Politecnico di Torino
Dept. of Control and Computer Engineering

Complex Systems Modeling and Control
Research group

Optimization of high-altitude wind energy generators

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AWE technologies: rough classification

Altitude range
Boundary Layer vs Jet Stream

Lift type
Aerodynamic lift vs Aerostatic lift vs Rotorcraft

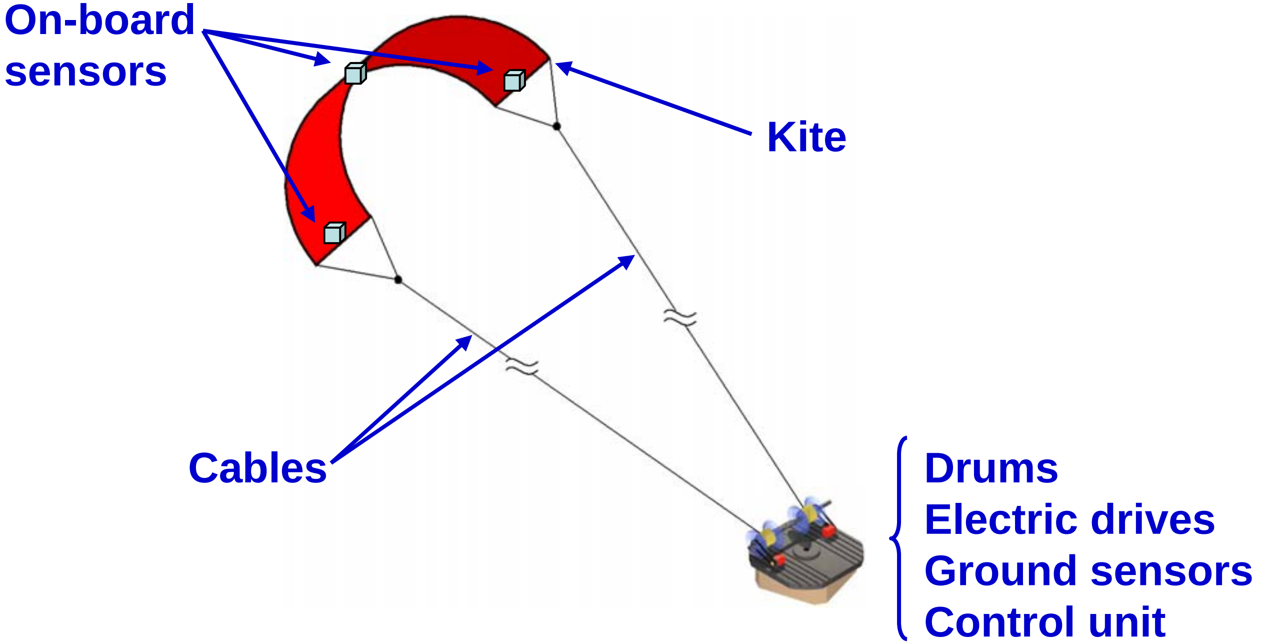
Generator position
Ground Level vs On Board

Kitenergy

Kitenergy is a AWE technology that works in the boundary layer, exploits aerodynamic lift of controlled tethered wings and generates electricity on the ground

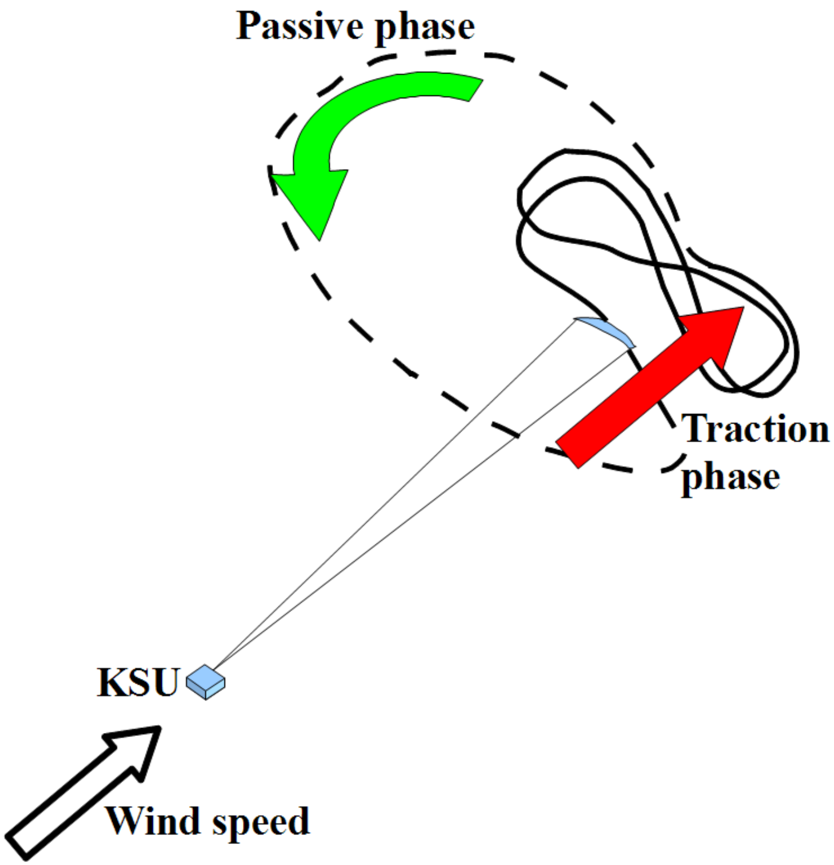
Kite Steering Unit

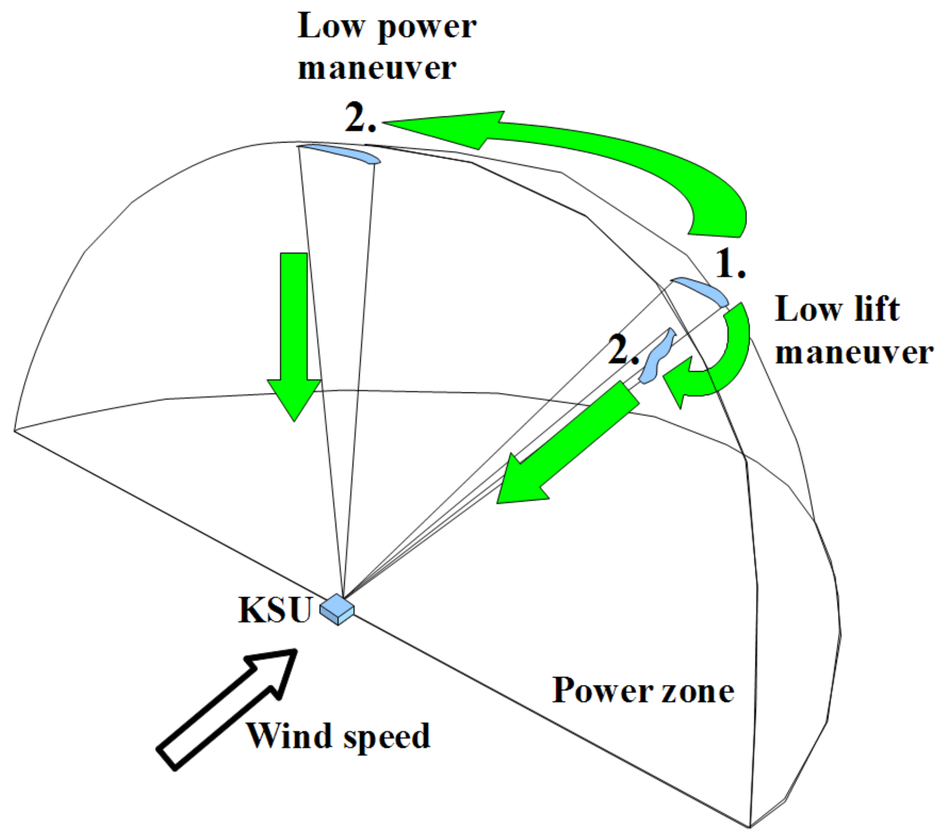
- The core of Kitenergy is the **Kite Steering Unit** (KSU)



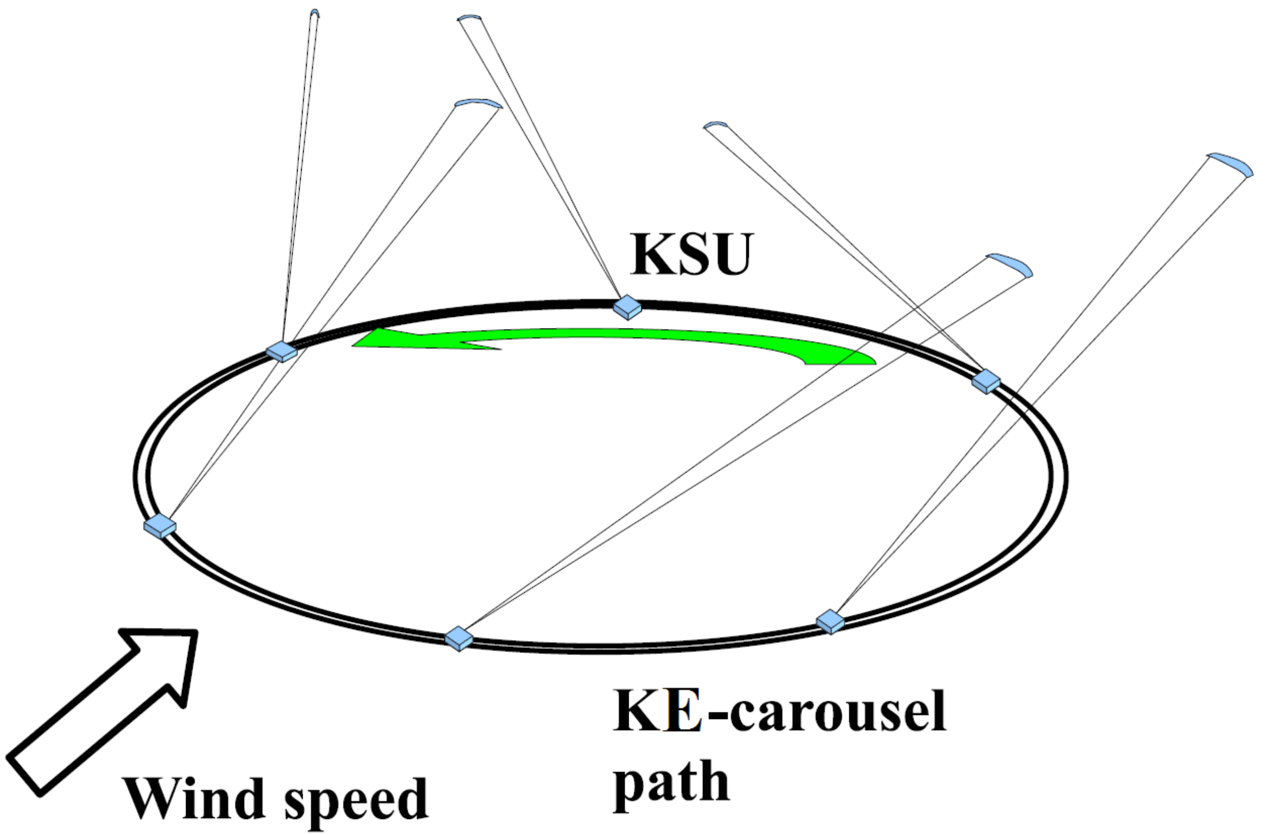
- The KSU can be employed to generate energy in **different ways**

KE-yoyo configuration (“yoyo”, “pumping kite”)

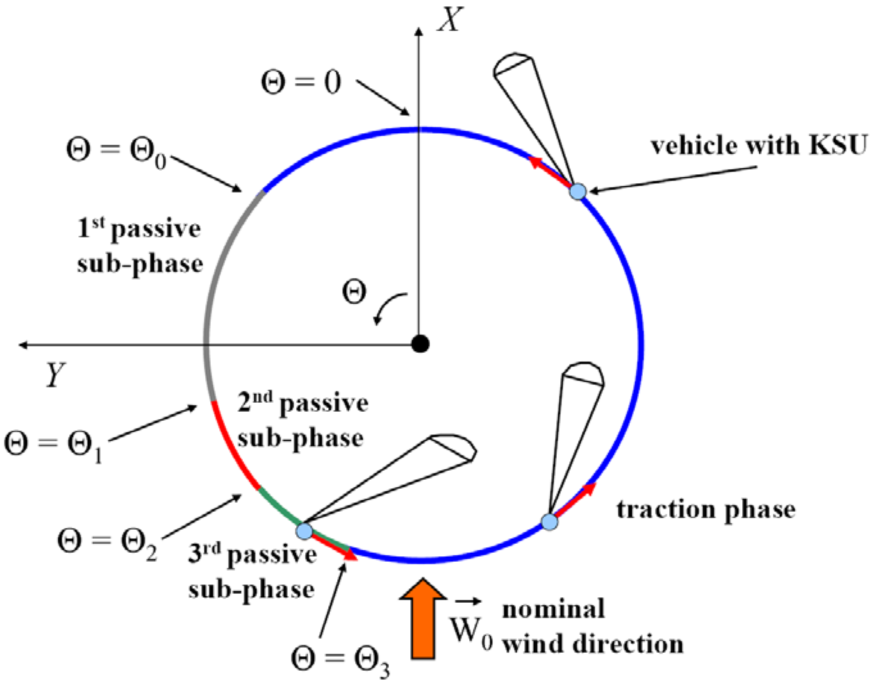




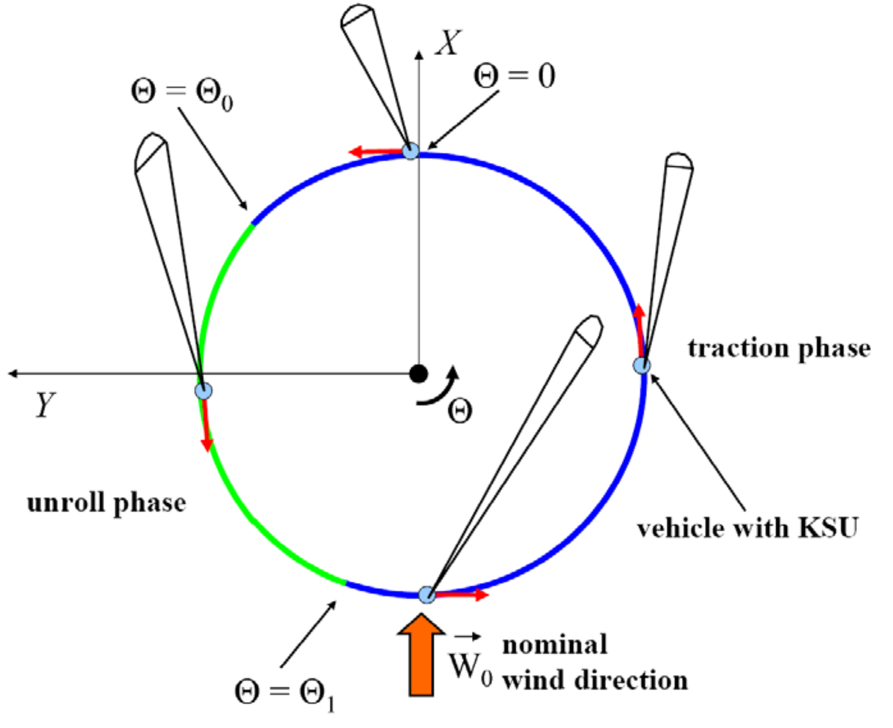
KE-carousel configuration



KE-carousel configuration

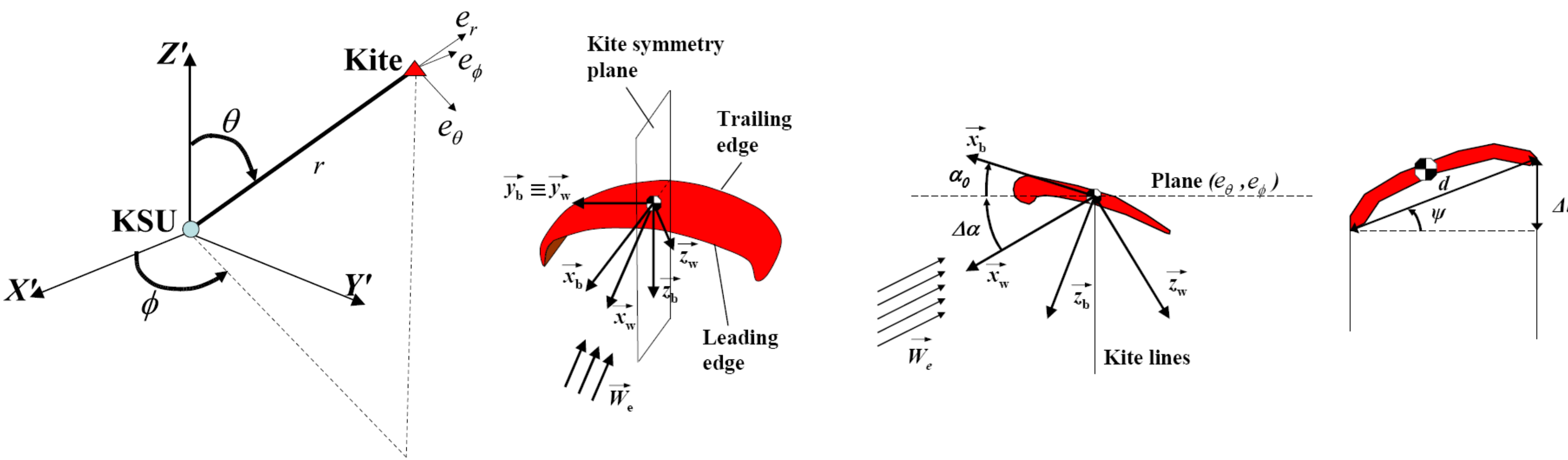


Operation of a KE-carousel with fixed cable length



Operation of a KE-carousel with variable cable length

Kitenergy model

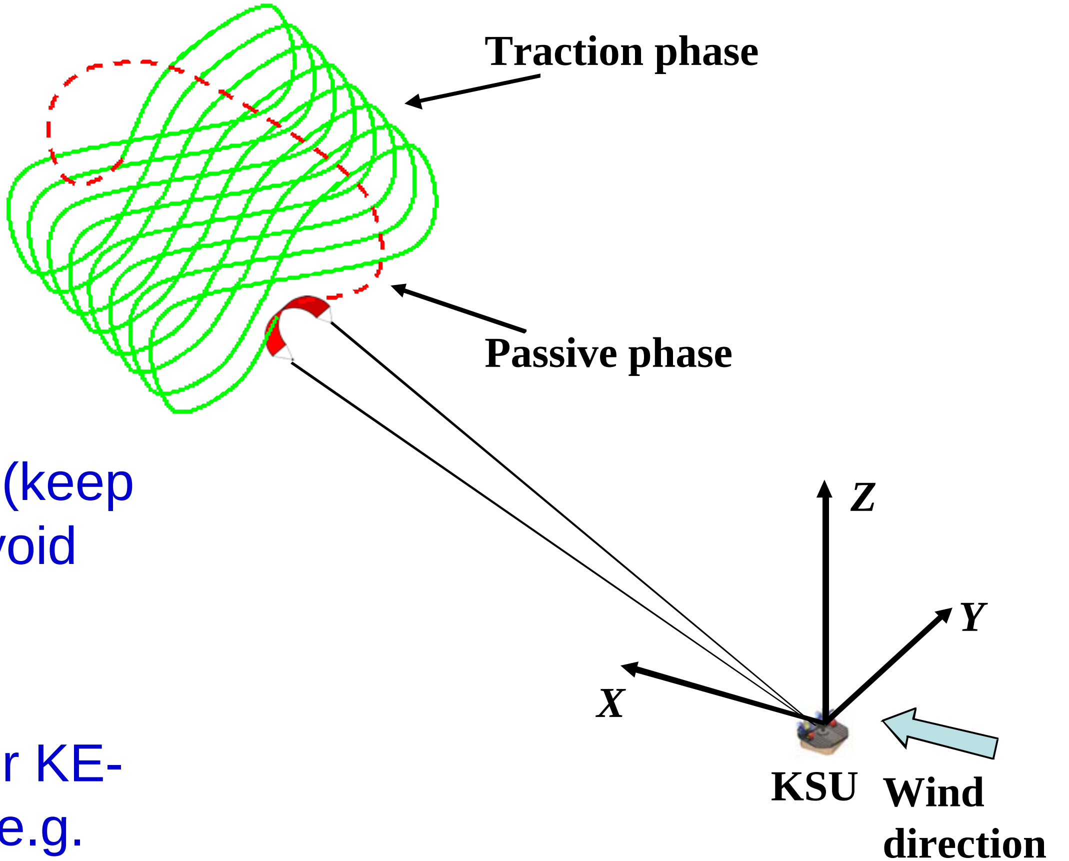


- The system model takes into account **apparent forces**, **gravity forces** (wing and cables), **aerodynamical forces**, **cable drag**, **wind shear**, **cable traction** forces.

- Model variables: $x = [\theta, \phi, r, \dot{\theta}, \dot{\phi}, \dot{r}]^T, \; p = \vec{W}_0, \; u = \psi, \; d = \vec{W}_t$

HAWE control problem

- **Keep stability** of the wing.
- **Maximize** the net **generated energy**.
- **Satisfy physical constraints** (keep the kite far from the ground, avoid line wrapping).
- Each configuration (KE-yoyo or KE-carousel) and working phase (e.g. traction phase, passive phase, etc.) has its own **performance goal**.



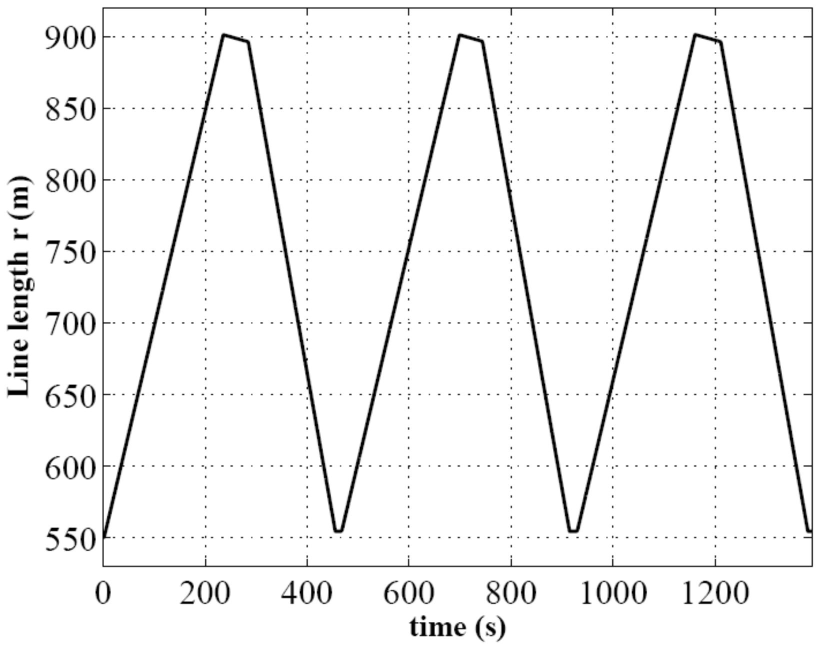
Model Predictive Control (MPC)

- MPC is a model-based control technique in which, at each sampling time kT_c, a Constrained Finite Horizon Optimal Control Problem (CFHOPC) is solved.

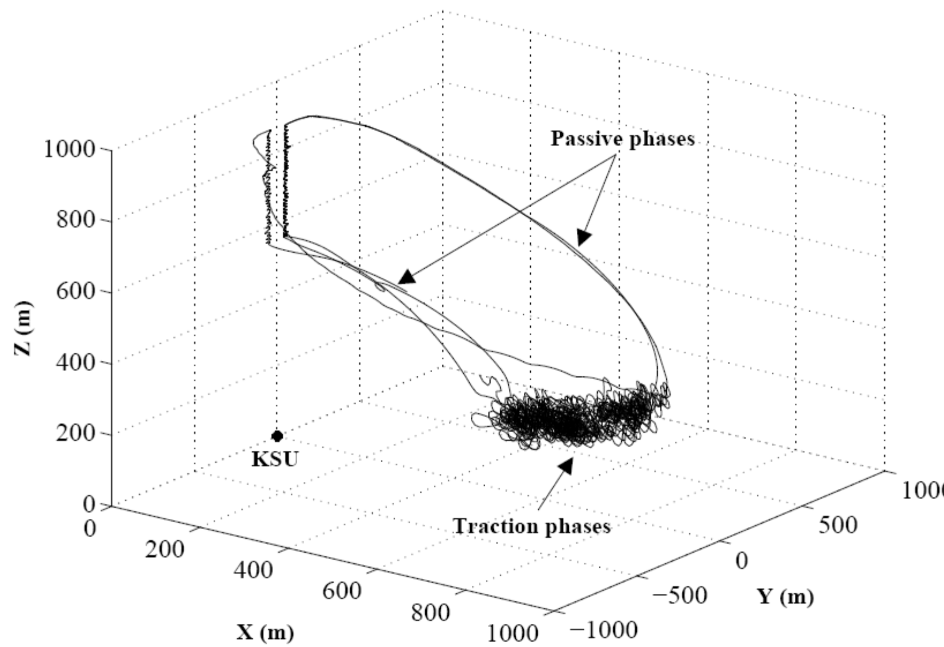
- In the CFHOCP, "future" control inputs are optimized up to the **control horizon N_C**, in order to minimize a cost function that involves the **predicted system behavior**, while satisfying constraints in the whole **prediction horizon N_P.**

- The predictions are computed by using the system's model and the **current state as initial condition**.

Simulation results: KE-yoyo (low power passive phase)



Cable length



Kite trajectory

Kitenergy potentials

- Theoretical, numerical and experimental results so far indicate that Kitenergy technology could provide large quantitites of renewable energy, available prectically everywhere, at **lower cost than fossil energy**

- For more details: see Kitenergy technology presentation (stream B, 11.30)

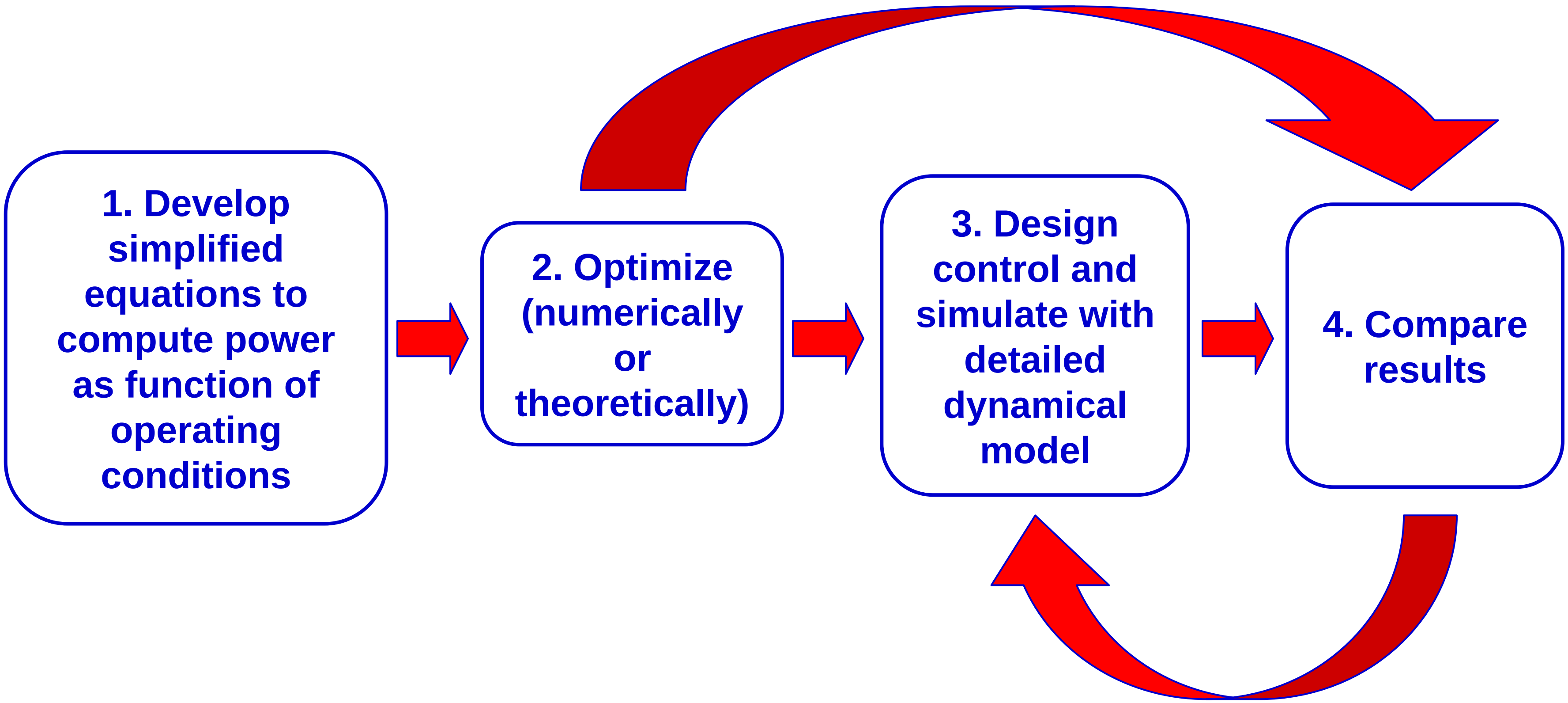
Three questions

1. How to easily compute the optimal operating parameters for a KE-yoyo and for a KE-carousel?

2. How “far” is the designed control law from optimality?

3. Is it possible to design a AWE generator that achieves continuously the maximal amount of power (“Loyd’s limit”)?

Methodology



Simplified kite power equations

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Crosswind Kite Power

Miles L. Loyd*

Lawrence Livermore National Laboratory, Livermore, Calif.

This paper describes a concept for large-scale wind power production by means of aerodynamically efficient kites. Based on aircraft construction, these kites fly transverse to the wind at high speed. The lift produced at this speed is sufficient to both support the kite and generate power. The equations of motion are developed, and examples are presented. One version, based on the C-5A aircraft, results in 6.7 MW produced by a 10-m/s wind. Extrapolation to newer technology, which is more comparable to modern wind turbines, indicates the production of 45 MW from a single machine. The detailed calculations are validated by comparison of their results with simple analytical models. The methodology used here lays the foundation for the systematic study of power-producing kites.

Simplified power equations

- Extensions of Loyd's seminal paper
- Similar equations obtained by different research groups (e.g. K.U Leuven, Tampere Univ., Politecnico di Torino)
- Main assumptions:
  - the kite flies in crosswind conditions;
  - the inertial and apparent forces are negligible with respect to the aerodynamic forces;
  - the kite speed relative to the ground is constant;
  - the kite speed relative to the ground is much higher than the speed of the KSU relative to the ground;
  - kite control angle is small

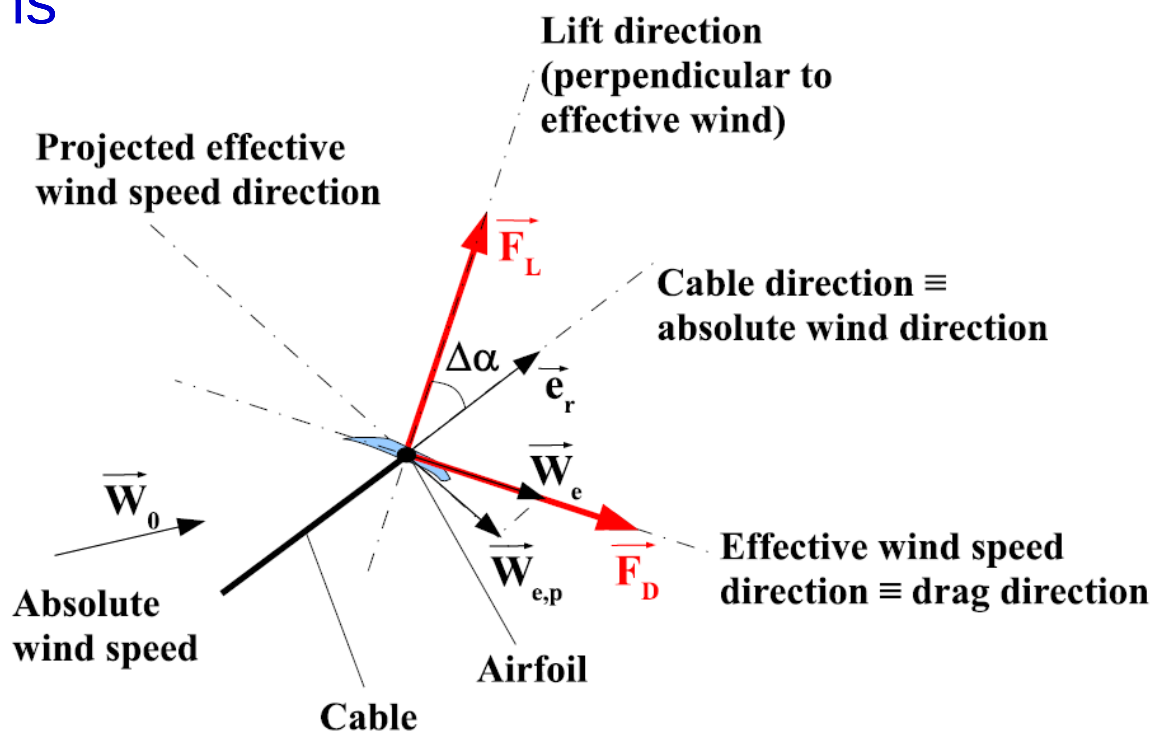
Simplified power equations

$$P = F^{c,trc}\dot{r} + \dot{\Theta} R F^{c,trc} \sin(\theta)\sin(\phi)$$

$$F^{c,trc} = C\left|W_{e,r}\right|^2$$

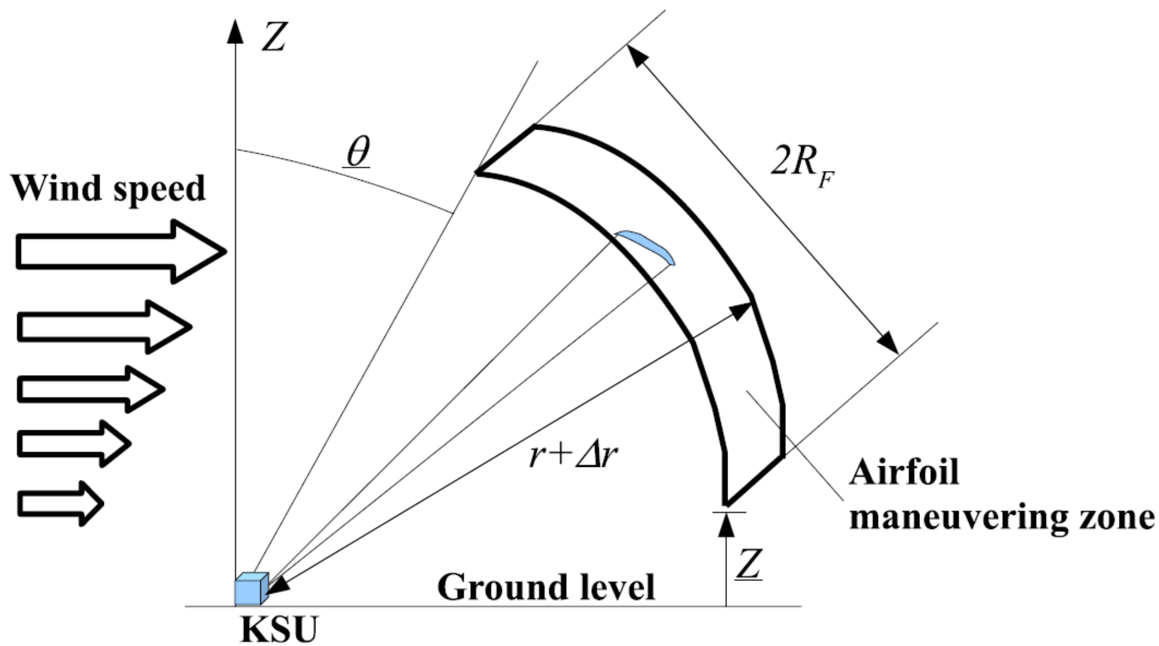
$$C = \frac{1}{2}\rho A C_L E_{eq}^2 \left(1+\frac{1}{E_{eq}^2}\right)^{\frac{3}{2}}$$

$$\left|W_{e,r}\right| = \left|W_0(r\cos(\theta))\sin(\theta)\cos(\phi+\Theta) - \dot{r} - R\dot{\Theta}\sin(\phi)\right|$$



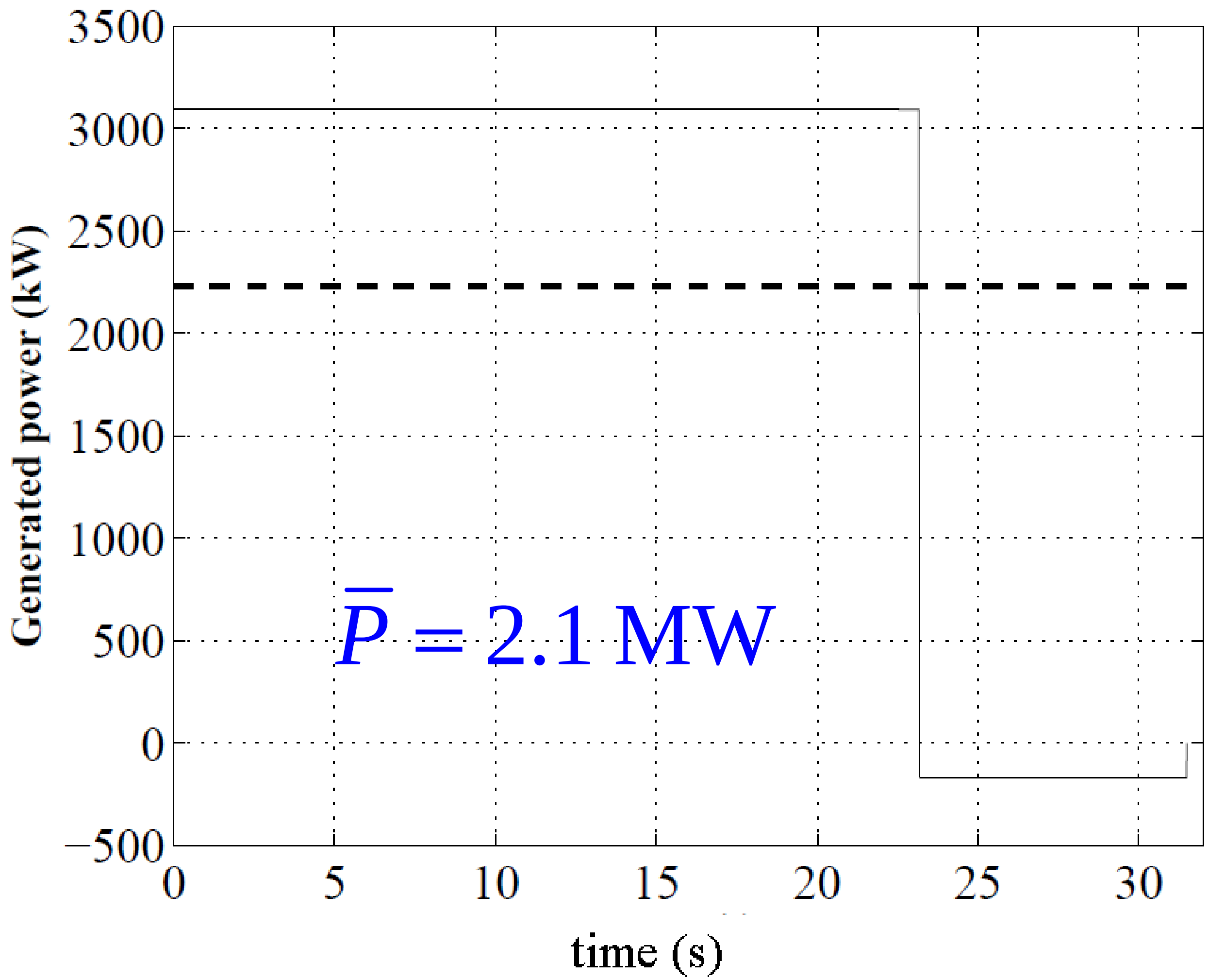
KE-yoyo optimization

$$\left(\theta^*_{\text{trac}}, \dot{r}^*_{\text{trac}}, \underline{r}^*, \theta^*_{\text{pass}}, \dot{r}^*_{\text{pass}}\right) =$$
$$\arg\max \overline{P}\left(\theta_{\text{trac}}, \dot{r}_{\text{trac}}, \underline{r}, \theta_{\text{pass}}, \dot{r}_{\text{pass}}\right)$$
$$\text{s. t.}$$
$$\dot{r}_{\text{min}} \leq \dot{r} \leq \min(W_x(\underline{r}\cos(\theta))\sin(\theta), \dot{r}_{\text{max}})$$
$$\underline{r}\cos\left(\theta + \frac{2\,R_F}{2(\underline{r}+\Delta r)}\right) \geq \underline{Z}$$
$$\theta \geq \underline{\theta}$$
$$F^{\text{c,trc}}_{\text{trac}} \leq 2c_s\overline{F}(d_l)$$
$$F^{\text{c,trc}}_{\text{pass}} \leq 2c_s\overline{F}(d_l)$$



KE-yoyo optimization

$$\begin{pmatrix} \theta^*_{\text{trac}} \\ \dot{r}^*_{\text{trac}} \\ \underline{r}^* \\ \theta^*_{\text{pass}} \\ \dot{r}^*_{\text{pass}} \end{pmatrix} = \begin{pmatrix} 69.1^\circ \\ 2.14\,\text{m/s} \\ 631\,\text{m} \\ 50^\circ \\ -6.0\,\text{m/s} \end{pmatrix}$$



KE-carousel optimization (fixed cable length and carousel speed)

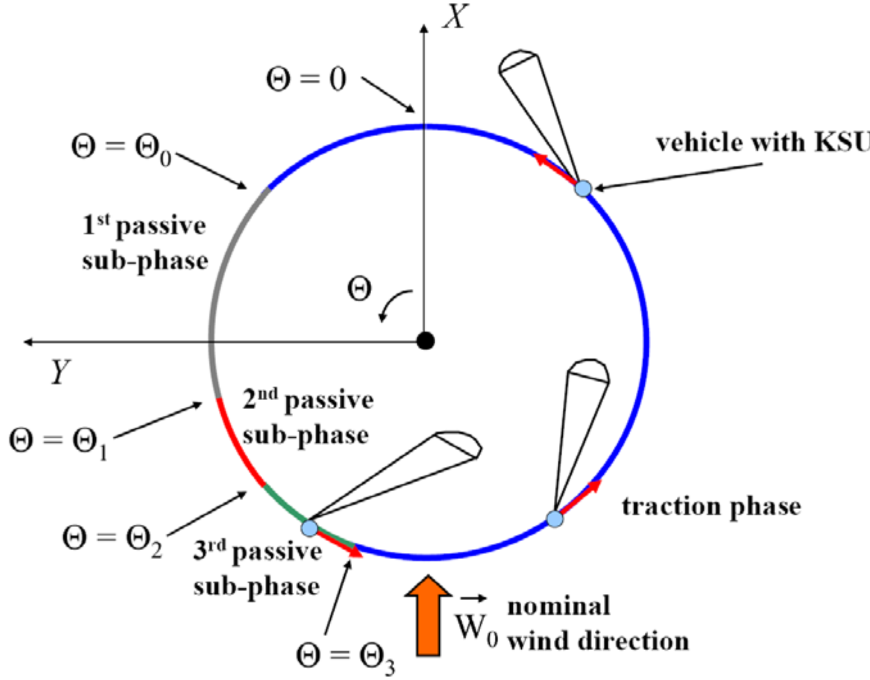
$$\bar{P}^{\text{const}*}_{\text{KE-carousel}} = \max_{\substack{r,\,\dot{\Theta},\,\theta_i,\,\phi_i \\ i=1,\ldots,N}} \frac{1}{N}\sum_{i=1}^{\text{const},N} P_{\text{KE-carousel}}\left(r,\dot{\Theta},\theta_i,\phi_i,\Theta_i\right)$$

s. t.

$$\theta_i \geq 0 \quad i=1,\ldots,N$$

$$F_i^{\text{c,trc}} \leq 2c_s\bar{F}(d_l) \quad i=1,\ldots,N$$

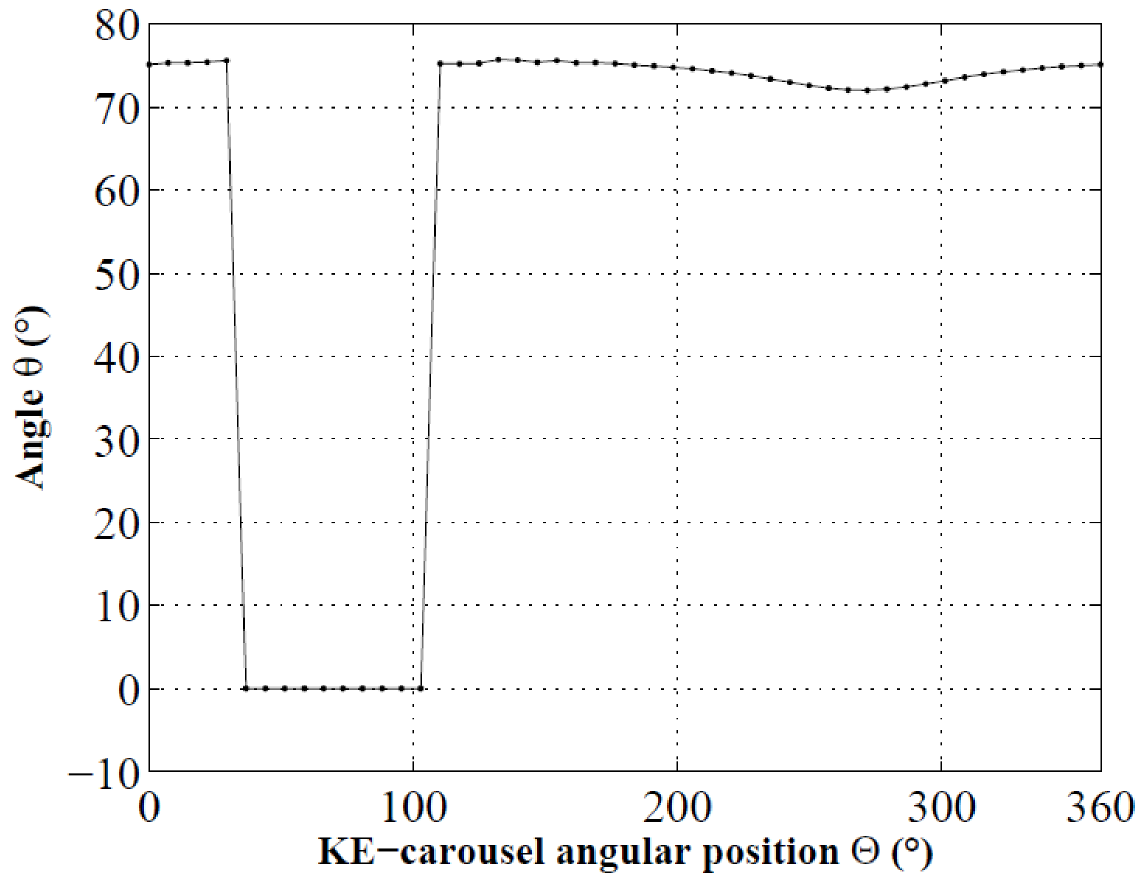
$$r\cos\left(\theta_i + \frac{5w_s}{2r}\right) \geq \underline{Z} \quad i=1,\ldots,N$$



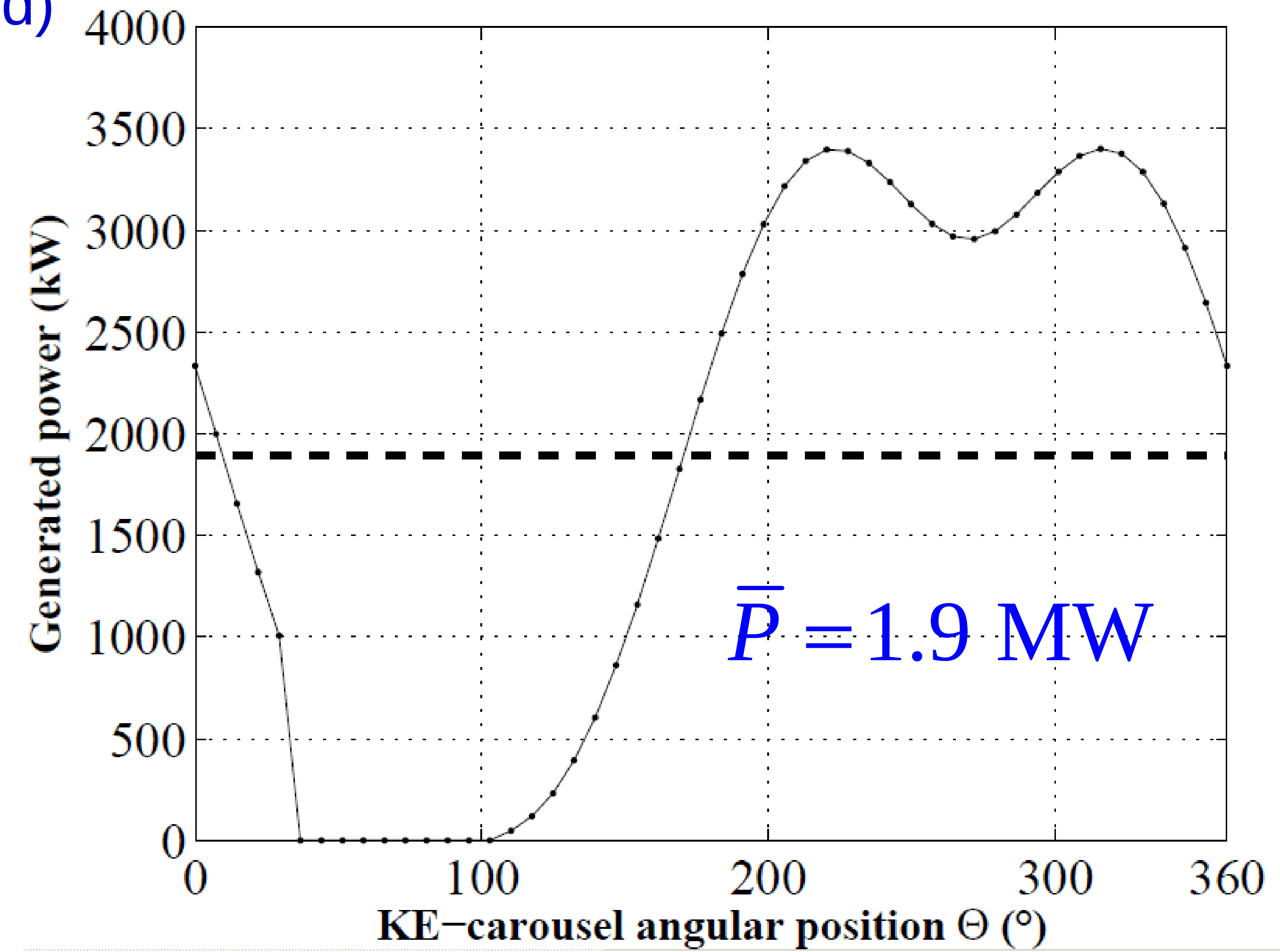
Operation of a KE-carousel with fixed cable length

KE-carousel optimization (fixed cable length and carousel speed)

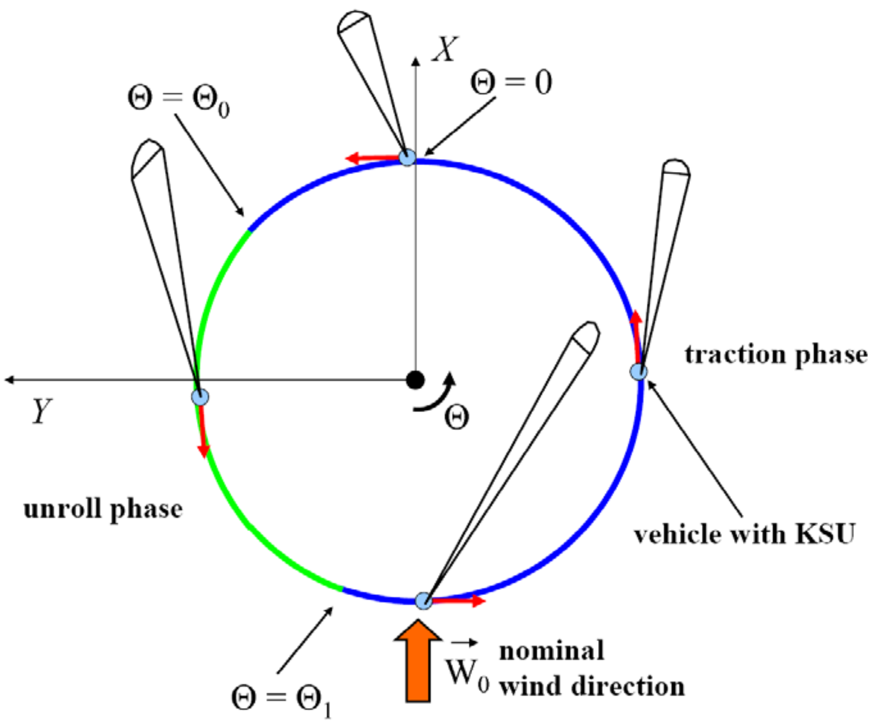
$$\begin{pmatrix} R\dot{\Theta}^* \\ r^* \end{pmatrix} = \begin{pmatrix} 3.98 \text{ m/s} \\ 375 \text{ m} \end{pmatrix}$$



KE-carousel optimization (fixed cable length and carousel speed)



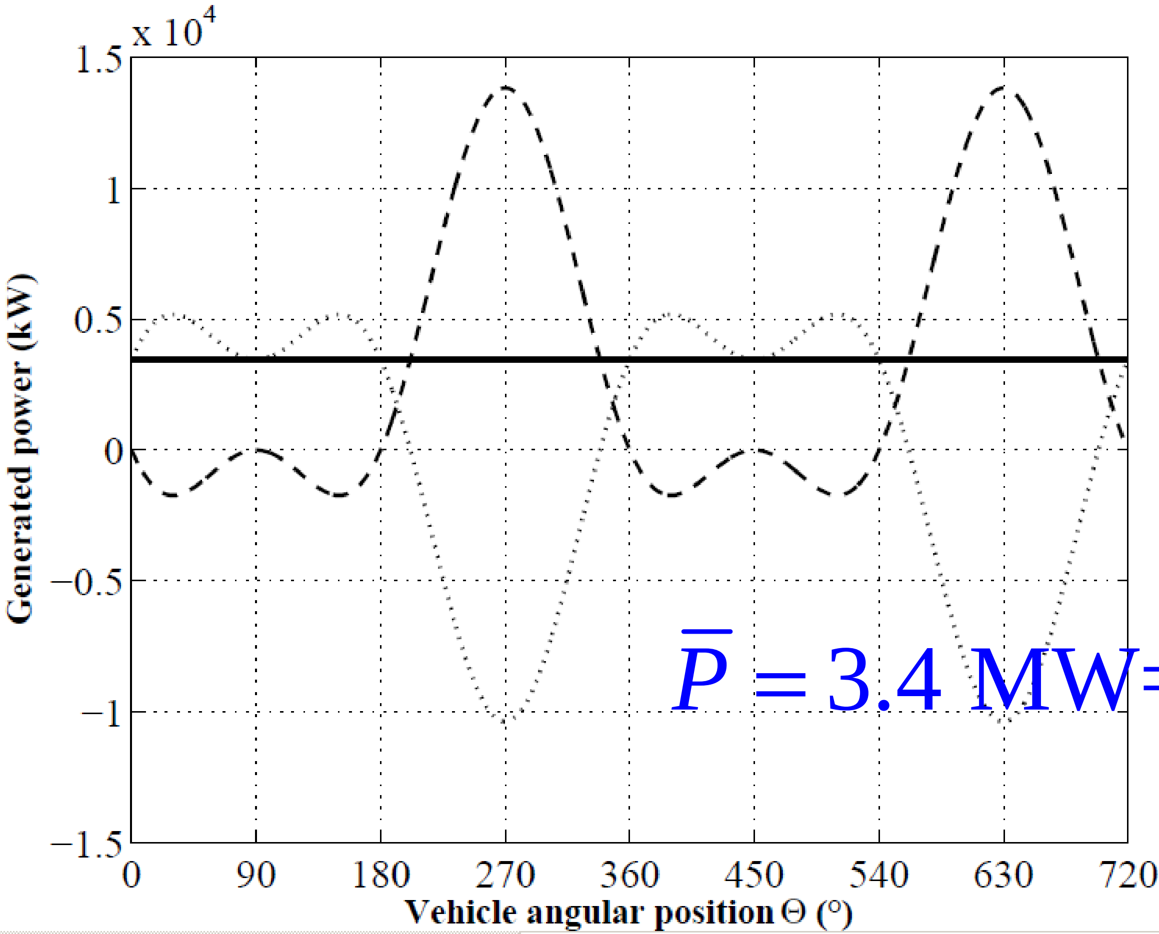
KE-carousel optimization (variable cable length and carousel speed)



Operation of a KE-carousel with variable cable length

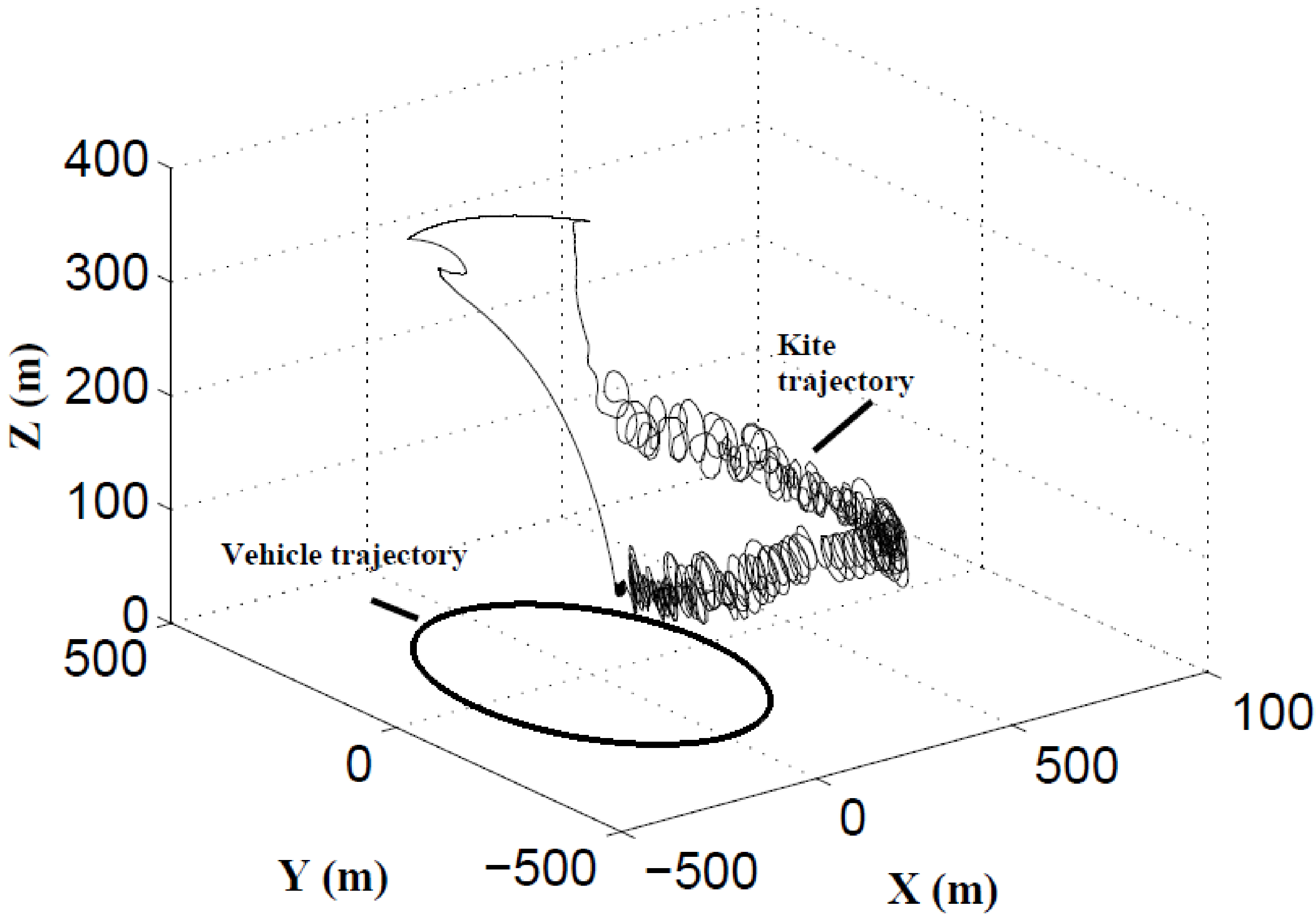
Analytical optimization…

KE-carousel optimization (variable cable length and carousel speed)

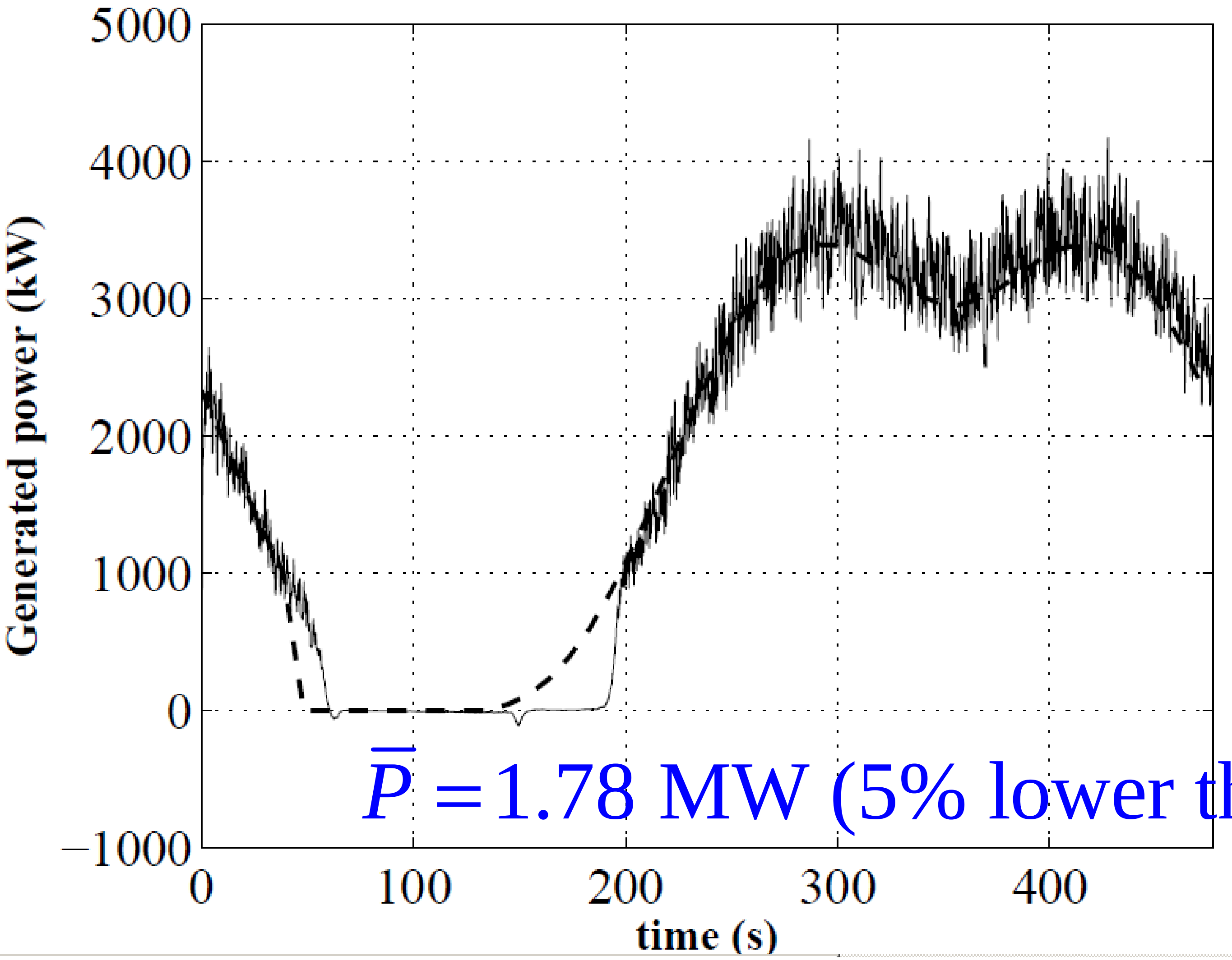


$$\bar{P} = 3.4\text{ MW} = \frac{4}{27} C W_0^3 \text{ !! but...}$$

Numerical simulations (example)



Numerical simulations (example)



$\bar{P} = 1.78$ MW (5% lower than optimal)

Three answers

1. How to easily compute the optimal operating parameters for a KE-yoyo and for a KE-carousel?

   Optimization with simplified equations

2. How "far" is the designed control law from optimality?

   Very good performance (5%-10% "suboptimal")

3. Is it possible to design a Kitenergy generator that achieves continuously the maximal amount of power?

   In principle yes, but practically subject to a lot of drawbacks

Concluding remarks

- Nice method to analyze the potentials of AWE systems
- Also applied to KE-farms and naval transportation
- KE-yoyo and fixed-speed, fixed-cable KE-carousel have similar performance (further development depends on other aspects like cable fatigue, structure cost, etc.)

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- **…**

Acknowledgements

SEVENTH FRAMEWORK PROGRAMME

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REGIONE PIEMONTE

Control of power kites for energy generation

Control of power kites for naval propulsion

Thank you! Questions?

More information, references, contacts:

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