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Novel Rigid-Wing Bi-Directional Sailboat Design and Method of Sailing

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***Abstract*— This paper proposes a novel design of rigid-wing bi-directional sailboat and its method of sailing. The proposed design features a bi-directional hull, a rudder on both ends of the vessel and a freely rotating rigid wing sail whose angle of attack is controlled by a tail rudder. The proposed method of sailing involves reversing the vessel's travel direction at every turn and is ideal for micro-scale autonomous robotic platforms as it overcomes the difficulty in turning the boat through the eye of the wind during an upwind sail. A simulation model using aerodynamic and hydrodynamic forces is developed to test the effectiveness of the proposed design and method of sailing and compared to the traditional method of sailing in station-keeping and sailing upwind scenarios. The effectiveness of the proposed method is demonstrated with a prototype model equipped with a rigid wing sail.**

I. INTRODUCTION

There is a growing need for small sensor-equipped autonomous platforms for water bodies for collection of data in studies such as environmental monitoring and oceanographic monitoring [1]–[6], and applications such as safety and security [7]. Most Unmanned Surface Vehicles (USVs) rely on electric motor or gasoline engines for propulsion which means their range and endurance are limited by their on-board energy storage, while these platforms benefit from higher travel speed and increased maneuverability.

The key to long range and endurance is to rely on natural energy resources such as wind and solar. Wind-propelled vessels or sailboats have been used by mankind for more than 5000 years [8], and in recent years wind-propelled USVs have received increased interest from researchers and the industry [4], [6], [10]–[14].

Traditionally, cloth or flexible materials have been used to form the sail which has benefits [9] [10] such as ability to conveniently stow when not in use, ability to reduce in area easily, ability to change shape and camber by changing tension of control lines, and easy repairability or modifications. They also have several drawbacks such as being prone to wearing and tearing, control lines breaking or jamming, requiring rigid spars and wires to maintain their shape and having different angles of attack at different points on the sail due to twisting resulting in reduced sailing efficiency.

Rigid wing sails have increased in popularity owing to having several benefits [9] [10] such as having increased lift to drag ratio, increased efficiency for traveling downwind, better reliability from lack of problems such as sail luffing or flapping, not requiring additional structure for support and ability to orient it directly to the wind for minimal aerodynamic forces.

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Fig. 1. Proposed novel design of micro-scale sailboat, featuring a bi-directional hull and a freely-rotating rigid wing sail.

Most unmanned sailboats are designed for sea-use, hence their hulls are large and heavy enough to withstand tough conditions in the ocean. Their hulls could be from 0.72m long [15] to 1.5m long [9] with wingsails as tall as 0.5m to 1.3m [10]. These vessels are designed to operate in conditions with winds up to 30 kn (15.43m/s) in open seas.

Generally, there is growing interest in making smaller or micro-sized robotic platforms due to advancement in actuator and sensor technologies. Smaller platforms usually cost lower hence they can be produced in large quantities and they are more conveniently transported and deployed. They can be easier to maintain and repair as well. However, sailboats cannot be designed too small as they must withstand harsh environmental conditions in the open sea and also be large enough to not be ingested by large marine animals. For deployments or data collection within closed waters such as lakes and reservoirs, USV platforms can be designed smaller.

In this work, we propose a micro-scale sailboat which is designed for deployment in closed waters. One of the challenges of micro-scale sailboats is the lack of momentum as they have small mass and operate at low speeds. Typically, sailboats travel upwind using a sailing method called tacking or beating whereby the boat turns through the eye of the wind back and forth in order to progress upwind, creating a 'zig-zag' course [16]. As sailboats turn into the eye of the wind,

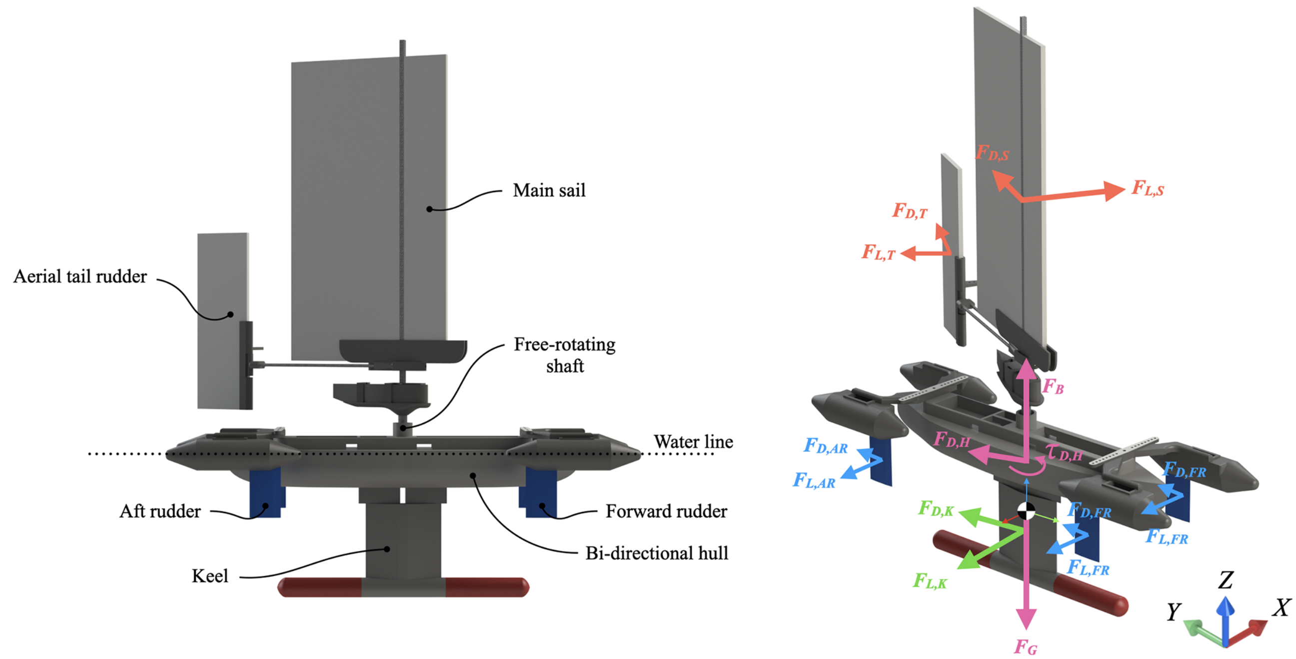

Fig. 2. Left: Components of the proposed design concept featuring bi-directional hull. Right: Free body diagram showing various forces acting on the sailboat, the body frame and the world frame.

they rely on their accumulated momentum to change their course of direction as the sail is also shifted to produce an opposite aerodynamic force. The novel design of sailboat, shown in Fig. 1, and method of sailing proposed in this work is intended to overcome this challenge for micro-scale sailboat platforms. It overcomes this challenging upwind maneuver by reversing the hull's travel direction at every turn in the 'zig-zag' course, instead of relying on accumulated momentum to turn the boat into the eye of the wind. For this method to work, the vessel is equipped with a rudder on both ends, a feature that is not common in most sailboats.

The contributions of this work are as follows -

- We propose a novel design featuring a bi-directional sailboat and method of sailing, intended for micro-sized sailboat platforms which have small mass and travel at slow speeds. A dynamic model of this platform is derived.
- Based on the dynamic model, we make several simulations of the proposed platform, including a polar plot, station-keeping maneuver and sailing upwind, whereby the Bi-Directional Sailing (BDS) method is compared to the traditional sailing method.
- A prototype is built based on the proposed design to verify the performance of the proposed sailing method.

II. Design Concept and Dynamic Model

In this section, we will elaborate on the design concept and derive the free body diagram of the proposed design.

A. Design Concept

The design concept comprises of a bi-directional hull, a forward and aft rudder system and a freely-rotating rigid wing sail with tail rudder, as shown in Fig. 2.

The hull's design features symmetrical ends on the forward and aft, as it is intended to travel in either direction with equal efficiency. The hull houses the main electronics such as microcontroller, sensors and battery. It also houses servo(s) that control the rudders. A keel is attached to the bottom of the hull. The purpose of the keel is to provide a low center of gravity which improves its stability. The keel is an ideal place to put high density components such as battery and also sensors for data collection purposes.

As the vessel is intended to move in either direction, a rudder is needed on both ends of the vessel. Depending on the number of actuators the vessel is equipped with, the two rudders can be controlled in tandem by a single actuator or they can be independently controlled by one actuator each. In the case with one actuator, the rudders connected in tandem work together effectively decreasing the turning radius of the vessel.

The sail is a rigid-wing sail and it is free to rotate about its vertical axis. It consists of a main sail and a tail rudder. The latter is responsible to generate aerodynamic forces which produce a torque which controls the angle of attack of the main sail. An actuator, embedded to the sail assembly, controls the angle of attack of the tail rudder. The mast is aligned to the quarter-chord of the sail where the aerodynamic forces are assumed to act on for flat plate airfoils. Hence, the aerodynamic forces acting on the main sail itself may not generate torque to rotate itself.

The center of gravity of the vessel is below the center of buoyancy, such that it is dynamically stable under windy conditions.

B. Free Body Diagram

The aerodynamic forces acting on the main sail and aerial tail rudder, and the hydrodynamic forces acting on the keel and the dual rudders can be modeled using lift and drag equations below -

$$F_L = \frac{1}{2}\rho U^2 C_L A \tag{1}$$

$$F_D = \frac{1}{2}\rho U^2 C_D A \tag{2}$$

where F_L and F_D are lift and drag forces respectively, C_L and C_D are lift and drag coefficients respectively and ρ is the density of the fluid and A is the surface area of the airfoil interacting with the fluid. The angle of attack of each airfoil component can be found from their interaction with the surrounding in the world frame as shown in Fig. 3. For main sail, aerial tail rudder and underwater dual rudders, γ is the actuated angle, ζ is the apparent fluid flow angle with respect to the zero line of the airfoil, α is the apparent angle of attack of the airfoil and U is the velocity of the fluid with respect to the airfoil.

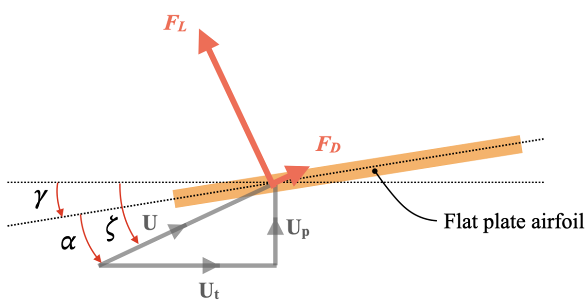

Fig. 3. A cross-section of an airfoil interacting with surrounding fluid, generating lift force F_L and drag force F_D.

The forces acting on the various components of the sailboat are shown in Fig. 2 where subscripts S stands for for main sail, T stands for tail rudder, K stands for keel, FR and AR stand for forward rudder and aft rudder respectively, F_G and F_B stand for gravitational force and buoyancy force respectively, $F_{D,H}$ and $\tau_{D,H}$ are the force and torque acting on the hull due to drag from water. $F_{D,H}$ is defined as -

$$F_{D,H} = F_{D,X} + F_{D,Y} \tag{3}$$

where $F_{D,X}$ are $F_{D,Y}$ are drag forces on the hull in body frame X and Y directions respectively. The drag forces can be further defined as $F_{D,X} = -k_x v_x$ and $F_{D,Y} = -k_y v_y$, where k_x and k_y are drag coefficients and v_x and v_y are the vessel's velocities in the respective direction. The torque can be defined by $\tau_{D,H} = -k_z \omega_z$ where k_z is the coefficient and ω_z is the rotational velocity of the vessel.

Next, we can derive the equations of motion for the sailboat. To make a simplified model, we make an assumption that the hull is completely stable and vertical at all times. Hence, only its motion in $\boldsymbol{x}$ and $\boldsymbol{y}$ axes, and its rotation about its $\boldsymbol{z}$ axis need to be defined as follows:

$$\begin{cases} m\ddot{x} = F_{S,X} + F_{T,X} + F_{K,X} + F_{R,X} - F_{D,X} \\ m\ddot{y} = F_{S,Y} + F_{T,Y} + F_{K,Y} + F_{R,Y} - F_{D,Y} \\ I\ddot{\theta} = \tau_R - \tau_{D,H} \end{cases} \tag{4}$$

where m is the total mass and I is the moment of inertia of the sailboat. Subscripts X denote the resolved forces along $\boldsymbol{x}$ direction and subscripts Y denote the resolved forces along $\boldsymbol{y}$ direction from the respective components of the sailboat. τ_R is the contribution of torque from the set of rudders from both forward and aft. θ stands for the heading angle of the boat. This dynamic model is used for the simulation in the following section.

III. Simulation

In this section, we describe how the simulation is setup and discuss the simulation results.

A. Simulation Setup

In order to predict the behavior of the proposed platform, a simulation is setup using MATLAB Simscape Multibody. Various rigid bodies representing the components of the sailboat are created. The model is constrained to a 2D plane, hence gravity force and buoyancy forces are assumed to be equal and opposite, and no roll and pitch motions of the vessel are considered for the simulation. Using rigid transform and transform sensor blocks in Simscape Multibody, the relative velocities of each airfoil components with respect to the world frame can be measured to compute lift and drag forces individually. The water body is assumed to be still, hence no velocity is considered from water currents. Wind is assumed to be blowing in a single direction at a constant velocity throughout each simulation.

They aerodynamic and hydrodynamic forces are modeled in the simulation according to Eqn. (1) and (2). For flat plate airfoils, the forces are assumed to act on the quarter-chord location. As the vessel is designed to travel in either direction, forces act on either forward or aft quarter-chord locations on the keel and the rudders with respect to the movement of the vessel in the water. The coefficients of lift and drag C_L and C_D are taken from flat plate airfoil database [17] using a lookup table with respect to angle of attack α.

TABLE I
TABLE OF SIMULATION PARAMETERS

Parameter	Value
Sail chord and height	80mm x 180mm
Aerial Tail Rudder chord and height	55mm x 85mm
Keel chord and height	50mm x 85mm
Rudder chord and height	16mm x 60mm
Weight	240g
k_x, k_y, k_z	0.1, 0.025, 0.002

The aerial tail rudder and dual rudders are controlled using PID controllers. For the aerial tail rudder, the gains are manually tuned such that the desired angle of attack of the main sail is achieved, with minimal oscillations and steady

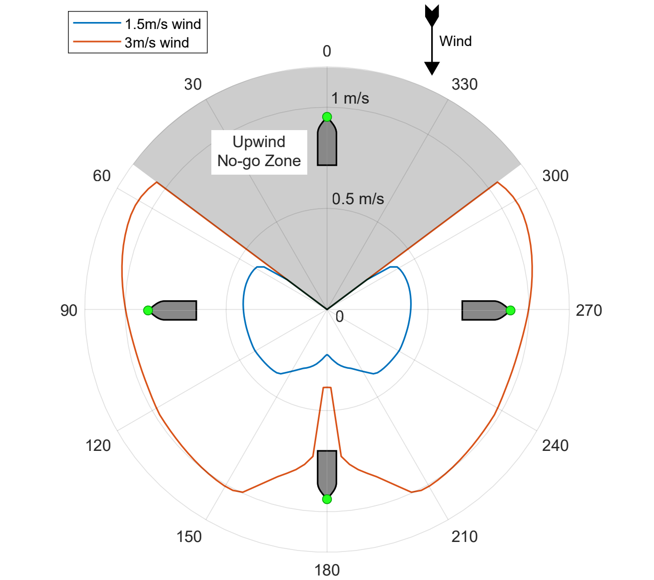

Fig. 4. The polar plot of proposed vessel obtained from simulation at two wind speeds, 1.5 ms^{-1} and 3 ms^{-1}.

state error. For the dual rudders, the gains are tuned such that the desired heading of the boat is achieved, with minimal oscillations and steady state error. The drag coefficients are manually set such that the vessel moves similarly to its real-life counterpart. The parameters set for simulation are shown in Table I.

B. Simulation Results

1) Polar Plot: A polar plot shows the speeds with respect to direction in which a sailboat can travel given a wind condition. The polar plot of the proposed vessel is obtained by simulating the model to travel in all directions until steady state velocity is reached with constant wind speeds of 1.5 ms^{-1} and 3 ms^{-1}. The plot is given in Fig. 4. It can be seen that the vessel is able to travel the fastest about 60 degrees with respect to the direction of incoming wind. It is not able to move directly towards the wind and it is also slow to move directly away from the wind. It is found to be most effective to move sideways to incoming wind, as it is the case with most sailboats.

2) Station Keeping: The Bi-Directional Sailing (BDS) method makes it easy for station keeping, which is demonstrated in this simulation. Traditional sailboat USVs are also able to station keep but it requires them to move in a pattern similar to figure '8', while maintaining enough momentum for a turn, resulting in larger footprint. For BDS method, it only needs to move sideways in small amounts as it is able to reverse its direction easily. Figure 5 shows the comparison between the two methods, both using identical dynamic models. In this simulation, wind is kept constant at 3 ms^{-1} throughout. The heading angle does not need to

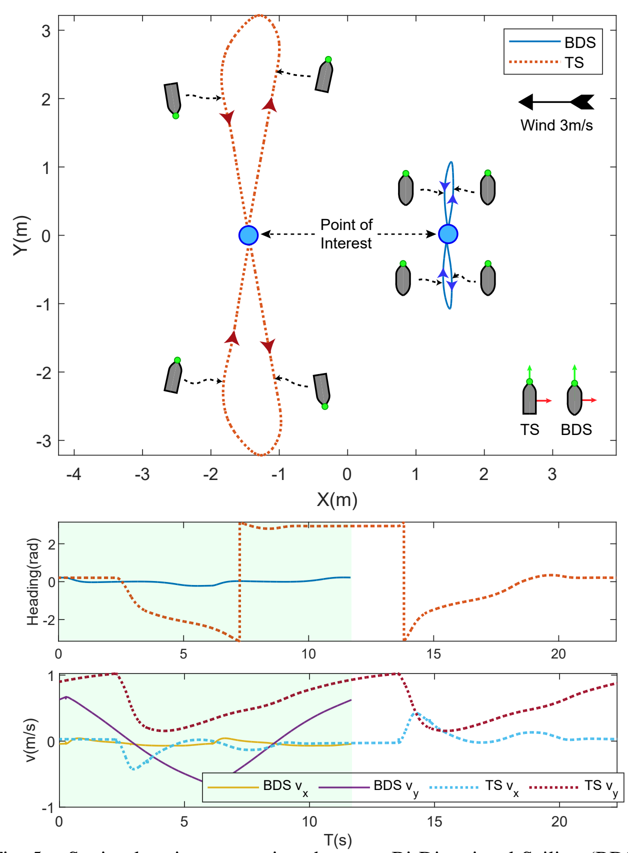

Fig. 5. Station keeping comparison between Bi-Directional Sailing (BDS) and Traditional Sailing (TS) methods. Green region denotes that duration for one cycle of BDS method in its station-keeping pattern.

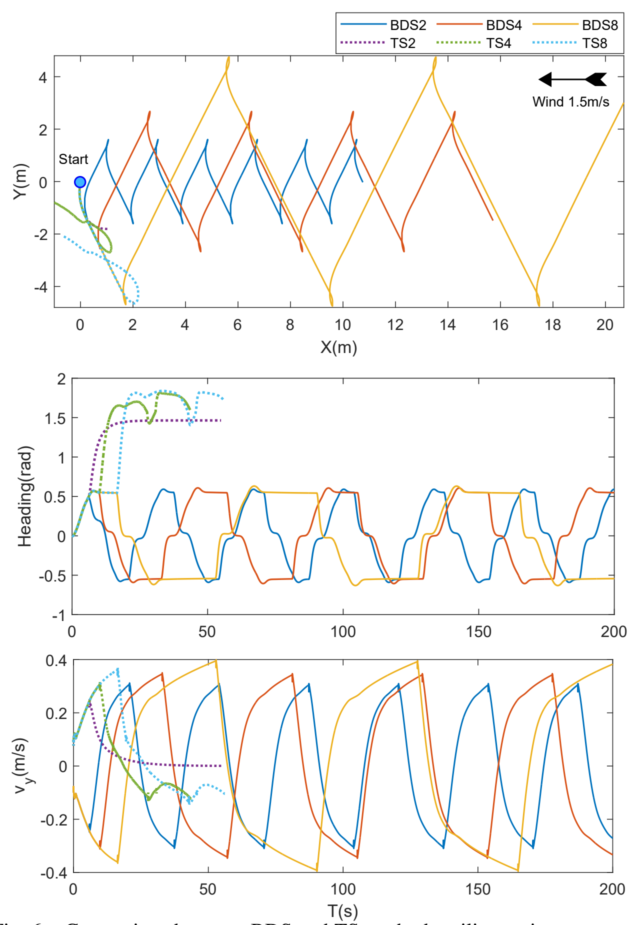

Fig. 6. Comparison between BDS and TS methods sailing a zig-zag course upwind at 1.5 ms^{-1} wind. The simulation is run for 200s.

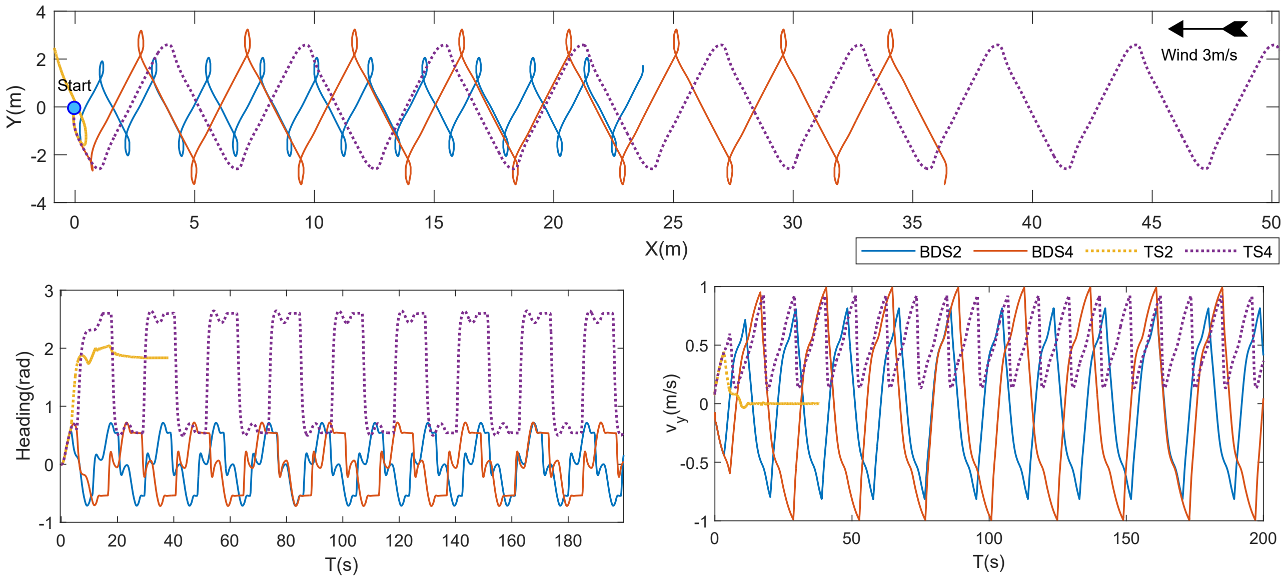

Fig. 7. Comparison between BDS and TS methods sailing a zig-zag course upwind at 3 ms^{-1} wind. The simulation is run for 200s.

change much with BDS, while it requires >180 degree turns in TS. The speed of the vessel reverses once in each cycle of BDS while in TS, the vessel always maintains a forward speed although it loses speed at every turn and regains along its straight paths.

3) Sailing Upwind: Sailing upwind in low wind condition is one of the strengths of BDS, intended for micro-scale USVs that do not have significant mass, hence small accumulated momentum, to maneuver a turn into the eye of the wind using traditional tacking or beating method in a 'zig-zag' course.

Both BDS and TS models start at the same initial condition and move at 60 degrees with respect to the wind in order to achieve the fastest speed. For BDS2, for example, the model begins its turn for the zig-zag course at 1m from its center line, effectively moving in a 2m channel upwind. In order to allow turning at higher speeds, 4m channel and 8m channel are also tested, as shown in Fig. 6. This is set at wind speed of 1.5ms^{-1}. It is found that all TS models are unable to make their first turn as they have not accumulated enough speed to turn into the eye of the wind. As for BDS models, all are able to accomplish their zig-zag maneuver upwind, while those with bigger channel sizes covering more distance in the same duration. This simulation proves the higher performance of BDS method at low wind speeds.

The same test is repeated for both BDS and TS models at wind speed of 3 ms^{-1}, as shown in Fig. 7. TS2 fails to make the turn as it does not have enough speed. TS4, however, is able to turn and it can be seen that it completes the simulation with furthest distance traveled. As the BDS method requires reversing its velocity at every turn, it loses some time to pick up speed again. It also moves backwards slightly at every turn as the aerodynamic drag on the sails pushes it back when there is no forward velocity of the vessel.

IV. Experimental Investigation

A. Prototype

Figure 8 shows a prototype built using mostly rapid-prototyping methods. Its hull is 3D-printed using PLA material and filled up with expanding foam for buoyancy. A small drill-bit is used as a weight at the bottom of the keel. It features dual rudders on both the bow and stern of the hull controlled by two independent servos. The sail mast is made from a round carbon fiber rod that rotates freely from the hull using bearings. Attached to the mast is a rigid sail featuring

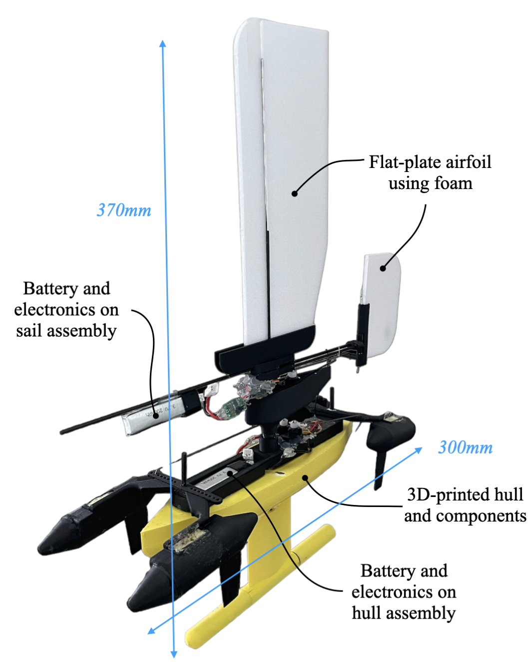

Fig. 8. 3D-printed micro sailboat prototype featuring bi-directional hull.

a flat-plate airfoil made from a 3mm thick foam sheet. The aerial tail rudder is held using carbon rods and it is actuated by a servo positioned such that the center of mass of the sail assembly coincides with the mast. For simplicity, two separate electronics systems are used in this small prototype - a battery, radio receiver and two servos on the hull, and a battery, radio receiver and a single servo on the sail assembly. The electronics are waterproofed by sealing with hot glue.

B. Experiment Results

The prototype was brought to a small semi-outdoors pond for testing. As the pond is located in between buildings, a consistent wind was not available. Hence a wind generator consisting of giant fan was used to generate a constant wind. The fan is put on a trolley and moved back and forth according to the position of the sailboat for consistent wind speeds. The wind speed around the sailing region is measured to be about 2 ms^{-1}. The prototype sailboat is manually controlled using radio control to move upwind in a zig-zag pattern using BDS method and is shown in Fig. 9. At this wind speed and prototype size, it was not possible to sail upwind using TS method. Hence, this test verifies the effectiveness of BDS method for micro-scale sailboats.

The prototype was also brought to a lake to test in real-world conditions, where it was met with some challenges. The main challenge was that a consistent wind was not available. Adding to this, it was found that wind speed was considerably reduced close to the surface of water, especially around the height of our main sail (<20cm). In the future, a slightly bigger prototype will be explored, with many areas to improve and optimize, such as the sail size and shape, keel and rudder size and location, and autonomous control methods.

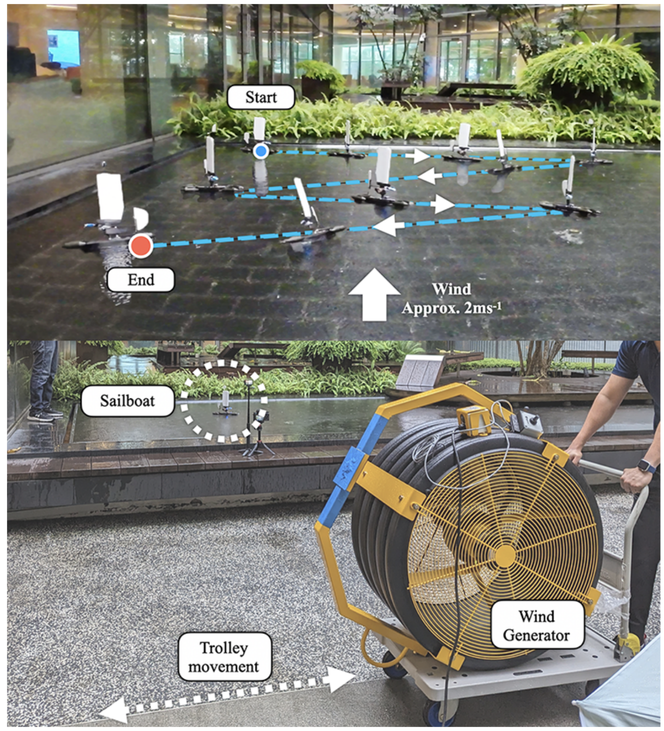

Fig. 9. Top: Zig-zag course using the BDS method in the upwind direction. Bottom: Experiment setup at a small pond showing the wind generator.

V. Conclusions and Future Work

In this work, a novel design of sailboat and its sailing method are proposed. The design concept is proven to work as intended by running simulations based on the dynamic model outlined in this paper. A polar plot, station keeping and sailing upwind scenarios are shown in simulations and compared to traditional sailing methods. A prototype was built using rapid-prototyping methods and an experiment is carried out in a small pond using artificial wind. In future work, autonomous sailing can be achieved by integrating a GPS, wind direction sensor and a magnetometer.

References

[1] R.R. Murphy, E. Steimle, C. Griffin, C. Cullins, M. Hall, K. Pratt, "Cooperative use of unmanned sea surface and micro aerial vehicles at hurricane wilma," *Journal of Field Robotics*, Vol 25(3), pp. 164-180, 2008.

[2] J. Zhang, J. Xiong, G. Zhang, F. Gu, Y. He, "Flooding disaster oriented USV & UAV system development & demonstration," *OCEANS 2016 - Shanghai*, IEEE, pp. 1-4, 2016.

[3] H. Cho, S.K. Jeong, D.H. Ji, N.H. Tran, M.T. Vu, H.S. Choi, "Study on control system of integrated unmanned surface vehicle and underwater vehicle," *Sensors*, Vol 20(9) 2633, 2020.

[4] N.A. Cruz, J.C. Alves, "Ocean sampling and surveillance using autonomous sailboats," in *Proceedings of the 1st International Robotic Sailing Conference*, 2008.

[5] P. Kimball et al., "The WHOI jetyak: an autonomous surface vehicle for oceanographic research in shallow or dangerous waters," *2014 IEEE/OES Autonomous Underwater Vehicles (AUV)*, pp. 1-7, 2014.

[6] C. Sauze, M. Neal, "An autonomous sailing robot for ocean observation," *Project Report*, Aberystwyth University, pp. 190-197, 2006.

[7] M.C.L. Patterson, A. Mulligan, F. Boiteux, "Safety and security applications for micro-unmanned surface vehicles," *2013 OCEANS - San Diego*, IEEE, pp. 1-6, 2013.

[8] J. Kimball, "Physics of sailing," *CRC Press*, 2009.

[9] M. Neal, C. Sauze, B. Thomas, J.C. Alves, "Technologies for autonomous sailings: wings and wind sensors," *Proceedings of the 2nd IRSC*, Matosinhos, Portugal, 2009.

[10] M.F. Silva, A. Friebe, B. Malheiro, P. Guedes, P. Ferreira, M. Waller, "Rigid wing sailboats: A state of the art survey," *Ocean Engineering*, Vol 187, 2019.

[11] C. Tretow, "Design of a free-rotating wing sail for an autonomous sailboat," *Degree Project*, KTH Royal Institute of Technology, 2017.

[12] R. Stelzer, T. Proll, "Autonomous sailboat navigation for short course racing," *Robotics and Autonomous Systems*, Vol 56(7), pp. 604-614, 2007.

[13] D. Santos et al., "Design and implementation of a control system for a sailboat robot," *Robotics*, Vol 5(1), 2016.

[14] C. Petres, M.A. Romero-Ramirez, F. Plumet, B. Alessandrini, "Modeling and reactive navigation of an autonomous sailboat," in Proceedings of *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 3571-3576, 2011.

[15] C. Sauze, M. Neal, "MOOP: A miniature sailing robot platform," *Robotic Sailing: Proceedings of the 4th International Robotic Sailing Conference*, pp. 39-53, 2011.

[16] J.J. Fetter, P. Isler, "Sailing for dummies," *John Wiley & Sons*, 2022.

[17] B.H. Wick, "Study of the subsonic forces and moments on an inclined plate of infinite span," National Advisory Committee for Aeronautics, United States, Report TN-3221, 1954.