P1: Energy optimal control of a towing kite

Towing kites allow modern sea going vessels, like container ships, to cross the ocean with renewable energy [1]. In contrast to sailing ships, wind energy is harvested with a large kite that is anchored to the ship and pulls it forward. These kites must be controlled to harvest as much wind energy as possible and to avoid crashing the kite.

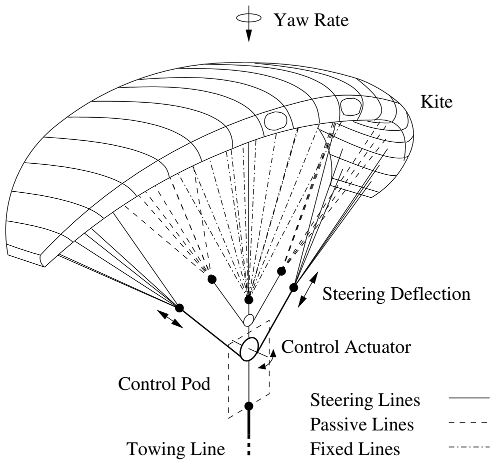

Figure 1: Towing kite schematic drawing.

Model predictive control is a suitable choice for this complex control task, as it allows to formulate the economic objective (maximize force on towing line), while considering the non-linear system equations exactly, as well as, complying with constraints to avoid crashing. To control the kite and to evaluate the developed controller, we consider the system model [1][2]:

$$\dot{\psi} = \frac{v_a}{L}\left(\delta - \frac{\cos(\theta)}{\sin(\theta)}\sin(\psi)\right), \tag{1a}$$

$$\dot{\theta} = \frac{v_a}{L}\left(\cos(\psi) - \frac{\tan(\theta)}{E}\right), \tag{1b}$$

$$\dot{\phi} = -\frac{v_a}{L\sin(\theta)}\sin(\psi), \tag{1c}$$

where ψ denotes the yaw angle of the kite and θ and ϕ are the zenith and azimuth angle with respect to the anchor point in a spherical coordinate system. The kite is controlled with the steering deflection δ and influenced by E and v_a (glide ratio and relative wind speed), which are computed as

$$E = E_0 - c\delta^2, \tag{2}$$

$$v_a = v_0 E\cos(\theta), \tag{3}$$

with reference glide ratio E_0 and ambient wind speed v_0. Finally, we need to consider two important quantities: The tether force T_f and the kite height h, for which we write the expressions:

$$T_f = \frac{\rho v_0^2}{2} A\cos(\theta)^2(E+1)\sqrt{E^2+1}\cos(\theta), \tag{4}$$

$$h = L\sin(\theta)\cos(\phi). \tag{5}$$

To implement the model, consider the parameters in Table 1 and the bounds in Table 2.

Table 1: Model parameters

L Tether length	A Kite surface	c	h_{min} minimum height	E_0 ref. glide ratio
400	300	0.028	100	6

Table 2: Variable bounds

	states			input
	ψ	θ	ϕ	δ
lower bound	$-\pi$	0	$-\frac{1}{2}\pi$	-10
upper bound	π	$\frac{1}{2}\pi$	$\frac{1}{2}\pi$	10

Tasks

The control task is to maximize the tether force (4) while satisfying a minimum height $h \geq h_{\text{min}}$ (5). For this purpose you need to discretize the ordinary differential equation shown in (1) with orthogonal collocation on finite elements and formulate the MPC problem. The MPC controller should be tested on the "true" system in the form of a CasADi integrator. Your obtained trajectories should mimic the results shown in Figure 2.

Complete the following tasks:

- Formulate the MPC problem with orthogonal collocation on finite elements
- Tune and evaluate your MPC controller with the ***true*** system for a constant wind-speed of $v_0 = 10\,\text{m}\,\text{s}^{-1}$.
- Use our provided wind model to implement a realistic wind trajectory affecting the simulator
- Update your MPC controller to cope with the uncertainty:
  - Implement soft-constraints for the kite height
  - Use the most recent wind-speed for the current prediction

Hints

- Consider a sufficiently long prediction horizon of approximately 10-20 seconds.
- Your discrete time-step could be between 0.05s and 0.5s.
- Visualize closed-loop trajectories by plotting θ over ϕ as in Figure 2.

Deliverables

The following materials have to be submitted in order to pass the semester project:

- **Recorded final presentation** (video screencast). The presentation must be **5-7 minutes** (for the entire group) and the file should not exceed **200 mb**. Highlight on the slides which group member(s) are responsible.
- **Written report** to present and discuss the obtained results. You must use the supplied template on Moodle and write no more than **3-4 pages** (for the entire group). Highlight which group member worked on which section.

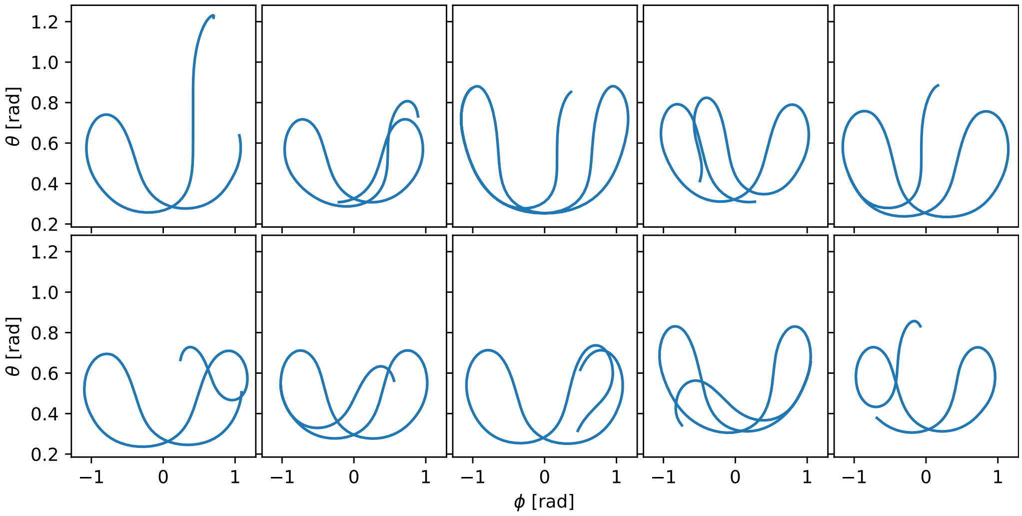

Figure 2: MPC controlled closed-loop trajectories for varying wind-speeds, glide ratios and height constraints.

- **Source code** of your project. Please ensure that the code is executable and optionally add a short explanation of the structure (readme).

Please ensure that all formal conditions (e.g. page limits, highlight responsible author) are satisfied, as we will deduct points for significant violations. Deadline for the submission is 25.01.2022. Please submit all deliverables via moodle.

Peer review

Part of this project is to submit a peer review of other projects. Peer reviewing will be available on moodle from 26.01.2022 and must be completed by 31.01.2022. You can only receive full additional points by participating in the peer-review process.

Responsible tutor

Please address questions to:

Name	Contact
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References

[1] Michael Erhard and Hans Strauch. "Control of Towing Kites for Seagoing Vessels". In: *IEEE Transactions on Control Systems Technology* 21.5 (Sept. 2013), pp. 1629–1640. ISSN: 1558-0865. DOI: 10.1109/TCST.2012.2221093.

[2] Benjamin Karg and Sergio Lucia. "Learning-Based Approximation of Robust Nonlinear Predictive Control with State Estimation Applied to a Towing Kite". In: *2019 18th European Control Conference (ECC)*. 2019 18th European Control Conference (ECC). June 2019, pp. 16–22. DOI: 10.23919/ECC.2019.8796201.