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An Adaptive Position Keeping Algorithm For Autonomous Sailboats

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***Abstract*— Autonomous sailboats are potential solutions for in-situ ocean measurement thanks to their high energy efficiency. Indeed, the ability for them to maintain their position is crucial for ocean data collection. Previous study has demonstrated a position keeping method for an autonomous sailboat and has theoretically proved the stability. As this method is ineffective against wind disturbance, we propose a more feasible algorithm for real environment in this paper. A retrofitted model sailboat is developed to evaluate the performance of our approach in an artificial wind field. Simulation and experiment results under several different cases show that our proposed algorithm is robust.**

I. INTRODUCTION

Hydrographic surveying and nautical charting are essential for providing useful data for resource exploration and safe navigation. An important method of such marine environment monitoring is remote sensing, which aims to obtain information related to global ocean. However, not enough details of the sea can be acquired by it. As a consequence, in-situ measurements are vital for a number of tasks such as observing water column structure. Drifting profilers, research vessels, moored and drifting buoys are commonly candidates for such missions. Recently, autonomous sailboats have been increasingly attractive as relatively new platforms for in-situ measurements [1]–[3]. Unlike buoys, autonomous sailboats can deploy themselves to specific areas of interest. As propelled by wind, they also overcome the limitation of energy storage compared to other Unmanned Surface Vehicles (USVs), which allows them to carry out long-term missions.

Monitoring marine environment requires the capacity for autonomous sailboats to pass way points and keep in target area. Specifically, by holding a fixed position as "virtual mooring", sailboats can estimate wave conditions [4] and perform as a base station for underwater vehicles. However, due to the uncontrollable and partially unpredictable nature of thrust force as well as the complex kinematics and dynamics, position keeping of sailboats is still challenging [5]. Only a few attempts have been made for this problem. A station keeping method for sailboats with propellers in the presence of unknown water is proposed in [6] while [7] has presented a control method for motor-less sailboats. The main deficiency of the latter is that this study does not focus on the maintaining strategy. It suggests to orient the sailboat front of wind and only meets the conditions where sailboat's velocity is positive. Paradoxically, the velocity must become negative under this situation on account of that sailing yachts are decelerated by wind and marine current and lose the thrust force at the so-called "no-go zone" [8]. In fact, owing to this inherent navigation constraint, motor-less sailboats cannot compensate most perturbance to maintain a exact position like other USVs. For this reason, the problem could be redefined as how to enable a sailboat to sail in a minimum area. To the best of our knowledge, such position keeping method for motor-less sailboat is underdeveloped. This paper is therefore dedicated to design a practical algorithm to enable a sailboat to stay in a target area under various wind fields, as shown in Fig. 1.

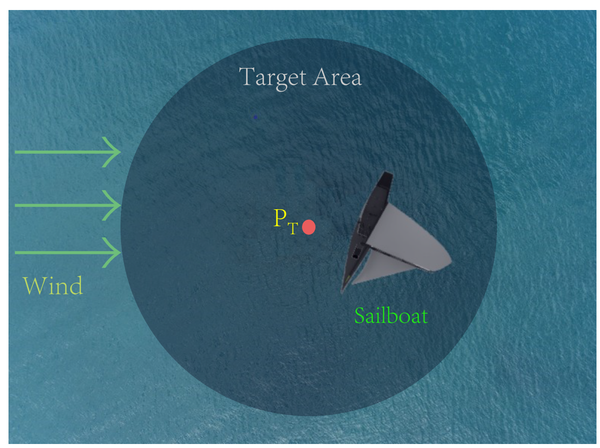

Fig. 1: The goal of this work is to enable a sailboat to keep in a circular target area and minimize the mean distance between its center and the sailboat. P_T represents the target point which is the center of target area. The wind field is assumed to be homogeneous and variable.

The remaining parts are organized as follows. A robust control algorithm is proposed in Section II. Section III describes the model of sailboats and figures out the minimum velocity for a tacking maneuver. Low-level controllers of sail and rudder are described in Section IV. After showing the performance of the designed algorithm by simulation in section V, an experiment is designed to verify the feasibility of this algorithm in Section VI.

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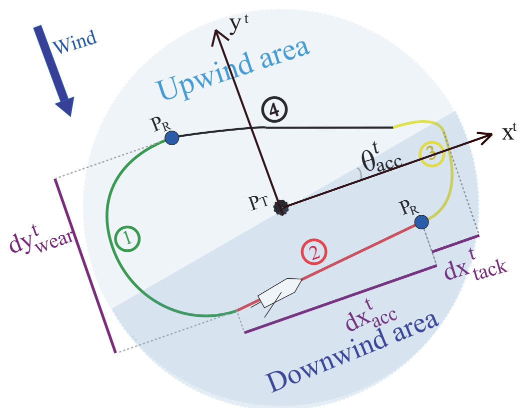


Fig. 2: In the ideal trajectory, 1 is the path of a wearing maneuver and 3 shows the path of a tacking maneuver. The sailboat accelerates along the direction given by $\theta_{acc}^t > 0$ in 2. θ_{acc}^t also divides the whole area into two parts (upwind area and downwind area).The sailboat navigates to upwind area in 4.

II. Control Algorithm

The strategy of reaching a target point is introduced in [7] and applied in this work in case of that the sailboat drifts out of the target area. Before developing the control algorithm, several assumptions are declared.

- The sailboat is assumed to attach a conventional soft sail with limited a sail angle ($\theta_s \in [-\pi\ ,\pi]$).
- We assume wave motion and water velocity are negligible as the problem is extended to a relatively large scale.
- All locations among the whole target area are assumed to share a common wind direction.

The center of the target area is defined as the target point P_T. The target coordinates are fixed in the target point, whose y axis is opposite to wind direction. Mean value of distance between the sailboat and its target point during a time period is regard as the assessment index.

A. Strategy Description

Intuitively, the best solution for position keeping is to circle around the target point. However, there are two main reasons making it unpractical.

- The sailboat will be continuously pushed downwind by wind force.
- When the wind speed is relatively high, the sailboat cannot reach a sufficient velocity to cross no-go zone.

In spite of that, a modified algorithm is developed based on this idea, as shown in Fig. 2. A tack is performed to move a sailboat upwind while a wear is executed to move it downwind. When it has turned downwind (has finished wearing), instead of tacking directly, it navigates toward a reference point to accelerate till being able to tack. To center the trajectory in the target area, another reference point in the upwind area is generated to initialize the wearing maneuver. Fig. 2 illustrates the ideal trajectory.

TABLE I: Parameters of Autonomous Sailboats.

Notations	Descriptions
x, y, ϕ, φ	position of sailboat in East-North-Up coordinate system
v, u, p, r	velocity in body-fixed frame in surge, sway, roll, and yaw
$\bar{x}, \bar{y}$	position of the target point in East-North-Up coordinate system
x^t, y^t	position of the sailboat in target coordinate
φ^t, ϕ^t	Eulers angles in target coordinate (yaw, roll)
$\theta, \bar{\theta}$:	course angle and desired orientation in n-frame
δ_r, δ_s	rudder/sail angle
$\bar{\delta_r}, \bar{\delta_s}$	max rudder/sail angle
φ_{tw}, v_{tw}	angle and speed of true wind
φ_{aw}, v_{aw}	angle and speed of apparent wind
v^*	desired forward velocity
$\bar{v}$	minimum initial forward speed for tacking
θ_d	angle for no-go zone

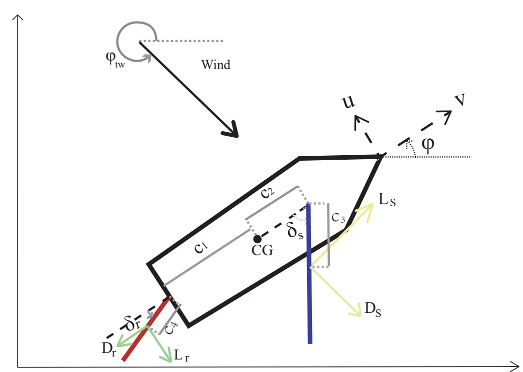


Fig. 3: We use a East-North-Up coordinate system. Both rudder and sail are modeled as foils. Counterclockwise is defined as positive direction for all angles. Refer to our sailboat used for experiment, $c_1 = 0.4$ is the distance from sailboat's center of gravity (CG) to the end of the rudder. $c_2 = 0.15$ is the distance from CG to the mast. $c_3 = 0.2$ denotes the distance from mast to the center of effort (CoE) of sail. The distance from CoE of rudder to the end of rudder is represented by $c_4 = 0.05$.

B. Desired forward velocity and orientation

Table I and Fig. 3 describes the parameters used in the following.

Step 1: This step aims to get the reference point $P_R = [x_r\ , y_r]$. The target area is classified into an "upwind area" and a "downwind area". According to current area, the position of a reference point in target coordinate $[dx_r^t\ , dy_r^t]$ is given to overlap the center of trajectory with the target point.

$$\begin{bmatrix} dx^t \\ dy^t \end{bmatrix} = \boldsymbol{R_t} \begin{bmatrix} dx \\ dy \end{bmatrix} \tag{1}$$

$$p = sign(sin(\varphi_{tw} - \varphi)) \tag{2}$$

$$q = sign(dy^t + dx^t * p * sin(\theta_{acc})) \tag{3}$$

$$dy_r^t = -\frac{1}{2} p * (dx_{acc}^t + q(-\frac{dy_{wear}^t}{2} + dx_{tack}^t)) \tag{4}$$

$$if\ (q > 0)\ or\ (dx_{acc}^t tan(\delta_d) > dy_{wear}^t):$$

$$dy_r^t = \frac{dy_{wear}^t}{2} \tag{5}$$

$else:$

$$dy_r^t = min(0, dx_{acc}^t * tan(\theta_{acc}) - \frac{1}{2}dy_{wear}^t) \quad (6)$$

$$\begin{bmatrix} x_r \\ y_r \end{bmatrix} = \begin{bmatrix} \bar{x} \\ \bar{y} \end{bmatrix} + \boldsymbol{R_t^{-1}} \begin{bmatrix} dx_r^t \\ dy_r^t \end{bmatrix} \quad (7)$$

where $\boldsymbol{R_t} = \begin{bmatrix} -sin(\varphi_{tw}) & -cos(\varphi_{tw}) \\ cos(\varphi_{tw}) & -sin(\varphi_{tw}) \end{bmatrix}$, $\begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} - \begin{bmatrix} \bar{x} \\ \bar{y} \end{bmatrix}$. Variables p and q represent the direction of heading angle relative to wind and current area, respectively (e.g. $q = 1$ indicates "upwind area"). dy_{wear}^t is the component of displacement for wearing in y axis while dx_{acc}^t is the component of re-accelerate displacement in x axis of the target coordinates. Both of them will be updated after corresponding maneuvers and will be slightly larger than actual values to enhance the robustness of the algorithm.

Step 2: This step determines the desired orientation and forward velocity for a sailing robot to reach the reference point. When the sailboat is in "upwind area", it navigates toward the reference point except that the target point is in no-go zone. The desired velocity is slow but able to supply sufficient rudder torque to compensate sail torque so that the sailboat can hold a course (e.g. $v_{upwind}^* = 0.2m/s$). When the sailboat is in "downwind area", its desired course is limited in order to accelerate the sailboat better.

$$\theta^* = atan2(y_r - y, x_r - x) \quad (8)$$
$$\bar{\theta} = \theta^* \quad (9)$$
$if\ q == 1:$
$$v^* = v_{upwind}^* \quad (10)$$
if $cos(\varphi_w - \theta^*) < cos(\varphi_w - \theta_d)$:
$$\bar{\theta} = sign(sin(\varphi - \varphi_w)) * (\pi - \theta_d) + \varphi_w \quad (11)$$
else:
$$v^* = \text{"}max\text{"} \quad (12)$$
$$\theta_{temp} = sign(sin(\varphi - \varphi_w)) * (\pi/2 + \theta_{acc}^t) + \varphi_w \quad (13)$$
$$\bar{\theta} \in (\theta_{temp} - 0.1, \theta_{temp} + 0.1) \quad (14)$$
where $v^* = \text{"}max\text{"}$ indicates that the sailboat will take the optimal angle for maximum acceleration.

Step 3: After passing the reference point, the sailboat will make one tack if it is in the downwind area and the velocity is sufficient. Otherwise, one wear will be made.

$if\ sin(\varphi - \varphi_{tw}) * sin(\theta^* - \varphi_{tw}) < 0:$
if $q <= 0$ & $v > \bar{v}$:
$$\delta_{it} = \varphi \quad (15)$$
$else:$
$$\delta_{iw} = \varphi \quad (16)$$

where variable δ_{it} and δ_{iw} function as triggers to start a tacking maneuver or a wearing maneuver.

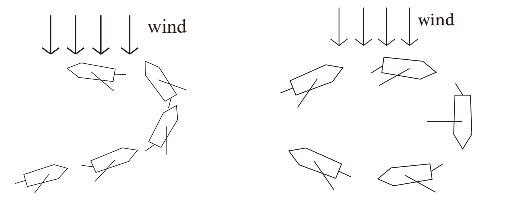


Fig. 4: (a): A tacking maneuver, (b): A wearing maneuver

C. Maneuvers

This section states the details of tacking and wearing maneuvers and demonstrates the algorithm.

1) Execute a Tack: During a tacking maneuver, a sailboat crosses through the no-go zone. In fact, the sailboat would not be stuck in dead zone for a long time since the sail torque turns it out. This reveals that the minimum initial speed for tacking could be which just allows a sailboat to turn through wind direction significantly before completely losing speed. In contrast, the sailboat will be oriented back to the initial orientation of tacking if its initial velocity is not sufficient. Turning through wind with this specific angle $\alpha > 0.2\ rad$ manifests that the sailboat tacks successfully. The algorithm of a tack is as follows.

if $\delta_{it}\ != None$ & $v > \bar{v}$:
$\quad \bar{\theta} = \varphi - 3 * sign(sin(\varphi_{tw} - \delta_{it}))$
$\quad$ if $sin(\varphi_{tw} - \delta_{it})sin(\varphi_{tw} - \varphi) < 0$ &
$\quad\quad cos(\varphi_{tw} - \varphi) > cos(\pi - \alpha)$:
$\quad\quad\quad \delta_{it} = None$

2) Execute a Wear: A wearing maneuver lets the stern of the sailboat cross through the wind. Its trajectory will approximately be a portion of a circle if the rudder keeps a fixed value. To minimize the turning radius, the rudder keeps its maximum angle and the initial velocity of the sailboat should be as low as possible. The algorithm is expressed as

if $\delta_{iw}! = None$:
$\quad \bar{\theta} = \varphi + 3 * sign(sin(\varphi_{tw} - \delta_{iw}))$
$\quad$ if $sin(\varphi_{tw} - \delta_{iw})sin(\varphi_{tw} - \varphi) < 0$ &
$\quad\quad cos(\varphi_{tw} - \varphi) < 0$:
$\quad\quad\quad \delta_{iw} = None$

III. Model and Minimum velocity of tacking

A. Dynamic Model

A dynamic model of sailboat is indispensable for state estimation and analyzing the performance of control algorithm. There exist a host of models with different complexity and fidelity. This section is to adopt an appropriate one according to the features of the proposed algorithm.

Recall that a successful tacking greatly depends on the initial velocity. The sailboat must re-accelerate for a extra distance if it fails in tacking due to insufficient initial velocity. On the contrary, surplus initial velocity reveals that accelerate distance could be shorter to reduce the deviation from target point. These two cases suggest an exact initial velocity to reduce the sailboat's deviation from the target point. [8] solved the minimum initial velocity by the concept of backward reachable set. However, wind drag, which is neglected in his model, substantially effects the tacking process in this work because the relative low speed reduces other drag forces. The tacking process actually involves complex dynamics and is highly nonlinear. Thus, the model is required to accurately depict the dynamics of the sailboat to find out initial speed of tacking via wind speed and initial orientation.

Compared to a typical three-degree-of-freedom (3-DOF) model in [7], nonlinear 4-DOF dynamic models for sailing yachts are more precise. [9] further considers the sail flap, which brings the main component of wind drag during a tack (In fact, the wind is not strictly uniform in space so that the sail flap occurs and inevitably generates drag force). For these reasons, we finally select it to give a better prediction of initial speed threshold of tacking. The sailboat dynamics is as (14) and (15).

$$\begin{cases} \dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{v} & (17) \\ \boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v},\boldsymbol{\eta}) + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} & (18) \end{cases}$$

where $\boldsymbol{\eta} = [x, y, \phi, \varphi]^T$ is the position and orientation in the earth-fixed frame (Different from [9], we choose the East-North-Up coordinate system),$\boldsymbol{v} = [v, u, p, r]^T$denotes the velocity in the body-fixed frame in surge, sway, roll, and yaw. The expressions for the system inertia matrix $\boldsymbol{M}$, the coriolis-centripetal matrix $\boldsymbol{C}$, the damping vector $\boldsymbol{D}$, the vector of restoring forces $\boldsymbol{g}$, the sail and rudder forces $\boldsymbol{\tau}$, and the transformation matrix $\boldsymbol{J}$ are given in [9].

B. Model Validation and Minimum Velocity for Tacking

Inspired by [10], we first determined the measurable parameters such as mass and area of the sail. Inertias, position of CG and CoE are then briefly estimated while drag and lift coefficients are taken from literature. Some coefficients (i.e. added mass coefficients) are still unknown. A more precise system identification usually takes expensive equipments such as towing tanks and wind tunnels. To achieve this in a simple way, we manual controlled the model sailboat in a pool and measured data including velocity, position, pose and commands. After synchronizing the commands in simulation with measured ones, we adjusted the parameters by comparing the simulated outputs and measured data. Fig. 5 shows the similarity between the predicted movement and the actual one to confirm the reliability of our model.

Recall that a proper initial velocity is vital for a sailboat to tack. Furthermore, there are two factors that affect the minimum initial velocity of tacking for a specific sailboat, which are wind speed and the angle between wind direction and sailboat's initial orientation, i.e. $\varphi_{tw} - \varphi$. Thus, we determine the minimum tacking velocities for possible cases, e.g. 900 cases with 30 different wind speeds and 30 different initial angles, by the binary search approach in simulation.

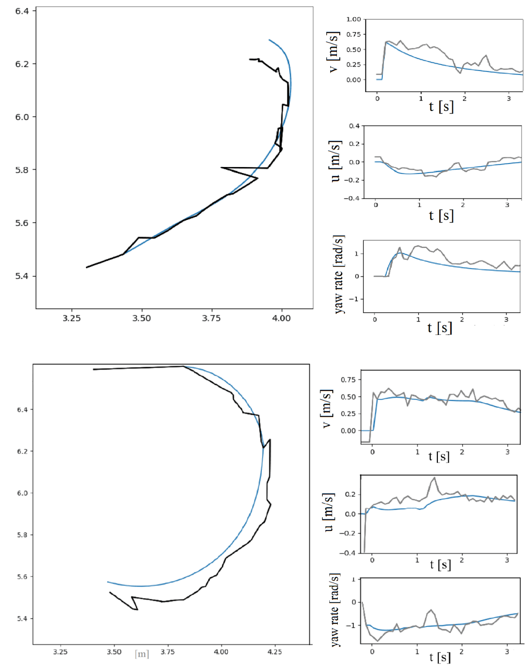


Fig. 5: The comparison of trajectory, velocity and yaw rate between simulation and measured data for a tack and a wear.

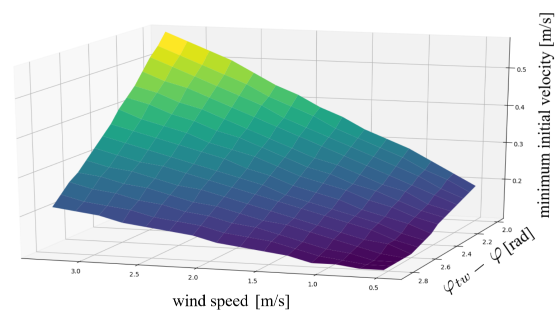


Fig. 6: The minimum velocity via different wind speeds and initial angles between wind direction and sailboat's orientation

Fig. 6 illustrates the minimum initial velocity via different wind speeds and initial angles.

IV. Low-level Control

A. Rudder angle

A simple PID controller is utilized to output rudder angle. Its integral gain will be reset to zero after a tack or wear to reduce overshooting.

As side drift invariably occurs owing to the sideway force, the sailing direction will be slightly leeward compared to the longitudinal axis of a sailboat. To compensate this leeward movement, the course angle is chosen as the input of rudder controller instead of the heading. However, the course angle is determined by the position of sailboats, which indicates that the noise of position may result in an inaccurate observed course angle. Although filters can eliminate the noise as much as possible, it is still probably to lose the course angle when the sailboat performs a tacking or wearing maneuver.

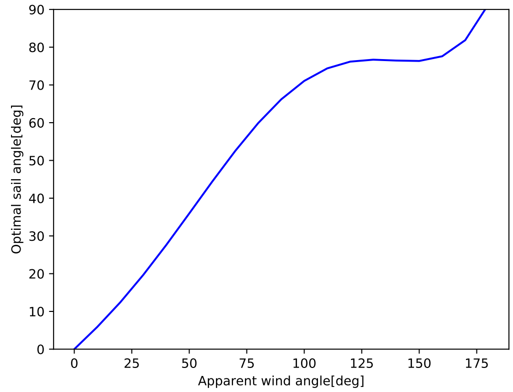


Fig. 7: The optimal sail angle via angle of apparent wind.

Hence, the course angle will be adopted when navigating to the reference point, otherwise heading angle will be adopted. The input error of the PID controller is given by:

$$e = \begin{cases} \bar{\theta} - \theta \quad , \ when\ tacking\ or\ wearing & (19) \\ \bar{\theta} - \varphi \quad , \ Otherwise & (20) \end{cases}$$

The rudder angle will be regulated to zero if the sailboat drifts backward since the velocity of sailboat to water is unknown. It is notably that the rudder angle will reach its maximum during this two maneuvers as the desired orientation is almost the reverse direction of the sailboat.

B. Sail angle

According to the control algorithm, the chosen sail controller should be able to provide maximum acceleration and enable the sailboat to maintain a low speed.

In literature, fuzzy controller [11], extremum-seeking approach [12] and model-based sail angle computation [13] were presented to regulate the sail. Fuzzy controller cannot provide optimal sail angle whereas the extremum-seeking approaches take a long time to converge. The model-based method proposed in [13], which overcomes the two disadvantages above, is utilized for maximizing the longitudinal acceleration. The optimal sail angle δ_{opt} under different ratio of attack is shown in figure 7.

On the other hand, few study investigates in controlling velocity of sailboats. Although an approach to control the acceleration of a sailboat is proposed in [7], it is challenging to figure out the real-time acceleration in experiment. Thus, a similar sail regulator based on velocity is developed. A PI controller is employed to output a bias term b to regulate forward velocity of sailboats, for which the input error $e_s = v - v^*$. The sail angle is given by

$$\delta_s = \delta_{opt} + b \tag{21}$$

The maximum sail angle under the constrains of wind is expressed as

$$\delta_{sMax} = min\left(\bar{\delta_s} \ , |pi - |\varphi_{aw}||\right) \tag{22}$$

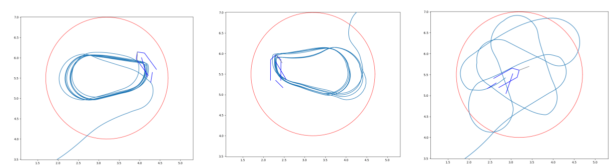
Since the sailboat attempts to slow down only when it navigates upwind, δ_{sMax} is always larger than optimal angle. We therefore define the range of sail such

$$\delta_s \in (\delta_{opt} \ , \delta_{sMax}) \tag{23}$$

V. Simulation

In this section, the performance of the position keeping algorithm will be tested under several cases including constant wind fields and a varying wind field. Also, the evaluation will be given according to the mean value of distance withing a duration T[s]. The parameter setting is as follows. p_T= (3.2$[m]$, 5.5$[m]$), d_T =1.5$[m]$, $v_{low} = 0.2\,[m/s]$, θ^t_{acc} =$\pi/7\,[rad]$. Both dy^t_{wear} and dx^t_{acc} are initially set to $1[m]$.

- case 1: $v_{tw} = 1.5$, $\varphi_{aw} = -\pi/2$, $x_{t=0} = 1$, $y_{t=0} = 3$, $\varphi_{t=0} = 0.5$ and T=100.
- case 2: v_{tw} =3, $\varphi_{aw} = -\pi/2$, $x_{t=0} = 5$, $y_{t=0} = 7$, $\varphi_{t=0} = 2.5$ and T=100.
- case 3: v_{tw} =3, $\varphi_{aw} = -\pi/2 + 0.5t$, $x_{t=0} = 1$, $y_{t=0} = 3$, $\varphi_{t=0} = 0.5$ and T=45.



(a) (b) (c)

Fig. 8: Simulation results.(a) Sailboat's trajectory in case 1 where the mean value of distance from the sailboat to the target point is 0.747m. (b) Sailboat's trajectory in case 2 where the mean value of distance from the sailboat to the target point is 0.770m. (c) Sailboat's trajectory in case 3 where the mean value of distance from the sailboat to the target point is 0.915m.

VI. Experiments

A. Experiment Setup

The experiment is carried out in a pool around 12m× 8m×3m to further confirm the robustness of the control algorithm. A wind-fan array is mounted in a short side of the pool to provide artificial wind filed. The wind field is assumed to be time-invariant with a speed relative to location. A motion capture system is implemented around the pool for sailboat localization. The real-time position of the sailboat is uploaded to a database.

A one-meter model mono-hull sailboat is retrofitted to validate our proposed algorithm. An Arduino Nano Mega328 microcontroller attached with a HC06 bluetooth module and a BNO055 Inertial Measurement Unit (IMU) is employed. All onboard measurements of sailboat will be transmitted to PC via the bluetooth module. After fetching the data of sailboat's pose and location, the commands of two servos are generated in PC and send to the development board. Lastly, the rudder servo and the sail servo are controlled by PWM signals generated by development board. Fig. 9 demonstrates the system framework of the experiment.

Fig. 9: The system framework of the experiment.

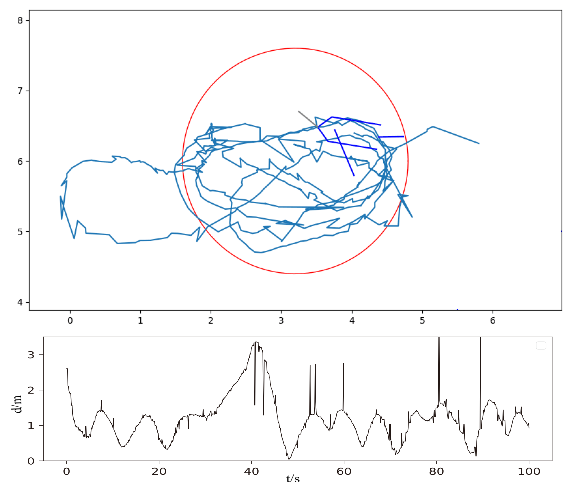


Fig. 10: This figure shows the trajectory of the sailboats in experiment as well as the distance between the sailboat and the target point. Although the sailboat fails tacking at $t = 30[s]$, it still returns to the target area. The mean distance is 1.203[m]. It is notably that the abnormal points are delete in the trajectory.

B. Result

Similar with the simulation, the sailboat aims to stay in a target area for 100s and minimize the mean value of distance to the center. Wind speed of the target area is about 1.5[m/s]. The distance between the sailboat and the target point is shown in Fig. 10.

VII. Conclusion

In this paper, a new practical method for position keeping of autonomous sailboat is presented. The objective of position keeping is defined in the first place. The minimum initial velocity for tacking is investigated. A sail angle regulator is proposed to allow the sailboat maintain a low velocity as well as reach its maximum velocity. An accurate model of sailboat is used to demonstrate the reliability and performance of the method under various wind fields by simulation. In addition, this algorithm is experimentally validated in a constant wind field. Experiment results show the sailboat is capable to stay in a target area within a radius of 1.6m and the mean value of distance is no more than 1.2m under a constant wind field (wind speed is around 1.5[m/s]).

In future works, the marine current and the waves disturbance will be considered. Energy management system will be included to turn the sailboat into semi-persistent presence in ocean. A field experiment will be carried out to further evaluate the robustness of the position keeping method.

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