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# Design Considerations for Sailing Robots Performing Long Term Autonomous Oceanography

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# IRSC 2008

International Robotic Sailing Conference

23-24 May, 2008

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# IRSC 2008 International Robotic Sailing Conference

23-24 May, 2008  
Breitenbrunn, Austria

[www.roboticsailing.org](http://www.roboticsailing.org)

IRSC 2008 is the first International Robotic Sailing Conference. IRSC 2008 will be held in Breitenbrunn at Lake Neusiedl in Austria from 23<sup>rd</sup> to 24<sup>th</sup> of May 2008 and coincides with the World Robotic Sailing Championship. The conference is being jointly hosted by Austrian Association for Innovative Computer Science (InnoC) and Yacht Club Breitenbrunn in cooperation with the Austrian Society for Artificial Intelligence (OEGAI).

**InnoC.at**



IRSC 2008 is part of Centrobot project, which is financed by the European Regional Development Fund, the Austrian Federal Ministry of Science and Research, and the Austrian Federal Ministry of Economics and Labour.



**BM.W\_F<sup>a</sup>**





## Foreword

The vision of machines which relieve more and more tasks of humans induced many scientific initiatives in mobile robotics. Research in fully autonomous sailing boats was recently stimulated by the Microtransat idea of Mark Neal and Yves Briere. An increasing number of research teams around the world try to teach their boats the complex task of sailing. The best routing decision, perfect handling of ever changing wind conditions and perfect timing during tack and jibe are some of the skills an autonomous sailing vessel has to master.

A robotic sailboat is able to autonomously navigate towards any given target without human control or intervention. The optimal route is calculated dependent on strategic goals and weather parameters. Rudder and sails as well as the manoeuvres tack and jibe are autonomously controlled. As sailboats operate in a highly dynamic environment an autonomous sailboat has to respond quickly to changing environmental conditions. Incoming data from sensors (GPS, compass, anemometer, etc.) have to be analysed permanently by intelligent control mechanisms.

World's best autonomous sailing boats compete on the Austrian Lake Neusiedl from 20<sup>th</sup> to 25<sup>th</sup> of Mai 2008 in order to win the first world championship in robotic sailing. Moreover the event is the ultimate trial for the Microtransat in autumn 2008. This will be the first transatlantic race for autonomous sailboats of up to 4m length.

Another highlight of the competition week is the human vs. machine race, a direct confrontation of a robotic and a human sailor. The IRSC2008 coincides with the world championship.

The contributions to the conference show the current focus of research in the robotic sailing community. In the recent years, routing and intelligent control algorithms dominated the scientific discussion. Due to the fact that the next grand challenge will be an autonomous transatlantic race in late 2008, energy supply issues and robustness of both boat and software are the research topics of today.

Breitenbrunn, May 2008

A handwritten signature in black ink, appearing to read 'Roland Stelzer', with a stylized, flowing script.

Roland Stelzer  
Conference Chair

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# A Biologically Inspired Approach to Long Term Autonomy and Survival in Sailing Robots

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## Abstract

Biologically inspired approaches have long been touted as a possible mechanism to improve the survival of robots operating autonomously in harsh environments. One method which has often been suggested is to mimic the endocrine system which is responsible for the modulation of a series of behaviours. The endocrine system contributes to the process of homeostasis which maintains a stable state within the body in the face of a changing external environment. An artificial endocrine system could be deployed to modulate the frequency of actuator use or sensor sampling. This could improve power management and task allocation within a sailing robot, helping it to maintain a steady state and continue operating autonomously for longer periods of time. This paper outlines the method for a simple test of this technique involving feedback of actuator temperature and a simple circadian rhythm on a small sailing robot.

## 1. Introduction

It is highly desirable that autonomous robots operating away from human contact for extended periods of time are able to adapt to changes in their environment. Such changes may include variations to both the external environment in which the robot is operating and the internal environment of the robot. Common examples of external changes might be a change of weather or season, moving to a new environment with different topography or even the interaction with other robots. Examples of the internal changes would include damage to the robot, available power levels, overheating actuators or even a change in the priorities of the robot's mission. One possible approach is to borrow ideas from biology, given

that biological systems are able to maintain a stable internal state in the face of massively fluctuating external conditions (a process known as homeostasis). A vast amount of research has already been conducted on techniques which exploit biological ideas to enhance the survivability and efficiency of robots, however there are at present no examples of this being tested beyond laboratory conditions. This work will outline an attempt to deploy these techniques on an autonomous sailing robot intended to perform missions lasting several months.

## 2. Biological Inspiration

In mammals three systems are particularly key to maintaining homeostasis, these are the neural, endocrine and immune systems. The neural system connects to the rest of the body via a series of point to point links known as nerves which connect the brain to each point, these carry high speed electrical signals and are responsible for a number of short term actions such as muscle movements. The endocrine system is able to modulate a variety of behaviours throughout the body with chemical messengers known as hormones. Hormones are produced by a series of glands and secreted into the bloodstream in response to certain triggers, these can either be as a result of neural, endocrine or immune activities. Hormones secreted into the blood reach virtually all cells in the body and will upon reaching a cell bind with it, if it features a correctly shaped receptor. Upon binding the hormone will either suppress or promote a particular behaviour of that cell. The immune system is responsible for removing foreign infections from the body, it can broadly be split into two parts the innate immune system and the acquired immune system. The innate immune system is present from birth and provides a first line response to infection, the acquired immune system is built up as a form of memory which remembers how previ-

ous infections were dealt with so that the process can be performed again when needed.

These three systems do not act in isolation, rather they act more as if they are a single system which contributes towards the maintenance of homeostasis. There is a high degree of coupling between them, with each handling a different timescale. The neural system works on the smallest time scale of between a few milliseconds and a few seconds, the endocrine system operates on a scale of between a few seconds and several months and the immune system on a scale of between minutes and decades. At present biologists understanding of the neural and endocrine systems is far better than their understanding of the immune system, given this, the time frame of the immune system and the computational complexity of artificial immune system algorithms its role will not be covered by this work.

### 3. Previous Work

#### 3.1 Long term autonomy in robotics

The majority of robots in operation today operate within close proximity to a human operator and for relatively short periods of time. There are few examples of real autonomous robots operating over long periods of time, currently those that do exist fall mostly into two categories, autonomous underwater vehicles and space robots. There are several examples of autonomous underwater vehicles such as ARGO floats and underwater gliders which gather ocean data autonomously over periods of several months while communicating with their operators only every few days. Space robots such as NASA's Spirit and Opportunity Mars Exploration Rovers or the long distance probes such as Cassini and Galileo operate at a considerable distance from their operators but tend to maintain regular contact with them. They display only a limited degree of autonomy, this is in part a reflection of the vast amount of time it takes to construct a space vehicle and how rapidly technology advances during this process and how conservative space roboticists are in their use of autonomy given their fear that an autonomous system will undertake incorrect decisions. As a result space robots tend to be at least partially teleoperated or when radio latency is too high, carrying out batches of previously stored instructions. None of these robots and at present virtually no operating robots make any serious attempt to make any decisions regarding their own survival, maintaining a stable state or even more than a basic attempt at power management.

#### 3.2 Biologically inspired control systems

##### 3.2.1 Artificial Neural Networks

Since 1940s a variety of algorithms inspired by the principles of the neural system have been devised. This began with the work of McCulloch and Pitts (McCulloch and Pitts, 1943), Hebb (Hebb, 1949) and Rosenblatt (Rosenblatt, 1958) during the 1940s and 50s. Between them they defined the basic principle of an artificial neuron (with Rosenblatt coining the term Perceptron to describe them) which contains a series of weighted inputs and a single output. Each input value (usually between 0 and 1) is multiplied by its weight, the sum of all weighted inputs is then taken and passed to an activation function which decides upon the output. The simplest activation function is simply a threshold above which the output is defined as 1 and below which it is defined as 0, more complex activation functions such as the sigmoid function can output values between 0 and 1. Later work involved placing perceptrons into three or more layers known as multi-layer perceptrons, these are able to solve quite complex pattern recognition problems and have been applied to many problems including collision avoidance and course holding systems in robots.

##### 3.2.2 Endocrine and Behaviour Modulation Mechanisms

Despite the lack of real robots making decisions involving their survival there has been a considerable amount of work developing potential techniques. Most of this work has been biologically inspired most likely due to the goal of mimicking the way biological systems are capable of adapting to their environments. The earliest example of such work dates from William Ashby back in the 1950s (Ashby, 1960) and his book "Design for a Brain" in which he details experiments involving an analogue computer which exhibited homeostatic properties able to return a system to a steady state when an external stimulus disrupted them. Later work with digital computers was first demonstrated by Ronald Arkin in the 1990s (Arkin, 1992, Arkin, 1993), he introduced the idea of artificial hormones which act to modulate the behaviour of other systems. In his case he modulated a route planning behaviour in response to available energy levels, as the energy levels dropped the system would leave less margin for error between obstacles and the planned path. A few years later the idea was again adopted by Canamero (Caamero, 1997), Gadanho and Hallam (Gadanho and Hallam, 1998) in their work on emotional robotics. They linked emotions of the robot such as fear, happiness and boredom to motivations such as hunger, cold, danger and curiosity through a hormone inspired system. Each motivation would trigger the production of a certain hormone and the hormone with the



highest concentration would dictate the behaviour of the robot at that time. This in turn would trigger corrective actions, for example finding food if hungry, which in turn would reduce the hormone concentration responsible for the current state eventually triggering a change in behaviour. A further variation of this idea was developed by Neal and Timmis (Neal and Timmis, 2003) and later Mendao (Mendao, 2007) who created an artificial endocrine system which produced hormones in response to certain stimuli, these hormones then modulated the behaviour of artificial neural networks (which were tasked with performing obstacle seeking and avoidance) by varying the weights of the network, as illustrated in Figure 1. They defined the idea of an artificial gland which produced a given hormone. Each gland produced hormone at a specified rate according to the formula:

$$g_t = \sum_k y_k \cdot r \quad (1)$$

and where  $g$  is the rate at which hormones are released,  $y$  is the input stimulus and  $r$  is the rate at which the hormone is produced. This model known as the “Leaky Gland” would create free hormone immediately available for use. This allowed for behaviours to be gradually suppressed or promoted as Mendao demonstrated by gradually switching between seeking black and white objects, this was in stark contrast to Canamero or Gadanho and Hallam’s “winner takes all” approach. Mendao also found that his artificial endocrine system would often lose momentum and stabilise upon a stagnant state in which virtually no behavioural changes took place. His experiment involved two hormones following sine waves which switched behaviour between seeking white and seeking black objects, this highly symmetrical environment tended towards a convergence of seeking both. He identified three factors causing this: the symmetrical nature of the environment, the lack of a topology through which hormones travel and the lack of pools in which hormones build up before they are secreted. He decided to implement a system of pools that would store hormones before they were released. In this model hormones are produced when a certain stimulus occurs, but stored in the pool until a threshold value is reached, upon reaching this threshold the pool is emptied and becomes “free running hormone” and it will begin to trigger behavioural changes, this level then decays at a linear rate. He decided not to implement the idea of an artificial topology given the great complexity involved. The choice of a linear decay rate is somewhat arbitrary with little basis from biology, however in biology hormones concentrations decay as hormones bind to receptors, but without an artificial topology there is no natural decay therefore some mechanism had to be chosen.

Many hormones within the endocrine are associated

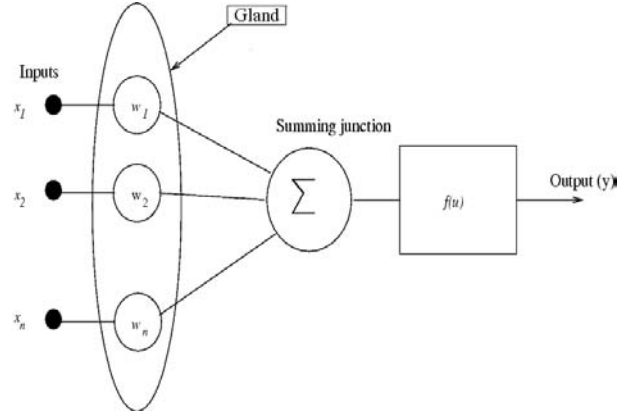


Figure 1: An endocrine modulated perceptron, as described by Neal and Timmis (Neal and Timmis, 2003). Hormones produced by the gland affect the weights of each input to the perceptron.

with the body’s own circadian rhythm, a form of biological clock. As a result our body’s gradually modify their behaviour depending on what time of day they think it is, common effects of this include a slowing of the metabolic rate at night as less energy is exerted and no food is consumed for several hours while we sleep. It would seem sensible for a robot operating on its own for long periods of time to have some notion of sleeping, this would be particularly important in a solar powered robot as it is dependant on solar energy to perform its task and for its survival. Several people have already experimented with this idea including Mirolli and Parisi (Mirolli and Parisi, 2003) who added a light sensor to a robot in order to allow the robot to determine what time of day it was and then went onto to simulate a form of biological clock for the robot. Rocks and Barnes (Rocks and Barnes, 2004) took a similar approach in attempting to produce a circadian rhythm for a Mars Exploration Rover, their robot was able to take stimulus from external sources to run an internal circadian rhythm. This rhythm dictated which tasks would be executed and when they would be executed. They also allowed for this rhythm to be re-entrained by external sources so that the rover could be landed at (or later moved to) any part of the planet and re-adapt to any timezone.

### 3.3 Alternative Approaches

Despite the vast body of work involving biologically inspired techniques as described in the previous section there is an alternative school of thought which says that robots should simply be robustly engineered. This approach is actually very popular amongst the few examples of real long term autonomous robotic missions. Few biologically inspired techniques are to be found amongst

the current generation of autonomous underwater vehicles (AUVs), autonomous maritime vehicles (AMVs) or space robotics. This is usually a reflection of the engineers of these vehicles attempting to take the simplest possible designs for software and instead focusing on robust hardware and control systems. There is also a fear amongst many operators of autonomous vehicles (or those funding them) that biologically inspired control systems are unpredictable and could endanger their robot. These fears are not completely unfounded and a biologically inspired control system could very well reduce the ability to predict what course of action a robot will take and in many cases may not even leave sufficient evidence of why it performed a certain action. However the authors believe that biologically inspired techniques can enhance a robot's ability to deal with unknown and unforeseen problems, enhance the autonomy of a robot and ultimately allow for longer missions with less operator intervention. This does not mean that basic engineering issues can be ignored and a robust construction is still required, however the possibility exists that a more intelligent robot could "outwit" its less intelligent counterparts to avoid troublesome situations and therefore could be constructed in a less robust (and cheaper!) manner.

## 4. Design for a system

The authors envisage a sailing robot who's control system is based around neuro-endocrine controller that is responsible for keeping the robot in an operable state for as long as possible. The robot will be intended to perform ocean monitoring at either a single fixed location or a series of locations. It will contain on-board sensing systems to record its oceanographic data and a long distance communications system to transmit its findings and receive new instructions. Power will be provided by photovoltaic solar panels and internal batteries. The robot will be controlled by as few as two actuators (perhaps more for redundancy), one controlling the rudder and the other controlling the sail.

The robot will be able to sense its current battery state, its solar panel state, the temperature of its actuators and their associated controllers and it will be aware of its current position and the current time via GPS. It will be able to vary the frequency of actuator movement, satellite communications and sensor sampling, it will also be able to choose between continuing its mission, temporarily halting the mission and even returning home.

A neural network will be responsible for positioning the sail with respect to the wind direction and the rudder with respect to the current and desired headings. An artificial endocrine system will modulate behaviours, controlling the weights of the neural networks thus affecting the frequency of actuator movements. It will

also control the frequency of sensor sampling and balance between the overall goal of performing the mission and preserving the robot.

### 4.1 Artificial Endocrine System

Several artificial hormones will be available to the system, these are stimulated by available energy levels, sunlight levels, actuator temperature and signs of danger to the robot. They will act as modulators to the neural networks and will vary the frequency and magnitude of actuator movements, they will also modulate the frequency of other systems such as the communications and navigation system. Details of each of these hormones are shown below.

1. Energy Level Hormone: Equivalent of insulin, released when electricity is available for use, for example when batteries are well charged and solar panels are active. Presence of this will increase the weights within the neural networks which control the actuators, increasing the level of actuator activity.
2. Actuator Thermoregulation Hormone: Regulates actuator and actuator controller temperatures through feedback from temperature sensors. Where redundant actuators or controllers exist there will be a hormone for each allowing gradual switching between them.
3. Danger Hormone: Equivalent of adrenaline, released when the robot is considered to be in danger, raising the weights within the steering and sailing neural networks causing them to react more dramatically. In biology adrenaline is often associated with the "fight or flee" response, in robotics this may translate to suppressing scientific data gathering and other behaviours which are not related to the immediate survival and promoting behaviours relating to avoiding danger and reaching safety. This hormone would typically be released in response to sensing dangerous conditions such as large waves, poor weather or in response to component failures.
4. Day/Night Hormone: Creates a circadian rhythm for the robot, releasing more of the hormone in the daytime. This can either be triggered through the presence of daylight or calculated from the time of year, location and time of day. Certain behaviours can be activated by this hormone depending on the time of day. A phase shifted version could also predict the amount of available solar energy later in the day, helping to schedule tasks around what will be available rather than the current availability.
5. Mission Hormone: This hormone creates a desire for the robot to perform its scientific mission and may override the requirements to save power. Ideally the



Figure 2: The ARC sailing robot.

robot operator would have some ability to configure which would have highest priority, performing the mission or preserving the robot. This decision would ultimately depend upon the operator's need to obtain data quickly and at an increased risk to the robot or whether they wished to extend the robot's lifetime in exchange for occasionally losing data.

## 5. Experiment Design

A simple experiment was devised to attempt to demonstrate some of the basic concepts of an endocrine inspired controller operating in a real world scenario. For this experiment a small sailing robot known as ARC (Sauze and Neal, 2006) (shown in figure 2) was used, it is controlled through two sail actuators and one rudder actuator. These are all unipolar stepper motors and each driven by a motor controller (shown in figure 3) consisting of a set of four power transistors, these are all connected to a common heatsink which in turn is connected to a temperature sensor. There are three controllers in total and each can control two motors. This configuration allows for the complete failure of one motor controller and also allows for control of a given motor to be switched to a different controller should the power transistors overheat.

For simplicity the experiment will focus only on a single actuator although the process could easily be scaled to control all three. A gland will produce hormone in response to stimulation from heat generated by one of the two motor controllers, the greater the hormone level the less the given controller is used. The glands will produce free running hormone directly and follow equation 1 to determine hormone production. The selection of which controller to use is based upon the difference between these two hormone concentrations. Additionally the greater the concentration of the hormone the less frequently an actuator will be allowed to move. This design should serve to keep the power transistors cool by

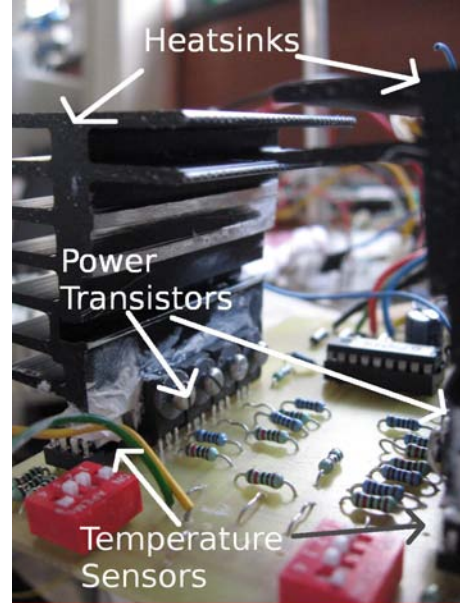


Figure 3: The ARC stepper motor controller, each set of power transistors is connected to its own heatsink.

flipping to the alternate set and when both overheat it will begin to reduce the frequency at which actuator is allowed to move.

A third hormone will represent a phase shifted circadian rhythm following the formula (note that the cosine function is assumed to be in degrees not radians):

$$y = -1 * \cos((t * 15) + 15) \quad (2)$$

where  $y$  is the amount of available sunlight in one hour and  $t$  is the current time of day in hours (so 6:30am would be 6.5). The  $+15$  term will phase shift the waveform by one hour so that the output of the formula represents the sun's elevation in one hour. This formula assumes day and night to be of equal length, in reality a more complex version of this formula which takes latitude, local solar time and season into account is required. It is perceived that this will give a clearer indication of available solar power when determining which events to schedule rather than the current level, for example if it is one hour before sunrise and the robot's batteries are running low then it might decide to start powering down systems, however as the sun will be rising soon after and begin to provide solar power this is unlikely to be a wise move. By producing a one hour phase shift this issue is avoided as is the chance that the robot will begin critical tasks shortly before sunset if the batteries are low but the solar panels are still providing a reasonable amount of power.

Another process will constantly attempt to move the actuator, although this scenario is somewhat unrealistic in a real world setting it is intended to speed up a process

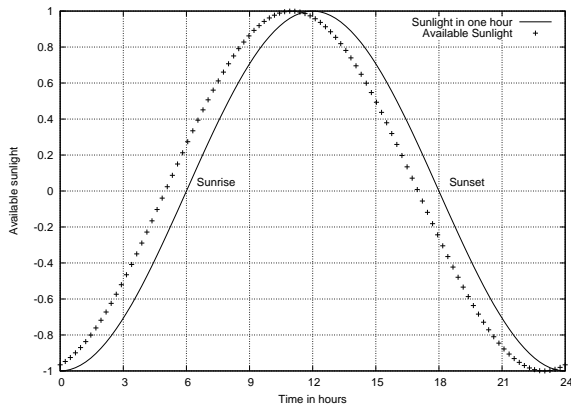


Figure 4: A graph of the circadian rhythm function shown in equation 2.

of overheating the motor controller. As the heatsinks heat up the frequency of actuator movement will drop and the temperature of the two heatsinks (or at least the temperature sensors) should remain approximately equal. In future this process will be replaced with an artificial neural network which is tasked with keeping sails correctly set or keeping the robot on course. This aspect was dropped from this experiment for simplicity and to speed up the process of overheating the power transistors.

One concept not explored by this experiment is the use of pools as described by Mendao (Mendao, 2007). Mendao suggested that without pools his algorithm tended to stagnate and converge upon a stable state in which it did not jump between behaviours and in part blamed this on the symmetry of his experiment. In this case there is symmetry between the selection of motor controller but a convergence to a situation where each is used approximately 50% of the time is desirable and the time based hormone will ensure that the entire system does show variation over time. Another design decision which needs to be taken is to decide how sensitive the system should be to each hormone, it could be that either the temperature or time hormone could be allowed to completely stop any actuator movements when they reach sufficient levels.

## 6. Results

Unfortunately due to a hardware fault no results have been gathered at this point. This has been due to a short circuit between the power transistors and heatsink caused by insufficient insulation, this has destroyed several of the power transistors on both controllers rendering them unusable. This requires a relatively small amount of work to replace the transistors but there was

simply not enough time before the deadline of this paper.

## 7. Conclusions and Future Work

This work has outlined the basic architecture of an artificial neuro-endocrine controller and proposed a simple experiment involving them. This experiment will only demonstrate a small subset of the full architecture described in section 4. Further experiments will need to be designed involving a full implementation of this architecture and long term experiments at sea. As discussed in section 2. the capabilities of the immune system have not been considered, however there are a number of artificial immune system algorithms available and integrating these as part of a longer term survival strategy may well be worth consideration. This would present some problems with regards to computational complexity and in a need to provide a rich set of state information about the robot as the immune system requires far more than the handful of variables that the current architecture presents.

## References

- Arkin, R. (1992). Homeostatic control for a mobile robot: Dynamic replanning in hazardous environments. *Journal of Robotic Systems*, 9:197–214.
- Arkin, R. (1993). *Survivable Robotic Systems: Reactive and Homeostatic Control in Robotics and remote systems for hazardous environments*, volume 1, chapter 7, pages 135–154. Prentice Hall.
- Ashby, W. R. (1960). *Design for a Brain: The Origin of Adaptive Behavior*. Springer, second edition.
- Caamero, D. (1997). Modeling motivations and emotions as a basis for intelligent behavior. In *Proceedings of the First International Symposium on Autonomous Agents (Agents'97)*, pages 148–155. ACM Press.
- Gadanh, S. and Hallam, J. (1998). Exploring the role of emotions in autonomous robot learning. In Ca namero, D., (Ed.), *Emotional and Intelligent: The Tangled Knot of Cognition*, pages 84–89.
- Hebb, D. (1949). *The organization of behavior : a neuropsychological theory*. Wiley.
- McCulloch, W. S. and Pitts, W. (1943). A logical calculus of the ideas imminent in nervous activity. *Bulletin of Mathematical Biophysics*, 5:115–133.
- Mendao, M. (2007). David meets goliath: A bio-inspired architecture measured against a traditional architecture. (pending review) *IEEE SMC UK&RI Journal of Applied Cybernetics*.

- Mirolli, M. and Parisi, D. (2003). *Artificial Organisms That Sleep in Advances in Artificial Life*, volume 2801/2003 of *Lecture Notes in Computer Science*, pages 377–386. Springer Berlin/Heidelberg.
- Neal, M. and Timmis, J. (2003). Timidity: A useful emotional mechanism for robot control? *Informatica*, 27:197–204.
- Rocks, C. and Barnes, D. (2004). Entrainment as a paradigm for modelling a planetary robot’s circadian rhythm. In *Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, ESTEC, Noordwijk, The Netherlands.
- Rosenblatt, F. (1958). The perceptron: A probabilistic model of information storage and organisation in the brain. *Psychological Review*, 65:386–408.
- Sauze, C. and Neal, M. (2006). An autonomous sailing robot for ocean observation. In *proceedings of TAROS 2006*, pages 190–197.

# A reconfigurable computing system for an autonomous sailboat

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## Abstract

This paper presents the computing infrastructure used in an autonomous unmanned small-scale sailboat. The system is built on a reconfigurable FPGA and includes custom designed interfaces for the various sensors and actuators used in the sailboat. The central processing unit is a 32-bit RISC microprocessor (Microblaze from XILINX) implemented as a soft IP (Intellectual Property) core, running at a maximum frequency of 50 MHz. The computing system runs uClinux, a simplified version of the popular Linux operating system. The usage of a reconfigurable platform enables the possibility to reconfigure completely the processing and control hardware system. This facilitates enormously the development of the control system and allows the selection of different hardware control systems, according to the navigation requirements and environmental conditions.

## 1. Introduction

The FEUP<sup>1</sup> autonomous sailboat (FASt) is a small sailing yacht capable of fully autonomous navigation through a predefined set of waypoints. The boat was custom designed and built as a response to the Microtransat challenge ([www.microtransat.org](http://www.microtransat.org)) and offers a flexible platform for various applications like data acquisition of oceanographic or atmospheric variables, wild life tracking and monitoring, surveillance and also support platforms for cooperative navigation with autonomous underwater vehicles (Curtin et al., 1993) (AUVs).

### 1.1 Sailing

Sailing can be an easy task or a very complex task, depending on the desired level of performance and also on the wind and sea conditions. In conventional sailing

boats the basic controls are the rudder and sail sheet. The rudder determines the course to navigate and the sail sheet is used much like the throttle of a car: loose it to stop the boat or pull it to go ahead. For a given course, boat speed, wind speed and wind direction, there is an optimum angle between the sail and the direction of the wind that maximizes the speed of the boat. If the boat speed changes (for example, slowing down when climbing up a wave or accelerating by surfing down a wave) the apparent wind direction and wind speed relative to the boat are modified, implying constant corrections to the sail angle to maintain the course with optimum speed. Alternatively, the sailor can keep the sail in the same position and alter the course with the rudder to keep the same apparent wind angle. Also, variations in the true wind speed due, for example, to the waves (wind speed increases in the crest of a wave), add important variations to the wind conditions seen by an observer on the boat. This results in the necessity of continuously adjust the sail and/or the rudder to keep the boat at its maximum speed. In addition, conventional fabric sails also have control lines that are used to adjust the shape of the sail, depending on the leg sailed (up-wind, down-wind), wind speed and sea condition. Although this is a simplified view of the close interactions that exist between the variables involved in the sailing process, it is clear that a control procedure should adapt dynamically to the environmental conditions.

Sailors have from several years the assistance of auto-pilots to provide autonomous steering, for limited periods of time. The auto-pilot is a valuable accessory in sailing yachts, allowing the automatic control of course according to some reference direction (GPS, compass or wind direction). However, in a sailing yacht the electric energy is usually limited and the usual sources of power are the sun and the wind. One type of fully mechanical auto-pilot is the wind-vane self steering system, very popular some decades ago (Belcher, 1982) and still in use by some sailors for long journeys. It combines a wind vane mechanically linked to a rudder and steers the boat automatically, relative to the apparent wind.

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Although this system has some limitations, it has the big advantage of not requiring any electric energy for working.

## 1.2 FPGAs

The computing system designed for FAST is based on a FPGA (Field-Programmable Gate Array), providing a flexible reconfigurable computing platform (Compton and Hauck, 2002). The system includes a RISC 32-bit central processor surrounded by a set of custom designed peripheral digital systems that implement the processes responsible for interfacing with sensors and actuators, and also for custom processing and control. This allows the integration of almost all the custom digital electronics into a single chip and simplifies significantly the design of the control software, alleviating the processor from the low-level interfacing and data processing tasks.

FPGAs are commercial integrated circuits that can be configured by the end user to perform any arbitrary digital system. The common configuration technology used in present FPGAs is based on SRAM and provides a virtually infinite number of re-configurations in very short times (tens to hundreds of milliseconds). Cutting-edge FPGA devices offer capacities equivalent to a few millions of logic gates, and include on-chip memory blocks exceeding 10 Mbit, dedicated functional blocks optimized for signal-processing applications, gigabit transceivers and, in some families, embedded high-performance processors. Furthermore, the digital systems implemented in such devices can run with clocks of a few hundreds of MHz and exceed one thousand input/output pins available for the user application. This is now a mature digital technology that offers flexible platforms for targeting complex and high-performance digital systems without incurring in the high costs and long turnaround times of silicon fabrication.

Another interesting attractive of FPGA technology is the ability to quickly modify the digital system implemented in the chip. Different configuration files can reside in low cost off-chip flash memories (or even hard disk) and loaded into the FPGA to configure a completely different system. Some FPGA families even allow partial reconfigurations without disturbing the rest of the chip. This is particularly interesting in applications where the processing requirements may vary along the time and also during the development and experimentation stages.

## 1.3 Paper organization

In addition to this introduction, the paper is organized as follows. Section 2 briefly presents the autonomous sailboat built at FEUP (FAST). Section 3 overviews the electronic system used in FAST and the hardware plat-

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
Wetted surface	1,0 m <sup>2</sup>
Ballast	16 kg
Sail area	3,7 m <sup>2</sup>
Mast height	3,4 m

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

form that implements the main computer is presented in section 4. The computing system is detailed in section 5, including the sensors and actuators. Main implementation results are presented in section 6. Section 7 summarizes the operating modes supported by the FAST control system and finally section 8 concludes the paper and presents the current status of the project.

## 2. The FAST project

The FAST project was launched at FEUP in the beginning of 2007 to participate in the Microtransat competition. The project aimed to build a small-scale autonomous sailing boat with two objectives in mind: minimize the energy required for sailing and navigate as fast as possible. Although the Microtransat rules establish a maximum length of 4m and the theoretical maximum speed of a boat is proportional to the square root of its length, we decided for a 2,5 m long mono-hull. This was determined after scaling down in length and displacement some real oceanic modern sailing boats, to keep the final weight not far from the 40 kg mark, in order to 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 and was developed with the free version of the boat design software DelftShip (<http://www.delftship.org>, former FreeShip). The hull bottom at the stern is flat to induce planning. To increase stability, the boat includes a deep keel with a ballast. The rig is a standard Marconi configuration with a small jib mounted on a boom, as used in smaller RC sailing boats. Main dimensions are presented in table 1.

### 2.1 FAST hull construction

The boat was built by a team of students and professors of FEUP, with the support of a local kayak builder (Elio Kayaks, <http://www.elio-kayaks.com>) that executed the fabrication of the parts in composite materials and gave a valuable help during all phases of the process. The construction started in the beginning of March 2007 with the assembly of the positive model. This was built start-

ing with plywood frames, a rough cover of strip planking and fibreglass with polyester resin, followed by various iterations of filling and sanding to achieve a final smooth surface. This full scale model was then used to build a negative mould and, afterwards, the final hull.

The hull has been fabricated using a sandwich of carbon fibre in the outer layer, a low density honey comb core in the middle and an inner layer of fibreglass. This sandwich was pressed with vacuum during the cure of the epoxy resin. This is the same construction process used to build high-performance racing kayaks and resulted in a very stiff hull, weighing less than 5kg, without the deck. The hull was reinforced internally at the points subject to the major mechanical forces: the attachment of the keel, foot of mast and the points where the shrouds connect to the hull. Two platforms placed at the bottom interior (front and middle) provide convenient space for mounting the electronic system. Figure 1 illustrates some stages of the construction process.



Figure 1: The construction of FAST: (top-left to bottom) assembly of the frames; strip planking; the mould; filling the mould with the layers of fibre and core materials; the final hull.

The keel was manually built starting from a core of rigid polyurethane foam shaped to a NACA profile, then laminated in vacuum with several layers of carbon fibre. The rudders were made from a wood core covered by fibre glass, firmly attached to a stainless steel shaft. Mast and boom were built with carbon fibre tubes used in competition paddles and some standard hardware of masts of small dinghies.

### 3. Electronic system

The electronic system used in FAST is assembled with various modules, some of them custom built for this application. Figure 2 presents a block diagram showing the general organization of the system and the approximate physical location inside the hull.

The computing system is implemented in a small FPGA-based single board computer (Atmark-Techno, 2006). This includes a 32-bit RISC microprocessor running at a 50 MHz maximum clock frequency (Microblaze (Xilinx, 2004)), surrounded by various custom designed dedicated circuits. The organization, characteristics and modes of operation of the computing system are detailed in the next sections.

The communications section includes a WiFi router (LinkSys WRT54GC), GSM modem (Siemens MC35), IRIDIUM SBD modem (model 9601) and a conventional RC receiver used in radio-commanded models. All these components are integrated as OEM modules and can be switched on/off under control of the software running in the computing system, depending on the operating mode of the system.

Sensors include the wind vane and anemometer, boom position, compass (Honeywell HMR3300), GPS (uBlox RCB-4H), inclinometer (two axis accelerometer ADXL202, from Analog Devices), voltage monitors, ambient light sensor, interior temperature (Analog Devices A/D converter AD7905) and a set of moisture sensors custom made with small pieces of gold plated PCB terminals. A total of 4 additional A/D channels and 12 digital I/Os are available for future expansion. The wind vane and boom position indicator were built with a magnetic field direction sensor from Austria Micro Systems (integrated circuit AS5040). This chip measures the orientation of the magnetic field created by a small magnet placed close to its case and provides 10 bit measures with 1 degree of accuracy. The chip was embedded in epoxy resin and is thus completely isolated from the water. The wind speed sensor is made with a conventional cup rotor actuating a hall-effect switch also embedded in epoxy.

Regarding the actuators, one DC motor controls the sail's position and two standard RC servos provide independent control of the two rudders. A second DC motor is planned to be installed for adjusting the sail area. The DC motors are standard window motors used in cars. Although this type of motor and the associated gear-

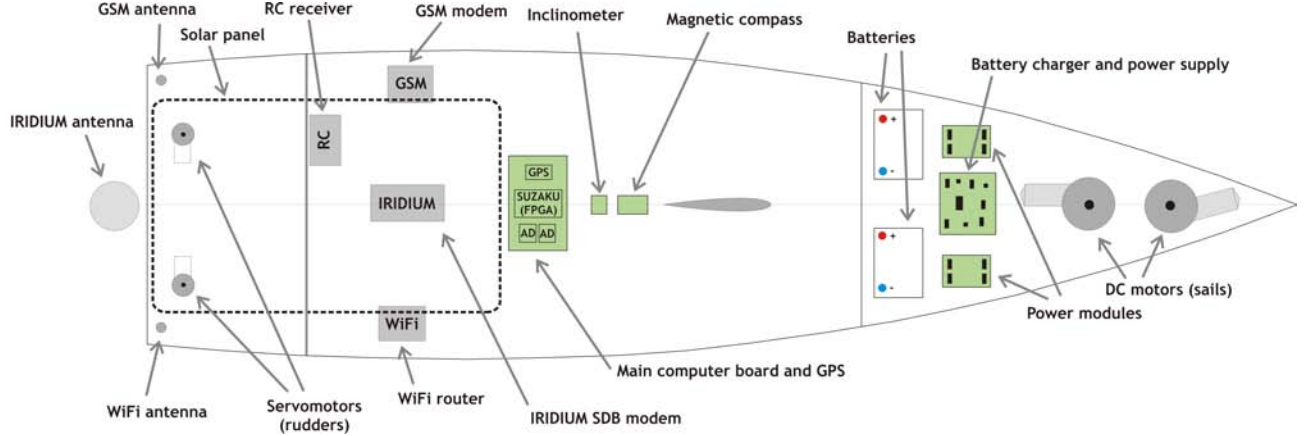


Figure 2: The organization of the FAST electronic system and its distribution inside the hull.

box is known for its low efficiency, they are extremely robust and once positioned and unpowered the gearbox naturally locks the motor's shaft. As the sail angle only needs to be adjusted to set a new course or when the wind direction changes significantly, this represents an important saving of electric energy when comparing to other combinations motor-gearbox that need power to react to the force of the sail sheet.

Finally, the power generation and control section includes a 45 Wp solar panel (Solara SM160M), two 95 Wh Li-ion batteries (BA95HCL), battery management module (BB-04S) and a ultra efficiency power supply (DC123SR) to provide all the voltages used by the system. This battery power system was included as an integrated solution provided by OceanServer (<http://www.ocean-server.com>).

#### 4. The computing platform

The computer board used in FAST is a commercial system from Suzaku (SZ130 (Atmark-Techno, 2006)), built around a Xilinx FPGA, model Spartan3E S1200. The system has 32 MB of SDRAM, 8 MB of SPI flash memory, serial interface and Ethernet port implemented by a dedicated chip external to the FPGA. A total of 86 I/O pins are available for the user application, directly connected to FPGA I/Os and distributed in edge connectors around the board. The FPGA is only partially occupied by the base project (processor and essential peripherals), leaving roughly more than 1 million equivalent logic gates available for user logic. Figure 3 depicts the organization of the SZ130 board and the reference project implemented in the FPGA that is included with the development kit.

The system runs uCLinux ([www.uclinux.org](http://www.uclinux.org)), a version of the popular Linux operating system that has been simplified and adapted for embedded applications running in processors with no memory management unit

(MMU). The operating system provides an interactive console through a standard RS232 port, a structured file system, multitasking and basic TCP/IP services (FTP, HTTP and TELNET).

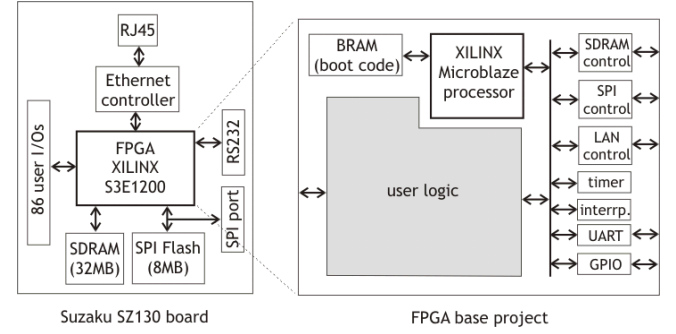


Figure 3: Organization of the Suzaku SZ130 board.

This board constitutes a convenient platform for building a digital integrated system, providing a combined hardware/software solution for a given problem. A design may include virtually any custom designed digital circuit that may fit into the FPGA's free resources. Combining conventional software execution with custom processing by dedicated hardware modules can alleviate significantly the computing load of the central microprocessor. Besides simplifying the development of the software (various concurrent processing tasks are done in hardware transparently for the software), this approach also permits to reduce the processor's clock frequency and thus the overall power consumption.

##### 4.1 Software development

The software for this machine is developed in ANSI C and compiled with a customized version of gcc. There are two levels of software that may be developed, depending on the usage or not of the underlying uCLinux

operating system. A stand alone program can be created with the compiler embedded in the XILINX EDK tools and integrated with the configuration data of the FPGA. When the FPGA boots, that program is started automatically and allows only basic console I/O. In this case, the uCLinux operating system is not started and thus there is no support for TCP/IP, file system and the other services provided by Linux. The development of programs to run on the uCLinux operating system can make use of the most common Linux standard libraries, including TCP/IP communication, file I/O and file system management. The compilation is done on a conventional Linux machine and transferred to the Suzaku board via FTP or through the RS232 serial interface.

The uCLinux file system is locally stored in the flash memory and loaded into a segment of the SDRAM (configured as a RAM disk) during the boot process. An image of the file system is maintained in the computer with the development system. The modifications of the uCLinux file system are done in this image and transferred to the Suzaku flash memory with appropriate commands.

During development, evaluation and debug, the support of such an operating system is a convenient solution because it eases the implementation of network communication processes, file management and multitasking of different program's parts. However, for applications requiring low power consumption, running on the top of an operating system may represent a significant overhead in terms of energy consumption. This platform supports easily both implementations that still have to be evaluated.

#### 4.2 Hardware development

The development of the digital system implemented in the FPGA is done with the EDK/ISE software tools from XILINX. The XILINX EDK (Embedded Development Kit) is a design tool that builds a combined hardware/software design, targeted to a XILINX FPGA-based board. The hardware part is assembled with pre-designed parametrizable modules (microprocessor, SDRAM interface, USART, etc.) and user designed components. The software part is built as a C program that will be later embedded with the FPGA configuration data. The ISE tool suite performs the complete digital design flow for XILINX FPGAs and translates the circuit models produced by EDK into the final bitstream used to configure the FPGA.

To attach a user-defined digital block to the microprocessor, the library of modules include general purpose I/O interfaces that attach to the microprocessor buses. A user's circuit is specified in standard hardware description languages (Verilog or VHDL) and integrated into the system's top-level description.

#### 4.3 FPGA reconfiguration

When the system is powered up, the FPGA is configured with the data stored in the beginning of the flash memory. Once the configuration is completed (less than 1 second), the I/O buffers associated to the FPGA pins are enabled and the system implemented in the FPGA starts running (freeing an internal global reset). The Microblaze microprocessor runs the code stored internally in the FPGA memories. If the startup of the uCLinux is enabled (this is the original configuration), then a boot loader is executed that loads the file system image stored into the flash to the SDRAM, builds the uCLinux file system and loads the operating system kernel. The complete process, from power-up to system idle state, takes approximately 42s, running the Microblaze at 50 MHz (76s if running at 25 MHz).

The reconfiguration of the FPGA can be done easily under control of software. When running uCLinux, the section of the flash memory that holds the FPGA configuration data (usually called *bitstream*) can be rewritten from a regular file stored in the file system, using one application included in the file system distribution. The running software can thus choose a bitstream from a batch of pre-built configurations, copy it to the flash memory and issue a `reboot` command to restart the system with a different FPGA configuration.

This unique feature of FPGA-based systems allows to change the digital circuit played by the FPGA, according to different processing needs that may be driven by several factors (eg. the availability of energy or environmental conditions). This is not yet being exploited in FAST, although it may be a good strategy to exploit for reducing the energy consumption.

### 5. The FAST computing system

The FAST computing system is implemented in the FPGA of the Suzaku board. Besides the central Microblaze processor, the system includes various dedicated controllers for interfacing the sensors and actuators used in the sailboat, some of them associated with custom computing modules. Figure 4 presents the general organization of the system.

The global strategy adopted during the design of this system was to create a set of autonomous interfaces capable of delivering to the software the data retrieved from the sensors in a format easy to be integrated in the software control system. Besides the implementation of the sensor's specific interface protocols, this includes parsing messages from the sensors, filtering, and units conversion. Although simple averaging filters have been implemented for the wind sensors and acceleration (inclinometer), there is enough room to include higher quality low pass filters.

The access to the peripherals from the Microblaze is



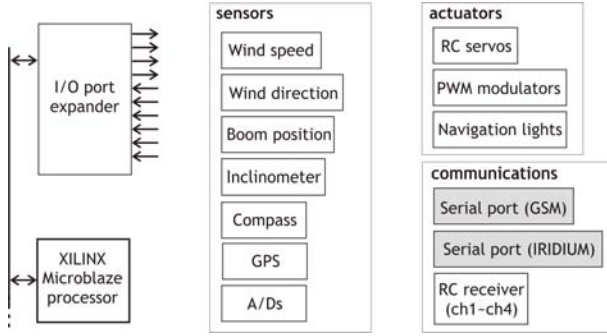


Figure 4: Simplified view of the organization of the FAST computing system implemented in the FPGA. All the sensors and actuators are accessed by the microprocessor via dedicated interfaces. The two shaded blocks are standard serial port controllers implemented as pre-built modules from the EDK library.

done through a port expander. This module uses only one pair of 32-bit memory-mapped bidirectional ports and makes available for the rest of the circuit a set of eight output ports and 16 inputs ports (32-bit each). This is implemented as a finite-state machine that interprets a set of simple commands issued by the microprocessor as memory writes and reads.

### 5.1 Sensors

The wind direction interface reads the AS5040 sensor sampled at 50 Hz and averaged using a sliding window of 64 samples (the boom position sensor is built with the same chip and is interfaced by another instance of this module). The output is an integer in the range  $[-180, +180]$  and the position of the direction reference can be corrected with an offset defined by software. The interface with the wind speed sensor outputs the number of 10 KHz clock periods during one revolution of the cup rotor, sampled at 10 Hz and averaged by a 64 tap mean filter.

The inclinometer reads the PWM outputs of the 2-axis accelerometer and returns two integers that are proportional to the X and Y acceleration. These values are sampled at a frequency approximately equal to 100 Hz, dictated by an RC network in the accelerometer board. These values are averaged with 128 tap average filters.

The magnetic compass provides the complete data (heading, roll and pitch angles) in ASCII format, as variable sized messages. Although the ASCII format is easy to interface with a software function, it is also important to have access to this data, from the hardware side, in numeric digital format. This allows for future integration of hardware control processes that directly link the heading/roll/pitch information to the controllers of the steering servos. This interface implements a parser

of the messages sent by the compass and performs the conversion ASCII to binary. The GPS interface is done in a similar way, extracting the relevant data (lat/lon, speed, course and status) from the binary protocol output (uBlox UBX protocol (u-blox, 2008)).

The interface with the radio-control receiver is done by 4 instances of the same controller, one for each channel of the radio. The standard control signal used in RC receivers and servos is a 50 Hz digital signal, where the high time defines the position of the servo (ranging from 0,8 ms to 2,2 ms). Each receiver module measures the high time of the corresponding channel and converts it to a two's complement 10 bit integer: zero means the control stick at the middle, +511 is full right (full front) and -512 is full left (full rear). One additional module monitors continuously the signal received from radio channel 1, looking for 8 consecutive valid pulses (criteria for valid pulses is frequency between 45 Hz and 55 Hz and high time between 0,5 ms and 2,5 ms) to assert a **radio present** signal. This notifies the rest of the system that the RC transmitter is in range and transmitting correct data.

The system includes an A/D converter with 6 analogue inputs, plus two additional channels that monitor of the 3,3 V supply and the chip temperature (AD7795). This is interfaced with a controller that implements the SPI and provides to the computing system a simpler interface to just select a channel and read the conversion result.

### 5.2 Actuators

The servo controllers receive a 10-bit two's complement number and generate the 50 Hz standard control signal, according to the timing referred above. For the moment, only two servos are being used for the two rudders, although additional servo controllers can be easily added. A hardware multiplexer selects the source of data that is routed to these servos: this can be the output of the RC channel 1 (to use the left-right stick) or the data sent by the software application running on the processor.

The sail sheet of both sails is commanded by one DC motor with a multi-turn potentiometer for position feedback. This motor is controlled by a PWM modulator that drives one power bridge assembled with MOSFET power transistors. The PWM module include a low-pass filter applied to the input data, to avoid high accelerations that result in high current draw. Another PWM modulator is included to support the control of the second DC motor.

## 6. Implementation

Current design, as represented in figure 4, uses less than 50% of the XC3S1200E FPGA resources and corresponds approximately to 1 million equivalent logic gates. All the modules support the maximum clock frequency of

4-input LUTs	7.314	(42%)
Flip-flops	3.997	(23%)
Occupied slices	4.730	(54%)
LUTs used as route-thru	324	(1,8%)
LUTs used as SRAM	256	(1,5%)
LUTs used as shift-registers	796	(4,6%)
Block RAMs	14	(50%)
Dedicated multipliers	8	(28%)
Equivalent gate count	1.078.257	

Table 2: Summary of the FPGA Spartan 3E 1200 occupation. LUT stands for Look-up table and is the elementary configurable block in Spartan 3E FPGA: a 16 bit SRAM implementing any 4-input combinational logic function

50 MHz allowed for the Microblaze processor, although most of them can run with much lower frequencies. Table 2 summarizes the occupation of the FPGA resources.

### 6.1 Power consumption issues

Electric power consumption is one of the great concerns in an autonomous sailboat. For a small boat, the reasonable sources of electric energy for long term navigation are photovoltaic panels and wind turbines. Best solution would be a combination of both but, as far as we know, the commercially available wind generators are too large and heavy for our sailboat. In both cases, the availability of energy always depends on the weather conditions which still have a high degree of uncertainty. The electronic system must consume the lowest possible energy and whenever possible adapt its behaviour to the power budget available at each stage.

According to our first estimates, the computing system will account for more than 50% of the total energy consumed by the system, assuming a continuous operation with the maximum power consumption measured for the present configuration. This represents approximately 500 mA for the 3,3 V supply (1,65 W, including 100 mW for the digital compass and the wind sensors) running the microprocessor at the maximum frequency of 50 MHz with the Ethernet port enabled. Disconnecting the Ethernet cable puts the Ethernet controller in power down mode and reduces the power consumption by approximately 200 mW; lowering the clock frequency to 25 MHz saves more 100 mW. The reconfiguration feature of the FPGA-based system can be exploited to further enhance the power management strategy. For example, once a course and sail position has been defined, the steering control can be made by a simple controller implemented directly in hardware the FPGA, disabling the microprocessor and all the peripherals not in use.

## 7. Operating modes

The FAST computing system supports three different modes of operation, depending on the purpose of the navigation. The selection of the control mode is done by the throttle level of the radio-command: middle for radio-commanded mode, front for WiFi semi-autonomous control and rear for fully autonomous sailing. When the radio transmitter is switched off, the boat enters automatically the fully autonomous mode, and checks for the presence of the RC radio signal at periodic intervals (this is currently set to 1 minute but can be software programmed). At the time this paper is being written, the two last operating modes were only implemented in a simulation program.

The simplest mode is the radio-commanded control mode, where the control is totally done through the radio-command, using only two control sticks: left-right turn and sheet control. In this mode, FAST behaves as a conventional RC sailing boat and logs the information received from the sensors, as well as the position of rudders and sail defined by the operator. In this mode, the WiFi link is active and the status of the boat can be monitored in real time from a computer in range of the wireless network.

The semi-autonomous mode is enabled by setting the throttle lever to the front position. This mode requires additional commands sent from a control program running in a PC in the range of the WiFi signal. Route control is done by the software running in FAST, by defining remotely the desired heading, course or apparent wind angle. Sail control can be done manually (the user specifies the boom angle) or autonomously, according to the rules established in the software for a given apparent wind angle. The tack and jibe maneuvers are performed automatically by the software running in FAST, upon request of the operator.

In the fully autonomous mode with the presence of the RC radio signal, the WiFi router is enabled and the operation of FAST can be monitored in real time from the remote PC. If the RC signal is not present, the electronic system switches off the WiFi router and the RC receiver, and starts the fully autonomous navigation to round a set of pre-programmed waypoints.

The first two modes are convenient during the development of the software and tuning of the control parameters. The short range of the WiFi link and radio control limits the operation of the boat to within a few hundred meters, even though these modes of operation are only intended to be used under visual operation.

## 8. Conclusions

This paper presented a FPGA-based reconfigurable electronic system used in an autonomous sailing boat. The FPGA implements the computing part and includes a



RISC microprocessor surrounded by several custom designed peripherals that interface with the sensors and actuators used in the sailboat. The hardware reconfigurability feature of the FPGA enables a short design iteration and allows fast reconfigurations of the running hardware. This may be exploited for minimizing the energy consumption by adapting the control and computing logic circuits to the specific requirements of navigation under given wind and sea conditions.

Designing and building a new boat from scratch has been a challenging and time consuming task, specially being a first prototype. We hope that our autonomous sailing platform will open, in a near future, interesting opportunities for applications in various fields.

## Acknowledgements

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## References

- Atmark-Techno (2006). SUZAKU-SZ130-U00, Hardware Manual (English version) V1.0.2, [online]. Atmark-Techno [cited 30 april 2008]. Available from World Wide Web: <<http://www.atmark-techno.com>>.
- Belcher, B. (1982). *Wind-vane Self-Steering*. International Marine Publishing Company.
- Compton, K. and Hauck, S. (2002). Reconfigurable computing: A survey of systems and software. *ACM Computing Surveys*, 34(2):171–210.
- Curtin, T., Bellingham, J., Catapovic, J., and Webb, D. (1993). Autonomous oceanographic sampling networks. *Oceanography*, 6(3):86–94.
- u-blox (2008). u-blox 5 NMEA, UBX Protocol Specification, Public Release [online]. u-blox AG, Switzerland [cited 30 april 2008]. Available from World Wide Web: <[http://www.u-blox.com/customersupport/gps.g5/u-blox5\\_Protocol\\_Specifications\(GPS.G5-X-07036\).pdf](http://www.u-blox.com/customersupport/gps.g5/u-blox5_Protocol_Specifications(GPS.G5-X-07036).pdf)>.
- Xilinx (2004). Microblaze Processor Reference Guide, EDK v6.2 [online]. Xilinx [cited 30 april 2008]. Available from World Wide Web: <[http://www.xilinx.com/support/documentation/ip\\_documentation/microblaze.pdf](http://www.xilinx.com/support/documentation/ip_documentation/microblaze.pdf)>.

# Design Considerations for Sailing Robots Performing Long Term Autonomous Oceanography

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## Abstract

Over the last four years we have developed five sailing robots of various sizes with the intention of performing long term ocean monitoring. These have demonstrated that a sailing robot could potentially perform long term ocean monitoring. A number of sensor packages, sail designs and hull designs have been tested. Wing sails have been found to be particularly suitable for this application as they minimise potential points of failure. Work with biologically inspired control systems that are capable of adapting the robot's behaviour to its conditions and the demands of its mission is currently ongoing.

## 1. Introduction

Since 2004 the authors have built five sailing robots varying in size between 50cm and 3.5m long, with the aim of performing long term autonomous oceanographic monitoring. Given that sailing robots can be deployed in a more flexible manner and at potentially lower cost than existing ocean monitoring systems such as data buoys, survey ships and satellites, it is hoped that they will supplement or even replacing these systems. Prior to the construction of their first boat the authors are aware of only three previous attempts to build sailing robots these are by Abril, Salom and Calvo (Abril and Calvo, 1997), Ross<sup>1</sup> and Elkaim (Elkaim, 2002). All of these focused on building proof of concept robots and illustrating their ability to sail a pre-determined course, however none appears to have continued their work or attempted to tackle many of the problems associated with maintaining long term autonomy of a sailing robot.

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<sup>1</sup><http://www.cs.cmu.edu/~br/CbotWeb/rb98.html>

## 2. Robot Specifications

### 2.1 AROO

AROO (Autonomous Robot for Ocean Observation) (Neal, 2005) was constructed in late 2004 as a proof of concept for a small but reasonably durable sailing robot. The hull is 1.5 metres long and constructed from ABS plastic. The sail consists of an 1 metre high aluminium wing sail driven by a 12 volt 60 rpm (reduced to 2 rpm by a reduction gear) DC electric motor. This is mounted inside the hull at the base of the mast, the entire mast is rotated in order to move the sail. Rudder control is provided by a single servo. AROO has only three sensors, two potentiometers to detect wind direction and sail position and a magnetic compass. These are connected to a Basic Stamp microcontroller which receives commands from another system via a serial port. This was initially connected to a Psion 5mx PDA and later to a more powerful Jornada 720, these are responsible for running the higher level control algorithms and allowing remote access to the control system. The Psion offered remote access only via an infra-red port which proved to be cumbersome, whereas the Jornada incorporated a wireless network card allowing remote access at distances of 10s of metres. AROO's sole power source is a 4.2 amp hour 12 volt lead acid battery, this was estimated (although never extensively tested) to provide between 3 and 36 hours of operation depending on the frequency of actuator use. AROO was only ever tested in a small lake, it took the first steps in demonstrating the concept of a sailing robot. In particular it demonstrated the feasibility of a wing sail in both incredibly light and incredibly high (45 knot) wind. Many lessons were learnt in the design, compass errors frequently appeared as a result of the boat tilting, the control system in part due to its distributed design was not able to respond in sufficient time and the combination of these resulted in wild



Figure 1: Aroo during a test on a lake in April 2005.

oscillations in the boat's course.

## 2.2 ARC

ARC was constructed in early 2006 and aimed to rectify many of the mistakes made in AROO (Sauze and Neal, 2006) and to introduce as much redundancy as possible. It features a similar length, but significantly wider hull built from plywood, two rudders (controlled by a single actuator), two independently controlled sails, a gimbaled compass, GPS receiver and initially a combination of an AtMega128 microcontroller and a Gumstix<sup>2</sup> single board computer running linux. The AtMega was later removed in favour of controlling everything from the Gumstix. ARC uses three stepper motors for sail and rudder control. The use of dual sails allows for redundancy in steering, as the sails can be set to different positions to provide steering. Additional redundancy is provided by the stepper motor controllers, there are three controllers in total and each can control two motors, giving two points at which each motor can be controlled. Initially no feedback of motor position was given, after powering on the microcontroller would rotate each actuator until a calibration micro switch was depressed indicating the actuator had reached its default position. This proved to be a major mistake as the sail actuators often missed steps when attempting to move the against the force of the wind, feedback potentiometers have since been included. ARC is powered by 20 1.2 volt, 2500 mA/hour AA rechargeable batteries which are connected in parallel between two banks of 10 to provide 12 volts and a peak current of around 4 amps. At present this is the only power source although the addition of solar panels is planned.

<sup>2</sup>[www.gumstix.com](http://www.gumstix.com)



Figure 2: ARC during the 2006 Microtransat Challenge.

## 2.3 Beagle-B

Beagle B was constructed in late 2006 by Robosoft (a French robotics company) and is intended to provide a serious oceanography platform. It is 3.5m long, features a 3m high carbon fibre wing sail, power is provided by two 15 watt solar panels and four 12 volt, 60 amp hour lead acid batteries. It includes a tilt compensated flux-gate compass, ultrasonic wind sensor, GPS, Iridium Short Burst Data transceiver and GM-862 GSM modem, two LA12 linear actuators for rudder and sail control and a YSI 6600 Sonde<sup>3</sup> for gathering oceanographic data. The whole system is controlled by a pair of Gumstix single board computers, one is responsible for the control of the robot and navigation while the other runs the oceanography sensors and communications. Beagle-B participated in the 2007 Microtransat Challenge<sup>4</sup> during which it autonomously sailed a total of 25km over 19 hours demonstrating its suitability for performing long term missions. During summer 2008 it will be deployed to measure water quality in Cardigan Bay off the west coast of Wales. Beagle-B once again demonstrated the feasibility of the wing sail design by frequently out running yachts being used to chase it, in particular during light winds when traditional sails on the chase boat collapsed.

## 2.4 Pinta

Pinta is our latest boat and unlike the previous boats is built with the intention of racing. It will be taking part in the 2008 World Robotic Sailing Championship and Microtransat transatlantic race. It is based upon a Topper Taz<sup>5</sup> sailing dinghy and unlike all the other boats it uses a single traditional sail controlled by a DC electric

<sup>3</sup>[https://www.ysi.com/portal/page/portal/YSI-Environmental/Products/Product.Family/Product?productID=EMS\\_SON00\\_6600V2](https://www.ysi.com/portal/page/portal/YSI-Environmental/Products/Product.Family/Product?productID=EMS_SON00_6600V2)

<sup>4</sup><http://www.microtransat.org/2007.php>

<sup>5</sup><http://www.toppersailboats.com/taz.aspx>

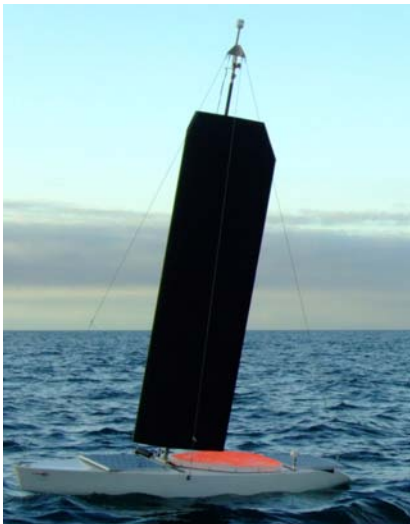


Figure 3: Beagle-B during the 2007 Microtransat Challenge.



Figure 4: Pinta under construction in January 2008.

motor and a winch mechanism. Its design is based heavily on lessons learnt from the previous robots, it uses the same model compass, ultrasonic wind sensor, GSM modem, satellite transceiver and a similar motor controller as beagle B. Its rudder is controlled by an off the shelf auto-helm, this simplifies the control system dramatically as only a target heading needs to be provided to it. Power is provided by 6 solar panels providing a peak of 120 watts and 16, 12 volt, 7 amp hour lead acid batteries which are all located inside the hull to provide extra ballast.

### 2.5 Dot Boat

Dot Boat was built as a simple proof of concept using a small 75cm long off the shelf radio control boat. The boat was already equipped with two servos for controlling the rudder position and the length of the sheets

controlling the sails. The radio control circuitry was replaced with an Embedded Fusion F200 single board computer which runs the Microsoft .NET Micro Framework an embedded version of .NET. Only two sensors were used, a magnetic compass and a potentiometer wind sensor. The control system is incredibly simplistic allowing the user to set the desired course by pressing one of two buttons on the control board (one to move the desired course left and one to move it right).

## 3. Design and Construction Lessons

### 3.1 Simulators

During the development of AROO we developed a simulator based on the open source sailing game Tracksail<sup>6</sup>, replacing the user interface with an API conforming to the same specification as that of the robot. The rationale behind this decision was that the same code could be executed either on the simulator or the real robot. Unfortunately the differences between the real world and the simulator are immense, the simulator lacked the noise of the real world, the wind was far too consistent and there was no concept of waves. The simulator also failed to model the inertia encountered while turning and the speed of turns was completely different to that of the real boat. It would of course be possible to improve the simulator to produce a closer match with the properties of a real sailing robot, however realistically simulating environmental conditions such as waves and wind variations would be significantly more complex. It would take many years to develop a simulator that would even come close to accurately modelling realistic conditions. For these reasons we have not attempted any further simulations.

### 3.2 Choice of programming language

The choice of programming languages is often a major point of debate amongst software developers. Traditionally many would choose to develop robot control systems in either C or assembly language given their popularity in embedded systems programming and their ability to gain low-level unobstructed access to I/O devices and memory. However in recent years many have come to question the wisdom of this given their complexity, poor error handling, lack of type safety and bounds checking. Recently many have begun to develop embedded systems with object oriented languages such as Java that are able to provide type safety, bounds checking and are also considered easier to use.

There are many robot developers who give relatively little attention to software engineering, especially amongst the research community where the goal is sometimes only to operate robots for short periods of time in

<sup>6</sup><http://tracksail.sourceforge.net>

order to demonstrate an algorithm's feasibility. However the requirements for producing robots capable of longer term autonomy are much closer to those of safety and security critical software. In long term autonomous systems there is a particular need to avoid memory leaks, buffer overflows, deadlocks and inconsistent program states and many of the techniques developed for safety or security critical software such as asserts, static analysis, memory leak detection and strict coding standards may be appropriate in robotics.

### 3.3 *Choice of Computers*

When evaluating the type of computer to use five possibilities emerged:

1. A traditional microcontroller such as a PIC, AVR or 68HC12.
2. A "easy to use" microcontroller such as the Basic Stamp, OOPIC or PICAXE.
3. A single board computer or PDA running an operating system such as Windows CE, VxWorks or Linux and using a processor targeted at embedded applications such as an ARM, MIPS or AVR-32 processor.
4. An embedded x86 PC running a full operating system such as Windows XP, Linux or FreeBSD. There are many specialist motherboards and processors targeted at embedded applications such as the PC/104 and Mini,Nano and Pico ITX motherboards and the AMD Geode, Via C3/C7 and Intel Atom processors.
5. A combination of the above or multiple computers.

AROO was developed as a split system, placing low level operations such as actuator positioning and reading sensors on a Basic Stamp microcontroller which communicated with a Linux based PDA via a serial port. This proved to be a poor choice as it introduced a latency of around one second into each command in part due to the instability of the serial port handling on the Basic Stamp. The Basic Stamp created the added disadvantage of having no ability to multi-task therefore any command had to be fully completed before another could be executed, as a full rotation of the sail could take over 1 minute this left the boat unable to perform any other actions during this time. Should the boat happen to be turning at the time a sail movement was required then the boat would be completely off course by the time the sail movement was complete. In developing ARC initially only a single microcontroller was used to control two sail and one rudder actuator, not wanting to repeat this problem a method was required to multitask during actuator movement. The solution was to place the motor handling code inside an interrupt handler which was triggered by the timer interrupt at regular intervals,

thus allowing other processes to continue. This approach brought latency levels into a range of less than 10 milliseconds which was more than acceptable, unfortunately using interrupts in this way brings with it a number of complexities and requires significant programming effort. The alternative approach which was considered was to use a series of microcontrollers each responsible for only a single sensor or actuator with a central co-coordinator requesting sensor data or actuator movements from the others. This approach was not followed as it was considered to add significant programming and hardware complexities in addition to a fear of repeating the same problem seen in AROO. A further problem of using the AtMega microcontroller was in performing high precision floating point calculations to determine the heading and distance to a waypoint using the great circle method. The GCC compiler for the AtMega only supports 32-bit floating point numbers, this triggered a divide by zero when the boat came within about 200 metres of its waypoint.

A decision was later taken to replace the microcontroller with a Gumstix single board computer. The Gumstix runs a slimmed down version of linux known as uClinux, but still offers all the advantages of an operating system such as processes and threads, filesystems, device drivers and network stacks. As the Gumstix lacked sufficient I/O ports to control 3 stepper motors a general purpose I2C I/O extender chip was installed on each of three stepper motor controllers. One major advantage to this approach was that it could be entirely developed in user mode without the need for any kernel programming, so an application crash cannot (at least in theory) crash the entire system. The stepper motors are driven by turning on and off each of the four pins in turn (and reversing the direction to change the motor direction), it was found for these particular motors that 2.4 milliseconds was the minimum time that a pin had to be held high in order to move the motor. This was found to be at the very limit of the Gumstix ability and required the kernel tick frequency (which determines the smallest time slice given to a process) to be changed from 100hz to 1khz, it was shown that another process could actually slow down the speed at which the motor turned, however due to the way stepper motors operate the only side affect is to slow down the motor. It is also worth noting that while the latency of the Gumstix is low enough to provide direct control of stepper motors it would not be low enough to directly control a servo or DC motor.

As uClinux provides locking and threading support the interrupt handler code could be dramatically simplified into a few threads. The eventual design was to split the program into a series of threads to gather wind sensor, GPS and compass data and to control rudder position with respect to desired heading and sail position with

respect to wind direction. Common data such as wind direction, current location, the current waypoint, heading and distance to the next waypoint, current heading, rudder position and sail position were all stored in global variables which could be locked during updates or reads to produce fully atomic operations. A slight variation on this approach is currently being considered, instead of splitting the control system into a series of threads which are each part of a single process it is proposed to split them into several processes communicating via sockets. Under threaded approach if one thread crashes or overwrites the memory of another it risks crashing the entire process, whereas if several processes are used then one cannot directly access the memory of another and should one crash then it can be restarted without restarting the entire system and potentially losing state information or requiring recalibration of sensors. However the downside to this approach is that explicit inter process communication is required whereas the threaded approach only requires the use of global variables and mutex locks.

The use of an operating system also speeds development time somewhat as there is no need to load new programs into microcontroller EEPROMs or to reboot when a new program is ready. The use of Linux is of significant help as it allows remote login to the system over the network. Additionally there is the potential to even compile code directly on the robot, however due to memory constraints of the Gumstix this technique is not currently being used.

Overall the use of the Gumstix in ARC proved to be highly successful, easing the complexity of the software and speeding up the development process significantly. As a result this architecture has been copied in Beagle-B and Pinta.

### 3.4 Navigation Algorithms

The control software of ARC, Beagle-B and Pinta share a common base differing only to accommodate hardware variations. At present the implementation of the navigation system is incredibly naive. Waypoints are loaded into the program, the distance and heading to the next waypoint are calculated and fed into the course holding routines which adjust the rudder. A waypoint is considered to be reached when the boat passes within 50 metres of it. In the event of overshooting a waypoint the boat will end up turning back towards the waypoint in order to reach it. It is intended that for ocean sailing waypoint tolerances maybe increased. The current control system makes no attempt to compensate for or avoid currents, tides, bad weather or the affects of the boat tilting. Despite this, the system still appears to be function well with Beagle-B having successfully sailed over 25km in a single mission, as shown in Figure 5. It is appreciated that a more extensive system is required for successful

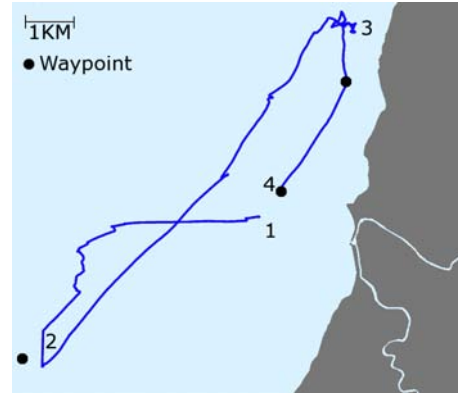


Figure 5: The route taken by Beagle-B during the 2007 Microtransat. Point 1 is the start, at point 2 the robot crashed for an unknown reason and stopped logging, at point 3 the wind dropped and the boat struggled against a strong tide, at point 4 the robot reached its final waypoint.

long term autonomy, but to date this has been beyond the scope of our work.

#### 3.4.1 Tacking and Jibing

The control system also has no awareness of a tack or jibe (turning the boat through the wind), the steering system simply follows the desired heading which is the heading to the next waypoint. If the course is not directly sailable (e.g. it is 45 degrees +/- the wind direction) then the desired heading is adjusted to 45 degrees from the wind direction and this course is followed until the desired point becomes directly sailable. Many human sailors would favour zig-zagging into the wind rather than taking this single tack approach although. This approach does have one potential problem, if operating near to the coast it is quite possible that the boat would attempt to sail into the shore when its course was not directly sailable. AROO took a totally different approach as it had no GPS so could not generate a desired heading to a waypoint, it instead would time alternate tacks and sail in zig-zag fashion. This algorithm was shown to work correctly in simulation, but was never tested in the the real world.

### 3.5 Power Systems

#### 3.5.1 Power Switches

Early in the development of AROO the need to easily switch the entire system off was demonstrated when a program did not run as expected causing the sail to be left rotating with a wire wrapped around it placing the sail actuator under considerable strain and draining the battery rapidly. Until this point the only power switch had been inside the boat and required a deck hatch to be



unscrewed in order to access it, this kept the switch waterproofed but prevented the robot from being switched off without first being on land and then taken apart. A magnetic switch was later installed and worked reasonably but was far from 100% reliable. For ARC a mechanical switch was placed on the deck inside a small plastic box whose lid was screwed on and sealed with silicone. This was easier to access than AROO's but still took over a minute to gain access. With Beagle-B this problem was believed to have been solved with a waterproof key based switch located on the deck. Unfortunately it turned out this only turned off power from the batteries and not from the solar panels. Under well light conditions this would leave the computer running and occasionally allow actuators to move, however the solar controller would often cut power when the sun was obscured by cloud or shadows. To make matters worse the switch was not completely waterproof and began to randomly cut the power, this was later found to be due to salt deposits forming inside it. This development has shown the clear need for a properly waterproofed, externally accessible power switch which will turn off everything.

### 3.5.2 *Choice of Battery Types and Solar Panel*

The choice of power system has a significant impact on the weight, lifetime and cost of a sailing robot. If long term operations are to be achieved then the obvious choice is to use photovoltaic solar panels to charge batteries during the day and batteries to power the robot at night. In this case the battery must be able to hold sufficient charge to power the robot through the night and preferably for several days should bad weather reduce solar panel efficiency. An alternative approach could be to simply power the robot with batteries, although this would limit mission lengths to a few weeks at best, however for many applications this may still be sufficient and will lower manufacturing costs.

In designing AROO and ARC this approach was taken as they were not intended to spend prolonged periods of time at sea and solar panels would have added additional complications to the electrical systems. AROO is powered by a single lead acid battery though to be capable of providing between 3 and 36 hours of operation depending mainly on actuator duty cycles. The choice of a lead acid was mainly due to the availability of spare batteries from other projects. ARC made use of rechargeable AA NiMH batteries, these provide a higher energy density than lead acid's and their shape and size allow them to be placed in the keel for ballast (which also frees space elsewhere), they are also relatively cheap, easily available and if required individual cells can be replaced. Beagle-B and Pinta both use lead acids because of their durability, low cost, low self-discharge rates and ability to deliver high peak loads. Again the batteries have been placed at a low point in the hull to provide ballast.

Various configurations for solar panels are possible. Ideally for maximum yield, a solar panel should be pointed directly towards the sun at all times. However this is rather impractical for a sailing robot as it would require additional actuators which maybe failure prone and it will require power to operate. A possible alternative is to place solar panels on fixed sloped surfaces or on the sail itself, this adds the disadvantage that for much of the day half the solar panels will receive virtually no sunlight while the others receive a significant amount. In Beagle-B the approach has simply been taken to place solar panels flat on the deck, whereas Pinta has opted for placing panels on an angled frame (which can be seen behind the boat in figure 4). As Pinta's sole task is to cross the Atlantic from east to west, the idea of an asymmetric configuration with more solar panels on what for the majority of the journey will be the south facing side has been considered.

### 3.5.3 *Power Budgets*

With Beagle-B the peak output of the solar panel is 30 watts, in reality this results in an average output of 10-15 watts during daylight hours and given 12 hours of daylight this would give an average output of 5-7.5 watts, at a latitude of 60 degrees in winter this would be nearer 6 hours and 2 watts. Figure 6 illustrates the power budget of Beagle-B and shows that just to run the robot requires an average of approximately 1.7 watts, leaving between 0.3 and 4.8 watts to run scientific instruments depending on lighting conditions. Given these constraints it is desirable to be able to switch off every sensor when not in use, to enter sleep modes on the computers and keep actuator use to a minimum. One feature of Beagle-B which aids this is its ability to sail for several hours without major actuator movements, during the 2007 Microtransat Race there were several times when the chase boat believed the computer had crashed as they had observed no rudder or sail movements. Given this actuator duty cycles can be kept to a minimum of say 1% or 36 seconds of actuator movement per hour. Sensor duty cycles can also be kept to a minimum once a stable course is established as there is no need to be sampling the GPS, compass or wind sensor more than a few times per minute perhaps at a 5% duty cycle or 3 checks per minute. Experiments with ARC demonstrated that it was actually able to correct its course without any intervention from the control system even when it was spun 180 degrees off course.

Obviously there are scenarios when the user might wish to be less cautious with power management, for example where station holding or higher frequency sampling is required. Another consideration is that given Beagle-B has 2880 watt hours of battery, a week long mission powered entirely by the batteries and using an average of 10 watts (or 20 watts if its reasonably sunny) is not infeasible. It would also be possible to

Name	Power	Duty Cycle	Average
Gumstix (x2)	2W	25%	0.5W
Wind Sensor	0.5W	5%	0.025W
Compass	0.5W	5%	0.025W
GPS	0.5W	5%	0.025W
Iridium Transceiver	1.75W	0.15%	0.0026W
Actuators (each)	60W	1%	0.6W
Total			1.7776W

Figure 6: The power budget for Beagle-B excluding any scientific sensing payload. The power column refers to the peak power consumption of the device when in use, duty cycle to the percentage of time it will be on and average to the average power consumption given the duty cycle into account.

spend a week sailing to a site of interest on a minimal power budget, then perform ocean sampling for a week nearly draining the batteries and then to sail back home again on a minimal power budget.

### 3.5.4 Intelligent Power Management

As demonstrated in section 3.5.3 there is little power to spare. Clearly there is a need for advanced power management systems. A simple approach might be to allow the operator to control the maximum duty cycles for any piece of equipment. However a more flexible system which is more in keeping with the idea of an autonomous vehicle is desirable, there are also many situations other than power management where it is desirable to modify the behaviour of the robot in response to changing conditions, for example an actuator overheating.

One potential strategy is to borrow inspiration from biological systems, which are capable of maintaining a stable state despite fluctuations in both their internal and external environments. A key contributor to this ability is the endocrine system which secretes chemical messengers known as hormones into the bloodstream, these rapidly reach virtually all cells in the body, upon reaching a cell they may bind with the cell, providing the cell has an appropriate receptor. Upon binding the hormone will either suppress or promote certain behaviours of the cell. The endocrine system does not act in isolation, the release of hormones is often the result of a trigger from the neural or immune systems and this in turn forms part of a wider feedback loop.

The analogy of using a hormone signal to suppress or promote a certain behaviour can form the basis of a power management system in a robot where the frequency (or presence) of certain behaviours is modulated by the hormone. The release of a hormone will be triggered by certain stimuli such as a process monitoring energy levels or actuator temperatures. This will then suppress or enhance certain behaviours depending on their binding affinity to the hormone. This

idea has been considered by many computer scientists to date (Arkin, 1992, Parisi, 2004), but has rarely been implemented beyond simulation. Such a system would allow many parameters to be included and for the robot to continuously adjust its behaviour between competing demands. This removes the need for complex sets of rules to ensure the correct behaviour is selected.

### 3.6 Actuators

So far three types of electrical actuator have been used to control our sailing robots' rudders and sails: standard DC electric motors, stepper motors and servos. Servos offer the advantage of being easy to position and being able to hold a specified position, however they suffer from a major drawback in that in order to maintain position they must continue to draw power. This was observed in AROO where rudder position was servo controller, as a result they have not been used in any boat since (apart from Dot Boat). AROO used a DC electric motor for sail positioning and a (non-linear) potentiometer for position feedback, however its accuracy was limited and the simplistic control system had no control over motor speed. Although this was an extreme case of simple hardware built from scrap components it demonstrated the difficulties of using a standard motor and the need for accurate feedback. Beagle-B's use of an integrated actuator and linear potentiometer coupled with a variable speed motor controller demonstrated that standard motors can be used successfully. Given the bad experience with standard motors and servos in AROO, ARC made use of stepper motors for both its sail and rudder actuator. These were found to be highly repeatable and accurate when tested in the lab under no load, it was perfectly possible to position them correctly without feedback. However when used for real, the sails in particular did not move consistently as a result of the force from the wind. To overcome this feedback potentiometers have since been added. Another problem discovered early in the development of ARC was that power transistors could easily overheat when heavy loads were placed on the sail, to overcome this new motor controllers were designed with large heatsinks and temperature sensors to provide early warning of overheating. To further prevent overheating each motor is connected to two redundant controllers and control can be switched between these at any point. A similar problem occurred in Beagle B, where the motor controller lacked sufficient heat sinks to prevent overheating when the actuators are under load. The acceptance testing of Beagle B took place during a very calm period, testing was conducted in a lake near the manufacturers site and everything performed flawlessly. However during the first sea trials the motor controller cut out after approximately 30 minutes as it had overheated while trying to move the sail in a force 3 wind, this was rectified with a large heatsink

but clearly demonstrates the need for testing in realistic environments. The motor controller selected for Pinta features an in-built temperature sensor and offers a "graceful degradation" feature whereby the maximum motor speed is restricted in proportion to temperature.

### 3.7 Communications

In the development of four robots a number of different communication strategies have been tested including IR, serial ports mounted in the deck, wifi, GSM modems and satellite transceivers. AROO featured a standard RS232 serial port connector in the deck for reprogramming its Basic Stamp microcontroller. This proved quite impractical as the port had to be waterproofed by bolting a cover over the port and sealing it with putty, a process which took several minutes. Infra Red communications were utilised in AROO as this was the only method available on the Psion PDA, the deck is built from clear acrylic which allows light to pass through. In order to communicate, another PDA had to be placed in a very specific spot directly above the deck in which it was very difficult to type or read the screen. This approach was quickly abandoned and the Psion was replaced with a more powerful Jornada PDA with a PCMCIA wifi card. This approach worked reasonably well and distances of over 100 metres were obtained. As these tests took place outdoors no access point was available so a peer to peer ad-hoc network was formed, unfortunately 802.11 ad-hoc mode has a quirk of forming a unique cell id for each network. It was found that a node would attempt to join any networks it found when the network card was initialised and if none were found it would form its own. The problem came that if two nodes went out of range from each other that one of them would then form itself into a new network and when it came back within range of the first node they would no longer communicate without user intervention. The effective result was that once the boat had gone out of range from the laptop communications could not be regained without restarting the network card. Initially in the development of ARC, an access point was carried around with the robot, later it was found that the network card in ARC (a Prism2 compact flash card) was actually capable of emulating an access point. This approach has copied in Beagle-B and Pinta. As the wireless card is placed underneath the deck and has no external antenna the range is relatively short but is sufficient to load new software or to monitor the robot from a chase boat very close by.

#### 3.7.1 Teleoperation

ARC and AROO completely lacked any teleoperation ability as they were operated in calm inshore waters or inland lakes and were relatively easy to pickup with a chase boat. However Beagle-B's size required non-

autonomous operation while being towed through a narrow harbour entrance. A teleoperated mode was developed which allowed a user to control the rudder and sail positions from a wifi enabled. This worked reasonably well to make minor adjustments while towing (e.g. adjusting the sail to point into the wind). However it was virtually unusable for actually sailing the boat as a result of three factors. Firstly the user was often unable to observe the rudder movements and had no idea what position the rudder was in, this was partially solved by displaying the rudder position on screen but this was difficult to read in sunlight. Secondly the teleoperation program operated via a secure shell (SSH) connection and this added a significant latency. Finally the wifi connection would frequently fail due to the distance between the operator and the robot or due to waves obscuring the line of sight between them. During development teleoperation was also tested using traditional radio control equipment, although this did not suffer from latency issues its range was limited and it suffered from problems of rudder visibility.

#### 3.7.2 Telemetry and Remote Monitoring

It is recognised that a robot gathering oceanographic data over long periods of time would ideally transmit this data back regularly. This requires a long range transmission system such as a satellite transceiver. Both Beagle-B and Pinta are equipped with an Iridium 9601 Short Burst Data transceiver, this is able to transmit messages of up to 205 and receive messages of up to 135 bytes, messages are sent to the transceiver via email to a predesignated address. The transceiver is able to perform a full send and receive cycle within less than 90 seconds consuming a peak of 1.5 amps for just a few seconds. This is ideal as it allows power consumption to be kept to a minimum. Both boats are also equipped with a GSM modem for use in coastal waters as it is significantly cheaper than Iridium. Software is currently being developed to store all transmitted data in a database and to provide an interactive map interface to illustrate the robot's position. Eventually this will be a two way interaction allowing for new waypoints or mission objectives to be uploaded.

### 3.8 Sensors

GPS has been found to be highly reliable on all three robots to be equipped with it (ARC, Beagle-B and Pinta). There were some initial fears that swaying of the boat or waves passing over the GPS antenna would disrupt reception, but these have proved to be unfounded. Compasses proved to be more problematic, AROO used a CMPS03 magnetic compass, however it was not tilt compensated and errors were induced as the boat rolled, triggering problems for course holding. The same com-

pass was reused in ARC, however it was placed on an aluminium arm which allowed it to swing horizontally, this virtually eliminated the errors in the compass readings. Both Beagle-B and Pinta used a Furuno PG-500 Fluxgate compass which provides automatic tilt compensation, these have operated almost flawlessly. One downside of the PG-500 is that it is unable to provide any tilt information, something which many other tilt compensated compasses provide and which could be of use in optimising sailing algorithms.

AROO, ARC and Dot Boat have all determine wind direction with potentiometers attached to a vane. This approach generates some level of noise, but readings can be averaged to reduce this. There is concern that they will not survive prolonged ocean conditions, for this reason Beagle-B and Pinta have "no moving parts" ultrasonic wind sensors. These have been found to be highly accurate, except in light winds where swaying of the boat in the waves can generate more airflow than the wind. Despite their accuracy there is still some level of noise, therefore there is still a need to average the readings.

### 3.9 Sail and hull design

Beagle-B, ARC and AROO all demonstrated the feasibility of wing sails. These offer several advantages over traditional sails, as discussed by (Elkaim, 2002) they maintain their shape in light winds when traditional sails would collapse, can sail closer to the wind and suffer from less drag. Additionally in the context of a sailing robot they are less failure prone as there are no ropes which could snap, jam or become entangled. However three major drawbacks have been encountered. Firstly in ARC and AROO the sails were driven by actuators inside the hull, this required a hole in the deck and has the potential to leak. Beagle-B's design solved this by placing a waterproof actuator on deck and running a power cable into the hull. The second and perhaps more serious problem is that all three boats use rigid sails which cannot be reefed to reduce their size in high winds. Finally the wing sail is not particularly stable when sailing downwind (running), particularly on single sail boats. As this is the least stable point of sail it may be advisable to sail on a broad reach instead and tack downwind.

It has been found that where holes in the deck are necessary for cabling, they should be secured using IP66 standard waterproof cable glands. Beagle-B places all electronics inside IP66 boxes with cable glands protecting any holes. These boxes are placed in the centre of the hull above the batteries, around the edge there is a lipped area into which any water should fall, this ensures that a significant amount of water can enter the boat before affecting the electronics. The other boats follow a similar principle by placing electronics in dedicated boxes away from anywhere that water might collect. ARC and AROO also have compartmentalised hulls to reduce the

chance that a breach would fill the entire boat.

Another cause for concern in waterproofing is where cleats or other mechanical attachments are made, during testing of Beagle-B a towing point ripped out of the deck causing a minor leak. It was later found that it had simply been screwed into the 5mm thick deck without any other support. The solar panels on Beagle-B are also a cause for concern since they overhang the edge of the boat and could potentially be dislodged by a large wave and are also quite sharp on the edges which is a potential hazard when towing along side.

## 4. Future Work

To date we have demonstrated the feasibility of a sailing robot as a possible oceanography platform. Work is currently ongoing to perform a long term test mission during which actual ocean data will be retrieved. A number of engineering issues have been highlighted with many more expected to arise during longer missions. Future work will needed to address the durability of the robot, to ensure it can survive prolonged periods at sea. Additional work on power management strategies is also required to maximise the amount of power available to running oceanographic instruments. It is hoped that biologically inspired approaches will aid in this. The end goal is that a robot should be able to remain at sea for several months without intervention from its operators.

## References

- Abril, J. Salmon, J. and Calvo, O. (1997). Fuzzy control of a sailboat. *Int. J. of Approx Reasoning*, 16(3-4):359–375.
- Arkin, R. (1992). Homeostatic control for a mobile robot: Dynamic replanning in hazardous environments. *Journal of Robotic Systems*, 9:197–214.
- Elkaim, G. (2002). *System Identification for Precision Control of a WingSailed GPS-Guided Catamaran*. PhD thesis, Stanford University.
- Neal, M. (2005). A hardware proof of concept of a sailing robot for ocean observation. *IEEE Transactions on Oceanic Engineering*.
- Parisi, D. (2004). Internal robotics. *Connection Science*, 16(4):325–338.
- Sauze, C. and Neal, M. (2006). An autonomous sailing robot for ocean observation. In *proceedings of TAROS 2006*, pages 190–197.

# 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 synergistic 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 trade-off 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 hard-

ware 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° 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

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 <sup>2</sup>
Ballast	16 Kg
Sail area	3.7 m <sup>2</sup>
Mast height	3.4 m

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

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.

### 5.2 The FAST project

The FEUP<sup>1</sup> 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 in 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.

<sup>1</sup>Faculdade de Engenharia da Universidade do Porto or School of Engineering of the University of Porto

## 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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## References

- Brown, M., Kelley, M., and McGill, P. (2001). MBARI vertical profiler. In *Proceedings of the MTS/IEEE Conference Oceans'01*, pages 2482–2485, Honolulu, HI, USA.
- Cruz, N., Matos, A., Cunha, S., and Silva, S. (2007). Zarco - an autonomous craft for underwater surveys. In *Proceedings of the 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 Journal of 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 *Proceedings of the MTS/IEEE Conference Oceans'06*, Boston, MA, USA.
- Griffiths, G., (Ed.) (2003). *Technology and Applications of Autonomous Underwater Vehicles*. Taylor and Francis, London.
- Kelley, J. G. W., Behringer, D. W., Thiebaut, 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 *Proceedings of the 3rd International Conference EuroGOOS*, pages 304–310.
- 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.
- 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 *Proceedings of the MTS/IEEE Conference Oceans'01*, pages 2470–2472, 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 '01, pages 117–122, Honolulu, HI, USA.
- Webb, D. C., Simonetti, P. J., and Jones, C. P. (2001). SLOCUM: An underwater glider propelled by environmental energy. *IEEE Journal of Oceanic Engineering*, 26(4):447–452.
- Wunsch, C. (1996). *The Ocean Circulation Inverse Problem*. Cambridge University Press, Cambridge, MA, USA.