Application Status and Trend of Autonomous Sailing Boat Based on New Energy

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Abstract. The autonomous sailing boat is becoming a rapidly developing technology for long time ocean science observations in recent years. In this paper, we give an overview of the representative autonomous sailing boat and typical application in the ocean researches, and point out the characteristics which are different from others. We discuss the control system method of autonomous sailing boat and summarize it into a three layer mode structure based on the application and effect. Based on the controlled target we analyse the relationship between the three layers, and discuss the typical control algorithm respectively and application boundary in each layer. We conclude with a brief outlook on the parameter selection of different application for design and the main problems of existing control algorithms. At the last part of this paper, we show a brief outlook on the development direction and key technologies to be broken through in practical application of global ocean environments.

Keywords: Autonomous sailing boat; Wind power; Sail; Control system; Ocean observations.

1. Introduction
Autonomous sailing boat is driven by wind, control systems and sensors are supplied by the electric energy obtained from solar panels. It performs multi tasks automatically without human assistance. The autonomous sailing boat becomes an alternative to global ocean science observation. In this paper, we summarize the representative and application, analyse the relationship between different parameters and proposed a kind of layer mode control system and discuss the different control algorithm respectively. We hope to provide ideas for the system design.

2. Development Status and Analysis
The HTW X-3 was developed by Harbor Wing Technologies in 2008 as shown in figure 1(a). It has trimaran structure and rigid wing sail. It is equipped with high-performance autonomous control system with remote communication and telemetry capabilities. [1]. Submaran S10 was developed by OCEAN AERO in 2016 as shown in figure 1(b). The key characteristic of this boat is that the vehicle can submerge under the surface in severe weather conditions after the wing sail fold and retract. According to the application the S10 is divided into three series with different speed, depth and endurance time: Scout, Discovery, and Navigator [2]. The Sailbuoy was developed by Offshore Sensing Company as shown in figure 1(c). It was the first sailing boat to finish the transatlantic sailing match in 118 days (total distance is 7800km) in the world. The Sailbuoy was designed specifically to deploy and operate in rough ocean environment such as Norwegian Sea. From 2013 to 2015, a mission of monitoring ice and measuring wave was completed successfully in 3-30m/s wind and 8-13m wave
in the North Sea[3][4]. Saildrone, as shown in figure 1(d), was developed by Saildrone Inc. Its sail can rotate freely around 360°, it has good motion control performance for active water rudder [5]. In order to collect oceanic and atmospheric carbon dioxide Saildrone-G5 completed a journey over 22,000 km in 196 days by NOAA’s Pacific Marine Environmental Laboratory in 2018. The height of wave is greater than 15m and the speed of wind is up to 130 km/h [6]. DATAMARAN Mark 7 and Mark 8 are developed by the AMS Company from 2016 to 2019. As shown in figure 1(e), cambered auto-trimming wing and electric propulsion are adopted. It is the first self-supporting sailing boat even in strong wind and severe sea states [7] [8]. Avalon was developed by the FIT in 2010. The dual rudder can provide a much better control performance and steering ability, as shown in figure 1(f) [9]. A-TirmaG2, as shown in figure 1(g), was developed by Universidad de Las Palmas in 2015. A special design of double wing sails and double rudders is used. The cylindrical shape and smooth slope can improve stability in harsh wind conditions [10] [11]. FAST was developed by the University of Porto in Portugal as shown in figure 1(h). In order to improve stability a deep keel and lead ballast was designed. A task named AcousticRobot’13 was performed in May 2013 off the Portuguese coast. FAST was used to record the acoustic noise. The results show that it is an effective tool to collect sound data in the sea area even suffering large background noise. Because of this feature of low self-noise it is great potential in the field of measuring underwater noise [12]. VAIMOS was designed and developed by the IFREMER for oceanographic measurements as shown in figure 1(i). The boat has a balanced soft sail and a vertical axis wind turbine [13]. In 2013, VAIMOS sampled the ocean gradients parameters in mixed layer surface (temperature, salinity, turbidity, chlorophyll) between two depths (per 10cm in 1m) at speed of 5~11km/h [14] [15] [16]. ASV Roboat was developed by the INNOC. It can be kept upright in heel because of two sails and keel's counterweight. In July 2012 ASV Roboat was used to observe marine animals for long periods in the Baltic Sea. It collects data about the migration route and behavior of marine animals, which is difficult to obtain before [17]. Shanghai Jiaotong University developed two autonomous sailing boats on a scale of 1:8, which equipped with soft sails and two rectangular wing sails [18][19]. Table 1 gives an overview of the main autonomous sailing boat mentioned above.

![Typical autonomous sailing boat.](image)

**Figure 1.** Typical autonomous sailing boat.

### 3. Research of Control System

Research on autonomous sailing boat control mainly refers to the algorithm focuses on the path planning, avoiding obstacles, the control of the rudder and the sails.

#### 3.1. Control System Layer Mode

The autonomous sailing boat control system always deals with the changing wind in sea conditions, various obstacles, and calculates the optimal path according to the objective constraints. Based on distributed control theory the control system can be divided into three different layers. As shown in figure 2 the main task of bottom layer is to control the sail and rudder; The middle layer selects the
optimal segment between two points based on the wind direction, heading orientation, and intended
direction; The goal of the top level layer is to divide route path between the starting point and the goal
point into a series of intermediate points [20] [21].
In the rapidly changing environment the research focuses on how to balance the three layers efficiently
and obtain optimal decisions when it execute multi-task processes. Gal [22] presented a distributed
and centralized multi-agents method in marine environment. Every agent can not only make an
optimal path choice by its own decisions, but also communicate with the central unit to exchange
information. Jordan et al. [23] proposed a voting method or mechanism, which decide the optimal path
in navigation with reactive collision avoidance.

Table 1. Specifications of typical autonomous sailing boat.

| Model          | Long (m) | Width (m) | Displacement(kg) | Load (kg) | Sail type   | Sail area(㎡) | Velocity (kn) | Endurance (d) |
|----------------|----------|-----------|------------------|-----------|-------------|---------------|---------------|---------------|
| HTW-3          | 9.14     | 4.27      | 1800             | 680       | Rigid wing  | 65.0          | 25            | 90            |
| Submaran S10   | 4.5      | 0.8       | 227              | 22        | Rigid wing  | 3.6           | 5             | 90            |
| sailbuoy       | 2.0      | 0.52      | 55               | 10        | Rigid wing  | 1.5           | 3             | 360           |
| saildrone      | 5.8      | 0.9*      | 300              | 90        | Rigid wing  | 6.1           | 8             | 196           |
| DATAMARAN-8    | 5.0      | 3.3       | 360              | 70        | Rigid wing  | 8.0*          | 20            | 180           |
| Avalon         | 3.95     | 0.7       | 440              | --        | Soft balance | 8.4          | --            | --            |
| A-TirmaG2      | 1.985    | 0.37      | 43               | --        | Dual wing   | 1.2           | --            | --            |
| FAST           | 2.5      | 0.67      | 50               | --        | Soft balance | 3.7           | --            | --            |
| VAIMOS         | 3.65     | 0.8*      | --               | 90        | Soft balance | 5.0*          | --            | --            |
| ASV Roboat     | 3.75     | 0.9*      | --               | --        | Soft balance | 4.5           | --            | --            |

* a: The size is estimated from the image or video.

3.2. Global Route Planning
The challenging of global route planning is that not every course is directly sailable. Based on the A*
algorithm, Langbein et al. [24] used a constraint processing rules to adjust dynamically the underlying
routing map in real wind conditions combined with weather information. Based on the
Nelder-MeadSimplex algorithm, Cabrera et al. [25] proposed a route planner that provides wind and
current prediction and optimal sailing time path under weather conditions. Mason et al. [26] modelled
the uncertainty by the tree branching method and developed a path planning method under uncertain
weather conditions. Based on the climate data of the pilot map, Gibbons-Neff et al. [27] used the speed
prediction program (VPP) to predict the optimal path. Du Mingshu et al. [28] applied
multidimensional dynamic programming to make a decision in a series of the shortest paths that differ
from the total path length.

3.3. Local Route Planning
Stelzer [29] proposed a fast plan algorithm based on VMG (Velocity Made Good) method, which
determines the course according to the real-time wind conditions. Xu et al. [19] proposed an obstacle
avoidance algorithm based on A*, developed a tracking navigation control algorithm based on LOS in
many obstacles condition. Yang [30] applied a regional grid model based on the speed curve of sailing
boats. Kang et al. [31] compared the application of the VMG and A* in local route planning. Tynan
[32] proposes an alternative method that a series of point has a certain strength and polarity and finally
forms a resultant force to the sailboat like attraction or repulsion.

3.4. Control Execution
The control execution layer controls the sail and the rudder separately. The input of sail control is
wind direction and heading direction, the output is the angle of sail; the input of rudder control is the
deviation of heading angle, and the output is the angle of rudder. Emami et al. [33] [34] used PID to
tool control small autonomous sailing boat. The fuzzy control is applied in uncertain environments because
of nonlinear of water flow and wind direction. The literature [35] [36] [37] [38] shows the suitability
of fuzzy for rudder control. Velagic [39] combined TS fuzzy with feedback loop to adjust the fuzzy
factors. Layne et al. [40] proposed a self-learning algorithm in which FC knowledge was generated automatically online, at the same time the new information is inputted. An ANN method is proposed, which does not need to be adjusted manually to various conditions [41] [42]. Sauze [43] proposed an artificial neuron-endocrine algorithm to control rudder and sails to improve energy management.

4. Discussion and Results

![Figure 2. Control system.](image)

![Figure 3. Length-width-displacement.](image)

![Figure 4. Sail area-Velocity.](image)

![Figure 5. Width- Velocity.](image)

The common structure forms are monohull and multihull; most boats adopt the form of keel or fixed plate. Generally speaking, the multi hull boat can carry more loads. It is obvious that the displacement is directly determined by the length and width as shown in figure 3, regardless of the hull structure. The hull length varies according to the survey environment and application. It is generally more than 2 meters, up to 9.14 meters, according to the endurance time from 90 days to 365 days as shown in table 1. For the types of sails, both soft sails and rigid wing sails are used. Besides the high construction cost, the performance of rigid wing sails is better than soft sail in control performance. As the main force and driving device, the sail area directly determines the speed of the sailboat as shown in figure 4. The width of the boat affects the displacement except catamarans as shown in figure 3. The width of the boat is also positively related to the speed of the boat as shown in figure 5.

For oceanographic research the most optimized choice is a length of about 4m monohull sailing boat with a rigid wing sail, considering safety and reliability. For the small-scale investigation near the shore, soft balance sail boat and length not more 2m is a good alternative for its economy.

The three distributed layer structure control system is the most effective way. This simplified architecture makes us focus on a single control target. However, the existing technologies have not yet solved the real autonomous problem at all levels. For layer mode the problem is how to divide efficiently smaller components and how to determine exactly the weight coefficient of each component. For global route planning the problem is how to balance the relationship of several goals, such as time, energy consumption and path length, etc. The problem of local route planning is how to reduce the calculation load while control correctly in real time. The problem for control execution is how to find a more suitable algorithm which closes to emulate the human helmsman behavior and ensure real-time performance.
5. Future Research Trend
The autonomous sailing boat is better other devices or platforms in high spatial and temporal resolution ocean observation, acoustic detection, marine mammal tracking, and marine dynamics research. So we look forward to the future research trend based on the foregoing results in this section. The movement of an autonomous sailing boat depends on wind and current. When the wind is too weak, it has not enough speed to move correctly, especially upwind. And it is difficult to estimate the whole sailing time in this condition. The path plan and collision avoidance are also affected by wind. Therefore, the hybrid energy, such as electric power supplied by renewable solar energy by other sources, could be an alternative to autonomous sailing boat. With the development of oceanic science research more autonomous sailing boat will be deployed into harsh environments equipped with more sensors for long-time observation. The energy management is a key factor of autonomous sailing boat. Intelligent power management can make autonomy operation in long time, such as real-time energy monitoring of equipment, equipment asleep.

The sailing boat cannot navigate in any direction because it depends on wind conditions, even will be lack in speed or controllability. A reliable and fast collision avoidance system is a priority to efficiency. The anti-collision system will be focused on real-time information processing in complex environments, which depend on radar, camera or other identification system, etc.

Sailing boat cannot stop immediately or move in every direction so it is important to have an efficient and reliable control algorithm especially in long term missions. To develop modelling and various robust control algorithms is a future research direction, such as self-learning or neural network or AI etc.

At last, in order to improve the capacity, stability, safety, reliability in different sea conditions, it is important to develop new conceptual design, new materials application.

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