very small wiper that periodically cleans the sensing window. However, the great majority of oceanographic sensors require regular maintenance to remove any growth and recalibration to ensure the specified accuracy. Anyway, it should be pointed out that the accuracy expected from long-term moored instrumentation is already less demanding as compared to data from oceanographic cruises or laboratory analysis of water samples.

Exposure to vandalism – Autonomous sailboats may be relatively slow as compared to motor boats and so they may be easy targets for vandalism, particularly close to shore. This risk may be reduced with cameras installed on board and warning signs.

Impossibility of fixing a velocity – One of the major inconveniences of using autonomous sailboats for ocean surveys is that it is impossible to stipulate *a-priori* the velocity, since it depends on the wind and sea state conditions. Therefore, it is feasible to define a given trajectory, usually as a set of waypoints, but it is not possible to predict the time that the boat will take to complete it.

3.3 Opportunities

Real mission scenarios for current prototypes– Given the possibility of transporting oceanographic sensors during very long missions, autonomous sailboats can play an important role in ocean-scale sampling. The opportunity to work 24 hours a day and transport radars and cameras (visual and infrared) make these vehicles a possible tool for coastal surveillance. Some of these possible applications will be detailed in the next section.

Future applications – The prototypes that are currently being developed are small scale models, mainly intended to demonstrate the feasibility of autonomous sailing, with little interest in mimicking the actions performed by a sailor in a real yacht. With the development of full scale models, it will be possible for a computer to control a greater number of sailing actions (fold/unfold multiple sails, compensate the onboard weight distribution, etc.), so that the prototypes may be used to test different sailing strategies in the field.

3.4 Threats

Absence of applicable legislation – There is currently an overall absence of legislation regarding the navigation of autonomous systems in the ocean. An hypothetical restraining legislation may completely forbid the deployment of such vessels and therefore make all current efforts useless. Furthermore, it may happen that different countries decide differently regarding this subject, which may pose difficulties for wide area missions.

Demonstration failure – Although all required subsystems have been separately demonstrated, a fully autonomous sailboat has yet to be fully validated in the field. In a first stage, it is crucial to have a sailboat consistently navigating through the predefined marks and harvesting energy from the wind and/or the sun for a significant length of time. Then, it is important to repeat the test under severe conditions to assess the robustness of the mechanical structure (hull, mast, keel, cables, etc.) and electronics in an extremely harsh environment.

4. Potencial applications of autonomous sailboats

4.1 Ocean Observation

Upper Ocean Dynamics – The dynamics of both the ocean and the atmosphere are mainly determined by the energy they exchange. Oceanographers have been studying the processes that occur in the top layer of the ocean (eddies, fronts, meanders, etc), since they are extremely important to define how this exchange occurs and, at the same time, are affected by the climatology of the atmosphere. Sailboats may be an important tool to contribute to the understanding of this interaction, as they can gather relevant data (both hydrological and atmospheric parameters), precisely at this boundary layer.

Ocean circulation – The study of the ocean circulation has direct impact in many different processes, such as biological activity and climate variability (Wunsch, 1996). Typically, circulation studies encompass multi-scale measurements and therefore these investigations can be supported by long-range autonomous sailboats. For this application, the sailboats should be equipped with acoustic doppler current profilers, with the capability to measure the oceans' currents from the surface down to 1000 meters of depth. Although these devices require significant power for each measurement, they can be programmed to work at very low duty-cycles.

Chlorophyll concentration – The chlorophyll concentration is important to estimate the amount and distribution of phytoplankton in the ocean, which is the basis of the ocean food chain. Phytoplankton grow by photosynthesis, a process which consumes carbon dioxide, and so they are also important in the ocean carbon cycle and, consequently, influence the greenhouse effect and climate change. Chlorophyll concentration is regularly obtained for the ocean surface by satellite measurements (Shevyrnogova and Vysotskaya, 2007). However, the scale is very coarse and it is important to complement the satellite observations and provide some means of periodically calibrate the satellite data. This can be made by *in-situ* measurements of chlorophyll, using fluorometers installed in autonomous sailboats.

Ocean acoustics – The fact that autonomous sailboats are very quiet makes them suitable for acoustic measurements in the ocean. These vehicles may transport hydrophones with a wide bandwidth (either omnidirectional or directional) and record acoustic activity throughout the journey. Currently, these measurements are routinely carried out to detect mammal sounds (such as whales, for example) using drifters, gliders or AUVs (Fucile et al., 2006).

Tracking pollution plumes – Satellite images are already being used to follow the evolution of pollution plumes in the ocean, which is particularly important in coastal areas (DiGiacomo et al., 2004). However, the information provided by satellite measurements has very low resolution and only gives data in 2 dimensions. Autonomous sailboats can transport hydrocarbon sensors together with towed sensors (dissolved oxygen, chlorophyll concentration, for example) to monitor the upper layer of the ocean, measuring the thickness and the concentration of the pollution layer. They can also measure atmospheric conditions (local winds, air temperature, etc.) that may influence the evolution of the plumes.

Calibration of basin-wide ocean models – Recent advances in the understanding of the processes governing the dynamics of the oceans have fostered the development of ocean forecast models (Kelley et al., 2002). Autonomous sailboats can provide these models with data from real *in-situ* observations, taken at multiple temporal and spatial scales.

4.2 Coastal surveillance

Detection and prevention of illegal trading – Illegal trading routes often include maritime itineraries, and so coastal surveillance is essential to mitigate this problem. If we consider an average velocity of 3 knots, then a sailboat can travel about 70 miles per day. Surely that illegal traders use extremely fast speed boats, but a clever distribution of sailboats along the coast, together with the installation of 360$^{\text{o}}$ cameras, may prove to be an effective tool for detection of illegal activities and trigger further actions from the relevant authorities. With sufficient media hype, emphasizing the random nature of sailboat location, these vehicles can also act as effective deterrence tools against illegal trading.

Surveillance of immigration routes – There have been several recent episodes of casualties in ill-equipped crafts overloaded with illegal immigrants. Autonomous sailboats distributed along the coast with visible and infrared cameras may guarantee a permanent presence, 24 hours a day. This is a scenario for which it is important to design sailboats that can withstand bad weather and high seas, since these conditions often prove to be critical to people safety.

4.3 Military applications

Mine countermeasures – Autonomous sailboats may be used close to shore for mine detection using sonars like sidescan or multibeam. This prevents operators to approach a potential minefield, and may also provide high resolution hydrographic data. This type of mission is already being conducted with AUVs (von Alt et al., 2001), but the advantage of using autonomous sailboats is that the data can be transmitted in real time to a mother ship, along with an accurate absolute positioning given by GPS. With a permanent team continuously analyzing the data, it is possible to validate the targets and go back to the same location in case of doubt.

Coastal survey – One or more autonomous sailboats may be launched from a mother ship and approach shore with visual or infrared cameras mounted on top of the mast. Since autonomous sailboats have reduced power dissipation on board, it is expected that their own infrared footprint be minimal and therefore they should be able to conduct surveys virtually unnoticed.

5. Status of Current Efforts

5.1 Autonomous Sailboats Initiatives

Probably the most important initiative to promote the development of autonomous sailboats is the Microtransat challenge. The Microtransat was first organized in Toulouse, France, in June 2006, by ENSICA, with 3 teams from 3 different countries. In September 2007, the second edition was held in Aberystwyth, Wales. The main goal of this competition is precisely to demonstrate the navigation capabilities of autonomous sailboats, and in the second edition, 2 sailboats successfully navigated for about 20 hours off the Welsh coast. The ultimate goal of the Microtransat is quite ambitious: to cross the Atlantic with an autonomous sailboat.

One of the best aspects of the Microtransat competition is the emphasis given towards the integration of students in the competing teams. Even though most of the teams have senior researchers involved (and usually the PIs), the involvement of students, particularly undergraduate, in multidisciplinary projects like these definitely contributes to provide a systems' perspective and stress the benefits (and surely the delusions) of team work.

Across the Atlantic, a similar initiative has been hosted in Canada, with Sailbot being organized in June 2006 by Queen's University. However, the 2007 edition, initially set for San Diego, was later canceled.

Overall, there are very few scientific publications regarding the development or deployment of autonomous robotic sailboats, since most of the current projects are at an early stage and some other older projects were discontinued. One such case was the Ghost Ship, led by Southampton University, a 28 ft. sailing boat fitted with an autopilot. She made a 300 miles unmanned mission in 2005, but apparently the project had no continuation.

Total length (LOA)	2.50 m
Length in the water line (LWL)	2.48 m
Maximum width (beam)	0.67 m
Draft	1.25 m
Displacement	45 Kg
Wet surface	1.0 m^2
Ballast	16 Kg
Sail area	3.7 m^2
Mast height	3.4 m

Table 1: Main dimensions of the FEUP Autonomous Sailboat - FASt

5.2 The FASt project

The FEUP[1] autonomous sailboat (FASt) is a small sailing yacht capable of fully autonomous navigation through a predefined set of marks. This boat was custom designed and built for joining the Microtransat challenge, by a team of professors and students of the Department of Electrical and Computer Engineering of FEUP. The boat is a flexible autonomous navigation platform, suitable for evaluating the feasibility of using such vessels for applications is diverse areas like ocean sampling, surveillance or even for military missions. The FASt project was launched in the beginning of 2007 with two major objectives in mind: minimize the energy required for sailing and provide a efficient sailing boat capable of autonomous navigation under a broad range of weather conditions. Although the Microtransat rules establish a maximum boat length of 4m, we decided for a 2.5m long mono-hull. This was decided after scaling down, in length and displacement, some modern and successful oceanic sailing boats and keeping the total weight not far from the 40Kg limit initially defined by the Microtransat rules. This will also facilitate the launch and transportation, either by towing or on the top of a car. The design was inspired on the modern racing oceanic yachts, with the hull bottom flat at the stern to induce planning. To increase stability, the boat has a deep keel with a lead ballast. The rig is a conventional Marconi configuration with a headsail rigged on a small boom, as used in smaller RC sailing boats. Main dimensions are presented in table 1.

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6. Conclusions and future work

It is currently possible to build autonomous sailboats using high-performance computers and remaining onboard electronics requiring low electrical power. At the same time, a combination of high density batteries with high-performance renewable power sources allows for the installation of an energy management systems with indefinite duration. With such a system in mind, we have identified a set of applications for which the utilization of autonomous sailboats may prove to be both effective and efficient. Autonomous sailboats are just starting to be tested in real scenarios. The outcomes from the approaching initiatives will allow for a better forecast on the true potential of using autonomous sailboats in the ocean, but from the preliminary results we are optimistic.

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