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Trajectory Optimization of Dynamic Soaring Considering Closed-Loop Dynamics

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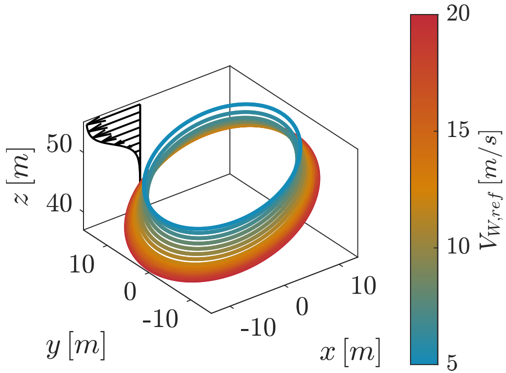
Dynamic soaring, a bio-inspired flight technique observed in wandering albatrosses, is a natural way of harvesting wind energy. In future applications, leveraging dynamic soaring may allow unmanned aerial vehicles (UAVs) to increase their range and endurance.

Autonomous dynamic soaring requires possibly optimal trajectory planning and precise tracking to maximize the energy gain in shear winds. Following a widely used approach to generate open-loop optimal control trajectories based on reduced order models (e.g. point mass models) results in poor energy extraction in closed-loop evaluations. Therefore, we directly include the closed-loop model into the trajectory planning process. This model contains a higher fidelity aircraft model and a tracking controller developed in [2]. Due to the complexity of the model (e.g. discontinuities) no analytical gradient information is available. Thus, the gradient is approximated numerically by forward finite differences. This leads to increased computational cost in the planning process. To counteract this, the trajectory is parameterized to reduce the number of decision variables in the optimization. The simplest parameterization of a loitering dynamic soaring trajectory is an inclined circle resulting in three parameters, the inclination angle δ, the reference height h, and the radius r. This reduces complexity, however, comes with a loss in optimality as the shape of the trajectory is preset.
The optmization objective is the mean total energy performing closed-loop dynamic soaring for 150 seconds and indicates the energy extraction capability of the planned trajectory. The optimal parameters are determined by single shooting using a Quasi-Newton method. The solution takes several minutes on a standard notebook, however, adaptation strategies exist to adjust the parameters online. The figure below shows the optimized trajectories for different shear wind speeds $V_{W,ref}$, indicated by the color of the trajectory. $V_{W,ref}$ is the wind speed prevailing in the free stream. The shape of the shear wind layer and the wind direction is plotted in black.



Optimal trajectories for different shear wind speeds.

References:

[1] Gücker F., Beyer Y., Steen M., Hecker P., Accurate tracking of highly dynamic airplane trajectories using incremental nonlinear dynamic inversion, Proceedings of the 2022 CEAS EuroGNC Conference, CEAS-GNC-2022-069