Journal of
Marine Science and Engineering

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Sailboat Test Arena (STAr): A Remotely Accessible Platform for Robotic Sailboat Research

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Abstract: Autonomous sailing robots have attracted much attention, but challenges arise due to the sailing tests require an environment with both aerodynamic and hydrodynamic fields and a sufficient number of sailing robots in readiness. A remotely accessible platform with the advantages of low cost, easy operation and high efficiency is the preferred method to solve this dilemma. Consistent with this goal is the design of Sailboat Test Arena (STAr), a remotely accessible platform for sailing robot design verification, autonomous algorithms validation and sailing control practices. All three parts require extensive testing in real water environments. Hereby, for testers around the world, STAr can be accessed without time difference. A variety of local and remote tests have been conducted in the STAr platform at various location around the world. The results show that STAr is a remotely accessible and effective tool in data collection and skill transfer. With continuous adoption and optimization, STAr will continue to serve as a tool to further promote low-cost, high-efficiency and diverse sailing research, and provide opportunities for more people to experience sailing.

Keywords: autonomous sailing robots; Sailboat Test Arena (STAr); remotely accessible

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Citation: Sun, Q.; Qi, W.; Liang, C.; Lin, B.; Maurelli, F.; Qian, H. Sailboat Test Arena (STAr): A Remotely Accessible Platform for Robotic Sailboat Research. *J. Mar. Sci. Eng.* **2023**, *11*, 297. https://doi.org/10.3390/jmse11020297

Academic Editor: Rafael Morales

Received: 14 December 2022
Revised: 25 January 2023
Accepted: 26 January 2023
Published: 1 February 2023

1. Introduction

Sailing robots [1] are wind-driven and stand out because they are environmentally friendly, energy-efficient and noise-free. The Microtransat Challenge [2] and the World Robotic Sailing Championship (WRSC) [3] are still popular and one of the most direct ways for people to learn about sailing and experience its culture. In marine monitoring, robots such as Saildrone [4,5], SailBuoy [6], "Patí a Vela" [7] and N-Boat [8] have gradually emerged in recent years. The research on energy management [9,10] and autonomous navigation [11–16] is also booming. Moreover, digital twin technology has already been applied in marine related research, such as data collection [17] and remote control [18], and will be one of the necessary technologies in the future remote sailboat control. These developments in sailing depend on repeated testing in practice.

However, in our experience, sailing experiments in the outdoor open water environment are expensive, time-consuming and risky. The double cost and risk are main barriers to exploration for robotic sailboat researchers. In the outdoor sailing experiments, except for the high robots design and manufacturing costs, launch and recovery are two main parts of the expense. Due to the uncontrollable outdoor wind field, test often needs to wait for the proper weather conditions to be carried out. Hereby, conducting experiments in an ocean environment requires consideration to avoid channel occupancy, entanglement in fishing nets, unpredictable obstacles and even seawater corrosion. Doing experiments in the sea requires additional consideration of the maintenance cost. Therefore, it is difficult to carry out experiments for a long time and repeatedly in an uncontrollable real environment. By establishing an indoor test platform, the test environment with ideal wind field and flow field conditions can be satisfied and there is no limit of duration and experiment times. However, setting up a controllable indoor sailing experiment platform also means a high cost of space, equipment, manpower and time. Therefore, a remotely accessible and shareable sailing testbed is one of the effective ways for researchers to ease the difficulties of conducting sailing experiments and promote the battle of sailing research.

The development of remotely accessible testbeds is growing in number and variety as summarized in [19,20]. These platforms have brought great benefits to education and scientific research, and are constantly updated and improved, such as famous Duckietown [21], Robotarium [22] and RoboTurk [23]. Duckietown is an open, inexpensive and flexible tool that saves money and time for educators and researchers. A batch of researches based on Duckietown, including teach autonomy [24], robotic guide [25,26] and reproducible and accessible evaluation of robotic agents [27], etc., keep emerging. Robotarium provides users with remotely accessible facility for swarm robots, emphasizing flexibility and security. To meet the large number of testing requirements, Robotarium has been upgraded from hardware, software and algorithm to enhance the level of automation [28]. RoboTurk is a crowdsourcing platform, which supports large-scale on-demand data collection for robotic skill learning. Toward imitation learning for multi-arm manipulation, MULTI-ARM ROBOTURK [29] was presented. However, to the best of our knowledge, there is still no remotely accessible testbed for sailing robots, and existing platforms cannot be used directly.

In this paper, we elaborate the Sailboat Test Arena (STAr), a remotely accessible platform for mini-sized sailing robots as shown in Figure 1. The platform was originally proposed and built in 2016, and has since been relocated and improved. Some research attempts have been carried out on sailboat in STAr, and the research directions mainly include autonomous navigation [30–34], energy optimization [35,36], vision-based localization [37], anemometer design [38], propulsion system design [39] and battery carrying barge design [40]. These studies provide a solid foundation for our goal of providing an Internet-shared testbed to promote the development of sailing.

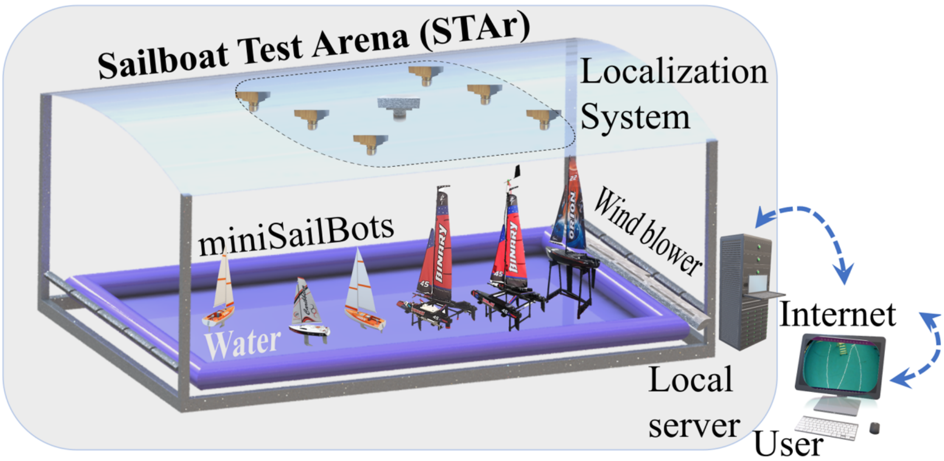


Figure 1. STAr architecture. The platform comprises of miniature sailing robots (miniSailBots), an arena including an 6 m (length) × 6 m (width) pool with 0.3 m depth water, a quasi controllable wind field, a localization system and a network server.

STAr is established with the goal of providing sailing enthusiasts and researchers with a remotely accessible, free, convenient and reliable sailing test arena. It provides three remote control modes including teaching mode, manual control mode and remote algorithm deployment mode. Setting up different modes makes it easier for testers from different backgrounds with different sailing robot driving bases to achieve their test objectives. Control operation teaching and personalized navigation are all achievable around the world. Test data and video of the whole test will be recorded. Thus, the test process is traceable, reproducible, shareable and learnable. Hereby, a navigation algorithm is designed based on Proportional-Integral-Derivative (PID) to verify the availability and effectiveness of STAr. Experiment results show that our sailing robots can reach the goal position successfully with the PID based algorithm.

This paper is organized as follows. Section 2 elaborates the design of STAr. Section 3 shows the multiple remote control modes of miniSailBots. Section 4 presents the remote experimental results and analysis. Section 5 gives the local testing experimental records. Section 6 concludes the study of STAr.

2. Design of Sailboat Test Arena (STAr)

Sailboat Test Arena (STAr) is an indoor remote Internet-accessible sailing testbed. As shown in Figure 1, STAr contains four significant parts: miniature sailing robots (miniSailBots), a pool with a wind field, a localization system and an Internet server. MiniSailBots contain different boat shapes and sizes. An array of electric fans are used to establish a stable wind field. We assume that the water flow in this platform is also stable because it is located indoors in an undisturbed environment and is only affected by a stable wind field. A motion capture system is used to realize localization function. The Internet server holds the local robots and components, the local server and user interface (UI) for remote users.

2.1. Miniature Sailing Robots (miniSailBots)

Our miniSailBots are all retrofitted from off-the-shelf sailboats and then equipped with automatic control, position and attitude information acquisition and communication capabilities. The different miniSailBots are shown in Figure 2a, including catamarans and monohull sailboats of different sizes. The types of vessels and their corresponding dimensions are miniSailBot-A (monohull, 0.260 m (length) $\times$ 0.090 m (width) $\times$ 0.435 m (height)), miniSailBot-B (catamaran with motors, 0.400 m $\times$ 0.255 m $\times$ 0.710 m), miniSailBot-C (catamaran, 0.400 m $\times$ 0.255 m $\times$ 0.710 m), miniSailBot-D (monohull, 0.465 m $\times$ 0.150 m $\times$ 0.920 m), miniSailBot-E (monohull, 0.950 m $\times$ 0.125 m $\times$ 1.470 m). The most commonly used model is miniSailBot-D, 0.465 m long, with easy steering, high speed and larger holding space for control equipment, as shown in Figure 2b. The necessary components are in blue boxes and the optional devices are in gray boxes. The red arrows are power lines. The wireless signal and wired signal lines are in blue. The control signals are with orange arrows. The FireBeetle-ESP8266 is the main control board, which contains the Wifi module for communication. "Servo sail" and "Servo rudder" are used for the execution of sail and rudder control commands, respectively. The battery supplies power to the on-board control components and is equipped with voltage and current modules to monitor its power consuming. The IMU is used to provide the attitude information. The hardware configuration supports the expansion of more sensors via IIC. Users can install motors for the sailing robots, of which miniSailBot-B is fitted.

Sail and rudder control commands come from the main control board and are used for the corresponding servo motor. The high-precision motion capture system provides rigid-body position information for miniSailBots. In this system, the position of multiple sailing robots can be obtained simultaneously and sent to the local server. The inertial measurement unit (IMU) is used to provide the attitude information of the sailing robots, including roll, pitch and yaw, of which are chosen as the control reference. Communication is achieved through the WiFi module (ESP8266), allowing the connection between miniSailBots and local server. The sailing robot equipped with motor is mainly used to study the improvement schemes of turning performance and energy optimization strategies.

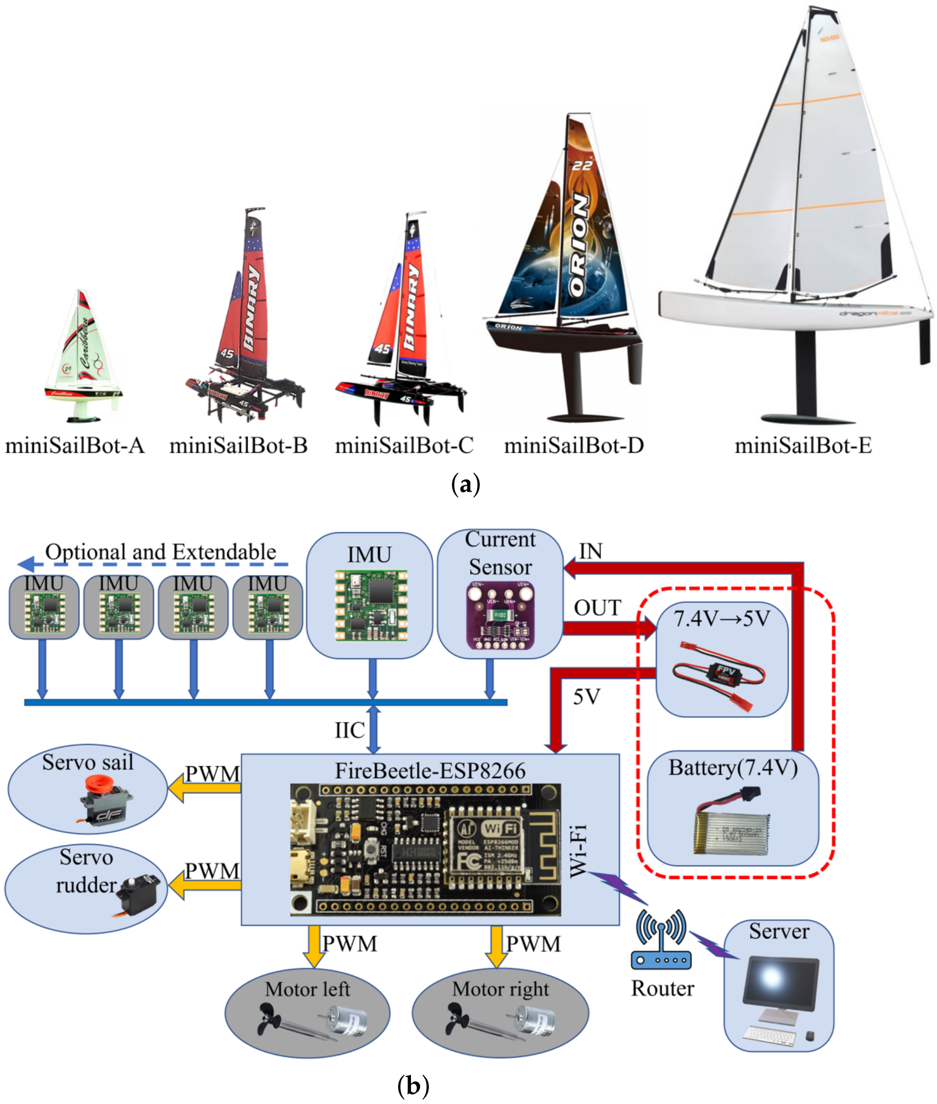


Figure 2. The miniSailBots and electronic hardware. (**a**) miniSailBots of different sizes. (**b**) Diagram of electronic hardware modification structure.

2.2. Wind Field

An ultrasonic weather station is used to collect the wind data with 12 × 11 sized observation points array as shown in Figure 3b. For each point, the test is conducted with 100 records during 20 s. The data types include time flag, wind speed, wind direction and position. The thin-plate spline method is used to interpolate the observed value, and the wind field distribution map has been shown in Figure 3a. The wind field is decreasing with the spreading distance in y-axis. When the fan is fully on, the average wind speed is close to 2.5 m/s. As shown in Figure 3b, the wind direction in different areas of the pool is conforms to the direction of the blower. Hereby, a stable quasi-controlled wind field is established.

2.3. Internet Server and User Interface

The Internet sever is established as a bridge between remote users and miniSailBots in STAr. All miniSailBots communicate with the transmission control protocol (TCP) server via Wifi. Human-robot interaction is activated where the players worldwide collect data of miniSailBoats in STAr. Figure 4 shows the Internet server framework of STAr. miniSailBots and localization system (motion capture) can be transferred via wireless communication. These data is received by TCP server that can hold the information including localization, motions, sensors and commands from miniSailBots. The main script is used to hold these information and stream to video server, file server and MySQL database. Apache and Dynamic Domain Name Server (DDNS) server are able to help the worldwide users to access miniSailBots remotely.

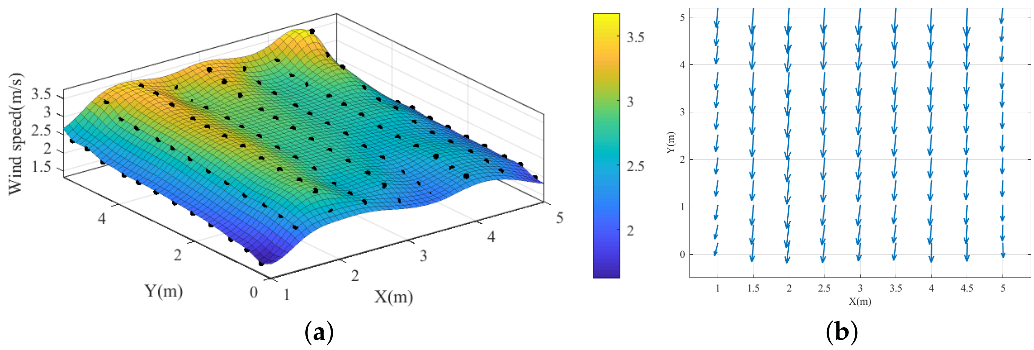


Figure 3. Wind field in STAr. (**a**) 3D wind field distribution. The black dots represent the monitoring sites. The color is used to show the magnitude of the wind speed. (**b**) display of wind direction and corresponding wind speed in the pool area.

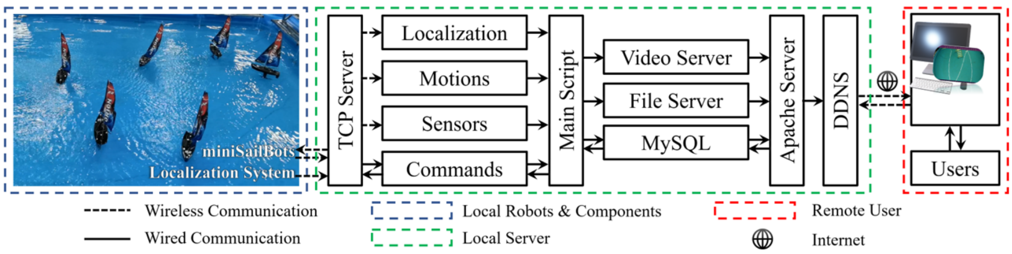


Figure 4. Internet server framework of STAr. The framework consists of local robots and devices, local server and remote users. The local server plays the part of connection between local robots and remote users.

Users can control miniSailBots from the keyboard with the example instructions on the web-page. And all data from miniSailBots is retrieved and listed on the website. From the perspective view of users, the system time-delay is approximately 100 ms$\sim$200 ms. According to our testing experience, this delay can still bring stable and smooth sailing robot control operation.

As shown in Figure 5, the numbers listed correspond to the following instructions:

(1) The STAr website is built and improved based on users' feedbacks. The homepage can be accessed via https://github.com/star-cuhksz/STAr, accessed on 29 January 2023.

(2) The top left corner is a drop-down list of key indices for the user to control the robot.

(3) In the upper right corner, through this panel, the real-time state of the miniSailbot are displayed, and users can obtain the position, speed and attitude, control signal delay and other information.

The main part in the center of the page is divided into left and right columns.

(4) The left column is a virtual pool with a static background. When the miniSailBot is sailing in the pool located at the actual test site, the corresponding position of the web page will display the small icon of the miniSailBot. Thus, users can visually perceive the position, speed and orientation of the miniSailBot.

(5) For the right column, the pull-down menu of the miniSailBots is located at the top. Only the miniSailBots checked and connected to the network by the administrator can be selected and controlled by the users.

(6) Three types of delay are shown: from user to server, between server and robot, and from server to user.

(7) The other two figures are rudder and sail commands sent by users.

(8) At the bottom of the column is the real-time video of the surveillance camera. Users can observe the actual scene of the test site through it. However, due to the large number of bytes of image data, image transmission usually has a greater delay than miniSailBot data transmission, which let the user control the robot through actual images is not always feasible.

(9) Four buttons below the virtual pool belong to the remote deployed algorithm control system of the STAr platform. "Download" button is used to download the script, and "Upload" is used to deploy script remotely. The detail of these two button will be mentioned in Section 3.3. The "Video" and "Data" button to download the video and data of the preceding experiment. Through these materials, users can check the result of the operation and further improve the algorithm.

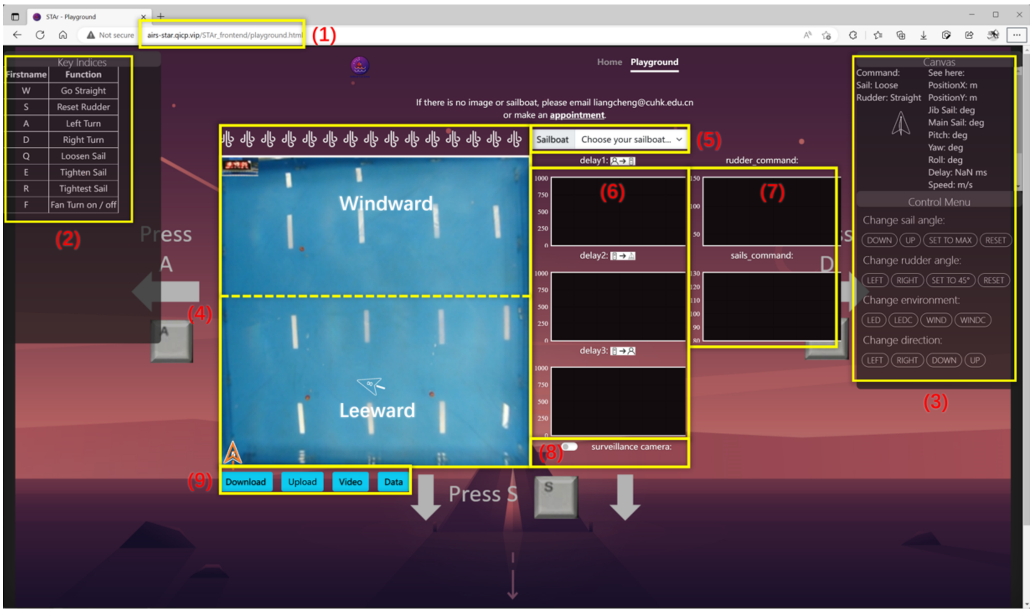
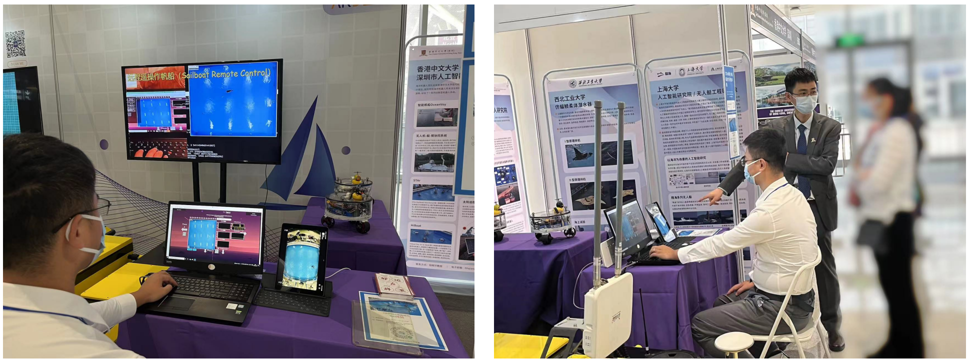


Figure 5. User interface of STAr. (1) The shared network address of STAr; (2) Key indices; (3) Information dashboard; (4) The pool region, wind direction, windward and leeward zones. (5) Selector for selecting a ready sailing robot. (6) Real-time display of delay. (7) Sail and rudder control commands. (8) Button for opening or closing the surveillance camera. (9) Buttons for remote algorithm deployment.

3. Multi-Mode Human-Robot Interaction

STAr offers three types of remote testing approaches, including teaching mode, manual control mode and algorithm deployment mode. These patterns allow users to control for different purposes. The remote teaching mode provides assistance for users who are not familiar with sailing to quickly grasp the operation essentials. It is stable and therefore a fast way to collect data. Sailing robot enthusiasts and researchers practice manual operation in remote manual control mode. The operator's own basic conditions are uneven, so the control performance is also different. STAr has been shown to visitors and provided them with experience at various technical conferences. As shown in the Figure 6, it is one of the technical conferences. Overall, the platform inspires both newcomers and those familiar with sailing to experience remote control. For advanced users or researchers, they can also deploy algorithms remotely and test their feasibility and effectiveness.



(**a**) (**b**)

Figure 6. Remote control from the exhibition hall of China National Computer Congress 2021. (**a**) STAr's control interface display and remote control demonstration. (**b**) Visitors watch the remote control process and experience the control of a real sailing robot.

3.1. Remote Teaching Mode

In this mode, the miniSailBots are controlled by commands from the Internet server. It is impractical to assume that all users are skilled sailors, so an automated operation demonstration is necessary. The remote teaching mode helps users quickly master the basic skills of control. When this mode is turned on, a miniSailBot immediately starts sailing following the given sample program while the automatic data collection is enabled without human intervention. Users can check the status of the robot and the corresponding operation command in the information panel, so as to quickly master the control operation and choose the appropriate route. The sailing route under the remote teaching mode is carefully selected by the administrator in advance. As shown in Figure 7b, the task of repeatedly switching from leeward to windward within the virtual boundary is considered the best demonstration task, as it comprehensively demonstrates how miniSailBot can sail at various angles to the wind.

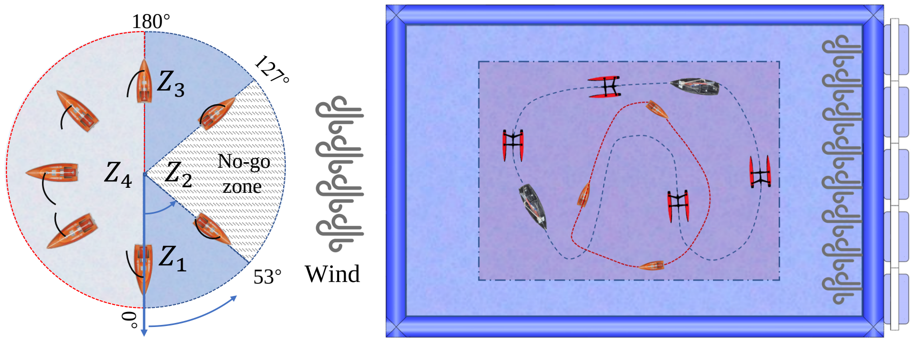
3.2. Remote Manual Control Mode

This mode allows users to manually navigate or take a race in the STAr. In this process, miniSailBot navigation is controlled according to the control command from the user, and all operations and even complex control strategies can be recorded. Sail control commands include "Loosen Sail", "Tighten Sail" or "Tightest Sail". "Left Turn" or "Right Turn" key operate the heading control. When the rudder command is released, it turns back to neutral state. The operational records from professional sailors can be used by other users for reference or for reinforcement learning.

The principle of adjusting sails according to the calculated angle of attack at a fixed wind direction and heading is shown in Figure 7a, which is recommended to testers for a better experience. Z_1 and Z_3 are port tack and starboard tack with "Tighten Sail" state, respectively. In Z_2, the sail keeps "Tighest Sail" from shaking due to the no-go zone. Z_4 is in jibbing with "Loosen Sail" state. In no-go zones, sailing robots cannot gain propulsion and can be dangerous in harsh conditions. Therefore, users need to understand the area range of all kinds of sailing robots and avoid sailing in this zone.

3.3. Remote Algorithm Deployment Mode

Moreover, for users who are familiar with sailing and have higher requirements, the algorithm can be deployed to our server through the "Upload" button to verify the feasibility and effectiveness of the navigation control strategy. The platform provides the application programming interface (API) for algorithmic deployment and a demo script where users are allowed to modify only parts of the script. After the script is uploaded to the STAr server, the administrator checks whether the script is illegal before running it for security reasons.



(a) (b)

Figure 7. Points of sail and path examples. (**a**) Different sail modes have been adopted in different zones. The wind blows from the right-hand side. (**b**) There are two path examples. The darker rectangle represents the active sailing zone. The wind direction is from right side.

By clicking the "Download" button, users can download a copy of the python script code prepared by the administrator to their computer. This python script code shows the API for controlling miniSailBot's rudder and sails and for reading the robot's sensor instructions. Users can write code, call the corresponding API, and add their own developed algorithms to realize the control of miniSailBot. After editing the script, users can click "Upload" to upload the script. For security reasons, the full access can not be authorized to run the the script automatically. After completing the code review, the administrator will run the script to control miniSailBot, complete the navigation experiment, and record relevant data and images. After the experiment is over, the administrator will notify the user, and the user can click the "Data" and "Video" buttons to view.

4. Remote Testing Experiments in STAr

A series of experiments have been conducted to show the capability of STAr platform. Experiments include sailing in remote teaching mode, remote manual control mode and remote algorithm deployment mode as elaborated in Section 3.

In the remote tests, to ensure the flexibility and stability of the control, miniSailBot-D is chosen as the test sailing robot in this section. As stated in Section 2.1, miniSailBot-D has the most appropriate length for the pool and is more maneuverable.

4.1. Remote Control by Practiced Researchers

This test is held in different cities (between Shenzhen and Huizhou) in Guangdong Province, China. A practiced researcher accessed the STAr in Shenzhen from Huizhou and conducted a remote test for more than 18 min. In Figure 8, to more clearly show the path and robot orientation, only a section lasting about 3 min was captured. It can be seen that the tester can obtain the corresponding smooth path according to the navigation target.

4.2. Remote Control by New Testers

Three participants in this part of the experiments are from Jacobs University Bremen, Germany. They had their first experience of remote sailboat control, and completed the remote tests after learning the control operation of STAr. These tests were done over the Internet between China and Germany. There was no specific route goal but the instructor encouraged testers to speed up in a straight line and perform tacking smoothly.

From Figure 9, it can be seen that the tester 01 is sailing in a nice path. The tester realizes sailing from leeward to windward repeatedly. Besides, the maximum velocity is 0.8 m/s.

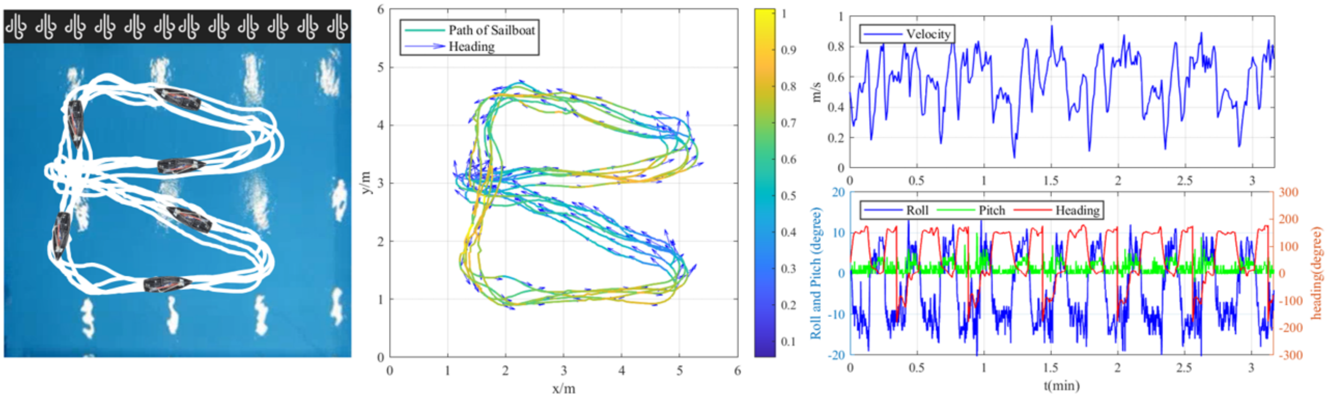


Figure 8. A remote sailing test in STAr by a practised researcher. The left picture shows the wind direction and sailing path in real test environment. In the middle figure, the path is added with arrows to represent the heading and color-bar distribution to distinguish the speed magnitude. The right figures are velocity and attitude versus time.

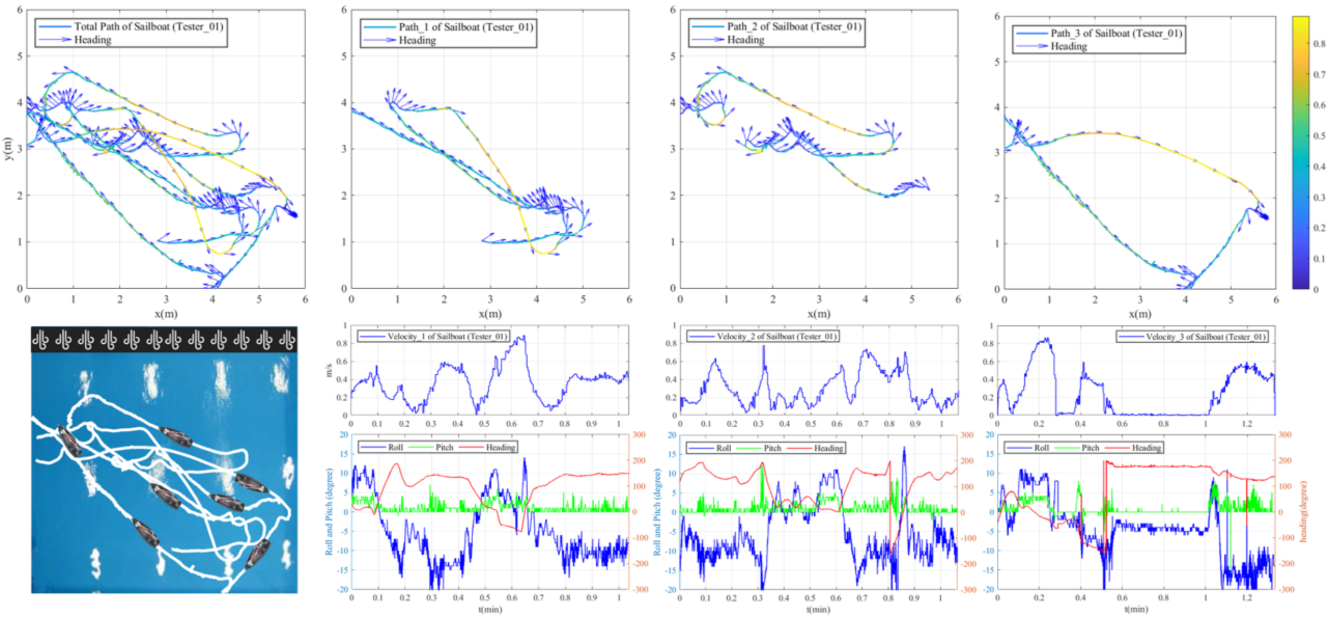


Figure 9. Remote sailing test (tester 01) in STAr. The leftmost figure of the first row and the remaining three figures are the total sailing path and the segmented paths, respectively. The arrow in the path indicates the heading. The graph in the second row is the path in the real test environment corresponding to the figure in the first row. The remaining three diagrams all contain the speed, roll, pitch and heading of the corresponding path.

For tester 02 in Figure 10, Path_1 shows a failed tacking, a successfully tacking motion and a downwind turn, respectively. Path_2 shows two parts of downwind turns. Path_3 fails to tack twice and Path_4 has a good tacking. From the velocity figure, the maximum velocity is just over 6 m/s.

For tester 03 in Figure 11, Path_1 is a good tacking motion. Path_2 begins with a tacking and then a downwind turn. After that, another trace execution fails. Path_3 shows a nice sailing record. The tester performs tacking and jibbing several times. Moreover, sailing from leeward to windward was achieved successfully.

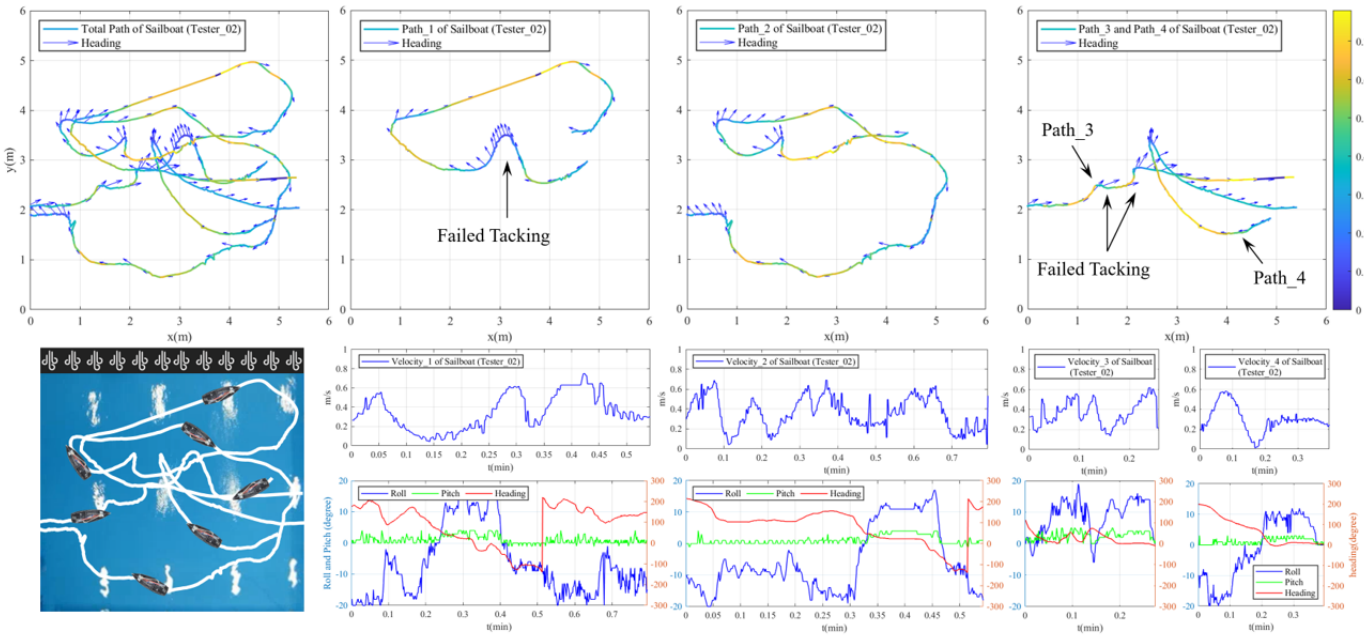


Figure 10. Remote sailing test (tester 02) in STAr. The content contained in the figure and its ordering correspond to that of tester 01.

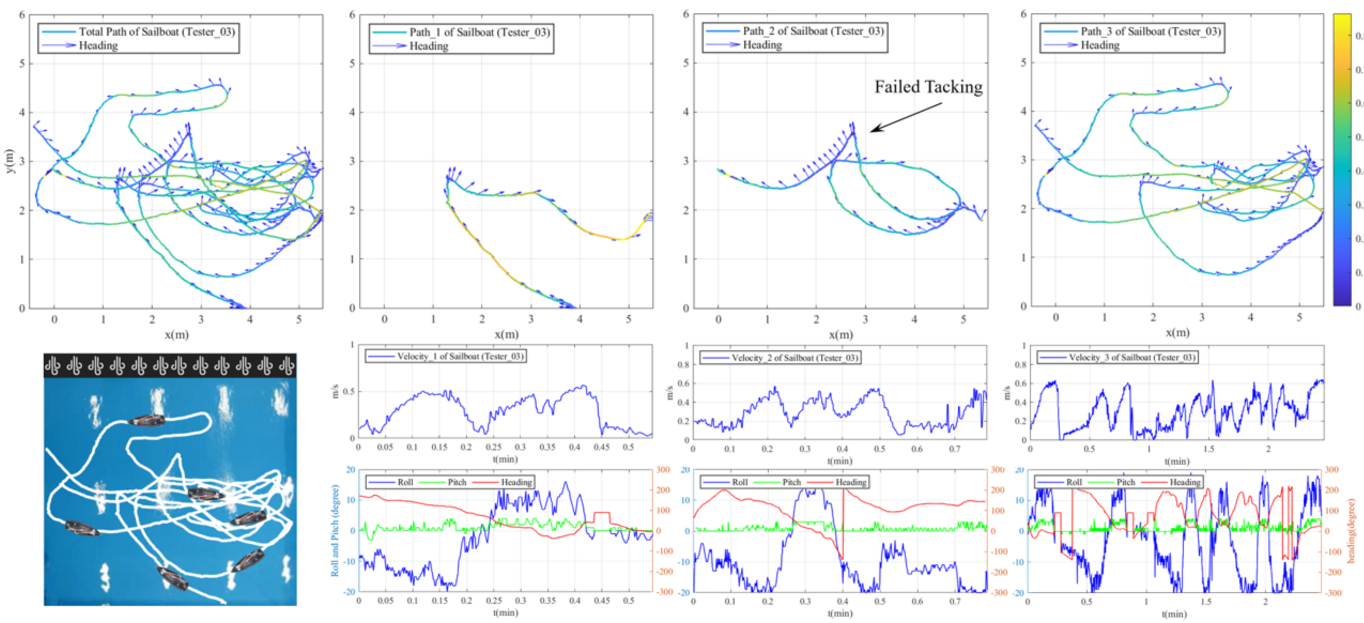


Figure 11. Remote sailing test (tester 03) in STAr. The content contained in the figure and its ordering correspond to that of tester 01 & 02.

From these three experiments, the remote control of STAr can be operated by unfamiliar users in several minutes. According to the teaching process, it takes about 1 min for testers to master the operation. Therefore, the sailing robot is easy to control, runs smoothly, and the control delay is as small as we expected.

Besides, more remote control tests are conducted from Carnegie Mellon University and University of Pennsylvania in the United States and The Chinese University of Hong Kong in China. All testers were able to control the robot stably for more than 10 min, with an average acceptable control delay of about 200 ms. So far, we have collected over 1000 h of miniSailBots data in STAr.

4.3. A Remote Testing Example with Teaching Mode

In this phase, the sailboat turns according to the virtual boundary. As shown in Figure 12, the path is smooth and beautiful, with several reciprocates between left side and right side. The maximum speed is about 0.6 m/s. It can be seen from the roll and pitch curves that the robot sails in a stable posture, and the variation trend of the corresponding speed is basically the same. Therefore, the remote automatic control under the teaching mode is stable and repeatable. The teaching mode can also be used as a tool to automatically control the sailing robot when the user is away or off-line.

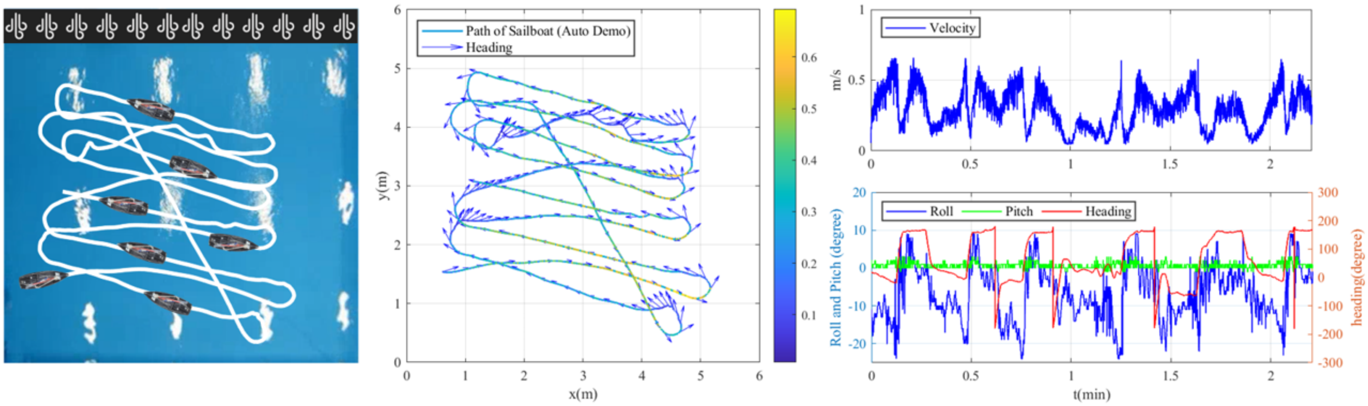


Figure 12. Automatic control in remote teaching mode. The left picture shows the path and wind direction in real test environment. The middle figure is the path of the sailboat with heading arrow and speed color-bar. The right figures are velocity and attitude versus time.

4.4. Remote Testing with Deployed Algorithm (PID)

In this test, a demonstration of a PID controller is performed in navigation. As shown in Figure 13, different colors correspond to the different target points. For each test, the sailboat starts from original point around (5.5, 0) and sails towards the target points, including (1.0, 1.5), (1.0, 2.0), (1.0, 2.5) and (1.0, 3.0), respectively. In the results, the miniSailBots can reach their targets successfully. It validated the remote test based on the deployed algorithm as expected.

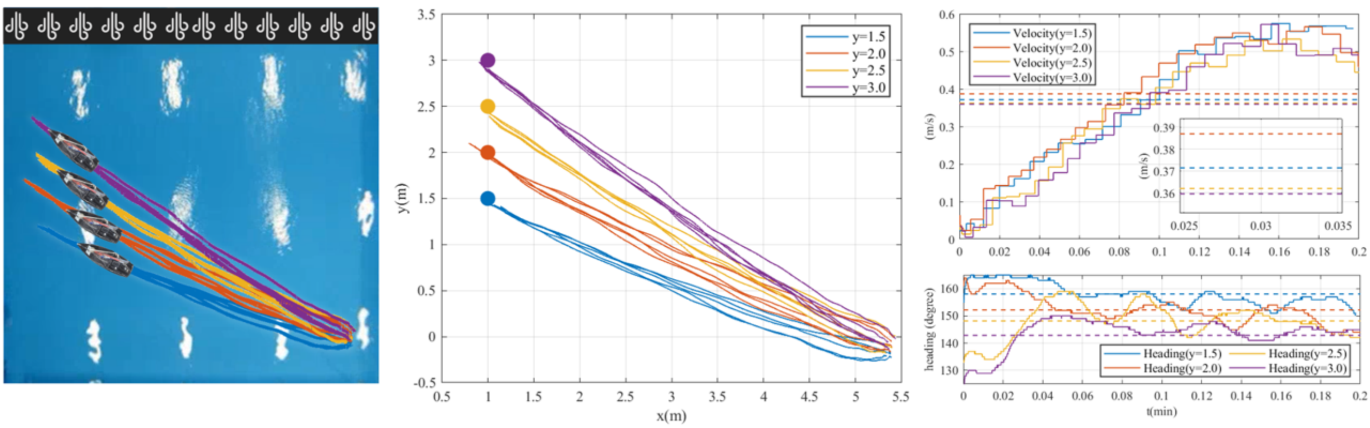
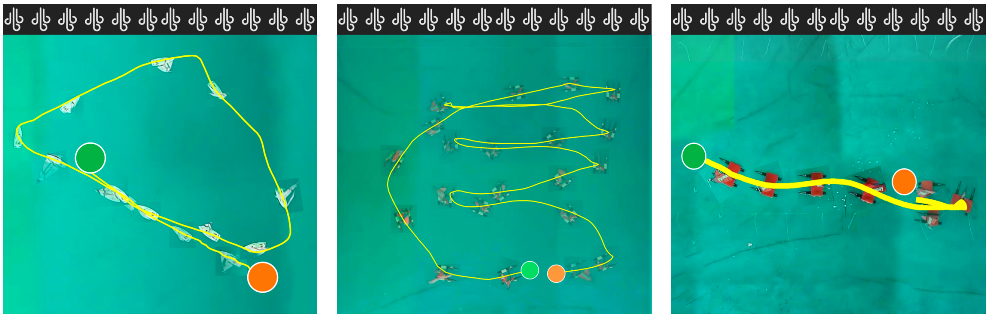


Figure 13. Remote algorithm deployment (PID) about sailing testing in STAr. The test is performed by using different given points (x = 1.0; y = 1.5 2.0 2.5 3.0). The left picture shows the path and wind direction in real test environment. To distinguish different target point, The blue, red, orange and purple represents the above given tests, respectively. The middle figure is the path of the sailboats and their target points. The right figures are velocity and heading versus time, and the dotted lines represent the average velocity and heading.

Except conducting the remote control directly, more API are proposed for users to implement. A demo script can be download by users. According to the API, users can modify the script as they want. It can give a higher authority and privilege than before. In this mode, the users' imagination can be stimulated.

5. Local Testing Experiments in STAr

From the initial phase of STAr to this current improved version, a number of research topics have been completed on it, including a lot of local tests to validate the abilities of STAr. Some comparisons among miniSailBot-A, miniSailBot-B and miniSailBot-C with automatic control has been done and the sample sailing trajectories have been shown in Figure 14. The quantization results have been displayed in Table 1. Intuitive comparison of indicators including sailing distance, speed, energy consumption, etc., can be used as a reference for the selection of robot type.



(**a**) (**b**) (**c**)

Figure 14. Local testing experiments. (**a**–**c**) are automatic sailing with miniSailBot-A, miniSailBot-B and miniSailBot-C, respectively.

Table 1. Performance of miniSailBots in STAr.

Name	[1] **Dis** (m)	$\bar{v}$ (m/s)	v_{max} (m/s)	E (J)	t (s)	E/t (W)	E/Dis (J/m $\times$ 10^{-2})
miniSailBot-A	35.75	0.31	0.59	531	120	4.43	0.15
miniSailBot-B	100.32	0.27	0.61	2727	360	7.58	0.27
miniSailBot-C	8.70	0.07	0.17	253	111	2.28	0.29

[1] **Dis** means the total distance. $\bar{v}$ is the mean sailboat velocity. v_{max} is the maximum sailboat velocity. E is the energy consumption. t is th test time duration. E/t is the average power during the testing. E/Dis is the energy cost divided by the total displacement.

Comparison of sailing performance of three types of miniSailbots:

- The miniSailBot-A is a monohull sailboat, which is flexible and fast. From Table 1, miniSailBot-A runs fast. $\bar{v}$ is bigger than miniSailBot-B. This is reasonable because the motor in miniSailBot-B is only used as an aid to tracking.
- Equipped with propellers, miniSailBot-B can run even faster. For example, the $\bar{v}$ value of miniSailBot-B is greater than miniSailBot-C. The electromechanical auxiliary system can improve the performance of the catamaran (such as miniSailBot-C). The maximum speed is the largest of the three robots. $\bar{v}$ is close to that of miniSailBot-A.
- From the $\bar{v}$ and v_{max}, miniSailBot-C has low mobility. Due to its large base, the robot can not turn (tacking) by novices in most cases. Thus, it is more challenging than other sailboats.
- From the E/t and E/Dis value, it can be analyzed that miniSailBot-A is an energy-saving robot and has better maneuverability in this scenario.

Moreover, the previous work as given in Figure 15 shows that STAr can help researchers to verify and validate the their topics.

As shown in Figure 15a, the hybrid catamaran sailboat was strengthened to improve the tacking success rate. The rational use control strategy of propeller of hybrid catamaran is studied [35].

As shown in Figure 15b, a force polar diagram (FPD) method is used to obtain an optimal sail angle [30]. It helps catamarans turn easily.

In Figure 15c, a collision avoidance scheme for autonomous sailing robot problem is studied by using the racing rule of sailing (RRS) [32]. The proposed method is validated in STAr.

From Internet-shared STAr platform, a quantity of the historical data is collected. The Q-learning is delicately designed to train the reinforcement learning model based on the history data [33]. The trained model can be used to control the sailing boat to reach the target successfully in the windward direction, as shown in Figure 15d. This demonstrates the STAr platform's ability to learn from data.

Figure 15e depicts an enhanced autonomous sailboat towing with a battery barge [40]. The results shows the effectiveness of this system for prolonging the sailing time and extending the sailing distance.

Figure 15f is a station keeping example conducted in STAr with a miniSailBot-E [34].

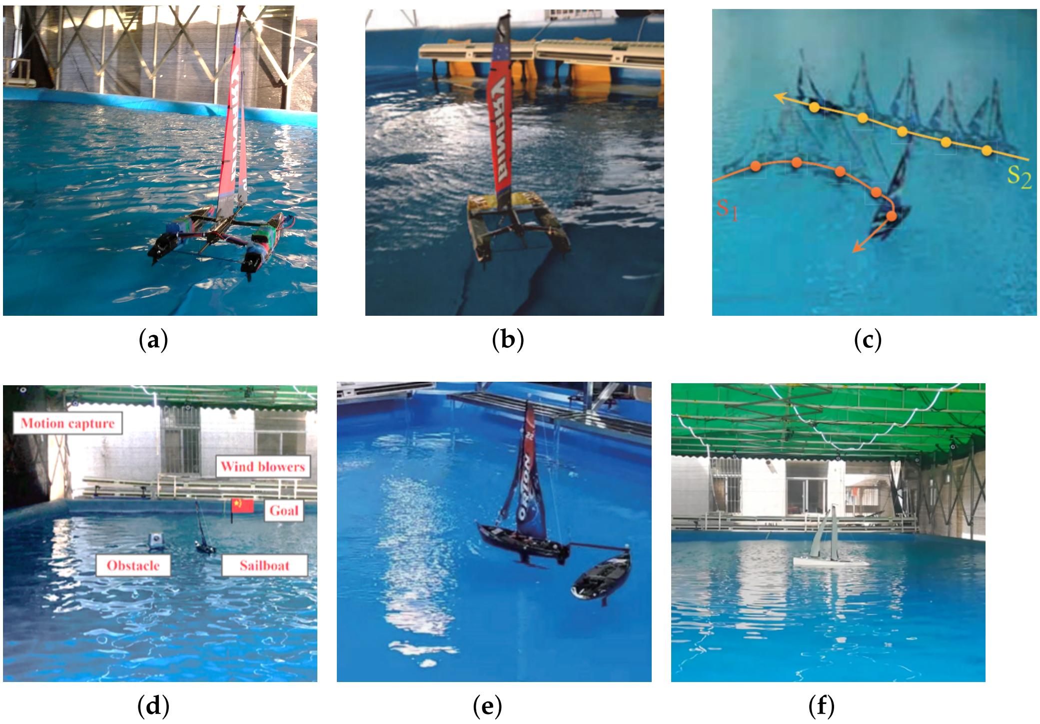


Figure 15. Previous works. (**a**) Automatic sailing with miniSailBot-B. (**b**) Automatic sailing with miniSailBot-C. (**c**) Collision avoidance by racing rule of sailing (RRS) with miniSailBot-D. (**d**) Collision avoidance by reinforcement learning (RL) with miniSailBot-D. (**e**) Enhanced autonomous sailboat with miniSailBot-D. (**f**) Station keeping with miniSailBot-E.

6. Conclusions

In this paper, STAr, a shareable, inexpensive, easy operated, efficient and remotely accessible test platform for research of sailing robots is introduced. The remote testing experiments with three designed remotely accessible modes show the potential of remote control for sailboats or other marine robots. From the local experiments, it can be found that various research topics have been conducted in STAr. Through a large number of local and remote experiments, the feasibility, robustness and high efficiency of STAr have been verified.

STAr contributes to provide a remote control solution for sailing robots and an open platform for researchers to access. All relevant materials can be found at https://github.com/star-cuhksz/STAr, accessed on 29 January 2023.

It can aspire to be and is becoming a testbed, remotely linking sailing robots' tests in real environment and research to improve the research efficiency of autonomous sailing. It can also enlighten the researchers to implement their various ideas timely.

With the continuous update, STAr is becoming more complete and stable. We have also built the surrounded wind fans and wave generator to simulate the vary wind direction and wave environment. However, there are still some important environmental elements needing to be considered, such as quasi-controlled currents, open water area, different depth of water, etc.

In the future, we will focus on improving the auxiliaries of STAr to meet different simulation scenarios in real environment. Besides, the remote control, digital twins and virtual models are the trends in robotics research and development. Based on these, we believe that STAr platform will bring more opportunities and development to the robotics community in the field of marine robotic research.

Author Contributions: Conceptualization, Q.S., W.Q., C.L. and H.Q.; methodology, Q.S., W.Q., C.L. and H.Q.; software, Q.S., W.Q., C.L. and H.Q.; validation, Q.S., W.Q., C.L., B.L., F.M. and H.Q.; formal analysis, Q.S., W.Q., C.L. and H.Q.; investigation, Q.S., W.Q., C.L. and H.Q.; resources, Q.S., W.Q., C.L. and H.Q.; data curation, Q.S., W.Q., C.L., B.L. and H.Q.; writing—original draft preparation, Q.S., W.Q., C.L., B.L. and H.Q.; writing—review and editing, Q.S., W.Q., C.L., B.L. and H.Q.; visualization, Q.S. and W.Q.; supervision, H.Q.; project administration, H.Q.; funding acquisition, H.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is partially supported by Project U1613226 and U1813217 from NSFC, China, Project AC01202101105 from Shenzhen Institute of Artificial Intelligence and Robotics for Society, and Project KQJSCX20180330165912672 and University Stability Support Program from Shenzhen Science and Technology Innovation Commission, China.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

STAr	Sailboat Test Arena
WRSC	The World Robotic Sailing Championship
PID	Proportional-Integral-Derivative
RL	Reinforcement Learning
miniSailBots	Miniature Sailing Robots
IMU	Inertial Measurement Unit
TCP	Transmission Control Protocol
DDNS	Dynamic Domain Name Server
API	Application Programming Interface
FPD	Force Polar Diagram
RRS	Racing Rule of Sailing

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