Carnegie Mellon University
Mechanical Engineering

Autonomous Sailboat

Tae Rugh, Ben Spin, Samaksh Judson, Denis Alpay, Chris Suzuki

THE ROBOTICS INSTITUTE

Motivation

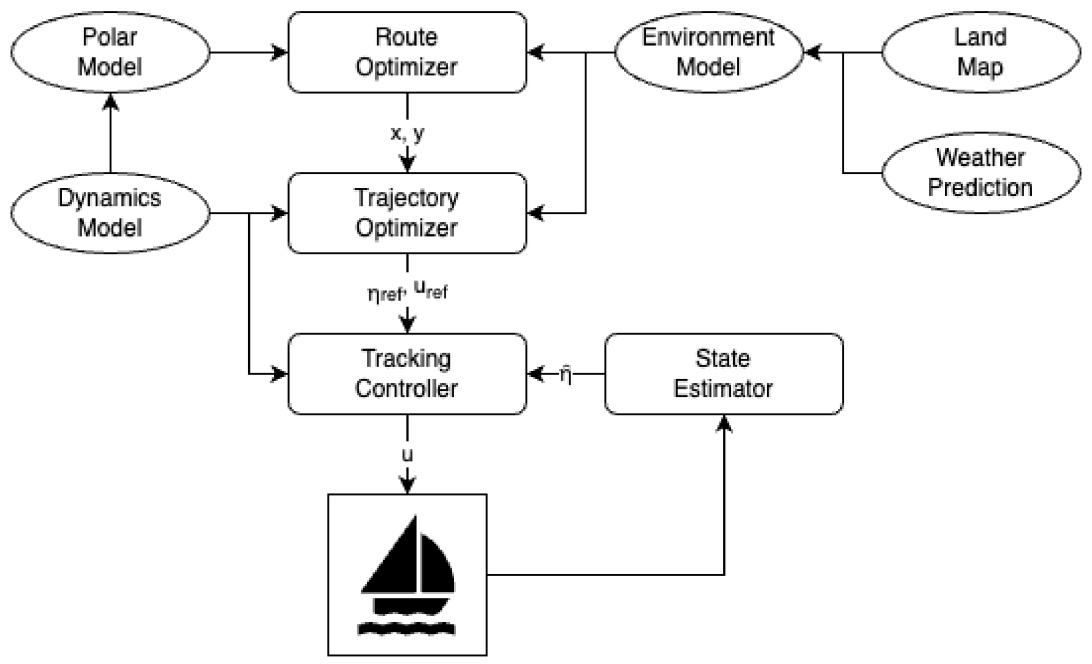
In this project, we leverage weather predictions to develop an optimal control system for autonomous sailboats.

Autonomous sailboats can potentially offer a carbon-neutral solution for the shipping industry. Most importantly, autonomous sailboats provide a unique and interesting control problem because the dynamics are highly coupled to the environment and the control is underactuated.

System Overview

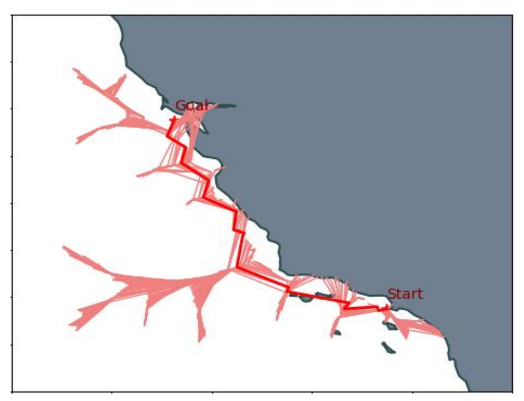
The environment is modeled with a land-ocean map and real-world weather prediction data. The sailboat dynamics are modeled as a 4 degree-of-freedom system with latitude, longitude, yaw, and roll.

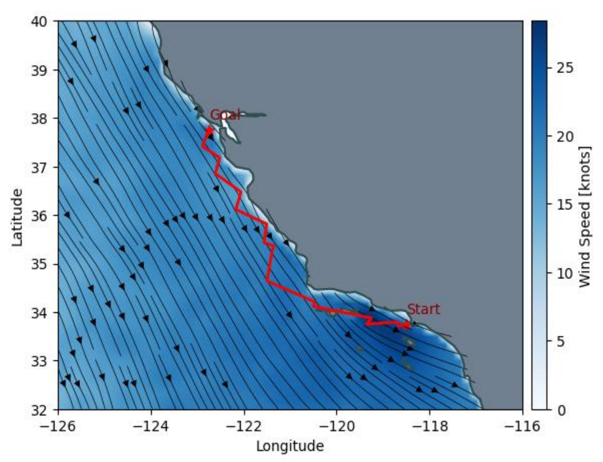
We propose a controller with 3 levels: A global route optimizer, which uses RRT* to find an optimal route, a trajectory optimizer which uses direct collocation to find an optimal trajectory along the route, and a tracking controller which uses MPC to track the trajectory.



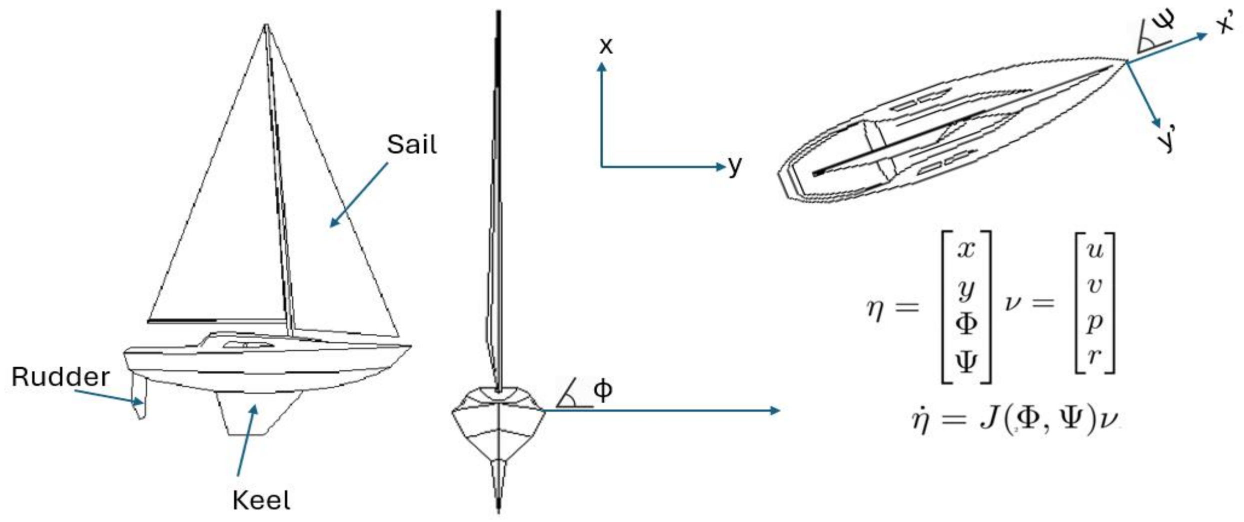
Route Optimizer

Global route optimization is done using the classic sampling-based planning algorithm, RRT*. The cost-to-go between nodes is the travel time, which is calculated by integrating the boat speed from the polar model, subject to the time-varying weather forecast.





Dynamics Model



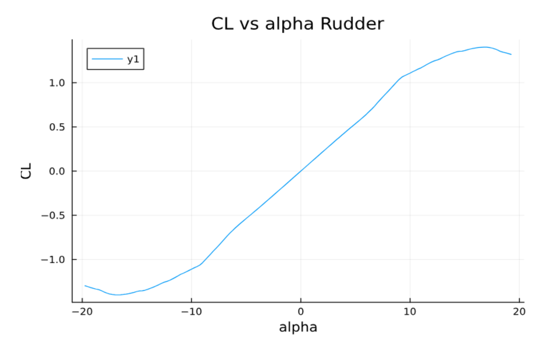
$$\eta = \begin{bmatrix} x \\ y \\ \Phi \\ \Psi \end{bmatrix} \quad \nu = \begin{bmatrix} u \\ v \\ p \\ r \end{bmatrix}$$

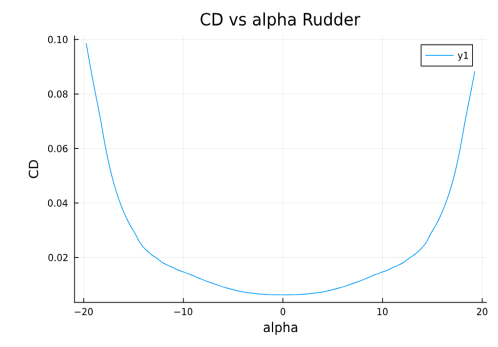
$$\dot{\eta} = J(\Phi, \Psi)\nu$$

$$F = S(\nu, \eta, \nu_w) + R(\nu, \nu_c, \sigma) + K(\nu, \nu_c)$$

$$F = M_{RB}\dot{\nu} + C_{RB}(\nu)\nu + M_A\dot{\nu} + C_A(\nu, \nu_r)\nu_r + D(\nu_r) + g(\eta)$$

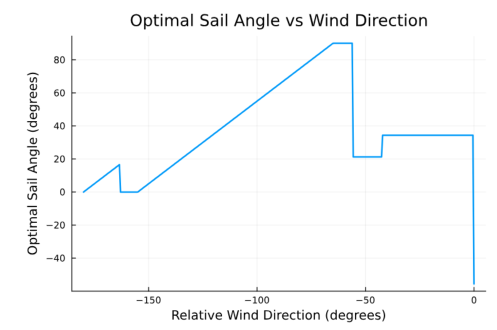
S, R, K – Sail, Rudder, and Keel Forces, RB is rigid body and A is added mass, M is mass matrix, C is Coriolis matrix , D is drag, g is Restoring Forces





We are modeling our sail, rudder, and keel as airfoils using NACA airfoil tools with correction terms.
Assumptions:

- Yacht is rigid
- Effect of waves are not modelled.
- Added mass coefficients are modelled as constants.

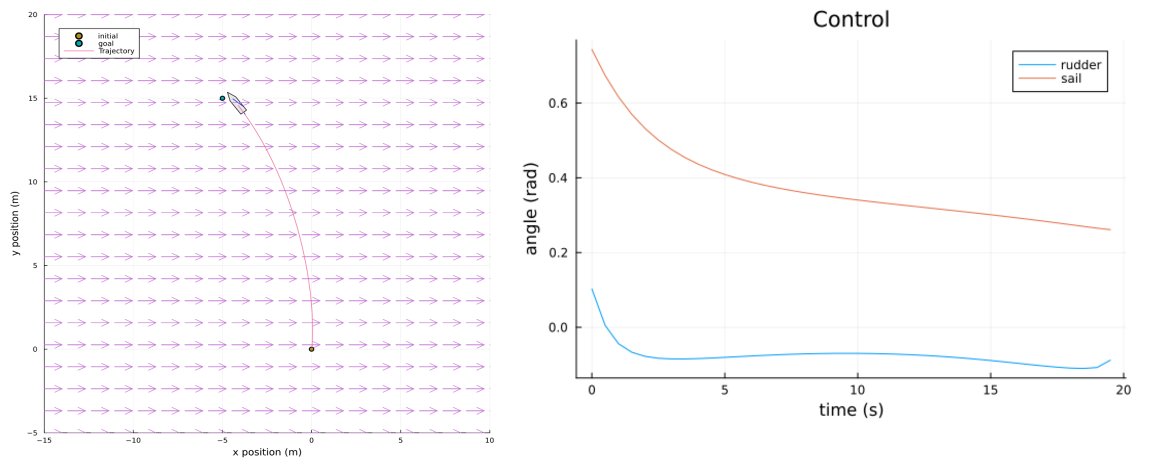


Trajectory Optimizer

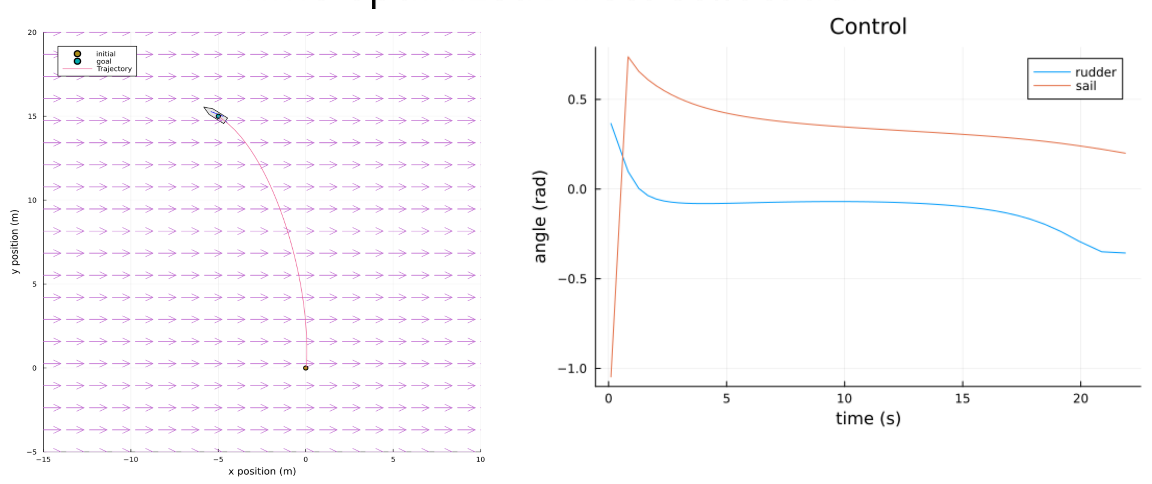
The trajectory optimizer uses waypoints from the optimized route to generate an optimal reference trajectory for a local distance horizon. We implemented both direct collocation and iLQR.

We found that the direct collocation method was a better choice because we have a good initial guess from the route optimizer. Additionally, direct collocation enabled us to implement a time optimization such that the total time to reach the end goal doesn't have to be set manually.

Direct Collocation



Time-optimized Direct Collocation



Course Controller

The heading of a sailboat does not necessarily point in the path that it is travelling in. The tracking controller reasons about the forces on the keel/sail/rudder to find the correct heading angle of the ship to move in the desired trajectory, then controls the ruder to align the ship in the desired angle.
The necessary drift from the course is calculated from:

$$\beta_b = -\alpha_k \cos(\phi)$$

Where α_k is the necessary angle of attack of the keel which is calculated from:

$$\alpha_k = \frac{2 * F_u}{\rho_w * A_k - C_{L0K} * (u^2 + v^2)}$$

Where F_u is the undesirable force which is calculated from forces of wind and water acting on the ship, ρ_w is the density of the seawater , A_k is the area of the keel, C_{L0k} is the lift coefficient of the rudder.

Roll Controller

Roll controller gets activated if the boat rolls more than 10 degrees and it uses an LQR to control the roll. The linear system model is given by:

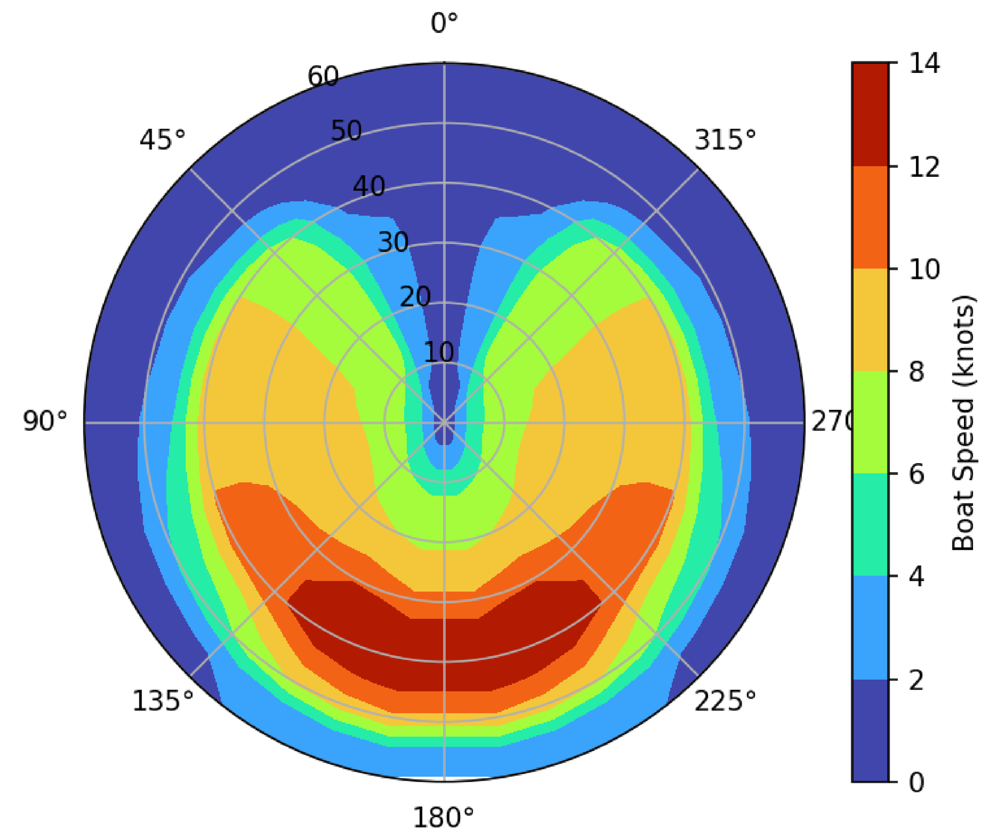
$$A = \begin{bmatrix} 0 & 1 \\ -\frac{\rho_w * g * \nabla * GM_t(1-2*\sin^2(\phi_w))}{I_{xx} - K_{\dot{p}}} & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{1}{I_{xx} - K_{\dot{p}}} \end{bmatrix}$$

And u is:

$$u = -K\begin{bmatrix} \phi - \phi_d \\ p \end{bmatrix} - K_i \int_0^t \phi - \phi_d \, dt + C_1 + F_u h_2$$

Where where ρ_w is sea water density, g is gravity, ∇ is the total displacement of the ship, GM_t is the transverse metacentric heigh, ϕ_w is the equilibrium point.

Polar Model



The figure above is a polar plot showing stable boat speed as a function of wind angle and wind speed. The maximum boat speed is determined by varying the sail angle for different wind angles and wind speeds. While plots generated using simulation data are smoother, they sometimes fail to capture real-world uncertainties.

Environment Model

We use oceanic weather data from the Global Forecast System wave model (GFSwave), provided by the National Oceanic and Atmospheric Administration (NOAA). From this, we can get forecasts to use for planning as well as historical data to use as a ground truth. This source provides many data variables for waves which we hope to incorporate into our model in the future, but currently we only use the wind velocity variables.

We also use a base map from Natural Earth to identify the land versus ocean. The route planner and trajectory optimizer use this data to avoid obstacles. The base map is available at varying levels of precision, which affects algorithm speed.

Future Work

Each of these systems described have been built and work on their own. Our next objective is to link them together into a cohesive controller framework as described in the system overview. Additionally, we plan to build an optimal tracking controller using model-predictive control, and compare this system to the course/roll controller results.

In the future, beyond the scope of this class project, we would like to simulate the system with model mismatch and measurement noise, implement a state-estimator, and do a robustness analysis.

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