Ocean sampling and surveillance using autonomous sailboats

Nuno A. Cruz, Jose C. Alves
Department of Electrical and Computer Engineering
Faculty of Engineering of the University of Porto
Rua Dr. Roberto Frias, 4200-465, Porto – Portugal
{nacruz, jca}@fe.up.pt

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, 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. 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.

Introduction

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, 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.

Although the use of autonomous sailboats for ocean sampling has been proposed in the past, there has been little attention from the scientific community regarding potential applications, even though there is a great demand of ocean data, particularly what concerns *in-situ* measurements (Legrand et al., 2003). In this paper, we show that this emerging technology may soon become an effective tool for a wide range of applications in real scenarios, complementing the other technologies available for ocean sampling and surveillance.

This paper is organized as follows. Section 2 provides some background regarding technology and paradigms for ocean sampling. In Section 3 we use a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) to assess 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.

Motivation

Technology for ocean sampling – a brief survey

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

Moored Instrumentation and Ocean Observatories – *In-situ* ocean observatories are unmanned systems located at a fixed site, providing information regarding the seafloor, the water column and/or the surface. They are important tools for monitoring time-variations of oceanic processes and 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 sensors can provide quasi-synoptic sections of evolving ocean fields. They are controlled from a ship via an umbilical cord, that provides power and communications. These systems have limited maneuverability, 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 remains 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 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 to get GPS coordinates 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. A recent glider model includes a heat engine that draws energy from the ocean thermocline, therefore allowing for very long range operations (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 – Some of the most recent technological advances, particularly in the last decade, have fostered 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.

The AOSN Concept

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

The fundamental idea behind this paradigm is to provide a synergetic observation system for a given region, taking advantage of the benefits of all technology available. Curtin *et al.* envisaged the installation of moored instrumentation linked to shore via radio or satellite, 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.

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 together 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.

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 sensors;
- **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.

The Role of Autonomous Sailboats - A SWOT Approach

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 possible to tow external sensors and arrays without the risk of the cables getting tangled. With a careful design it is also feasible to install 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.

Weaknesses

Risk of collision – Small sailboats are hard to detect from a large ship radar, 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, which can cause serious damage to the hull in case of collision.

Vulnerability to bad weather – When sailing for hundreds or even thousands of miles, it is very likely that a sailboat will encounter harsh conditions. Current weather forecast can anticipate incoming storms several days in advance, which may be useful to change the course of the sailboat. Nonetheless, if the wind is not favourable, it may be impossible to sail away from danger.

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 – Bio-fouling is a nuisance associated with long term ocean deployments. Some oceanographic optic sensors already feature 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.

Exposure to vandalism – Autonomous sailboats may be significantly slower than motor boats and so they may be targets for vandalism, particularly close to shore. This risk may be reduced with on board cameras and warning signs.

Impossibility of fixing a velocity – Since the velocity depends on the wind and sea state conditions, it is impossible to stipulate *a-priori* the time that the boat will take to complete a mission.

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.

Applications for future prototypes – 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.), mimicking the actions performed by a sailor in a real yacht. This way, future prototypes may be used to test different sailing strategies in the field.

Threats

Absence of applicable legislation – There is a lack of legislation regarding the navigation of autonomous sailboats and an hypothetical restraining legislation may completely forbid their deployment.

Demonstration failure – Although all required subsystems have been separately demonstrated, a fully autonomous sailboat has yet to be fully validated in the field.

Potencial applications of autonomous sailboats

Ocean Observation

Upper Ocean Dynamics – The dynamics of both the ocean and the atmosphere are determined by the energy they exchange. Oceanographers have been studying the processes that occur in the top layer of the ocean (eddies, fronts, etc), since they are extremely important to define these exchanges. 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 ocean circulation has direct impact in many different processes, such as biological activity and climate variability (Wunsch, 1996). Circulation studies encompass multi-scale measurements and therefore they can be supported by long-range autonomous sailboats. Sailboats can be equipped with acoustic doppler current profilers, with maximum range of 1000 meters.

Chlorophyll concentration – Chlorophyll concentration provides a good estimate of the amount of phytoplankton in the ocean (the basis of the ocean food chain). This measurement is regularly obtained by satellite for the ocean surface, but the scale is very coarse (Shevyrnogova and Vysotskaya, 2007). Autonomous sailboats can carry fluorometers to provide complementary *in-situ* data.

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

Tracking pollution plumes – Satellite images are already being used to track the evolution of pollution plumes in the ocean (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 relevant sensors (hydrocarbon, dissolved oxygen, chlorophyll concentration, for example) to monitor the thickness and the concentration of the pollution layer.

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

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. A pseudo-random distribution of sailboats along the coast, together with the installation of 360^{o} cameras, may prove to be an effective tool for detection of illegal activities and trigger further actions from the relevant authorities.

Surveillance of immigration routes – There are frequent 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.

Military applications

Mine countermeasures – Autonomous sailboats may be used close to shore for mine detection using sidescan or multibeam sonars, which 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

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

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

Status of Current Efforts

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. In September 2007, the second edition has been hosted in Aberystwyth, Wales, in which 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 Ocean. One of the best aspects of the Microtransat competition is the emphasis given towards the integration of students in the competing teams. In fact, 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 was held 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.

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. FASt was custom designed and built by a team of professors and students of the Department of Electrical and Computer Engineering at FEUP. This boat is a flexible platform, suitable for the Microtransat challenge and also for applications in ocean sampling and surveillance. 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. The Microtransat rules establish a maximum boat length of 4m, but we decided for a 2.5m long mono-hull 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.

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 system 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.

[1] Faculty of Engineering of the University of Porto

Acknowledgements

The authors would like to acknowledge the Department of Electrical and Computer Engineering at FEUP and the companies sponsoring the construction of FASt, the FEUP Autonomous Sailboat.

References

Brown, M., Kelley, M., and McGill, P. (2001). MBARI vertical profiler. In *Proc. MTS/IEEE Conf. Oceans'01*, Honolulu, HI, USA.

Cruz, N., Matos, A., Cunha, S., and Silva, S. (2007). Zarco - an autonomous craft for underwater surveys. In *Proc. 7th Geomatic Week*, Barcelona, Spain.

Curtin, T., Bellingham, J., Catapovic, J., and Webb, D. (1993). Autonomous oceanographic sampling networks. *Oceanography*, 6(3):86–94.

DiGiacomo, P. M., Washburn, L., Holt, B., and Jones, B. H. (2004). Coastal pollution hazards in southern California observed by SAR imagery: stormwater plumes, wastewater plumes, and natural hydrocarbon seeps. *Marine Pollution Bulletin*, 49:1013–1024.

Eriksen, C. C., Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., Ballard, J. W., and Chiodi, A. M. (2001). Seaglider: A long-range autonomous underwater vehicle for oceanographic research. *IEEE J. Oceanic Engineering*, 26(4):424–436.

Fucile, P. D., Singer, R. C., Baumgartner, M., and Ball, K. (2006). A self contained recorder for acoustic observations from AUV's. In *Proc. MTS/IEEE Conf. Oceans'06*, Boston, MA, USA.

Griffiths, G., (Ed.) (2003). *Technology and Applications of Autonomous Underwater Vehicles*. Taylor and Francis, UK.

Kelley, J. G. W., Behringer, D. W., Thiebaux, H. J., and Balasubramaniyana, B. (2002). Assimilation of SST data into a real-time coastal ocean forecast system for the U.S. East Coast. *Weather and Forecasting*, 17:670–690.

Legrand, J., Alfonso, M., Bozzano, R., Goasguen, G., Lindh, H., Ribotti, A., Rodrigues, I., and Tziavos, C. (2003). Monitoring the marine environment operational practices in europe. In *Proc. 3rd Int. Conf. EuroGOOS*.

Marchaj, C. A. (1996). *Sail Performance: Techniques to Maximize Sail Power*. International Marine Publishing.

Maycock, P. and Bradford, T. (2007). PV market update: Demand grows quickly and supply races to catch up. *Renewable Energy World*, 10(4).

Petersen, W., Petschatnikov, M., Schroeder, F., and Wehde, H. (2004). Application of a ferrybox: Automatic measurements in the north sea. In *Proc. MTS/IEEE Techno-Oceans'04*, Kobe, Japan.

Shevyrnogova, A. and Vysotskaya, G. (2007). Long-term dynamics of chlorophyll concentration in the ocean surface layer (by space data). *Advances in Space Research*, 39(1):197–202.

Skene, N. L. (2001). *Elements of Yacht Design*. Seafarer Books, UK.

Soreide, N. N., Woody, C. E., and Holt, S. M. (2001). Overview of ocean based buoys and drifters: Present applications and future needs. In *Proc. MTS/IEEE Conf. Oceans'01*, Honolulu, HI, USA.

von Alt, C., Allen, B., Austin, T., Forrester, N., Goldsborough, R., Purcell, M., and Stokey, R. (2001). Hunting for mines with REMUS: A high performance, affordable, free swimming underwater robot. In *Proc. MTS/IEEE Conf. Oceans'01*, Honolulu, HI, USA.

Webb, D. C., Simonetti, P. J., and Jones, C. P. (2001). SLOCUM: An underwater glider propelled by environmental energy. *IEEE J. Oceanic Engineering*, 26(4):447–452.

Wunsch, C. (1996). *The Ocean Circulation Inverse Problem*. Cambridge University Press, USA.