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Modeling and Course Control of Sailboats

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Abstract: This paper proposes a method of transforming a heading controller into a course controller in sailboats by adding a small correction term. Sailboats usually have large drift angles because of considerable side forces, mainly caused by the sail. Even small deviations from the correct course angle can cause large errors, and thus course controllers in sailboats plays an essential role. The solution is based on the dynamics of the system, and the model presented builds upon previous work and adds detail in areas such as how to model wind, current and drag. The solution has roots in the fact that the purpose of the keel is to create a side force that counterbalances the unwanted drift forces. Simulation results show the effectiveness of the proposed approach.

Keywords: Course Control, Sailboat, Modeling.

1. INTRODUCTION

The history of sailboats goes back to one of the earliest civilizations of mankind in Mesopotamia where the Tigris and Euphrates rivers inspired the development of many watercrafts, including sailboats, see Carter (2012). However, autonomy in sailboats is a topic that has gained attention only in recent years, see Xiao and Jouffroy (2014).

Sailboats require little to no energy to operate, making them well suited for long operations such as oceanographic research. Moreover, with the increased focus on clean energy, sailboats could also provide a green option for transporting goods, see Michael et al. (2014). The propulsion force of the sailboat is created by the wind, and the only energy needed to operate the boat is by trimming the sail and controlling the rudder. Fitting the sailboat with solar panels or extracting energy directly from the sail itself makes them very much self sustainable in terms of energy, see Jaulin and Le Bars (2014).

For a motorized boat the heading angle is almost considered synonyms with the course angle of the ship, though due to wind and current forces small drift angles may appear. This problem is easily handled by an integrator term in the controller, as unwanted drift caused by wind and current can be seen as slowly changing errors. However, in sailboats it is more challenging to control the course and this is due to the fact that the wind provides the main propulsion force but at the same time causes large heel and drift angles. The side forces are especially large when sailing closed hauled or reaching.

Solving the course control problem by an integrator term has been done for sailboats (Saoud et al. (2015)), but it has multiple shortcomings. The drift created can be bigger than what is usually observed on a motorized boat, meaning that the integrator term would have to be large. To make the matter worse, when sailing upwind, the sailboat has to constantly do tack maneuvers. This would cause a huge error to appear after each tack, as the integrator term needs time to catch up. Furthermore, one would need to be able to estimate the drift angle, which is not an easy task in sailboats.

Xiao and Jouffroy (2014) have addressed the problem by using a nonlinear system solver to calculate the necessary drift angles to keep a desired course, then storing the results in a lookup table. The drawback of this is that the lookup table is quite large as it depends on several variables, and would need to be recomputed every time a small change is applied to the boat.

In this paper, a simple solution based on the dynamics of the system is proposed. The advantage of this solution is that the drift angle needed to sustain a course is calculated directly, which drastically reduces the need for integral action and removes any need for a lookup table. When the necessary drift angle is known it is trivial to convert an existing heading controller into a course controller. Knowing the drift angle is also useful for purposes besides control, such as state estimation.

In what follows, before the solution of the course controller is presented, a mathematical model of a sailboat is constructed in section 2. This model has many similarities to the model proposed by Xiao and Jouffroy (2014), though some modification has been made. The theory of the course controller is tightly connected to the model, and the controller will be tested on the developed model.

2. DESCRIPTION OF SYSTEM DYNAMICS

The model presented in this paper is very similar to the work done by Xiao and Jouffroy (2014). The most noticeable differences are how drag and restoration forces are handled. In addition, wind simulation has been improved,

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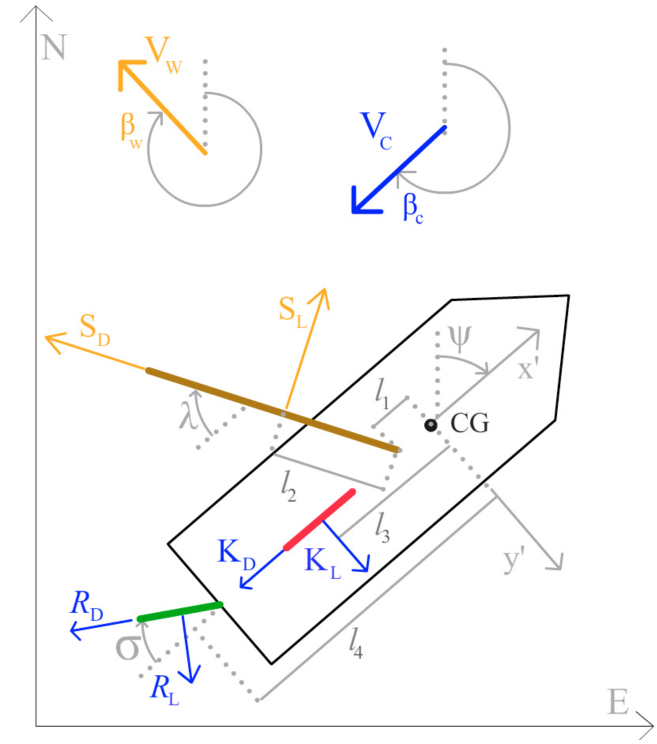

Fig. 1. Definition of positive direction of important parameters, including forces created by the sail and the keel

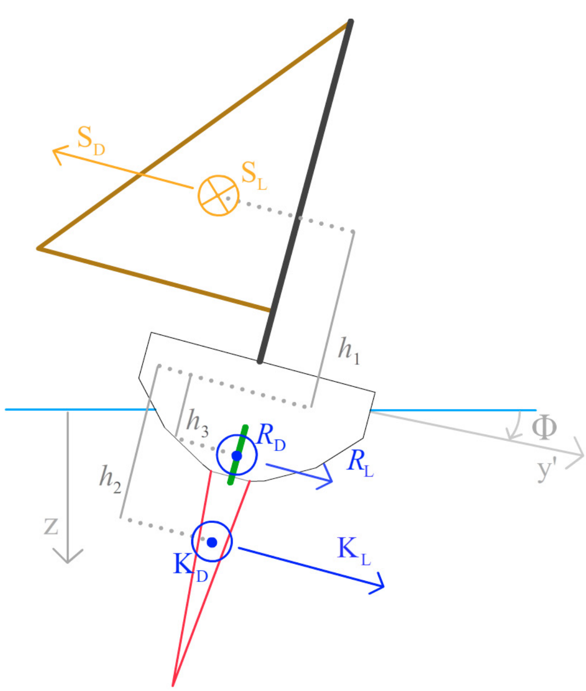

Fig. 2. Definition of positive direction of forces created by the rudder

effects due to current has been added, and a delay has been added to the actuators (rudder and sail) to make it more realistic.

Before presenting the system dynamics, description of the essential parameters in modeling the system, the direction of forces, axis and angles are presented in Figure 1 and 2 and Table 1. All lift and drag forces are shown for an angle of attack equal to zero. Throughout the paper, the notation of Society of Naval Architects & Marine Engineers (SNAME) has been adopted.

In what follows we will use two different reference frames: the north-east-down (NED) reference frame (n-frame) and the body reference frame (b-frame). The NED coordinate system will be treated as inertial, and the b-frame is connected to the body of the ship. The origin of the b-frame, CO, is set to be at the center of gravity (CG) midship and at the waterline.

2.1 System equations

Assumptions The following assumptions are used throughout the paper and are borrowed from Xiao and Jouffroy (2014), see source for a more detailed description of each assumption.

- The yacht is rigid, and movement in heave and pitch are neglected.
- Waves, and the effect caused by them (first order and second order), are not modeled.
- Added mass coefficients are modeled as constants.

Table 1. Variable description

variable	description
CG	Center of gravity
CO	Center of body frame
ρ	fluid density $[\frac{kg}{m^3}]$
g	gravity $[\frac{m}{s^2}]$
R_n	Reynolds number
β	drift angle $[rad]$
χ	course angle $[rad]$
β_w, β_c	wind/current angle $[rad]$
V_w, V_c	wind/current vector $[\frac{m}{s}]$
$U(z)$	absolute wind speed $[\frac{m}{s}]$
U_{10}	absolute wind speed at $z = -10$ $[\frac{m}{s}]$
U_{10_m}	mean absolute wind speed at $z = -10$ $[\frac{m}{s}]$
λ, σ	angle of sail/rudder $[rad]$
S_L, K_L, R_L	Sail/keel/rudder lift $[N]$
S_D, K_D, R_D	Sail/keel/rudder drag $[N]$
x, y	north/east position $[m]$
x', y'	body reference frame coordinates$[m]$
u, v	linear velocity $[\frac{m}{s}]$
u_r, v_r	linear velocity relative to current $[\frac{m}{s}]$
p, r	angular velocity in roll/yaw $[\frac{rad}{s}]$
ψ, ϕ	roll/yaw angle $[rad]$
M_{RB}, M_A	rigid/added mass matrix
$C_{RB}(\nu), C_A(\nu_r)$	rigid/added mass Coriolis-centripetal matrix
$D(\nu_r)$	drag matrix
$g(\eta)$	restoration forces
S, K, R	Forces/moments by sail/keel/rudder $[N/Nm]$
$J(\theta, \psi)$	transformation matrix from b- to n-frame
V_{ws}, V_{ck}, V_{cr}	motion of fluid relative to sail/keel/rudder $[\frac{m}{s}]$
$\beta_{ws}, \beta_{ck}, \beta_{cr}$	angle of fluid relative to sail/keel/rudder $[rad]$
$\alpha_s, \alpha_k, \alpha_r$	angle of attack of sail/keel/rudder $[rad]$
$C_L(\alpha)$,$C_D(\alpha)$	lift and drag coefficient of foil $[-]$
A_s, A_k, A_r	area of sail/keel/rudder $[m^2]$
Asp_k, Asp_r	aspect ratio of keel/rudder $[-]$
m	mass of sailboat $[kg]$
I_{xx}, I_{zz}	Inertia of sailboat about x/z axis $[kgm^2]$
$X_{\dot{u}}$, $Y_{\dot{v}}$, $K_{\dot{p}}$, $N_{\dot{r}}$	added mass in $x'/y'/\phi/\psi$ $[kg\ /\ kgm^2]$
L_{WL}	waterline length $[m]$
B_{F0}, B_L	drag coefficients in roll (friction/lift) $[-/\frac{kg}{rad}]$
S_H	wetted surface of hull $[m^2]$
Δ	displacement $[m^3]$