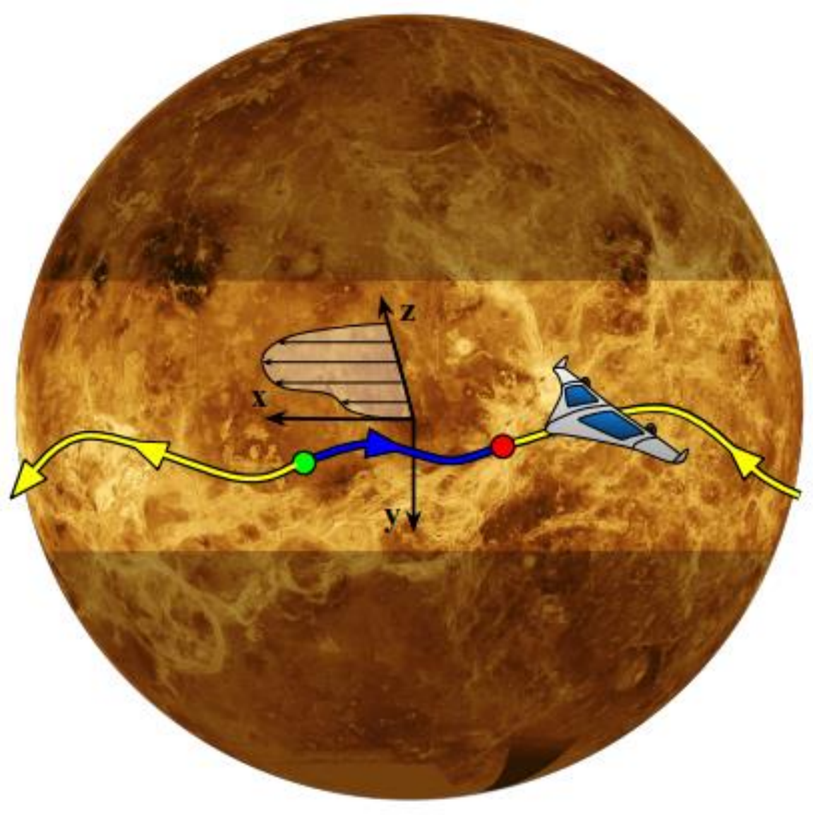
Towards Finding Energy Efficient Paths for Hybrid Airships in the Atmosphere of Venus

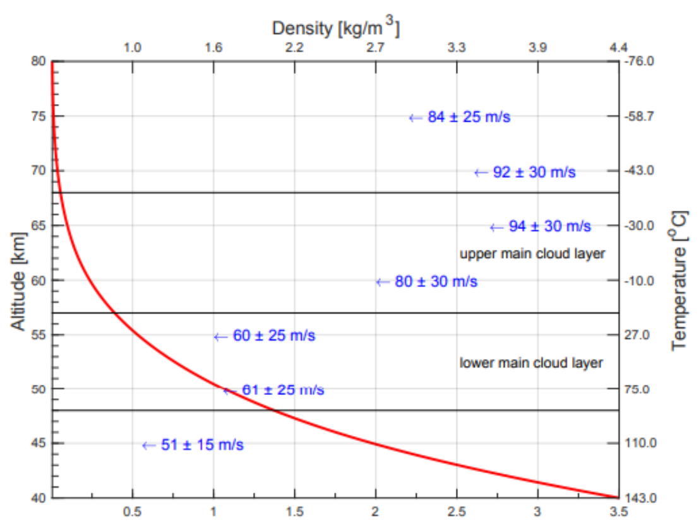
Bernardo Martinez Rocamora Jr., Anna Puigvert i Juan, Guilherme A. S. Pereira

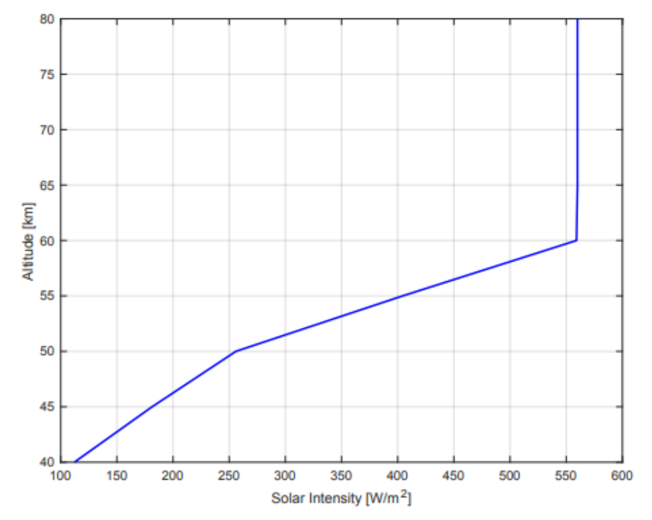
Field and Aerial Robotics Laboratory, Department of Mechanical and Aerospace Engineering,
Benjamin M. Statler College of Engineering and Mineral Resources

Introduction

- Venus is key to understanding Earth's planetary and climate evolution[1]
- Planet Venus is our "closest" neighbor
  - Similarity in size, mass and gravity.
  - Greenhouse turned the surface into an inhospitable place (460ºC and 90bar)
  - The cloud layer is a harsh environment. But it has an Earth-like temperature and pressure at 50-70 kilometers
- Longitudinal wind speeds: 90-120 m/s







Motivation

- Advancing technology for future exploration missions in challenging environments that have strong winds like the Venusian atmosphere

Research Goals

- Development of a motion planner that can handle environmental flows and that accounts for vehicle dynamics and battery state

Problem Statement

The problem can be defined as

minimize $C(\boldsymbol{x}(t), \boldsymbol{u}(t))$

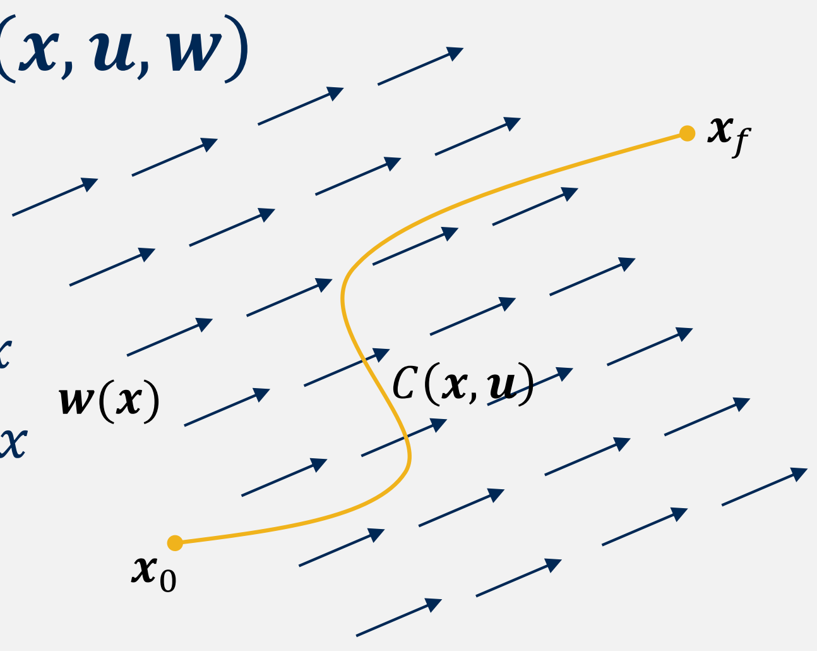
subject to $\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{w})$

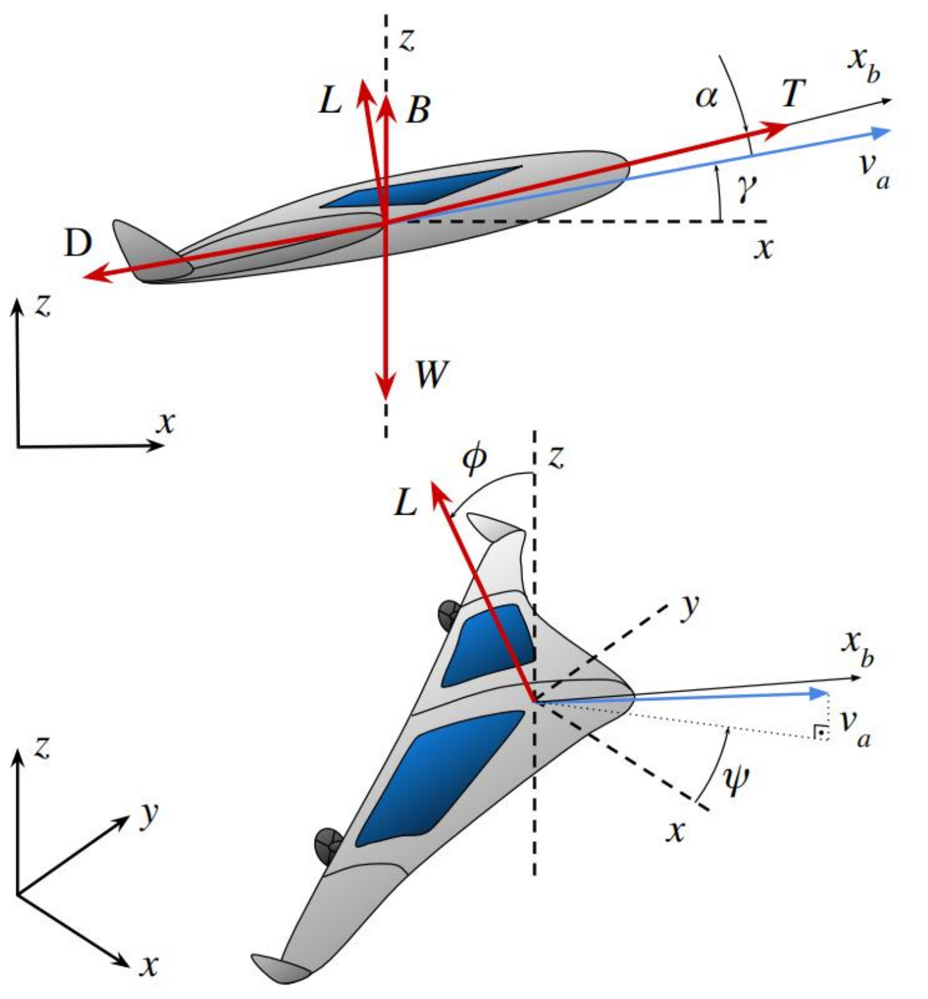
$\boldsymbol{x}(0) = \boldsymbol{x}_0$

$\boldsymbol{x}(t_f) = \boldsymbol{x}_f$

$\boldsymbol{x}_{min} \le \boldsymbol{x} \le \boldsymbol{x}_{max}$

$\boldsymbol{u}_{min} \le \boldsymbol{u} \le \boldsymbol{u}_{max}$





The Airship Point-Mass Model with Buoyancy

The airship model was based on [2][3]

Balance of forces in the x-z plane

$$(W - B)\cos\gamma = L\cos\phi + T\sin\alpha$$

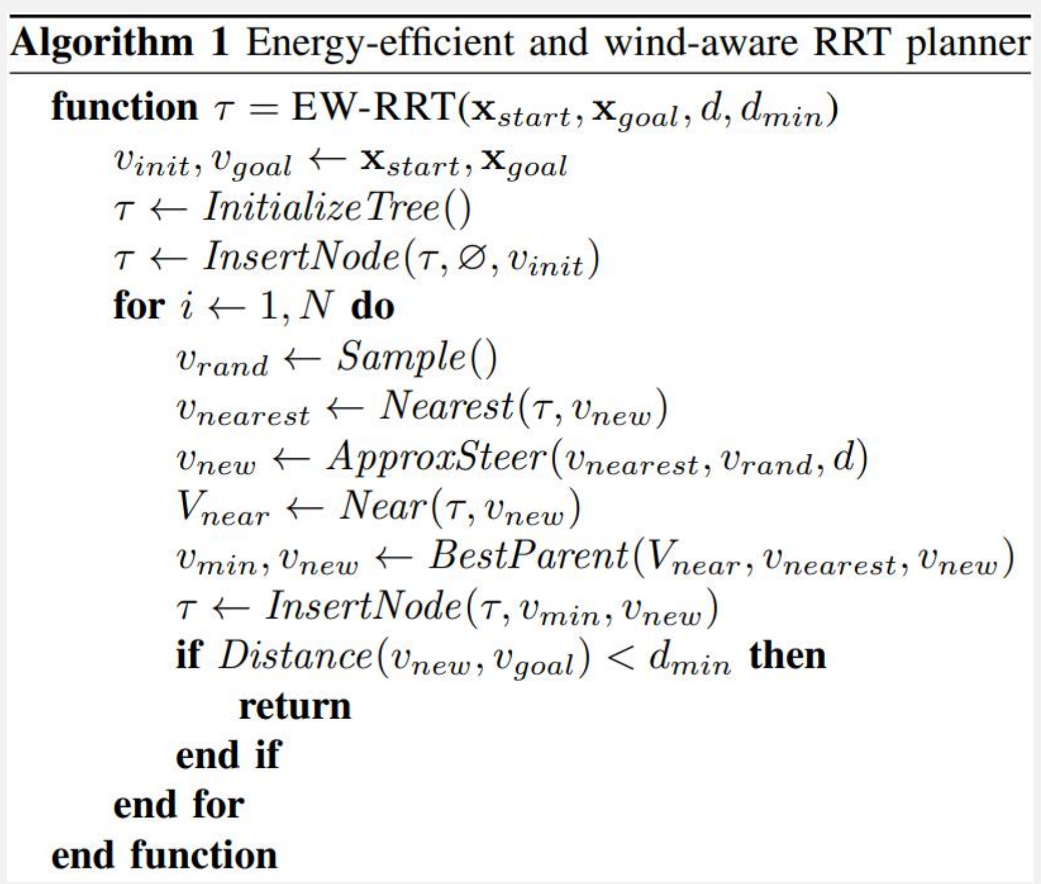
$$(W - B)\sin\gamma = D - T\cos\alpha$$

Assuming $\alpha \approx 0$, then $T\sin\alpha \approx 0$ and $T\cos\alpha \approx T$:

- Lift force and coefficient: $\mathrm{L} \approx \frac{(W-B)\cos\gamma}{\cos\phi} = \frac{1}{2}\rho v_a^2 S c_L \Rightarrow c_L = \frac{2(m-\rho V)g\cos\gamma}{\rho v_a^2 S\cos\phi}$
- Drag force and coefficient: $c_D = \sum_{i=0}^{n} a_i\, c_L^i = c_{D,0} + \frac{c_L^2}{\pi\, AR\, e} \Rightarrow D = \frac{1}{2}\rho v_a^2 S c_D$
- Required thrust force: $T = \frac{D-(W-B)\sin\gamma}{\cos\alpha} = \frac{\frac{1}{2}\rho v_a^2 S c_D - (m-\rho V)g\sin\gamma}{\cos\alpha}$

Energy-Efficient and Wind-Aware RRT

Sampling-based motion planner uses a tree of kinematically feasible trajectories considering the effect of the wind drift



Algorithm 1 Energy-efficient and wind-aware RRT planner

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function $\tau$ = EW-RRT($\mathbf{x}_{start}, \mathbf{x}_{goal}, d, d_{min}$)
    $v_{init}, v_{goal} \leftarrow \mathbf{x}_{start}, \mathbf{x}_{goal}$
    $\tau \leftarrow InitializeTree()$
    $\tau \leftarrow InsertNode(\tau, \varnothing, v_{init})$
    for $i \leftarrow 1, N$ do
        $v_{rand} \leftarrow Sample()$
        $v_{nearest} \leftarrow Nearest(\tau, v_{new})$
        $v_{new} \leftarrow ApproxSteer(v_{nearest}, v_{rand}, d)$
        $V_{near} \leftarrow Near(\tau, v_{new})$
        $v_{min}, v_{new} \leftarrow BestParent(V_{near}, v_{nearest}, v_{new})$
        $\tau \leftarrow InsertNode(\tau, v_{min}, v_{new})$
        if $Distance(v_{new}, v_{goal}) < d_{min}$ then
            return
        end if
    end for
end function
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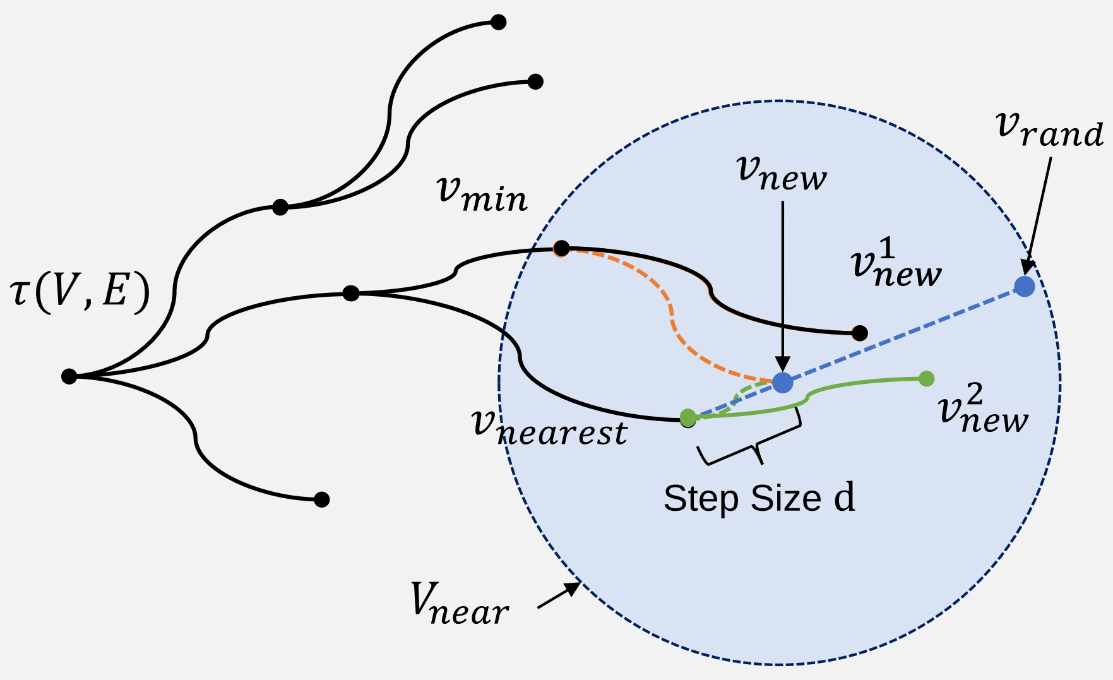


Proposed Cost Function

Cost for new pair (edge) is then given by:

$$C = \begin{cases} \boxed{E_{prop}} + \boxed{E_{pot}^{opp}} + \boxed{E_{solar}^{opp}}, & \text{if } b + \Delta b \ge 0 \\ \infty, & \text{if } b + \boxed{\Delta b} < 0 \end{cases}$$

Where the battery level changes according to $\Delta b = -E_{prop} + E_{solar}$

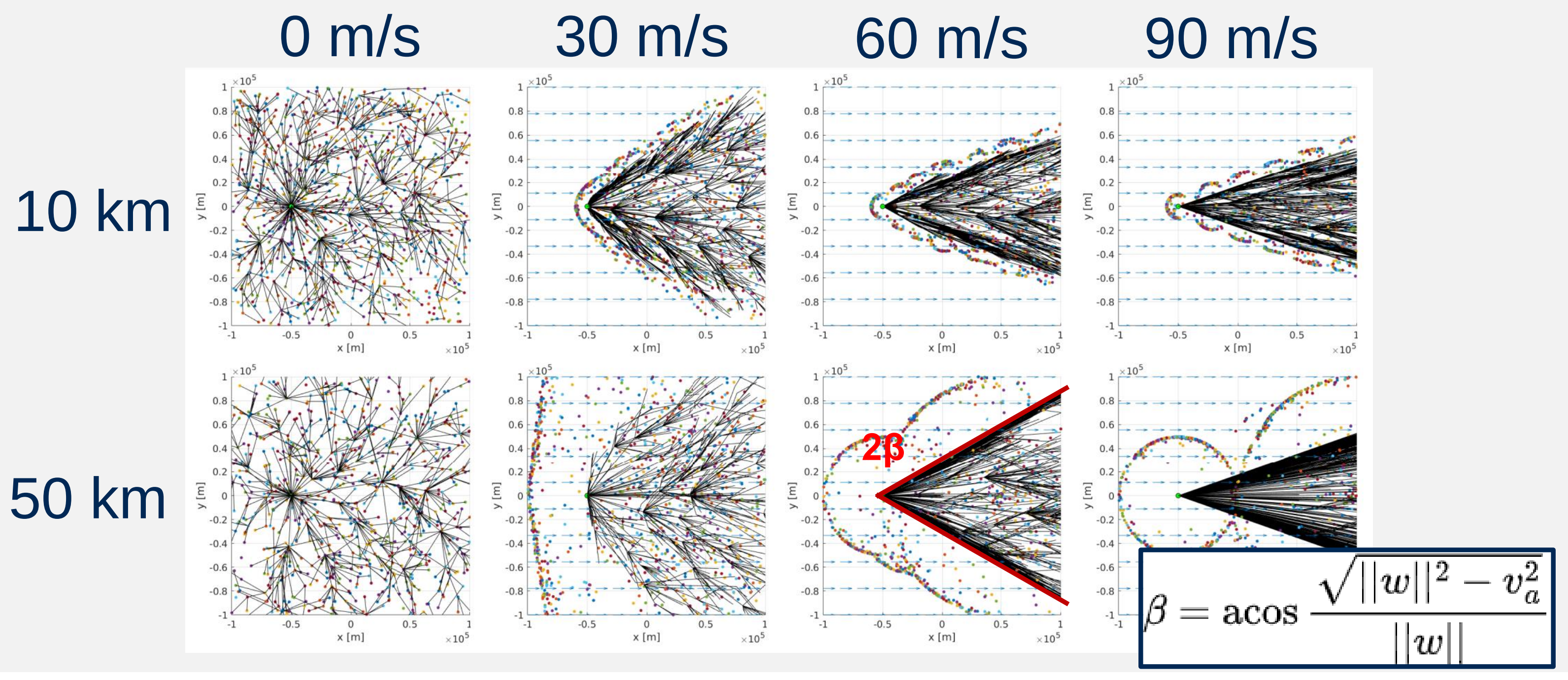
Cost due to energy discharge at the propellers: $\mathrm{E_{prop}} = \int_{t_0}^{t_f} \frac{T v_a}{\eta_{prop}\eta_{shaft}} dt$

Cost of opportunity for the potential energy: $E_{pot}^{opp} = E_{pot}^{max} - E_{pot} = mg(h_{max} - h)$

Cost of opportunity for the solar energy: $E_{solar}^{opp} = E_{solar}^{max} - E_{solar} = \int_{t_0}^{t_f} P_{solar}^{max} - I_{solar}\eta_{panels}A_{panels} dt$

Results

Parametric investigation of wind speed and planning

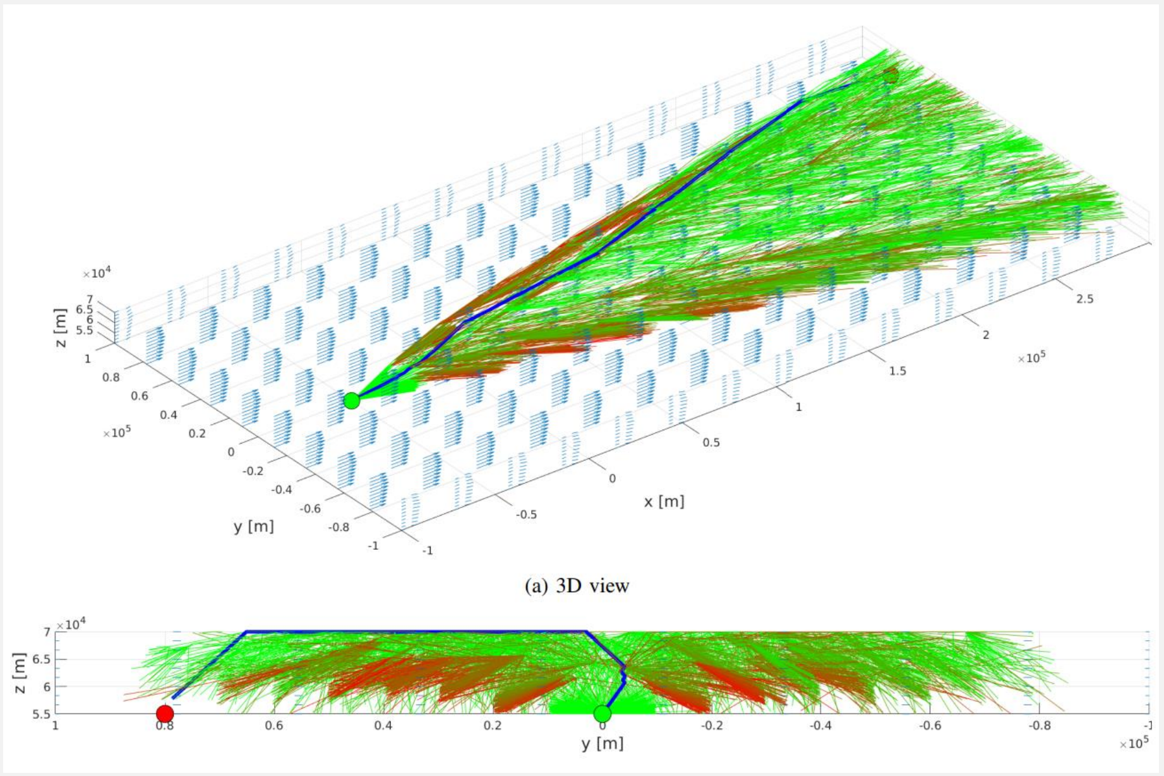


$$\beta = \mathrm{acos}\frac{\sqrt{||w||^2 - v_a^2}}{||w||}$$

Example mission

- Time-invariant and unidirectional wind
- Environment 400km x 200km x 15km

- Higher altitudes layers of the atmosphere preferred
  - Higher solar intensity
  - Lower air density
- Battery capacity is preserved on the planned path (green edges)
- The paths generated are not optimal



Conclusions

- A motion planning strategy was developed to find efficient paths for solar-powered hybrid airships flying in the atmosphere of Venus, where strong winds are present and battery charging is a function of the vehicle's altitude
- Future work will provide optimal paths, and going around the planet to mitigate feasibility constraints due to the wind

References

[1] VEXAG (2014). Venus Technology Plan. Venus Exploration Assessment Group (VEXAG).

[2] Griffin, K, Sokol, D., Lee, G, Polidan, R. "Venus Atmospheric Maneuverable Platform (VAMP) – A Concept for a Long-lived UAV at Venus." Venus Upper Atmosphere Investigations Science and Technical Interchange (STIM) Meeting, 2013.

[3] Chakrabarty, A., and Langelaan, J. "UAV flight path planning in time varying complex wind-fields." 2013 American control conference. IEEE, 2013.

West Virginia University
BENJAMIN M. STATLER COLLEGE OF ENGINEERING AND MINERAL RESOURCES

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