Control of Airborne Wind Energy Systems

A proposal for an open invited track at the 2017 IFAC World Congress

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Abstract

Airborne wind energy is an emerging field in the landscape of innovative renewable energy systems that has experienced an ever-increasing development in the last decade. Today, a thriving multi-disciplinary community of researchers and technologists in academia and industry all over the world is well-established. The delivered research results are gradually assessing and eliminating feasibility risks and improving our understanding of airborne wind energy systems, ultimately bringing these concepts closer and closer to industrialization. The claimed advantages of these systems are lower installation costs, higher capacity factors, higher density of generated power per unit area of occupied land, and higher flexibility with respect to the current established renewable technologies, up to a level that could render airborne wind energy competitive with fossil fuels without the need for political and economic incentives. Airborne wind energy is also an umbrella name for a series of different technologies, which all share the peculiarity that the energy-harvesting component of the system is not supported by a static, rigid structure, rather it is linked to the ground by tethers and kept airborne by means of automatic control systems. Indeed, a common aspect of all airborne wind energy systems is the crucial role played by control, in its broader sense. Modeling, identification, estimation, control and optimization methods are enabling the development of this field, which at the same time is presenting new challenges to the controls community. The goal of this open track session at the 2017 IFAC World Congress is to bring together researchers from industry and academia to present and share their latest advancements and discuss the current and future research and development needs in this timely and thriving field.

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I. Introduction and Motivation

Airborne Wind Energy (AWE) systems generate renewable energy from wind by exploiting tethered aircrafts, whose motion is stabilized by active control systems [1], [2]. The claimed advantages of this concept over established technologies like wind turbines are the lower construction and installation costs and the possibility to reach stronger winds blowing at higher altitudes, in the range 200-600 m above ground. The main drawback is a higher complexity of the system, which calls for a significant effort of research and development involving several disciplines, primarily aerodynamics, controls, materials, mechanics and power electronics. While the first ideas and conceptual studies concerning airborne wind appeared in the late 1970s [3], [4], it is only in the last decade that a significant and growing research and development effort has been undertaken by academia and industry, with the aim to transform those concepts into products. Such an effort has been favored by improvements in sensor, computation, material, aerodynamics and power electronics technologies, which make nowadays feasible to develop airborne wind energy systems that are able to cope with stringent requirements in terms of reliability and optimality of operation. Today, an ever-growing community of scientists and technologists from different disciplines is working worldwide to develop airborne wind energy systems.

Fig. 1. Examples of Airborne Wind Energy generators. From left: a ground-based generator with soft kite from TU Delft [5], a buoyant system from Altaeros Energies [6], two rigid wings for ground-based generation by Ampyx Power [7], a 600-kW system with onboard generation from Makani Power-GoogleX [8], and a semi-rigid wing concept from EnerKite [9].

In the current situation, AWE is an umbrella-name for a set of different specific implementation approaches (see Fig. 1 for some examples) which can be classified by the way the lift force that keeps the aircraft airborne is generated - either aerodynamic lift, like the one produced by standard airplane wings or kites immersed in a wind flow [10], [11], [5], [9], [7], [8], or aerostatic lift, like the one obtained by using lighter-than-air structures [6] - and by the placement of the electrical

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generators - either on-board of the aircraft [8], [6] or on the ground [10], [11], [9], [5], [7]. Among the systems that exploit aerodynamic lift and ground-level generators, a further distinction can be made between concepts that rely on rigid wings [7], similar to gliders, and concepts that employ flexible wings like power kites [10], [11], [5], [9]. Small-scale prototypes (10-50 kW of rated power) of the mentioned concepts have been realized and successfully tested to demonstrate their power generation functionalities. Moreover, scientific contributions concerned with aspects like aerodynamics [12], [13], [14], [15], [16], controls [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], resource assessment [27], [28], economics [29], [30], prototype design [31], and power conversion [32], have recently appeared, gradually improving and expanding our understanding of such systems.

Notwithstanding the continuous development of the field, several relevant aspects still need to be addressed in order to ultimately prove the commercial feasibility of the idea. Many of such challenges involve deeply control, modeling, identification, estimation and optimization aspects. Each one of the mentioned technologies has specific features that imply different problems and require ad-hoc control approaches, and all of them will have to reliably operate in changing wind conditions, adapting their configuration in order to extract the maximal possible energy while keeping stability and avoiding failures. The involved control problems are nonlinear, multi-variable, with uncertain and relatively fast dynamics, multiple competing objectives, operational constraints, and subject to unmeasured disturbances, hence presenting important challenges to the controls community. The multi-disciplinary nature of airborne wind energy systems and their relatively early development, hence the little availability of established design guidelines, confer to control and optimization an even higher importance, since all of the system components have to be designed and integrated by taking explicitly into account aspects like system controllability, observability, and robustness.

"Control of Airborne Wind Energy Systems" is an open invited track at the 2017 IFAC World Congress dedicated to this timely, thriving and exciting research field. The session aims to bring together researchers working in airborne wind energy to present and share their results, to establish connections and to discuss on the current and future research needs in the field.

II. Session topics

The topics of relevance for this invited session include, but are not limited to, the following:

- Control strategies for AWE systems
- Modeling of AWE systems
- Optimization of power generation cycles
- Combined control design/system design studies and optimization
- Autonomous take-off and landing of AWE systems
- State and parameter estimation for AWE systems
- Fault diagnosis and fault tolerant control of AWE systems
- Experimental results of implemented concepts

References

[1] U. Ahrens, M. Diehl, and R. Schmehl, Eds., *Airborne Wind Energy*, ser. Green Energy and Technology. Springer-Verlag Berlin, 2014.

[2] L. Fagiano and M. Milanese, "Airborne wind energy: an overview," in *American Control Conference 2012*, Montreal, Canada, 2012, pp. 3132–3143.

[3] M. S. Manalis, "Airborne windmills and communication aerostats," *Journal of Aircraft*, vol. 13, no. 7, pp. 543–544, 1976.

[4] M. L. Loyd, "Crosswind kite power," *Journal of Energy*, vol. 4, no. 3, pp. 106–111, 1980.

[5] R. van der Vlugt, J. Peschel, and R. Schmehl, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 23. Design and Experimental Characterization of a Pumping Kite Power System, p. 403.

[6] C. Vermillion, B. Glass, and A. Rein, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 30. Lighter-Than-Air Wind Energy Systems, p. 501.

[7] R. Ruiterkamp and S. Sieberling, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 26. Description and Preliminary Test Results of a Six Degrees of Freedom Rigid Wing Pumping System, p. 443.

[8] D. V. Lind, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 28. Analysis and Flight Test Validation of High Performance Airborne Wind Turbines, p. 473.

[9] A. Bormann, M. Ranneberg, P. Kövesdi, C. Gebhardt, and S. Skutnik, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 24. Development of a Three-Line Ground-Actuated Airborne Wind Energy Converter, p. 427.

[10] F. Fritz, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 20. Application of an Automated Kite System for Ship Propulsion and Power Generation, p. 359.

[11] M. Milanese, F. Taddei, and S. Milanese, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 21. Design and Testing of a 60 kW Yo-Yo Airborne Wind Energy Generator, p. 373.

[12] A. Bosch, R. Schmehl, P. Tiso, and D. Rixen, "Dynamic nonlinear aeroelastic model of a kite for power generation," *AIAA Journal of Guidance, Control and Dynamics*, vol. 37, no. 5, pp. 1426–1436, 2014.

[13] J. Breukels, R. Schmehl, and W. Ockels, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 16. Aeroelastic Simulation of Flexible Membrane Wings based on Multibody System Dynamics, p. 287.

[14] A. Bosch, R. Schmehl, P. Tiso, and D. Rixen, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 17. Nonlinear Aeroelasticity, Flight Dynamics and Control of a Flexible Membrane Traction Kite, p. 307.

[15] R. H. L. F. Gohl, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 18. Simulation Based Wing Design for Kite Power, p. 325.

[16] R. Leloup, K. Roncin, G. Bles, J. Leroux, C. Jochum, and Y. Parlier, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 19. Estimation of the Lift-to-Drag Ratio Using the Lifting Line Method: Application to a Leading Edge Inflatable Kite, p. 339.

[17] B. Houska and M. Diehl, "Optimal control for power generating kites," in 9^{th} *European Control Conference*, Kos, GR, 2007, pp. 3560–3567.

[18] M. Canale, L. Fagiano, and M. Milanese, "High altitude wind energy generation using controlled power kites," *IEEE Transactions on Control Systems Technology*, vol. 18, no. 2, pp. 279 –293, mar. 2010.

[19] J. H. Baayen and W. J. Ockels, "Tracking control with adaption of kites," *IET Control Theory and Applications*, vol. 6, no. 2, pp. 182–191, 2012.

[20] M. Erhard and H. Strauch, "Control of towing kites for seagoing vessels," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 5, pp. 1629 – 1640, 2013.

[21] L. Fagiano, A. Zgraggen, M. Morari, and M. Khammash, "Automatic crosswind flight of tethered wings for airborne wind energy: modeling, control design and experimental results," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 4, pp. 1433–1447, 2014.

[22] L. Fagiano, K. Huynh, B. Bamieh, and M. Khammash, "On sensor fusion for airborne wind energy systems," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 3, pp. 930–943, 2014.

[23] U. Fechner and R. Schmehl, "Feed-forward control of kite power systems," *Journal of Physics: Conference Series*, vol. 524, p. 012081, 2014.

[24] M. Zanon, S. Gros, and M. Diehl, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 12. Model Predictive Control of Rigid-Airfoil Airborne Wind Energy Systems, p. 219.

[25] M. Erhard and H. Strauch, "Flight control of tethered kites in autonomous pumping cycles for airborne wind energy," *Control Engineering Practice*, vol. 40, pp. 13–26, 2015.

[26] A. Zgraggen, L. Fagiano, and M. Morari, "Real-time optimization and adaptation of the crosswind flight of tethered wings for airborne wind energy," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 2, pp. 434–448, 2015.

[27] C. Archer and K. Caldeira, "Global assessment of high-altitude wind power," *Energies*, vol. 2, no. 2, pp. 307–319, 2009.

[28] C. Archer, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 5. An Introduction to Meteorology for Airborne Wind Energy, p. 81.

[29] L. Fagiano, M. Milanese, and D. Piga, "High-altitude wind power generation," *IEEE Transactions on Energy Conversion*, vol. 25, no. 1, pp. 168 –180, mar. 2010.

[30] U. Zillmann and S. Hach, *Airborne Wind Energy*, ser. Green Energy and Technology. Berlin: Springer-Verlag, 2014, ch. 7. Financing Strategies for Airborne Wind Energy, p. 117.

[31] L. Fagiano and T. Marks, "Design of a small-scale prototype for research in airborne wind energy," *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 1, pp. 166–177, 2014.

[32] J. Stuyts, G. Horn, W. Vandermeulen, J. Driesen, and M. Diehl, "Effect of the electrical energy conversion on optimal cycles for pumping airborne wind energy," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 2–10, 2015.