Introduction

My advisors and I have been looking into airborne wind energy, which is similar to traditional wind turbines in that it harvests energy from the wind. However, instead of being attached to the ground with a tower, the turbine flies at very high altitudes, up to about 1000 ft. The advantages of being so high are that the winds are generally a lot stronger and steadier. We have been specifically looking at a buoyant air turbine, which is basically a horizontal wind turbine inside of a ring shaped helium balloon. The balloon takes the system to high altitudes, and tethers link the balloon to the ground allowing us to control it.

Transition

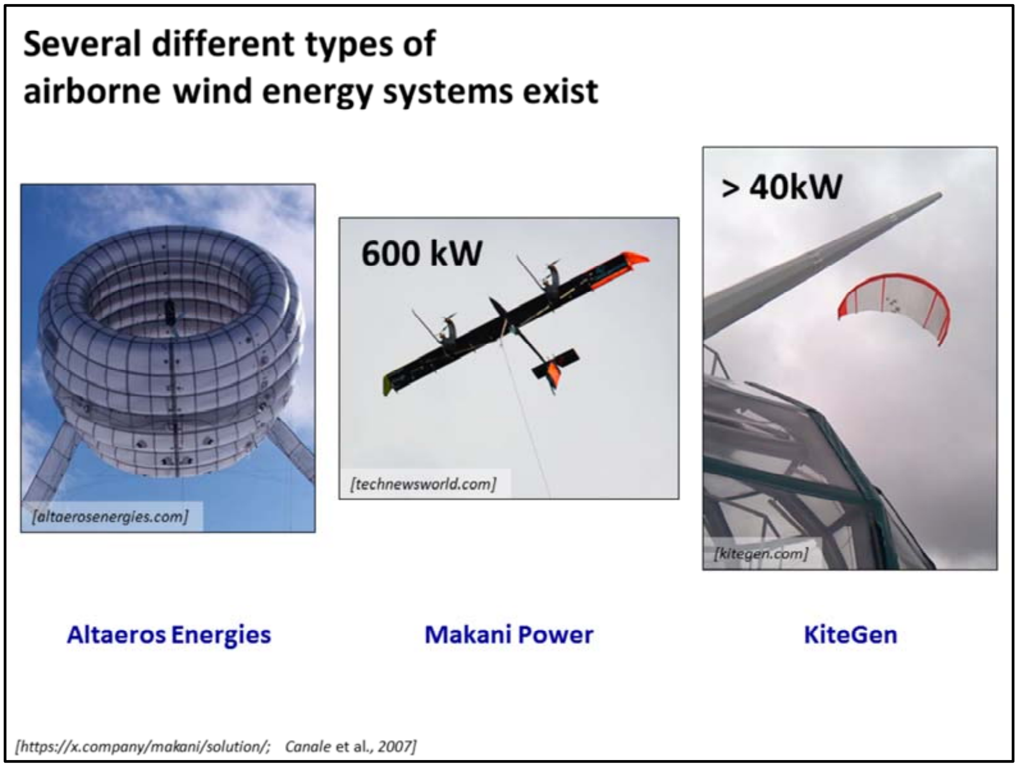
When we are looking at an airborne wind turbine, there are a lot of systems that exist; furthermore, there are a number of companies looking at these systems.

Reference for Image

http://inhabitat.com/worlds-first-airborne-wind-turbine-to-bring-renewable-energy-and-wifi-to-alaska/

References for Presentation Content

Kehs, M., Vermillion, C., and Fathy, H., 2015, "Maximizing average power output of an airborne wind energy generator under parametric uncertainties," *Proc. of the ASME 2015 Dynamic Systems and Control Conference*.



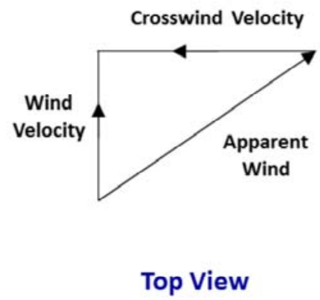
Content

One company that is looking at buoyant wind turbines is Altaeros Energies. Another company, Makani Power, is looking at a plane like system with rigid wings to allow the turbine to fly and harvest energy. There are also kite based systems being looked at by the company KiteGen. These systems are all similar in that they harvest wind energy at high altitudes.

To give some perspective on the capacity of these designs, Makani Power's design generates about 600 kW and KiteGen has a prototype that generates 40 kW, but KiteGen is also simulating much larger systems and different kite configurations. When compared to conventional turbines, which typically generate 1-3 MW, these airborne wind energy systems are still going to generate a lot less power, but there is also the added benefit of less materials to manufacture. To provide more perspective, KiteGen projects that their system has the potential to cost less than fossil fuels in power per unit cost.

References for Images
http://www.altaeros.com/energy.html
https://www.technewsworld.com/story/78118.html
http://www.kitegen.com/en/it/wp-content/uploads/kite_stem.jpg
References for Content
Makani kites, *https://x.company/makani/solution/*
Canale, M., Fagiano, L., and Milanese, M. 2007, "Power Kites for Wind Energy Generation," *IEEE Control Systems Magazine*, 27(6), pp. 25-38.

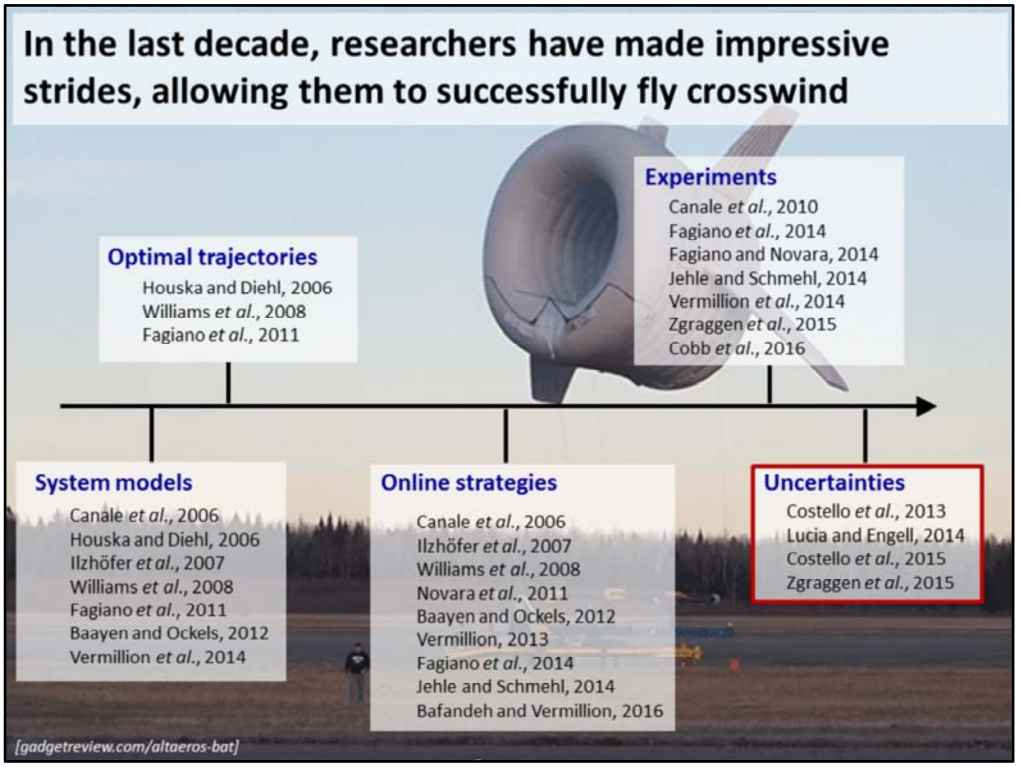
Power is related to the *cube* of apparent wind speed, and this speed can be increased by flying in figure-8 trajectories



Content

These airborne wind energy systems show a lot of potential because they can fly crosswind, which is something conventional systems cannot do. Going back to the buoyant air turbine, if you roll the system, the wings give it a lift force; therefore, forcing the system to fly across the wind. The benefit from flying crosswind is an increase in apparent velocity of the wind coming into the system. Because the power is related to the cube of the wind speed, any increase in the apparent velocity is going to have a huge impact in the amount of power generated.

Reference for Image
clipartfest.com



Content

There has been a lot of research in the last decade to get these systems closer to being commercially viable. Researchers have developed models for the system, determined what the optimal crosswind trajectories are, developed online strategies for how to implement these trajectories, validated their work with experiments, and during the last few years investigated how uncertainties come into play with these systems. At these high altitudes there is a lot of uncertainty with wind speed, as well as some uncertainty with system models and model parameters.

Transition

Our research falls into this uncertainty category since optimal trajectory changes significantly with wind speed.

Reference for Image

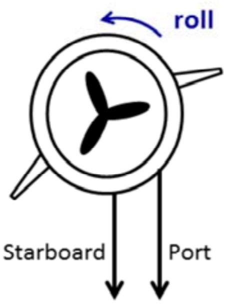
gadgetreview.com/altaeros-bat

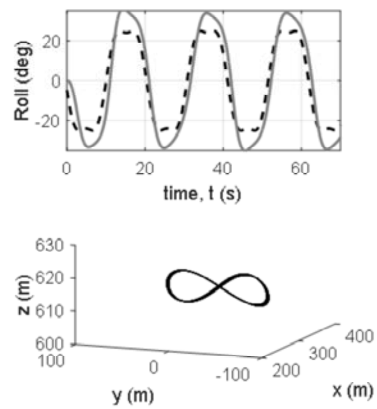
Content

We want to see if we can use extremum seeking to optimize a buoyant air turbine's figure-8 trajectory. Extremum seeking is a tool from adaptive control that takes into account a lot of the uncertainties. More specifically we want to maximize net power even if wind speed is uncertain. Therefore, wind speed is the uncertainty that we are looking at in this study.

Reference for Image
gadgetreview.com/altaeros-bat

Our controller builds on the fact that the system's roll dictates the figure-8 trajectory



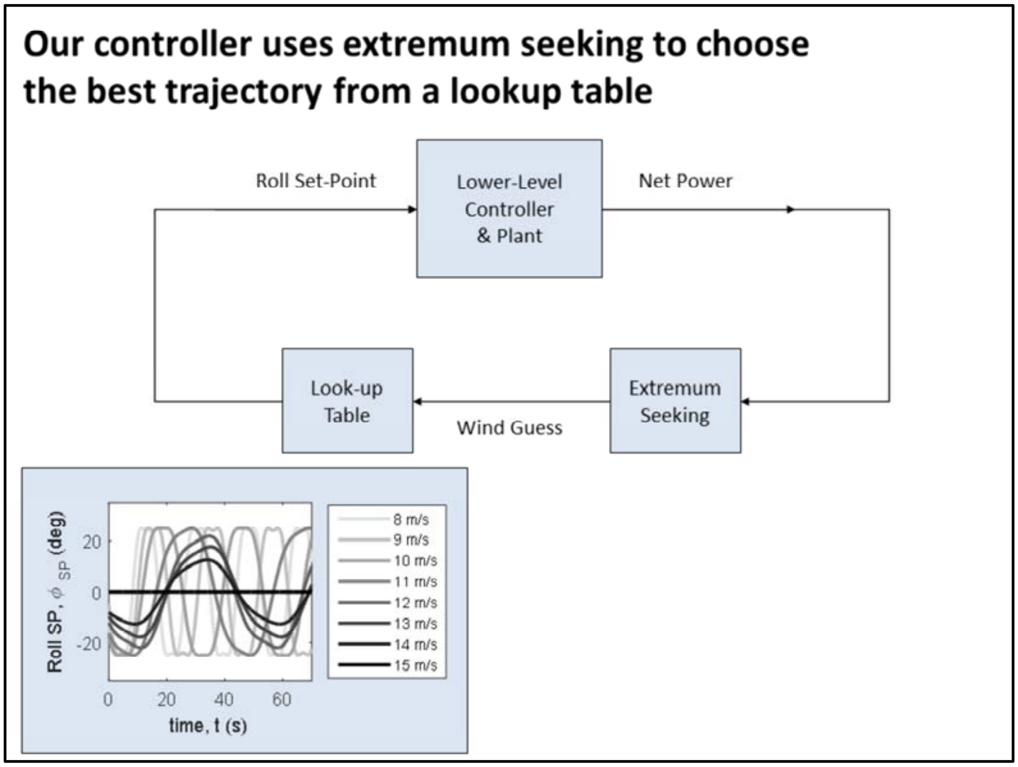


Content

Our controller builds on the fact that the system's roll dictates the figure-8 trajectory. We start by setting a roll set-point profile, followed by using a motor controller that pulls on the left and right tethers to achieve the desired roll. Then our motor controller gets close to the desired set-point. To get the figure-8 shape we are going to want a periodic trajectory for the roll set-point. The motor controller implements the roll set-point giving you a figure-8.

Transition

The challenge is how do we pick and optimize that roll set-point.



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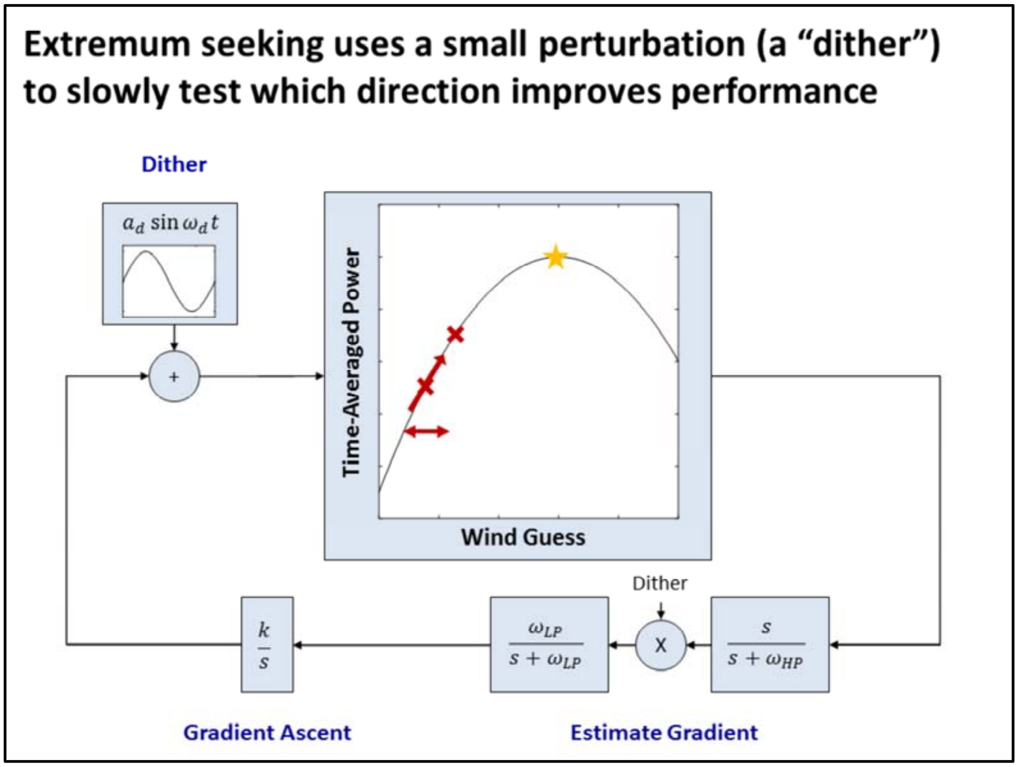
Our controller uses extremum seeking to choose the best roll set-point that generates the most power. Since wind is the only uncertainty in this study, we come up with a lookup table. We can compute what the optimal trajectory is at each wind speed using MATLAB and system models. The results are displayed in the lower left hand side of the slide; moreover, these are the optimal roll set-points for different wind speeds. Then if we have a guess of the wind we can simply implement that trajectory.

Transition

To get this guess, we are going to use extremum seeking, which takes into account the wind's uncertainties.



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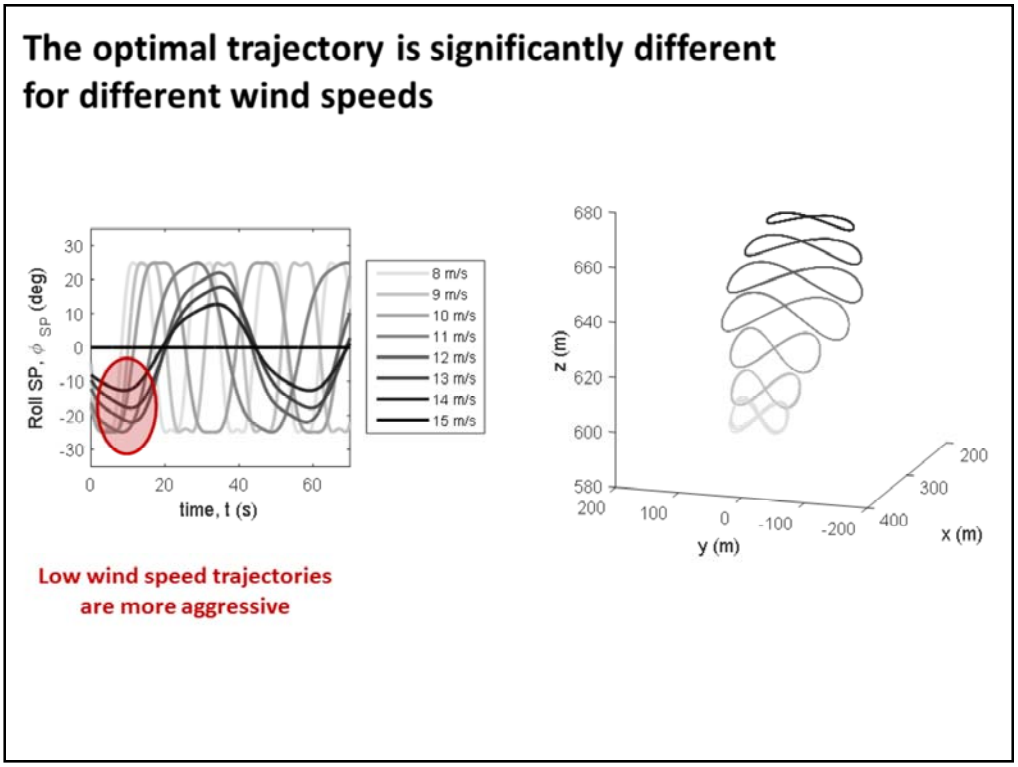
Let's say you have a function with a maximum at the yellow star, but you do not know what this function looks like. Also, you are initially operating at the red X which is not optimal. What extremum seeking does is perturb the system around the operating point, and to get these perturbations, also called a "dither," you just add a small sine wave to the system. The sine wave will allow you to check the performance of the system to the left and the right of your operating point. Then you use filters on the left and right data to approximate the gradient of the system. Using gradient ascent you climb a little higher toward the optimum, and this process repeats itself until you reach the optimum. The only issue with extremum seeking is it tends to be fairly slow. The slow speed is caused by the sine wave, which needs to have a slow frequency in order to give the system time to get a good average of what the power would be to the left and right of the operating point.

Transition

Now, we will look more into what these optimal roll set-point trajectories look like.



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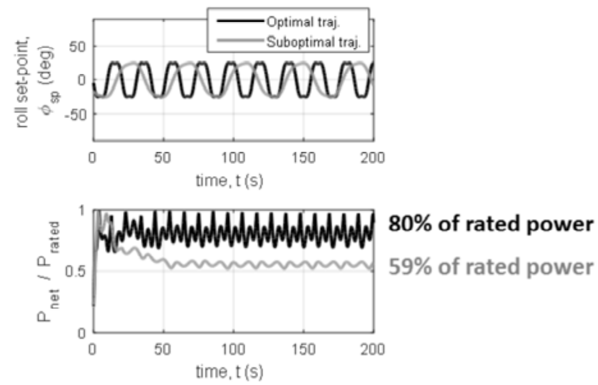
Displayed are some optimal trajectories for different wind speeds, and you will notice that low wind speed trajectories are more aggressive. By more aggressive, we mean that their amplitudes are a little larger and their periods are a little shorter. This comes into play when determining how good the trajectories do when acquiring power.

The optimal trajectory is significantly different for different wind speeds



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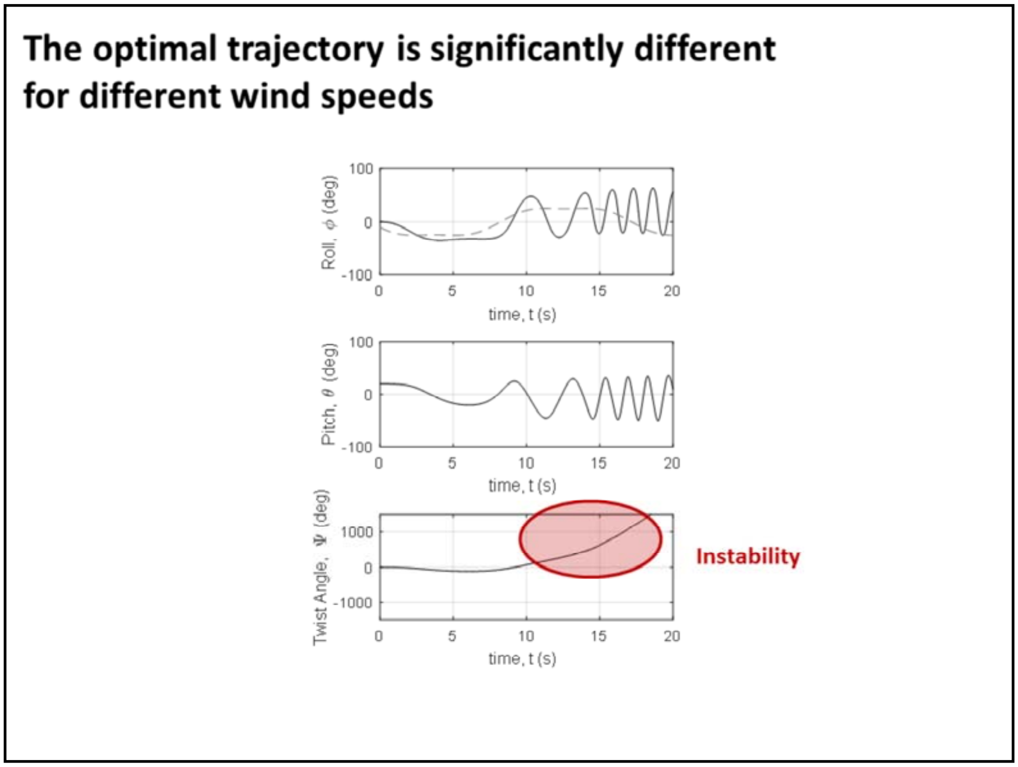
Here we have an example with a 9 m/s wind speed. The optimal trajectory is shown in black, and it is fairly efficient being able to get 80% of the rated power. Now if we were to put in a sub-optimal trajectory, shown in gray, the system would only be able to get 59% of the rated power. This study shows that it is important to be operating at that precise optimum; otherwise, a large amount of power could be lost.



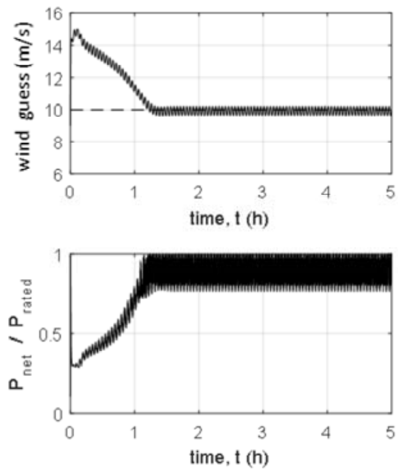
Content

These aggressive trajectories also lead to the problem of instability. For example, if you implement an aggressive trajectory, which works efficiently at low wind speeds, in a high wind speed environment the system can become unstable. The displayed graph shows an unstable system that is twisting out of control.

Transition

Now, let's take a look at what our controller does when we put it all together using extremum seeking.

The controller converges to the best trajectory in the bank in less than 2 hours



True wind: **10 m/s**
Initial guess: **14 m/s**

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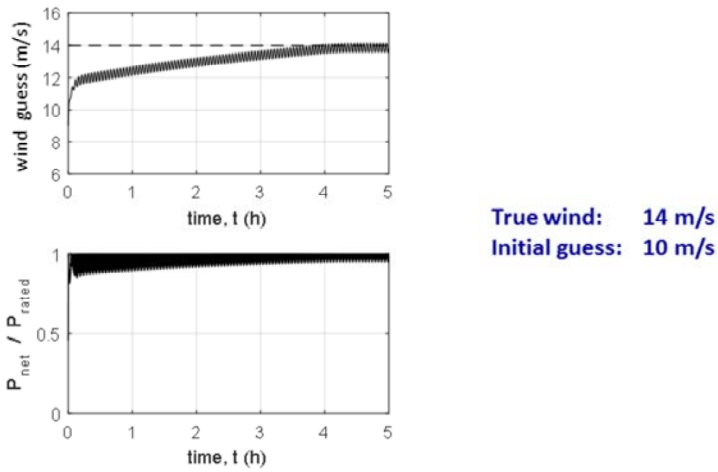
Here is a simulation where our wind guess is too high. Extremum seeking through the sine wave perturbation is able to test the direction that improves the amount of generated power. Over the course of the simulation, the amount of generated power doubles that of the initial operating point. This simulation took less than 2 hours to complete, yet the extremum seeking had a substantial impact on the amount of generated power.

The controller converges to the best trajectory in the bank in about 4 hours



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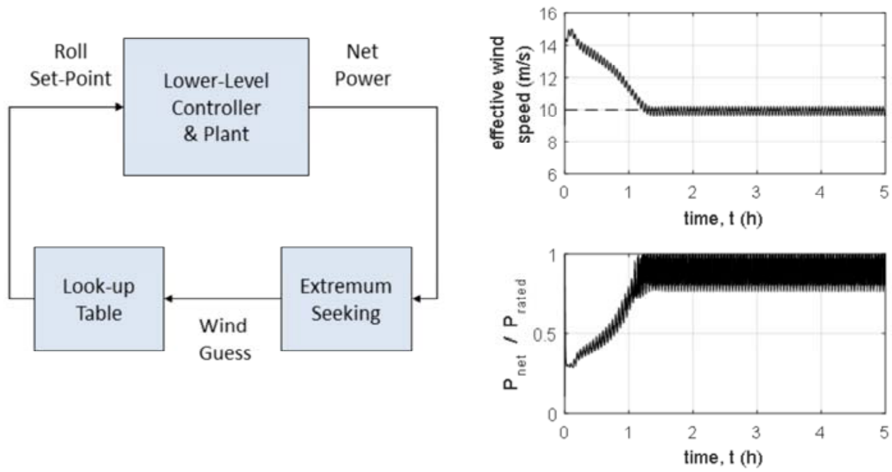
Here is another simulation where our wind guess is too low. Again, extremum seeking is able to find the optimum, and power is increased. However, in this case it took about 4 hours to converge on the optimum. The reason this case had a longer convergence time is because the cost-function gradient was a little more shallow.

Although convergence is slow, extremum seeking can select the optimal trajectory out of the bank of trajectories



Conclusion

In conclusion, the convergence speeds that we are looking at are slow, and we are looking at ways to increase our convergence speed for future work. Overall, our study did show that extremum seeking is a good tool for optimizing the trajectories of airborne wind energy systems. In addition, by looking at the aggressiveness of the different trajectories, we were able to show the importance of flying at the precise optimal trajectory in terms of power generation.

Thank you

Questions?