AAS Endurance: An autonomous acoustic sailboat for marine mammal research

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***Abstract*—This paper presents a joint research project of the Austrian Society for Innovative Computer Science, Austria and Oregon State University, USA which is intended to be realised within the next three years. The aim of the project is to develop an autonomous sailboat for passive acoustic monitoring of marine mammals and mitigation of human impacts on them. Performance tests of the autonomous acoustic sailboat - *AAS Endurance* - will include an open sea transect of at least one month duration. The work presented here discusses shortcomings of current ways of acoustic marine mammal monitoring and outlines advantages of a robotic sailboat for this task, as well as problems to be solved with this new technology.**

***Index Terms*—autonomous sailboat, robotics, marine mammals, bioacoustics, passive acoustic survey, underwater acoustics, line transect**

I. Introduction

Passive acoustic monitoring (PAM) is a widely used technique to estimate the abundance and distribution of marine mammals. A principal problem of PAM is the limitation in spatial and temporal coverage of the observations (see Fig. 1). Measurement can either be done with a moving platform (e.g., research vessel) or stationary recording devices (e.g., anchored autonomous recorders). Moving platforms offer the possibility of sampling a large area in a short period of time. However, because of the high costs of ship time, such passive acoustic line transects can be conducted only occasionally, and temporal coverage is very limited. In contrast, stationary recording devices [1] allow continuous sampling of an area. Their disadvantage lies in the limited spatial coverage of the devices.

Autonomous and remotely navigable passive acoustic platforms offer the possibility of sampling an area of interest with high temporal and spatial resolution at low cost. In this paper we introduce such a technology based on an autonomous acoustic sailboat (AAS). The extended payload and availability of energy on the proposed research platform allows operation of additional sensors such as measurement of chlorophyll and zooplankton density. The multi-sensor platform is therefore well-suited for investigating broader oceanographic and ecological questions, including predator-prey dynamics, patch scales, prey densities, and trophic energy flow.

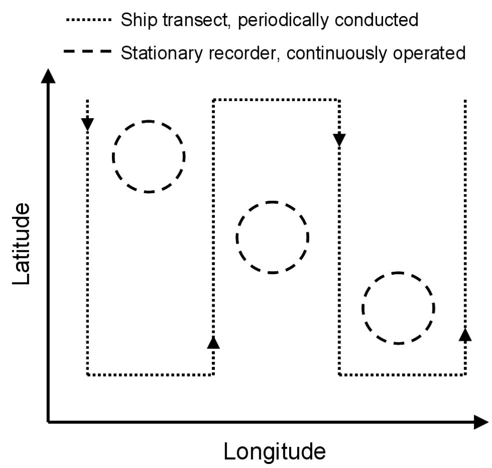

Fig. 1. Comparison of the spatial and temporal coverage of ship transects (dotted line) and stationary recorders (dashed circles)

II. Autonomous and Remotely Navigable Passive Acoustic Platforms for Marine Mammal Research

To date, two autonomous and remotely navigable passive acoustic platforms are available for marine mammal research: wave-powered vessels (e.g., the Wave Glider^{TM} [2]) and ocean gliders (e.g., the Seaglider^{TM} [3]).

The Wave Glider provides a submerged (swimmer) and a surface (float) unit. Both units are connected via a tether and allow the swimmer to move up and down as a result of wave motion. The swimmer includes several fins which interact with the water as the swimmer moves up and down, and generate forces which propel the vehicle forward. The Wave Glider, developed by Liquid Robotics, Inc., has proven long-term capabilities in a five-month test trial, and the device seems well-suited for long-term passive acoustic monitoring of marine mammals. However, as the Wave Glider is a relatively new device, and to date there have been no reports of long-term acoustic recording capability, the following discussion will focus on the comparison of gliders with the proposed autonomous acoustic sailboat.

Gliders are commercially available from several manufacturers (e.g., [4]), and all types are based on the same principle. Changes in buoyancy cause the glider to move down and up in the water, and as with a airplane gliders, wings transform this vertical motion into forward motion. A stable, low-drag, hydrodynamic shape allows the glider to fly efficiently through the oceans. These devices are optimized for extremely low energy requirements and designed to operate at depths up to 1000 m. Gliders are capable of long-term operation and have been used extensively for oceanographic research for a number of years.

In the last years several research groups in the United States and Canada have started using gliders to investigate cetaceans [5], especially the deep-diving species in the beaked whale family (Ziphiidae; [6]). Research on beaked whales came to the fore because little is known about these animals and because of atypical stranding events which are suspected to be related to military sonar activities [7]–[9].

Because of their long dives (up to 1.5 h) and brief surfacing periods these animals are difficult to detect visually. Beaked whales vocalize extensively underwater to navigate and detect prey [10]. PAM is therefore the preferred method to determine presence/absence of beaked whales. However, as beaked whales appear to start echolocating at depths greater than 400 m, and because their emission beam pattern is narrow [11], the detection probability increases with depth [12] and sound reaches the surface only occasionally. Accordingly gliders are better suited for investigation of these animals than surface vessels.

Gliders are also used to investigate baleen whales [5]. Because of the glider's low speed (0.25-0.5 m/s, or 0.5-1 kt), flow noise is relatively low, which is advantageous for recording low-frequency baleen whale vocalizations. However, the internal electronics and mechanics of gliders periodically produce self-noise, and during such periods passive acoustic observations are not possible. An advantage of submerged operated vehicles is the limited surface time, which minimizes the risk of a collision with other obstacles, reduces damage from high-energy surface phenomena (wind and waves), and reduces the possibility of potentially harmful human action. Furthermore gliders can be deployed in polar regions, where ice coverage prohibits the usage of surface vehicles, and in areas with high wind and waves where the traditional visual means of marine mammal observation are ineffective.

III. Limitations of Passive Acoustic Gliders

Submerged operated platforms such as gliders also suffer from some drawbacks:

- **Speed:** The typical horizontal cruise speed of most gliders is approximately 0.25 m/s (0.5 kt). This low speed does not allow surveying a large area for a target species in a reasonably short time period. To be able to conduct a survey in a shorter amount of time, a larger number of gliders (number depending on the size of the area of interest) must be deployed. A larger number of devices significantly increases the complexity and cost of a survey.
- **Payload:** Most gliders are relatively small instruments and provide relatively limited payload capacity. Larger payloads allow for more batteries and sensors, so the small capacity of gliders limits both their deployment duration and their capability for measuring a wider suite of oceanographic parameters. An additional constraint in gliders is that the payload must be horizontally balanced.
- **Continuous real-time access:** As gliders stay submerged most of time, these platforms do not provide continuous real-time access. For real-time monitoring, such to warn of the presence of an endangered species, the minimum response time of a glider is the time it takes to rise to the surface - potentially several hours - plus a small amount of data transmission time.
- **Sensors:** The operating power for gliders comes from batteries. Because of constraints in payload mass, the amount of energy available for operating power-intensive electronics such as optical sensors is small.
- **Computational power:** Because of the energetic limitations, sophisticated and thus energy-intensive computations cannot be run continuously onboard a glider.
- **Reliability:** A malfunction at depth can cause the loss of a glider.
- **Duration:** Because of the limited energy capacity, acoustic glider deployments for marine mammal studies are limited to a duration of several weeks.

IV. Autonomous Sailing Vessels

An autonomous sailing vessel (ASV) is a sailboat equipped with sensors for wind speed and direction and motor-driven actuators for controlling sails, rudder, trim, etc. Using its intelligent control system [13]–[16], it can automatically steer the vessel to a desired point, maintain station at a location when desired, or follow any other long-term directions a shore-based pilot provides it. Autonomous sailboats are aimed to be used for several tasks on sea, especially for ocean sampling and observation [17]–[21].

The Roboat (see Fig. 2) is a type of ASV in development and use since 2007 [14], [15], [22], [23]. The basis for the Roboat is a commercial sailboat designed by Jan Herman Linge, the boat type Laerling. The boat was originally created for kids to learn sailing, and therefore safety and stability are the major characteristics of the boat. It has a length of 3.75 m

Fig. 2. The Roboat autonomous sailing vessel (ASV)

and comprises a 60 kg keel-ballast, which will bring the boat upright even from the most severe heeling. The boat can carry large payloads such as a battery bank and multiple sensors. Including batteries the overall weight of the boat is 300 kg. Additional payload of up to 50 kg is possible without impact on the sailing behaviour. The sail area of mainsail and foresail together is 4.5 m^2. It is equipped with solar panels providing up to 285 W of power during conditions of full sun and a direct methanol fuel cell delivering 65 W as a backup energy source. The Roboat features a three-stage communication system, combining WLAN, UMTS/GPRS and an IRIDIUM satellite communication system, allowing continuous real-time access from shore [23]. This can be used, for example, to track and navigate the ship, or to transmit information on acoustic detections, to a shore-based command center. The rudder and sails as well as the tacks and jibes are autonomously controlled by incoming data from various sensors (GPS, compass, anemometer, etc.) on an NMEA200-bus, which are analysed on an onboard PC running Linux. It has been successfully tested on Austrian Lakes, the Adriatic Sea in Croatia, and the Irish Sea in Wales. The Roboat is virtually unsinkable, so the danger of losing the device is small, and any detected system malfunctions can be immediately reported to the command center.

V. The AAS Endurance

The *AAS Endurance* will be a specially-equipped Roboat. Unique features of the *AAS Endurance* include the following.

A. Acoustic System

An acoustic streamer (towed array) will contain three hydrophones, a depth sensor, and a compass module for determining the orientation of the streamer. The captured sound will be sent to a BARIX Instreamer, which will digitize the analog signals with sampling rates up to 48 kHz. Data will be streamed continuously via the boat's WLAN interface to a base onshore, or to a manned vessel if within reach. This arrangement was successfully implemented and is being used in an autonomous listening station in Antarctica [24]. In parallel, the analog hydrophone signals will be sent to an onboard high-quality recording system with sampling rates up to 192 kHz and resolution of 24 b running on a low-power PC. Signals will also be sent to automated call-detection software running on DMON hardware developed by Mark Johnson of Woods Hole Oceanographic Institution. Such software will listen for calls of target species of marine mammals; such algorithms have been developed for many species of cetaceans (whales, dolphins, porpoises) and pinnipeds (seals, sea lions, walrus) (e.g., [25]–[28]). Most cetaceans and pinnipeds are reliably detectable from the surface, and data recorded from surface vessel towed arrays make clear that even beaked whales can be detected [29], although the detection probability is lower.

This acoustic data-capture and processing system will allow onboard real-time detection of marine mammal calls and storage of high-quality data for further laboratory analysis. If the sailboat's WLAN is within reach of shore, acoustic data can be streamed to the command center in real time. In addition, the spatially separated hydrophones provide information for estimating the direction to any sound sources encountered using time-of-arrival delay methods [30].

B. Optical System

An optical camera mounted at top of the mast can be aimed in any desired direction. The acoustic system will use its multiple hydrophones to estimate the bearing to a marine mammal sound source and provide this bearing to the optical system. The optical system can then be aimed in the desired direction to potentially allow visual identification of any vocalizing marine mammals when they surface.

C. Energy System

To produce energy independently of weather conditions, a methanol fuel cell is integrated as a backup system, allowing continuous provision of 65 W over a period of four weeks. The advanced energy system allows the Roboat to run sophisticated algorithms, such as for detection and classification of marine mammal calls, continuously over extended periods of time. This energy system is not available on other types of autonomous acoustic platforms.

D. Speed

AAS Endurance will have a maximum speed of approximately 2.3 m/s (4.5 kt). This allows sampling an area of interest with high temporal and spatial resolution at low cost.

VI. Challenges

A. Obstacle Detection and Avoidance

An important problem to be solved for long-term unmanned and autonomous missions on sea is reliable obstacle detection and avoidance. Static obstacles such as landmasses can be predefined on the sea map which is the basis for the routing system. A combination of multiple techniques, such as thermal imaging, radar, camera, and automatic identification system (AIS) will be used to detect dynamic obstacles. Research in this field has been carried out for autonomous underwater vehicles [31] and motorised autonomous surface vehicles [32]–[35]. The obstacle avoidance task is different for sailing vessels, as they can not navigate in any direction directly, depending on wind conditions. Therefore a novel approach to autonomous obstacle avoidance will be an essential part of this research project.

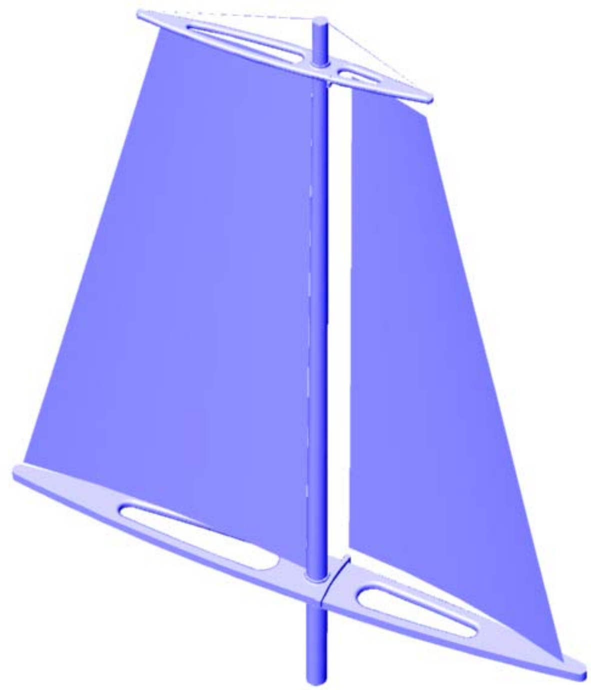

Fig. 3. Balanced rig example (source: [37])

B. Energy Balance

The currently used ASV Roboat can operate energetically autonomously with an average power consumption of 30 W. The solar system generates enough energy to sail continously, but doesn't provide any additional energy for the acoustic monitoring facilites. In order to compensate this lack of energy, there are basically two possible approaches: generating more power or increasing efficiency. The first approach within the research project will be to save power by the use of more efficient components (computer, sensors, drives) and by optimising the control algorithms. Furthermore, a balanced rig design (also known as Balestron rig, Aerorig^{TM}, swing rig, and EasyRig^{TM}) provides great potential to save power [36], [37]. A balanced rig consists of an unstayed mast carrying a main and jib (see Fig. 3). The main boom extends forward of the mast (the mast passes through the boom) to the tack of the jib. The main and jib are sized so that the force from the mainsail is slightly higher than that from the jib. That is, the combined center of effort is just behind the mast. Therefore the force needed to control the sheets is much lower than for a conventional sloop rig. The new rig will be equipped with motors for autmatic reefing in order to avoid damage during storms.

VII. Project Timeline

To date (April 2009) the planning phase of the project is completed and funding has been requested. We plan to build and test *AAS Endurance* over the next three years.

In the first year of development the sailboat will be equipped with the control and energy system in Vienna, Austria. A first system test will be conducted on Lake Neusiedl, Austria. In a second step the acoustic system will be integrated. A more comprehensive test will be performed on the coast of the Baltic Sea in northern Germany. Goals of this test are (1) to verify that the control (including obstacle avoidance) and energy systems are working properly, (2) to evaluate the impact of the acoustic streamer on vessel speed and behavior, (3) to test mechanisms to optimize the depth and alignment of the acoustic streamer, and (4) to test the optical system for the potential verification of recorded sounds. A final tuning based on the result of the Baltic Sea test will be conducted in Vienna, Austria.

In the second year, *AAS Endurance* will undergo its first deep-water tests over 3-5 days off the coast of Newport, Oregon, USA. The goals of this test are optimization of the acoustic systems, especially noise reduction; assessment of vessel self-noise in various sea states; and testing of marine mammal detection capability. Some acoustic data will be transmitted in real time to shore, allowing analysis of acoustic system performance and wave and flow noise levels in various modes of sailing. Real-time marine mammal call detection algorithms will be implemented in the on-board acoustic system, allowing sending of encounter information nearly instantaneously via IRIDIUM communication link while on transect.

After successful completion of these tests, *AAS Endurance* will be transported to Hawaii, USA. After a final test off Kailua, Hawaii, USA, *AAS Endurance* will be sent on a transect from Kailua, Hawaii, USA to Newport, Oregon, USA, a direct distance of approximately 4100 km. The estimated transect time is approximately 4 weeks. A comprehensive data analysis to characterize the system's performance at detecting marine mammal vocalizations will be conducted afterwards in the lab.

After the two-year development period, *AAS Endurance* will reach operational capability. A first scientific survey of marine mammals will be conducted in the third year.

VIII. Discussion and Future Work

The autonomous acoustic sailboat offers major advantages compared to submerged operated vehicles, including payload, speed, continuous real-time access, energy, and onboard computational power. However there are also challenges such as reliable obstacle avoidance linked to this new technology which must be addressed.

Gliders remain an important and powerful platform to investigate deep diving animals such as beaked whales or surveying polar regions where ice coverage prohibits the usage of surface vehicles. Both platforms are useful tools to gain knowledge of marine ecosystems, especially - as here proposed - of marine mammals.

AAS Endurance offers the operation of a multi-sensor platform and is therefore suitable to investigate broader ecological questions. The autonomous acoustic sailboat could, for example, be navigated to follow tagged animals using position information transmitted by the tag. Such a mission would help gain information on species-specific seasonal and diurnal vocalization in behavior. This baseline information is very important for projects utilizing passive acoustic recordings to estimate the distribution and abundance of marine mammals. Additional sensors for oceanographic variables such as chlorophyll and zooplankton density could help to understand the ecology of many marine mammal species.

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