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Design of a Towing System by Multi Autonomous Sailboats*

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Abstract— **For researchers or administrators of relevant institutions who need to collect hydrological data of a certain water area, using autonomous sailboats to tow floating detection equipment is an energy-saving and convenient scheme for deploying detectors. However, due to the limited pulling force provided by a single autonomous sailboat, this scheme is not suitable for floating equipment with large masses. This paper proposes a new approach for multiple autonomous sailboats to tow floating objects. A system of linear arrangement and connection of two autonomous sailboats is considered an appropriate solution for towing heavy floating objects because of its ability to provide greater pulling force. The main part of the article introduces a new design of multi sailboat towing system that can tow floating objects to sail with or against wind. Repetitive experiments have been conducted at the test site equipped with a motion capture system to find the best strategy to control the sails and rudder, in order to increase the towing system's pulling force and tacking success rate. Three connection modes are proposed, compared, and tested. The best one is applied to the sailboat's towing system and improves its performance.**

I. INTRODUCTION

In recent years, a variety of intelligent robots have been applied in various fields. Among these robots, autonomous sailboats [1] show many advantages of low energy consumption, environmental friendliness, and low manpower demand, which let them get more and more attention.

Autonomous sailboats have been used in many fields, such as marine animal research [2][3], environmental monitoring [4][5], and even collecting energy from waves [6]. When it is necessary to use many instruments and equipment to complete the task, how to transport huge equipment that cannot be placed on the deck has become a major issue. Thus, some researchers consider using sailboats to tow floating equipment [7][8][9]. Researchers can collect target data for a long time by allowing floating platforms with sensors to be towed by autonomous sailboats to sail in the lake or at sea. In order to tow heavy objects, the autonomous sailboats must provide enough pulling force. Therefore, improving the pulling force of the sailboat has become an important goal of the towing system. Many methods are used to achieve this goal.

According to the principle of sailboat sailing, the main driving force comes from the sails. The angle of attack (abbreviated as AOA) of the sails will greatly affect the force exerted by the wind on the sails. For this reason, much research has been done to study the relation between the sails' AOA and the driving force. Such as using extremum seeking to optimize the sails' AOA [10], using the nonlinear dynamic model to compute the optimal sails' AOA [11], applying deep learning technology to fine-tune the sails' AOA [12], and so on. Although the above research results can be used to adjust the AOA of sails and increase the pulling force of the sailboat, the limited main sail's area makes it impossible to further increase the pulling force.

A straightforward idea makes it practical to further improve the pulling force, that is, to use multiple sailboats to cooperate and tow the floating objects together. Multiple sailboats can cooperate variously. The multiple autonomous sailboats tow the floating objects side by side requires complex algorithms to schedule to avoid collision accidents. Even so, it is difficult to maintain non-collision under the disturbance of sudden wind or current. Connecting two parallel sailboats with rigid mechanisms can completely avoid collision, but when sailing crosswind, the sails of the sailboat in the upwind zone will block the wind from blowing to the sails of the sailboat in the downwind zone, resulting in a decrease in the total pulling force. Therefore, the adaptability of the whole system to various wind directions is insufficient. Thus, it is the best plan to connect multiple sailboats in series and tow the floating objects together. Under this scheme, due to a lack of speed reducer, it is dangerous for sailboats to be simply connected with ropes. Some further improvement of connecting mechanisms is necessary. The main contribution of our study is that we came up with two kinds of new expandable connecting mechanisms other than rope connection. The above three connecting mechanisms have been mechanically analyzed and respectively installed into the autonomous sailboat towing system for comparative experiments to compare their safety and environmental applicability. Finally, we will use the best connecting mechanism to build the series towing system of double autonomous sailboats, showing it can provide greater pulling force than the single sailboat towing system.

The paper is organized as follows. Section II introduces the dynamics of the sailboat. Section III describes the design of the single sailboat towing system and compares different connection modes. Section IV shows the design of the multi sailboats towing system and compares it with a single sailboat towing system. Section V describes the layout of the test site introduces the coordinate system which will be used in the experiments, and details the sailboat model used for the tests and the hardware which builds up the control system

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of the sailboat. Then the section shows the experiments to find the best combination of sails' angles and to find the best initial speed and rudder degree of tacking, in order to make sure the sailboat can have enough pulling force to tow floating objects and complete tacking. Conclusions are in section VI, including the description of the possible sailboat towing systems to be studied and their potential application prospects.

II. SAILBOATS DYNAMICS

The Fig.1 shows all parts of a monohull sailboat. An ordinary monohull sailboat has two sails, a jib sail and a main sail. The upper ends of the sails are tied to the upper part of the mast, while the lower ends of the sails are tied to the jib boom and the main boom respectively. The jib/main boom is controlled by the jib/main sheet. Sailors can change the angles between the booms and the long axis of the boat by adjusting the lengths of the jib sheet and main sheet.

Forces applied to the sailing sailboat can be seen in Fig.2. The red arrows indicate the forces exerted by wind flow, while the blue arrows indicate the forces exerted by water flow. The direction pointed by the bow of the sailboat is called heading, while the actual sailing direction is called sailing course. The heading and course are not always coincident due to the sailboat drifting. The angle between them, marked as γ, is called leeway, which shows the level of the drifting. When the actual wind speed is not zero, the apparent wind vector can be obtained by adding the actual wind vector and the speed vector of a sailboat. As shown in Fig.2, if we set the reference line in the east-west direction, the angle between the reference line and the apparent wind direction is denoted as α while the angle between the reference line and the sailboat's heading is denoted as β. The angle between the jib/main boom and the long axis of the hull is denoted as θ_1 / θ_2. Assuming that the AOA of apparent wind against the main sail and jib sail are θ_{main} and θ_{jib}, we can derive them from the geometric relationship:

$$\begin{cases} \theta_{\text{main}} = \alpha - \beta - \theta_1 \\ \theta_{jib} = \alpha - \beta - \theta_2 \end{cases} \tag{1}$$

If neither θ_{main} nor θ_{jib} is 0, the speeds of the apparent wind on the windward and leeward sides of the sails are not equal. Specifically, the apparent wind on the windward side of the sails flows faster, this will lead to pressure difference on two sides of the sails. From the Bernoulli equation, we have:

$$p = p_0 - \frac{1}{2}\rho \Delta V^2 \tag{2}$$

Transpose and multiply A, which is the area of sail, on both sides of the equation (2), we get:

$$\Delta F = \frac{1}{2}\rho A \Delta V^2 \tag{3}$$

Here ρ is the density of the fluid, ΔF and ΔV^2 are respectively the difference of force and difference of velocity square on two sides of the sail. In Fig.2, the difference of force introduces the lift force L_1 and L_2. They are both perpendicular to the direction of apparent wind and can be written as:

$$\begin{cases} L_1 = \frac{1}{2} C_{L1} \rho_{air} A_1 V_{aw}^2 \\ L_2 = \frac{1}{2} C_{L2} \rho_{air} A_2 V_{aw}^2 \end{cases} \tag{4}$$

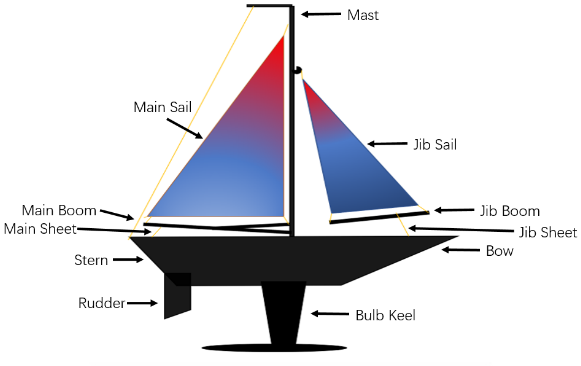


Fig. 1. Sailboat Labels

V_{aw} is the speed of apparent wind. A_1 and A_2 are the areas of the main sail and jib sails respectively. C_{L1} and C_{L2} are the lift coefficients, they depend on the orientations of the main sail and jib sail, which means:

$$\begin{cases} C_{L1} = C_{L1}\left(\theta_{\text{main}}\right) \\ C_{L2} = C_{L2}\left(\theta_{jib}\right) \end{cases} \tag{5}$$

Due to fluid friction, the drag forces D_1 and D_2 are added to the sails. In fluid mechanics, drag force can be written as:

$$D = \frac{1}{2} C_D \rho A V^2 \tag{6}$$

Thus, the expressions of D_1 and D_2 are acquired:

$$\begin{cases} D_1 = \frac{1}{2} C_{D1} \rho_{air} A_1 V_{aw}^2 \\ D_2 = \frac{1}{2} C_{D2} \rho_{air} A_2 V_{aw}^2 \end{cases} \tag{7}$$

C_{D1} and C_{D2} are the drag coefficients. Similar to C_{L1} and C_{L2}, they also depend on the orientations of the main sail and jib sail:

$$\begin{cases} C_{D1} = C_{D1}\left(\theta_{\text{main}}\right) \\ C_{D2} = C_{D2}\left(\theta_{jib}\right) \end{cases} \tag{8}$$

L_1, L_2, D_1 and D_2 are called aerodynamics forces. Since the keel can be considered as a thin foil in the flowing water, the above force analysis can also be applied to the keel. Hence, the lift force and drag force on the keel are:

$$L_3 = \frac{1}{2} C_{L3} \rho_{water} A_3 V_w^2 \tag{9}$$

$$D_3 = \frac{1}{2} C_{D3} \rho_{water} A_3 V_w^2 \tag{10}$$

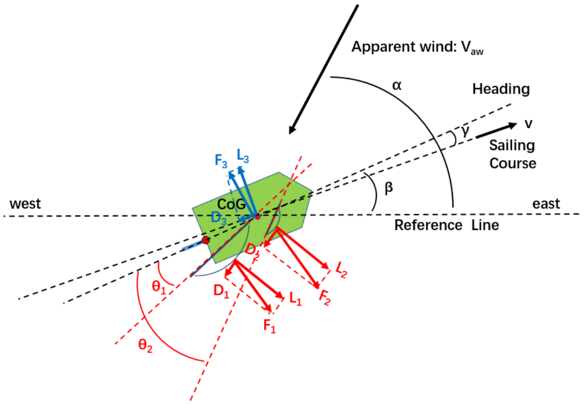


Fig. 2. Aerodynamics and Hydrodynamics Forces on Sailboat

$$\begin{cases} C_{L3} = C_{L3}(\gamma) \\ C_{D3} = C_{D3}(\gamma) \end{cases} \tag{11}$$

In equations (9) and (10), A_3 is the area of the keel and V_w is the speed of apparent water current. L_3 and D_3 are called hydrodynamics forces. The lift and drag coefficients of the keel mainly depend on leeway, which is angle γ.

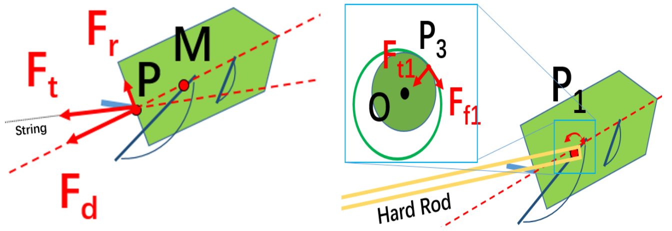
As shown in Fig.2, L_1 and D_1, L_2 and D_2, L_3 and D_3 are combined into force F_1, F_2 and F_3 respectively. When the net force of F_1, F_2, and F_3 is not 0, the sailboat accelerates towards the direction of the net force. As the sailboat gradually speeds up, the apparent wind and current may change and lead to changes of F_1, F_2, and F_3. The three forces will gradually reach a balance, and the sailboat will sail at a constant speed.

III. SAILBOAT TOWING SYSTEM

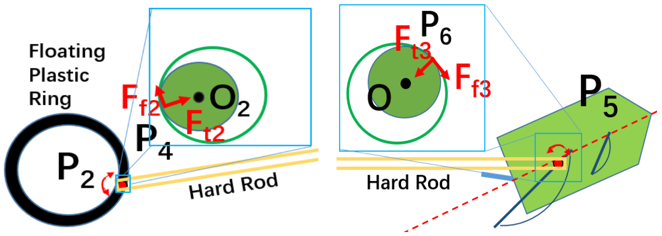
The most straightforward way for a sailboat to tow the floats is to connect the floats by a string. When the wind drives the sailboat, the connecting string is tensioned to pull the floating object forward. Besides, using hard rods to connect the sailboat and the floats is also a good scheme. We will discuss these connection modes in detail in the following part.

A. Connection Material Optimization

1) Soft Connection: Considering a floating ring as the object to be towed. From Fig.3(a), through mechanical analysis, it is obvious that the selection of the string connection point is very important since it will produce different moments to the sailboat while tacking. If we tie the long string to the point P, which is the center point of the stern, the tension on the string will hinder the turning of the sailboat. The pulling force contributed by string is F_t, it can be decomposed into two forces F_r and F_d, in the two directions which are perpendicular to each other. During the left tacking, while the rudder of the sailboat provides a moment τ_{rudder} to let the sailboat spin counterclockwise, the string provides moment τ_{string} to let the sailboat spin clockwise at the same time. This reverse moment may cause the failure of tacking.



(a) Soft Connection Force Analysis (b) Two-Ends-Free Hard Connection (Sailboat Side)



(c) Two-Ends-Free Hard Connection (Floating Object Side) (d) One-End-Free Hard Connection

Fig. 3. Force Analysis of Three Different Connection Modes

2) Two Ends Free Hard Connection: Install a vertical bar at the stern of the sailboat and the front end of the floating objects respectively. Use a long rod with holes at both ends and sleeves for the above two vertical bars. The long rod can rotate around both vertical bars. In this way, we have made the two ends free hard connection between a sailboat and a floating object.

As for the two ends free hard connection, both the sailboat's and the ring's vertical bars can rotate in the holes at the ends of the connecting rod. Just like Fig.3(b) and Fig.3(c) show, we do the mechanical analysis of the connecting point between the sailboat and rod. The interaction of forces occurs at the contact point P_3, which is between the vertical rod and the inner wall of the connecting rod's hole. During left tacking, the pressure F_{t1} from the connecting rod, acting on the vertical rod always points to the center of the latter, which is point O in the figure. Since the vertical rod is fixed at the spin axis of the sailboat, the F_{t1} won't contribute any reverse moment to the sailboat. However, the contact point has friction force F_{f1} in the tangential direction. The vertical bar needs to rotate counterclockwise, so it may slide with the inner wall of the hole. If that happens, F_{f1} is provided by sliding friction. Otherwise, it is provided by static friction. The same analysis can be applied to the point P_2 at the other end of the connecting rob. But here, the contact point becomes point P_4 and the inner wall of the hole will apply forces F_{t2} and F_{f2} to the vertical bar fixed on the floating object, which will eventually drag the floating object forward and following the steering. Therefore, compared with a soft connection, two ends free hard connection can reduce the effect of the reverse moment on tacking to a certain extent. What's more, it ensures a safe distance between the sailboat and the towed floating objects, so many collisions and accidents can be avoided.

3) One End Free Hard Connection: Fixed one end of the rod, which is close to the floating object, to prevent the rod from rotating around the vertical bar at this point. Then we make the one-end-free hard connection between the sailboat and the floating object.

Refer to Fig.3(d), same as two ends free hard connection, the one-end-free hard connection can also avoid collision. The uniqueness of this kind of connection is that since the connecting point on the towed object is fixed and cannot rotate, the angle between a front sailboat and connecting rod is relatively large during tacking. In other words, different from the situation of two ends free hard connection, the connecting rod cannot follow the forward sailboat to spin in time, which causes contact point P_6 to slide along the inner wall of the hole. The vertical bar has sliding friction with the inner wall of the hole, F_{f3} is mainly provided by sliding friction. Since the maximum static friction is larger than sliding friction, this connection method further reduces the influence of reverse moment on tacking.

B. *Multi Sailboats Towing System*

For the scene of pulling floating objects, the volume and the mass of the object will affect the resistance of the object when it is moving in the water, which means a sailboat wants to complete tacking when towing a floating object with great resistance, it requires a greater driving force to maintain the necessary. In order to get more pulling force, we can connect one sailboat with another sailboat, and use the same connection mechanism to connect the rear ship with the floating objects.

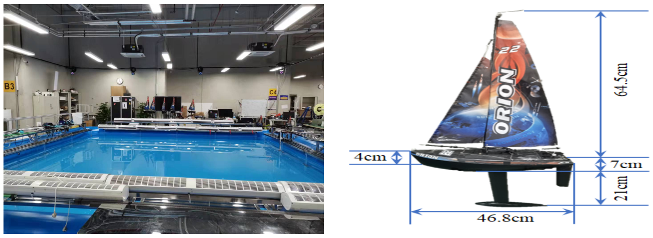
The cooperation of two sailboats introduces complexity to the system, sometimes there will be collisions between sailboats or between sailboats and the towed floating objects. According to the previous discussion, the one-end-free hard connection mechanism is safer due to its ability to avoid the collision, and it has better tacking performance in theory.

IV. EXPERIMENT AND RESULT

A. *Test Site Settings*

The test site we used for our autonomous sailboat research is composed of a pool, fans, a motion capture system, and a computer. The main body of the test site is a double-layer nested square inflatable pool, as shown in Fig.4(a). The dimension of the inner pool is $6m \times 6m$, and the width of the pool's wall is 1 meter in total. The depth of water is 30cm, deep enough for small surface vehicles' navigation and testing. Stainless steel brackets are installed on the four sides of the pool and 7 air curtain machines (or fans) are placed on the bracket which is located on the one side of the pool. These fans can continuously blow air into the pool to create a stable wind field. The small sailboat model can sail freely, and be driven by the wind at any position in the pool.

Above the pool, there is a solid metal hanging ceiling bracket surrounding the test site. 16 infrared cameras are mounted on the ceiling bracket, these cameras together with a switchboard, a server, and the supporting software (Motive), constitute the high precision infrared motion capture system (MoCap system). After fixing multiple marker points on the robot, the MoCap can locate these maker points and give their precise coordinates with an accuracy of 1mm. Researchers can build up a virtual rigid body in Motive software, which represents the position and posture of the robot.



(a) Advanced Sailboat Research Test Site (b) The Monohull Sailboat

Fig. 4. Test Site and the Sailboat Used

Our coordinate system is described in Fig.5. It applies to all experiments in the paper. Since our pool's length and width are both 6 meters, the ranges of coordinates x and y are both $[0,6]$ meters. The point O is the geometric center of the sailboat, its coordinate represents the sailboat's position, θ is the yaw angle of the sailboat, and its range is $[-180,180]$ degrees.

B. *Sailboat Type and Control System*

1) Sailboat Introduction: The sailboat we used is the Joyway8803 model monohull sailboat. It is a kind of sailboats that have two sails, a jib sail and main sail, and one mast. As Fig.4(b) shows, several marker points have been attached to the hull, mast, and booms, in order to obtain the position and attitude of the sailboat in real-time through the MoCap system. More narrowly, 4 marker points are located at the four ends of the sailboat deck for positioning the sailboat and acquiring the attitude. 2 marker points on the jib boom and 1 on the top of the jib sail jointly build the rigid body of the jib sail. 2 marker points on the main boom and 1 on the top of the mast jointly build the rigid body of the main sail. There are two steering machines in the cabin, one is connected to the jib/main sheet through a long cord and pulley, and the other is connected to the rudder through a connecting rod. By controlling these two steering machines, we can manipulate the sails and rudder, so as to manipulate the whole sailboat.

2) Hardware, Communication and Control system: We use microcontroller unit (MCU) ESP8266 with a Wi-Fi module to control the sailboat. The MCU can also help one sailboat communicate with computers and other sailboats through Wi-Fi and UDP protocol. After receiving the position and attitude of the sailboat from MoCap, the computer obtains the corresponding commands of sails and rudder through the algorithm and sends them to the MCU on board through a Wi-Fi router. MCU receives the message and sends specific commands to the steering machines that control the rudder and sails respectively. The whole process can be referred to in the diagram Fig.5.

3) Rudder and Sails Control Logic: We experimented to explore the best way to control sails and rudder. The details are expanded in the following part. As for rudder control, two

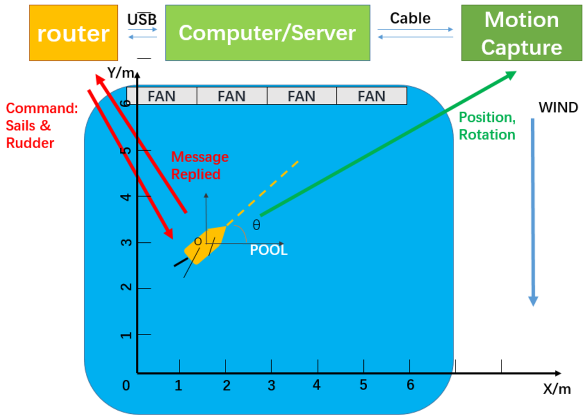


Fig. 5. Coordinate System and Information Flow

different control modes are designed. One is the autonomous free sailing mode, the rudder of the sailboat is usually in the centering position during sailing in this mode. Only when the sailboat is sailing towards and approaching the preset boundary, the command will be issued to control the rudder and turn the sailboat to the preset direction to leave the boundary. The advantage of autonomous free sailing mode is that a large number of various sailing behaviors will be generated, which will facilitate researchers to use statistical methods to study some specific sailing behavior.

Another is the PID control mode, which is mainly used for repetitive experiments that require variable control. PID controller will be applied to control the rudder to make sure the sailboat is sailing towards a specific waypoint. Assuming the coordinates of the target waypoint is (x_p, y_p). During sailing, the MoCap system can obtain the position and altitude of the sailboat in real-time, which means the coordinates (x_s, y_s) and the yaw angle θ of the sailboat are knowable. Then computer can calculate out the target yaw angle θ_p by equation: $\theta_p = arctan\left[(y_p - y_s)/(x_p - x_s)\right]$. Then $\Delta\theta = \theta_p - \theta$ is sent to the PID controller to get the rudder control command value at the next moment. The controller adjusts the yaw angle by operating the rudder, to reduce $\Delta\theta$ as much as possible so that the bow of the sailboat always points to the target point during sailing. The control system block diagram is given in Fig.6. PID parameters are tuned to be suitable: $K_p = 2, K_i = 0.1, K_d = 0.01$.

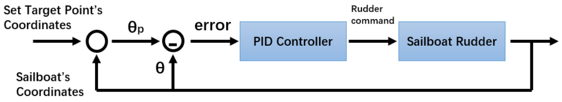


Fig. 6. PID control system block diagram

As for sail control logic, the monohull sailboat has a jib sail and a main sail. The jib/main boom is controlled by the steering engine via the jib/main sheet. By sending different commands to the steering machine, the connecting cord will contract to different lengths, and the maximum opening angles of the main sail and jib sail will change at the same time. These two angles are denoted as θ_1 and θ_2 in Fig.2, and we call them the main sail angle and jib sail angle for convenience. Refer to the formulas (4) to (8) in Section II, different jib/main sail angle configurations will provide different driving forces for the sailboat.

As for sailboats, the difficulty of sailing is how to sail against the wind. The area of the main sail is much larger than the area of the jib sail, so the former provides most of the pulling force during sailing. To find the best main sail angle θ_1 to support sailboats sailing upwind, an experiment is designed: let a sailboat sail from the point (1.0,0.5) to (5.0,1.0) using PID control mode. And by sending commands with different values to the steering machine, we can change the angle θ_1. For each main sail angle θ_1, the sailboat sails along the fixed route for 5 times.

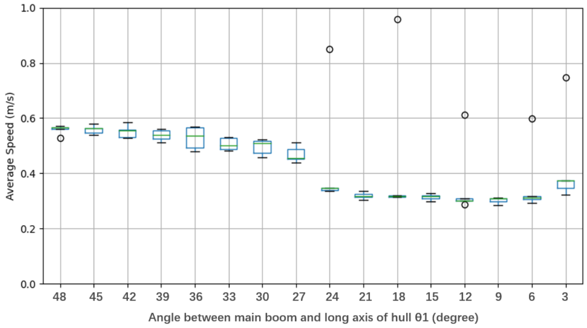
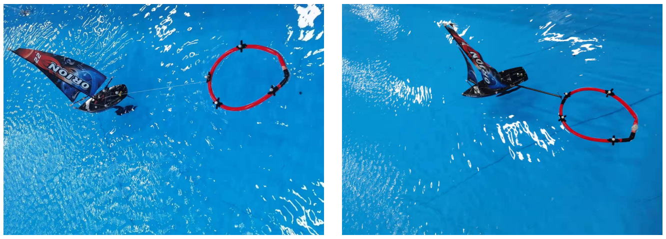


Fig. 7. Average Speed of Different Sail Angle

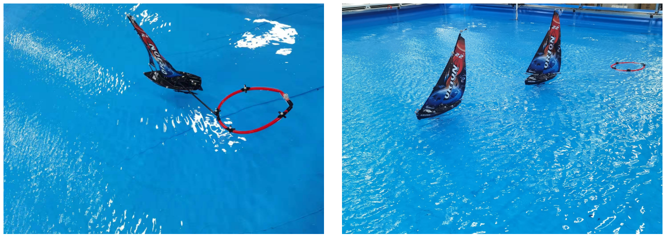
The result of the experiment is shown in Fig.7. For each attempt to use a specific main sail angle θ_1, we can calculate the average speed of the sailboat from its sailing data, and make the box plot of average speed versus θ_1. In Fig.7, for a specificθ_1, most data points fall around the mean value. A few outliners are represented by hollow dots, and they may come from the error caused by environmental disturbance. From the overall trend, the average speed of the sailboat increases with the increase of the main sail angle. In addition, it should be pointed out that the main sail angle of 48 degrees is the maximum allowed by the mechanical structure of the sailboat. From the analysis in Section II, in a stable wind field and current field, the average speed of a sailboat sailing upwind at a constant heading angle β only depends on the total driving force provided by the sails, and the two are positively correlated. Thus, we can conclude that increasing the main sail angle θ_1 to 48 degrees will provide the maximum driving force for the sailboat. To obtain as much pulling force as possible, we decided to use 48 degrees as the main sail angle to do a series of experiments in the next parts.

C. Single Sailboat Towing System Experiment

An experiment was done to test the three connection mechanisms of the single sailboat towing system using autonomous free sailing mode. The performances of the three connection mechanisms during sailing were compared and



(a) Soft Connection (b) One End Free Hard Connection



(c) Two Ends Free Hard Connection (d) Two Sailboats towing system using one end free hard connection

Fig. 8. Actual Sailing Scenarios

tested under various sailing conditions. The corresponding sailing data is recorded and stored, such as the trajectory and speed of the towing system, whether the collision occurred, and whether the tacking was successful. In this experiment, the success rate of tacking of the towing system was emphatically investigated. For the towing system equipped with each connection mechanism, we recorded 100 times of tacking attempts and counted the number of successes and failures respectively. The actual sailing scenarios of the three types of single sailboat towing systems are shown in Fig.8(a), Fig.8 (b) and Fig.8 (c).

In general, the result of the experiment shows that all three systems can successfully tow the floating object downwind or upwind. However, the system with soft connection often encountered collision events while the other two have never experienced them. Especially when the sailboat turned from the windward area to the downwind area, it was likely to hit the towed floating object. Both two types of hard connection can ensure a safe distance between the sailboat and the towed floating objects, hence many collisions were avoided. This advantage was clearly observed in the test. As for the tacking success rate, one end free hard connection significantly improved the rate and won the first prize. (see Table 1)

TABLE I

PERFORMANCES OF THREE CONNECTION MECHANISMS

	Soft connection	*Two ends free hard connection*	*One end free hard connection*
Collision Times	16	0	0
Tacking Success Rate	11/100	81/100	96/100

D. Two Sailboats Towing System Experiment

In this part, we test the performance of two sailboats towing system equipped with one-end-free hard connection mechanism, the front boat and rear boat are connected by hard rod, while the rear boat and annular floater are connected by hard rod too (see Fig.8(d)). To show the superiority of the new system over the old system in towing capability, let the two and single sailboat towing system do a set of comparative experiments. Using PID control mode, both systems are required to sail from (0, 0) to (5, 2) 10 times, and the sailing data would be recorded. Since the sail leg is identical, the maximum, minimum, and average speed of the system in the sail leg can be used as performance indicators, to show the strength of towing ability.

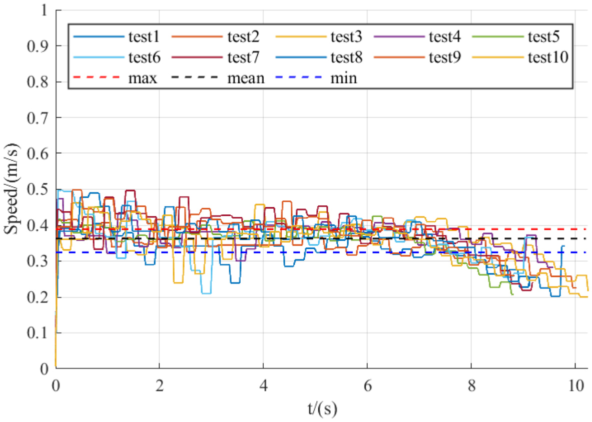


Fig. 9. Towing System's Speed Test

The result can be seen in Fig.9 and Table 2. In Fig.9, the solid lines with different colors represent the instantaneous speed in different attempts. The dotted lines of three colors represent the mean value of the maximum speed, the mean value of the minimum speed, and the mean value of the average speed of all 10 attempts. The specific values can be seen in Table 2. The two sailboats towing system can achieve higher maximum speed, minimum speed, and average speed in the same sail leg, which indicates that it has stronger towing ability.

TABLE II

SPEEDS OF TWO DIFFERENT TOWING SYSTEMS

	Max Speed (m/s)	*Min Speed (m/s)*	*Average Speed (m/s)*
Single Sailboat Towing System	0.2963	0.2301	0.2631
Two Sailboat Towing System	0.3889	0.3242	0.3626

V. CONCLUSIONS

In conclusion, the results of the experiments described above show that the towing system of the multi-autonomous sailboats we designed has more powerful towing capability than that of a single autonomous sailboat. Moreover, the new connection methods are verified in experiments and used to improve the sailboats' capacity for towing objects. In the experiment, we use the average speed of the autonomous sailboat towing system when pulling the floating objects with the same mass, rather than the mass of floating objects that can be pulled at the same speed, as the main indicator to measure the towing ability of the system. This is because it is very difficult to strictly control the speeds of sailboats to be consistent, but it is more convenient to measure the speeds. In the future, we will try to connect more sailboats in series to obtain a greater pulling force.

Our experiments reveal the potential of an autonomous multi sailboats towing system. This system has lots of advantages, such as saving manpower, and energy saving, and being environmentally friendly. It has great application prospects in the fields of transportation, environmental monitoring, the fishery industry, and so on.

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