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IFAC-PapersOnLine 49-23 (2016) 552–556

Roll Stabilization Control of Sailboats

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Abstract: This paper reports a way of dynamically controlling the sail of a sailboat to reduce the heel angle and roll motion caused by the wind. This is mainly to increase robustness and safety for autonomous sailboats but could also be used to increase comfort for crew. The solution consists of a linear quadratic regulator (LQR) controlling the moment created by the sail. A lookup table will then choose the optimal angle of the sail, optimized for maximum forward acceleration, given the relative wind direction and desired moment. Simulation results are presented to show the effectiveness of the approach.

Keywords: Roll Control, Modeling, Sailboat.

1. INTRODUCTION

This paper is a continuation of Wille et al. (2016). The model and the course controller presented in Wille et al. (2016) is the foundation of the theory developed in this paper. It is recommended to read the other paper first as theory and equations from the previous paper will be referenced directly (Equations 1 - 59) and notation reused.

The large surface area of the sail provides the sailboat with forward thrust. However, it also makes the boat vulnerable against strong winds. This can cause large heeling angles, a lot of roll motion due to wind gusts, and in worst case cause the boat to capsize. Autonomous Sailboats will never be a viable option if they cannot handle a variety of different weather conditions. Robustness of a system is an important aspect of autonomy.

The solution presented in this paper controls the roll motion by utilizing the sail. It will reduce the heeling angle and the roll motion created by the wind. The controller design is simple but effective, and the states used in the feedback loop are easy to estimate.

2. SAIL CONTROLLER

2.1 Optimal angle of the sail for forward thrust

The sail is used to create forward propulsion for the sailboat. There is an optimal sail angle that gives the highest forward acceleration for a given relative wind direction. The objective is thus to create a map from relative wind direction to the optimal angle of the sail. We begin by defining a way of measuring the force created by the sail in the forward direction independent of the wind speed:

$$S_{x'_r}(\beta_{ws}, \lambda) = \frac{S_{x'}(\beta_{ws}, \lambda, V_{ws})}{V_{ws}^2}, \tag{60}$$

where $S_{x'}$ is the force created by the sail in positive surge direction (see (29)) and $S_{x'_r}$ is the force divided by the wind speed (relative to the boat) squared. $S_{x'_r}$ is a function of λ and β_{ws}, and there will be an optimal λ given a β_{ws}.

However, λ cannot be chosen freely; it is restricted to a certain range depending on the wind direction and λ_{sat}. This is because we only have control of a rope limiting $|\lambda|$, and the rope only works through tension. When the wind is hitting from starboard, it follows that $\lambda > 0$ and that the torque created by the sail around the mast has to be positive (meaning a positive angle of attack). When the wind is hitting from port side, $\lambda > 0$ and the torque has to be negative (negative angle of attack).

The following equations describe the upper and lower limits of a stable angle of the sail, $\lambda \in [\lambda_l, \lambda_u]$, given a relative wind direction:

$$\lambda_u = \begin{cases} \beta_{ws} + \pi & \text{if } \beta_{ws} < 0 \\ 0 & \text{if } \beta_{ws} > 0 \end{cases} \tag{61}$$

$$\lambda_l = \begin{cases} 0 & \text{if } \beta_{ws} < 0 \\ \beta_{ws} - \pi & \text{if } \beta_{ws} > 0 \end{cases}. \tag{62}$$

In addition to (61) and (62), λ_{sat} still applies. That is, $\lambda_u \in [0, \lambda_{sat}]$ and $\lambda_l \in [-\lambda_{sat}, 0]$.

The optimal angle of the sail can then be found by traversal of all viable λ, trying to maximize $S_{x'_r}$ for a given β_{ws}. This can be computed off-line, and the results stored in a lookup table. In this paper, an optimal λ was found for a step size of $1deg$ in β_{ws}. In order to avoid unnecessary discontinuities in the control action, when there is only a small difference in the optimal λs between a step change in the lookup table, a new optimal λ is found based on a linearized solution between the two data points (this is computed on-line).

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Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.493

2.2 Relative moment of the sail

In the same manner that we defined the relative force in surge direction, the relative moment in roll is defined as

$$S_{\phi_r}(\beta_{ws}, \lambda) = \frac{S_\phi(\beta_{ws}, \lambda, V_{ws})}{V_{ws}^2}, \quad (63)$$

where $S_{\phi r}$ is calculated at each optimal λ and is added to the lookup table. This solution of λ will hereafter, be referred to as the unconstrained solution, λ_{100}.

Before applying the control law to reduce roll motion and heel angle, we have to be able to control the amount of moment created in roll by the sail. This is done by finding new optimal λs, though with a restriction on the maximum relative moment created at each solution.

To produce the desired result, the same traversal algorithm as discussed earlier is performed again, but with the restriction that the solution has to produce a relative moment of 67% or less compared to that of λ_{100}. This solution will hereafter be referred to as λ_{67}. Both λ_{67} and its relative moment is added to the lookup table.

This is then repeated for a 33%- and a 0% (or as low as possible) constrained solution, referred to as λ_{33} and λ_0. However, a new constraint is added, which is that $sign(\lambda_{100} - \lambda_{67}) = sign(\lambda_{67} - \lambda_{33}) = sign(\lambda_{33} - \lambda_0)$. In more practical terms, this is to ensure that the different solutions all move the sail in the same direction compared to the previous solution. This is important when we try to find a continuous solution of the relative moment in the next step.

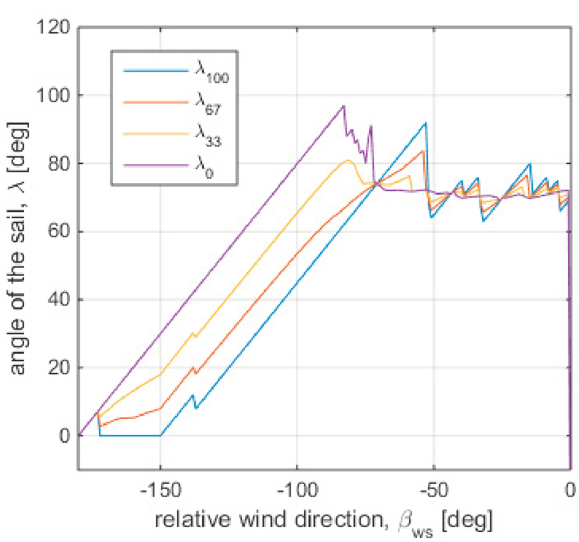

Fig. 1. Optimal position of the sail

We then have all that we need to reverse the process. By entering β_{wr} one finds the solutions of λs that corresponds to that relative wind direction. Then, by applying the restriction of the desired $S_{\phi r}$, the ideal λ is found based on a linearization (computed on-line) between the different $S_{\phi r}$ created by λ_{100}, λ_{67}, λ_{33} and λ_0.

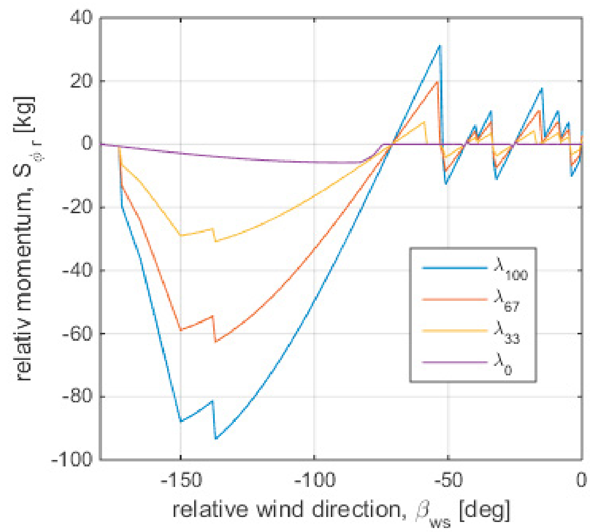

Fig. 2. Relative moment in roll caused by optimal sail position

3. MOMENT ANALYSIS WHEN BEAM REACHING

Beam reaching describes the maneuver of sailing perpendicular to the wind. Figure 3 shows the result of the moment in roll when beam reaching at $U_{m_{10}} = 5\frac{m}{s}$. It is easy to see that the sail and the restoring moment are dominating. Together they generate roughly 91% of the moment in roll. The keel produces another 8%. From (9) and (10) one can see that the two Coriolis terms provides no moment in roll, and it follows that the remaining 1% is caused by the rudder and the drag.

4. ROLL CONTROLLER

The roll controller will be split into two mirrored controllers which will step in when the heeling angle gets too large. For now, we will look into the controller which will govern for roll (ϕ) bigger than zero. The heeling angle

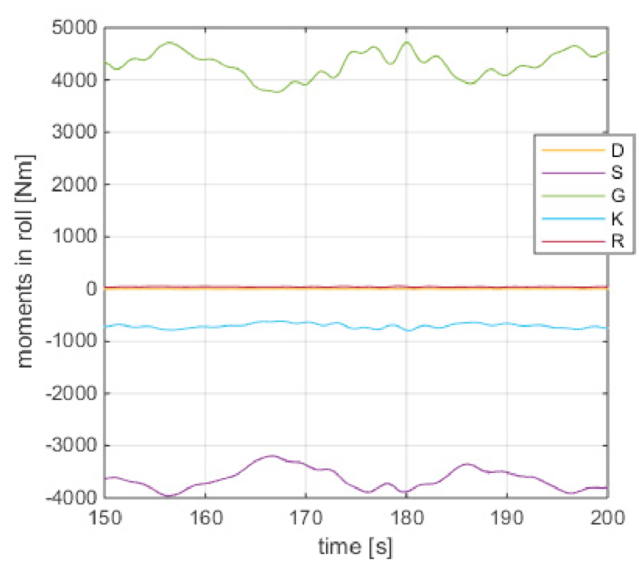

Fig. 3. Moments while beam reaching