Developing SailSwarm: Small Uncrewed Sailing Vessels for Maritime Environments

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***Abstract*—Swarms of robots are rarely operating in the wild, and their duration of operation is often limited to a scale of hours. We propose a self-organizing fleet of custom-built uncrewed surface vessels (USVs) in the form of sailboats. We report on the actual construction of two USV platforms, one out of the shelf with custom electronics called *Aqua Flash* and another fully produced in-house from hull-shape to electronics called *Onyx Pearl*. We detail the design thinking involved in producing these platforms, especially from the perspective of long-term autonomy, communication, actuation, and choice of materials. We describe the autonomous sailing experiments carried out with *Aqua Flash* and buoyancy profile experiments carried out with *Onyx Pearl*, which is in the early stages of development.**

***Index Terms*—Uncrewed Surface Vessel (USV), Robotic Sailboat, Energy-aware decision-making, Long-term Autonomy**

I. Introduction

Considering the earth's surface is about 71% water, it holds enormous challenges and potential in logistics, mobility, resources, and energy. Hence, interest in marine robotics is high [1]. Many complex classes of independently operating robots have been developed around the world for various surface and underwater missions. Some have become workhorses of scientific and commercial underwater exploration and exploitation [2]. These operate on a varying level of autonomy, from being remotely piloted to having near-full autonomy to perform their specific missions. An interesting challenge is the cooperation of robots where a multi-robot system can perform specified missions in a group [3].

Swarm robotics [4] involves designing, constructing, and deploying large groups of robots that coordinate and cooperate to solve complex tasks. It takes inspiration from natural self-organizing systems, such as social insects, fish schools, or bird flocks, characterized by emergent collective behavior based on simple local interaction rules. Typically, in swarm robotics we extract engineering principles from studying those natural systems to provide multi-robot systems with comparable abilities. However, robot swarms are studied rarely in the wild [5] and seldom with operation over larger temporal scales (e.g., several days). These experiments predominantly involve battery-powered Uncrewed ground vehicles (UGV), Aerial vehicles (UAV), and USVs. Given that these platforms move or propel themselves with battery-powered motors, they are limited in long-term performance and need human intervention (charging, maintenance, etc.) to operate for a long duration.

We focus on a special class of USV, autonomous sailboats, which can be a promising platform for long-term missions [6]. Autonomous sailboats are propelled (mainly) through wind, and the battery is used to power the computing unit and actuators that control both sail and rudder of the USV [7]. These platforms rely on relevant sensors, such as a GPS sensor to provide their position, an anemometer to measure wind direction and speed, and an IMU to calculate the directional heading [8]. They also have auxiliary systems, such as communication modules to send information to a base station or remote control and other sensory payload collecting data on water resources [9]

The rest of the paper is organized as follows: Section II provides the construction and components used to develop the two platforms. Section III describes the motion control principles. Section IV provides the experiments performed using the developed sailboat platform to test autonomous sailing algorithms at a local lake. Section V summarizes where and how we plan to use a swarm of these platforms.

II. Construction

We developed two sailing USV platforms: Boat *Aqua Flash* (Fig. 1(a)) is built for rapid prototyping of electronic computing and sensing, and Boat *Onyx Pearl* (Fig. 1(b)) is being developed with a MaxiMOOP [10] hull constructed from carbon fiber and a custom Gaff-shaped (held by a rigid rod on top) crosscut sail made of Mylar (BoPET polymer made from stretched PET). The sails are adjusted using a servo actuator (controlling the yaw of the sail mast). Steering is achieved with a servo-actuated rudder. Additionally, Boat *Onyx Pearl* is equipped with a thruster that can provide propulsion as a backup option in the absence of wind or in the case of sail damage. The computing, communication, and sensing onboard differ between the two platforms.

The rapid prototyping platform *Aqua Flash* has a length of 1,000 mm with a mast height of 1,578 mm. It has an ESP32 microcontroller, 9 DOF IMU, a GPS Module, and a Flysky RC receiver. The GPS module is a simpleGNSS Pro board from ArduSimple based on ublox NEO-F10N with an IP67 u-blox ANN-MB1-00 Antenna for GNSS Dual Band (L1/L5) providing sub-meter standalone precision at a maximum rate of 8 Hz. Communication is implemented with an onboard Wifi module on ESP32. It transmits key data (heading, latitude, longitude, program status, and roll) to a base station and

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(a) Boat *Aqua Flash* in lake Constance, point to point motion experiments

(b) Left: Boat *Onyx Pearl* with the carbon fiber hull, top-right: Mylar sail and top-left: balanced rudder and T200 thruster.

Fig. 1. The two sailboat platforms

receives wind direction and target coordinates, which are described in the experiments and later used for point-to-point sailing.

Boat *Onyx Pearl* has a length of 1,200 mm with a mast height of 1,600 mm. It combines a Raspberry Pi 5 and ESP32 MCU for processing and real-time computing. It also has a suite of sensors and communication equipment, such as an LCJ Capteurs CV7 ultrasonic wind sensor, RTK GPS with subcentimeter accuracy, 9 DOF IMU MPU-9250, NORA-B120 Bluetooth 5.2 BLE module (up to 400 m) for local boat-boat and local broadcast communication, and RFDesign UAV RFD900x telemetry for long-range (up to 10 km line of sight) communication to the base. The RTK system is also developed in-house using the ArduSimple simpleRTK2B platform, which works both in Base and Rover configurations. The RTCM correction data is sent to the rovers using a Unidirectional Point-to-Multipoint communication based on the Digi XBee SX 900 RF Module.

III. Motion Control

Autonomous navigation for sailboats presents unique challenges compared to standard terrestrial vehicles, requiring more sophisticated strategies to manage environmental conditions. Factors and constraints, such as wind (see Fig. 2), waves, and tide, significantly influence the available directions of travel. Our approach to optimizing efficient motion while ensuring stability draws inspiration from both traditional robotic bang-bang control with hysteresis and the decision-making processes used by experienced sailors.

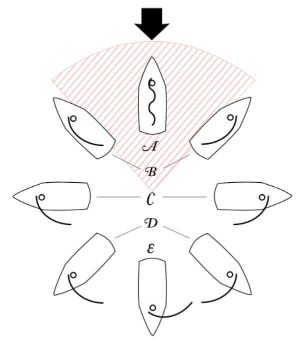

Fig. 2. Points of sail. The arrow represents the direction of the wind. The red is the "no sail zone" because it is impossible to sail into the wind. A. No-go zone 0-30°, B. Close hauled 30-50°, C. Beam reach 90°, D. Broad reach 135°, E. Running 180°, Source: Wikicommons

For point-to-point navigation, we have developed a control algorithm that first processes the boat's current location using GPS data and calculates the target heading to reach the destination. If the desired direction of travel lies outside the "no-go zone" (the region close to the wind direction where sailing is not feasible), the sails are trimmed to an optimal position to maximize driving force. The precise trim position for each heading was determined experimentally to ensure maximum efficiency. However, if the target heading falls within the "no-go zone," the algorithm divides the boat trajectory into several short segments of close-hauled sailing. This technique enables the boat to reach destinations that would otherwise be inaccessible and is the optimal practice used by experienced human sailors.

Once a viable target heading is determined, the algorithm employs a modified line-following technique to maintain the desired course. Using the 9-DOF IMU, we obtain consistent heading readings with a precision of $\pm 3°$, regardless of the boat's tilt or pitch. The system continuously compares the real-time heading to the target heading, and if it deviates beyond a predefined tolerance of $\pm 10°$, the servo-controlled rudder makes the necessary adjustments. Under most conditions except when the boat is motionless, steering with the rudder proves to be energy efficient and highly responsive, requiring only a small change in the angle of the rudder to generate a sharp turn of the boat.

Capsizing, typically due to strong winds, is the largest threat to the stability and endurance of an individual boat. Our algorithm takes significant precautions to minimize this risk using both predictive and reactive modifications to the motion control. Using the 9-DOF IMU, the boat repeatedly calculates its current roll. If this roll becomes too large due to the heeling force from the wind, the boat intelligently eases the sails until it reaches a level within a specified heeling tolerance. This response of easing the sail under increased wind is precisely what experienced sailors do. By constantly updating the trim positions, the boat is able to maximize its speed while preventing the risk of a capsize.

In addition to this responsive technique, our algorithm also considers the wind speed as a variable when plotting its course and adjusts its planned angle of sailing to minimize this threat.

IV. EXPERIMENTS

Experiments have been performed with boat *Aqua Flash* in both controlled pond and lake (lake Constance, south of Germany) environments (video online[1]). With this boat, we were able to demonstrate successful directional maneuvering, including turning to a specific heading, as well as sailing maneuvers, such as luffing (turning into the wind), bearing off, tacking, and gybing (turning with the back of the boat passing through the wind). Combining these moving capabilities and location coordinates, we performed point-to-point sailing trajectories and extended them to multi-point trajectories on the lake. The sailboat can also retain its final position through active station-keeping, moving in a figure 8 path, repeatedly accounting for drift caused by currents and variable winds. During multiple testing days exhibiting strong to heavy winds, the boat consistently demonstrated stable performance.

As of now, boat *Onyx Pearl* is under development and has only entered the water to perform buoyancy, waterline, and freeboard (distance from the deck to the water surface) measurements. Our tests yield a maximum payload capacity of about 23.5 kg (including deck, hull, and keel, which weigh 10.8 kg in total) with a freeboard of 155 mm.

V. DISCUSSION AND CONLCUSION

We plan to build several of these sailboats and engineer swarm behaviors with energy-aware decision-making to study and improve temporal and spatial survivability [11] of swarms in the wild. We see many unique challenges for both the platform and the coordination of a group of boats. The nontrivial motion of sailboats constraint by (changing) wind direction and speed makes the geodesic path sometimes inefficient or nonviable. Coordinating a (small) swarm of these vessels is an added challenge, given they need to follow the rules of COLREG (International Regulations for Preventing Collisions at Sea) while avoiding each other and other real-life floating objects (boats, other water users, animals, debris, etc).

Heterogeneity is a common feature of (robot) swarms with a variety of advantages [12], [13]. Our swarm of sailboats may acquire heterogeneity in terms of the various auxiliary sensors each USV can carry. These sensors could include CTD (conductivity, temperature, and depth; a package of electronic instruments that measure these properties), multi-beam sonar, cameras, and bongo nets to collect plankton. It would be challenging to put all equipment on a single boat, as marine sensing equipment can be bulky and requires profiling water columns. Distributing these over the swarm ensures robustness and keeps the payload within manageable limits. Another option for heterogeneity in sailboat swarms could be boats of different sizes enhancing task specialization and adaptability.

As we want to achieve long-term autonomy (LTA), robustness and survivability of our robots are significant compared to short-term goals, such as task optimization [14]. This approach requires a shift from task optimization to ensuring robustness in handling environmental uncertainties and disturbances. Our autonomous sailboats need to be informed by the specific requirements of the environment and ecosystem, considering energy availability and traffic. LTA involves deployment scenarios that extend beyond a mission running on a single battery charge. The ability of the robotic system to recharge autonomously becomes crucial for its continued operation and changes tradeoffs between task completion, risks, and survival.

Our inspiration comes from circumnavigating sailboats with superior endurance compared to motor-propelled boats and the energy management of social animals. For example, optimal movement theory [15] combines multidimensional considerations of movement decisions, merging ecological landscapes based on a unified expectation of cost-benefit analysis. We could profit from the swarm setup by using social sampling (boats observing or informing other boats in the swarm, e.g., about local wind situation) to obtain and share real-time information and to reduce uncertainties collectively.

Plans for future versions of *Onyx Pearl* include the integration of LIDAR and vision-based obstacle avoidance systems. We also consider solar-based charging hardware for additional energy harvesting to enhance autonomy. Our future swarm of autonomous sailboats can potentially be used for long-term monitoring of chemical and physical markers in water bodies and marine life, providing quiet operation and minimal environmental impact. This approach could possibly reduce costs and logistics, for example, in limnological studies (study of inland water ecosystems).

With the development and study of swarms of autonomous sailboats, we hope to support swarm robotics research in its effort to make the important next step out of the lab and possibly push for more forms of heterogeneity in swarm robotics. We want to establish a new benchmark of swarm robotics within the novel domain of autonomous sailing, and we envision pushing swarm robotics into the reach of future real-world applications on inland waters and oceans.

[1] https://praked.github.io/publications/Developing-SailSwarm-IROS2024

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