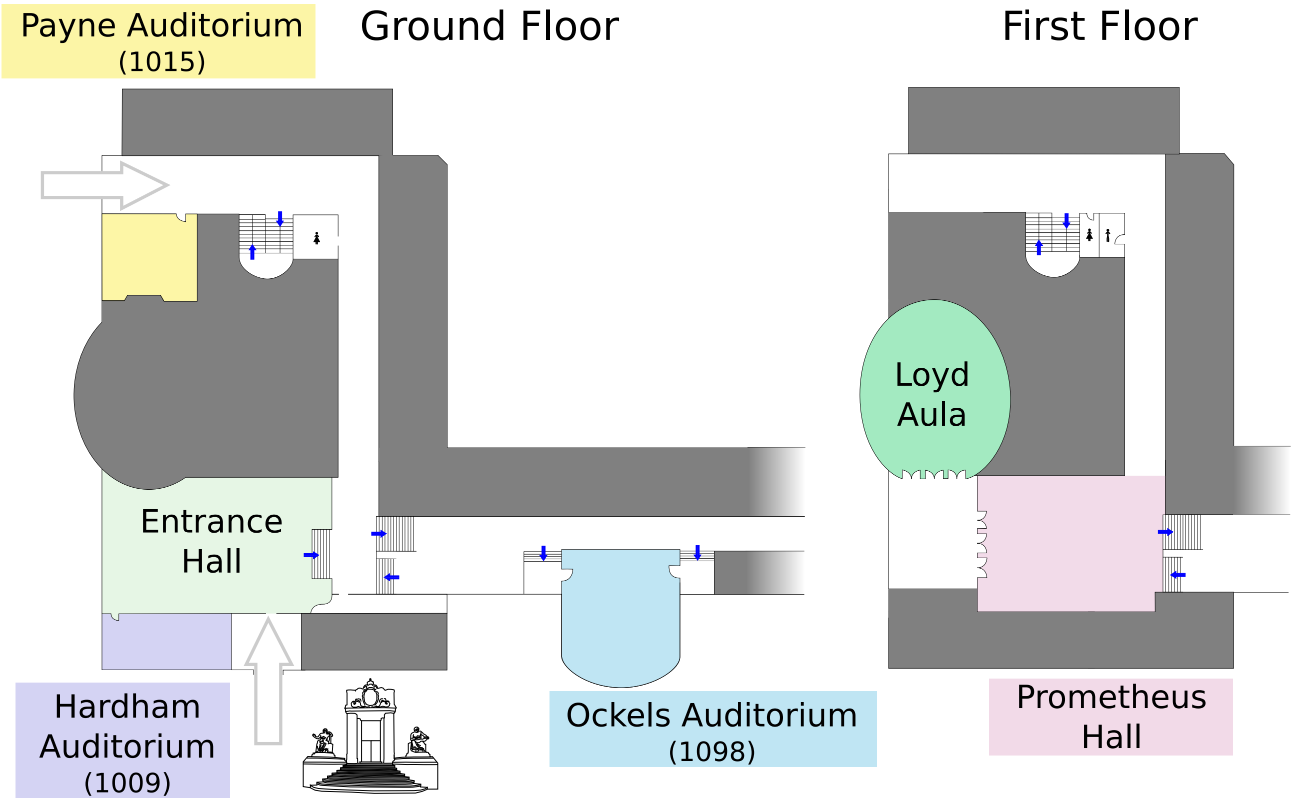
AIRBORNE WIND ENERGY CONFERENCE 2017

5-6 OCTOBER
UNIVERSITY
OF FREIBURG
GERMANY
awec2017.com

BOOK OF ABSTRACTS

Map of Conference Building



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BOOK OF ABSTRACTS

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* Schedule reflects the status at the time of printing of this book and may be subject to change.

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17:30	End-of-Day					

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* Schedule reflects the status at the time of printing of this book and may be subject to change.

Welcome and Introduction to the Airborne Wind Energy Conference 2017

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[2]Department of Mathematics, University of Freiburg
[2]Faculty of Aerospace Engineering, Delft University of Technology

Moritz Diehl
University of Freiburg

Rachel Leuthold
University of Freiburg

Roland Schmehl
Delft University of Technology

Dear conference participants,

Welcome to Freiburg and welcome to the 7th international airborne wind energy conference AWEC 2017! We are excited to present to you an inspiring program in a beautiful location for the two and a half conference days.

The scientific program of AWEC 2017 includes:

- Two invited keynote presentations of 40 minutes, by
  - Dr. Fort Felker, General Director of Makani/X and formerly director of the National Wind Technology Center at the US National Renewable Energy Laboratory (NREL), and
  - Prof. Dr. Henrik Stiesdal from the Technical University of Denmark, who, among other, was Chief Technology Officer of Siemens Wind Power from 2004 until his retirement in 2014;
- Two plenary presentations of 20 minutes, by
  - Dr. Michiel Kruiff, Head of Product Development of Ampyx Power (NL), and
  - Prof. Dr. Lorenzo Fagiano, Professor of Controls at the Politecnico di Milano;
- Fourteen contributed talk sessions in three parallel tracks with altogether 52 presentations
- Two poster sessions, each preceded by plenary spotlight presentations, with altogether 33 poster presentations;
- An outdoors exhibition that takes place on October 4 from 1pm to 4 pm on the newly renovated “Platz der alten Synagoge” directly in front of the conference venue;
- A concluding panel discussion on the future of airborne wind energy.

All abstracts presented in this book have undergone a peer review process, and we want to thank all authors and all reviewers at this place for having contributed to a high quality scientific program, as we believe.

In order to make orientation easier, we decided to rename the four main conference auditoria after renowned researchers in airborne wind energy:

- “Loyd Aula” (Aula 1115) honoring Miles Loyd, an engineer at Lawrence Livermore National Laboratories who laid the scientific foundation of airborne wind energy in 1980;
- “Ockels Auditorium” (HS 1098) honoring Wubbo Ockels (1946-2014), the first Dutch astronaut in space, who established one of the pioneering research groups of airborne wind energy in 2004 at Delft University of Technology;
- “Payne Auditorium” (HS 1015) honoring Peter Payne (1927-1997), an aerospace engineer and inventor who, together with Charles McCutchen, filed a first patent on an airborne wind turbine in 1975; and
- “Hardham Auditorium” (HS 1009) honoring Corwin Hardham (1974-2012), co-founder and first CEO of the pioneering company Makani Power.

Core organisation team at the University of Freiburg (from left): Moritz Rocholl, Moritz Diehl, Gaby Kieninger, Patrick Caspari, Rachel Leuthold

The side program of AWEC 2017 includes:

- three parallel guided city tours of each 1.5 hours that will try to bring Freiburg's past to life;
- a welcome reception on October 4 evening;
- two lunches and four coffee breaks in the conference premises, free for all conference participants;
- a dinner at Schlossbergrestaurant Dattler on October 5, with a view on Freiburg and the upper Rhine valley, and includes the showing of a short film.

The city of Freiburg and its surroundings are worth a visit. Freiburg is one of the sunniest and warmest cities in Germany and a prime tourist destination. Freiburg has a population of about 220 000 people, and is often called the "capital of the black forest", with the black forest mountains on its east and the warm upper Rhine valley to its west. The city is home to many students, of which more than 25 000 study at the Albert Ludwigs University of Freiburg, one of the largest and oldest German universities (founded in 1457).

Though Freiburg and its region do not generally feature strong winds, the city and its university have a strong tradition in their support for renewable energy. Among other, the German movement against nuclear power started here in the 1970's with the successful protests against a planned power station in "Wyhl am Kaiserstuhl". And already since 1981, Freiburg hosts the Fraunhofer Institute for Solar Energy Systems, which was the first non-university research center for applied solar energy in Europe and is still one of its largest with more than 1000 employees. Since 2002, the city is governed by a mayor from the green party, the first for a large German city.

Since 2007, the University has a Center for Renewable Energies (ZEE), which organizes in particular an international master program in Renewable Energy Engineering and Management (REM). Finally, in 2016, the university has founded a new Department of Sustainable Systems Engineering (INATECH) within the Faculty of Engineering and fostered an alliance with the Fraunhofer society within the new "Sustainability Center Freiburg", which cosponsors AWEC 2017. Since 2015, Freiburg University is also part of the European Initial Training Network AWESCO on Airborne Wind Energy (coordinated by TU Delft) which also cosponsors AWEC 2017.

The conference would not have been possible without the support of its sponsors, who are listed on page 8, to which we want to express our sincere gratitude. We are also grateful to the city of Freiburg for making the outdoors exhibition on the "Platz der alten Synagoge" possible and for always being supportive to our event.

We also want to thank all members of the programme committee and organising committee - listed on page 9 - for their efforts in making the conference a success. And within the organising committee, we want in particular thank three members of the core organizing team, Gaby Kieninger (finances and administration), Moritz Rocholl (general organizational support), and Patrick Caspari (rooms and media), who made this conference possible! They are shown on page 6, during one of the weekly AWEC preparation meetings.

Last but not least, we are grateful to you, the participants of AWEC 2017, not only for coming to the conference, but also for your various contributions and your hopefully active participation in the discussions after talks, at lunches, dinners and coffee breaks. We very much look forward to an inspiring and exciting conference together with you!

Sincerely,

Moritz Diehl

University of Freiburg
Freiburg, Germany

Rachel Leuthold

University of Freiburg
Freiburg, Germany

Roland Schmehl

Delft University of Technology
Delft, The Netherlands

Institutional Sponsors

University of Freiburg Founded in 1457, the Albert Ludwigs University of Freiburg matriculates more than 25,000 students from over 100 nations in 196 degree programs. The university's Faculty of Engineering is also home to the Systems Control and Optimization Laboratory of Prof. Dr. Moritz Diehl, a research group that studies the optimal control of airborne wind energy systems, including multiple-kite systems and rotation-launch.

AWESCO The Marie Skłodowska-Curie doctoral training network funds 14 PhD researchers at 11 different universities and companies in Europe to work on Airborne Wind Energy System Modelling, Control and Optimisation. The project is coordinated by Dr. Roland Schmehl, Delft University of Technology, runs from 2015–2018, and has a total budget of €3.4 million that is provided by the European Union within its framework program Horizon 2020 and by the Swiss Federal Government.

Sustainability Center Freiburg The Sustainability Center Freiburg is a cooperation between the University of Freiburg and the city's five Fraunhofer institutes. Together with small companies and large ones such as Daimler AG and Robert Bosch GmbH, the Sustainability Center conducts research and develops sustainable technologies and solutions. Through cooperation with partners from society, such as the city of Freiburg, results from the scientific community are brought directly into real life.

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- Patrick Caspari, Uni Freiburg, Germany
- Moritz Diehl (chair), Uni Freiburg, Germany
- Gaby Kieninger, Uni Freiburg, Germany
- Rachel Leuthold, Uni Freiburg, Germany
- Christine Paasch, Uni Freiburg, Germany
- Kerstin Pfeiffer, Uni Freiburg, Germany
- Moritz Rocholl, Uni Freiburg, Germany
- Roland Schmehl, TU Delft, Netherlands
- Mara Vaihinger, Uni Freiburg, Germany
- Andrea Zanelli, Uni Freiburg, Germany
- Udo Zillmann (sponsor chair), Airborne Wind Europe, Germany

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- Rolf Luchsinger, TwingTec, Switzerland
- Guido Lütsch, German Airborne Wind Association
- Alexandre Trofino Neto, UF Santa Catarina, Brazil
- Christopher Vermillion, UNC Charlotte, USA
- Axelle Viré, TU Delft, Netherlands

Hovering flight test of the 600 kW energy kite

Transportation of the 600 kW energy kite to the test location (28 October 2016)

Transportation to the test location (28 October 2016)

Fort Felker

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Progress and Challenges in Airborne Wind Energy

Fort Felker
Makani / X

How our electricity is generated has a big impact on our planet, which is why many of us at X are exploring moonshots in clean, renewable energy sources. The Makani team is focused on unlocking the potential of wind energy. Currently only 4% of the world's electricity comes from the wind, but easier access to strong, steady winds in more places on the globe could push that number far higher.

In my Keynote address to the 2010 Airborne Wind Energy Conference [1] I highlighted a number of engineering challenges that the nascent industry faced, including: safety and reliability, bringing a rigorous risk management approach to product development and operation, the need for design standards and certification, the need for validated dynamic simulations, the definition of appropriate design load cases and safety margins, and the importance of a comprehensive testing program. Considerable progress has been made in the last 7 years, and this progress will be illustrated using examples from the development of Makani's M600 energy kite system.

In addition to engineering challenges, airborne wind energy technologies face tremendous business challenges. Renewable energy systems must demonstrate long-term power generation performance, and low and predictable operations and maintenance costs to justify the large upfront investment that is required to deploy these systems. Competing renewable energy technologies have accumulated many decades of operational experience that has established that their performance and reliability are "bankable". The long, difficult and expensive effort needed to demonstrate bankable reliability and performance for airborne wind energy system largely lies ahead of the new industry. The presentation will review how adjacent industries have successfully overcome these hurdles, and how these examples can serve as models for the eventual commercial success of airborne wind energy systems.

Finally, the technology used in Makani's M600 system will be described, and I will provide an update on the overall progress of the project. The system is designed to produce 600 kW of electricity. Our largest kite to date, it has a wingspan of 26 m, and has eight onboard rotors that are each 2.3 m in diameter. For comparison, our previous prototype, Wing 7, was a 20 kW system with a 8m wingspan and with four rotors 0.7 m in diameter. Key lessons learned in the M600 project and planned future work will be described.

References:

[1] Felker, F.: Engineering Challenges of Airborne Wind Technology. Presented at the Airborne Wind Energy Conference 2010, Pasadena, CA, USA., 28–29 September 2010. https://www.nrel.gov/docs/fy10osti/49409.pdf

Tethered aircraft during the very first instants after autonomous take-off (20 January 2016)

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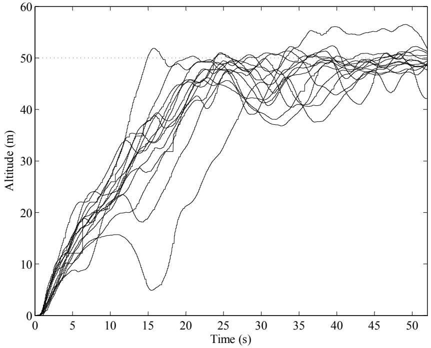
ABB

POLITECNICO
MILANO 1863

On Autonomous Take-Off of Tethered Rigid Wings in Compact Space for Airborne Wind Energy

Lorenzo Fagiano[1,2], **Eric Nguyen-Van**[2], **Felix Rager**[2], **Stephan Schnez**[2], **Christian Ohler**[2]
[1]Politecnico di Milano, [2]ABB Switzerland, Corporate Research

Notwithstanding the significant achievements and continuous improvements made in the last years, one problem that is still open for most Airborne Wind Energy systems is the aircraft's capability to take-off autonomously in compact space without large extra-costs, e.g. due to additional required equipments. This is, in turn, a prerequisite to achieve long-term fully autonomous tests, which would allow the community to ultimately assess the energy conversion efficiency and the capability of these systems to withstand a large amount of operational hours.



Experimental results of 14 overlayed tests. Course of the aircraft altitude.

In a recent research activity carried out at ABB Corporate Research, we delivered a small-scale experimental demonstration of a linear take-off approach, in which a ground station is augmented with a linear motion system to accelerate a motorized glider to take-off speed. The experimental results show that a fully autonomous take-off can be realized in very compact space, with a rather small additional power on the ground station to accelerate the aircraft. In this presentation, we will provide an overview of the adopted solutions (hardware and software) and we will present and comment the obtained experimental results. The presented material has been recently published in peer-reviewed journals, see [1-3]. A movie of the tests is also available on-line [4].

References:

[1] L. Fagiano and S. Schnez. On the take-off of airborne wind energy systems based on rigid wings. Renewable Energy, 107:473–488, 2017.

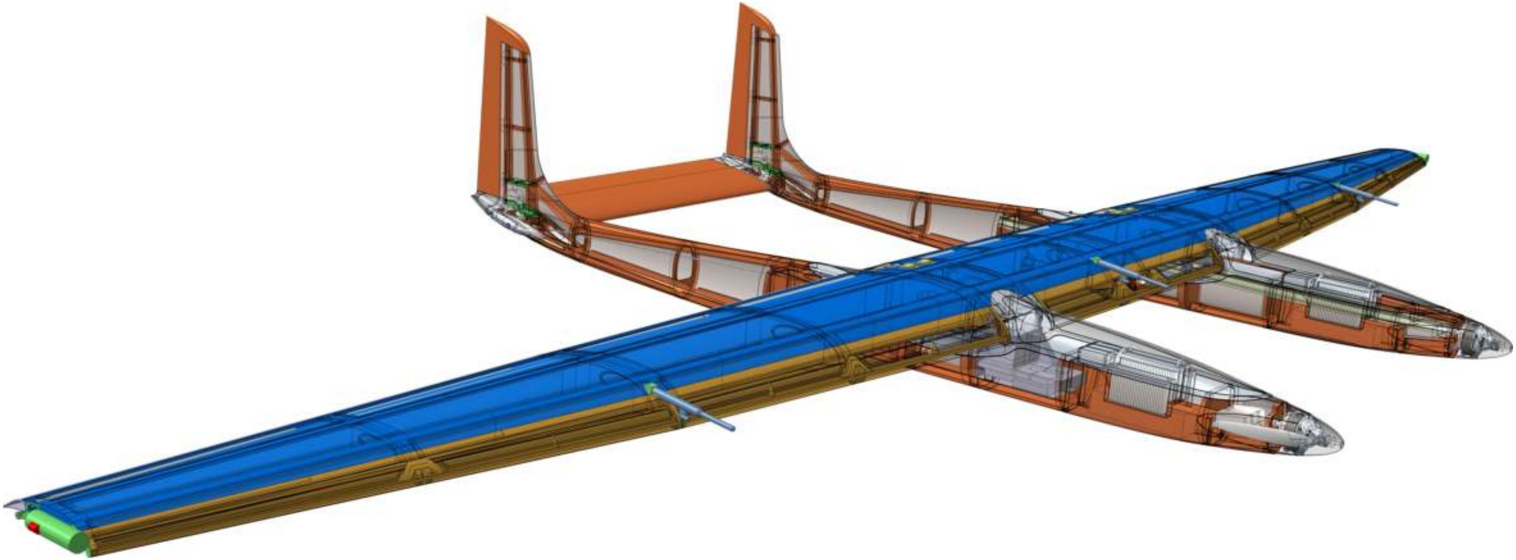
[2] L. Fagiano et al., Autonomous take off and flight of a tethered aircraft for airborne wind energy. IEEE Trans. on Contr. Sys. Tech., In press, 2017. DOI:10.1109/TCST.2017.2661825

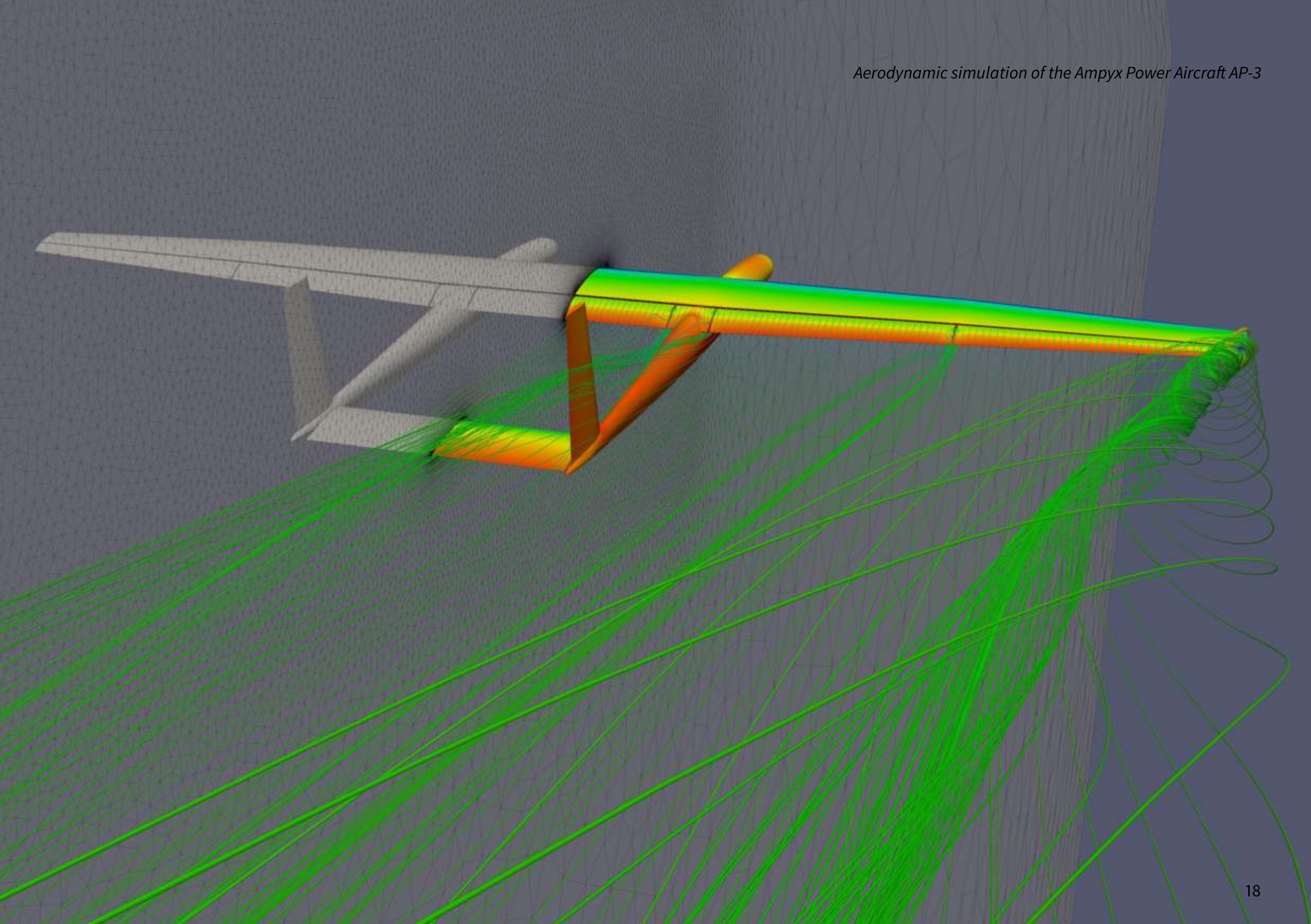
[3] L. Fagiano et al., A small-scale prototype to study the take-off of tethered rigid aircrafts for airborne wind energy. IEEE/ASME Trans. on Mechatronics, 2017. DOI:10.1109/TMECH.2017.2698405

[4] L. Fagiano et al., Autonomous tethered takeoff and flight for airborne wind energy – video. March 2016. https://www.youtube.com/watch?v=UPiTiHPXciE

Rendering of the Ampyx Power Aircraft AP-3

Internal design of the Ampyx Power Aircraft AP-3





Aerodynamic simulation of the Ampyx Power Aircraft AP-3

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AP-3, a Safety and Autonomy Demonstrator for Utility-Scale Airborne Wind Energy

Michiel Kruijff, Richard Ruiterkamp
Ampyx Power B.V.

So far Airborne Wind Energy (AWE) has been demonstrated at tens of kilowatt level, a scale much smaller than what would be commercially viable in the utility sector. Long duration flight data is needed to substantiate the practicality and safety of commercial operation and help predict the cost of maintenance. Building on the controllability demonstrator AP-2 (20 kW), Ampyx Power is addressing these more advanced questions with its third and fourth generation AWE systems: AP-3 (under construction) and AP-4 (in design). These systems feature rigid drones driving the ground-based generator that they are tethered to. Each generation is an order of magnitude larger than its predecessor. This presentation focuses on the design of AP-3.

AP-3 is a 250 kW system using a 375 kg drone with a wingspan of 12 m. AP-3 is the pre-commercial prototype, designed to be a demonstrator of safety and autonomy. It should roll out late 2018.

With AP-3 we will showcase full functionality of the commercial product. This means, 24/7 automatic operation without human intervention. The full cycle will be automated: launch, power generation, landing, repositioning and relaunch. The AP-3 system features safe automated response to any off-nominal condition, such as a sudden drop in wind or a failure of one of the systems, say the winch, a sensor or a control surface.

AP-3 wing plugs at Orange Aircraft.

All solutions are as much as possible designed to be scalable to the commercial prototype AP-4 (2 MW). The AP-3 system is already designed to be certifiable. The AP-3 drone is in fact a platform for verification of the actual AP-4 avionics, control and software. Most of the architecture of the AP-4 drone and launch & land system will be inherited from AP-3.

The automatic landing has to be spot-on to limit the size of the landing platform: the drone shall touch down within meters from the target. The AP-3 and AP-4 drones will overfly the platform horizontally between 0.5 and 4 m altitude. They are then arrested by the tether itself through a damper system in the platform. The drones drop onto a funnel, over which they are winched back into the catapult for storage until the next launch.

We intend to fly AP-3 on a site in Ireland that we will develop with utility provider E-ON. There we will build up AP-3 flight hours to prove the avionics. We intend to eventually fly the AP-3 at night and in extreme weather for days in a row. We aim to fly sufficient hours to gain meaningful experience on operations and maintenance aspects.

First commercial offshore wind farm in the United States (1 October 2016)

Henrik Stiesdal

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Airborne Wind Energy – Challenges and Opportunities Based on Experiences from the Conventional Wind Industry

Henrik Stiesdal
Department of Wind Energy, Technical University of Denmark

Airborne Wind Energy Systems (AWES) have significant potential to expand the field of wind power by capturing energy at altitudes that can not be reached with ground-based wind turbines, thereby benefiting from higher and more persistent winds. However, while the potential advantages of AWES are clear, the full range of challenges may not be equally clear. Based on experiences from the development, expansion and maturing of the conventional wind industry, the challenges facing the AWES industry are of such magnitude that it cannot be stated with certainty that this industry will be commercially viable.

The operational challenges vary considerably as a function of the airborne wind energy system (AWES) concept. Still, for all concepts, the requirements for operational reliability and robustness under conditions of long service intervals are high, much higher than known from other, apparently similar industries. The conventional wind industry has had to learn the hard way that experiences could not readily be transferred from other industries due to the much higher equipment demands posed by wind industry application. The same will apply to the AWES industry, but aggravated by the requirements for low weight.

The environmental challenges are considerable for all types of wind turbines, and in tendency, most will be more severe for AWES. Wind does not always behave in accordance with the textbooks' descriptions of smooth logarithmic wind shears and well-defined turbulence spectra. In addition to normal turbulence, large wind turbines often experience high and uneven shear conditions, pronounced veer, and gust front passages. Due to the larger areas swept by AWES and the significant altitude variations, these phenomena are likely to affect AWES even more than conventional wind turbines. Furthermore, wind turbines experience other environmental conditions having a detrimental effect on performance: rain, snow, hail and icing, and insect fouling. Finally, all large wind turbines are at some point hit by lightning and also AWES must be able to handle lightning.

The regulatory challenges for AWES comprise a combination of challenges shared by the conventional wind industry and challenges particular to the AWES industry. Experience shows that radar interference, noise emission, and visual impact are limiting factors for onshore wind power deployment. In addition to these challenges, AWES have particular challenges regarding aviation and on-ground safety. The scaling challenges are of particular concern regarding AWES. Experience shows that the conventional wind industry needed megawatt-scale turbines to reach grid parity. However, the square-cube law will severely limit the size potentials for AWES, and new thinking will be required to reach competitive infrastructure cost levels. In the face of all these challenges, it is perhaps difficult not to lose heart. However, the AWES opportunities remain unaffected – subject to the above challenges, the potential to change the game by exploiting hitherto inaccessible wind resources, using lightweight, low-cost equipment.

Flying the Makani M600 prototype (6 January 2015)

The Makani M600 flying high above the desert (12 April 2017)

AWEsome: An Affordable Standardized Open-Source Test Platform for AWE Systems

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The development of AWE systems requires significant financial investments and man-power for engineering the required hard- and software components. For research groups and startups this is a major hurdle that has to be overcome to get the first prototype into the air. Many algorithms and concepts are, however, universal and not specific to the individual approach. They could in principle be shared in an open environment between all stakeholders in AWE to the benefit of the individual project and the AWE community as a whole. It is our aim to facilitate the development of such an open platform: AWEsome, the "AWE Standardized Open-source Model Environment".

We present an affordable test platform for airborne wind energy systems that consists of low-cost (below US$ 1000) hardware and is entirely based on open source software. It can hence be used without the need of large financial investments, in particular by research groups and startups to test their design strategies, to facilitate inexpensive tests of new ideas, to train themselves in flight operations before switching to more expensive hardware, or for PR purposes. We also expect that the control system can be easily adapted to different hardware platforms and steering strategies.

Our system consists of a modified off-the-shelf model aircraft that is controlled by the pixhawk autopilot hardware and the ardupilot software, ArduPlane, for fixed wing aircraft. The autopilot software can be compiled for different target hardware and also a SITL environment. It provides full logging of sensor data, derived data and control commands. Moreover, it employs the MAVlink protocol for a two-way-communication with a ground control station (GCS). The latter is a simple PC or laptop running the respective software, e.g Mission Planner or APM Planner.

We have implemented new flight modes for the autonomous flight of the aircraft attached to a tether of constant length along periodic patterns. The control algorithms are developed and tested using the SITL environment together with the flight dynamics model JSBsim. Moreover, first field tests have been performed and the respective data has been analyzed, including also measurements of the system's performance.

All developments are available on GitHub and [1] for the benefit of the entire community.

Some main future developments are the construction of a winch system controlled by ardupilot, the integration of additional sensors and of upgrades to the pixhawk autopilot hardware and the improvements of the flight control software and of the simulation environment.

We invite other research groups, startups and maker space projects to join this open source development and contribute to a common playground for the whole AWE community.

References:

[1] www.awesome.physik.uni-bonn.de

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Methodology Improvement for the Performance Assessment of a Pumping Kite Power Wing

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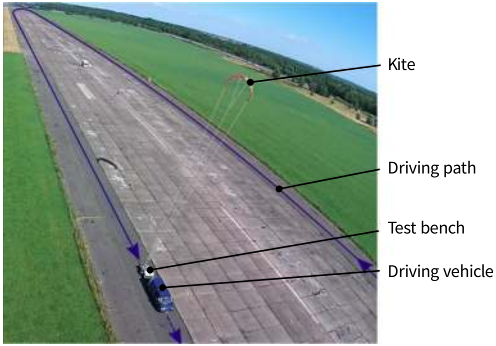
Pumping kite power systems are a promising way of harnessing clean energy from high-altitude winds in a cost-effective way. The power output of such innovative systems is directly related to the wing aerodynamic properties that therefore play a key role. Moreover, the latter, often assumed with best guess, are also required for computational simulations at development stage.

Recently, the research group of TU Berlin [1] designed a towing test bench and procedure for evaluating flexible airfoil performances in an automated and repeatable manner. By towing the kite at a prescribed speed, relevant information, such as tether force and elevation angle, are extracted and can be translated into wing aerodynamic properties thanks to a simple analytical model (point massless kite, straight massless-dragless tether).

With the purpose of improving the assessment of wing aerodynamic properties and their exactitude, the present work takes advantage of the TU Berlin test bench by investigating the prototype wing from Kitepower. An alternative testing methodology is suggested and compared against the current procedure from TU Berlin, indicating a dynamic behaviour of the kite. An improved 2D quasi-steady point mass model is implemented to compute the kite aerodynamic properties by taking both wing and tether mass as well as tether aerodynamic effects into consideration. It shows noticeable discrepancies in C_L (+16%) and C_D (-10%) with respect to the simple analytical model. Eventually, a detailed tether model from differential equations is developed to assess its sag and effects on the intrinsic kite performance. This leads to even more difference in C_D (-25%). Eventually, this work provides C_L and C_D of the kite itself and shows that such aspects as tether drag and sag should not be neglected when assessing the intrinsic aerodynamic properties of the wing.



For the case of vanishing wind, the ground vehicle tows the kite back and forth the runway while measuring forces, angles, speed for different line configurations.

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Application of the Estimation-Before-Modeling Method to the Aerodynamic Characterization of Power Kites

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The aerodynamic characterization of kites is of paramount importance in the analysis of kites applied to wind energy generation because it is a key component of flight simulators. However, due to flexibility effects of the kite structure and the typically large sideslip and attack angles, severe difficulties arise.

This work applies a Estimation-Before-Modeling (EBM) method, a widespread technique in aerospace engineering that makes use of data obtained during flight testing, to the aerodynamic characterization of power kites with four control lines. The procedure includes two main steps: an estimation phase and a modelling phase.

The estimation phase involves a Kite Estimator (KE) that receives a comprehensive set of measurements and provides the time history of the state vector of the system. In this phase, aerodynamic forces and moments are components of the extended state vector of the kite and they are estimated from the measurements by using stochastic filtering and smoothing techniques. The KE has been fed with experimental data obtained during a test campaign with two different power kites (10 m^2 and 13 m^2).

In the modelling phase, a multivariable regression algorithm has been used to determine the nonlinear coefficients of the aerodynamic model. The regression algorithm compares the aerodynamic forces and torques provided by the KE and the one computed theoretically with a flight simulator of a four-line kite.

The accuracy of the aerodynamic model obtained with the EBM technique was assessed by comparing time histories of the experimental trajectories and the one provided by the kite simulator updated with the new aerodynamic model.

Flight tests of an instrumented 13 m^2 COTS kite.

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Multiple-Wake Vortex Method for Leading Edge Inflatable Tube Kites used in Airborne Wind Energy Systems

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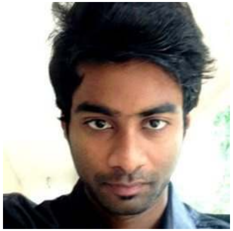

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In this study we propose a robust vortex model for time-dependent vortex shedding at separation locations and trailing edge. The model, which is able to capture flow separation and reattachment phenomena, aims at improving a previously developed a multiple-wake vortex lattice model [1], which could not describe flow reattachment phenomena on suction and pressure surfaces.

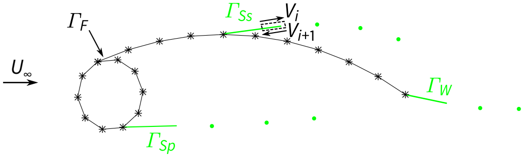
Starting from potential theory the two-dimensional Leading Edge Inflatable (LEI) kite airfoil is discretized by several straight panels with point vortices at quarter chord point of each panel. A constant-strength vortex panel is shed at each separation location and is convected in the next time step as vortex blob without change in its strength for further time steps. The circulation is defined as a closed line integral of the tangential velocity component around the fluid element.

$$\Gamma \equiv \oint_C V \cdot ds$$

Considering a closed line integral around the separation panel, as described in Katz [2], applying the above equation, we get

$$\frac{d\Gamma_S}{dt} = \frac{D}{Dt}\oint Vds = \frac{d}{dt}(V_i ds - V_{i+1} ds) \cong \frac{1}{2}({V_i}^2 - {V_{i+1}}^2),$$

and Γ_{Ss}, Γ_{Sp} are separated wake strengths defined using above formulation on suction and pressure sides respectively.



2D LEI kite airfoil discretized into straight panels with vorticity placed at quarter chord point.

Together, the N_p bound vortex strengths Γ_{Sp}, as well as Γ_{Ss} and Γ_W, give N_p + 3 unknowns. The boundary conditions are no flow penetration through the surface (applied at three-quarter chord point on each panel) and the vorticity shed during the time step at separation locations, along with Kelvin-Helmholtz theorem, form N_p + 3 boundary conditions. Circulations obtained from iterative solution scheme are post processed using time-dependent Bernoulli's equation for momentary pressure distribution.

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Ampyx Powerplane AP-2A1 during free gliding flight with folded launch-assist propellers (23 December 2015)

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An Optimal Sizing Tool for Airborne Wind Energy Systems

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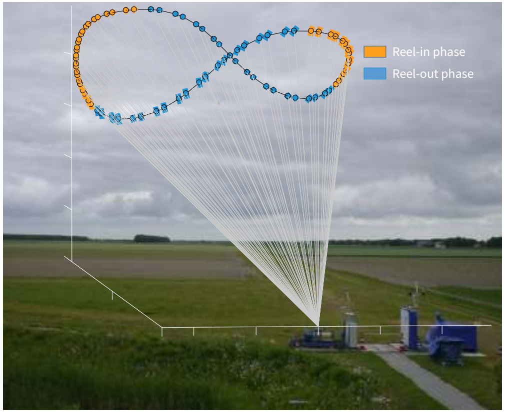
Airborne Wind Energy (AWE) is an emerging technology that is capable of harvesting wind energy by flying crosswind flight patterns with a tethered aircraft. An AWE system (AWES) is mainly characterized by high power-to-mass ratio, high capacity factors and lower installation costs with respect to conventional wind turbines.

Nevertheless, AWES need to be scaled-up in order to be both attractive for investments and competitive in the energy market. Such scaling process requires numerous iterations and trade-offs among the different components in terms of requirements that have to satisfy both technological and economical viability.

In this paper, we will show an approach that addresses systematically the viability assessment of an AWES for scaling-up purposes via formulation of an optimal control problem (OCP) combined with statistical analysis. More precisely, the patterns are optimized with respect to the average power output for a range of wind speeds; subsequently the power curve, annual energy production and capacity factor are computed for a given wind distribution [1,2].

The OCPs are solved via the dynamic optimization toolbox openOCL implemented in the Matlab Environment and freely available in [3]. As a matter of example, the rigid wing pumping mode AWES designed by Ampyx Power B.V is used as case study.



Typical optimal pattern for a rigid wing pumping mode AWES.

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Kite as a Beam Modelling Approach: Assessment by Finite Element Analysis

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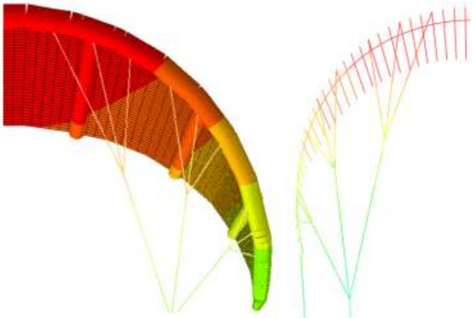
The *beyond the sea*® project attempts to develop a tethered kite system as an auxiliary propulsion device for merchant ships. Since a kite is a flexible structure, fluid-structure interaction has to be taken into account to calculate the flying shape and aerodynamic performances of the wing [1]. For this purpose, two fast and simple models have been developed.

The fluid model is a 3D nonlinear lifting line [2]. This extension of the Prandtl lifting line is intended to deal with non-straight kite wings, with dihedral and sweep angles variable along the span, taking into account the non-linearity of the lift coefficient. This model has been checked with 3D RANSE simulations and shows good consistency, with typical relative differences of few percent for the overall lift.

The purpose of the structure model, Kite as a Beam, is to model the kite as a succession of equivalent beams along its span. The kite is considered as an assembly of elementary cells, each one composed of a portion of the inflatable leading edge, modeled as a beam, two inflatable battens, modeled as beams of half stiffness due to cell connectivity, and the corresponding canopy, modeled as a shell. The tangent stiffnesses of the equivalent beam are finally calculated in two steps. First of all, the cell is put under pressure and then subjected to different linear displacement perturbations [3].

The validity of this fluid-structure interaction model has not been checked so far. The aim of the present study is to compare the results of this fast structure model with a more time-consuming Finite Element (FE) method.



Complex FE model with shell and beam elements (left), Kite as a Beam model (right). The color scale represents the displacement magnitude.

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Challenges of Morphing Wings for Airborne Wind Energy Systems

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Aircraft wings commonly utilize hinged control surfaces to alter their aerodynamic properties, with the aim of achieving controllability of the aircraft and adaptability to different flight conditions. However, the discrete shape changes resulting from the deflections of the control surfaces result in sub-optimal airfoil geometries and in a decrease in aerodynamic efficiency. On the other hand, morphing wings enable spatially smooth and continuous geometrical changes of the wing shape by using smart materials and novel distributed compliance structural concepts. Thereby, more aerodynamically efficient deformed shapes can be achieved, and the wing's performance can be improved for different flight conditions, compared to conventional wings.

Airborne Wind Energy (AWE) presents a very promising application field for morphing, since AWE aircraft experience a wide range of flight conditions, including take-off, traction phase, retraction phase, and landing. Furthermore, the wide range of wind speeds - and the resulting flight speeds - encountered by the aircraft, result in a constantly changing environment for the aircraft. By controlling the camber deformation, and thereby optimally adapting the airfoil shape, the extracted power for every flight situation can be maximised.

This study presents the design, manufacturing and testing of a rigid AWE aircraft with a selectively compliant wing with an area of 1.5m^2 and a span of 5m. The morphing concept developed by the authors consists of a continuous skin and a selectively compliant internal structure, enabling smooth camber changes, constant or varying along the span. In order to solve the conflicting requirements of stiffness for load carrying and compliance for morphing, CFRP are utilized. The wing is comprised of a rigid wingbox, carrying the majority of the structural loads, and a compliant trailing section, made of a composite skin. Actuators are used to introduce mechanical energy in the system and the deformation is guided by the distributed compliant ribs, thus achieving favourable camber morphing.

The ideal wing characteristics are determined by an optimization, which accounts for aeroelastic interactions in the assessment of the wing behavior. The optimization variables describe the aerodynamic shape, the inner compliant structure, the wing skin composite layup, and the actuation strategy. The objective of the optimization is to maximize the produced power of the aircraft. The result of the optimization is a morphing wing capable of achieving an optimized shape and a favourable lift distribution along the span for a wide range of wind speeds.

A full scale experimental demonstrator is manufactured according to the optimized shape and structure. Following the manufacturing, a test campaign is performed to evaluate the performance benefits of the morphing wing. Preliminary results show that the performance is improved and the weight can be decreased, while achieving sufficient rolling moment.

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Kite Flight Simulators Based on Minimal Coordinate Formulations

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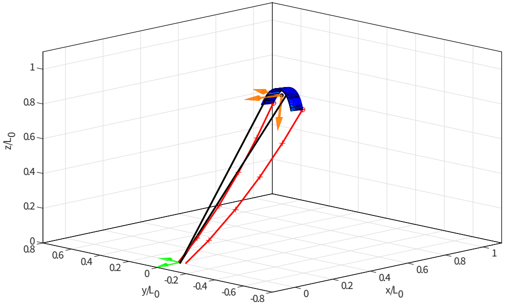
Analytical mechanics techniques are applied to the construction of three kite flight simulators with applications to airborne wind energy generation and sport uses. All of them were developed under a minimal coordinate formulation approach. This choice has the main advantage of yielding a set of ordinary differential equations free of algebraic constraints, a feature that distinguishes the simulators from codes based on classical mechanics formulation and improves their robustness and efficiency.

The first simulator involves a kite with a flexible tether, a bridle of variable geometry, and several on-board wind turbines. Such a simulator, which models the tether by a set of rigid bars linked with ideal joints, can be used to study the on-ground generation of electrical energy through yo-yo pumping maneuvers and also the on-board generation by the wind turbines. The second simulator models a kite linked to the ground by two rigid control lines. This numerical tool is aimed at the study of the dynamics of acrobatic kites and the traction analysis of giant kites to propel cargo ships. The third and last simulator of this work considers a kite with four control lines similar to the ones used in kitesurf applications. Two of them are rigid tethers of constant length that connect the leading edge of the kite with a fixed point at the ground. The other two tethers are elastic and they link a control bar with the trailing edge of the kite.

The performances of the simulators in terms of computational cost and parallelization efficiency are discussed. Their architectures and user interfaces are similar, and appropriate to carry out trade-off and optimization analyses for airborne wind energy generation.



Four-line kite simulator.

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Tether Traction Control in Pumping-Kite Systems

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In recent years, Airborne Wind Energy (AWE) technology has been undergoing a rapid development. Several companies and research groups around the world have already built prototypes to validate different configurations of AWE systems, all of which rely on the control of electric machines. An appropriate machine control can optimize power production and also allow for the tethered wing to fly robustly regardless of wind fluctuations while respecting system constraints such as the maximum tether traction force and reel speed. These machines should also be capable of operating both as a motor, during take off, landing and the retraction phase, as well as a generator during the traction phase.

Alternated current machines are commonly used in the industry mainly due to advanced features such as the well known Vector Control, also referred to as Field Oriented Control (FOC). In this scheme, the magnetic flux and electromagnetic torque currents are regulated in the inner loop, whereas the machine speed is controlled in the outer loop. Although speed control is suitable for many applications, using it as the outermost control loop in a pumping-kite system might be problematic, especially when the kite is exposed to high levels of wind gusts. Keeping the machine speed constant in this scenario may cause the traction force and the airfoil angle of attack to fluctuate strongly, reaching values that may eventually lead the kite to a stall condition or to structural damage.

We can mention two ways to deal with the wind perturbations at the ground station level. One way is to add an external loop to the FOC. This loop compares a given traction force reference to the instantaneous measured value and, based on this control error, generates a speed reference to the FOC. In this approach, the traction force control operates continuously and is capable of effectively rejecting high amplitude perturbations of the wind speed as long as its frequency is lower than the cutoff frequency of the closed loop dynamics. A second way of dealing with wind perturbations is to equip the ground unit with springs and dampers in order to reject high-frequency perturbations of the wind in the tether traction force, an approach which is limited by the maximum displacement of the springs and dampers.

In this work we have implemented the first strategy mentioned in the previous paragraph in a computer simulation of the pumping-kite system. The simulations were parameterized to represent the ground station prototype under development by the UFSCKite team, which is based on a single permanent-magnet machine of 12 kW and designed to support up to 800 kgf of pulling force. Different wind scenarios were tested to verify the performance of the traction force control and its implications on the angle of attack. The results show the effectiveness of the proposed control strategy, not only for tracking set-points of the traction force but also to prevent the kite from stalling.

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Modeling and Control of Magnus Effect-Based AWE Systems

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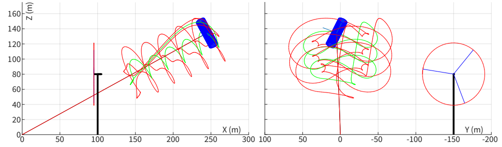
At GIPSA-lab, EOFLY is a multi-disciplinary research group working on the development of airborne wind energy systems, drones, and conventional wind turbines [1].

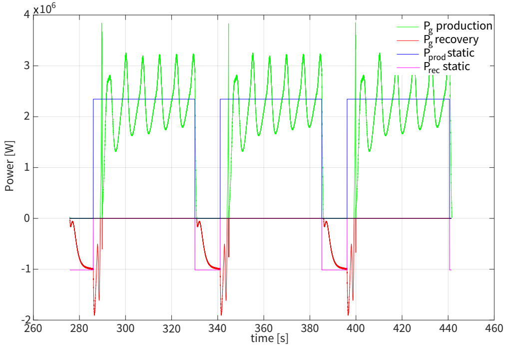
Our current research work is focused on the modeling and control of Magnus effect-based AWE systems. In our approach, a rotating cylinder designed as an aerostat is used to drive a ground-based generator. Our choice of Magnus based aerostat stems from various factors such as high lift coefficient, naturally robust and stable design, and lighter than air capabilities. A study about experimental data available on Magnus cylinders has been done in order validate the aerodynamic model [2].



Trajectory and swept area of Magnus based AWE system in xz plane (left) and yz plane (right) with crosswind manoeuvre in comparison to a 1.5MW conventional wind turbine.

Then, a point-mass dynamic model of the Magnus based AWE system is developed and validated in a simulation environment.

A bang-bang control strategy is applied to control the trajectory of an airborne module that performs crosswind maneuvers. Simulation results show that a 500 m^2 Magnus based AWE produces a net output power around 1.5 MW for a wind speed of 10 m/s. In other terms, the prodction is 3 kW/m^2. Finally, a simplified model of the whole cycle is proposed and validated with dynamic simulations. This model is then used to generate a power curve, compared to that of a conventional wind turbine.



Simulated output power during production and recovery phases with a comparison with a simplified model (P_{static}).

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Windswept & Interesting tethered airborne wind turbine generating electricity (17 December 2016)

Windswept & Interesting tethered airborne wind turbine (30 August 2017)

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Daisy & AWES Networks: Scalable, Autonomous AWES with Continuous Power Output

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Windswept and Interesting Ltd (W&I) design, test and publish novel Open Source Hardware AWES. The company primarily focuses on developments which exploit the operational benefits of Kite Networks. Our AWES Kite Network concepts are simple to make and operate. Our autonomous Kite Network prototypes dispel the myth that an AWES necessitates a control system.

The W&I "Daisy" concept flies rings of power kites, line networked, at a wide radius around a lifting kite tether. The power kites are set to expand their rings while rotating. The wide separation of tense ring and kite tethers allows reliable torsion transmission from multiple kites simultaneously. Our tensile torsion transmission method tests reveal the surprising applicability of ring connected rope ladders in AWES. Torsion was dismissed in early AWES computation as only single line systems were considered. Our simulations of large rotating kite networks "OM Kites" suggest that completely soft (kite and line only) torsion transmission can be very scalable. With less line drag per kite, Kite Networks can also be very efficient.

W&I will present models of the enhanced safety inherent in Kite Network designs. Line networks avoid many breakaway failure modes. A line lattice Lifting Kite Network maintains good nodal tether spacing in turbulent wind. Lift Kite Networks enable dense packing of Daisy Kite Network stacks which increases AWES ground use efficiency [1].

W&I marketed a minimally viable AWES. Our small rotary kite network prototypes have met many small power needs. Arrayed unit AWES designs allowed scaled production from small premises. W&I runs most tests inside an Aerodrome Traffic Zone (ATZ), < 30 m AGL and < 2 kg without conflicting CAP393 Air Navigation Order restrictions. The light-weight system is so compact, I will be demonstrating it throughout this summer on a flying tour of festivals including nearby AWEC 2017 Freiburg.

W&I intends to incorporate standard AWES active control systems as our models scale. Small kite network experiments have revealed huge opportunities and potential for AWES.

References:

[1] "Go fly a kite ... and make energy". Deutsche Welle, 11 August 2017. http://www.dw.com/en/go-fly-a-kite-and-make-energy/av-37785089

Tensile torque transmission system of the Windswept & Interesting tethered airborne wind turbine (5 September 2016)

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EPSRC
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Modelling and Simulation Studies of a Networked Rotary Kite System

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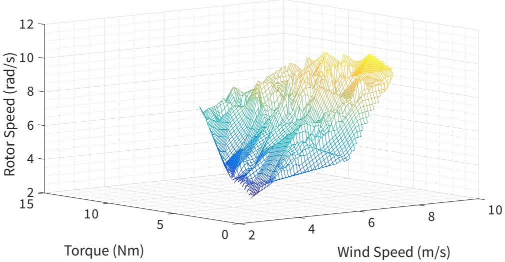
Windswept and Interesting Ltd. (W&I) has been developing an open source rotary Airborne Wind Energy System (AWES) for several years. The Daisy Kite was developed using a minimalistic design approach. The network of standard lightweight kites and lines generates continuous power and provides redundancy for enhanced safety. The airborne components weigh under 2 kg, making the Daisy Kite a portable off grid solution. Several Daisy Kite prototypes have been produced, the most recent one is depicted in the figure together with test results. Experimental work is continuing to provided greater understanding of the concept and its operating strategy. It has highlighted the need for more accurate control over the power take off. At present the only control is provided by a mechanical brake.

Previous development of the Daisy Kite has mostly relied on experience gained from field tests for making alterations to the design. To explore the fundamentals behind the Daisy Kite design a aerodynamic model of the system has been produced. This model focuses on the steady state response of the system. The experimental data from the most recent prototype has been compared to the results produced by the aerodynamic model. Models using the CAD package Rhino were used to explore networked kite stability. This has provided an insight into the scalability of the Daisy Kite design and methods for improving its safe and efficient operation [1].

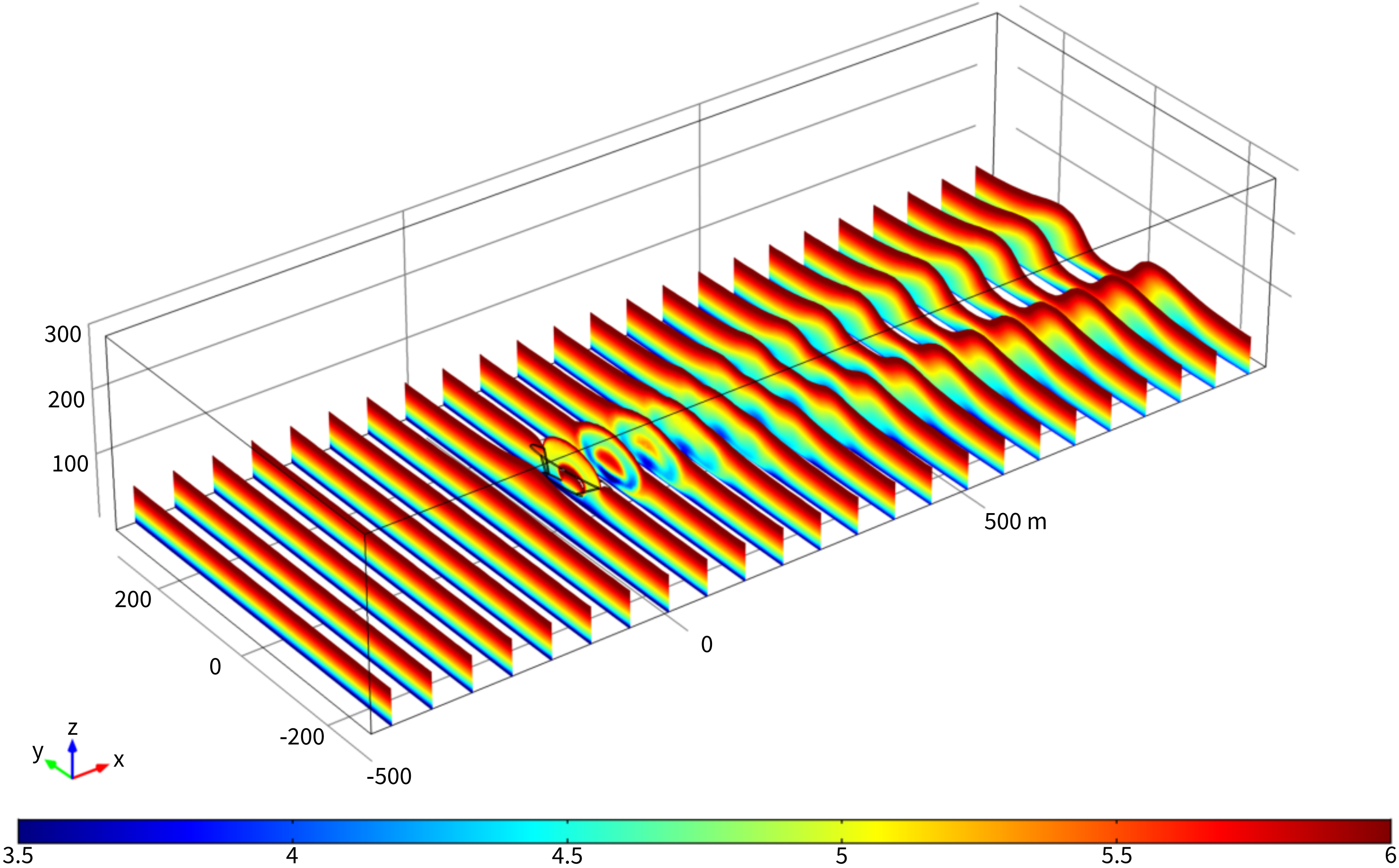


The most recent Daisy Kite prototype undergoing tests and measurement data (June 2017).

References:

[1] O. Tulloch, H. Yue, J. Feuchtwang, R. Read: "Modelling of a Rotary Kite Airborne Wind Energy (AWE) System". SUPERGEN Wind Hub General Assembly. Cranfield University, 23 November 2016. https://www.supergen-wind.org.uk/files/GANov2016/OT%20Poster%20Strathclyde.pdf

Wind velocity (in x direction) downwind of the trajectory of 80m long tethers, outer half aerodynamically shaped



Fusing Kite and Tether into one Unit

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We propose to fuse the tether and kite together into one unit, resulting in an aerodynamically shaped airborne flying tether with high aspect ratio. With this concept we turn the aerodynamic tether into an energy harvester that eliminates the need of a separate kite.

Many airborne wind energy systems under development use high speed crosswind kite systems with some kind of soft or hard wing that is connected to the ground by one or more tethers. In these systems it is well known that the drag forces of the fast moving tethers have large negative impact on power output and also limits altitude.

By using an aerodynamic profile for the tether we can 1) reduce the drag forces and 2) produce lift forces perpendicular to the tether and its motion.

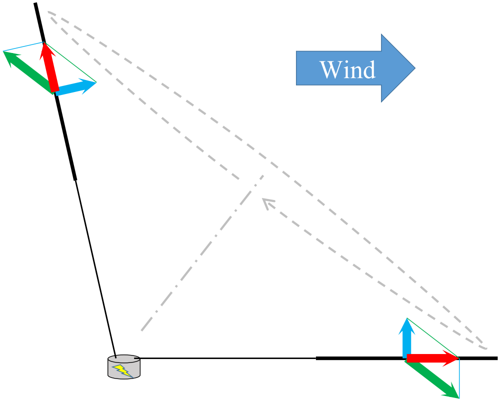
How can these lift forces be used for energy harvesting?

The lift force is perpendicular to the tether, but the tether itself can only take forces in its own direction. Our solution to this problem is to balance the lift force with a centrifugal force, which with correct distribution of mass gives a resulting force in the direction of the tether. The suggested flight path for the flying tether can be described as a cone with its rotational axis pointing about 50 degrees upwards in the downwind direction. With this proposed arrangement we can have a ground based vertical axis generator as illustrated in figure or it can be airborne and tethered to the ground by a cable.

What airfoils could be used in this concept?

A requirement for the airfoil used is that the pitching torque produced should stabilize the angle of attack. For that we need an airfoil with high positive pitching moment and place the center of mass close to the leading edge. It is also desirable that the airfoil have high lift to drag ratio. The airfoils we have developed for this have C_m around 0.05 and L/D ratio around 100 at Reynolds 10^6.

The flight path of the tether can be controlled by moving weights inside the tether, tilting the generator or control surfaces. This concept may also be used for traction or lifting.



Conical path of flying tether and resulting forces. Blue are lift forces, green centrifugal forces and red the resultning tether forces.

Kiwee One airborne wind turbine with 1 m rotor diameter (1 July 2017)

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Inertia-Supported Pumping Cycles with a Roto-Kite

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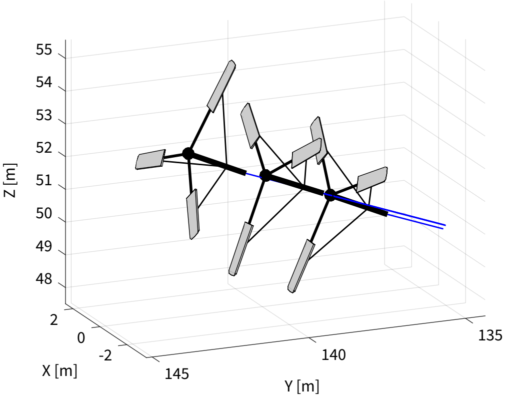
It has been shown in simulation that multiple-kite systems show great potential over single-kite systems due to reduced tether drag [1]. Rotary kites are an interesting subclass of multiple-kite systems, because they are easy-to-build and yield simpler dynamics. Additionally, rotary kites offer a possible 'elegant solution' for the take-off problem of more general multiple-kite systems, where the rotary kite is launched first, and the tethered kites are released and unrolled from the central point after take-off at high altitude.

Here, we present recent simulation results for a pumping airborne wind energy system consisting of a fast spinning rotor – the roto-kite – with three blades, which is connected to a ground-based generator by a tether. The airborne system is controlled by both collective and cyclic pitch control. Power is generated by a pumping cycle, i.e., by unrolling the tether in the generation phase, and winding it up in the retraction phase, which is typically characterized by lower tether tension. For the simulation study, systems with varying airborne area are modelled by differential-algebraic equations and analysed with the help of numerical optimal control techniques.

The surprising result of the optimal control computations is that the overall system efficiency can reach nearly 100% of Loyd's limit, even though the retraction phase uses almost 50% of the cycle time, which is chosen to be very short by the optimization solver. This gain in efficiency of 10-15% compared to conventional pumping cycles is possible by exploiting the inertia of the spinning rotor to store energy harvested in the retraction phase, as detailed plots of the power flow between the wind, the tether, and the roto-kite's rotational energy reveal. This counterintuitive behaviour is discussed in detail, and possible use cases for the discovered new cycle, such as sinusoidal pumping cycles, are presented.



Three stages of a simulated power-optimal pumping trajectory of a roto-kite.

References:

[1] Zanon, M., Gros, S., Andersson, J., Diehl, M.: Airborne Wind Energy Based on Dual Airfoils. IEEE Transactions on Control Systems Technology, Vol. 21, No. 4 (2013)

The Sea-Air-Farm Project

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Ampyx Power is developing an alternative for wind turbine generators, an Airborne Wind Energy System. An autonomous aircraft fixed to a tether follows an optimized flight pattern. During reel-out, the tether pulls with very high tension on a winch, which in turn drives the generator. When the tether is completely reeled-out, the plane dives back towards the platform and the tether is reeled-in at very low tension. This system has been developed on multiple 20 kW prototypes; currently, a 200 kW prototype is being built, while the upscaling to a 2 MW model is ongoing. This system will generate a similar amount of energy to a conventional wind turbine, but with much less materials. This is partly because it operates at much higher altitudes -with more winds-, and partly because it flies at much higher speeds than the spinning blades of a wind turbine.

On the short term, Ampyx Power intends to deploy this technology on land, and to replace the first generation offshore WTGs that have been installed in Europe since 2000. However, on the long term, we foresee an enormous potential in the floating offshore wind market, where the advantages of the AWES system over traditional wind turbines (low weight, minimal foundation loads) have even more weight than for the case for bottom-fixed foundations.

Ampyx Power built a consortium to implement a full fledged feasibility study, and obtained subsidy from the Netherlands Enterprise Agency [1].

- Ampyx Power investigated the upscale from AP-3 to AP-4 (2 MW)
- Mocean Offshore designed a dedicated floater with mooring and innovative cable hang-off
- Marin tested the floater in their test basin, after which the Mocean design was further refined
- Independent Energy expert ECN validated Ampyx Power's yield models, developed a wake model and calculated the annual energy output
- Based on the knowledge available, all parties contributed to the design of a conceptual offshore windfarm and its installation and O&M strategies.
- An overview of the relevant certification and consenting regulations and bodies is made.
- Based on the above, ECN estimated the resulting LCoE, making use of their dedicated cost models.

While the final reporting is expected by December 2017, we will already be able to share in our presentation the results of all work packages as described above. *References:*

[1] Netherlands Enterprise Agency (RVO): "Exploratory Research and LCoE of Airborne Offshore Wind Farm". Project no. TEWZ116048. https://www.rvo.nl/subsidies-regelingen/projecten/exploratory-research-and-lcoe-airborne-offshore-wind-farm

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A Study on Wind Power Evolutions

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ENGIE France Renewable Energy (EFRE) develops, builds, finances, and operates ENGIE's renewable electricity generation assets in France, including wind, photovoltaic, marine, and hydropower. ENGIE's renewable electricity generation fleet in France (wind, solar and hydro) now reaches nearly 6,000 MW of installed capacity [1].

Albeit mature, innovation is still important in the wind energy field. New technologies are emerging with short-, medium- and long-term commercialization prospects: new generation wind turbines (NGWTs) with large rotors and airborne wind energy systems (AWESs). In order to better understand future changes in these wind power systems, EFRE has commissioned a study to 4 students of the ENSE3 engineering school at Grenoble (France), under the supervision of researchers from GIPSA-lab and GAEL. The study aims at providing some decision-making elements for EFRE positioning on NGWTs and AWESs in France. In the first place, the study addresses the evolution of wind turbine technology as well as the social, economic and legislative context in France. Different limits and challenges that currently face conventional wind turbines are then analyzed. In the second place, a study on NGWTs and AWESs is conducted. These emerging technologies are compared to conventional wind turbine according to the previously listed challenging aspects and what could be their respective positions in the coming years: complementary or substitution. Special attention is given to several factors such as social acceptance, cost, environmental impact, regulatory changes, quality of production, and site selection. The study shows that low-wind-speed turbines are the future of onshore production in France, as sites with high-wind-speed are becoming rare. The development of AWESs is more unpredictable as the technology is still under development and facing significant technical challenges. In order to outperform HAWTs in the near future, AWESs need to be developed for niche markets and eventually for low-wind-speed sites.

One of ENGIE's wind farms.

References:

[1] http://www.engie.com

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A Policy Recommendation for Airborne Wind Energy

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The history of the introduction of new energy technologies provides empirical evidence of which strategies works and which fails. Studying the top 10 wind turbine suppliers reveals that all turbine models has been a part of a gradually increase in scale from origin designs <300 kW in the 80s and early 90s. Attempts to jump directly to large scale consequently fail. The lack of the higher subsidies offered in early phase of introduction makes later introduction more challenging and prevent companies entering with new designs.

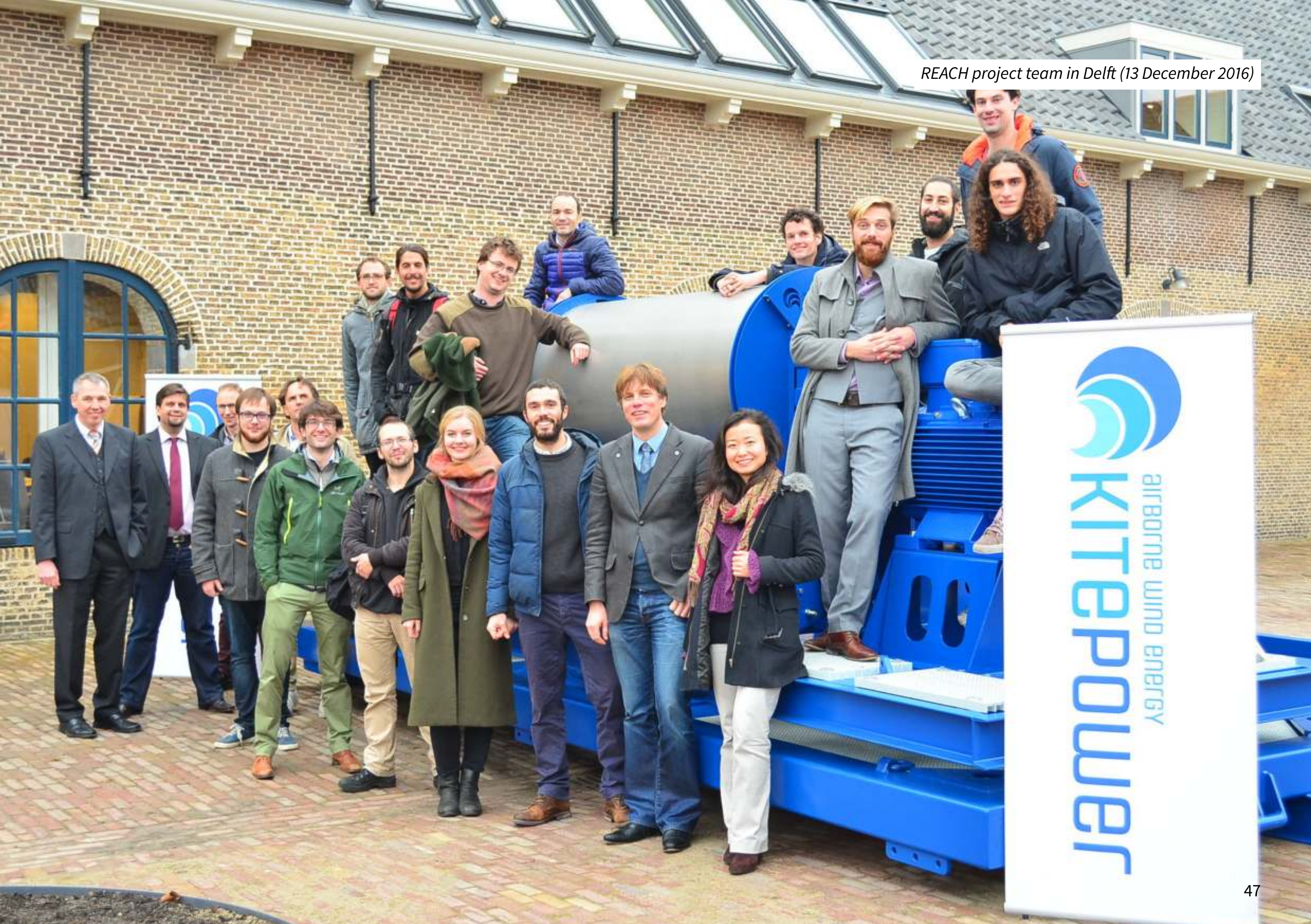
This paper discusses the main implication of scaling up in small steps from the view of investors, AWE companies, and governments. If smaller scales give negative system performance, apparently, then the return of investments will be lower and the need for subsidy higher. Yet, it is more cost efficient to learn in small scale, for all stakeholders. Historically, solving the drawbacks of introduction cost in small scale is the best strategy.

Kitemill recently sold a pilot plant to the first customer as a proof of commitment from the customer and its funding partners. The same financial model is intended when Kitemill will supply the five first demonstration plants after sufficient pilot operation. Indicatively, it shows that the current scale of 30 kW is small enough to attract investments.

Operational hours will be one important key to mature the technology. Operational hours need to be accumulated for each step, by each single AWE supplier. Then scaling up in small enough steps for the operational experience to be valid for each next iteration.

All new energy capacity is a result of political will and determination. It is unlikely for a large technology shift to occur without strong public incentives. The need of subsidy each kWh decreases as the scale increase. It is likely that the first wave of AWE technology introduction will be both supported and funded in order to be matured, rather than for its energy yield. Though, subsidies as a function of operational hours to mature the AWE industry exponentially increase with introduction scale. Social economists will favour smaller scale. AWE companies should optimize the introduction strategy based on this.

Kitemill is prepared to support further discussions about policy recommendations and introduction strategies.


REACH project team in Delft (13 December 2016)

Kitepower's new 100 kW ground station in Delft (13 December 2016)


100 kW ground station of Kitepower B.V. in operation at testcenter Valkenburg (24 July 2017)

Kite Control Unit KCU2, designed and built by Kitepower and Maxon Motor, steering a 25 m^2 kite (24 July 2017)

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Kitepower – Commercializing a 100 kW Mobile Wind Energy System

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At Kitepower, we focus on commercializing mobile 100 kW Kitepower systems that are suitable for temporary operation and installation in remote locations. Kitepower is a spin-off from the research group at TU Delft first established by Wubbo Ockels and now at the core of REACH, a €3.7 million EU H2020 FTI program [1]. Within this project, Kitepower integrates almost 20 years of academic knowledge in high altitude wind energy from the TU Delft with hardware from experienced industrial partners. We pair the agility and the drive of a startup company with the knowledge of a top research institute – TU Delft – and in a next step combine it with the production capabilities and expertise of the established companies Maxon Motor, Dromec and Genetrix.

Kitepower itself is responsible for the commercialization, the overall system architecture, design, simulation and the control software. We improved our 20 kW prototype and developed the 'Model A' of our 100 kW product with a peak power of 180 kW. We believe that we are the first to have a mobile wind energy system of this size operational. Besides numerous flight hours, we already had several night flights. With our new Kite Control Unit (KCU) which is no longer dependent on battery power, we are moving towards two months of operation until the end of the year. The major advantage of our system lies in the fact that we use a KCU and a soft kite. These are simple components that are very robust, easy to control, have a low weight as well as low costs and are easy to manufacture and to replace. Although the soft kite inherently has a lower aerodynamic performance, we believe that its simplicity and robustness fits perfectly with the off-grid market. We are currently working on a new wing design with improved aerodynamics and structure to make a high efficiency, high wing loading soft kite possible. The 100 kW product is based on a 20 ft container and a 50–80 m^2 kite. The system is marketed as an add-on for diesel generators in order to save on diesel costs in remote locations. It is estimated that the system can save up to 150000 L of diesel – 400 t of CO$_2$ – per year under appropriate wind conditions. We are running multiple pilot systems until our final product is ready by the end of 2018.

Kitepower "Model A" ground station with 180 kW peak power

References:

[1] EC Community Research and Development Information Service (CORDIS): REACH Report Summary, 15 May 2017. http://cordis.europa.eu/result/rcn/198196_en.html

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Policy Development and Roadmapping for Kite Energy

Gustaf Kugelberg
KiteX

An advocacy-coalition should be formed to promote supportive regulations.

Wind energy is well integrated into the political agenda in many countries and there is a supportive regulatory framework to drive its implementation and development. Building on key learnings from the experience of “policy entrepreneurs with previous success in influencing the political agenda-setting in wind energy, as well as insights from policy science, this presentation will focus on four key components for building political support for kite energy.

Identify key supporters. It has been shown that a broad support for a policy issue, in this case the establishment of certifications and regulations around kite energy, is vital for favorable political agenda-setting. To influence the political agenda, kite energy stakeholders need to build support for its development and identify supporters from civil society groups, environmental organizations as well as from prominent leaders.

Define the opposition. It is also vital to know the key opponents to kite energy and their main arguments; this could be traditional wind energy stakeholders, environmental groups, aviation authorities etc. This will help frame our message, putting us in a better position to preemptively deal with the opposition.

Develop an advocacy-coalition and a common strategy. It is essential to get organized and gather knowledge on key policies and regulations in this area. This will help define the goal and key objectives of the strategy. What are the key regulations concerning land–, water and airuse that should be in place to promote kite energy? What changes to current regulation would kite energy require? What are the benefits, compared to traditional wind turbines, for various stakeholders? These and other questions need to be answered.

Develop a supporter coalition. Build a coalition of supporters and ensure that messages are aligned, and that goals and objectives are clearly understood. Engage in the policy process and actively take part in committees and advisory councils to regional/national policy development.

This effort could be launched out of a network organization like Airborne Wind Europe or events like the International Airborne Wind Energy Conferences with the establishment of a working group with representatives from various industry players.

Top-down view of 30 kW Kitemill airplane (17 August 2016)

Kitemill prototype in flight (3 March 2016)

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From Prototype Engineering towards Commercialization

Lode Carnel
Kitemill AS

When the main functional challenges for airborne wind energy are solved, this breakthrough energy source will face introduction problems as it is not a proven technology. Therefore, it is important that working prototypes try to collect a lot of operational hours in relevant environments as early as possible. Kitemill has developed prototypes as well as obtained the needed regulatory agreements for outdoors testing. The presentation describes the history of Kitemill until now and our strategy going forward. The developed prototypes are presented as well as our current technical status.

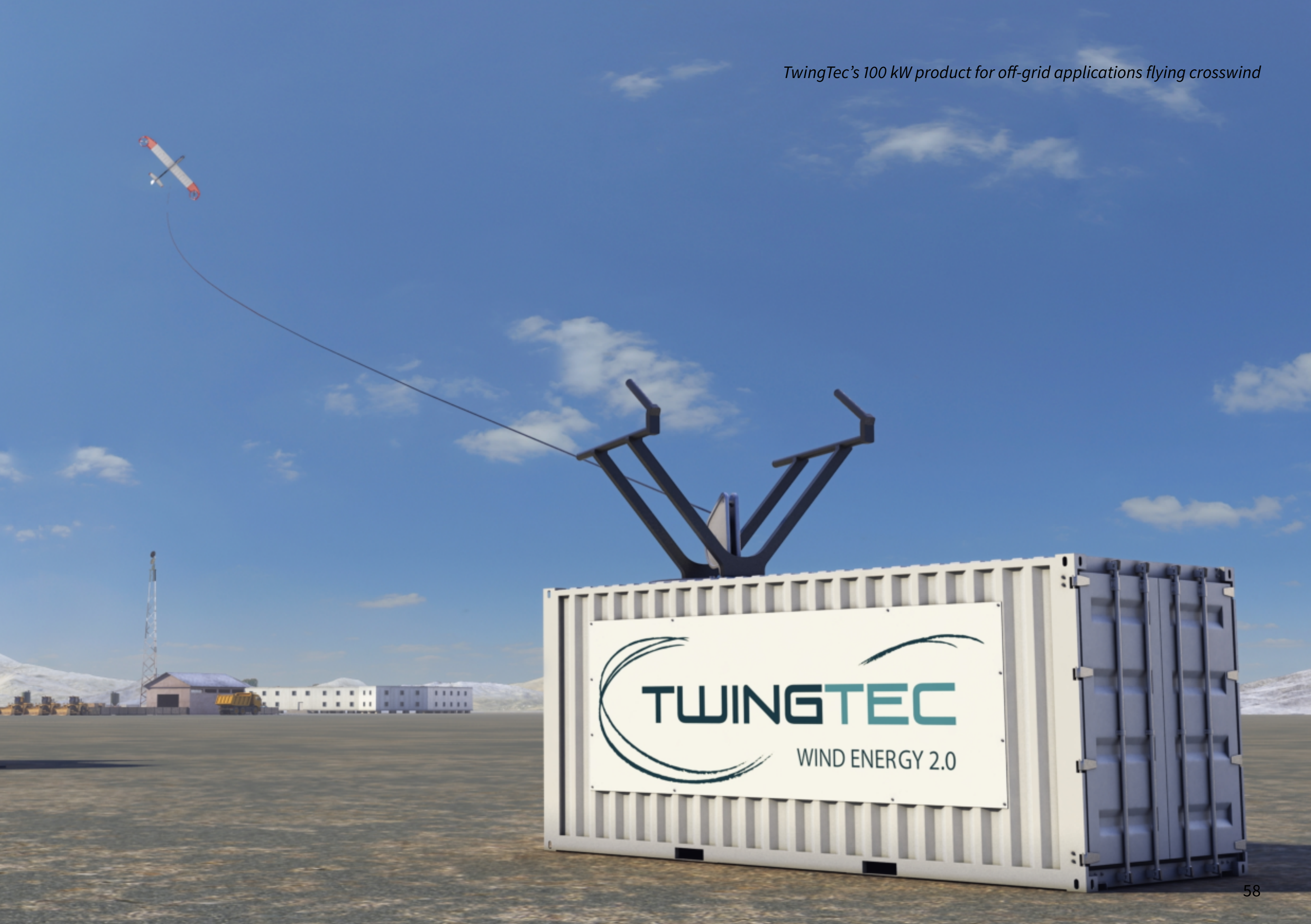
Kitemill has over time had a continuous dialogue with the civil aviation authorities resulting in two zones where kite turbines can operate, one permanent and one temporary one.

Early on, Kitemill identified rigid wings as the most promising concept to extract airborne wind energy. The initial focus of Kitemill was on demonstrating functionality of our small-scale setup (5 kW). After manual demonstrations, an autopilot was developed using commercial-off-the-shelf components. Later, the rigid wing was combined with a quadcopter technology towards a fully functional 5 kW system including VTOL. The main technical challenge is currently the autopilot during high acceleration phases. Following the testing of this prototype, we designed, developed and constructed a 30 kW system. The project started in the beginning of 2015 and the plane was flown for the first time during the second half of 2016. Currently we have developed the VTOL system for the 30 kW plane and initial take-offs were performed. During summer 2017, it is anticipated to fly the 30 kW system in production as well.

The technical results of Kitemill led to a sale of a 30 kW demo plant at Lista, Norway. Initial weather analysis was done based on weather data from the last 25 years and this with our technical data lead to the business case. The demo will be part of an airborne wind energy center where also other companies are invited to participate. The demo plant will then be commercialised where Kitemill will follow DNV standards for technology qualification. Additionally, during this extensive testing phase Kitemill will accelerate the development towards the necessary robustness level on all the disciplines.

The TwingTec team (20 December 2016)

TwingTec's 100 kW product for off-grid applications


TwingTec's 100 kW product for off-grid applications flying crosswind

Off-shore wind farm with TwingTec's 2.5 MW units

TwingTec's prototype during launching (30 September 2016)

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Off-grid, Off-shore and Energy Drones: TwingTec's Roadmap to Wind Energy 2.0

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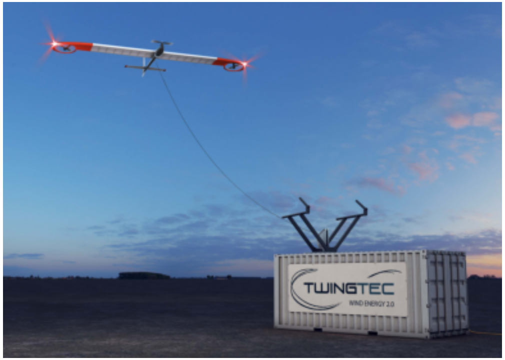
Cédric Galliot, Flavio Gohl, Jannis Heilmann, Corey Houle
TwingTec AG

Current wind turbine technology can only access a small fraction of the global wind energy potential. The massive structures stick to the ground and can off-shore only be deployed in shallow waters. Wind Energy 2.0, the next generation wind energy technology, will expand the range of wind energy up to several hundred meters above ground and to basically the whole surface of the planet, land or sea. An array of 20 x 20 energy drones will produce 1 GW of electrical power. Installed off-shore on floating platforms such Giga-Islands will be a major element of the future sustainable energy economy.

TwingTec is at the forefront of the development of Wind Energy 2.0. The key drivers of TwingTec are a strong focus on the market, a reliable technology, a professional team and a clear product roadmap. In phase I TwingTec has developed its technological concept in close cooperation with leading Swiss R&D institutes. The main guidelines of the development were economics, fully autonomous operation and safety. We realised some years ago that the emerging civil drone technology is key to fulfil these requirements. Thus, our airborne device evolved from a kite into an energy drone. Starting this year TwingTec has entered phase II which is focused on reliability and safety. To this end TwingTec is currently developing a scaled pilot system together with industrial partners. The system is highly mobile and can be readily demonstrated at customer sites. Commercialisation will start in phase III in 2018. TwingTec is convinced that the off-grid market provides a very interesting opportunity for Wind Energy 2.0 with products in the range of 100 kW to 500 kW. TwingTec is currently lining up first commercial projects in Canada with mines and remote communities. Finally, TwingTec will step into the utility scale with a 2.5 MW system focussing on off-shore applications, where the ultimate potential for airborne wind energy lies.



TwingTec's 100 kW product during launch

EnerKíte's ram air wing EK30 high up in the sky

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Airborne Wind Energy – a Game Changing Technology and a Global Success?

Alexander Bormann, Christian Gebhardt, Christoph Hauke, Stefan Skutnik
EnerKíte GmbH

Wind Energy can power the world a hundred times over, transition towards renewable energy however struggles with volatility, low cost of fossil fuel, acceptance and other risks in renewable energy projects. With these facts in mind the EnerKíte team develops a unique technology, which can harness the stable and persistent high-altitude winds. Our aim is to make this abundant source of energy commercially viable, from small power ratings until utility scale, starting at comparatively low levels of maturity.

With respect to scalability, minimal operational risks and low cost of energy, EnerKíte conducted intensive work on the implementation of the rotating launching and landing device and it's unique semi-rigid wing-technology. Proceeding from customer requirements, typical operating conditions, legal frameworks and logistical constraints the overall system and its specific sub-systems are chosen and developed towards an all integrated AWE system.

Recent price drops in the renewable energy market are forcing innovations to be competitive at 50 €/MWh or less at utility scale, even for off-shore projects. Competitiveness however, can also be achieved from the energy systems perspective with creating business models based on high onshore capacity factors, low system cost of electricity and all above flexibility of operation. EnerKítes are designed to deliver 90% of its rated power over 50% of the time of the year, enabling cost efficient base-load capability with renewables.

The presentation will focus on recent achievements, the scalable product roadmap and an outlook towards 100% renewable energy systems in typical applications. Based on GIS-supported, parametrical studies, we can estimate, that EnerKítes at utility scale may power the world a hundred times over – from prospective onshore operations at suitable sites around the globe alone.

EnerKíte

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Commercialisation of AWE 2017–2037

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IDTechEx Ltd.

This presentation shares research in IDTechEx report, “Airborne Wind Energy 2017–2027”. The primary unfulfilled need is continuity of supply of green energy. We advocate a bold approach creating major new markets. For example, a large ship emits NO_x and particulates of millions of cars: it could be made energy independent. A long life, low cost genset with no battery needed would create a huge market. Both could be achieved with multimode harvesting of which AWE is a part.

We need a zero-emission replacement for 600 GW of diesel gensets and power stations. Like them, the replacement should be demand responsive/ almost always available/ no huge batteries. In this presentation we focus on off-grid 10 kW to 1 MW AWE opportunities - arguably as big or bigger than the on-grid and accessible earlier. Continuity of high wind must deliver superior continuity of electricity production. Testing is modest as yet: we simply do not know and underfunding is a threat.

Ship power promises few AWE systems yearly: smaller and more difficult than off-grid land power of potentially millions yearly, including microgrids, diesel gensets and charging parked electric buses and trucks in remote locations. Longer term, Google Makani’s envisioned floating chemical factories and servers would boost the marine market as would viability on smaller craft. All need to be leveraged with new photovoltaics. There is scope for leveraging electric sails, solar roads as decking, triboelectrics and DEG wave power. Being in the most appropriate regions of the world and able to rise through still air to operate helps: easiest with drones. Several developers have moved to drones: only one has gone the other way. Most admired by developers is Google Makani.

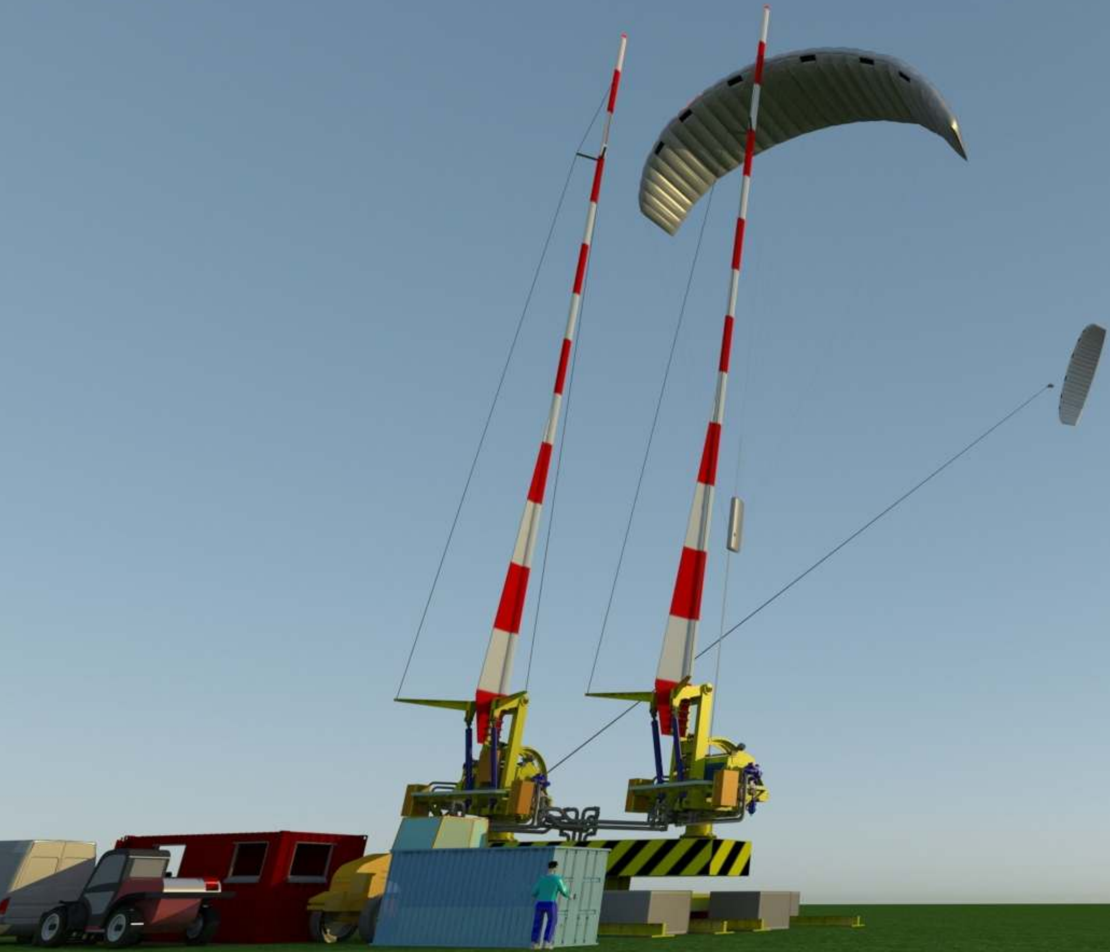
Transportability helps advancing armies, disaster areas and powering the new farm robotics in the fields. Our initial assessment is that largest off-grid accessible market is for groundgen with electricity for lighting, sensors etc produced on-board. Sophisticated autonomy and structural health monitoring are important for continuity and safety. Four AWE developers sell product soon. Based on take-off of other “new” energy, off-grid AWE sales may be three hundred units in 2028, later billions of dollars. Most popular power output may be 10–100 kW.

Ram air kite and suspended control unit of Kite Power Systems Ltd. in operation (6 July 2015)

Aerodynamic control of the ram air wing of Kite Power Systems Ltd. (16 March 2015)

Ram air wing of Kite Power Systems Ltd. during flight, seen from the kite control unit

Computer rendering of the 500 kW unit of Kite Power Systems Ltd.



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Kite Power Systems – Update & Progress on the Development of a 500 kW Kite Energy System At West Freugh, Scotland

Simon Heyes
Kite Power Systems Ltd.

Kite Power Systems Ltd. (KPS) will provide an update on site activities since securing equity investment from E.ON, Shell, Schlumberger and Scottish Enterprise at the start of 2017. This will include company relocation, test site development, environmental permitting and development of a 500 kW demonstrator unit.

KPS has relocated from Essex, England to Glasgow, Scotland and trebled the size of the team to 28. KPS has two test sites near Stranraer, Scotland (West Freugh and Castle Kennedy).

West Freugh is a Ministry of Defence owned military range which is operated by QinetiQ. The site is within the smallest air danger area in the UK, with exclusion extending up to 35,000 ft altitude (way in excess of the KPS operational limits). Approval for operating at the site was achieved through consultation the UK Ministry of Defence (MoD) and the Civil Aviation Authority (CAA).

KPS obtained planning consent for the site in summer 2016. The area is within the Luce Bay and Sands Special Conservation Area with designated bird species including Greenland White Fronted Geese and Hen Harriers. KPS has conducted bird surveys and bird impact modelling supported by Natural Power consultants.

The development of a 500 kW demonstrator unit has progressed, with the system to be completed and commissioned in Dumfries, Scotland, ready for deployment to the test site in 2017.

KPS has identified a pilot array site for deployment construction as early as 2020, comprising of up to 10 × 500 kW systems, with a total power output of 5 MW. This phase of activity is moving from feasibility to environmental scoping.

Protected Greenland White Fronted Geese migrate to the area around West Freugh during October to April. Picture courtesy of Royal Society for the Protection of Birds (RSPB).

Working on the Ampyx Power AP-2 (20 December 2016)

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Design Automation in the Conceptual Design of Airborne Wind Energy Systems

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For the development of a successful airborne wind energy (AWE) system, there is a need to have an accurate estimate of the final system's performance early in the design process. In order to increase the commercial value, a design should be optimized within the limits of the considered concept. In order to come up with a sound performance prediction of of a whole range of concepts, a combination of Multi-disciplinary Design Optimization (MDO) and Knowledge-Based Engineering (KBE) techniques are used. By these techniques, the process of finding a feasible and optimized design of a complete energy generating system can be largely automated. In this fashion, a large number of system concepts can be elaborated and compared accurately, thus generating the design knowledge that is sought before making any commitment to develop such a system in detail.

The proposed methodology uses KBE to capture the knowledge and experience that a human design engineer possesses and subsequently emulates it in an automated fashion. It typically works in a logical fashion, using rules and reasoning logic to make design decisions.

The focus of MDO is on the structuring of a design optimization that involves multiple distinct disciplines of a given to-be-designed product (e.g. aerodynamics, structures, control, etc.). It makes a complex design process more manageable by creating an effective division between different parts of the overall design problem, while maintaining consistency between them. The basis of MDO is numerical optimization, which is typically a heuristic trial and error method. In comparison to a rule based reasoning method, such an approach inherently requires more effort to come up with a design that is feasible. On the other hand, no preexisting design-knowledge is required to find this design, with the added bonus of finding a design that is also optimal within the imposed set of constraints.

The best results of the combined MDO and KBE approach in conceptual design automation are obtained by a combination of the two techniques that complement each other in an effective way. While the overall AWE system is a complex and novel combination of various components and sub-systems, actually a lot of these latter are very mature systems and well understood in terms of their design characteristics. For these lower-level designs, preexisting knowledge can be applied in a KBE fashion to efficiently find a feasible and close to optimal design solution. On an overall systems level, where such knowledge does not exist yet and complex systems interactions are at play, MDO-based processes would be more appropriate to find the optimum design point in a complex and unknown design landscape.

The implementation of innovative MDO and KBE design techniques will be described as well as their specific interaction in this framework. Tentative design results will be qualitatively presented for the various conceptual system architectures treated and recommendations will be made on successful candidates for further development.

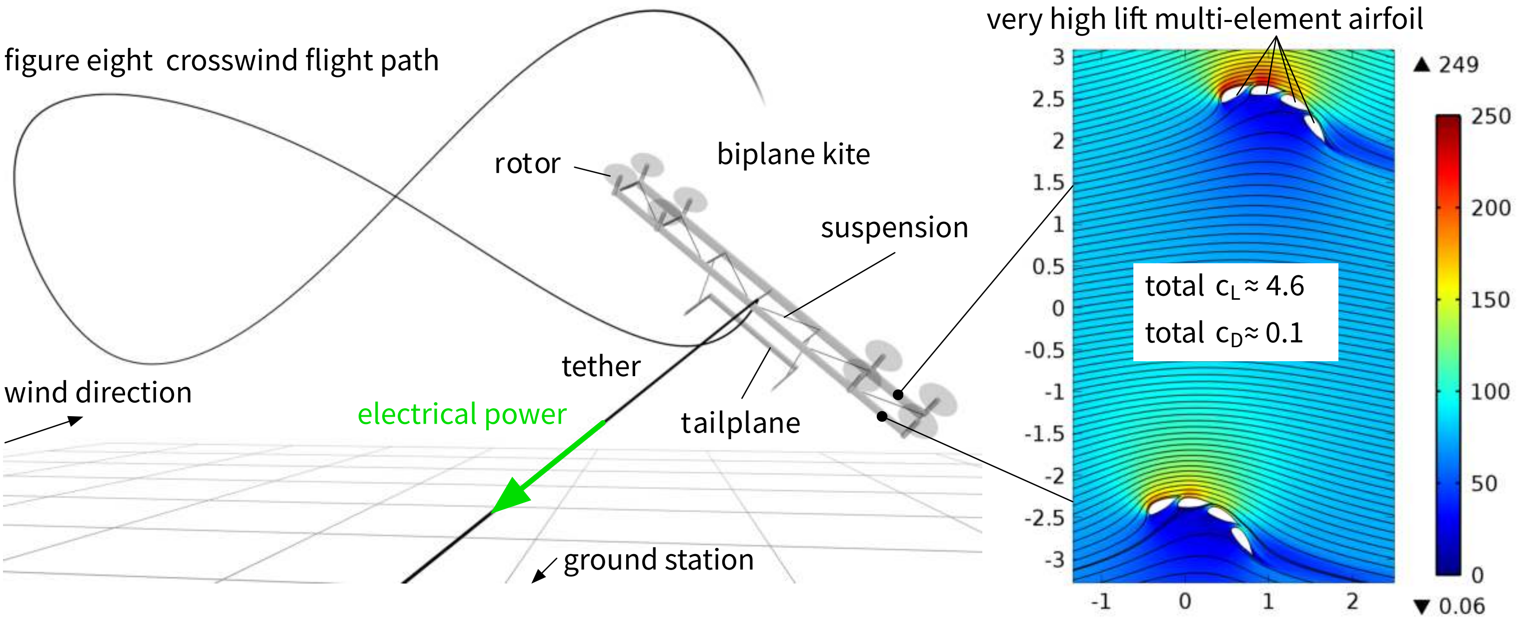

Illustration of "drag power" with biplane kite (left) with a very high-lift multi-element airfoil (right), cf. [3]

Power Curve and Design Optimization of Drag Power Kites

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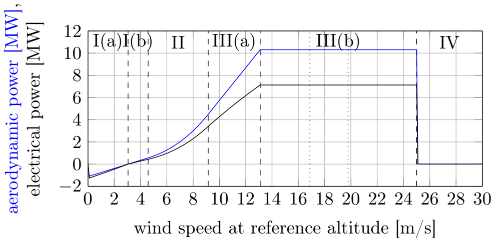
This study considers kites with onboard wind turbines driven by a high airspeed due to crosswind flight ("drag power" [1, 2]). An optimal power curve and an optimal overall power plant design with requirements for a detailed kite design are derived. For that, the model of [3], which extents Loyd's model by an airfoil polar model, a 3D wing model, a tether drag model, a wind field model and an economics model, is further extended by a model for the electrical cables of the tether and their sizing, an actuator disk model for the rotors for crosswind flight in turbine and propeller mode as well as for hovering, and a drivetrain model (efficiencies, masses, costs). A biplane kite with a very high lift multi-element airfoil is considered, as it is found as optimal in [3].

The power curve with all meaningful regions and required actuations (rotor drag coefficient/induction factor, lift coefficient, actuated drag via air brakes or sideslipping) is derived. With a genetic algorithm, all free design parameters are optimized and numerous parameter studies are performed. One result is that a 40 m wingspan biplane kite with a wing area of 80 m^2, a lift coefficient of 4 and a tether length of 370 m achieves a nominal electrical power of 7 MW, i.e. it has a power density of 90kW/ ^{2}. Moreover, the kite power plant has a maximum allowed cost of 5.5 Mio.USD to achieve a LCOE of 0.05 USD/kWh and the kite has a maximum allowed wing mass density of 140 kg/m^2. A biplane kite is expected to be superior to a monoplane kite with respect to its ability to sustain the very high wing loading of 1600 kg/m^2 caused by the high lift coefficient.

First simple component verifications have been conducted, but further verifications are planned for both, component level and system level. In this talk, the derivation and underlying assumptions of the kite model are presented and key results of the parameter studies are discussed.



Optimal power curve for a 40 m wingspan biplane kite.

References:

[1] M. Loyd: Crosswind Kite Power. Journal of Energy ***4****(3), 106-111 (1980)*

[2] U. Ahrens, M. Diehl, R. Schmehl (Eds): Airborne Wind Energy. Berlin-Heidelberg, Springer, 2013

[3] F. Bauer, R. M. Kennel, C. M. Hackl, F. Campagnolo, M. Patt, R. Schmehl: Drag power kite with very high lift coefficient. Submitted for publication in Renewable Energy (Elsevier), 2017. Available from http://www.eal.ei.tum.de/en/research/projects/research-bauer/

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OpenAWE: An Open Source Toolbox for the Optimization of AWE Flight Trajectories

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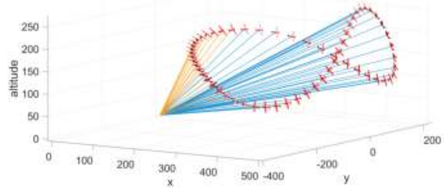
[2]Department of Microsystems Engineering (IMTEK), University of Freiburg

We present OpenAWE [1], a Matlab/Octave toolbox for solving optimal control problems with an airborne wind energy (AWE) system. For example, the toolbox can be used to find a flight path that produces maximal power (see Figure), or to find launch and landing trajectories. Parameters of the system can be optimized. Therefore, using the toolbox can accelerate the design process in the development of an airborne wind energy system and help with the implementation of a control system.

OpenAWE is implemented using object oriented programming and provides functionality to easily specify the objectives of the optimal control problem. The objectives of the optimization problem are specified by a user supplied cost function that is being minimized, and a set of constraints that are satisfied in the solution of the problem.

The toolbox contains a library for modeling the system which consists of the airborne components, the tether, and the winch. The current prototype of Ampyx Power named AP2 serves as a reference model [2]. Two types of tether models are provided: a straight-line tether and a static tether approximation that is capable of representing the tether shape [4].

To benefit from ongoing research and state of the art algorithms, the toolbox is built upon our own developed Open Optimal Control Library (OpenOCL) [5]. It uses CasADi for automatic generation of derivatives [6], and Ipopt to numerically solve the non-linear optimization problem [7].



An optimal flight path for generating power with an AWE system computed by OpenAWE. Here, a periodic power cycle at 8 $\frac{m}{s}$ wind speed with logarithmic profile is shown for the current prototype AP2 of Ampyx Power.

References:

[1] Koenemann, J.: Open Airborne Wind Energy Toolbox (2017). http://openawe.github.io

[2] Ruiterkamp, R. and Sieberling, S.: Description and preliminary test results of a six degrees of freedom rigid wing pumping system. Airborne Wind Energy. Springer, 443–458 (2013)

[4] Koenemann J., Williams P., Sieberling S., and Diehl M.: Modeling of an airborne wind energy system with a flexible tether model for the optimization of landing trajectories. IFAC World Congress (2017)

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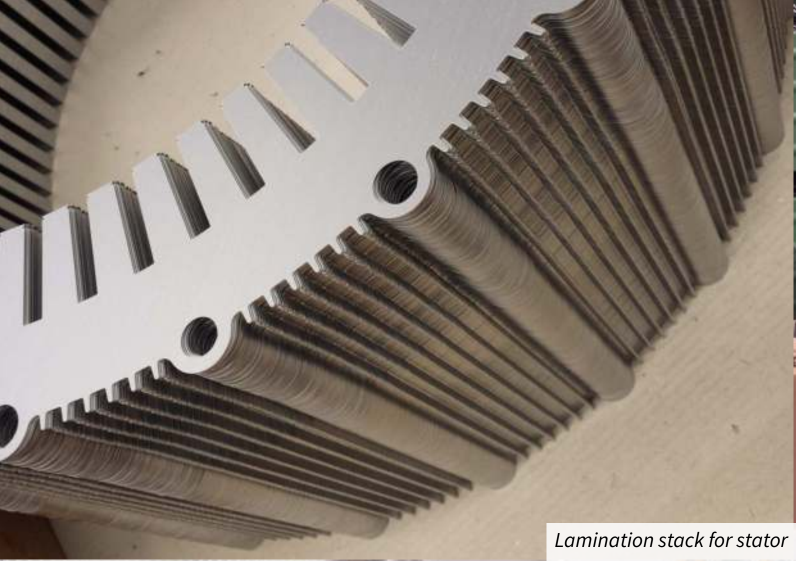
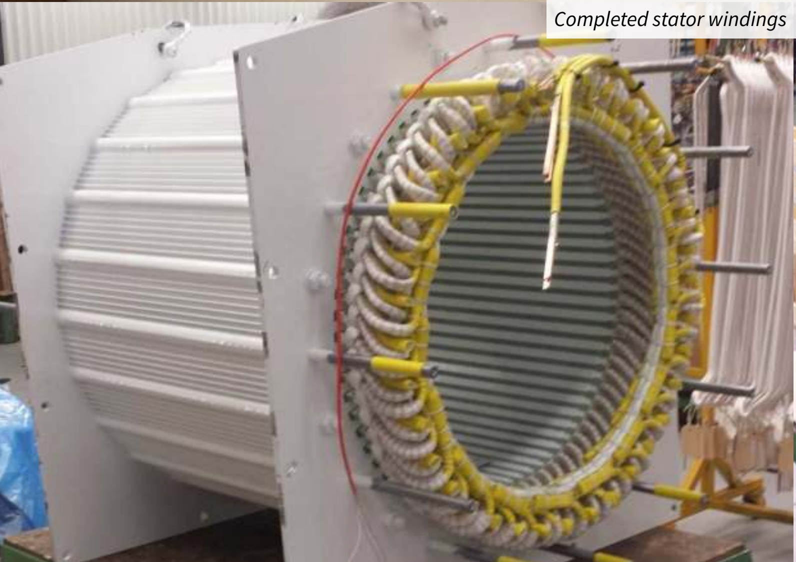
[7] Waechter A. and Biegler L.T.: On the Implementation of an Interiorpoint Filter Line-Search Algorithm for Large-Scale Nonlinear Programming. Mathematical Programming, 106/1/25-57 (2006)

The making of E-Kite's 80 kW direct drive generator



Lamination stack for stator

Fitting windings into stator



Completed stator windings

Rotor with fitted windings

E-Kite's 80 kW ground station (13 May 2016)

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Highly Efficient Fault-Tolerant Electrical Drives for Airborne Wind Energy Systems

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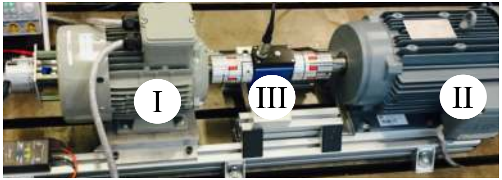
Airborne wind energy systems are considered to be a highly efficient cost-effective replacement for conventional wind turbines (CWTs). However, several correlated design and engineering aspects hinder the commercialization of such technology. The selection of a highly efficient fault-tolerant electrical drive is still challenging especially for those AWE concepts based on reel-in/out for power generation. Employing the same topology of three-phase electrical drives as those for CWTs is disadvantageous due to two reasons.

1. Failure rates of the electrical components of CWT in several studies indicated that power converters are highly likely to fail [1], [2]. Upon isolation of the faulty part, the machine behaves as a single phase machine, which is non-self-starting, incapable of reversing rotation direction and derates to $\approx$ 33% of the pre-fault condition to avoid substantial overheating.
2. Fault-tolerance using a backup machine and/or converter is of limited fault-tolerance capability and is cost-ineffective.

A suitable alternative is to split each phase into two independent phases, which is also known as dual three-phase machines (DTMs). In case of a fault, one of the DTM configurations can reach up to $\approx$ 80% of the pre-fault torque [2]. Additionally, subsidiary achievements such as higher efficiency, 50% reduction in converter ratings [1], significant reduction in DC-link voltage requirement, and lower torque ripples (which translates into less audible noise) are granted for the same machine and hardware configuration.

The shown figure represents the practical test-bench containing interior permanent magnet synchronous machine (IPMSM), which has been rewinded as a DTM. It is currently undergoing several experiments, which aim at enhancing the drive performance during pre- and post-fault operation.



Practical setup containing: I- IPMSM-DTM, II- load machine resembling the Kite, and III- torque sensor.

References:

[1] I. G.-Prieto, M. J. Duran, H. S. Che, E. Levi, M. Bermudez, and F. Barrero, "Fault-tolerant operation of six-phase energy conversion systems with parallel machine-side converters," IEEE Trans. on Power Electron., *vol. 31, pp. 3068–3079 (2016)*

[2] W. N. W. A. Munim, M. Duran, H. S. Che, M. Bermudez, I. G.-Prieto, and N. A. Rahim, "A unified analysis of the fault tolerance capability in six-phase induction motor drive," IEEE Trans. on Power Electron., *no. 99, pp. 1–1 (2016).*

Kitepower’s new 100 kW ground station (24 July 2017)

100 kW (left) and 20 kW (right) ground stations of Kitepower B.V and Delft University of Technology at testcenter Valkenburg (28 July 2017)

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Operation of Direct Interconnected AWE Systems under Normal and Fault Conditions

Mahdi Ebrahimi Salari, Joseph Coleman, Daniel Toal
Mobile & Marine Robotic Research Centre, University of Limerick

Direct interconnection is a novel technique for interconnecting AWE generators without power electronic converters. This technique is suited to remote and offshore installations where access for maintenance and repair is limited and costly. In this technique, unlike the conventional approach for renewable energy systems, generators are interconnected directly to each other without any back to back power converter and after dispatching the generated power to the shore, the shore-side back to back converter provides grid code compliance prior to grid interconnection.

Power electronic converters suffer the third highest rate of failure among wind turbine subassemblies [1-2]. Considering the high expenses of off-shore operations for repair and maintenance, relocating back to back converters from the offshore site to the shore will cause a significant cost improvement for offshore AWE systems. In addition, this approach can increase the reliability of the system by decreasing the breakdown rate since the back to back converters are installed in shore and their access is not dependent on weather conditions and time for repair and maintenance.

An offshore airborne wind energy farm has been modelled and simulated. Direct interconnection technique has been implemented and analysed as a new approach for interconnecting the generators and dispatching the generated power to the load. The offshore farm consists of three non-reverse pumping mode airborne wind energy systems which utilize low-speed permanent magnet synchronous generators for electrical power take off.

This research is aiming to implement and study the practicality and reliability of direct interconnection approach for offshore pumping mode airborne wind energy systems. The interaction of direct interconnected AWEs has been investigated and synchronization, frequency control and load sharing control of the AWE farm will be discussed in the presentation. In addition, the operation of the AWE farm during three fault condition scenarios including power blackout due to failure in a unit operation, delay in a unit transmission from recovery mode to power mode and failure in the operation of frequency and load sharing controllers will be discussed. This fault study is helpful for designing a protection system to improve the reliability of the system in the future.

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Efficient and Power Smoothing Drive-Train Concept for Pumping Kite Generators using Hydraulics

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A challenge for Pumping Kite Generator (PKG) ground systems is to produce consistent electrical power output to the grid despite the cyclic mechanical power exchange with the kite. Electro-mechanical systems coupled with battery or capacitor accumulators have been proposed for electrical conditioning. However, their economic potential is impeded by poor efficiency (especially at part loads), and high accumulator costs. Taking advantage of emerging high efficiency digital hydraulic machines *New Leaf* has improved on a hydraulic drive-train concept proposed by *Crosswind Power Systems* [1].

The concept introduced in this presentation decouples the winch and generator functions. It consists of high efficiency variable displacement hydraulics (i.e. where one device couples to the winch and another device drives a generator at constant speed) working in conjunction with a hydro-pneumatic accumulator (see Fig. 1). Our presentation shall demonstrate that this PKG drive-train configuration, versus an electro-mechanical analog, can generate consistent electrical power at significantly higher efficiency throughout the whole operational range of wind speed, and especially at part-load. Additionally, the high power density of hydraulic systems may lend themselves to serving fast response grid regulation; and since they do not require inverters, nor gearboxes (i.e. two of the major components responsible for most of the failures in conventional wind turbines), they may demonstrate better durability than electro-mechanical solutions. They are also lower-cost than their electrical solution counterparts. Moreover, the concept avoids using electro-chemical energy storage with limited usable life. Taken together, a hydraulic-based PKG ground station offers several mechanisms to drive LCOE reductions of PKG systems.

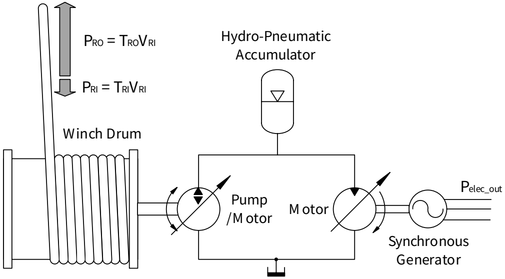
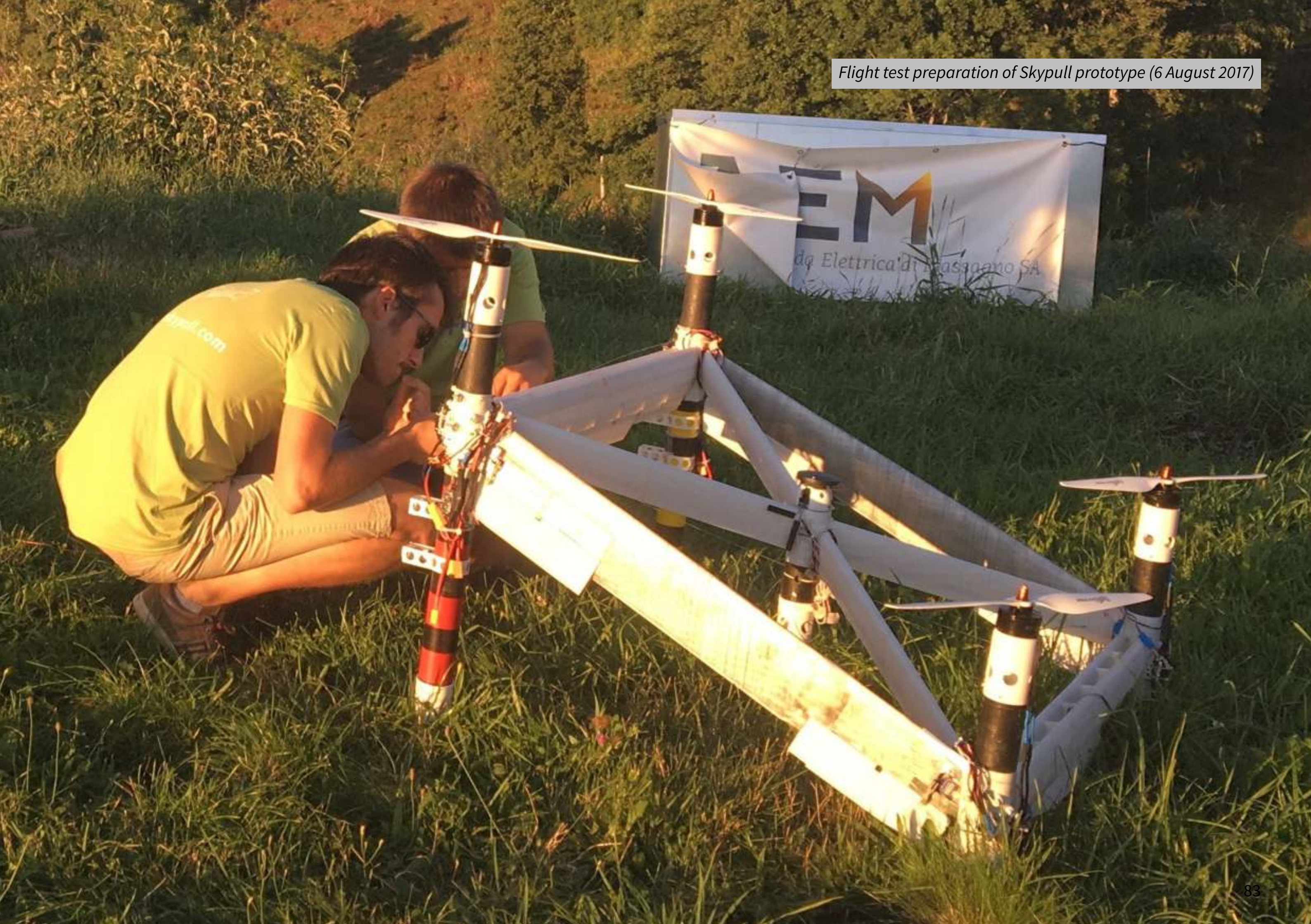


Figure 1. PKG hydraulic drive-train concept with hydro-pneumatic accumulator to generate consistent electric power. It uses a large displacement digital hydraulic pump/motor combination to directly drive a winch drum, and a high-speed digital hydraulic motor to spin a synchronous generator at constant speed.

References:

[1] Tattersfield, M.A., Atwater, J.F., Houle, C.P., 2013. Method And System For Harnessing Wind Energy Using Tethered Airfoil. Patent US2013/028537A1.

Skypull prototype SP1 125a, 1 kW power system drone (2 March 2016)



Flight test preparation of Skypull prototype (6 August 2017)

Flight testing of Skypull prototype (6 August 2017)

Nonlinear Model Predictive Control of a Large-Scale Quadrotor

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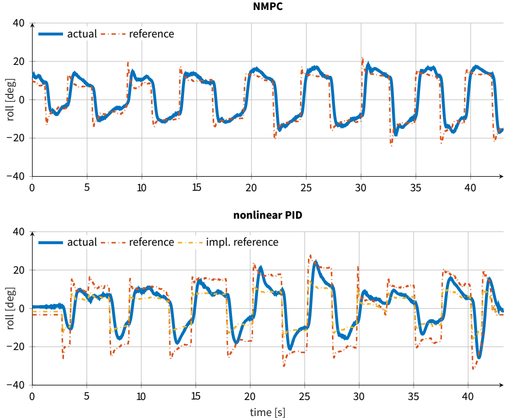
Several concepts in airborne wind energy (AWE) that emerged in the last few years exploit quadrotor-like systems to leverage the advantages of vertical take-off and landing strategies. Although the dynamics can be rather different after transitioning into a power generating phase, during take-off and landing, the system can be expected to share some similarities with a "pure" quadrotor system.

In this talk, the problem of controlling a large-scale quadrotor is addressed with nonlinear model predictive control (NMPC). NMPC is an optimization-based control technique that allows one to directly take into account nonlinearities of the model and physical constraints by formulating a nonlinear nonconvex optimization problem. In order to be able to solve such problems online, as the state of the system changes, efficient numerical algorithms and software implementations are required.

In the application described, NMPC is used to stabilize the attitude of the quadrotor. In order to achieve the required sampling time, inexact schemes are used such as the Real-Time Iteration (RTI) scheme and the so-called partially tightened formulation [2]. Moreover, the solver `HPMPC` [1] is used that exploits a cache efficient data format and vectorized instructions to improve execution time. Experimental results are presented that show real-time feasibility of the proposed approach and a large improvement of the control performance over classical control solutions.



Tracking of roll steps on the physical system: comparison of an NMPC and a nonlinear PID controller. The NMPC controller, with a sample rate of 10ms, was deployed on an embedded platform with an ARM Cortex A9 processor running at 800MHz.

References:

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Stability Certificates for a Model-Based Controller for Autonomous Power Kites

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ETH Zurich

One of the main challenges we are facing in AWE systems research is the reliability of the controller for automatic flight operation of the kite within a given range of environmental conditions. Various control designs ranging from structurally simple model-free proportional-integral-derivative (PID) controllers to more complex model-based optimal control algorithms have been employed for the automatic control of kites. Independent of the choice of controller, the challenge of assessing the reliability remains. With reliability we refer to the guarantee of stably controlling the kite such that it does not diverge from a desired range of trajectories.

We propose an algorithm for controlling the crosswind flight in the energy-generating phase of a two-phase pumping cycle with guarantees of stability. The controller is based on a parameter varying linear quadratic regulator (LQR). For this model-based controller, we employ the kinematic model suggested by Wood et al. [1] to represent the kite's dynamics. In order to make our controller feasible in real time, LQR gains depending on the state of the kite, i.e., its position, heading and velocity, are computed offline. Similar to an approach proposed by Tedrake et al. [2], the control gains are stored in a so called LQR-tree library. Given an estimate of the kite state at any measurement instance, the corresponding stabilizing LQR gain can be recovered from the library. A crucial step for this library-based control scheme to guarantee stability is the assessment of the stabilizing region of the state space for each LQR gain. This information is obtained by performing a region of attraction (ROA) analysis for each gain. Our ROA analysis mainly follows the procedures proposed by Manchester [3]. The method is based on a Lyapunov analysis where sums-of-squares programs are employed in order to obtain certificates of semi-algebraic set containment which guarantee stability for the considered region. Using semi-definite relaxations, the set containment problem is solved efficiently by a series of semi-definite programs. The obtained certificates allow us to choose a stabilizing controller gain at any instance such that the kite follows a predefined desired trajectory.

The controller performance is sensitive to the accuracy of the state estimates. Measurements of the position and orientation of the kite from line angles or onboard sensors are often noisy and biased due to, e.g., line sag and time delays. In order to obtain more accurate measurements and improve the control performance, we are working on an active camera tracking system for state estimation. The pan-tilt-zoom camera system is able to detect both the position of the kite in the wind window and its heading in real time. In this talk we will briefly highlight the benefits of this vision based estimation approach.

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Flying the Kitemill prototype on RC control (4 March 2016)

Kitemill prototype with Vertical Take-Off and Landing system (4 March 2016)

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Towards Robust Automatic Operation of Rigid Wing Kite Power Systems

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A key enabler of success in the field of airborne wind energy (AWE) is the ability to operate the AWE system in a reliable manner throughout every phase of flight. In this contribution a modular path following flight control architecture will be presented that allows to control a rigid wing AWE system during all phases of the flight, including vertical takeoff, power generation and vertical landing. It is a first step towards a flight control architecture with increased reliability and robustness in nominal as well as in adverse conditions compared to existing approaches.

The cascaded control structure consists of two separate outer loop controllers connected with a switching logic which is controlled by a high-level state machine. The flight path controller for vertical takeoff and landing (VTOL) guides the system along a predefined flight path up to the operational altitude or lands the system. To guide the kite along the path during VTOL mode common thrust vectoring is used. For improved control effectiveness the control surfaces of the wing are used along with the thrusters using a pseudo-inverse control allocation method to generate the required moments. This allows to exploit the complementary control effectiveness of thrusters as well as control surfaces with respect to the current flight condition.

For the power generation mode the second outer loop controller is activated. A novel path following controller for AWE systems has been developed that can be applied to soft was well as rigid wing kites. Different flight patterns can be generated consisting of circle and great circle segments. This allows to solve the path following control problem on a sphere similarly to straight line and orbit following control problems of untethered aerial vehicles. Since during power generation mode the thrusters are not in operation, only the lift vector is controlled using the orientation of the kite with respect to a tether reference frame. This allows to generate the required centripetal force to guide the kite along the curved paths on the tangential plane. In this way the model dependency of the controller is reduced to a minimum, while at the same time the control method is intuitive from a flight physical point of view. To enhance the disturbance compensation capabilities the baseline controller is enhanced with an adaptive part, which allows to recover a defined reference behavior in case of large disturbances or failures.

So far simulation results using a generic rigid wing kite model demonstrate the feasibility of the proposed control approach. Due to the modularity of the control architecture, the low computational demand and the reduced model dependency the proposed flight control architecture can be easily tested on different platforms in the future.

Nonlinear Model Predictive Path Following Control of a Fixed-Wing Single-Line Kite

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AWESCO
Airborne Wind Energy
System Modelling, Control & Optimisation

A reliable flight control of Airborne Wind Energy (AWE) kites is known to be a challenging problem both from academic and industrial perspectives. In recent years, several modeling and trajectory tracking strategies were suggested for the fixed-wing single-line class of energy kites [2]. However, validation and experimental results for these methods are not available. This work aims at further studying AWE systems dynamics and application of optimization-based algorithms for path following control of energy kites. To assess the quality of the developed model an experimental study was carried out with a micro-scale indoor AWE system prototype.

A mathematical model of a fixed-wing single-line kite with 6 DoF is derived. Aerodynamic model of a flying vehicle includes lift and drag coefficients as well as stability and control derivatives. A tether dynamics is described utilizing the Kelvin-Voigt viscoelastic model.

The software framework consists of the kite simulation module, generic Extended Kalman Filter (EKF) implementation, and Nonlinear Model Predictive Path Following (NMPF) control algorithm. For the latter, we consider the constrained output path following problem of a closed path defined as a parametric curve in the output space of the system [1]. The path parameter is treated as a virtual state, governed by an additional ODE. The Chebyshev pseudospectral collocation technique is chosen for the trajectory discretization to account for the inherently unstable and highly nonlinear nature of the system.

The test platform comprises a radio controlled commercial propelled airplane, tailored with a nylon thread to the ground station unit. The station is capable of measuring line angles, tether force and control reeling in of the tether. The flying facility is equipped with OptiTrack^{TM} motion capture system that provides ground-truth position and attitude measurements.

Throughout piloted flight experiments we identified viscoelastic parameters of the tether and adjusted values of some stability and control derivatives. Then the developed estimation and control framework is successfully tested to track a circular path in the flight simulator. Further research will be focused on extending the presented approach to operate with environmental and parametric uncertainties.

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AWE Systems in an Innovation Course

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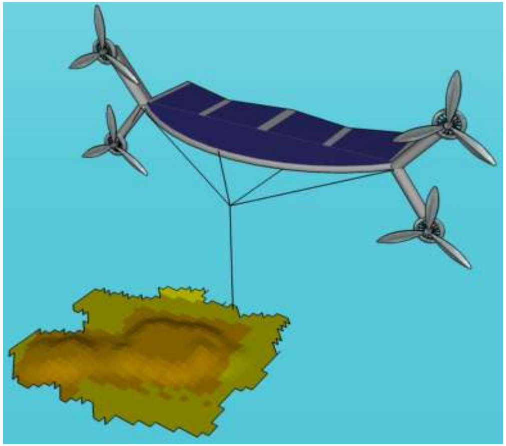
ENSE3 is an engineering school of Grenoble Institute of Technology, France. Its objective is to prepare the engineering students to face the challenges of energy transition, the growing problems of water resources, planning and sustainable development.

The Innovation and Management course given at the final year allows graduate students from different specializations to work in project mode on the generation of an innovative concept and its development, both on the technical level and on aspects making the link with a potential market. Each year, a challenge is offered from which students have to propose a creative application of a technology, identify and characterize the innovation, propose a segmentation of the market. On the basis of a chosen segment, students have to establish a value proposition that will be evaluated in a final competition during which they pitch their project. In 2015, the challenge was about airborne wind energy systems. The main question to answer was “ How to harvest high altitude wind energy and how to get advantage of it?”

Forty groups of more than 300 graduate students have tried to find innovative solutions and applications related to AWE systems. They have produced concepts, using brainstorming, in relation with the challenge. After that they compared their concepts with existing technologies. They have analyzed the scientific, technical and technological environments to deduce threats and opportunities. Then, they have tried to build a business model by studying the available market for their proposed concept by defining the eventual profile of their future clients.

Several innovative concepts have emerged. They cover small scale AWE system integration in urban districts for energy satisfaction or even publicity, to the usage of AWE in disaster areas, the hybridization of AWE with photovoltaic, and finally offshore deployment AWE systems.



An imagined AWE system to be used for islands.

FTERO student team testing the LARAII prototype (17 May 2017)

FTERO student team preparing the first flight of the CLARA prototype (16 May 2017)

FTERO student team with CLARA prototype (5 May 2017)

ftero – On the Development of an Airborne Wind Energy System

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The ever-growing consciousness towards the independence from fossil fuels, and the awareness of the profound effects of non-renewable energies on the climate, has motivated researchers around the world to search for innovative renewable alternatives for energy production. Airborne wind energy (AWE) is a very promising candidate for this problem. The ftero project, represented by ten BSc students in their final year, aims to push the boundaries of current AWE systems by building a demonstrator featuring innovative concepts capable of radically improving the reliability and performance of the technologies current state.

The core focus of the ftero project is to develop a fully functional AWE system, primarily focusing on the aerodynamic, structural and control aspects of the aircraft. The developed system consists of a mobile ground station, developed for the vertical take-off and landing, the aero-structurally optimised aircraft, and an efficient controller for the take-off, landing, traction, and reel-in phase. Throughout the project, multiple prototypes were built in order to test and evaluate the aerodynamic and structural characteristics as well as the control strategies of the aircraft. Utilizing the know-how obtained by these prototypes, the final aircraft comprises of a high aspect ratio, high-lift wing with 5m span, two fuselages and two tether attachment points. In particular, the outer shape of the wing and its internal load-carrying structure have been concurrently optimized to maximize the power production while maintaining the structural efficiency – and hence the mass – to a minimum. Two electric motors, each mounted on the fuselage enable zero-length take-off and landing with the airplane in a vertical nose-up attitude. The advantage of this vertical take-off and landing system are the possibility to perform very space-efficient autonomous start and landing manoeuvres. In the rear-most section of the fuselages, the fully moving horizontal tail enables large control moments, necessary not only during the traction phase, but also during the take-off and landing manoeuvers. For testing purposes, a ground station was adapted to handle loads up to 10kN, and to produce a maximum power of 40 kW.

The possibility of designing and optimizing synergically all the various components of the AWE system enables the demonstration of the technical feasibility and the actual performance of every aspect of the technology, while dually permitting to introduce innovation and optimisation in every scientific discipline involved. The system will further allow to test future aerodynamic, structural, and controls concepts on a physical system. To this end, several scientific studies on structural optimisation and control theory are conducted in cooperation with ftero, including an ongoing study aiming to extend the functionality, operational envelope and performance of the aircraft by means of compliant morphing wings.

SkySails Power kite attached to mast,
ready to launch (August 2016)

SkySails towing kite being launched from catamaran Race for Water (April 2017)

SkySails towing kite being launched from catamaran Race for Water (May 2017)

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Recent Advances in Automation of Tethered Flight at SkySails Power

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This contribution presents most recent advances in automation of tethered flight at SkySails and the application to yacht propulsion. Experimental data obtained from the very recent Atlantic crossing of the yacht "Race For Water" [1] will be presented. This solar yacht, weighing approximately 100 metric tons and measuring 35 m, features a propulsion system capable of running the yacht by 100 % renewable energy and has recently been equipped with a SkySails kite system [2].

Tethered flight automation for airborne wind energy at SkySails has first been developed for traction of large marine vessels [3] with kite sizes ranging from 20 m^2 up to 320 m^2. Subsequently, in order to demonstrate the applicability of the kite system to electric power generation from airborne wind energy in lift mode [4], flight automation algorithms have been extended to allow for optimal pumping cycles [5] and demonstrated on a 55 kW small-scale functional prototype [6].

In this work, experiences from both applications are merged to extend the flight automation algorithms for application to traction of yachts. Key novelties include the use of target point control in traction applications, a versatile control pod setup suitable for the use of a range of different kite sizes and finally a stepping set point adaptation of the wind window angle for force control. Flight test data from the yacht "Race For Water" for kite sizes ranging from 20 m^2 to 40 m^2 shows that the control approach is suitable for application in offshore conditions, where significant heave, pitch and roll movements can occur depending on the prevailing sea state. Although the underlying feed-forward, feed-back control approach is significantly relying on model information, data from flights at very low apparent wind speeds as well as data from flight in rainy conditions show the robustness of this approach, in spite of the expected model mismatch in such conditions. An analysis of propulsive performance data shows that under ideal conditions, a 30 m^2-sized kite alone can propel the ship to higher speeds than the 500 m^2 on-board photovoltaic arrays, underlining the high power density of airborne wind energy, when comparing kite and photovoltaic array areas.

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Composite photo of an optimized flight path for the TU Delft kite (August 2017)

Flying the 25 m^2 kite of Kitepower at a tether length of 250 m (27 July 2017)

Systematic Reliability and Safety Analysis for Kite Power Systems

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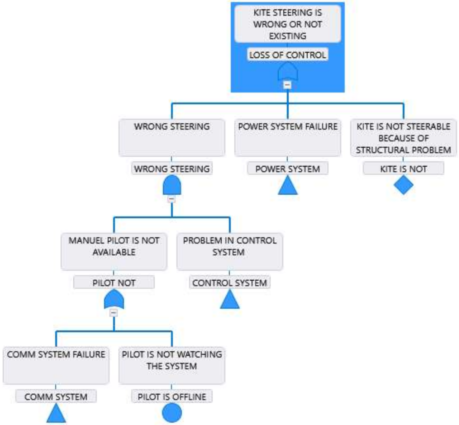
Due to the emerging interest in Airborne Wind Energy, a considerable number of prototype installations is approaching a commercial stage. As a consequence, operational safety and system reliability are becoming crucial factors for technology credibility and public acceptance.

In our case study, we investigated the reliability and safety level of the current 20 kW technology demonstrator of Delft University of Technology, which is also the starting base of the EU Horizon 2020 project REACH. The objective of the REACH consortium is to develop a commercial 100 kW version of the demonstrator. The project team systematically improves the system's reliability and robustness with the aim of demonstrating 24 hours of continuous automatic operation without any pilot intervention. To achieve this goal, reliability and the safety level of the system are analyzed using two traditional methods, FMEA (Failure Mode and Effects Analysis) and FTA (Fault Tree Analysis). From the conducted analyses, hazardous situations and the mechanisms that lead to unoperational or hazardous states are defined. Consequently, mitigations are offered to prevent these mechanisms. It is found that a majority of the proposed mitigations can be performed by a Fault Detection, Isolation and Recovery (FDIR) software component. Development process improvements are offered for the components for which it is impossible to decrease the risk using the FDIR.

In this talk, author will present the key points and the important results of the reliability analyses. In addition, proposed FDIR architecture will be discussed.



Loss of control subtree from Fault Tree Analysis

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Guaranteed Collision Avoidance in Multi–Kite Power Systems

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Kite power systems that aim to harvest high altitude winds may have long tethers that span areas with a radius of several hundreds of meters. An efficient use of land, not using wings with huge areas, is obtained when multiple kite systems are used. When a set of kites is densely packed in an area to further increase the efficiency in the use of land, a collision avoidance system must be developed.

One of the main challenges of the collision avoidance system involves guaranteeing that the constraints imposed along the trajectories of each kite are in fact satisfied for all times. The problem is relevant and non–trivial due to the fast moving of the kites and the fact that it is only possible to verify the constraints at a discrete set of times, with a limited sampling rate.

Here, we adapt to the multiple–kite system scenario a recently developed condition for state constrained optimal control problems, that when verified on a finite set of time instants (using limited computational power) can guarantee that the trajectory constraints are satisfied on an uncountable set of times. For the constrained nonlinear optimal control problem that results from the multi–kite maximal energy problem, we develop an algorithm which combines a guaranteed constraint satisfaction strategy with an adaptive mesh refinement strategy.

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Safety Analysis of Airborne Wind Energy Systems

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Safety and Reliability are two of the most important lifecycle properties that any Airborne Wind Energy (AWE) system must exhibit. Many hazards can be present during the operation of an AWE system including potential collision of the unmanned aerial vehicle (UAV), failure of the automated control system and entanglement of the tether connecting the UAV to the ground station. These hazards could lead to accidents that result in severe financial losses and harm to people and wildlife. Safety and reliability in the engineering and operation of AWE systems are thus essential to the success of this technology.

Like in many areas of technology today, AWE is experiencing a fast pace of technological progress, an increase in complexity and coupling between subsystems and more complex relationships between humans and automation. These represent significant changes in the types of systems we are attempting to build today and the context in which they are being built. These changes are stretching the limits of safety engineering. Therefore, the technical foundations and assumptions on which traditional safety engineering efforts are based are inadequate for the complex systems we are building today such as AWE systems. The world of engineering is experiencing a technological revolution, while the basic engineering techniques applied in safety and reliability engineering, such as fault tree analysis (FTA) and failure modes and effect analysis (FMEA), have changed very little.

This paper introduces a new approach to building safer systems developed by Prof. Nancy Leveson at MIT [1] that departs in important ways from traditional safety engineering. The new model called STAMP (Systems-Theoretic Accident Model and Processes), changes the emphasis in system safety from preventing failures to enforcing behavioral safety constraints. Component failure accidents are still included, but the conception of casualty is extended to include component interaction accidents. Safety is reformulated as a control problem rather than a reliability problem. This change leads to much more powerful and effective ways to engineer safer systems, including modern complex sociotechnical systems such as the one in the area of AWE.

We will perform a hazard analysis on an AWE system that is currently being developed by a team of MIT students using a new approach to hazard analysis based on the STAMP causality model, called STPA (System-Theoretic Process Analysis). Our presentation will demonstrate how the application of STAMP and STPA leads to engineering and operating safer and more reliable AWE systems and overcome some of the limitations of traditional safety engineering techniques widely used today including Fault Tree Analysis, Event Tree Analysis and HAZOP.

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High Altitude LiDAR Measurements of the Wind Conditions for Airborne Wind Energy Systems

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Airborne wind energy (AWE) systems are flying in heights between 100 m and 1000 m. Thus, for a resource assessment as well as for power curve estimation the wind conditions over these heights have to be considered. Besides, new methods for both have to be developed on basis of these analyses.

During extensive measurement campaigns within the OnKites II project ('Studies of the potential of flight wind turbines, Phase II', funded by the German Federal Ministry for Economic Affairs and Energy, BMWi) high-resolution wind data up to 1100 m height were collected at different locations onshore and nearshore [1]. Within measurement campaigns near Pritzwalk and Emden (Germany), the scanning LiDAR system Galion G4000 of the company Sgurr Energy was used. The scanning LiDAR system measured the wind speed at 40 measurement heights during six months at each site which allows a better estimation of the wind resources at these heights. The results of the analyses of the data will be shown.

The analyses of the LiDAR data show a strong dependence of the vertical wind profile on different stratification conditions of the atmospheric boundary layer. Thus, the shear of wind speed plays an important role for AWE systems. Up to an altitude of around 400 m the highest gradients in wind speed can be found. For an estimation of wind resources the distribution of wind speed is used by calculating the Weibull distribution. The Weibull parameters have been analyzed at all 40 measurement heights. Besides, an investigation of downtimes of AWE systems because of very low as well as too high wind speeds at both locations has been done.

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LES Generated Turbulent Inflow Fields from Mesoscale Modelling Driven by LiDAR Measurements

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Modeling the wind inflow for airborne wind energy applications is subject to many uncertainties due to the lack of reliable high resolution measurements or simulations. This study aims at reducing these uncertainties by generating an inflow database adapted from simulations and long term Light Detection And Ranging (LiDAR) measurements.

The Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) recently completed a LiDAR measurement campaign in northern Germany [1]. During 2015 and 2016 wind velocities of up to 1000 meters at two on-shore locations were measured to assess the energy yield potential of airborne wind energy systems. Ilona Bastigkeit will present the outcome of this campaign in a separate talk.

These measurements, together with data from the European Reanalysis (ERA) database ERA-Interim [2], were implemented into Weather Research and Forecasting (WRF) [3], a numerical mesoscale weather reanalysis tool. We investigate wind and weather data in the temporal scale of minutes and a spatial resolution in the order of kilometers. They shine a light on the wind variability and the occurrence of extreme weather events and calms. This allows for preliminary siting, yield assessment and an estimation of downtime.

Results from these large scale reanalyzes serve as input into high resolution Large-Eddy-Simulations (LES) using the Parallelized Large-Eddy Simulation Model for Atmospheric and Oceanic Flows (PALM) [4]. These high resolution simulations provide an insight into high frequency turbulence distribution which can not be provided by remote sensing technologies such as LiDAR.

Simulations and measurements are compared in terms of mean wind speeds and direction, profile shape and statistical variability. Together they offer a comprehensive data set which can be used for inflow modeling for control, optimization or load estimation.

This project was partially funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag and Projektträger Jülich.

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Large Eddy Simulation of Airborne Wind Energy Systems in the Atmospheric Boundary Layer

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KU Leuven

Airborne Wind Energy (AWE) is a novel solution in the field of renewable energy technologies. However, unlike for conventional wind turbines, the effects of AWE systems on the wind environment have not yet been studied in much detail. We have developed a computational framework using Large Eddy Simulation to investigate the interaction between kite systems and the atmospheric boundary layer. Simulations are carried out using the in-house flow solver SPWind developed at KULeuven. For the discretization of the incompressible Navier-Stokes equations, we use a Fourier pseudo-spectral scheme in the horizontal directions and a fourth-order energy-conserving finite difference scheme in the vertical direction. Time integration is achieved using a fourth-order Runge-Kutta scheme. The kite system considered in the study is composed of a tether and a rigid wing. The dynamics of the system are described using a Lagrangian formulation along with an aerodynamic model for the external forces and moments. A lifting-line technique is then implemented in the simulation framework in order to model the effects of the kite systems onto the flow field. A turbulent inflow is generated using precursor methods for fully-developed turbulent boundary layers [1]. In the study, a number of configurations related to different operation conditions of kite systems are considered. We investigate different tip-speed ratios, operation altitudes and operation modes as defined by Loyd in [2]. The objective of the study is to quantify the interaction between the kite systems and the boundary layer in terms of flow induction and wake development. Therefore, we look at instantaneous flow characteristics as well as at time-averaged quantities.

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Long-Term Corrected Wind Resource Estimation for AWE Converters

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At AWEC2015 an approach has been presented to estimate the potential power yield of airborne wind energy (AWE) systems over larger areas [1]. This approach has been demonstrated for an Enerkíte EK200 system. It has been shown thereby that the potential power yield may depend on certain AWE specific factors, like minimum wind speed for departure, the optimal operational height or de-icing measures of the airborne system. The presented results have only covered a two-year period, 2012 and 2013, due to the limited availability of high resolution meteorological input data. However, it is known from wind resource estimation for conventional wind power plants that coverage of a decade, better 30 years or more, is required for a power predication. This is as the average wind speed and wind speed distribution vary significantly from year to year.

To achieve this long-term wind resource estimation for AWE, a technique commonly referred to as Measure-Correlate-Predict (MCP) has been applied, which is state of the art for conventional wind turbines. Thereby the MERRA2 meteorological reanalysis dataset, which covers 1980 till today, has been employed as long-term reference. The year 2012 of the already presented wind resource estimation for AWE has been used as training data, while 2013 has been kept back as independent evaluation dataset. Transfer functions between the long-term reference values for 2012 and training data have been computed for potential power yield, as well as for the power not produced due to unmet starting conditions and de-icing measures. By application of the transfer functions on the full time span covered by MERRA2 virtual long-term data has been computed. The quality of the long-term data has been evaluated by comparing the virtual long-term data of 2013 with the evaluation dataset.

This presentation will cover a review of 2015's results and methods, an introduction to the MCP method as well as the used transfer functions. The long-term results for potential power yield and power not produced due to unmet starting conditions and de-icing measures will be shown and compared to the equivalent measures generated from the two-year period. Finally, the quality of the long-term data will be discussed.

References:

[1] Brandt, D., et al.: Adapting wind resource estimation for airborne wind energy converters. In: Proceedings of the 6th Airborne Wind Energy Conference, Delft University of Technology, The Netherlands, 15-16 June 2015. http://resolver.tudelft.nl/uuid:cfc030a3-d6d1-4baf-99b3-d89e5fa8aefc

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AWE Policy Initiative – Preparing the Grounds for AWE-Specific Support Schemes

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Several AWE systems are at the brink of commercialization. While some companies claim that their systems will soon be able to compete with wholesale market prices (Kitemill, Makani Power), others target specific entry markets, e.g. re-powering of first-generation offshore wind farms (Ampyx Power, Kite Power Solutions) or off-grid applications (Enerkite, Twingtec, Kitepower).

However, the actual costs of electricity have not yet been proven and niche markets are either limited in size or pose other potential problems (e.g. higher investment risks in developing countries). To reach market readiness, the so-called "valley of death" needs to be crossed where high amounts of capital are required [1].

How can investors be convinced that AWE technologies will provide a reasonably secure return on investment? **AWE systems will require policy support through specific incentive schemes.** AWE technologies are not yet mature enough to be able to participate in competitive tenders with conventional wind power. AWE-specific market push and pull-policies like grants or revenue support would reduce the risk for investors and thus unlock capital. Incentives may differ by AWE system, like power class, legal classification (e.g. aircraft vs. obstacle), or by market and application (permanently grid-connected utility scale, micro-grid, temporary).

It seems that the AWE sector itself is not yet sufficiently aware that support policies are required – so far, the focus has been mainly on technological, regulatory and certification issues. Therefore the **AWE Policy Initiative** has been formed as part of the Airborne Wind Europe network. It aims to achieve AWE-specific support schemes in Europe to accelerate the large-scale deployment of AWE systems.

The planned activities of the initiative include:

- Scoping: Initial desk research on applicable legislation; interviews with companies and policy makers about needs and pre-requisites.
- Research and lessons learned from other RE technologies: provide justification for specific incentives; assess support schemes regarding usefulness, political support, ease and timing of implementation; define interdependencies with non-technological barriers like standardization and certification.
- Policy recommendations: propose range for potential support levels and cost reduction plans; develop a European policy road map up to 2030; develop a common position of AWE industry regarding policies.
- Communication, advocacy and capacity building: advocate at European and national level; provide capacity building to AWE stakeholders on policy issues; build network of policy experts within AWE sector.

At AWEC 2017 the findings of the initial Scoping Exercise will be presented.

References:

[1] IEA-RETD (2014), Accelerating the commercialisation of emerging renewable energy technologies (REInnovationChain), Utrecht, 2014.

Flight testing the 600 kW energy kite (13 December 2016)

The Makani M600 on the test stand (12 April 2017)

The rotors of the Makani M600 (12 April 2017)

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Pulling Power From the Sky: Makani and the Collective Ideal of Airborne Wind

Andrea Dunlap, Kate Stirr
Makani / X

The Airborne Wind community is composed of people who are dreaming up and actualizing diverse ideas for new technology that harnesses the power of the wind to provide additional, economically significant, renewable energy options for the globe.

As individuals, many of us are drawn to the field of Airborne Wind for the engineering, design, and social challenges presented by working on wild new technologies. Often beautifully simple in concept and equally so in execution, Airborne Wind offers the opportunity to creatively tackle complexity across multiple spheres of expertise. It is a field that brings together engineers, communicators, analysts, strategists, and artists. This interdisciplinary effort is underwritten by a collective drive to generate disruptive new technology that will combat climate change by increasing access to cheap, renewable energy.

Just as the Airborne Wind community is a subset of a broader global initiative to create technological solutions to climate change, Makani represents a microcosm of the creative technologists that make up the Airborne Wind field. From our scrappy beginnings experimenting with soft kiteboarding kites, through eight rigid kite designs, to our present 600kW prototype, Makani's ability to learn and grow has always been tied to our ability to aggregate and synthesize diverse perspectives while working towards a common goal.

Within our team at Makani, we endeavor to be actively curious, making data-based decisions, while remaining playful and seeking substantive results. Beyond solving the immediate challenges that face us as we continue to test our current energy kite, we are striving to do meaningful work alongside others in the Airborne Wind community knowing that it is our collective efforts that will make the world a better place.

Drawing from Makani's archive of flight testing footage and from interviews with Makani team members, this video seeks to communicate the common challenges and passions that underlay the development of Airborne Wind technology.

The Makani M600 on the test stand (24 May 2017)

Winch Control of Tethered Kites

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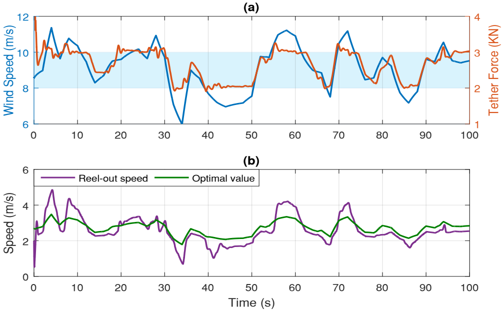
Winch control has an important role in both efficiency and safety of AWE systems with tethered wings. In this research, a force control scheme is presented that guarantees the convergence of reel-out speed to its optimal value, upon which maximum mechanical work is generated. Besides, it can keep tether's force within certain limits. The lower bound is imposed to make sure the wing stays aloft and controllable, and the upper bound prevents the system from force overload. Reel-out speed can take the optimal value only within those boundaries. The controller's ability to prevent the force from violating the lower and upper bounds can have an impact on the capacity factor of the system; enabling it to operate in turbulent wind environment.

Having an asynchronous generator as winch, the controller commands the synchronous speed to the generator that causes it to rotate at the optimal speed. The winch controller's performance is assessed in a simulation environment, in which the wing is represented as a point-mass and the winch is modeled as presented reference [1]. The wing flies along a figure-of-eight path. Since tether's dynamics is important in evaluating winch's performance in simulation environment, a dynamic model of cable with varying length is used. This model consists of elastic rod elements and takes into account the effect of mass transfer. The quasi-steady model introduced in reference [2] is the basis for generating the optimal synchronous speed.



Simulation results of a tethered wing with area of 9 m^2, completing each figure-of-eight in 24 seconds on average, and a 20 kW winch. The initial and final tether length are 600 and 860 m, respectively.
(a) - Tether's force remains 2 to 3 kN (the cyan strip) as the wind speed (measured at kites altitude) changes randomly. The limits are selected for illustration purposes only. Wind speed derivation takes its maximal value of 1.8 m/s^2 at 34 s.
(b) - Reel-out speed takes its optimal value while tether's force is within 2 to 3 kN. The small gap between the optimal value and reel-out speed is due to errors in parameter estimation.

References:

[1] Fechner, Uwe, et al. "Dynamic Model of a Pumping Kite Power System." Renewable Energy 83 (2015): 705-716

[2] Schmehl R., Noom M., van der Vlugt R.: Traction Power Generation with Tethered Wings. In: Airborne Wind Energy. Springer (2013)

Outdoors rotational test at University of Freiburg (27 February 2017)

Rotational test setup of the University of Freiburg (11 July 2016)

University of Freiburg "Half-Betty" wing, used to test rotational flight optimal control algorithms. (11 July 2016)

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Non-Linear Modeling with Learned Parameter Refinements for NMPC on a Real-World Aerodynamic System

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In this work we present a combined modeling and control approach to nonlinear model predictive control of a rotational launch setup. While the continued interest in airborne wind energy (AWE) has produced many promising solutions regarding power generation trajectories and kite configurations, the task of autonomously launching and landing one or multiple kites is still a challenge.

A major differentiating factor between current AWE launching approaches is the availability of on-board propellers allowing the kite to fly to its crosswind operation region, drastically simplifying take-off and landing. However for lift-mode systems where those motors cannot be reused for power generation, this comes with the cost of increased weight and additional complexity. If implemented robustly, a passive take-off and landing procedure could potentially increase the efficiency and durability of the system significantly.

We present a modeling and control approach for a rotational launch maneuver based on a reduced-DOF real-world setup. We describe the system dynamics using a quadratic state space model, using linear regression in combination with hyper-parameter optimization to identify the model parameters. A nonlinear model predictive controller is then designed based on the identified model.

The model performance was empirically evaluated comparing the simulated behavior with the real-world system behavior. The controller was evaluated using a variety of reference trajectories, analyzing the dynamic behavior in a wide range of scenarios. Based on these experiments on the real-world system, we could show that aerodynamic systems in a forced rotational motion can be adequately controlled using our approach. A future free-flight setup on the basis of this approach and empirically obtained data is currently in the planning stages [1].

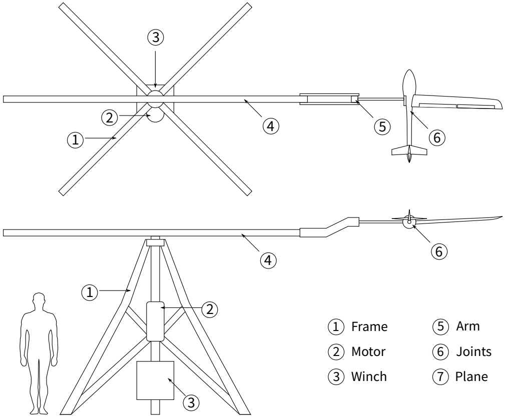

Illustration of the carousel with attached plane.

References:

[1] Schlagenhauf, J. F.: Nonlinear Model Predictive Control of a Constrained Model Airplane. MSc Thesis, University of Freiburg, 2017. *https://freidok.uni-freiburg.de/data/12264*

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Determination of Optimal Control Laws in Airborne Wind Energy Scenarios With a Self-Consistent Kite Dynamics Model

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In the reel-in and real out phases of yo-yo airborne wind energy generation schemes, appropriate control laws should be imposed to the lengths of the bridle and the main tether of a power kite. The determination of the optimal control laws that maximize the energy production for a given wind conditions is a complex problem that requires a kite flight simulator and robust and efficient optimization algorithms. This work makes use of a recently proposed kite flight simulator based on Lagrangian formulation that explicitly removes the tension force from the equations of motion. Although being a low-order dynamical system with only five degrees of freedom, the simulator captures self-consistently the dynamics of the full system (kite, bridle and tether) and provides a reliable framework with a moderate computation cost. Optimal control laws for the lengths of the three lines of the bridle and the tether are determined by embedding the kite flight simulator in a homemade optimal control library. The continuous-time optimal control problem is transcribed into a nonlinear programming problem using a collocation method and imposing periodic boundary conditions for the trajectories. The optimal open-loop control laws that maximize the generated power were determined by using an interior point solver. As expected, optimal trajectories involve a reel-out phase with the kite flying in cross-wind conditions and a reel-in phase at low angle of attack. The stability of the resulting periodic orbits is studied by using Floquet theory, and the main features of the trajectories are compared with previous works already available in the literature.

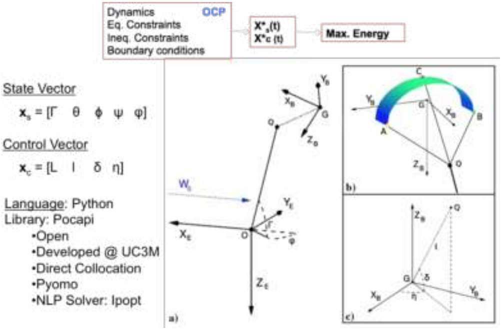

Figure: Methodological block diagram for the determination of optimal control laws in a self-consistent kite dynamics model.

References:

*[1] J. Alonso-Pardo and G. Sánchez-Arriaga: Kite Model with Bridle Control for Wind-Power Generation. Journal of Aircraft **52**(3), 917-923 (2015)*

Mobile development platform EK30 (November 2016)

EnerKíte V-wing EK202 in flight (July 2017)

Comparison of Launching & Landing Approaches

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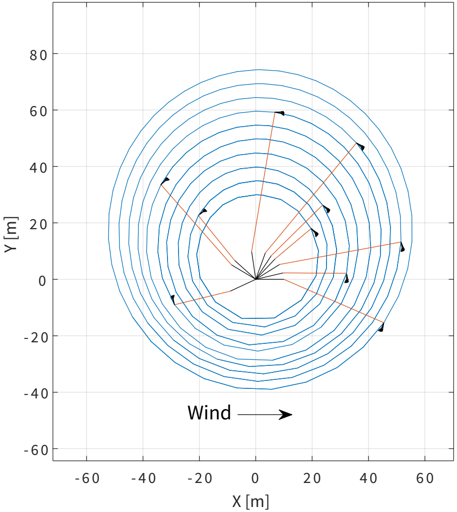
The market entry and success of airborne wind energy systems hinges on the capability of reliable, scalable and cost efficient launch and landing technologies. A conceptual analysis and comparison of the three currently favored approaches vertical take-off, catapult and rotating arm is presented. This analysis estimates the different masses and powers necessary both airborne and on the ground and it reveals the scaling effects with respect to different power ratings, wing sizes, weights and the concerns due to economic, safety and process complexity arguments. Particularly, the effect on low nominal wind speed designs of added systems to the wing are discussed. From this comparison, the choice at EnerKíte for a rotating arm is motivated.

For the onboard propulsion variants, simple formulas and comparisons to existing technologies are utilised that are similar to the analysis in [1]. For the rotating arm, an additional in-depth analysis shows the theoretical development stages within the last years at EnerKíte. From geometric formulas for rough power and sizing requirements, over point mass models and optimal control results, and up to detailed simulations for a semi-rigid EnerKíte wing. This analysis underlines the results of the general comparison and illustrates the viability of the development path of the launch and landing system at EnerKíte.



Example of a detailed look at the rotating arm. Periodic trajectories with increasing line lengths at 6 m/s wind speed during rotation. Optimal control result with the aim of minimal change in angle between arm and kite and simple torque control functions. Note the asymmetric trajectories due to the wind direction and magnitude.

References:

[1] Fagiano, Lorenzo, and Stephan Schnez.: On the take-off of airborne wind energy systems based on rigid wings. Renewable Energy 107 (2017): 473-488.

EnerKíte

Experimental rig for measuring relative flow mounted in the bridle line system (24 March 2017)

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Experimental Characterization of a Force-Controlled Flexible Wing Traction Kite

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In order to use flexible wing kites effectively for power generation their size must be increased and aerodynamic performance should be systematically improved. Validated models are essential for an efficient design process. The largest uncertainty in current modeling approaches is the apparent wind speed v_a experienced by the kite. In this work we develop an in-flight measurement setup for the apparent wind speed vector. An air data boom with a Pitot tube and a pair of wind vanes is used to measure the relative flow below the wing, at sufficient distance not to be influenced significantly by the wing itself.

In-flight measurement of apparent wind speed and inflow angles (24 March 2017)

The experimental data supports the current quasi-steady model of a pumping kite power system [1]. In this work we propose a mechanistic model for the resulting aerodynamic coefficient c_R. A sole dependency of this coefficient on the angle of attack, as it is common for rigid airfoils, must be rejected. Instead, we find that the coefficient strongly depends on the wing loading and to a lesser extent also on the power ratio, i.e. the non-dimensional pitch parameter of the wing and the inflow angle, as assumed in [2].

We further observe that the force-controlled characteristic of the system majorly affects the flight dynamics. Important findings are that by changing the tether reeling velocity to obtain constant traction force the ground station balances wind gusts which thus hardly affect the relative flow vector but the power output. Sudden controller-induced changes in reeling velocity cause inflow angle variations similar to fluttering observed on rigid airfoils. Further can c_R and v_a not vary independently for any force-controlled phase. The presented relation of different parameters affecting c_R can be used for flight path optimization as well as kite and control systems design.

References:

[1] van der Vlugt, R., Bley, A.,Noom, M., Schmehl, R.: Quasi-Steady Model of a Pumping Kite Power System. Submitted to Renewable Energy, 2017. arXiv:1705.04133 [cs.SY]

[2] Fechner, U.: A Methodology for the Design of Kite-Power Control Systems. PhD thesis, TU Delft, doi:10.4233/uuid:85efaf4c-9dce-4111-bc91-7171b9da4b77, 2016

Towing test bench of TU Berlin in operation at former airfield Pütnitz, Germany (19 May 2016)

Automatic Measurement and Characterization of the Dynamic Properties of Tethered Flexible Wings

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Despite the lack of reproducible measurements, the design and significance of flexible tethered airfoils has increased considerably. While existing design methods have proven useful in achieving a high degree of maturity on product level, this has primarily been accomplished by the empirical variation of wing parameters. Measurements under reproducible conditions, including reproducible steering inputs, have not been carried out yet.

To address this lack of measurements, we established the project TETA within a doctoral research project. A test bench was developed that allows for accurate testing of different types of tethered airfoils. The test bench can be used stationary or by moving at a specific velocity to simulate different wind speeds as well as reducing influences by gusts.

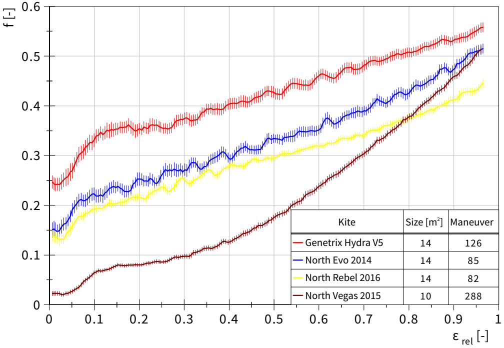
The test bench focuses on the constant airflow generation, the measurement of the entire kite system under realistic conditions and the possibility to initiate repeatable, automated maneuvers.

The findings described in this thesis enable an objective measurement of specific dynamic wing properties of highly flexible tethered airfoils (e.g. aerodynamic coefficients and forces). In the scope of this work, airfoil properties, which are defined as dynamic, are determined against variable control inputs or kite positions.

The dynamic properties are successfully determined by using the "Linear Power" maneuver. Hereby, the ratio between front lines and control lines (ϵ_{rel}) is automatically varied within a predefined length (see figure).

A brief overview of the experimental procedure as well as exemplary results are given, including a short description of the data processing.

The measurement results are essential for the development and characterization of these airfoils as well as for the validation and improvement of simulation models. Furthermore, it demonstrates that the method is suitable for comparing basic airfoil design concepts. The thesis makes a decisive contribution to the evaluation of follow-up designs and simulation models of highly flexible tethered airfoils.



Exemplary measurement curve: force ratio between back and front lines $f = (F_{SL,l} + F_{SL,r})/F_{PL}$ against power ratio ϵ_{rel} (P=95%).

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High Fidelity Aeroelastic Analysis of a Membrane Wing

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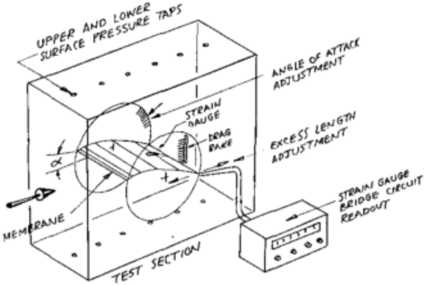
Through aeroelastic modeling of membrane wings such as Leading Edge Inflatable (LEI) tube kites used in Airborne Wind applications, one can gain a better understanding of processes relevant for flight stability and performance optimization. The aim of this project is to establish a baseline for a partitioned aeroelastic solver suitable for membrane wings at high Reynolds numbers by coupling high fidelity structure and fluid models.

An in-house implementation of a dynamic, nonlinear Finite Element structural solver employing shell elements is used to model the canopy of the membrane wing [1]. As a first step, an unsteady lumped vortex particle method is used for the fluid model. Eventually the transient Navier-Stokes Finite Element solver Fluidity [2] is used to model the highly nonlinear flow around the membrane wing at high angles of attack present in crosswind flight of the kite.



Validation data setup [4]

The quantitative validation of the solver is initially done on the classical Fluid-Structure Benchmark case as proposed by Turek et al. [3]. Subsequently, a qualitative verification on the test case of Greenhalgh [4] as pictured on the left is carried out as well. While limitations in the experiment description make quantitative verification for this test case difficult, qualitative verification for steady inflow conditions at different angles of attack and hysteresis effects around an angle of attack close to zero are still possible.

While the benchmark cases of this project deliver proof of concept of the applied methodology, they are of little practical relevance. Nevertheless, in future projects the solver can be extended to include three-dimensional effects, a more realistic wing design and unsteady boundary conditions.

References:

[1] Bosch, A. et al: Dynamic Nonlinear Aeroelastic Model of a Kite for Power Generation. Journal of guidance, control and dynamic ***37****(5), 1426-1436 (2014)*

[2] Krishnan, N. et al: An Immersed Boundary Method using Finite Element Methods. Computer Methods in Applied Mechanics and Engineering (2017). Draft version.

[3] Turek, S. et al: Numerical Benchmarking of Fluid-Structure Interaction: A comparison of different discretization and solution approaches.

[4] Greenhalgh, S. et al: Aerodynamic Properties of a Two-Dimensional Inextensible Flexible Airfoil. AIAA Journal ***22****(7), 865-870, (1984)*

A Wake Model for Crosswind Kite Systems

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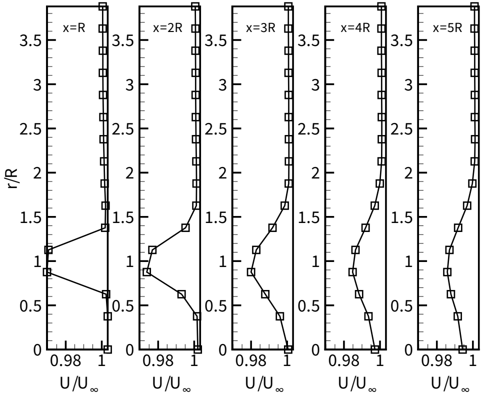
A general perception is that the induction factor of a crosswind kite system is always negligible. For example, Loyd [1], in his seminal paper, neglects "the induced effects of the kite slowing the wind."

In a recent study [2], Kheiri et al. showed that unless the ratio of the kite planform area A_k to the swept area A_s (i.e. the solidity factor $\sigma = A_k/A_s$) is very small (practically viable only for small-scale systems), the induction factor for a crosswind kite may not be imperceptible. For example, for a 2MW system with $\sigma = 0.005$ flying a circular pattern straight downwind on a plane perpendicular to the wind flow, the induction factor is estimated to be 0.18.

Therefore, one may expect presence of a low-speed, highly-turbulent wake flow behind a crosswind kite, similarly to the conventional wind turbines, which may influence performance and power generation of neighbouring kites.

For a small-scale crosswind kite (e.g. 100 kW, $\sigma = 0.003$) in a simplified straight downwind configuration, the induction factor is calculated analytically as $a \simeq 0.05$. Our CFD simulations performed on a super-computer at Concordia University agree well with the predicted value. For this system, the wake flow profile at different axial distances x from the rotor plane is shown in Figure 1. These results are obtained after the kite has completed 20 revolutions from its position at rest.

The present paper studies the wake flow downstream of a crosswind kite system. A theoretical wake model is developed based on existing models for conventional wind turbines. Moreover, CFD simulations are made for different scales of crosswind kite systems, which are used for both calibration and comparison purposes.

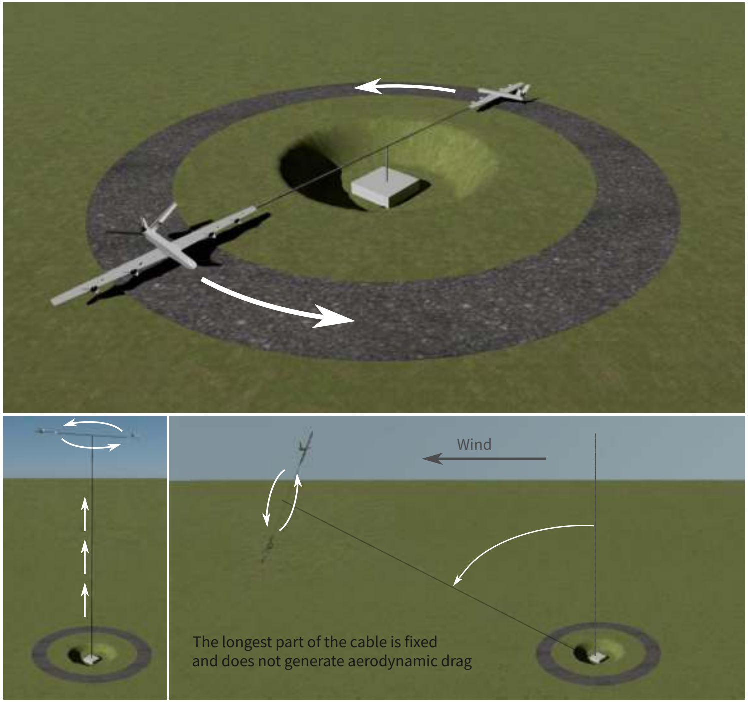


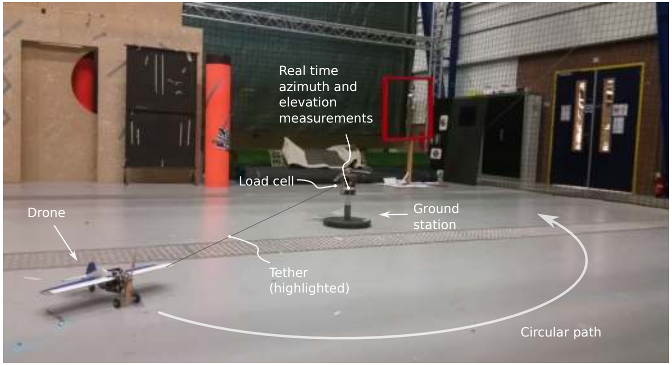
Wake flow velocity profiles for a 100 kW crosswind kite ($\sigma = 0.003$, $a = 0.05$) at different distances (i.e. $x = R, 2R, .., 5R$) downwind from the kite, where r and R are, respectively, the radial distances of any point in the flow, and the centroid of the kite to the rotation axis.

References:

*[1] Loyd, M. L.: Crosswind Kite Power. Journal of Energy **4**(3), 106-111 (1980)*

[2] Kheiri, M., Bourgault, F., Saberi Nasrabad, V.: Power Limit for Crosswind Kite Systems. In Proceedings of ISWTP 2017, Montreal, Canada, May 2017.





Experimental take-off system (top): Experimental rotational start of a half dual-drone system in fully automated take-off and landing sequence. The axi-symmetric round-the-pole flight of a single wind drone has been investigated by means of a dynamic model and an experimental test setup in order to investigate the dual drone concept.

Dual drone concept (left): Two wind drones are linked by a cable at their starboard wing-tip. They accelerate along a circular landing strip using the power from the motors until take-off (top-left). After take-off, the two drones lift the main cable to the desired altitude (bottom-left). i. e. the main cable is kept fixed and the drones continue to rotate thanks to wind power while using their motors as generators.

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Preliminary Test on Automatic Take-Off and Landing of a Multi-Drone Low-Drag Airborne Wind Energy System

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Crosswind Airborne Wind Energy Systems are currently able to reach altitudes of several hundred meters above ground level. Although this is higher than conventional wind turbines, the optimal altitude is limited by the increasing aerodynamic drag of the tether. Simple models for steady-state crosswind flight suggest that for typical wind shear profiles the power loss due to sweeping a longer tether through the air outweighs the power gained by accessing more powerful winds at higher altitude.

A possible solution to this problem is represented by the so called "dancing kite" concept, where a single long cable is attached to two shorter cables, each connected to a kite. The kites are flown in such a way that the long cable is kept in a fixed position with respect to the ground, thus not dissipating power by drag forces, and only the two short cables follow the crosswind motion of the kites. This concept might be the first that is able to reach altitudes of several thousand meters, thus reaching the extreme power densities of the jet streams, allowing to build low cost and powerful wind turbines.

Envisioning a take-off system for such a concept is particularly challenging, and having repeatable and robust take-off and landing capabilities is crucial for the success of the dancing kite principle.

Extending the dancing kite principle to a rigid wing setup can have several advantages, above all, it allows for simple take-off and landing sequences. For example, attaching the tethers to the wing tip of several drones results in a multi-drone system that can take-off and land on an axisymmetric circular runway. For this purpose, the axisymmetric round-the-pole flight of a single wind drone has been investigated by means of a dynamic model and an experimental test setup. In this work, a simple 3-degree-of-freedom model represents the flight of the wind drone in spherical coordinates. The drone is modelled as a point mass with aerodynamic properties, throttle and pitch control. The model also takes into account the stabilizing effect from the lift of the horizontal stabilizer, from the pitch angular velocity, and from the restoring pitch moment due to the centre of gravity being below the aerodynamic centre.

The experimental campaign demonstrated full autonomous take-off and landing capabilities of a small scale wind drone flying round the pole in an axisymmetric configuration. The passive stability of the flight suggests that autonomous take-off and landing can easily be achieved in a dual drone system.

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Experimental trial of a Rotary airborne wind energy system (10 December 2016)

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Rotary Airborne Wind Energy Systems with Ground Based Power Generation: Overview and Practical Experiences

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Rotary airborne wind energy systems that use rotors similar to conventional wind turbines and ground based generators combine some of the known benefits of crosswind kite power systems with potential additional benefits such as continuous energy generation and passive control.

The author provides an overview of rotary designs in literature and practice. This includes different methods for power transmission (torsion, reel in/out, etc.), rotor designs (rigid blades, soft wings, number of blades, stacked rotors, etc.), hub designs (fixed vs variable pitch) and cheap sources for lift and passive control.

Airborne wind energy systems without crosswind motion typically have a bad power/blade area ratio. The author discusses a rotor design that can alleviate this disadvantage. It treats the blades of the rotary wing as independent airborne wings that are only connected for easier control and launch. The airfoils start at some distance from the hub thus achieving high tip speeds with smaller blade area than conventional rotors.

Practical experiences with a torsion based rigid blade rotary airborne wind energy system are being shared. The author discusses the design rationale, lessons learned, successes and dead ends [1,2,3].

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Pumping Cycle Based on Elastic Tether

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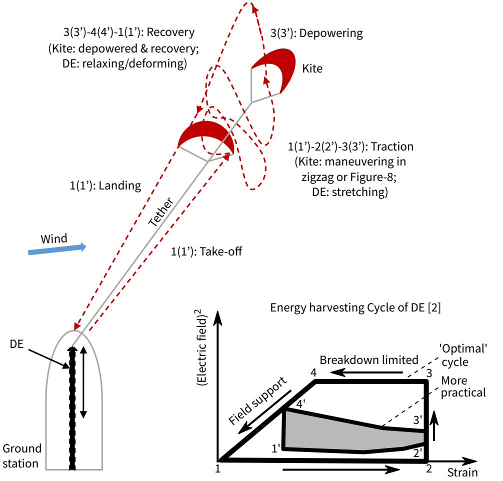
This work is focused on a Pumping Cycle (PC) Airborne Wind Energy System (AWES) concept for adopting a Dielectric Elastomer Generator (DEG) for Power-Take-Off (PTO) since a wind powered generation concept based on a fluttering flag made of Electro-Active Artificial Muscle appeared [1].

Reeling in the recovery phase is inherently required for a pumping AWES owing to the maximal tether length. To address this issue, a rubbery tether is applied in PC. Traction power to be generated in the traction phase is transferred to the rubbery tether and stored as tension power there. At the end of traction phase, a depowered kite is pulled towards the ground station by the tension power stored in the rubbery tether, resulting in less reeling and noise. Such PC can be applicable for an AWES at a Demilitarized Zone (DMZ) or close to a city.

The main features of the PC are as follow: (1) traction power is stored as tension power in an elastic tether, (2) output power is generated for the recovery phase if an elastomeric tether made of DEG is configured for PTO, and (3) the Energy Harvesting Cycle (EHC) of a DEG [2] for (2) depends the PC and can be optimized by kite control.

A hand-made toy kite system was used to observe the PC, as limited to validate only the PC concept. Thus, an engineered prototype of an AWES is further required to reveal some problems such as automatic control including take-off and landing, efficiency in energy conversion, continuous power generation, selection of DE materials, etc.



Observing a pumping cycle based on a toy kite and rubber tether.

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On the Way to Small-Scale Wind Drones – A Networked Approach

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In 2016 Uwe Fechner presented the paper "Downscaling of Airborne Wind Energy Systems" [1] at the Torque conference in Munich. Here, we report on our efforts in the development of small-scale Airborne Wind Energy (AWE) systems with vertical launch and landing. We are trying to accelerate development of small-scale Airborne Wind Energy systems by providing the key components that are always needed but not yet available off-the-shelf. We aim at reducing development costs for any AWE startup, but also to provide components and systems for educational purposes.

The first part our presentation we explain how cooperation with other startups is shaping the structure of our R&D programs. We have been supplying control systems and simulation models to the Dutch startup e-kite and the Swiss startup SkyPull. A case study discusses how component-suppliers help AWE system integrators achieve leaner development cycles. The role of scale economies, specialization and institutional arrangements is assessed in terms of their impact on product development cycle and cost.

The second part of the presentation discusses technical challenges of hardware and software component development for the AWE industry. We plan to offer four products in 2017: a fast and reliable wireless link (Ariadne), a flight control computer tailored for the needs of the airborne wind energy industry (Athena), a ground control computer and a small scale ground-station (1.4 kW continuous electrical power, total mass below 30 kg).

Distributed control challenges will be reviewed together with opportunities for recycling know-how from the conventional drone industry. We are integrating Pixhawk (hardware) and PX4 (software) stacks within a Linux based framework that was developed from scratch to handle the specific needs of airborne wind energy. All systems are resilient and share the transversal concern of enabling safe launch and landing procedures in both regular, strong and turbulent wind conditions. Wind tunnel validation is planned for the end of the year and involves both internal aerodynamic know-how and cooperation with leading European wing designers.

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High-Sky Wind Energy Generation on a Tethered System

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We propose a tethered system for airborne wind energy generation utilizing high and steady wind power over the canopy of the ground wind boundary layer (HSWG).

The system employs a straight blade type windmill lifted to higher altitudes by an inflatable kite. The mechanical energy generated by the windmill is transferred to the generator on the ground by means of a tether loop connecting the rotational axes of the windmill and the generator. A wind tunnel experiment is conducted to examine the energy transfer efficiency of the tether system and the performance of the phase 1.5 windmill model: diameter 0.6 m × span 0.6 m × 2, which is expected to produce a power of 6 kW. The model is operated at 120 m altitude in a wind velocity about 1.5 times higher than on the ground. Flying in periodic figure-eight patterns the apparent wind velocity doubles. The model is expected to produce thus about 30 times larger wind energy generation with respect to the usual on ground operation of 0.2 kW.

Transfer efficiency of energy through tether system is very important for the present tether system and torque transfer performance is tested in the wind tunnel test. It is seen from the result that the tether tension has much effect on the slipping characteristics at the rotation pulley of both the windmill and the generator. The mechanism under investigation is expected to have energy transfer performance of up to 70% and finally 90%. Field testing to float the phase 1.5 windmill model with a kite started in 9 March 2017 and further field demonstration for the phase 1.5 windmill is now in the planning. Results will be presented at the conference accompanied with those in recent study.

Wind tunnel test of phase 1.5 of HSWG at Kyusyu University (Test section 3.6 m × 2.0 m) Windmill (diameter 0.6 m × span 0.6 m × 2) at the upper right is connected through tether to the generator on the lower left (13 September 2016).

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GNSS Jamming Mitigation for Large-Scale Airborne Wind Energy Systems Using Cable Measurements

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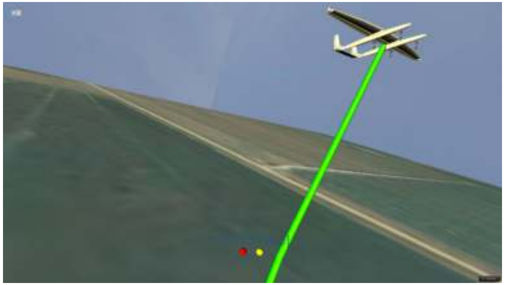
This research presents a method for mitigating the effect of GNSS jamming on large-scale airborne wind energy systems. Onboard navigation systems for airborne wind energy systems typically utilize a combination of inertial measurement unit (IMU) and Global Navigation Satellite System (GNSS) measurements, fused together via a Kalman filter. To keep the cost of the total system low, system designers are forced to utilize lower grade IMUs compared to what would normally be used in commercial aviation. However, this renders the system susceptible to GNSS outages, either malicious or accidental. The risk is compounded by the widespread availability of jammers in recent years [1].

When operated in an autonomous mode, the ensuing navigation drift can quickly result in system divergence and crash. This research investigates methods of mitigating such GNSS outages by using measurements that are already available for use by other functions, such as: 1) Static pressure, 2) Tether length, 3) Tether reel-speed, 4) Tether tension, 5) Wind speed, and 6) Cable direction. Static pressure provides a very effective way of constraining altitude drift, and has been used for this purpose in aircraft navigation systems for several decades. However, the use of tether length/speed/tension/direction is application-specific and requires additional processing before the data can be used by the onboard systems. This research investigates alternative implementations of the fusion of these measurements using a sparse quadrature Kalman filter in combination with a cable model that accounts for sag as a function of tether tension and predicted drag.



Simulation of predicted cable shape used as a measurement model inside of a Kalman filter.

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The M600 energy kite has 8 turbines and a 25 m wingspan (21 November 2016)

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A Low-Cost Fiber Optic Avionics Network for Control of an Energy Kite

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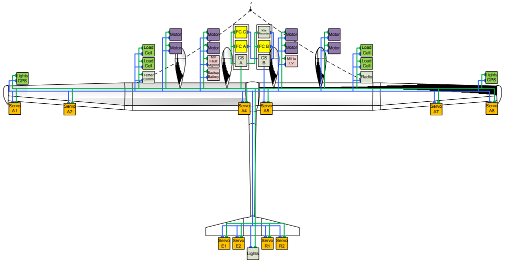
We describe low-cost and fault tolerant data communication on an energy kite with on-board flight control and power generation. The requirements on availability and safety of a modern wind turbine demand that the kite avionics system has a failure rate and fault tolerance on par with equivalent systems on commercial aircraft. Yet, substantially lower cost targets for wind turbines do not allow the straight-forward adoption of solutions that have successfully addressed similar operational requirements in commercial and military aircraft. This paper describes the design and implementation of a low-cost avionics bus, used on a prototype energy kite, that retains safety critical traits of modern avionics buses.

The control system for flight and power generation is based on a modular and scalable architecture: motor controllers, control surface actuators and centralized computer modules each incorporate a microcontroller, purpose-designed for safety-critical applications. The microcontrollers, in addition to performing local control functions and issuing motor commands, collect sensor data over diverse short distance busses local to each node and collate this data into messages adhering to the avionics I/O protocol. These messages are routed between the over 20 nodes that are distributed on the energy kite, which has a wingspan of 25 meters, using dual-redundant Ethernet networks. Plastic Optical Fiber is used as physical medium for low-cost robust interconnections and immunity to electromagnetic interference (EMI). Zero-failover time, deterministic message routing with bounds on latency, and a rich set of diagnostic features are achieved, without requiring new low-level hardware protocols, by leveraging features available in modern network switches.



The M600 kite network consists of two independent Ethernet networks, routed by two core switches (CS A, CS B). The networks link triple-redundant flight computers (FC A, FC B, FC C), motor controllers, control surface servo controllers, telemetry links, power converters, sensors and anti-collision lights on the kite.

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An Open-Source Software Platform for AWE Systems

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Airborne wind energy prototypes are complex mechatronic devices involving many multidisciplinary aspects and for which there are currently no established design guidelines. Therefore, newcomers to the field are required to either purchase expensive software and hardware not specifically designed for AWE applications or build their own solutions from scratch. Given the importance of prototyping, this scenario poses an economical and technical entry barrier, delaying experimental results, and limiting cooperation among the different organizations. As an attempt to partially overcome this challenge, we propose an open-source embedded software platform on top of which AWE systems can be developed.

Similarly to what happened in other areas, such as computer vision and robotics, we believe that a standardized software platform could ease the development process of AWE prototypes. Based on our own experience, software teams involved in any mid- to large-scale projects are usually composed of people from different backgrounds and levels of expertise. In order to cope with this diversity, low-level details should be abstracted away from the average developer, allowing them to focus on the aspects directly related to their tasks. Moreover, changes in the requirements, physical characteristics of the prototypes, and operating conditions are common, and their impact in the software should be minimized, which requires great flexibility from the tools and components employed.

This work proposes a lightweight software platform written mainly in C, and initially targeting low cost single-board computers running Linux. Regarding its architecture, the proposed platform is designed in such a way that it allows for the AWE system to be split into highly decoupled functional modules running in a distributed fashion as independent processes, possibly across several computational units, and capable of exchanging information through a standard, high-performance communication infrastructure based on the publisher-subscriber pattern. Implementation intricacies are kept transparent to the end developer by means of a standardized API that provides extensible and versatile data structures upon which developers can build and configure their own specific modules.

Besides providing a carefully chosen set of dependencies, which are fetched and installed during an automatic build phase, the platform also provides a series of facilities to the developer, including remote deployment, real-time monitoring, logging, code instrumentation and debug tools. The designed platform is suitable for application in AWE and could indeed benefit its growing community, especially in what comes to module reuse and sharing. Other advantages such as high flexibility, lower development and maintenance efforts, and ease of integration with external systems including user interfaces and simulation environments are demonstrated through case studies involving two small scale AWE prototypes operating both in a lab environment and in real-world conditions.

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Ram-Air Kite Reinforcement Optimisation for Airborne Wind Energy Applications

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Ram-air kites are made of thin coated woven fabric and are attractive for the airborne wind energy industry due to their low weight and easy storage ability. The aerodynamic load is transferred from the top canopy through the ribs into the bridle system causing high stresses on the ribs. In order to spread the load as equally as possible, reinforcements are added on the ribs which also sustain the airfoil shape. The most common reinforcement strategy is to simply sew additional fabric onto highly stressed locations of the ribs. For the kite designer one of the challenges is to find a balance between the right amount and orientation of reinforcements, and the extra weight added to the structure.

In this study the layout of a rib reinforcement used in ram-air kites is expressed as an optimization problem. The objective is to find an optimum reinforcement layout such that the deformation of the rib is minimized. Also, the force from the kite acting on the tether is included into the expression and should be maximized, leading to a multi-disciplinary optimization (MDO).

For simplicity, the optimization is initially done in a two-dimensional analysis of the flow and structure. To obtain the aerodynamic pressure acting on the rib the panel method software XFOIL [1] is utilized. The resultant deformations are computed with the finite element method which takes the position of the reinforcements into account, augmenting the element's stiffness based on [2]. Finally the optimum layout is found with a gradient based optimization method.

The optimization is easily extendable to 3D which will eventually yield a more realistic load case acting on the rib structure due three-dimensional flow effects. Also the inflated kite structure in three dimensions behaves considerably different due to the curvature of the canopy.

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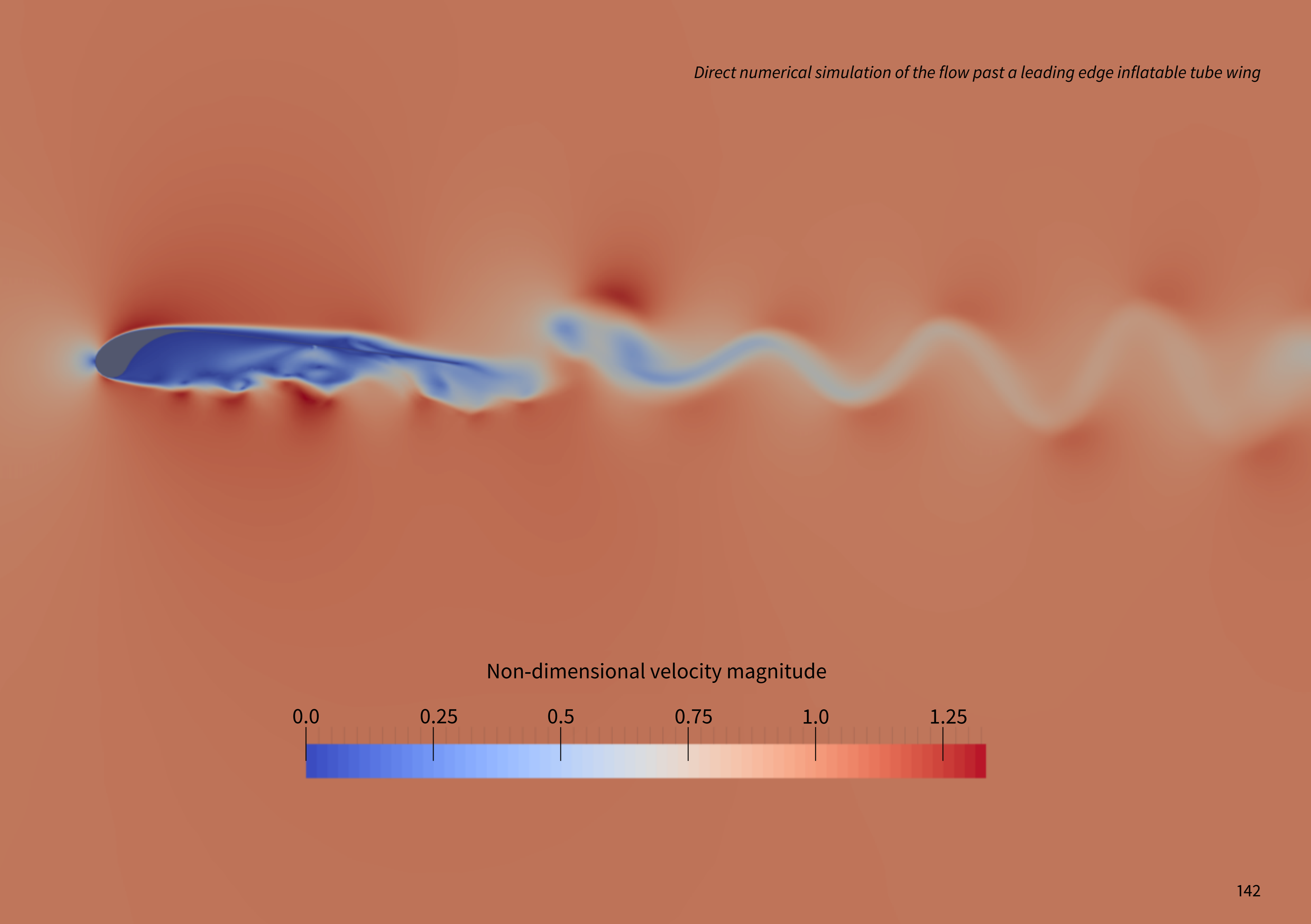
Non-dimensional velocity magnitude
0.0
0.25
0.5
0.75
1.0
1.25

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Direct Numerical Simulations of Flow Past a Leading-Edge Inflatable Wing

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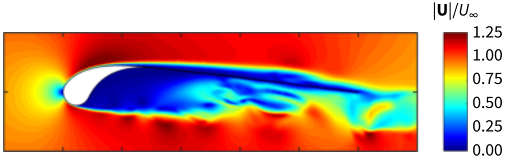
Leading-edge inflatable wings, such as used in the TU Delft's kite power prototype, are commonly used to harness wind energy at high altitudes. The wing is composed of a thin canopy, with an inflated tube at the leading edge and pressurized struts to support the membrane. Although the kite power concept has demonstrated its efficiency in harnessing wind energy, the detailed aerodynamics of the wing is still unclear. It is particularly interesting to understand the interactions between flow vortices and the membrane wing, and their impact on the system performance.

In this work, a fully nonlinear Navier-Stokes solver [1] is used to compute the flow past a leading-edge kite power wing. At this stage, relatively low Reynolds numbers ($\mathrm{Re} \approx 5000$) are considered in order to be able to perform direct numerical simulations. The code is first validated on a well-benchmarked NACA0012 profile at similar Reynolds numbers. It is then applied to the TU Delft kite power wing. For the latter, dynamic mesh adaptivity [2] is used to resolve the shear layers developing near the kite boundary and in the wake. It is observed that the vortices shed at the leading-edge impact on the canopy, hence potentially generating strong fluid-structure interactions when the wing is made of deformable fabric materials. This result is expected to hold at higher Reynolds numbers, although this will be further investigated through large-eddy simulations.



Two-dimensional view of the velocity contours of flow past a three-dimensional kite wing at $\mathrm{Re} = 5000$.

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Fluid-Structure Interaction Simulations on Kites

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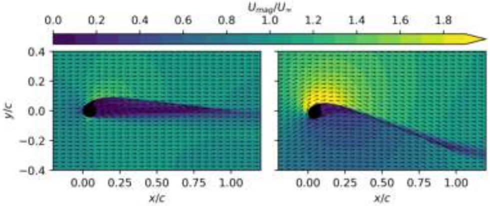
In the kite power group at TU Delft we are currently investigating leading edge inflatable (LEI) kites. The kite consists of a membrane canopy which is supported by an inflatable tubular frame. The frame transfers the wind loads from the canopy to the bridle line system which is further connected to the main tether. This tensile structure is highly flexible and exhibits large displacements as a result of the aerodynamic loads. Consequently, the loads and displacements are strongly coupled and form a complex fluid-structure interaction (FSI) problem. The flow separates both on the suction side due to the high angle of attack to maximize the lift force, and behind the tubular leading edge, where a constant separation bubble is formed. Moreover, the low aspect ratio and high anhedral angle of the kite make the flow highly three dimensional and the effect of wingtip vortices and crossflow cannot be neglected.

Currently, at TU Delft we use a simulation method which was initiated by Breukels [1]. His aerodynamic model uses two dimensional finite strip-approximation which divides the wing into two dimensional sections (airfoils) and neglects the three dimensionality of the flow. The section forces are calculated from two dimensional simulations with computational fluid dynamics (CFD). In this project, we continue the work by Breukels and use a full three dimensional CFD model. The model is coupled with a nonlinear structural finite element method (FEM).

At this stage we are focusing on two dimensional LEI kite airfoils. The two dimensional simulations are used to verify and validate the framework and also to study the effect of flow transition. The CFD simulations are carried out by using OpenFOAM which is coupled with a TU Delft in-house structural solver by an efficient preCICE coupling environment. The results are compared to already existing experimental data from sailwing airfoils [2, 3].



The velocity field around the LEI kite airfoil with 0 (left) and 15 degrees (right) angle of attack.

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Fast Aero-Elastic Analysis for Airborne Wind Energy Wings using Viscous-Inviscid Interaction

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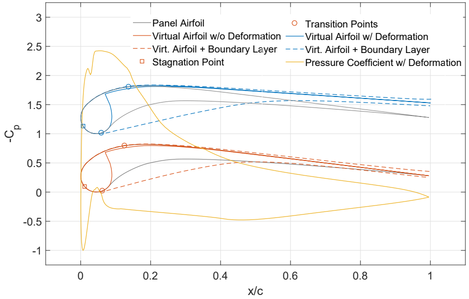
Lightweight or semi-rigid wings as well as textile kites commonly used in Airborne Wind Energy applications have strong aero-elastic deformations during flight. These effects have been investigated in a number of works. Due to the computational complexity of computational fluid dynamics, fast methods rely on simple inviscid methods or pre-computed assumed functional relations for the aerodynamic pressure distribution. These approaches lack the ability to accurately model changes in drag, change in lift slope and separation. Ongoing research into methods that use Navier-Stokes equations improve these predictions, but are not be feasible for fast design iterations and even less feasible for dynamic simulation besides singular validation runs.

Viscous-inviscid interaction methods allow for fast aeroelastic simulations that are similar to inviscid methods in complexity and runtime, but can predict drag and effects of separation. Viiflow is such a method and differs from other viscid-inviscid interaction methods in its unique coupling solver that enables parabolic boundary layer marching together with a fast and reliable global newton method. This method is presented as well as a structural model and the coupling mechanism, which facilitates viiflow to combine the aerodynamic and structural model into a single newton method.

The elastic deformations are modeled using the same mechanics that are used to model the viscous displacement thickness as well as some geometry peculiarities. This allows to keep the inviscid panel operators constant – and the solver runtime short.



Leading-Edge inflatable kite case provided by the FSI group at TU Delft. The thick leading edge and thin canopy are modelled using virtual displacements (blue and red lines) from the actual panel geometry (grey line). The boundary layer adds thickness to this virtual airfoil (dashed lines). Here, the canopy is assumed to be a simple beam fixed to the leading edge with a free end, which under load deforms from its original shape (red) to its final shape (blue).

Multiobjective Airfoil Design for Airborne Wind Energy

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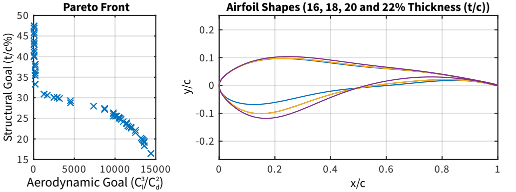
Pumping-mode airborne wind energy systems (PM-AWE) consist of an airborne drone (UAV) that flies tethered to a ground station. The tethered UAV is expected to generate high lifts when reeling the tether out, descend with low force and damp gusts during take-off or landing events. These missions take place in unpredictable environmental conditions. Winds can be more or less turbulent, ground proximity prompts leading edge soiling and aero-structural effects induce shape deformations. Conventional aviation airfoils were not designed for these conditions but wing designers miss specialized alternatives.

The need for specialized airborne wind energy airfoils was first identified by Venturato [1]. He redesigned the Clark Y airfoil with a genetic optimization approach based on a simple performance goal and a RANS CFD solver. This type of CFD model cannot capture important physical phenomena like laminar bubbles or turbulent transition but Venturato's work had the groundbreaking merrit of raising awareness about specialized airfoils.

Here we present a collection of airfoils designed for the needs of the airborne wind energy industry. The design exercise builds upon an established airfoil optimization framework with a proven track record in the conventional wind turbine industry [2,3,4,5]. The method is known to provide a broad coverage of the design space thanks to the use of a CST parametrization, a tuned version of the RFOIL viscous-inviscid solver and multi-objective genetic optimization algorithms. Candidate airfoils are assessed in terms of conflicting structural and aerodynamic goals. Pareto fronts quantify compromises between glide ratio, maximum lift, building height, stall harshness and resilience to leading edge soiling. Finally, desirable pitching moment characteristics are framed within the broader question of planform design, a question on which we hope to engage the audience in a lively discussion.



Pareto front quantifying compromise between design goals.

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Aerostructural Analysis and Optimization of Morphing Wings for AWE Applications

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AWE aircraft operate at extreme wing loading over a wide range of wind speeds. Additionally, the presence of flow inhomogeneities and gusts create a complex and demanding flight environment. Until now, maneuvering capabilities and adaptation to different wind speeds is achieved by conventional wing control surfaces and - in case of ground generator-based systems - by varying the reel-out speed. The design of these wings with conventional control surfaces is always the result of a compromise between the requirements at different flight conditions, leading to penalties in terms of power production. In contrast, considerably greater adaptability to different flight conditions can be attained by shape-morphing wings. They achieve optimal aerodynamic characteristics – and hence maximize the extracted energy – across a wide range of wind speeds by adapting the airfoil camber, and thus the lift distribution, along the wingspan. Furthermore, gust loads can be actively alleviated through morphing, which leads to a substantially expanded flight envelope without requiring excessively conservative structural safety margins. Moreover, active load alleviation demands lower control requirements on the ground station reeling system, as the effects of possible disturbances can be mitigated directly by morphing the wing.

In this work, a procedure to analyze and concurrently optimize a morphing wing for AWE applications in terms of aerodynamic shape, compliant structure, and composite layup is presented. The morphing concept is based on distributed compliance ribs and electromechanical linear actuators. The multidisciplinary optimization aims to maximize the power production of the AWE morphing wing by using an evolutionary algorithm. Within the optimization, the response of the investigated morphing wing to aerodynamic loads and actuation inputs is evaluated by a two-way weakly coupled 3-D fluid structure interaction (FSI) analysis. The structural behavior is assessed using a 3-D finite elements model, and the aerodynamic properties are evaluated by means of a 3-D panel method and a nonlinear extended lifting-line technique. To validate the result of the optimization and to analyze the dynamic response of the morphing wing to gusts, a high-fidelity FSI simulation environment is set up. Within this simulation environment, the aerodynamic characteristics of the identified optimal individual are assessed by solving the RANS equations, and by applying momentum source terms to model gusts and flow inhomogeneities.

The application of the proposed multidisciplinary quasi-steady FSI optimization, combined with the high-fidelity transient FSI, allows a relatively fast assessment and identification of the optimal aerodynamic and structural properties of AWE wings. Moreover, it permits to accurately predict the benefits that morphing wings can bring to AWE airplanes, namely a drastic increase in the power production of these systems with limited structural complexity and mass.

The 50 m^2 kite which is installed on the "Energy Observer" yacht, in the launching phase (23 June 2017)

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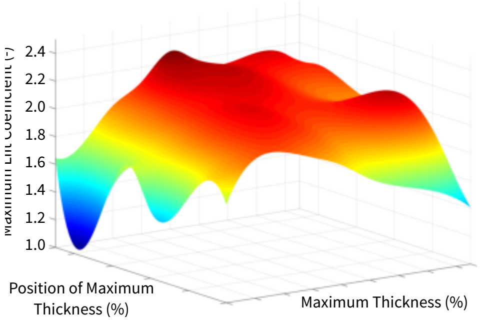
Kite Profile Optimization using Reynolds-Averaged-Navier-Stokes Flow Simulations

Richard Leloup, Tanguy Raffray
Beyond the sea®

In the kitesurfing industry, empirical methods are used to design the kites due to the absence of any alternative, especially numerical methods. Nevertheless, the kites dedicated to auxiliary propulsion of ships developed by the Beyond the sea® project are bigger, more complex and more expensive. Thus, the 3D Lifting Line method was developed to calculate the local and global aerodynamic forces and thereby the aerodynamic performances of a kite [1]. This method was then integrated into a Fluid-Structure Interaction loop in order to evaluate the deformation and stress in the canopy, in the inflatable tube structure and in the lines [1]. Up to now, the potential flow solver XFOIL was used to evaluate the 2D profile aerodynamic characteristics, which are given as an input to the 3D Lifting Line method. In this study, the RANS CFD software OpenFOAM was used in order to improve the accuracy of 2D profile aerodynamic calculations despite a computation time increase by 20 times.

The objective of this study is to compare several kite profiles by varying two different parameters: Maximum Thickness (MT) of the profile and Maximum Thickness Position (MTP). The comparison was performed as follow: first, the intervals of maximum thickness position and maximum thickness were adjusted. Then, a study of the variation of the two parameters MTP and MT was carried out on the previously defined intervals. It was thus possible to plot a surface as shown in figure 1 and then to determine the best profiles in terms of aerodynamic performances (better lift coefficient, better fineness, greater stall angle, etc.). This allowed us to determine the best profile for static flight and for dynamic flight. The integration of the calculations on a 2D profile in the 3D Lifting Line method will make possible to evaluate the aerodynamic performances of a given kite 3D geometry and thus to compare many geometries. Therefore, the manufacture of many prototypes during the design process of a kite will be drastically limited.



Maximum lift coefficient (CLMAX) as a function of Maximum Thickness (MT) and Maximum Thickness Position (MTP).

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Structural Analysis and Optimization of an Airborne Wind Energy System

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For pumping cycle airborne wind energy systems, the airborne mass of the system plays a crucial factor in the performance of the system[1]. This is especially pronounced during low-wind conditions, where the additional force component to overcome gravity is more pronounced in comparison to the aerodynamic forces. Additionally, the airborne mass also affects the take-off speed, thus further influencing the site-specific Levelized Cost of Electricity (LCOE) of the system.

For rigid as well as semi-rigid kites, it is essential to analyse and model the structure of the kite right from the initial design stage, especially given the load couplings commonly witnessed in composite structures. Complete 3D finite element analysis of such composite structures is computationally expensive, and thus uncommon in the initial design stage. However, oversimplified structural models, such as simple uniform and isotropic beams do not capture the intricacies of composite structures and either lead to too optimistic or too pessimistic results, depending on the material assumptions.

An approach to capture the anisotropic coupling effects, which are important for an accurate estimate of composite structure deflections is described here. The main load-bearing member of the structure - the wing box, is modelled as a slender composite beam. The 3D composite shell problem is solved by determining the complete anisotropic 2D cross sectional stiffness, which is then utilised in a 1D beam analysis.

This approach serves to reduce the 3D problem to a 2+1D finite elements problem which is computationally fast, while being sufficiently accurate for initial design. This structural model is then utilised to minimise the weight of the composite wing box, by optimising the internal geometrical shape and orientations of the composite ply fibre.

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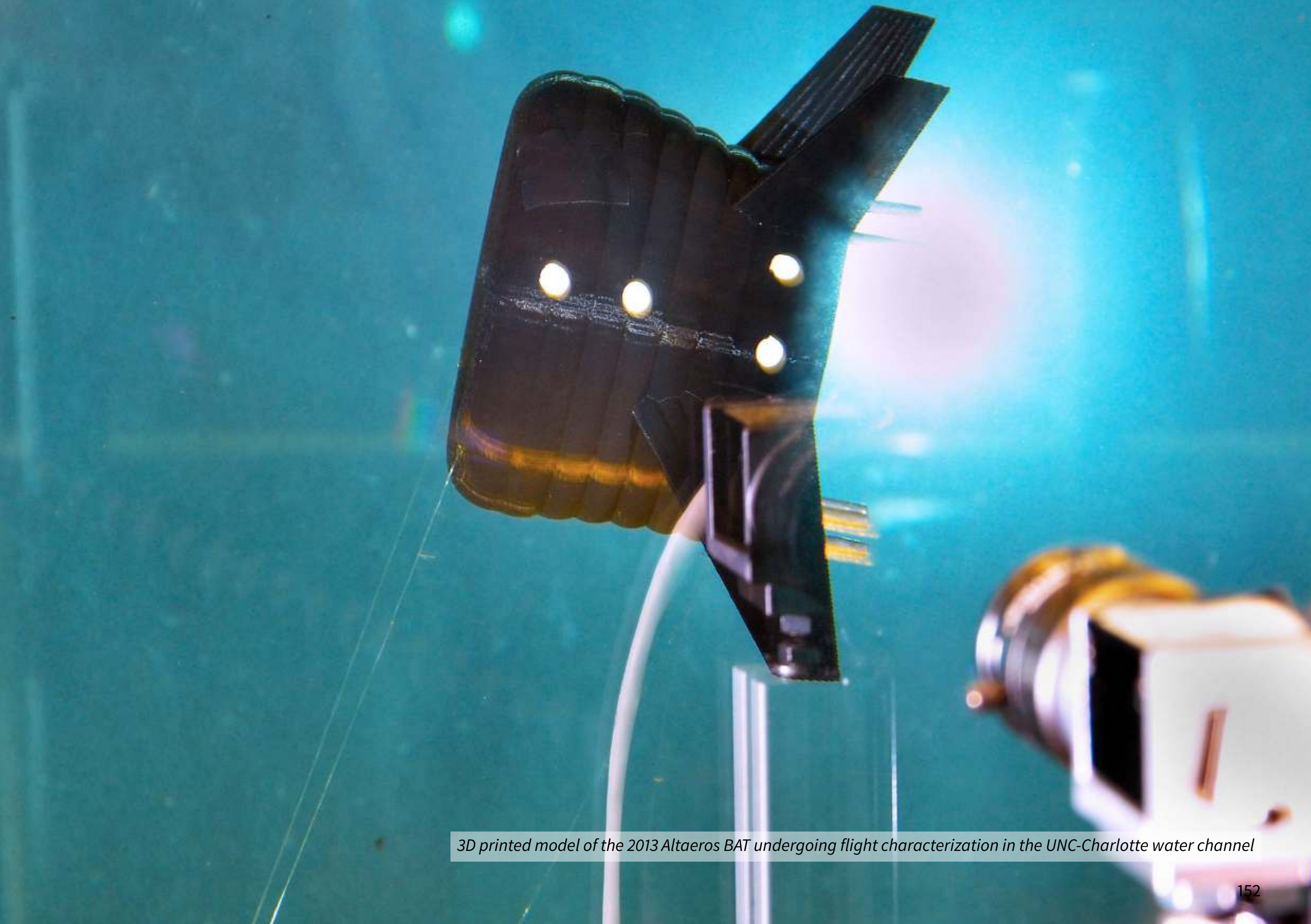
Test operation of the Altaeros BAT in 2013



3D printed model of the 2013 Altaeros BAT undergoing flight characterization in the UNC-Charlotte water channel

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Evolution of a Lab-Scale Platform for Dynamically-Scalable Characterization of Airborne Wind Energy System Flight Dynamics and Control

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Over the past four years, researchers at the University of North Carolina at Charlotte, University of Michigan, and Altaeros Energies have developed a *lab-scale* platform for characterizing the flight dynamics and control of airborne wind energy (AWE) systems. This work started in 2013 with a lab-scale, water channel-based system for characterizing *passive* flight dynamics. The system was enhanced in 2014 to support *closed-loop control* and was further augmented in 2015-2016 with additional image processing and control features that allowed for the demonstration of *crosswind flight*. This presentation will review the evolution of this lab-scale platform, discuss the dynamic scaling results that relate lab- and full-scale flight behavior, and review recent successful efforts to emulate crosswind flight at lab-scale.

The lab-scale system described herein began as a simple platform for qualitatively assessing the performance of the Altaeros Buoyant Airborne Turbine (BAT), as described in [1] and [2]. In 2015, this system was augmented to incorporate closed-loop control, still under stationary operation [3]. Recently, we have shown in [4], using dimensional analysis (via the Buckingham Pi Theorem) that these lab-scale results correlate with full-scale flight results, with the only difference being uniformly accelerated time constants at lab-scale. Finally, we have recently extended our lab-scale framework and dynamic similarity analysis to accommodate *crosswind flight*, as initially disclosed in [5]. In fact, the dynamic similarity results from [4] have been extended to crosswind flight as well. Furthermore, these dynamic similarity results have been corroborated through validation experiments at multiple model scales. This presentation will review (i) the state of the UNC-Charlotte experimental platform, (ii) the dynamic similarity analysis, and (iii) the validation experiments used to corroborate the results of this analysis.

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Experimental Setup to Study Airborne Wind Energy Generation Using a Train of Kites

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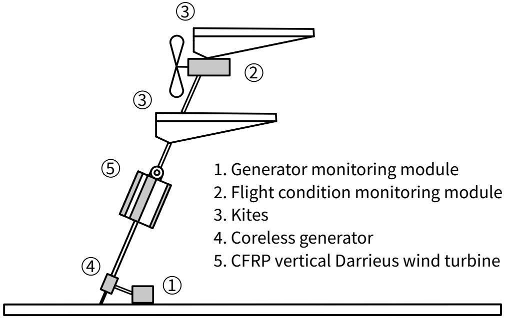
We present an experimental study of airborne wind energy generation with a vertical axis wind turbine (VAWT) lifted by a kite train to higher altitude. The Darrieus type turbine has a diameter of 0.6 m, width of 0.6 m, mass of 2 kg and is made of carbon fiber reinforced polymer (CFRP) hybrid material. The rotor is mechanically connected to a generator on the ground. Important state variables of the system - such as altitude, wind velocity and tether state - are monitored by a module attached to one of the kites of the train.

The full experimental setup has been implemented in a low-cost manner. Internet of Things devices, homemade frameworks, and adapters manufactured with a 3D printer have been used in the experiment. The first experimental campaign provided valuable scientific and technical information. We successfully collected study data including generated electrical power, wind speed, angle of attack of the kites, altitude and static pressure. The pressure gauge requires calibration before each test and we plan to measure the tether tension.

The next goal is to improve the durability of the test setup and to increase the measurement data volume. Future goals are scaling up of the experiment and implementing automatic take-off and landing (ATOL) by lifting drones.



Experimental wind energy conversion with lifted wind turbine.

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Preparing the Kitemill plane at the Lista Airborne Wind Energy Center (10 May 2017)

Synchronous flying at Lista Airborne Wind Energy Center (9 June 2016)

Tore Meinert

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Lista AWE Center AS

The Establishment of an Airborne Wind Energy Test Center in Lista, Norway

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The global airborne wind energy industry consists of individual organizations developing their own proprietary technology and solutions. Several common challenges are therefore dealt with in parallel which results in multiple budgets used to reach the same goal. There exist different technology solutions which complicates the picture for financial investors.

Additionally, there are common risks to the industry, such as permits, certifications, wind conditions, site evaluation, system specification etc. Having these challenges in mind, there has been founded an airborne wind energy test center at Lista during 2017 along the Norwegian south-coast. This presentation will describe the motivation and mission of the test center as well as the characteristics of the test site.

Lista is a city that is characterized by extremely good wind conditions and a mild climate in Norwegian terms. This is confirmed by the presence of windfarms harvesting wind power despite the low electricity prices in Norway. The historical wind data have been analyzed from the past 30 years and compared with other places in Norway. This analysis confirms the potential of the test center to offer wind conditions normally only present offshore. The test center is located next to Kitemill's test site on the airport, which is currently a temporary danger area that is activated issuing a NOTAM. Lista Test Center has now applied for a permanent permit to operate the test center encompassing a large part of the entire airport. The mission of the center is to provide facilities for other AWE players to test out their equipment on the same spot and to avoid each company having to deal individually with common problems. Several systems can be compared and tested in a common environment. Once operational, the test center will serve as a demonstration place for politicians that are committed to introduce a new energy technology.

The center is an independent organization apart from Kitemill and is owned by industry representatives from the region around the airport who are committed to renewable energy. The first customer of the test center will be Kitemill and other AWE companies are strongly encouraged to join as well.

Activity and the operational area at Lista Test Center

Testing in the Aerodrome Traffic Zone of the former naval airbase Valkenburg (23 August 2012)

Testing at the former naval airbase Valkenburg (27 March 2012)

Testing at the former naval airbase Valkenburg (27 March 2012)

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airborne wind energy
KITEPOWER

Unmanned Valley Valkenburg – Drone and Airborne Wind Energy Testing in the Netherlands

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Unmanned Systems are playing an increasingly important role in our economy with a significant impact on our society. Airborne Wind Energy is an emerging industry that offers alternatives to conventional wind turbines. At the former naval air base Valkenburg in the Netherlands, we are providing test facilities for Airborne Wind Energy Systems (AWES) and related technology. This open-air lab is uniquely located in an area with adjacent housing, thereby allowing for tests in a realistic urban environment. We are already performing regular tests with Kitepower systems in Valkenburg and are thus shaping the public perspective on this type of novel systems. Because of its former use as a naval air base, the air space above the field is restricted by an Aerodrome Traffic Zone (ATZ). Inside this air space, future flight tests will be possible without special permit controlled by the local Quality and Safety Manager.

Impact on local residents is measured based on interviews to assess the public perception of renewable (wind) energy in general and Airborne Wind Energy in particular. The test center itself offers the opportunity to perform future safety analyses. Further tests will be conducted on a possible interference of AWES and drones.

The Unmanned Valley Valkenburg (UVV) will additionally be capable of featuring tests beyond the visual line of sight above the North Sea. The site itself is located within 30 minutes from drone manufacturers as well as leading research institutes like TU Delft, University of Leiden, and the European Space Research and Technology Centre. Above all, the test center is accessible to international parties thanks to its close proximity to Schiphol Airport. The municipality of Katwijk holds the chair of the foundation and guarantees operation of UVV on the airfield for the next 5 years.

Layout of former airbase Valkenburg (Runway no longer present).

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Working on the Ampyx Power AP-2 (20 December 2016)

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System Identification of a Rigid Wing Airborne Wind Energy Pumping System

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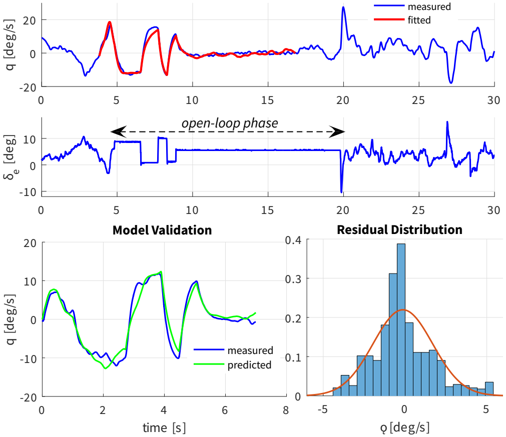
Airborne Wind Energy (AWE) refers to systems capable of harvesting energy from the wind by flying crosswind patterns with a tethered aircraft. Tuning and validation of flight controllers for AWE systems depends on the availability of reasonable a priori models. Due to the non-conventional structure of the airborne component, an intensive flight test campaign must be set in order to gain additional insight about the aerodynamic properties.

In this paper, several aspects related to the system identification of the airborne component of a rigid wing AWE pumping system are provided. The studies rely on the second prototype AWE system developed by Ampyx Power B.V.

More precisely, aerodynamic coefficients are estimated from real flight tests using an efficient multiple-experiment model-based parameter estimation algorithm [1]. Mathematical models rely on the full six degree of freedom aircraft equations of motion. Both model selection and estimation results are assessed by means of R-*squared* value and confidence ellipsoids.

Subsequently, optimized maneuvers are computed by solving a model-based experimental design problem that aims to obtain more accurate parameter estimates and reduce the flight test time [2].

Finally, several theoretical and practical aspects of the proposed methods are provided.



Data fitting and model validation along the longitudinal dynamics computed from real flight experiments [3].

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On Robust Sensor Fusion of GNSS and IMU for Airborne Wind Energy Systems

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One of the biggest challenges facing commercialization of airborne wind energy (AWE) systems is to prove robustness of the technology under various environment conditions. Besides advanced control strategies, an accurate estimate of the system's state is required to guarantee a fault tolerant operation.

In this study, we present a state estimation approach to track the motion of a kite of an AWE system using exclusively onboard sensors. We use nonlinear optimization methods to formulate a sensor fusion problem, which includes measurements from an inertial measurement unit (IMU) and a global navigation satellite system (GNSS) receiver. The highly dynamic maneuvers of energy kites present challenging conditions for consumer grade sensors. Fast turn maneuvers, which are typical for flight trajectories during power generation, can provoke GNSS outages or result in a poor measurement accuracy leading to a degraded estimation performance. The observed behavior raises objections regarding the practical use of GNSS measurement updates for AWE systems [1,2]. We show that these issues can be overcome by considering the sensor-specific limitations in a moving horizon approach for sensor fusion of IMU and GNSS. The presented algorithm allows to robustly track the motion of a kite, which is validated using a recorded flight dataset of a soft-kite AWE system during power generation.

Xsens MTi motion tracker portfolio. The MTi-G710 (right) was used for the data collection in this study.

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System Identification, Adaptive Control, and Experimental Measurements of a Pumping Kite Power System

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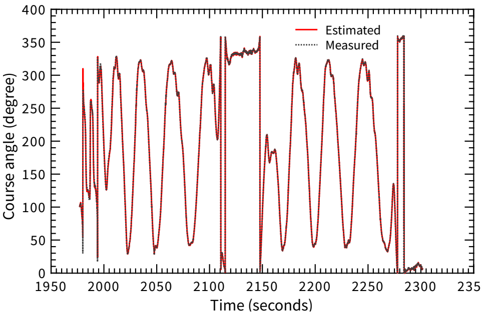
This work demonstrates the derivation of the equations governing the operation of a kite power system, followed by adaptive control with time-varying gains. Because the available mathematical kite models are generally derived with aggressive assumptions, we use least square estimation as a system identification (SI) algorithm [1] to predict the kite parameters in real-time and compare between the measured and expected course angle to check the accuracy of the model as shown in the figure. The SI algorithms are chosen to minimize the computational effort per time step.

Two different controllers are tested separately to stabilize the kite motion; the first controller is a fuzzy controller which is chosen due to its strength in stabilizing non-linear systems. The other controller is an adaptive pole placement controller which updates its control gains in real-time depending on the parameters generated from the SI algorithms. The SI algorithms with fuzzy and adaptive controllers are compared with the mathematical model of the fixed-tether-length kite system with PID controller at different wind conditions.

The novelty of this work is to predict the governing equation of the kite in real-time. Thus, the change in kite's size, wind speed, and tether length [2] would be updated in the mathematical model of the kite. Moreover, the governing equations resulting from the SI algorithms are used to design an adaptive controller that adapts its gains in real-time based on the change of the governing equations of the kite.



Time history of the estimated and the measured course angle.

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Radio-Frequency Positioning for Airborne Wind Energy Systems

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Despite the promising outlook in terms of economical feasibility, AWE technology is currently at an intermediate development stage, with challenges yet to be overcome before it can reach the market. One of these challenges involves obtaining a reliable estimate of the aircraft position and velocity in space. Since these variables are used for flight control, accuracy in their estimation plays a crucial role for both optimizing the power output of the AWE system and for ensuring operational robustness. Due to its simplicity, the usual approach within the AWE community is to combine measurements of the tether angles and length obtained by rotary encoders on the ground unit. Estimators utilizing these measurements have been proven effective when the tethers are kept highly taut, which typically occurs during the reel-out phase. However, during the reel-in phase, when the traction force is lower, estimation results based on the assumption of taut tethers degrade. Other popular strategies make use of a standalone GPS or a GPS associated with an IMU and a barometer. However, GPS signal loss has been reported in situations in which the aircraft is subject to high accelerations or flying at low altitudes. Furthermore, signal quality can vary depending on meteorological conditions and location, which makes it not reliable enough for AWE applications. Finally, industrial grade GPS receivers and IMUs compatible with the AWE requirements can be costly. Another investigated alternative has been the use of cameras and computer vision techniques.These approaches, however, do not seem to address real-world situations such as changes in lighting and weather, occlusion, and the presence of extraneous objects in the images, and, therefore, are not suitable for a system which is expected to work uninterruptedly and, to some extent, be independent of environmental conditions. More recently, an approach combining range measurements from ultra-wideband devices and readings from an IMU was proposed. In this approach, the distances between a radio transceiver fixed to the aircraft and a number of beacons scattered on the ground are measured, resulting in a larger accuracy than encoder-based schemes, specially when the tethers are not highly taut. However, to the best of our knowledge, no experimental results validating this setup are available in the literature. Lateration of range information obtained through time-of-flight measurements has several advantages over more conventional positioning techniques. It is simple, inexpensive, weather independent, and does not rely on any strong assumption about the system. Moreover, it allows for all computations to take place on the aircraft, eliminating communication delays which could jeopardize the performance of the automatic controllers. Motivated by these characteristics, this work presents a setup based on 2.4 GHz radio-frequency devices and on an Extended Kalman Filter for the real-time position and velocity estimation of a tethered aircraft. These variables are validated against line angle and length data obtained from rotary encoders at the ground station, demonstrating a good performance of the implemented measurement system. Furthermore, it is shown that the same setup can be used as a communication infrastructure, allowing for cost and complexity reduction.

Twingtec's energy drone (20 December 2016)

Airborne wind energy research team at the University of Freiburg (3 February 2016)

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The Effect of Realistic Wind Profiles on Multiple-Kite System Optimal Control

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[2]Chalmers University of Technology

Multiple-kite airborne wind energy systems (MAWES) have raised interest recently, as systems that are expected to be more efficient than other airborne wind energy (AWE) systems. This is because Loyd's limit for the power produced by an airborne wind energy (AWE) system is inversely proportional to the the square of the system drag coefficient [3], and single-kite systems may have significant tether drag. MAWES, in contrast, aim to limit tether drag by balancing the forces on multiple kites to prevent the tether from flying cross-wind.

Existing studies of MAWES [2,4,5] typically consider the wind-field to follow a logarithmic wind profile. However, logarithmic wind profiles are known to be approximate, and are not generally considered valid at altitudes above 500 m [1].

It is not known to what extent this logarithmic wind profile assumption influences the results of MAWES optimal control studies. The purpose of this work is to study the effect of realistic wind profiles on optimal MAWES pumping-cycle kite trajectories. A periodic optimal control problem (OCP) is solved for a MAWES, using wind profiles based on realistic wind data measurements in Göteborg, Sweden. This study focuses on the effects to the optimal flight path and the optimal flight altitude as a result of these realistic wind profiles.

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CHALMERS
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AWESCO
Airborne Wind Energy
System Modelling, Control & Optimisation

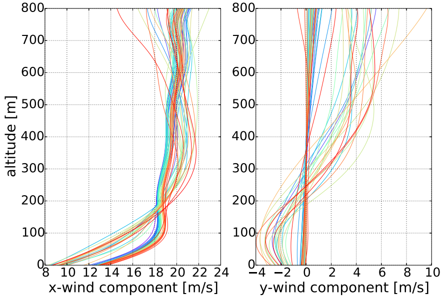
AWE Optimization on Big Wind Data

Elena Malz, Sébastien Gros
Chalmers University of Technology

Airborne wind energy systems (AWE) are currently simulated and optimized using simple logarithmic wind profiles. This representation is known to be sufficient for wind power plants up to 100 m altitude, but AWE systems are likely to operate beyond that height, such that logarithmic profiles might not be adequate. Indeed, the optimization of AWE systems ought to take into account the overall wind profile at its location (wind speed and directions at different altitudes).

Wind data are abundantly available in electronic formats, either as direct measurements or as the output of state-of-the-art atmospheric models (or a combination of both), and could be used to investigate the optimal power output of AWE systems at different times and locations. Obtaining the optimal power output of AWE systems for a large number of wind data can be useful for e.g. estimating the performance of AWE systems, optimizing their design for realistic wind conditions, assessing installation sites, and for the integration of AWE systems in the power grid.

However, the optimization of AWE systems is known to be a computationally intensive and involved problem. Hence, computing the optimal trajectory and power output of AWE systems for a large number of wind profiles is a very challenging task. In this paper, we will present an early tool development which aims at tackling this problem. The MERRA [1] data on which the proposed tool is tapping consists of wind speeds and directions for a vertical resolution of 100m, available for every degree of latitudinal and longitudinal coordinates, and at a time resolution of 3 hours over the last 30 years. The solution approach we will propose is based on a combination of big data analysis using tools such as clustering, function approximators and data structuring, as well as techniques from parametric nonlinear programming (NLP) to handle the optimization problem on large data sets efficiently.



Example data of wind speed and direction projected into Cartesian coordinates

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Offshore Airborne Wind Energy TKI Sea-Air-Farm Aerodynamic Performance, Installation and Operation and Maintenance

**Gabriele Bedon, Marco Caboni, Kisorthman Vimalakanthan,
Novita Saraswati, Ashish Dewan, Gerard Schepers**
Energy research Centre of the Netherlands (ECN)

High altitude wind maps suggest a great potential to supply a significant portion of energy needs. Airborne wind energy has a large potential not only because of the power density but also because regions with sufficient resources are widespread around the world. However, there is no location over the land that can guarantee any power 95% of the time. ECN, Ampyx Power, Mocean-Offshore, and Marin are investigating the feasibility of offshore airborne energy in the TKI Sea-Air-Farm project. This project aims to investigate, select and design technical concepts for offshore application of Airborne Wind Energy Systems (AWES), combined into a conceptual design of a 350 MW airborne wind farm which then, through a weight reduction, load reduction on the support structure and lower costs for installation and O&M eventually leads to an overall LCoE, competitive to the costs of existing offshore wind technology.

An aerodynamic review of the power-plane aerodynamics and power production is conducted by ECN. The tools developed and validated for wind turbines are adapted to perform a critical review of the performance. The airfoil properties, estimated from the open source tool SU2 [1], are compared to OpenFOAM estimations, obtaining a good agreement. These properties are afterward included in the ECN Aeromodule [2], a free wake vortex line method to perform estimations of horizontal axis wind turbines. By providing the power-plane path, estimations of power production are obtained.

Moreover, ECN uses its validated tools to estimate the costs for installation, operation, and maintenance for the offshore airborne technology [3,4]. The current state-of-the-art strategies are adapted and compared in order to find the most suitable one for the power-plane case. To the authors' knowledge, this represents the first attempt in literature to estimate these costs, which have a very important impact on the cost of energy and on the final feasibility of this technology.

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1:25 scale model of the Ampyx Power Floating Airborne Wind Energy System in the wave basin of MARIN (14 July 2017)

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Limiting Wave Conditions for Landing Airborne Wind Energy Aircraft on a Floating Platform

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The potential for the application of airborne wind energy in a deep-water offshore environment on top of floating foundations is enormous. Where conventional wind turbines would require a very stable platform to reduce motions at the nacelle, AWE requires just enough stability to take-off, land and not negatively affect cross-wind performance. This also scales well with increasing capacity of AWE systems, which most of all has influence on the mooring configuration instead of the steel structure. That is why Ampyx Power started an investigative study into this offshore application in collaboration with Mocean Offshore, Marin and ECN [1].

A driving factor in the design of the floating foundation are the maximum allowed motions in different sea states. A study into the effects of wave induced motions on the landing performance is therefore performed. Time domain simulations are made of the floater, which was designed by Mocean, in a multitude of different wave conditions. These simulations are validated by experiment at the Marin test basin. The floater motion data is then used as the moving landing position in a simulation model of a tethered aircraft making a horizontal landing. Especially, heave and pitch motions of the floater are expected to affect landing performance, which is why a 3DOF model is used. By comparing the simulations with limits to landing (e.g. maximum allowed relative vertical velocity), statistical data can be gathered on the probabilities of landing failure for different sea states.

Based on the results, recommendations can be made with respect to the floater design requirements, as well as on the design of the aircraft (e.g. landing gear or control system).

Impression of offshore floating airborne wind energy system.

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The Kitepower 2.0 project team at Valkenburg airfield (8 November 2014)

Kitepower Research group and startup company Kitepower B.V. of Delft University of Technology (23 June 2017)

AWESCO members: (above) at the midterm project meeting (8 February, 2017), and (below) during a course (3–4 March, 2016)

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EU Horizon 2020 Projects AWESCO and REACH – Advancing Airborne Wind Energy Technologies by Systematic Research and Development

Roland Schmehl
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Airborne wind energy is the central theme of several projects funded by the European Union within its framework programme Horizon 2020. In this presentation I will highlight two specific projects in which I am involved as coordinator, AWESCO and REACH, and will show how the two parallel actions not only complement each other but create a synergy effect, interleaving also with other parallel actions.

AWESCO ("Airborne Wind Energy System Modelling, Control and Optimisation") is a Marie Skłodowska-Curie doctoral training network, co-financed by the Swiss Federal Government and comprising 14 PhD fellows active at 8 universities and 3 industry partners [1]. The aim of this network, which runs from 2015 to 2018, is to collaboratively address the key challenges of airborne wind energy to support the commercialisation of the technology. The group photo at the top of the page 176 shows the AWESCO PhD researchers together with their supervisors and management staff at the midterm meeting of the project at KU Leuven, on 8 February 2017. The photos below illustrate a training course at the University of Freiburg, on 3–4 March 2016, during which the researchers had to collaboratively invent and design concepts for high-performance depower of a softkite for pumping cycle operation. This course on Project Management and Strategic Skills was managed by my colleagues Ni Yan and Ricardo Pereira.

REACH ("Resource Efficient Automatic Conversion of High-Altitude Wind") is a Fast Track to Innovation Pilot [2]. The project runs from 2015 to 2018 and aims at commercially developing a 100 kW pumping kite power system originally designed and tested at Delft University of Technology. At the centre of the project is the startup company Enevate BV using the trademark Kitepower^{TM} to market the developed system. Although the two projects AWESCO and REACH have different goals they are tightly linked through the participation of the university and the startup on both projects.

Parallel actions in H2020 are the projects AMPYXAP3 [3], EK200-AWESOME [4] and NextWind [5], all in the SME Instrument scheme, however, in different phases. The two supported SME's, Ampyx Power and Enerkite, are also consortium partners in the AWESCO network and in this way linked to the research activities. A very recent Eurostars project is TwingPower [6]. This setup shows how the EU effectively uses different financing instruments to increase the readiness level of the technology and supports the commercialisation.

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http://cordis.europa.eu/project/rcn/193938_en.html

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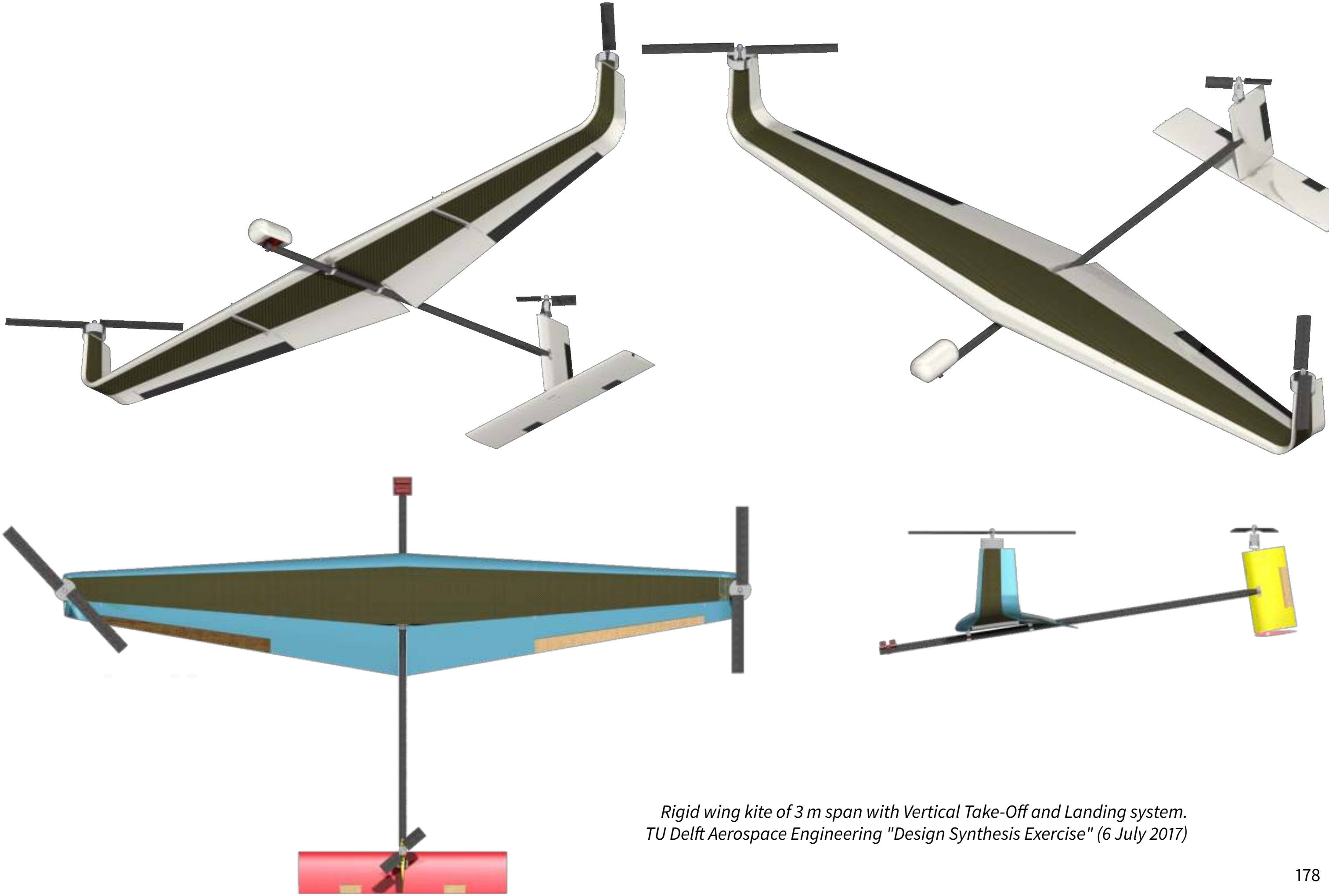

Rigid wing kite of 3 m span with Vertical Take-Off and Landing system.
TU Delft Aerospace Engineering "Design Synthesis Exercise" (6 July 2017)

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Do We Still Need Airborne Wind Energy?

Udo Zillmann
Airborne Wind Europe

The world has started decarbonization in earnest. In western countries, practically all newly installed electricity generation capacity is renewable and installation figures exceed even the most optimistic scenarios. Wind and solar are now in many places the cheapest sources of electricity and feed in tariffs are reduced and in many cases abolished as a result. In the latest auctions for offshore wind, the winners requested no guaranteed feed in tariffs but were happy with earning only the market price. We have reached grip parity.

This is great news for our planet. But what does it mean for Airborne Wind Energy?

The promise of Airborne Wind Energy has long been the ability to produce renewable energy cheaper than coal. For that we now have solar and wind. Is it then worth spending further funds and subsidies on a technology which is in its infancy and has so far only produced small prototypes? With many technical, legal and financial obstacles still to overcome? In other words: do we still need Airborne Wind Energy?

The future of the Airborne Wind Energy industry depends on a convincing answer to this question.

The industry will require years and lots of funding before the first large scale products can be mass produced. This can still be a very rewarding investment. But it has to be shown that AWE has clear advantages over conventional wind and solar. Not only over the present wind and solar, but also over future, even more efficient wind and solar. Potentially even lower costs will not be enough as a single argument.

A lot of challenges remain until we have a 100% renewable energy system. One is intermittency: what happens when the wind does not blow and the sun does not shine? How much storage, grid infrastructure and backup power does the future energy system need and how much will this cost?

High-Altitude Wind is not only strong but also widely available and steady. With this resource, AWE can produce at higher capacity factors and can produce at times and at places where conventional wind turbines can't. It is a more reliable and stable electricity source that can solve many problems of the renewable energy system of the future.

There are strong arguments for AWE. But the industry has so far lacked the means to form and communicate these arguments to policy makers, investors and the public. This is the aim of the newly formed industry association Airborne Wind Europe. Our mission is to create a strong environment for the development of AWE, to improve access to funding and to enhance business opportunities for our members. To achieve this, we engage with European and national policy makers, we help shape research agendas and we work on legal and technical guidelines as well as the education of the public. Airborne Wind Europe is a strong voice with a clear message: We need Airborne Wind Energy for our future.

Airborne Wind Europe


Structural load tests on the Makani M600 (29 June 2017)

Servicing the Makani M600 prototype (26 October 2016)

Preparing the Makani M600 prototype for a flight test (10 October 2016)

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A Techno-Economic Analysis of Energy Kites

Nicholas Tucker, Megan Quick
Makani / X

Over decades, wind turbines with ratings measured in 100s of kilowatts have long since made way for systems in the MW range, with offshore systems poised to soon reach 10 MW. What lessons can the AWE industry learn and apply from this? Makani has been exploring many factors that drive wind energy economics in our own massive scale-up from a 25 kW demonstrator to a 600 kW energy kite, the M600.

Makani utilized the knowledge gained while developing and testing our 600 kW energy kite to inform a techno-economic systems model for Makani energy kite concepts. With ongoing testing of several prototypes and refinement of our designs, we continue to look ahead to what's next and optimize for future design iterations.

This talk will review our techno-economic systems model, a toolset developed to evaluate and refine a range of energy kite concepts. In the model we consider five key areas to evaluate the levelized cost of energy (LCOE) of a system: capital cost, performance, mass, balance of plant cost, and operation and maintenance cost. Building on lessons from the M600 development, we have created cost and mass models for each sub-system that scale with rated power and other key parameters. Performance analysis methods, validated by full-scale flight test data, have been developed to evaluate the energy production.

This techno-economic model has been used to investigate sensitivities and optimize the design of Makani energy kites. This has allowed for trade studies across the entire design space, with some interesting findings.

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An Energy Utility Perspective and Approach to Airborne Wind

Kester Gunn, Henrik Wall
E.ON Climate & Renewables

E.ON started technology tracking of AWE over five years ago. Initial monitoring of technology development has led to in-depth discussions, cost modelling and a technical review of selected technologies, as well as active research and development [1].

In 2016 E.ON decided to engage more actively with the emerging AWE industry, to speed up commercial development. To date, this has involved investment in one AWE company (Kite Power Systems, KPS) [2], and collaboration with another (Ampyx Power) to develop a test site in Ireland [3]. The test site, in County Mayo, will be used over 4-6 years as Ampyx demonstrate their technology up to an expected 2 MW scale. To maximise the value potential E.ON intends that other AWE developers, which meet our due diligence standards, can also use the site. E.ON are currently undertaking feasibility studies, and aim to begin construction activities in late 2018.

E.ON's primary area of interest for AWE is in developing, constructing, owning and/or operating utility scale, grid-connected offshore windfarms. Consequently, E.ON is focusing its engagement towards technology developers aiming for this market.

E.ON assesses AWE technologies according to three categories:

Technical – device design and operation; level/scale of testing; planned next stages of development. Our aim is to identify the possible key risks and mitigation strategies, as well as the OPEX and the CAPEX requirements.

Commercial – advantages of the technology; modelling for a “commercial” device; funding requirements and sources. This requires cost breakdowns to compare with conventional wind.

Governance – commercial and technical; risk management; Health and Safety policies; compliance with relevant standards; etc.

E.ON have found that being a sparring partner in the field of Governance brings most value, e.g. assessing which standards should be followed for "traditional" aspects of the engineering.

To be successful, technology developers must have a roadmap to commercialisation. Decisions may include in-house or outsourced manufacturing, seeking OEM acquisition or licensing of technology. Before a multiple megawatts can be installed of any technology in a commercial setting it is likely that it will need to be shown as "bankable", and thus need significant de-risking. E.ON are focussed on helping AWE overcome this hurdle, whether by working with research institutes, or by investment or development of a test site, to bring AWE to commercial readiness by early to mid 2020s.

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Third Party Materials

AWEC Archive

The Airborne Wind Energy Conference (AWEC) is hosted as an international public event since 2010. The archived documentation of the following events is openly accessible:

AWEC 2011, 24-25 May, Leuven, Belgium
Book of Abstracts, edited by Jacqueline De Bruyn, Moritz Diehl, Reinhart Paelinck, Richard Ruiterkamp, 73 pages.
ISBN 978-94-6018-370-6
doi:10.4233/uuid:54a23dff-74f9-4007-b1d6-e92e0c458491

AWEC 2013, 10-11 September, Berlin, Germany
Book of Abstracts, edited by Guido Lütsch, Christian Hiemenz, Roald Koch, 77 pages.
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doi:10.4233/uuid:f91af52c-4e76-4cf5-917a-129455b3fca9

AWEC 2015, 15-16 June, Delft, The Netherlands
Book of Abstracts, edited by Roland Schmehl, 123 pages.
ISBN 978-94-6186-486-4
doi:10.4233/uuid:6e92b8d7-9e88-4143-a281-08f94770c59f

Mediasite Video Showcase, edited by Roland Schmehl, 56 presentations.
https://collegerama.tudelft.nl/mediasite/Showcase/Channel/conference-airborne-wind-energy

AWEC 2017, 5-6 October, Freiburg, Germany
Book of Abstracts, edited by Moritz Diehl, Rachel Leuthold, Roland Schmehl, 188 pages.
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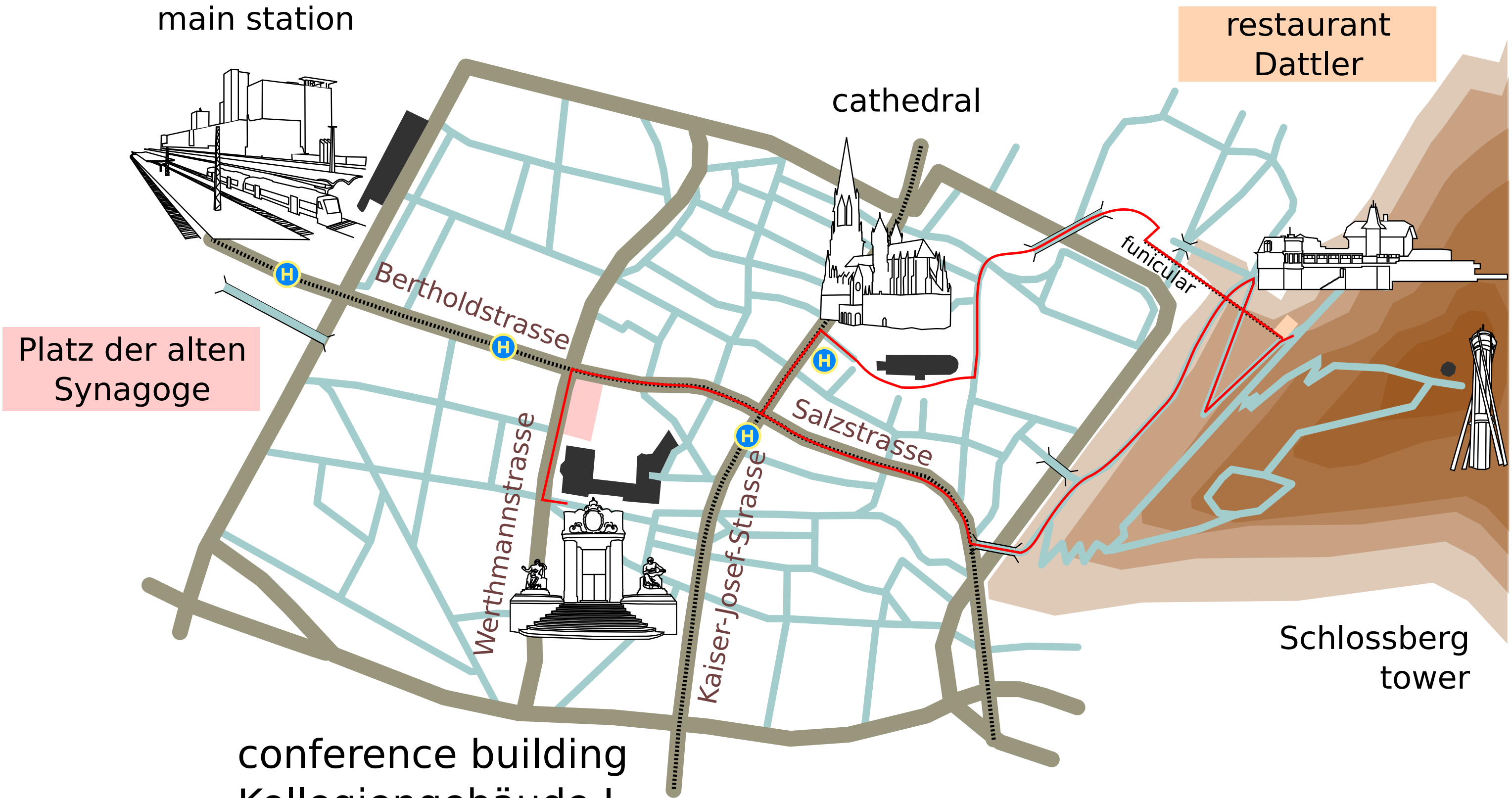
Map of Freiburg Conference Locations



conference building
Kollegiengebäude I

Platz der Universität 3
79098 Freiburg im Breisgau

AWESCO
Airborne Wind Energy
System Modelling, Control & Optimisation

Airborne Wind Europe

LEISTUNGSZENTRUM
NACHHALTIGKEIT FREIBURG

maxon motor

airborne wind energy
KITEPOWER

EnerKíte

TWINGTEC
WIND ENERGY 2.0

ampyx
power

KITEMILL

DSM

aenarete
Smart Wind

UNI
FREIBURG

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