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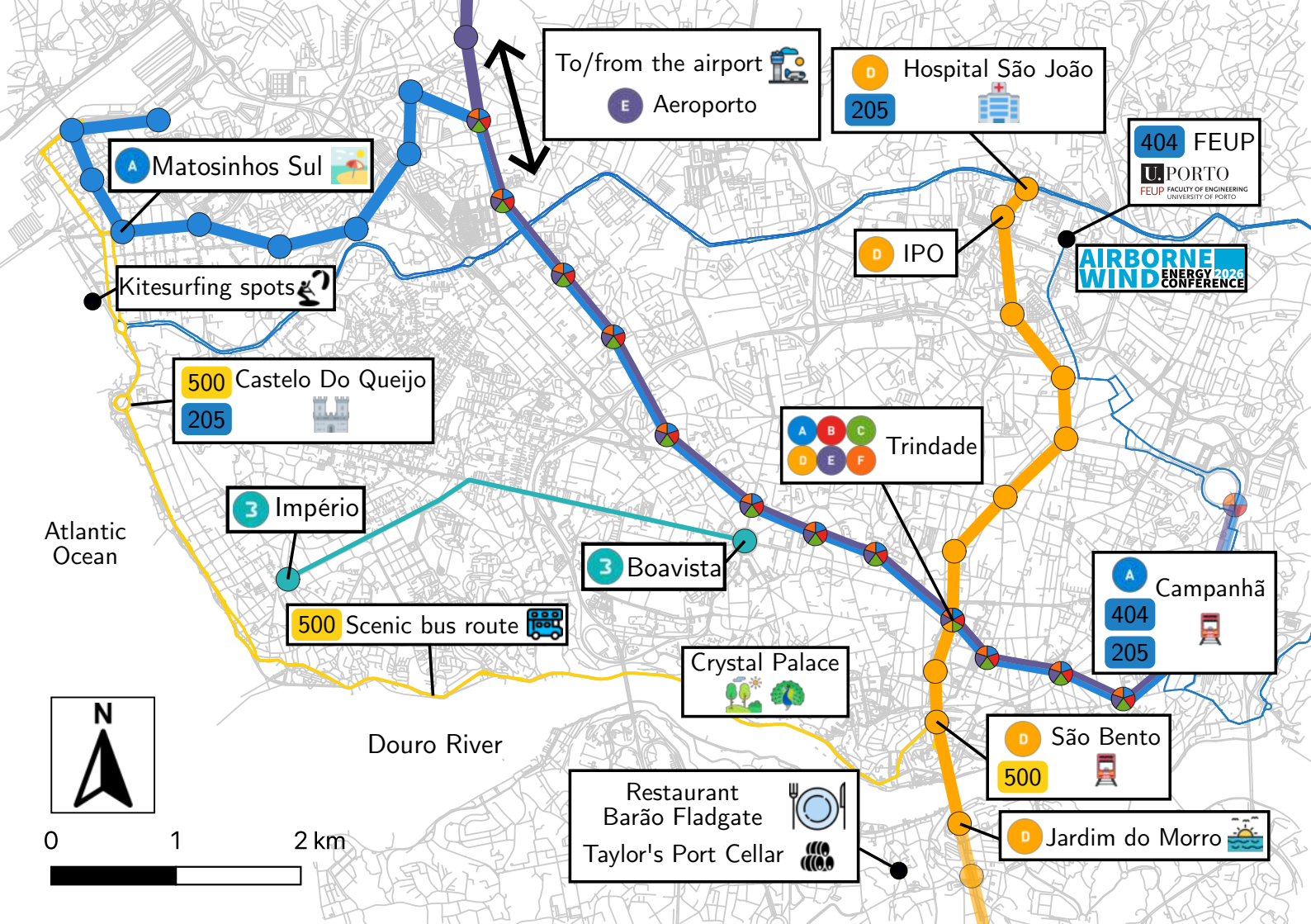
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# AIRBORNE WIND ENERGY 2026 CONFERENCE

24-26 June 2026  
PORTO  
Universidade do Porto  
AWEC2026.COM

## BOOK OF ABSTRACTS





A Matosinhos Sul

To/from the airport  
E Aeroporto

D Hospital São João  
205

404 FEUP  
UPORTO  
FEUP FACULTY OF ENGINEERING  
UNIVERSITY OF PORTO

AIRBORNE WIND  
ENERGY 2026  
CONFERENCE

D IPO

Kitesurfing spots

500 Castelo Do Queijo  
205

3 Império

A B C  
D E F  
Trindade

Atlantic Ocean

3 Boavista

500 Scenic bus route

A Campanhã  
404  
205



Crystal Palace

Douro River

D São Bento  
500

0 1 2 km

Restaurant Barão Fladgate  
Taylor's Port Cellar

D Jardim do Morro

**AIRBORNE**  24-26 June 2026  
**WIND ENERGY 2026** **PORTO**  
**CONFERENCE** Universidade do Porto  
AWEC2026.COM

**BOOK  
OF  
ABSTRACTS**

### *Editors*

Fernando A. C. C. Fontes  
Faculty of Engineering  
University of Porto (FEUP)  
Porto  
Portugal

Stefanie Thoms  
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Delft University of Technology  
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The Netherlands

### *Layout*

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# Technical Program - Thursday, 25 June 2026

Time	Page		Page		Page	
8:00	REGISTRATION				[HALL]	
9:00	<b>CONFERENCE OPENING</b>		Fernando A. C. C. Fontes, <i>University of Porto</i>		[AZORES]	
			Roland Schmehl, <i>TU Delft</i>			
9:20	<b>PLENARY TALK I</b>		Enrico Degiorgis, <i>European Commission</i>			
9:45	<b>PLENARY TALK II</b>		Moritz Diehl, <i>University of Freiburg</i>		23	
10:05	<b>POSTER SPOTLIGHTS I</b>					
10:20	<b>POSTER SESSION I &amp; COFFEE BREAK</b>		poster abstracts listed on the following page		[COFFEE LOUNGE]	
10:40	<b>OEM PANEL</b>		moderated by Kristian Petrick, <i>Airborne Wind Europe</i> , with:		[AZORES]	
	Kristian Petrick, <i>Airborne Wind Europe</i>	36	Pieter Willems <sup>1</sup> , <i>Kitepower</i>	40	Florian Breipohl <sup>2</sup> , <i>Enerkíte</i>	46
	Thomas Härklau, <i>Kitemill</i>	49	Giorgio Sella, <i>Kitenergy</i>	50	Luís Tiago Paiva, <i>UPWIND Energy</i>	51
	Garrett Smith, <i>Wind Fisher</i>					
11:40	BREAK					
11:45	<b>MODELLING &amp; SIMULATION I</b> [MADEIRA]		<b>SECTOR DEVELOPMENT I</b> [AZORES]		<b>AERODYNAMICS &amp; STRUCTURES I</b> [BERLENGAS]	
	Alessandro Genoni, <i>Wind Fisher</i>	52	Kristian Petrick*, <i>Airborne Wind Europe</i>	59	Tom Lolies, <i>FAIR aero</i>	64
	Matthieu Duponcheel, <i>UCLouvain</i>	53	Eiji Itakura, <i>Toyota Motor Corporation</i>	60	Jean-Baptiste Crismer <sup>3</sup> , <i>UCLouvain</i>	65
	Oriol Cayon*, <i>TU Delft</i>	57	Michael McWilliam, <i>DTU</i>	62	Thomas Haas*, <i>VUB</i>	66
	Roystan Castelino, <i>NOA</i>	58	Reinhart Paelinck, <i>Mozaero</i>	63	Omid Heydarnia, <i>Ghent University</i>	67
13:00	CONFERENCE GROUP PHOTOGRAPH [LAWN BEHIND AMPHITHEATRES]					
13:15	LUNCH [COFFEE LOUNGE]					
14:30	<b>CONTROL &amp; OPTIMIZATION I</b> [MADEIRA]		<b>TESTING &amp; OPERATIONS I</b> [AZORES]		<b>SYSTEM DESIGN &amp; PROTOTYPING I</b> [BERLENGAS]	
	Duc H. Nguyen*, <i>University of Bristol</i>	68	Xintong Deng <sup>4</sup> , <i>TRINA</i>	76	Jakob Harzer, <i>University of Freiburg</i>	81
	Johannes Waibel, <i>EPFL</i>	73	Achim Kuhn, <i>University of Stuttgart</i>	77	Christof Beaupoil*, <i>someAWE Labs</i>	83
	Sérgio Vinha, <i>University of Porto</i>	74	Bixiong Luuoc <sup>5</sup> , <i>CPECC</i>	78	Leonardo Cecchin, <i>Politecnico di Milano</i>	84
	Amit Shivam, <i>University of Porto</i>	75	Sofia Trombini*, <i>Politecnico di Milano</i>	79	Jacob Fine, <i>Exponent</i>	85
15:45	BREAK					
15:50	<b>PLENARY TALK III</b>		Gerdien de Vries, <i>TU Delft</i>		[AZORES]	
16:10	<b>POSTER SPOTLIGHTS II</b>					
16:25	<b>POSTER SESSION II &amp; COFFEE BREAK</b>		poster abstracts listed on the following page		[COFFEE LOUNGE]	
16:45	<b>MODELLING &amp; SIMULATION II</b> [MADEIRA]		<b>SENSING, ESTIMATION &amp; WIND RESOURCE</b> [AZORES]		<b>NOVEL CONCEPTS</b> [BERLENGAS]	
	Espen Oland*, <i>Kitemill</i>	106	Sam Kaufman-Martin*, <i>USCB</i>	111	Zhen Hua, <i>Zhonglu Co.</i>	125
	Andrea Bertozzi, <i>Politecnico di Milano</i>	108	Monika Pasquali, <i>Bordeaux INP</i>	112	Yuan Wei <sup>7</sup> , <i>NWEPDI</i>	128
	Joren Bredael, <i>TU Delft</i>	109	Henry Pinedo, <i>Universidad Nacional de Jaén</i>	113	Jean-Sébastien Brouillon*, <i>ETH Zurich</i>	130
	Alessandro Croce, <i>Politecnico di Milano</i>	110	Pim Haanen <sup>6</sup> , <i>TU Delft</i>	118	Antonin Bavoil <sup>8</sup> , <i>Université Côte d'Azur</i>	131
18:00	END-OF-DAY					
19:30	CONFERENCE DINNER [BARÃO FLADGATE RESTAURANT, RUA DO CHOUPELO 250, 4400-088 - VILA NOVA DE GAIA, PORTO]					

\* Session chair

<sup>1</sup> Replaced by Sweder Reuchlin, *Kitepower*

<sup>2</sup> Replaced by Hayden Mans, *Enerkíte*

<sup>3</sup> Presented by Grégoire Winckelmans, *UCLouvain*

<sup>4</sup> Presented by Taewoo Nam, *TRINA*

<sup>5</sup> Presented as poster by Leming Li, *Tsinghua University*

<sup>6</sup> Presented by Jelle Poland, *TU Delft*

<sup>7</sup> Presented as poster by Leming Li, *Tsinghua University*

<sup>8</sup> Presentation cancelled

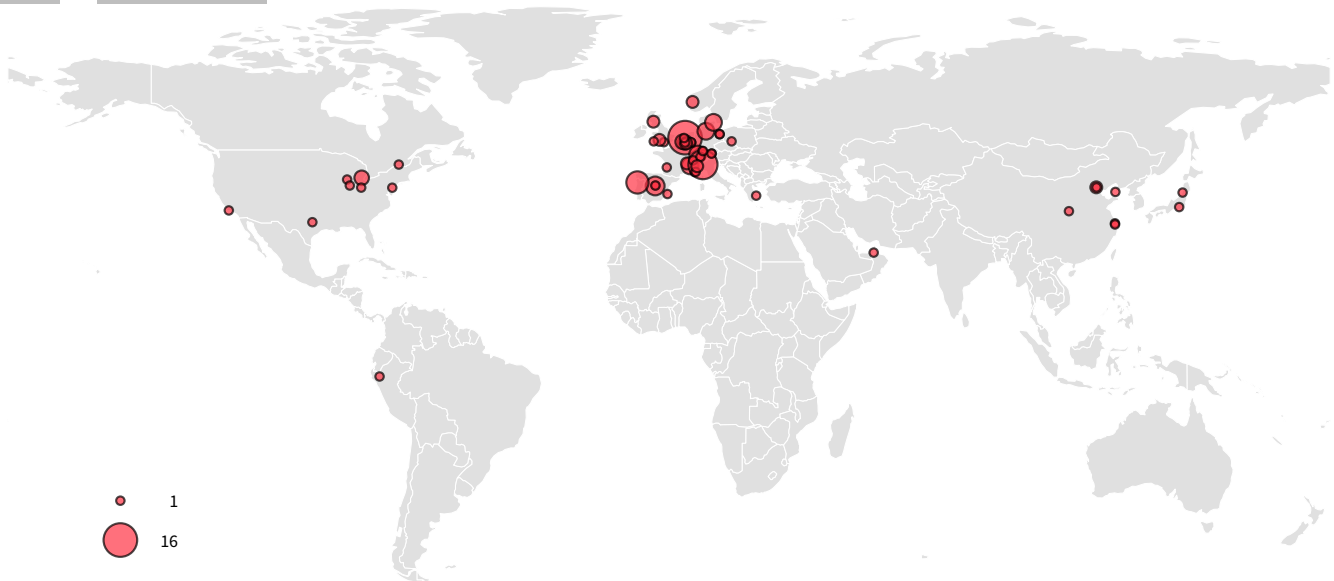
# Poster Presentations - Thursday, 25 June 2026

Time	Page		Page		Page	
10:20	<b>POSTER SESSION I &amp; COFFEE BREAK</b>				[COFFEE LOUNGE]	
	Kim Selina Polkläser, <i>RWTH Aachen</i>	24	Bah Oum Selema Hind, <i>Grenoble INP</i>	25	Muhammad Amjad, <i>University of Strathclyde</i>	26
	Nasouh Alrayyes, <i>Université Lyon 1</i>	27	Ziwei Chen, <i>University of Strathclyde</i>	28	Duc H. Nguyen, <i>University of Bristol</i>	29
	Yidi Huang, <i>Shanghai Jiao Tong University</i>	30	Yahya Khurshid, <i>UAU</i>	31	Leming Li, <i>Tsinghua University</i>	32
	Rui C da Costa, <i>University of Porto</i>	33	Conrado G. da Costa, <i>University of Porto</i>	34	Gabriel M. Fernandes, <i>University of Porto</i>	35
16:25	<b>POSTER SESSION II &amp; COFFEE BREAK</b>				[COFFEE LOUNGE]	
	Timon Schulze, <i>CargoKite</i>	87	Hiroki T Endo, <i>Tsuruoka KOSEN</i>	88	Jamie Pickar, <i>Swarthmore College</i>	89
	Hongmiao Zhou, <i>UC3M</i>	90	Junhao Wang, <i>Tsinghua University</i>	91	Miguel Alonso Resta, <i>UC3M</i>	92
	César Eduardo Perdomo Díaz, <i>UC3M</i>	93	Xiaoyu Li, <i>CPECC</i>	94	Marco Ghivarello, <i>GHIVA Progettazione CAD</i>	97
	Thijs van Lith, <i>TU Delft</i>	100	Jelle Poland, <i>TU Delft</i>	103		

## Room naming scheme

Room B001	:	MADEIRA
Room B002	:	AZORES
Room B003	:	BERLENGAS
Room B037	:	COFFEE LOUNGE

Accepted abstracts per city



# Technical Program - Friday, 26 June 2026

Time	Page		Page		Page
9:00	<b>OPENING DAY 2</b>		Fernando A. C. C. Fontes, <i>University of Porto</i>		[AZORES]
9:10	<b>PLENARY TALK IV</b>		Nicolas Gonzales Casares, <i>European Parliament</i>		132
9:30	<b>PLENARY TALK V</b>		Alessandro Croce, <i>Politecnico di Milano</i>		133
9:50	<b>PLENARY TALK VI</b>		Simon Watson, <i>TU Delft</i>		134
10:10	COFFEE				[COFFEE LOUNGE]
10:30	<b>CONTROL &amp; OPTIMIZATION II</b> [MADEIRA]		<b>TESTING &amp; OPERATIONS II</b> [AZORES]		<b>AERODYNAMICS &amp; STRUCTURES II</b> [BERLENGAS]
	Zakeye Azaki, <i>Grenoble INP</i>	135	Taewoo Nam, <i>TRINA</i>	139	Niels Pynaert, <i>Ghent University</i>
	Luís Roque*, <i>Politecnico do Porto</i>	136	Camille Marrel, <i>Wind Fisher</i>	144	Maxim Notable, <i>Ghent University</i>
	Yufei Zhu <sup>9</sup> , <i>TRINA</i>	137	Filip Korzekwa, <i>Njord Energy</i>	146	Mojtaba Kheiri*, <i>Concordia University</i>
	Lorenzo Fagiano, <i>Politecnico di Milano</i>	138	Kartik Anand Pant, <i>Purdue University</i>	147	Rigo Bosman, <i>RigoRopes</i>
11:45	BREAK				
11:50	<b>AWETRRAIN PANEL</b>		moderated by Lorenzo Fagiano, <i>Politecnico di Milano</i> , and introduced by project lead Michael McWilliam, <i>DTU</i> , with:		[AZORES]
	Huilin Liu, <i>TU Delft</i>	155	Agustí Porta, <i>Kitemill</i>	156	Andrea Bertozzi, <i>Politecnico di Milano</i>
	Anastassia Saving, <i>DTU</i>	158	Amirhosein Farmani, <i>DTU</i>	159	Dario dos Santos Rocha, <i>Kitepower</i>
	Hanna Yousef, <i>TU Delft</i>	161	Alessandro Cappellari, <i>Politecnico di Milano</i>	162	Karanvir Singh Grewal, <i>Politecnico di Milano</i>
	Rather Laasani Sanya Shabir, <i>DTU</i>	164	David Tapia Pino, <i>HM</i>	165	Ugwuanyi Sylvanus Ugochukwu, <i>HM</i>
13:20	LUNCH				[COFFEE LOUNGE]
14:20	<b>MODELLING &amp; SIMULATION III</b> [MADEIRA]		<b>SECTOR DEVELOPMENT II</b> [AZORES]		<b>SYSTEM DESIGN &amp; PROTOTYPING II</b> [BERLENGAS]
	Robert Selje II, <i>Baylor University</i>	166	Rudo Enserink, <i>shapewave</i>	173	Simon Tanguy, <i>Université Lyon 1</i>
	Carolina Nicolás-Martín, <i>UC3M</i>	168	Eric Lang*, <i>E3-Design</i>	174	Jonas Keplinger, <i>University of Freiburg</i>
	Uwe Fechner*, <i>TU Delft</i>	169	Florian Schuster, <i>Enerkite</i>	176	Matteo Bordignon*, <i>Politecnico di Milano</i>
	Jelle Poland, <i>TU Delft</i>	170	Sander Schroeder, <i>Kitedynamics</i>	178	
15:35	BREAK				
15:40	<b>CONTROL &amp; OPTIMIZATION III</b> [MADEIRA]		<b>TESTING &amp; OPERATIONS III</b> [AZORES]		<b>AERODYNAMICS &amp; STRUCTURES III</b> [BERLENGAS]
	Mattia Alborghetti <sup>10</sup> , <i>Politecnico di Milano</i>	184	Will Kennedy Scott*, <i>Swift Airgen</i>	187	Bart van de Lint, <i>Open Source AWE</i>
	Yan Pang <sup>11</sup> , <i>Dalian University of Technology</i>	185	Jorge González García, <i>UC3M</i>	189	Patrick Roeleveld <sup>12</sup> , <i>TU Delft</i>
	Rachel Leuthold*, <i>University of Freiburg</i>	186	Dirk Heutelbeck, <i>HAW Hamburg</i>	190	Filippo Trevisi, <i>Politecnico di Milano</i>
16:40	BREAK				
16:45	<b>POSTER AWARDS &amp; FAREWELL</b>		Roland Schmehl, <i>TU Delft</i>		[AZORES]
17:00	<b>CONFERENCE CLOSING</b>		Fernando A. C. C. Fontes, <i>University of Porto</i>		[AZORES]

\* Session chair

<sup>9</sup> Presented by Taewoo Nam, *TRINA*

<sup>10</sup> Presented by Filippo Trevisi, *Polimi*

<sup>11</sup> Presentation cancelled

<sup>12</sup> Presented by Roland Schmehl, *TU Delft*



# Welcome and Introduction to the Airborne Wind Energy Conference 2026

**Fernando A. C. C. Fontes<sup>1</sup>, Stefanie Thoms<sup>2</sup>, Roland Schmehl<sup>3</sup>**

<sup>1</sup>Faculty of Engineering, Universidade Porto

<sup>2</sup>Airborne Wind Europe

<sup>3</sup>Faculty of Aerospace Engineering, Delft University of Technology



**Fernando A. C. C. Fontes**  
Universidade Porto



**Stefanie Thoms**  
Airborne Wind Europe



**Roland Schmehl**  
Delft University of Technology

Dear conference participants, dear friends,

Welcome to the 11th International Airborne Wind Energy Conference, AWEC 2026! Since its first edition in 2009 in Chico, California, AWEC has been the premier global forum for the AWE community, with previous editions held in Stanford, Leuven, Hampton, Berlin, Delft, Freiburg, Glasgow, Milan, and Madrid.

This event gives us the opportunity to share experiences, discover new ideas, and initiate collaborations. As airborne wind energy moves from research and prototypes towards markets and society, joining forces across academia, industry, policy, and stakeholders is now even more decisive for the technology's future.

The scientific programme of AWEC 2026 reflects the strong and growing engagement of the AWE community. With a record 120 submitted abstracts, it covers diverse topics and provides insights into excellent research and visionary company developments.

The programme of the conference includes:

- Six plenary keynote talks by prominent speakers in renewable energy and AWE, spanning policy, governance, research, long-term experience, strategic visions, opportunities, and challenges:

**Enrico Degiorgis**, Policy Officer for renewable energy and wind energy research and innovation at the European Commission, Directorate-General for Research and Innovation;

**Moritz Diehl**, Professor of Systems Control and Optimization, director of the Department of Microsystems

Engineering (IMTEK) and managing director of the university's Center for Renewable Energy (ZEE) at the University of Freiburg;

**Gerdien de Vries**, Professor of Governance of Behavioural Interventions at the Faculty of Technology, Policy, and Management/Director of the Energy Transition Lab at TU Delft;

**Nicolás González Casares**, Member of the European Parliament and Committee on Industry, Research and Energy (ITRE) – spokesperson for the Spanish Socialist Delegation for Energy;

**Alessandro Croce**, Professor of Flight Mechanics at the Department of Aerospace Science and Technology, coordinator of the POLI-Wind Laboratory at Politecnico di Milano, Board Member of Airborne Wind Europe;

**Simon Watson**, Professor of Wind Energy Systems and Director of DUWIND at TU Delft, scientific coordinator of the EU Horizon project MERIDIONAL;

- Eighteen contributed talk sessions in three parallel tracks with altogether 67 oral presentations.
- Three poster sessions, preceded by two plenary spotlight presentations, with altogether 24 poster presentations.
- OEM panel, including seven pitches by industry leaders of the AWE sector.
- The AWETRAN panel, including 12 pitches by PhD candidates of the EU Marie Skłodowska Curie Doctoral training network.



*Library of the Faculty of Engineering, University of Porto.*

Following a well-established tradition of the conference, the parallel-session rooms have been deliberately re-named. This year, they carry the names of Portuguese islands and archipelagos: Azores, Madeira, and Berlengas.

Islands face some of the most demanding energy-transition challenges: high energy costs, dependence on imported fuels, limited land availability, logistical constraints, and vulnerability to extreme weather and climate change. At the same time, they are natural laboratories for innovative renewable-energy systems, including AWE. If the transition to clean and resilient energy can happen on islands, it can happen anywhere.

- “Azores” refers to Portugal’s Atlantic archipelago, an autonomous region composed of nine main islands. Located far from the European mainland, the Azores evoke the opportunities and challenges of remote island energy systems.

- “Madeira” refers to the Portuguese archipelago in the Atlantic Ocean, including Madeira, Porto Santo, the Desertas, and the Selvagens. Its mountainous terrain, oceanic setting, and strong identity make it a fitting symbol of island resilience and renewable-energy potential.

- “Berlengas” refers to the small archipelago off the coast of Peniche, recognized by UNESCO as a Biosphere Reserve. Its protected natural environment highlights the importance of developing renewable technologies with low visual, material, and environmental impact.

Overall, Portugal provides an inspiring setting for a conference on an innovative renewable energy technology. Having phased out coal-fired electricity generation in 2021, the country has rapidly expanded the role of renewable electricity, with wind energy playing a central role in the national mix. Renewable production supplied 71% of Portugal’s electricity consumption in 2024, and 80% in

January 2026. Its Atlantic-facing geography, strong wind regimes, and growing offshore ambitions make Portugal a compelling place to discuss the next generation of wind-energy technologies. If high-altitude winds are added to this picture, the potential gains yet another, still unexploited, dimension.

Porto, a welcoming city on the Atlantic coast, is a fit setting for discussions on the future of renewable energy. The Porto Innovation District brings together universities, hospitals, research centres, startups, and companies in a high concentration of talent and technology, contributing to Porto's growing reputation as one of Southern Europe's leading technology and startup hubs.

AWEC 2026 takes place at the Faculty of Engineering of the University of Porto, in the heart of the Porto Innovation District, offering participants the opportunity to be immersed in a dynamic environment of research, innovation, and entrepreneurship. New ideas and networking will also be fostered by the social programme, which includes

- a welcome cocktail on 24 June at the Faculty of Engineering campus, Rua Dr. Roberto Frias;
- lunches and coffee breaks on the conference premises;
- a banquet at the Barão Fladgate restaurant, Taylor's Port Wine Cellars, located at Rua do Choupelo 250, 4400-088 Vila Nova de Gaia.

The high quality of the scientific programme is supported by the Programme Committee and the work of the anonymous peer reviewers who provided valuable feedback to the authors. This Book of Abstracts summarises the contributions of the participants and reflects the current state of the art of the AWE sector. It would not have been possible without the joint effort of authors and reviewers. We sincerely thank all of them.

We also express our sincere gratitude to our sponsors (listed on pages 9–10). Special thanks are due to Paulo, Sara, and Ana Cristina from the SYSTEC team at the Faculty of Engineering, Universidade do Porto, for their contribution to the local organisation. We wish all AWEC 2026 participants a fruitful and inspiring experience in Porto!

Sincerely,



Fernando A. C. C. Fontes  
Universidade Porto  
Porto, Portugal



Stefanie Thoms  
Airborne Wind Europe  
Brussels, Belgium



Roland Schmehl  
Delft University of Technology  
Delft, The Netherlands

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**Universidade do Porto, Faculdade de Engenharia** With origins dating back to the eighteenth century, the University of Porto is one of Portugal's leading research universities, with more than 35,000 students and 3,700 faculty members and researchers. The Faculty of Engineering (FEUP), the largest school within U.Porto, hosts over 8,000 students and combines advanced engineering education with strong links to industry and international research networks. Located in the Porto Innovation District, FEUP also plays a leading role in UPTEC — the Science and Technology Park of the University of Porto — recipient of the 2013 European RegioStars Award for Smart Growth. Research in airborne wind energy at the University of Porto started in 2014 within the UPWIND research project, led by Fernando Fontes.



**Airborne Wind Europe** As the association of the European airborne wind energy industry, Airborne Wind Europe promotes the generation of energy from winds at higher altitudes by means of airborne wind energy systems. It represents the interests of the airborne wind energy industry as well as academia to decision makers in politics and business, provides reliable and high-quality information and data on airborne wind energy and is coordinating the industry at all levels.



**Delft University of Technology** The TU Delft is the oldest and largest technical university of the Netherlands. According to the 2026 QS World University Rankings, it is the top-ranked university of the country and among the top-15 universities worldwide in the field of engineering and technology. Founded in 2004 by Wubbo Ockels and continued in 2009 by Roland Schmehl, the Airborne Wind Energy Research Group is a pioneer and international leader in this innovative technology.



**European Academy of Wind Energy** EAWE is an international community that promotes and supports the development of wind energy science to exploit wind energy to its full potential for the benefit of the world. EAWE is a non-profit organization governed by Europe's leading universities and research institutes on wind energy. A Technical Committee "Airborne Wind Energy" was established in June 2019.



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Moderator: Kristian Petrick, Airborne Wind Europe

- Florian Breipohl, EnerKíte, Germany
- Thomas Harklau, Kitemill, Norway
- Sweder Reuchlin, Kitepower, Netherlands
- Giorgio Sella, Kitenrg, Italy
- Luís Tiago Paiva, UPWIND Energy, Portugal
- Garrett Smith, Windfisher, France

### **AWETRRAIN Panel**

Moderator: Lorenzo Fagiano, Politecnico di Milano, Italy

Project coordinator: Michael McWilliam, DTU, Denmark

- Huilin Liu, TU Delft, Netherlands

- Agustí Porta, Kitemill, Norway
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## **AWEC 2026 is dedicated to ingenuity**

Inventors and engineers have brought great technological achievements to humanity. But sometimes it takes even more. Ingenuity refers to someone's ability to come up with clever new ways of doing something.

In a world facing a polycrisis, answers cannot be simple. We are all aware of the effects of unlimited fossil fuel consumption: global warming, rising sea levels, droughts and floods, declining biodiversity, injustice, poverty, loss, hunger, migration pressure, and far more uncertain consequences. Understanding and solving current problems requires exploring new pathways.

A serious and profound, probably even radical transformation of the current industrial landscape and beyond would be an important next step. Airborne wind energy can and should be part of that. Recent studies have demonstrated the technology's real impact, not only by deploying renewable energy systems at GW scale but also through this transformation process. Shifting expertise from established sectors such as electrical components, machinery, and transport equipment could create a cumulative value of 3-10 billion EUR over the next 10 years. AWE technologies lie at the intersection of the aerospace, energy, advanced materials and digital control systems sectors. They combine expertise in lightweight structures and aerodynamics from the aerospace sector, power gen-

eration technologies and grid integration from the energy sector, and products from the electronics and IT sectors for autonomous control and system optimisation. These technologies take into account weather conditions, grid integration, and the potential need for evasive manoeuvres when sharing airspace with other aircraft. Advancements in these technologies can also support spillovers into other sectors, such as autonomous driving and drone technologies, as well as the aerospace sector. Adapting that, airborne wind energy can enhance energy security and system flexibility, as well as industrial competitiveness.

Thinking about where deployment of airborne wind energy systems can have the biggest impact now, again, we come back to the islands. Islands are uniquely challenged by climate change and the need for decarbonization. They have high energy prices, rely on imported fuels, lack space and resources, and are vulnerable to natural disasters. If the transition to clean and renewable energy can happen on islands, it can happen anywhere.

The airborne wind energy community is committed to a prosperous future, strengthening the power of all being, hope and confidence – making Airborne Wind Energy happen, in Europe and the world!

















### Theo Jansen

Artist, Sculptor, and Engineer

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## Strandbeesten

### Theo Jansen

If you repeat the word ‘wind’ often enough it will start blowing.

Theo Jansen is a Dutch contemporary artist, sculptor, and engineer.

In the spirit of Leonardo da Vinci, he once focused his attention to study science and physical phenomena before he shifted to art. His most exceptional creations are definitely Strandbeesten – beach animals.

Since 1990 Jansen has been fashioning these lumbering creatures, that wander up and down the nearby beaches of the North Sea, driven by the wind.

These breathtaking creatures traveling over sand resemble walking animals and they are constructed from PVC pipes, wood, fabric airfoils, and zip ties. In fact, materials used for their production are being constantly improved and designed to adapt sand beaches or different types of environments in which they are released.

The majority of the Jansen’s animals carry Latin titles that often refer to a specific animal (Mulus, 2017), insect (Chalibi, 2018), animal or human body part (Umerus, 2009) or just a Latin noun, adjective or verb (Percipiere Excelsus, 2006). The names’ meanings are connected to each beast’s movement or method of creation.

One might call Jansen a kinetic artist, or kinetic sculptor, since his creations move, and he is also an engineer of considerable talent. The strandbeesten harness the

wind with windmill-like vanes, or sails, or flapping wings. The early strandbeesten simply moved where the wind pushed them, but more recent have sophisticated mechanical mechanisms that will turn them away from the water, should they wander that way, or even reverse their motion should they run into something.

Jansen likes to call this “evolution,” but all of the evolving really takes place in Jansen’s creative mind. He is the Intelligent Designer who learns from his mistakes, which is what a really Intelligent Designer ought to do.



*Animaris Omnia, one of Jansen’s Strandbeesten (beach animals).*



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## Vertical Airborne Wind Energy Farms Based on Dual-Wing Systems

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Dual-Wing Airborne Wind Energy Systems [1–3] consist of two identical wings that are attached to one Y-shaped tether and fly fast crosswind circles around each other. Their main benefit over single wing systems is that they can fly in arbitrary altitudes without tether drag compromising their aerodynamic efficiency. We can envisage many small scale systems operating above each other in a “vertical wind farm” [4,5] where each individual dual-wing system is assigned a desired operating altitude and a wind-direction dependent flight cylinder that it should never leave (Figs. 1 and 2).

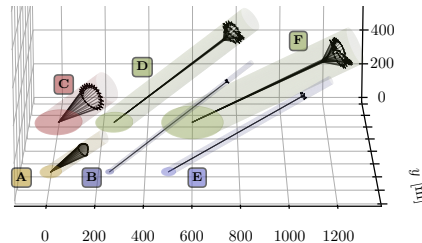


Fig. 1: Flight cylinders of different system configurations [5].

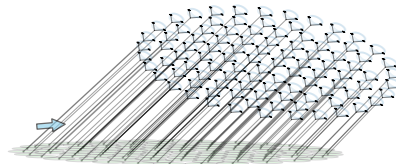


Fig. 2: Vertical 50 MW wind farm of 99 systems on a 7 km<sup>2</sup> area [5].

When optimizing dual-wing systems for such a vertical wind farm, the power density  $PD$  – the ratio of yearly av-

erage power to occupied ground area – becomes an important design criterion, encouraging narrow flight cylinders. Unfortunately, this leads to a lower Loyd-efficiency  $\bar{P}_S$ , measured as the power per wing surface area. The trade-off can be visualized as a Pareto curve (Fig. 3).

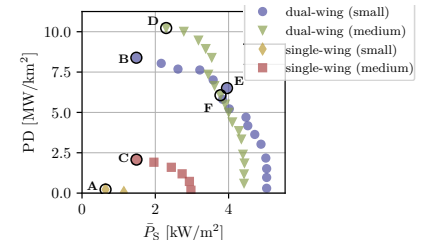


Fig. 3: Trade-off between power density  $PD$  and Loyd-efficiency  $\bar{P}_S$  [4,5].

The talk discusses the possible role of dual-wing based vertical wind farms in a fully renewable energy system, and outlines future research challenges.

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## Multi-Wing Airborne Wind Energy Systems: Challenges

**Kim Selina Polkläser, Dieter Moorman**  
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Airborne Wind Energy Systems (AWES) that are nearing commercialization exhibit a clear trend towards single tether implementations [1]. However, during crosswind flight, the motion of a single tether significantly limits system efficiency due to the generated drag [2]. Concepts aimed at minimizing the influence of tether drag along the majority of its length have been proposed and patented as early as the 1970s [3]. These concepts suggest employing two or more flight systems circling each other while being connected to a main tether that bifurcates. The split ends connect to the flight systems, generating drag due to their movement through the air, while the motion of the primary tether remains negligible [2]. Studies indicate that this approach has potential to enhance overall system efficiency significantly and generate more power across all scales compared to single tether systems under simplified conditions [2,4]. Previous research [e.g. 2] has investigated and demonstrated the opportunity of performance improvements of multi-wing AWES based on simulation results. However, to the best of the authors' knowledge, none of these studies investigate feasibility, implementation, or synchronization of two or more flight systems based on a comprehensive nonlinear model designed for validation in flight tests.

In the MW-AWE-project, we develop a multi-wing airborne wind energy system in cooperation with the University of Freiburg. The realization involves distinct and independent development stages, each presenting unique challenges. However, it is anticipated that the synchronization task of the two flight systems, including safety measures in case of a lack thereof, will pose as a,

maybe even the, major challenge within this project. By employing a VTOL flight system for vertical take-off and landing, along with ensuring safe and reliable operation of both flight systems prior to incorporating tether and winch, we aim to mitigate other known challenges identified in previous research.

In the proposed setup, the synchronization requires a precise coordination of the flight systems in both time and space, relative to one another, while following optimal trajectories for safe and efficient operation. The synchronization task is homogeneous in that it involves coordinating multiple flight systems, yet heterogeneous in its requirement to also coordinate the airborne system with the winch, which exerts the target force on the main tether. This highly coupled and nonlinear system necessitates a robust control and synchronization approach capable of managing its complexity.

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# Addressing Nonlinearities in Airborne Wind Energy Systems

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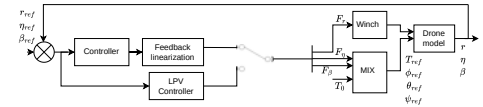


Take-off and landing phases of airborne wind energy systems (AWES) are critical under extreme wind conditions. Automating these phases remains a major challenge due to the need for control strategies guarantee the robustness of the system across a wide range of conditions. AWES dynamics are highly nonlinear and subject to uncertainties, motivating the use of nonlinear and robust control approaches. In previous work, feedback linearization was used to handle system nonlinearities [1].

This work explores the potential of using advanced control approaches to address the nonlinearities of airborne wind energy systems (AWES), highlighting the challenges these nonlinearities pose for control design and performance analysis. Two widely used approaches are investigated: feedback linearization [1] and quasi-linear parameter-varying (quasi-LPV) modeling. Feedback linearization transforms the nonlinear system into an equivalent linear representation through state-dependent coordinate and input transformations, whereas the quasi-LPV approach represents the nonlinear dynamics as linear models with parameters varying across operating conditions. The quasi-LPV framework is naturally compatible with robust control techniques such as  $H_\infty$  control, while often leading to conservative control laws in order to guarantee robustness. For both methods, sensitivity to model uncertainties and measurement errors is analyzed to assess their robustness.

The second part presents experimental results on a hybrid quadcopter/Magnus-effect wing UAV, showing that feedback linearization combined with sliding mode control outperforms PID, particularly in handling wind dis-

turbances. A feedforward compensation strategy based on extended Kalman filter estimation further improves tracking accuracy and robustness.



Control architecture : two different approaches are used to handle non linearity



The experimental setup : The ground station and the tethered hybrid Quadcopter/Magnus-effect wing UAV.

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## Scalability Analysis of a Rotary Kite Airborne Wind Energy System with Tensile Rotary Power Transmission

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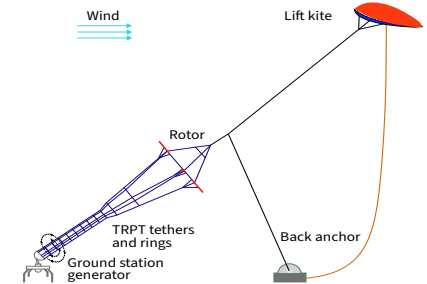
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A ground-generation rotary kite airborne wind energy (AWE) concept [1] utilises a tensile rotary power transmission (TRPT) mechanism to transfer torque from the top rotor to a ground-based generator via a set of rotating rings interconnected by tethers. The system relies on the integrated performance of the lift kite, rotor aerodynamics, TRPT mechanical efficiency and generator operation. While this concept has been demonstrated for small-scale applications ( $\approx 1.5$  kW), medium-scale power generation (tens to hundreds of kW) remains unexplored.

In contrast to conventional horizontal-axis wind turbines, where scaling analysis typically follows similarity laws under preserved flow conditions, the rotary AWE system exhibits strong aero-structural coupling between rotor aerodynamics and TRPT torque transmission. This coupling necessitates the development of a novel scaling framework. This study proposes a scalability analysis method for the TRPT-based rotary kite AWE system. Rotor aerodynamics are evaluated using the mid-fidelity QBlade tool to estimate the maximum available power condition over a range of wind speed 4–15 m/s at a specified elevation angle. The aerodynamic results are then integrated with a steady-state torque transmission model that accounts for structural integrity, geometric configuration and twist angles between TRPT rings [2,3].

The main objective is to investigate how TRPT geometry scales to meet increasing power demands, achieved with a parametric sensitivity analysis. Key parameters, including tether diameter, number of tethers, TRPT ring radius and section length, are systematically varied to characterise trade-offs between torque transmission capacity

and transmission losses inherent in the TRPT system. The interaction between rotor performance and TRPT transmission is incorporated using simplified engineering relationships to assess the sensitivity of overall transmission efficiency to design parameters. Both single-rotor and multi-rotor configurations are explored as potential upscaling strategies. This study provides a quantitative assessment of design trade-offs under steady-state conditions, establishing a foundational framework for scaling analysis of TRPT-based rotary kite AWE systems.



Side view of TRPT AWE system configuration.

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## Modeling and Observation of Tethers for AWE Systems

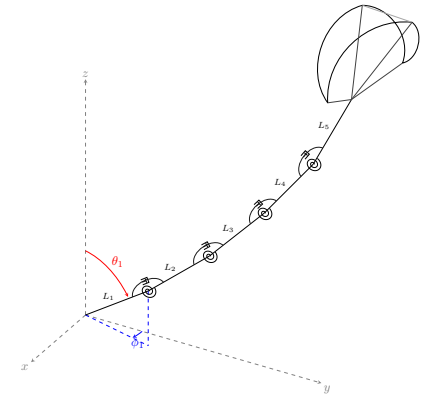
**Nasouh AlRayyes, Tanguy Simon, Ahmad Hably, Ulyess Serres, Daniele Astolfi**  
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While state estimation is crucial for the reliability and robustness of Airborne Wind Energy systems, current estimators often rely on simplified rigid or quasi-static tether models [1]. This limits their ability to capture dynamics like sagging, elasticity, and inertia [2]. As part of the Anemodyne project [4], we address this by integrating a dynamic tether model into the state estimation framework.

First, a discretized geometric tether model is derived using  $N$  lumped masses connected by spring-damper elements. This approach effectively captures the flexibility of the tether and its response to external forces. Model parameters, such as stiffness and damping coefficients, were experimentally identified and validated against real-world data.

Based on this formulation, an observability test was conducted to verify the feasibility of reconstructing the complete states of the system [3]—including the position and velocity of the internal tether nodes—solely from standard sensors e.g. IMU and load cell (kite force measurement) at the kite and tether angle measurements at the ground station.

Using this model, an Extended Kalman Filter (EKF) was designed for real-time state estimation. Simulations demonstrate the EKF successfully recovers internal states and reduces estimation errors compared to simplified models. We are currently preparing a test bench to determine the minimal number of elements required for physical fidelity. This enhanced accuracy enables robust observation, especially during slack tether phases (take-off and landing), contributing to the reliability and autonomous operation of AWE systems.



*Tether discrete model,  $\phi_1$  and  $\theta_1$  represent the azimuth and elevation angle of the first link respectively, and  $L_i$  is the length of each segment*

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## Power Efficiency Analysis of a Rotary Kite Airborne Wind Energy System

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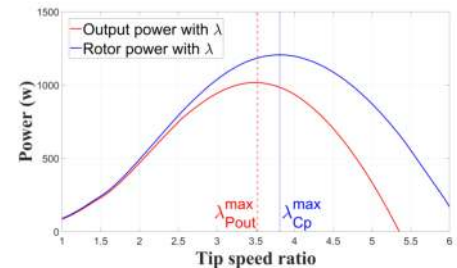
In a rotary kite airborne wind energy (AWE) system, a tensile rotary power transmission (TRPT) unit is responsible for transmitting torque from the airborne rotor to the ground station [1]. The torque transmission efficiency relies on the axial force from the lift kite and the twist deformation along the rotating multi-ring TRPT, which introduces distributed torque losses along the TRPT tube.

This work refines an aero-structural coupled modeling and simulation framework [2] to quantitatively evaluate torque transmission performance under steady-state operating conditions. The refined framework improves the accuracy of transmission-efficiency prediction and enables stability-aware optimization of axial force, with the corresponding twist angle determined by the steady-state torque transmission condition. A geometry-exact representation of TRPT deformation is formulated, enabling detailed computation of local twist, torque loss, and tangent stiffness for each TRPT segment.

Model-based analysis reveals that a positive tangent stiffness is required to ensure stable TRPT operation, and a lower bound on the axial force is determined accordingly. Moreover, a segment-by-segment optimization is carried out to determine the critical operating boundaries under a common axial force, with the twist angle optimized individually for each segment to ensure stable operation and minimum torque loss.

Simulation results show that torque loss in the top segment accounts for approximately 89% of the total torque loss caused by TRPT, enabling a simplified yet reliable estimation of torque transmission efficiency using a single-segment TRPT model. In addition, the torque transmis-

sion efficiency is found to stay around 86.33% across the wind speed range of 4–15 m/s based on the optimal aerodynamic tip-speed ratio (TSR). When considering the influence of torque loss on the overall power generation, the optimal TSR value is reduced compared to its pure aerodynamic calculation (as shown in the figure). These findings provide practical guidelines for TRPT design, stable operation, and power-maximizing control of this rotary AWE system.



TSR comparison: maximum aerodynamic performance (blue) and maximum overall performance (red)

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## Sensitivity Study of Circular Reel-Out Parameters in Rigid-Wing AWES

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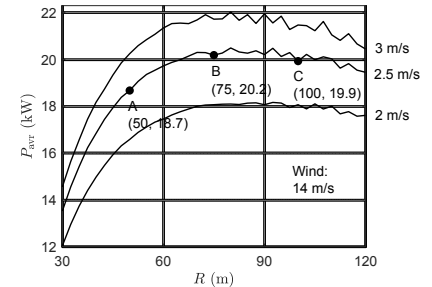
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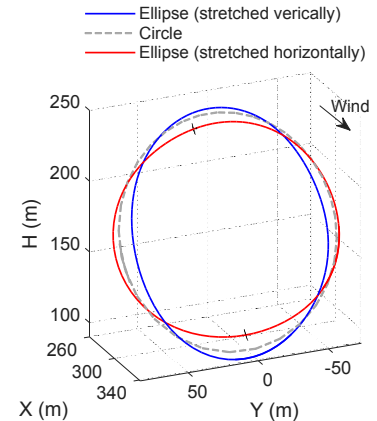
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This study on circular reel-out in rigid-wing AWES is divided into two parts. In the first part, we investigate the impact of two design parameters: reel-out speed (i.e., winch speed) and trajectory radius on power. These relationships are found by running a large parameter sweep on a high-fidelity simulation that includes nonlinear aerodynamics and a flexible tether model. Once the combination with the highest power output is found, a sensitivity analysis is done to determine whether choosing a slightly reduced power configuration provides other benefits. It was found that excessively large radius circles cause in a small drop in power generated (relative to the maximum value) and impose significant penalties on structural load, power quality (how much it fluctuates), airspace and ground space usage, and flight control. Due to these penalties, the approach of flying at the largest radius possible within the given airspace is not recommended. Regarding the reel-out speed, faster reel-out provides more power and alleviates structural load at the cost of lower airspeed relative to the wind, which increases the risk of stalling the airframe. Therefore, the ideal reel-out speed for practical use should have some margin below the maximum reel-out speed possible.

In the second part, the circular flight path is stretched either vertically or horizontally into an elliptical path while keeping the sweep area constant. In terms of power generation, a small degree of stretching in either direction can be tolerated with no or negligible loss. This alternative reel-out path can be used for operating in an area with height or ground coverage restriction.



*Influence of trajectory radius and winch speed on power.*



*The three reel-out trajectories shown provide equal power.*





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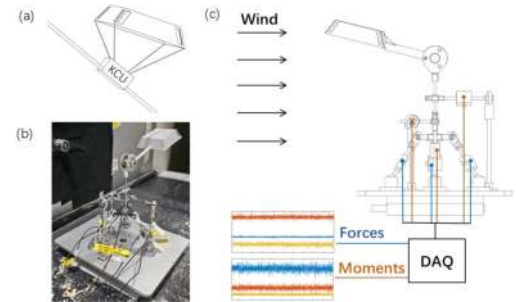
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## Stability Enhancement of a Thin-Walled Trapezoidal Kite for Airborne Wind Energy

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Compared to the conventional wind turbines, airborne wind energy systems (AWES) are advantageous because of their capability to harvest the wind energy with much improved quality at higher altitudes [1]. In the development of a novel AWES, we propose an architecture utilizing an aerostat to guide the movement of a kite along an anchored tether track. Within this framework, it is critical to ensure the aerodynamic stability of the kite, as the working unit. In the present work, a thin-walled kite structure is adopted as a case study. The lift force is generated from the concave front. Meanwhile, the lateral located symmetrical venting ports will enhance the inertia moment of the structure, which is important to improve the overall dynamic stability. For further validation, an in-house-made measurement system is used to quantify the aerodynamic loads, including both the force vector and the torque vector. Experiments are performed in a low-speed wind tunnel with different inlet speeds, attack angles and sideslip angles. Results demonstrate that such a venting mechanism is indeed advantageous to stabilize the kite against turbulent disturbance. The roll and yaw oscillations can be effectively mitigated. More insightful understanding from in-depth parametric analyses will be necessary for potential applications in AWES.



*Wind tunnel test of the kite model with venting port design. (a) Simplified schematic of the tethered kite and Kite Control Unit (KCU) on a fixed track. (b) Experimental setup. (c) Schematic illustration of the six-component measurement system.*

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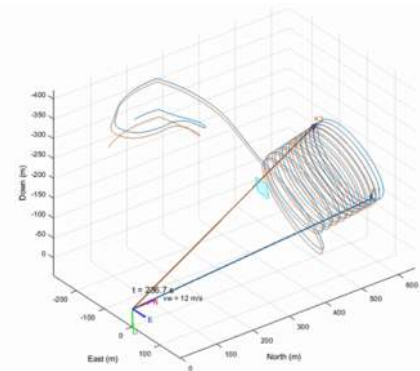
## Phase-Coordinated Multi-Aircraft Airborne Wind Energy System for Enhanced Pumping-Cycle Performance

Yahya Khurshid, Mohamed M. Kamra, Tarek N.Dief  
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Single-aircraft pumping-cycle Airborne Wind Energy System (AWES) produces intermittent power: net output alternates between positive (traction) and negative (retraction) phases, producing a pulsed profile that complicates grid integration [1].

This work investigates whether coordinating two rigid-wing AWES aircraft with a mutual phase offset can reduce this intermittency, using the experimentally validated KM1 6-DOF model [2]. The core mechanism is: when one aircraft is in traction, the other retracts, yielding a near-continuous combined power output, as illustrated in the figure. This mechanism is implemented on the validated KM1 6-DOF rigid-wing model developed by Kitemill AS, adopting all system constraints from that platform directly individual winch power limits ( $P_w^{\max} = 35$  kW), maximum tether force ( $F_t^{\max} = 7500$  N), tether length bounds (400–650 m), and the full nonlinear aerodynamic model. No inter-aircraft communication is assumed; controllers operate independently in parallel. Tether non-interference is enforced via a fixed lateral separation of 50 m.

Validated results on the KM1 6-DOF high-fidelity simulator demonstrate the effectiveness of the coordination mechanism: the dual-aircraft farm achieves a mean combined power of 14.58 kW (Kite 1: 7.78 kW; Kite 2: 6.80 kW), representing a  $2\times$  improvement over the single-aircraft baseline, with a phase balance ratio of 1.14 and measurably reduced power intermittency. The peak-to-mean ratio of 5.55 and maintained tether forces below  $F_t^{\max}$  across the full simulation confirm both the intermittency reduction and safe operation within structural limits.



Simulated 3D trajectories of the dual-aircraft AWES farm. Kite 1 (blue) and Kite 2 (orange) on a shared crosswind loop, demonstrating phase-coordinated traction–retraction cycling from a common ground station.

The results are specific to the KM1 platform. The coordination approach is model-agnostic in structure and extensible to  $N > 2$  aircraft; scaling and wake-interaction studies are ongoing.

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## Numerical Simulation Model of Parachute-Based Airborne Wind Energy System

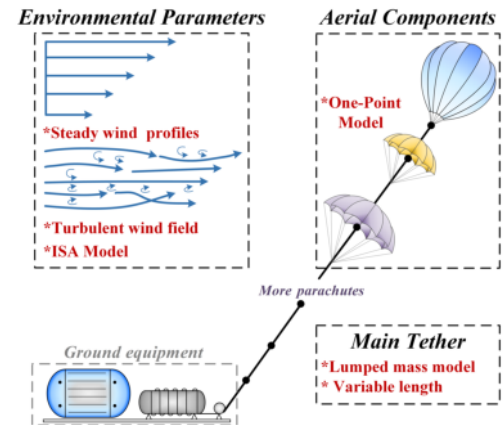
Leming Li, Xiaojing Niu, Junhao Wang  
Tsinghua University

The Parachute-Based Airborne Wind Energy System (PB-AWES) is a newly developed GG-AWES. A demonstration prototype successfully commenced electricity generation in 2024 at a test site located in Jixi County, Anhui Province, establishing a milestone as China's inaugural GG-AWES. An advanced configuration is presently under development, specifically engineered to deliver enhanced power output and superior operational performance [1].

Given the inherent experimental constraints associated with large-scale systems, a comprehensive three-dimensional (3D) dynamic operational model has been formulated specifically for PB-AWES. The system comprises three components: aerial components, tether, and ground equipment, wherein the aerial components are characterized through one-point approximation. However, since the aerial component is a special circular working parachute, in order to describe its dynamic characteristics more accurately, we calculated the aerodynamic coefficients of a shape-similar rigid structure under different angles of attack using CFD simulation. The tether is modeled employing the lumped-mass approach, wherein nodal points are dynamically added or eliminated to accommodate real-time length changes during deployment and retraction. Furthermore, wind velocity and atmospheric density constitute critical environmental parameters. Wind directions are prescribed via either steady wind vertical profiles or stochastic turbulent fields, whereas density follows the ISA model.

The developed model was validated against a preliminary field experiment conducted in 2025, demonstrating

reliable accuracy with a relative error of approximately 15% in altitude prediction. Furthermore, it can also capture the dynamic behavior of the system during the operational cycle in a steady wind field, enabling comprehensive analysis of kinematic characteristics and energy conversion performance.



Numerical simulation model of PB-AWES

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## What-If Analysis and Sensitivity Analysis of Quasi-Steady NLP-Based AWE Power Estimation Models

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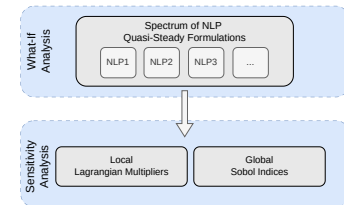
This work proposes a systematic evaluation of modelling strategies for the power estimation of soft-wing, ground-generation airborne wind energy (AWE) systems. Quasi-steady (QS) models are often used to predict power performance of AWES. In fact, they provide a computationally efficient and controller-independent estimation of the maximum achievable cycle power [1].

To investigate the impact of model formulation, multiple QS approaches are considered within a unified nonlinear programming (NLP) framework. These formulations span increasing levels of physical detail, including additional physical effects and refined discretisation of the pumping cycle, and are systematically compared to analyse the trade-offs between model fidelity, computational efficiency, and robustness to parameter uncertainty [2]. The analysis investigates how increasing model complexity and constraint definition influence computational performance, solution stability, and sensitivity to uncertain parameters, aiming to identify where additional complexity yields diminishing practical benefits.

The formulations are further evaluated by sensitivity analyses (SA). A local SA identifies the marginal impact of system constraints at the optimal operating point [3]. This is complemented by a global SA, to quantify how parameter uncertainties and their nonlinear interactions propagate through the different formulations [4].

This work aims to clarify how different levels of physical detail influence the model performance, and to iden-

tify which parameters drive more importance and uncertainty in AWE power production.



Flowchart of the two-stage methodology for the analysis of NLP-based quasi-steady AWE power estimation models.

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## Collision Avoidance Risk Mitigation of Aircraft with AWE Using Software-Defined Radio

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Airborne Wind Energy Systems (AWES) operate within a large and dynamically changing volume of airspace, designated as the operational envelope, subject to the risk of aerial collision throughout their operation [1,2].

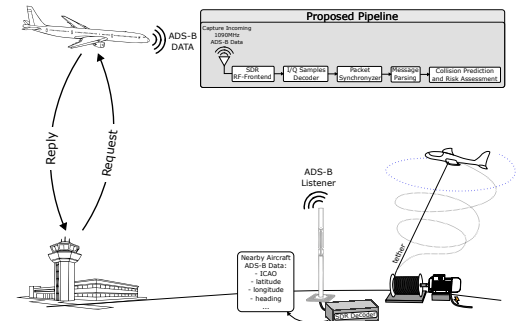
The AWES, comprising the kite and tether system, has been described as a three-dimensional obstacle that may conflict with other airspace users during launch, landing, production, and transitional flight phases [3]. Results from AWES testing and operational demonstrations indicate that air-risk mitigation is relevant for safe operation and deployment approval [1,2].

Thus, we propose an air-risk mitigation concept for AWES based on the surveillance of nearby aircraft. In particular, we present an approach that uses a low-cost Software-Defined Radio (SDR) receiver integrated at the AWES ground station.

The receiver continuously monitors the Secondary Surveillance Radar (SSR) frequency band to capture Automatic Dependent Surveillance Broadcast (ADS-B) transmissions from nearby aircraft [3]. Next, a signal-processing pipeline detects and decodes these transmissions, providing aircraft identification and state, including position, altitude, speed, and course angle.

The decoded aircraft information is then evaluated with the current kite state. Based on their relative position and estimated flight trajectories, a conflict assessment is performed and used to trigger predefined operational events, such as hovering the kite, reducing operational envelope height, or initiating a landing maneuver.

The proposed approach enhances operational safety for AWES in shared airspace and supports future risk-based certification and deployment strategies.



*Proposed air-risk mitigation for AWES. The Aircraft ADS-B messages are received and decoded at the ground station to trigger safety actions whenever airspace regulation rules apply (e.g., see-and-avoid).*

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## Identification of Aerodynamic Parameters Using a Tethered Aircraft in a Rotational Motion under Varying Operational Conditions

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This work presents a coupled numerical-experimental analysis of a tethered aircraft prototype to identify and validate its aerodynamic characteristics under varying operational conditions.

A detailed three-dimensional (3D) virtual prototype of the tethered aircraft is developed in a computer-aided design (CAD) environment, resulting in a manufacturable geometry fully compatible with Computational Fluid Dynamics (CFD) analysis. Steady-state CFD simulations are then performed to analyse the flow field and extract key aerodynamic characteristics of the system. Lift ( $C_{l_{sim}}$ ) and drag ( $C_{d_{sim}}$ ) coefficients are computed for a range of angles of attack ( $\alpha$ ) and wind velocities ( $V_w$ ) representative of realistic operating conditions [1].

Experimental validation is performed with a physical prototype tested in a controlled wind environment. The aircraft operates in circular trajectories, and aerodynamic forces are indirectly measured using onboard and ground-based sensors, with particular emphasis on tether-load measurements obtained from load cells. Based on the experimental measurements, a parameter identification method [2] is used to determine the corresponding real lift ( $C_{l_{real}}$ ) and drag ( $C_{d_{real}}$ ) coefficients under the same operating conditions as those considered in the simulations.

A direct comparison between CFD-based predictions and experimentally identified coefficients is presented, highlighting similarities and discrepancies, as well as the influence of tether inclusion on aerodynamic performance. The results contribute to the aerodynamic modeling

framework of the UPWIND tethered aircraft and provide a validated foundation for subsequent design optimization and control system development.



*Experimental trial for parameter identification of a tethered small-scale aircraft prototype during circular trajectory in a wind-controlled environment [3].*

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## Securing Socio-Political Support for Airborne Wind Energy

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Social acceptance describes a favourable or positive response by society to a proposed or existing socio-technical system or a technology. It is helpful to distinguish between three dimensions of acceptance (D{u}tschke, Fraunhofer ISI, 2021):

Socio-political acceptance refers to the general social climate regarding the object of acceptance, i.e. typical opinions held by opinion leaders, the media or the population. The presentation to be held at AWEC2026 will focus on the socio-political acceptance of Airborne Wind Energy (AWE), building on work carried out during the Horizon project JustWind4All.

Local acceptance plays a role in connection with location decisions and refers to the approval or rejection expressed by those affected, such as residents of an infrastructure, without them having to be directly actively involved. This aspect has been discussed in detail in the JustWind4All Energy Read “Securing local acceptance of AWE projects”.

Market acceptance refers to the acceptance of market actors, i.e. providers, investors, clients, finance institutes. Those entities are usually directly dealt with by the AWE technology developers.

There is obviously an interdependence between market actors, policy makers and society as a whole. Given that AWE technology is not yet widely commercialised, there is no sufficient experience and traction in the markets and society to have a significant impact on policy makers –

which in turn is part of the challenge that the AWE sector faces.

The aim is to share experiences and activities of Airborne Wind Europe and the AWE sector in its efforts to gain public support. This support is crucial as the technology still requires public funding on European and national level as well as AWE-specific policies and regulation, which are not yet in place. The presentation will also explain what has been achieved so far; it is thus also a stocktaking on the tangible and publicly available results of these efforts. Furthermore, it will provide recommendations on how to increase support in future.

The target group are especially newcomers to the AWE sector like recently hired employees and students that engage in the AWE sector, e.g. through the AWETRAN or other research projects. AWE-developers will better understand the extent of the playing field that they need to be active in to be successful which goes beyond the purely technical development of a new technology.

By explaining the challenges that the AWE sector faces in its efforts to increase awareness and acceptance, the session aims to inspire participants to bring forward ideas or concrete actions that can help the AWE sector.

*References:*

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<https://airbornewindeurope.org/archivos/10101>

*Kitepower's V9 kite flying at the company's Bangor Erris test center in Ireland (July 2025).*





*Onboard ram-air turbine and flexible membrane wing (60 m<sup>2</sup>) as seen from the kite control unit that is suspended below the wing, during the Kitepower flight at the Bangor Erris test site, Ireland, on (November 2023).*



*Kitepower team (December 2025).*



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## Operational Validation of Containerized Airborne Wind Energy Systems in Behind-the-Meter Applications

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Kitepower BV

Kitepower, a pioneer in airborne wind energy, has achieved a substantial increase in operational maturity, marking a clear transition from advanced system testing toward early real-world validation of its containerized kite power systems. Two systems are in parallel operation on two sites in Ireland and the Netherlands, demonstrating the capability to manage deployments across national boundaries and under different regulatory and operational conditions. This represents an important step toward scalable operations and future fleet-based system management.

While research and development activities continue at Kitepower's dedicated test site in Ireland, with the focus on increasing the system's performance, reliability, and endurance, a second system has been operating in active commercial environments. Pilot deployments with two large construction companies in the Netherlands, Mobilis TBI and Dura Vermeer, explored the use of airborne wind energy as a behind-the-meter power source on construction sites, directly targeting the reduction of on-site emissions from temporary power generation typically supplied by diesel generators. These pilots enabled the system to be evaluated under realistic operational constraints and provided valuable insights into integration, safety, logistics, and user interaction, informing further system refinement.

In parallel, notable progress has been achieved within several European Union funded research and innovation projects. The Interreg DEM-AWE project [2] was suc-

cessfully completed, while the MERIDIONAL project [3] advanced key technical objectives and the AWETRAN project [4] entered its active phase, contributing to training and workforce development. In addition, a cross-border operational authorization was granted in Germany, marking a major regulatory milestone, enabling near-term deployment in a new market for Kitepower.



*Kitepower in operation near Vianen, the Netherlands, at the Groene Waarden construction site for bridge renovation [1].*

### References:

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[3] <https://meridional-project.eu/>

[4] <https://awetrain.eu/>

*Kitepower's first use in a major Dutch construction project, the Tiel-Waardenburg dike reinforcement in partnership with Dura Vermeer (May 2025).*



*Dual land use at the Tiel-Waardenburg dike reinforcement project (May 2025).*



*Dual land use at the A27 Houten-Hoopolder infrastructure project (October 2025).*





*Top-down aerial view of EnerKite's EK100-10P system (August 2025).*





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## Transition from Development to Demonstration: Status and Technical Progress of EnerKite. Focus on a 100 kW System (2024–2026)

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EnerKite presents the development status of its 100-kW airborne wind energy system from 2024 to 2026, focusing on the transition from research-driven development to pre-commercial demonstration. Since the AWEC 2024 conference in April 2024, several milestones have enabled a more systematic assessment of technical maturity, operational readiness and regulatory integration.

In early 2024, EnerKite completed the first commercial sale, indicating initial market interest. Subsequently, the BMWK (Federal Ministry for Economic Affairs and Climate Action)-funded long-term test project EKEleVate was launched at the Energy Lab Ketzin (Germany). The project investigates the operation of a 100-kW airborne wind energy system within a local mini-grid and contributes to establishing a more consistent approval practice for airborne wind energy in Germany.

A major technical milestone was reached in 2025 with the commissioning of the EK100-10P ground station and the first flight using a newly developed carbon high-performance wing with grid-shell design. In parallel, EnerKite advanced system integration and industrialization through a modular ground station architecture, standardized system variants and the establishment of initial small-series production of carbon wings. Within the BMWK-funded WingScale consortium, EnerKite addressed the scale-up of ultra-light composite wings from prototype to series production, focusing on scalable and resource-efficient manufacturing processes in cooperation with industrie partners. By early 2026, EnerKite is

preparing customer-side demonstration projects based on the current system configuration. The inclusion of airborne wind energy in the German Renewable Energy Sources Act provides an important regulatory foundation. The presented status highlights both progress and remaining challenges in transferring airborne wind energy from controlled test environments to real-world demonstrative operation. The period 2027–2028 marks a critical transition. Key challenges include long-term operational robustness, industrializing production, standardizing regulations, synchronizing market entry, financing, and production ramp-up. Addressing these challenges in parallel is essential for establishing airborne wind energy beyond pilot-scale deployment.



*EK100-10P flight testing*



*Kitemill's Spark 15 in flight (March 2026).*





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## Airspace Sovereignty as an Accelerator for the Energy Transition: Security-Driven Deployment Pathways for Airborne Wind Energy

**Thomas Hårklau, Asgeir Løno, Marius Dyrseth**  
Kitemill AS

Airborne Wind Energy (AWE) is increasingly supported through security, resilience, and strategic-autonomy programmes. Since 2024, such instruments have enabled AWE development, reflecting recognition that energy technologies with strong material efficiency and supply-chain resilience serve both security and energy objectives.

This paper examines how airspace-sovereignty initiatives—notably the EU Drone Wall—can function as deployment pathways for AWE. Using Kitemill as a case study, it shows that characteristics required for security applications (autonomous operation, persistent presence at 300–500 m AGL, low logistical footprint) are identical to those required for high-availability energy generation.

The core contribution is a deployment mechanism: security-driven funding can accelerate energy technologies by financing deployment and industrial scale-up where energy markets alone remain insufficient. The

paper concludes with guidance for positioning AWE research to engage security programmes while remaining relevant to energy-market deployment.



*Kitemill's autonomous kite system during crosswind flight operations, demonstrating the persistent airspace presence capability now driving security market adoption.*





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## From Torino to Osaka EXPO: Listen to the Market

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Kitenergy was the protagonist of various initiatives at Expo Osaka 2025, including the presentation of the industrial version of the K100, the latest generation of AWE generator recently developed and built. The K100 represents the state-of-the-art of AWE technology developed by Kitenergy to serve, across the world, numerous communities that currently lack electricity or are still relying on diesel as the main energy source.

Representatives from around twenty countries, coming from the South Pacific region, the Indian subcontinent, the Arabic peninsula along with delegations from South America and Africa validated a global interest participated in the workshop organized at the Italian Pavilion. Bilateral meetings confirmed great interest in this innovative solution.

Japanese prefectures valued the technology highlighting its capacity to timely provide energy access even in complex scenarios; the contacts will progress to verify the necessary certification process for Japan.

The interest in the technology, coming from different regions that don't have much in common has helped Kitenergy reshape its vision around the market potential for our industry. Given that the interest came from different ranges highly advanced countries, we went be-

yond the belief that the technology would mostly be used in developing countries, indeed, the generator has a global appeal without a clear clusterization in the demand/interest.

This was confirmed by the numerous bilateral meetings that Kitenergy had with global Japanese companies operating in various business sectors like: robotics, mobility, electronics and aeronautics and, telecommunications. Kitenergy is discussing a framework agreement for the joint development of its products and to jointly enter the Japanese and Southeast Asian markets.

The Kitenergy's Expo Osaka participation concluded with a meeting with the director of the innovation sector at a government agency, with whom it was decided to install, as soon as they were ready, some K100 pilots to allow Kitenergy to adapt the technical specifications to the needs of the Japanese market.

With these countries a solid foundation has been laid for pre-orders of the K100 generator. The K100 generator also attracted great interest from the Italian Minister Francesco Lollobrigida, who expressed interest in attending the future K100 testing campaigns.



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## UPWIND Energy: First Steps from Lab to Business

Luís Tiago Paiva  
UPWIND Energy

The journey from fundamental research to a market-ready product is rarely linear. Born from over a decade of research in optimal control and Airborne Wind Energy (AWE) systems at Universidade do Porto, the company is now translating that academic foundation into a commercially deployable ground-generation fixed-wing AWE device, with a clear target: clean, portable, and affordable electricity for off-grid and remote locations, starting with islands and communities currently dependent on diesel generation.

The architecture of the UPWIND Energy device is underpinned by two core innovations. The first is a single-tether bridle system. The bridle geometry controls the effective roll angle, enabling stable crosswind flight patterns — the key to maximising power output in a pumping-cycle configuration — without the complexity of multi-line or multi-tether arrangements. This topology directly reduces mechanical failure points and simplifies ground station design, both critical for deployment in off-grid environments with limited maintenance infrastructure.

The second is the patented Circular Take-Off and Landing (CTOL) mechanism: a circular launch and recovery strategy executed via a tethered support vehicle that guides the aircraft along a defined ground trajectory. The support vehicle manages launch and recovery, with transitions between modes handled without human intervention — eliminating the need for runways, catapult systems, or manual handling. Together, the bridle system and CTOL mechanism define a fully autonomous flight cycle, from launch through power generation to recovery, making the airborne element light, simple, and robust.

A functioning small-scale prototype has validated au-

tonomous flight trajectory tracking and the CTOL strategy in controlled environments, confirming the aerodynamic and control assumptions underpinning the system. This milestone marked the transition from pure research to active technology development.

That journey took a visible step forward at Web Summit 2025 in Lisbon, where UPWIND Energy presented to an international audience of investors, industry leaders, and deep-tech scouts. The company is now seeking pilot deployment partners and investment to accelerate the path from validated prototype to first commercial unit.



UPWIND Energy at Lisboa 2025 Web Summit



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## Flight Dynamics of Magnus Effect-Based Airborne Wind Energy Systems

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The Magnus effect has historically been explored for ship propulsion and recently revitalized for Airborne Wind Energy (AWE) [1,2] thanks to the high-lift wings. While recent experimental efforts have expanded the understanding of the static aerodynamic behavior of Magnus effect spinning cylinders [1], the dynamic response of Magnus effect wings in flight, influenced by the angular momentum of rotating wings, remains poorly understood. Conventional fixed-wing flight dynamics require adaptation to these systems, as gyroscopic coupling and aerodynamic derivatives specific to Magnus rotors alter the flight characteristics.

This study investigates the flight dynamics and stability criteria of the Magnus Airborne Generator (MAG), a novel AWE system consisting of two coaxial rotating cylindrical wings. The substantial rotational inertia of the wings introduces cross-axis coupling, modifying both the translational and rotational response of the system.

To account for these effects, a dynamic model was developed that explicitly incorporates the inertial contributions of the rotating masses and reformulates the aerodynamic force and moment derivatives in a framework adapted to Magnus effect lift generation. Applying the methodology of classical flight dynamics, the linearization of the equations of motion enables the derivation of stability criteria and characteristic dynamic modes.

The static aerodynamic force and moment derivatives, traditionally central to aircraft stability analysis, are obtained through a mixed approach combining analytical formulations, dedicated wind-tunnel experiments and

high-fidelity CFD when required. Particular emphasis is placed on derivatives with respect to mean rotation ratio and differential wing rotation, which have no direct analogue in fixed-wing aircraft.

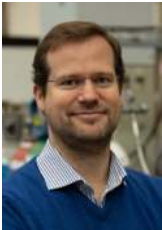
This work constitutes the first dynamic framework for a Magnus effect AWE system. By extending and applying classical flight-dynamics methodology to rotating-wing systems, it provides the basis for the systematic analysis of stability modes, controller design, and design improvements of future MAG platforms.



*The current MAG prototype, as a representation of the system studied in this work*

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## Validation Using Flight Test Data of an Actuator Line Model of AP2 for Large Eddy Simulations

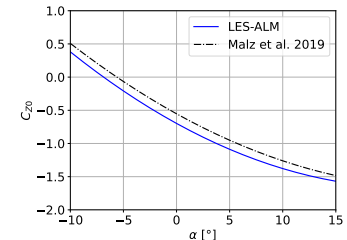
**Matthieu Duponcheel, Jean-Baptiste Crismer, Philippe Chatelain, Grégoire Winckelmans**  
UCLouvain

One of the main challenges in airborne wind energy is the control of the kite in turbulent winds or subjected to unsteady perturbations such as gusts and wakes. Large Eddy Simulation (LES) combined with simplified aerodynamics models such as the Actuator Line Method (ALM) is particularly well suited to simulate AWES (Airborne Wind Energy Systems) in turbulent atmospheres and to investigate control strategies, as performed by Haas et al. [1].

Crismer et al. [2] developed an LES-ALM framework based on a 4th order finite difference LES solver and the ALM methodology of Trigaux et al. [3], with a two-way coupling using the awebox library [4] to solve the kite dynamics and track its trajectory with its MPC (Model Predictive Control) controller. They used this framework to investigate the effect of turbulence on the flight tracking capability of a MW-scale rigid-wing AWES.

In the present study, we aim at validating the aerodynamic predictive capabilities of the LES-ALM framework for the AP2 AWES. AP2 is a rigid-wing 5.5m-wingspan sailplane-like AWES originally developed by Ampyx Power (e.g. see [4]). First, the aerodynamic derivatives used in simplified models are estimated using multiple LES-ALM simulations and compared to those obtained by Malz et al. [4] using system identification of the flight data. A good agreement is found between the two approaches, as shown for instance in the figure. Second, the actual flights performed for system identification will be simulated in the LES-ALM framework by imposing the recorded trajectories and velocities in a quiescent atmosphere. The time-history of the aerodynamic forces predicted by the LES-ALM will be compared to those derived

from the accelerations measured during the AP2 flights. Finally, some tethered flights will also be simulated using the LES-ALM framework with synthetic inflow turbulence and compared to the flight measurements.



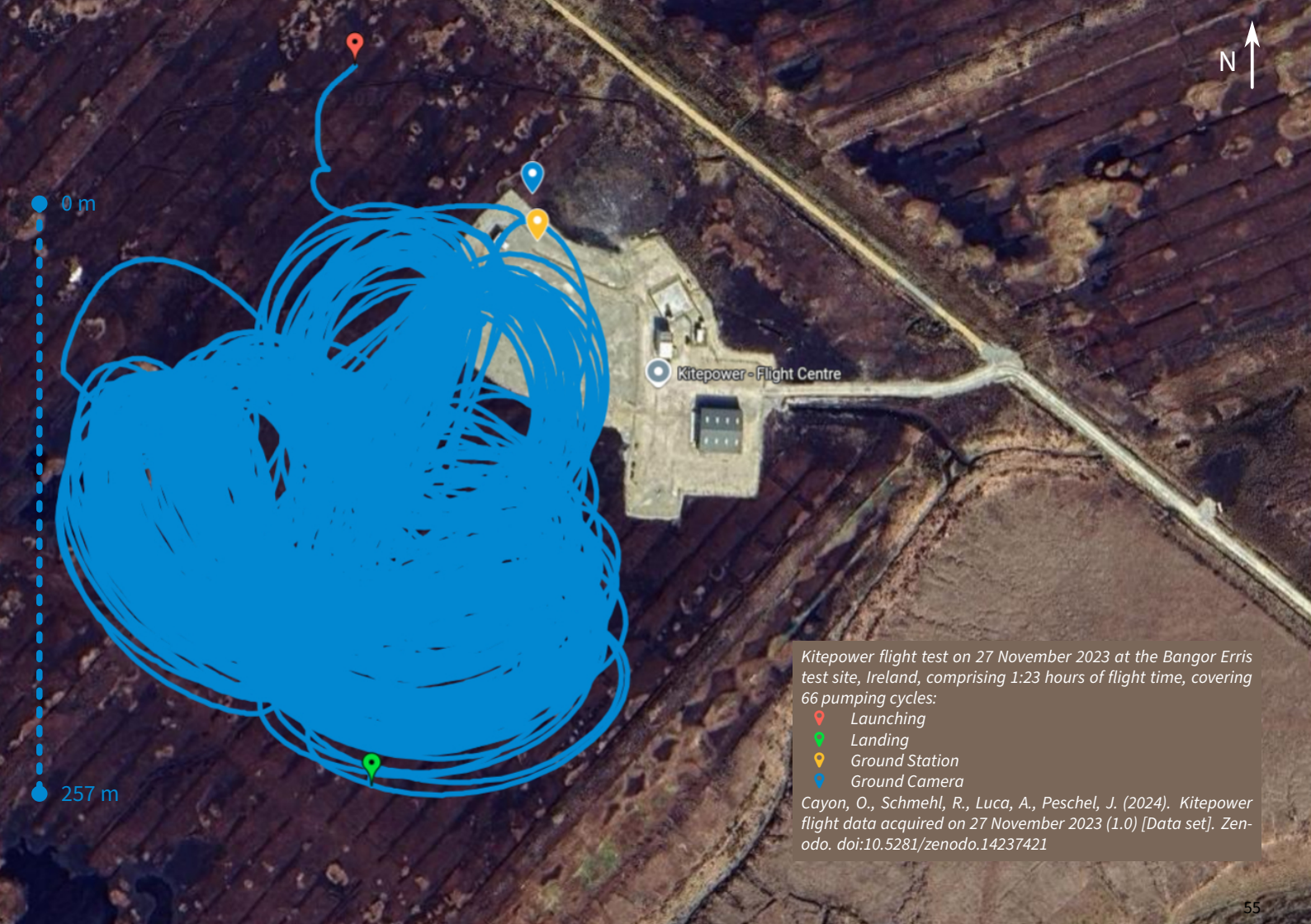
*Aerodynamic derivatives: vertical force coefficient  $C_{z0}$  of AP2 in the body-frame.*

### References:

- [1] Haas, T., De Schutter, J., Diehl, M., and Meyers, J.: Large-eddy simulation of airborne wind energy farms, *Wind Energy Sci.*, 7, 1093–655 1135 (2022)
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*Kitepower's test centre at Bangor Erris with the 60 m<sup>2</sup> V9 kite casting its shadow on the paved ground area, roughly between the ground station and the hangar (September 2024).*



Kitepower flight test on 27 November 2023 at the Bangor Erris test site, Ireland, comprising 1:23 hours of flight time, covering 66 pumping cycles:

- Launching
- Landing
- Ground Station
- Ground Camera

Cayon, O., Schmehl, R., Luca, A., Peschel, J. (2024). Kitepower flight data acquired on 27 November 2023 (1.0) [Data set]. Zenodo. doi:10.5281/zenodo.14237421

*Kitepower's V9 kite flying high above the Bangor Erris test site, Ireland (March 2025).*





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## Operational Optimisation of Soft Kites for Pumping Airborne Wind Energy

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Pumping airborne wind energy systems require the coupled optimisation of the flight trajectory, the aerodynamic operating point, and the winch control to maximise net cycle power. For soft kites, this remains challenging because high-fidelity dynamic models are too expensive for large parametric studies and optimisation. In contrast, lower-fidelity models often rely on oversimplified assumptions that neglect relevant dynamics.

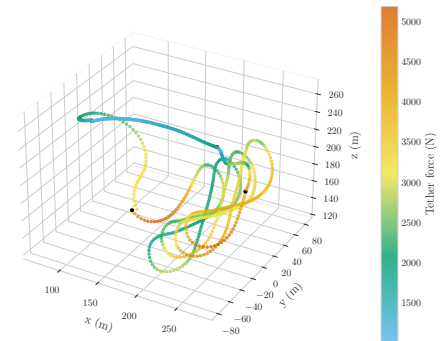
This work investigates the performance of soft kites using a reduced-order quasi-steady framework. The formulation describes the kite as a point-mass moving through a sequence of trimmed equilibrium states, enabling fast evaluation of operational behaviour without relying on high-fidelity dynamic simulations [1].

The system is modelled with coupled radial and tangential motion, where radial motion is constrained by a winch control curve that relates tether force to reeling speed. The aerodynamic operating point is set by the kite's depower setting, which modifies the mean angle of attack and thus the kite's effective aerodynamic characteristics. This allows winch control and aerodynamic trim to be treated as explicit design variables.

The pumping cycle is parametrised using B-splines in elevation and azimuth, which define the angular trajectory through a set of control points, while the radial dynamics are obtained from the winch control curve. The optimisation is formulated over four phases: reel-out, reel-in, and two transition phases, each with a distinct winch control curve. For the present study, the aerodynamic operating point is assumed constant within each phase. The objec-

tive is to maximise total cycle power.

The framework is validated against experimental data from two soft kites of different sizes, demonstrating its potential for trajectory optimisation, control strategy development, and kite design.



Parametrised pumping-cycle trajectory of the TU Delft V3 kite, fitted from experimental data and simulated using the proposed quasi-steady framework. Colour indicates tether force magnitude.

### References:

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This work has been supported by the MERIDIONAL project, which receives funding from the European Union's Horizon Europe Programme under the grant agreement No. 101084216.



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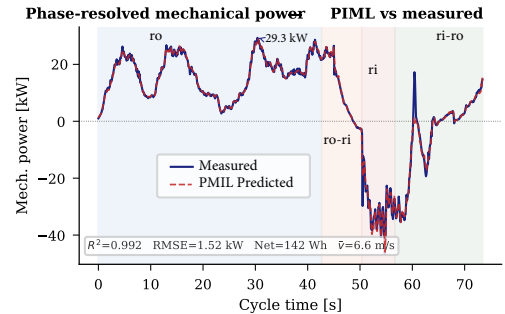
## Physics Informed Machine Learning for Full Cycle Power Prediction in Pumping Kite Airborne Wind Energy Systems

Roystan V. Castelino, Panagiotis Kosmopoulos  
National Observatory of Athens

Accurate power prediction across the complete pumping cycle is a key challenge in airborne wind energy, particularly during transition phases and reel-in, where nonlinear aerodynamic-tether coupling resists conventional modelling [1]. Single-model data-driven approaches underestimate transient losses and fail to generalise across the physically distinct retraction regime [2].

This work presents a physics-informed machine learning (PIML) framework for instantaneous mechanical power prediction across all four cycle phases, using flight data from the open-source Meridional dataset. Four independent XGBoost regressors are trained—one per phase (RO, RO-RI, RI, RI-RO)—with a feature set built from first principles [3]. The primary power proxy is the tether-force-reel-speed product  $\dot{P} = F_t \dot{l}$  ( $r = 0.95$  with measured power; cf.  $r = 0.82$  for apparent wind speed alone, encoding  $P = F \cdot v$  directly). Additional inputs include  $v_a^2$  (Loyd cubic scaling [4]), normalised tether force  $F_t/v_a^2$ , kite 3-D speed, and two-lag temporal features at 10 Hz.

The framework achieves a global  $R^2 = 0.992$ , RMSE = 1.52 kW, and MAE = 663 W. Phase-resolved  $R^2$ : 0.994 (RO), 0.995 (RO-RI), 0.826 (RI), 0.971 (RI-RO)—versus  $R^2 = -0.04$  on reel-in for a single-model baseline. Predicted net cycle energy (141.3 Wh) deviates from the measured value (142.1 Wh) by only 0.88% over 73.4 s (see figure), demonstrating sub-1% cycle-energy accuracy and providing a foundation for yield assessment and real-time control of pumping-kite AWE systems.



Measured and PIML-predicted mechanical power

References:

- [1] Fechner, U., van der Vlugt, R.: Dynamic model of a pumping kite power system. *Renewable Energy*, 83, 705–716, 2015.
- [2] Vermillion, C. et al.: Electricity in the air: Insights from two decades of advanced control research and experimental flight testing of airborne wind energy systems. *Annual Reviews in Control*, 52, 330–357, 2021.
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## Introducing Airborne Wind Energy-Specific Standards into the IEC 61400 Series

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Airborne Wind Europe

In 2024, Airborne Wind Europe – the association of the AWE industry – initiated the process to expand the main standard of the wind industry, the IEC 61400 series which mainly covers Horizontal Axis Wind Turbines, to Airborne Wind Energy (AWE) systems.

In summer 2025, two so-called New Work Item Proposals were presented to the relevant Technical Committee (TC 88) which received a positive vote by the majority of national committee members.

A team of experts from currently 6 countries have started to work on the two Technical Specifications (TS) which may be turned into standards at a later stage:

**Airborne wind energy systems (IEC TS 61400-80):** The purpose of this standard is to provide an overarching framework for AWE systems within the IEC 61400-series using the IEC 61400-2 on small wind turbines as basis.

**Power performance measurements of AWE systems (IEC TS 61400-12-80):** This topic has been identified as a priority for both AWE developers and customers to allow fast commercialization of AWE systems. The existing IEC 61400-12-1 will be largely adapted but amended in a way that it accommodates AWE-specific provisions (e.g. at which height to measure the wind speed as there is no “hub height”). The experience of SkySails Power with the verification of their power curve is being used by the Working Group.

The scope of work includes ground- and fly-gen systems as well as all types of kites (soft-, fixed-, semi-rigid wing).

The approach on standardisation taken by the AWE sector is in line with two studies which recommended to first use the wind related standards as a basis and then later to complement them with aviation related standards [1], [2].

The AWE sector’s standardization efforts will facilitate the future commercialization and deployment of AWE systems, helping to reduce investment risk, costs and market entry barriers. It will benefit all parties involved in manufacturing, installation planning and permitting, operation, utilization, and regulation of AWE systems but also investors, citizens and society in general, allowing them to build up confidence in the seriousness of the sector to define and adhere to recognised standards.

At the AWEC 2026, it is planned to present the draft TS on power performance measurement (IEC TS 61400-12-80) and the structure of the overview TS on AWE systems (IEC TS 61400-80). In the years to come, the scope of topics for standardization will be widened until eventually all AWE-relevant aspects are covered.

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## ‘Mothership’ Project Current Development Progress

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The Mothership Project started in 2018 at Toyota’s Future Research Center as a proposal-driven, bottom-up effort. It addresses future social challenges—especially those facing Japan—such as energy security, disaster response, population decline and aging, rising social costs, and the need for new industries. The project aims to break this stagnation through technological innovation by developing an ultra-high-performance kite, the “Mothership,” that uses strong winds above Japan [1].

The Mothership extracts energy from high-altitude jet streams, especially the westerlies, and transfers momentum via a tether to generate regenerative power on the ground. It also acts as a communication and observation platform at various tropospheric altitudes, similar to a stationary satellite. Its wing shape and high aspect ratio generate powerful lift, enabling it to carry payloads and serve as infrastructure for aerial logistics and mobility. Thus, it promotes new industries [2].

Key technical development centers on an inflatable structure that is large, lightweight, and suitably rigid. Despite its flexibility, it features lateral dynamic control systems for stable flight even in turbulent winds and vertical dynamic control integrated with a ground winch to ascend through windless layers like air pockets. Lateral stability benefits from research on birds of prey aerodynamics, allowing attitude restoration during large posture changes—a capability fixed-wing aircraft lack—demonstrated in more than 12-hour storm flight. For vertical stability, the Mothership maintains low pitch in strong winds, while in calm conditions, the winch reels in the tether to create relative wind speed, increasing elevation angle, lift, and drag, enabling altitude gain to

reach stronger winds. This technology has been validated through testing.

The project aims to set records for high-altitude and long-duration flights to showcase the Mothership. It is preparing for practical use as an emergency communication relay, weather observation platform, and eventually for weather control. These unique applications rely on the ultra-high-performance Mothership kite. The project steadily advances toward its ultimate vision by growing its team and capabilities.



*Takeoff scene during the long-duration flight challenge. In the foreground, the aerodynamic rudder called the covert, modeled after birds of prey, is visible.*

### References:

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*AWETRAIN team at Kitepower's workshop in Delft, The Netherlands (March 2026).*



**Michael K. McWilliam**

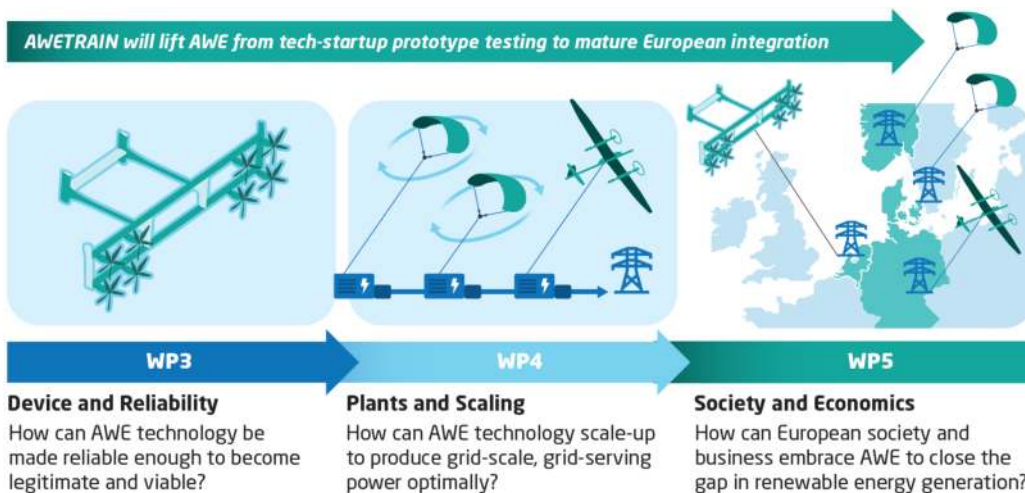
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## Airborne Wind Energy Training for Industrialization Network (AWETRAIN)

**Michael K. McWilliam**  
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This presentation will introduce to the airborne wind energy community the AWETRAIN project. This project is in collaboration with the Technical Delft University of Technology, Politecnico Milano, Munich University of Applied Sciences, Kitemill and Kitepower. The project will run until the end of 2028. It has hired 12 PhD students over a wide range of topics related to Airborne Wind Energy. However, the common theme across all project is looking at what it will take to achieve a large scale industrial deployment across Europe. This includes the 3 work packages shown in the figure above. In addition,

the training program will by focus on multi-disciplinarity, agility, awareness and auto-didacticism. This talk will introduce all the project and show how they work together to achieve the larger goals of the project. For more details see [1].

References:

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*This work has been supported by the AWETRAIN project, which receives funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101168734.*



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## Bridging the Gap: Proven Estimation and Control for Institutional AWE Research

**Reinhart Paelinck<sup>1</sup>, Kevin Rand<sup>2</sup>**

<sup>1</sup> Mozaero (Fuchszeug BV)

<sup>2</sup> LightForce BV

As the Airborne Wind Energy (AWE) sector matures, there is an increasing need for standardized, high-performance benchmarks to validate new academic theories in aerodynamics, optimization, and sensor fusion. While simulation environments are plentiful, the transition to physical flight remains a significant hurdle for institutional researchers and startups. Mozaero leverages its avionics development expertise and extensive flight heritage to address this gap with the launch of the LightForce autonomy platform.



*LightForce Electronics*

This presentation introduces the LightForce hard- and software platform as a commercial-grade baseline for institutional R&D. Unlike experimental “from-scratch” controllers, LightForce represents refined technology honed through years of utility-scale development.

By providing a stable, high-reliability and adaptable environment, Mozaero enables a “plug-and-play” research model where new modules or hardware can be tested

against a known, industrial-strength performance standard.

Key areas covered in this work:

- **System Robustness:** Documentation of the controller’s ability to handle the non-linearities of tethered flight, offering an interface enabling a “control-as-a-service” model that allows researchers to focus on their specific domain expertise.
- **Validation Capabilities:** A look at the telemetry and diagnostic tools available to researchers for verifying their own experimental models against Mozaero’s established flight logic.
- **Research Enablement:** A demonstration of how institutional partners can now leverage LightForce “grey-box” solutions to focus on higher-level aerodynamic research, sensor fusion, and grid integration without the need to develop base-level flight stability from scratch.

Mozaero seeks to support the AWE community with a professional-grade, off-the-shelf alternative or fallback to home-grown control solutions, thereby accelerating the path from theoretical research to flight-proven reality.



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## Multi-Fidelity FSI Simulation Strategy for the Design of Ram-Air Parafoil Wings

**Tom Lolies, Guillermo Fernandez, Kaoane Jondeau**

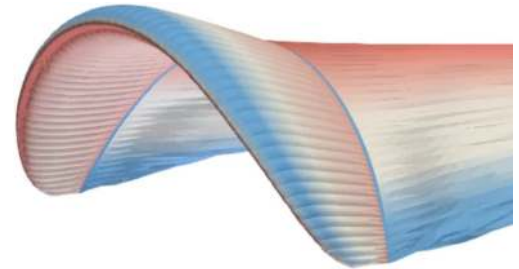
FAIR aero

Ram-air parafoil design is highly iterative and has long relied on empirical know-how and testing. Modern development increasingly depends on large numbers of simulations to predict geometry, aerodynamic loads, and structural response across operating conditions, often requiring fluid–structure interaction (FSI) [1]. Turbulence-resolving approaches (DNS/LES) are impractical for routine industrial use. Fully coupled Reynolds-averaged Navier–Stokes (RANS) is a practical modeling compromise, but it still can be unnecessarily expensive to deploy on simpler cases (for instance, high Reynolds numbers attached flows at low angle of attack); conversely, low-fidelity models are fast yet often lose accuracy in separated flows and strongly deformed configurations.

We present a multi-fidelity, fully coupled FSI framework integrating three aerodynamic solvers within a single partitioned coupling environment: a Vortex Step Method (VSM) for rapid pre-design calculations, a 3D Panel Method (3DPM) capturing three-dimensional pressure gradients with viscous coupling, and a viscous RANS solver [2] providing high-fidelity pressure and shear fields. All solvers share a common structural model and consistent load/deflection transfer, enabling direct comparison of aeroelastic response and computational cost.

The methods are evaluated across different kite geometries (single skin, double skin or leading edge inflatables). The FSI simulations are performed in a "virtual wind tunnel" framework, and different angles of attack or trailing edge flaps are obtained using line trimming (numerical activation of power/depower control). The results quan-

tify the accuracy–cost trade-offs associated with different fidelity levels. Aerodynamic only validations are presented on an inflatable leading edge [3] and double skin paraglider [4] rigid reference wings.



*Simulated pressure field for a high-performance double-skin glider under fully coupled fluid–structure interaction (FSI).*

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## Large Eddy Simulation of an Airborne Wind Energy System Flying in the Wake of a Wind Turbine

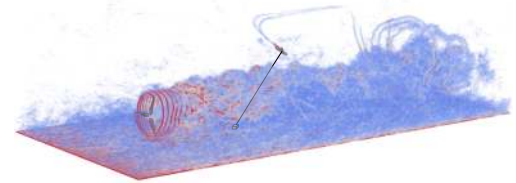
Jean-Baptiste Crismer, Matthieu Duponcheel, Grégoire Winckelmans  
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Wind energy installed capacity is expected to increase substantially in the coming decades. Airborne wind energy has the potential to contribute to this growth. In particular, it may increase the power density of existing wind farms by deploying such systems within wind farms or in their immediate vicinity. Airborne wind energy could also be used to repower aging wind farms by reusing existing infrastructures and foundations. In such scenarios, airborne wind energy systems (AWES) will be exposed, for a fraction of their trajectory, to wind turbine (WT) wakes.

The present work investigates the interaction between the DTU 10 MW reference WT [2] and the MegAWES [3], a reference rigid-wing ground-generation AWES. To this end, the large-eddy simulation (LES) framework for AWES developed at UCLouvain [1] is employed. LES allows an accurate prediction of the atmospheric boundary layer wind and of the wake dynamics. Within our framework, the AWES is represented using an actuator-line (AL) for the main wing, augmented with models for the control surfaces (elevator, rudders and ailerons). It is coupled to a 6-DOF rigid-body dynamics model and to the nonlinear model predictive controller implemented in the AWEbox toolbox [4], enabling controlled flight simulations. The AWEbox toolbox is also used to generate the optimal trajectories flown by the AWES. The wind turbine blades are also modeled using ALs.

The case in which the AWES operates alone is compared with the case in which it operates downstream of a WT. The impact of the WT wake is assessed in terms of flight path deviation, loads and, power output. The effective-

ness of the flight path tracking strategy allows the waked AWES to properly follow its planned trajectory reliably. However the velocity deficit from the WT wake significantly reduces the power output of the AWES, by roughly 10%.



Volume rendering of the vorticity field for a preliminary simulation with uniform wind of a rigid-wing AWES flying a four-loop trajectory downstream of a wind turbine.

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## Wake Analysis of the Figure-of-Eight Flight Pattern

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The figure-of-8 flight pattern, also known as a lemniscate, is a widely used trajectory in the operation of Airborne Wind Energy (AWE) systems. This crosswind flight path is universally employed across various system archetypes, irrespective of whether the flying device is a rigid fixed-wing aircraft or a soft kite, or whether the system operates with ground-based or on-board power generation.

In the context of farm deployment of future large-scale AWE systems, the aerodynamic wake generated by the flying devices becomes a critical factor. Aerodynamic wakes are characterized by velocity deficit and increased turbulence downstream of the operation region. For conventional wind turbines, wake effects directly impact the energy yield and mechanical loading of downwind systems, reducing both performance and lifetime. Given the unique nature of circular and lemniscate flight trajectories, the characterization of AWE wakes and their effects on farm performance and operation remains an open research question.

Previous computational fluid dynamics (CFD) studies of AWE wakes have primarily focused on circular trajectories. These investigations have ranged from idealized crosswind, circular path [1] to realistic circular trajectories of both ground-based and on-board power generation systems operating in farm configurations [2]. Consequently, the wake dynamics associated with complex figure-of-8 trajectories, despite being the prevalent flight

pattern, remain less explored.

This work investigates the wake dynamics of AWE systems operating in figure-of-8 patterns using high-fidelity CFD simulations. To accurately capture the aerodynamic interaction between the device and the flow field, the AWE system is modelled using the Actuator Line Method (ALM) with a modified implementation of the “*turbines-Foam*” library in OpenFOAM. The ALM approach is particularly well-suited for this analysis as it captures the wake of the flying device without the computational cost of resolving the entire wing geometry. This study focuses on characterizing the wake shape, quantifying the strength of the velocity deficit, and analyzing the wake mixing characteristics downstream.

Given the prevalence of figure-of-8 trajectories in current AWE prototypes, understanding the resulting wake dynamics is essential for the future deployment of large-scale AWE parks.

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## Wake Steering in Horizontal-Axis Wind Turbines Using Airborne Wind Energy Systems

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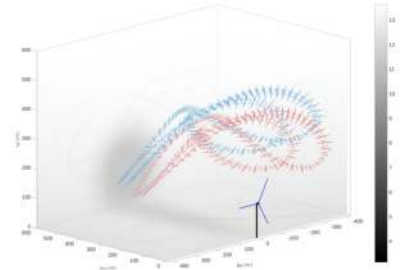
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Integrating Airborne Wind Systems (AWES) with Horizontal Axis wind Turbines (HAWT), as patented by [1], enables various co-location scenarios. While operating AWES in HAWT wakes poses challenges, such as reduced wind speed, increased turbulence, and wind shear [2]; it also offers opportunities. Coordinated operation can enhance wind-resource utilization and minimize land-use conflicts. Additionally, AWES may exploit wind-speed gradients in wakes for dynamic-soaring manoeuvres [3], and kite-induced turbulence can accelerate wake recovery, shortening wake length [4].

We optimize AWES flight paths within HAWT wakes, assuming the winch is next to the HAWT tower base. Our path-planning algorithm integrates an analytical wake model into the trajectory optimization problem, enabling identification of flight paths that maximize energy capture while minimizing wake-induced losses.

The simulation results show that wake-aware path planning can significantly mitigate performance losses while preserving efficient crosswind flight. The findings indicate that lemniscate trajectories are more robust to wake effects than circular paths, as their lateral motion naturally avoids low-velocity wake regions. Therefore, lemniscate trajectories show promising performance when operating in the presence of HAWT wakes. These trajectories can allow AWES to fly in the vicinity of the wake, benefiting from increased turbulence for wake recovery, while avoiding direct entry into the wake region, which is important for maintaining control authority and ensuring operational safety.



Optimal lemniscate trajectories with (blue) and without (red) HAWT wake.

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# Controlling Rigid-Wing AWES Flying Circular Reel Out Trajectories Using Only PID

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<sup>1</sup> University of Bristol

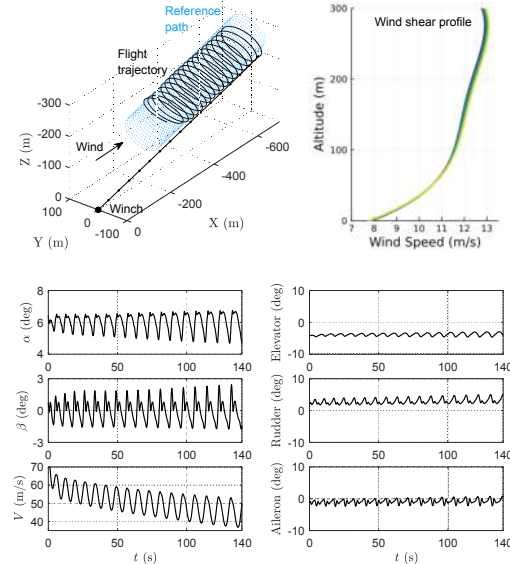
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<sup>3</sup> Kitemill AS

Various flight control schemes for rigid-wing AWES systems have been proposed, many of which require a strong mathematical background to successfully implement. In this work, we propose a simple alternative based purely on the proportional-integral-derivative (PID) structure. This controller is capable of tracking a desired angle of attack and sideslip while following a reference path defined by a cylinder with circular cross section—thereby achieving all the essential requirements of an AWES flight controller in for reel out phase. Reference-path-following can be achieved purely using aileron. This capability frees up the elevator and rudder for controlling the angle of attack and sideslip, which provides additional power.

The path-following algorithm works by tracking the roll angle on a non-static reference frame. This reference frame's orientation is controlled by an outer PID loop, which dynamically shifts the centre of the circular orbit to follow the reference path.

The controller is verified in a high-fidelity simulation with a flexible tether and a realistic wind field. The wind field model was derived from LIDAR measurement from Kitemill's test site and included turbulence. Performance is strong with remarkable robustness across a wide wind speed range. Our proposed scheme can therefore be used as a starting point for rapid AWES controller development and for benchmarking against more advanced feedback algorithms.



*Simulated closed-loop response and the wind profile. The angle of attack and sideslip set points are 6° and 0°, respectively.*

This work is funded by the UK Engineering and Physical Sciences Research Council (EPSRC), grant number EP/Y014545/1.

*ÆTHER's support boat facilitates the launch of a kite over Lake Geneva.*



*ÆTHER's support boat facilitates the launch of a kite over Lake Geneva.*



*ÆTHER team members monitoring the wing's aerodynamic behavior.*



*ÆTHER's open-air lab: lightweight mobile infrastructure for airborne wind energy.*





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## Cyclic Control of a Centrifugally-Stiffened Dual-Kite System

**Johannes Waibel, Colin N. Jones**  
EPFL

Multi-kite Airborne Wind Energy (AWE) systems can significantly increase power output [1]. We consider a dual-kite system for pumping-type generation with a Y-shaped tether. An additional tether which directly connects the kites introduces centrifugal stiffening, i.e., the kites are forced to orbit each other and, under certain conditions, behave like a rigid rotor. This study explores the highly nonlinear dynamics of the centrifugally-stiffened dual-kite rotor and its stabilization in the wind window.

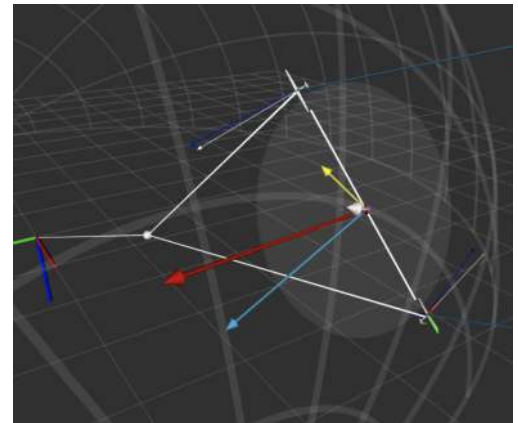
Initial promising simulation tests suggest that the centrifugally-stiffened dual-kite rotor resembles a helicopter and can be controlled with cyclic lift variations commanded by a human operator. However, the nonlinearities of crosswind flight result in a systematic offset between commanded and actual accelerations. This motivates a more sophisticated control strategy which takes into account physical knowledge.

Using comprehensive visualization of the 3D forces and velocities and of the cyclic evolutions of key aerodynamic quantities, we can analyze qualitatively how cyclic control commands propagate through the system and which effects work in favor of and against the intended control behavior.

From our dynamic 3D rigid-body simulator customized to the novel architecture, we find that even small parameter changes in wind and tether configurations can result in significantly different dynamic behavior of the overall system. Model-based optimal control approaches as in [2] might therefore be hard to deploy in a real-world setting.

For the time being, we suggest a simpler, model-free pol-

icy based on integral control terms and state estimation, which imitates a human operator's control strategy. The proposed approach is validated under significant atmospheric disturbance in our real-time simulator.



*3D force visualization during cyclic control maneuver.*

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- [2] Zanon, M., Horn, G., Gros, S., and Diehl, M.: Control of Dual-Airfoil Airborne Wind Energy systems based on nonlinear MPC and MHE. *2014 European Control Conference (ECC)*, 1801–1806 (2014)



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## A Motion Primitive Framework Addressing All Operating Phases in AWES

Sérgio Vinha, Gabriel M. Fernandes, Manuel C. R. M. Fernandes, Fernando A. C. C. Fontes  
SYSTEC, ARISE, Faculdade de Engenharia, Universidade do Porto

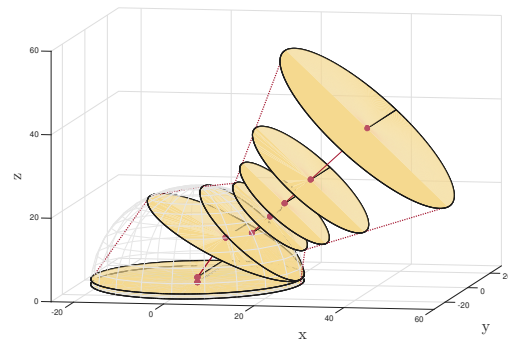
This work proposes a unified motion-primitive framework for trajectory description and reference generation across all operating phases of airborne wind energy systems, including take-off, transition to crosswind operation, power production, retraction, and landing.

Assuming a taut tether, the kite motion is intrinsically constrained to a spherical surface, making spherical geometry a natural and fundamental tool for trajectory representation. Within this setting, admissible paths are described using circular motion primitives defined as planar intersections of the sphere, yielding curves with constant spherical curvature [1].

Each operating phase is represented as a sequence of circular primitives, parameterized by the position of the circle center on the sphere and an angular progression along the path. This geometric parametrization enables a compact and phase-independent description of path references, while preserving curvature continuity at transitions between primitives. As a result, smooth trajectories can be constructed across phase boundaries, which is particularly relevant for transition maneuvers.

The use of spherical motion primitives has previously been explored for the initial operating phases, in particular take-off and landing, where simulation results have demonstrated the feasibility of the approach [2]. Building on these results, the present work extends the motion-primitive concept to all phases of airborne wind energy operation and emphasizes its role as a unifying geometric layer. In addition to simulation studies, the present work includes preliminary experimental results that pro-

vide further support for the applicability of the proposed framework. The proposed formulation decouples high-level path specification from low-level guidance and control design, allowing established control frameworks to be applied directly to the generated spherical references.



Sequence of motion primitives that define a reference path.

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- [2] Vinha, S., Fernandes, G.M., Fernandes, M.C.R.M., Fontes, F.A.C.C.: Motion Primitives and Control on a Spherical Surface with Application to Tethered Aircraft, CEAS Conference on Guidance, Navigation and Control EuroGNC 2026, Madrid, May 2026.



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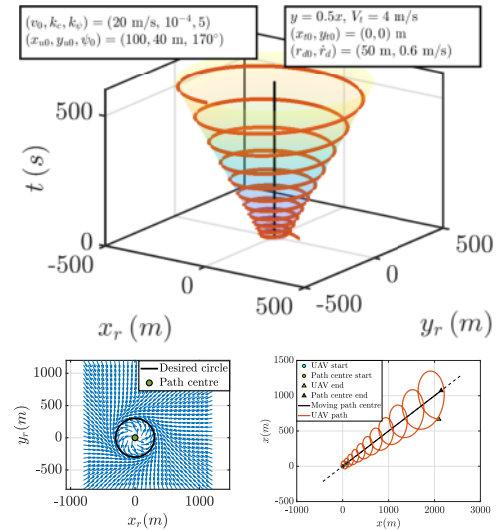
## Vector Field Guidance for AWES

Amit Shivam, Manuel C. R. M. Fernandes, Sérgio Vinha, and Fernando A. C. C. Fontes  
 SYSTEC–ISR ARISE, Universidade do Porto

Airborne wind energy systems (AWES) operate in cross-wind conditions where power generation relies on repetitive flight patterns during tether reel-out. Unlike conventional path-following problems, these patterns are not fixed trajectories but time-evolving geometric sets (e.g., expanding circular or figure-eight orbits) governed by wind conditions and tether length. To address this, we formulate AWES guidance as a set-stabilisation problem, in which the objective is to drive the system toward a desired geometric manifold rather than tracking a predefined trajectory. A vector-field guidance law is constructed such that the commanded velocity direction at each state is computed analytically from the geometry of the desired set, eliminating the need for time-parameterised references. An arcsine-based shaping function is employed to regulate the heading command, ensuring bounded curvature and smooth convergence toward both fixed and expanding circular sets.

The heading guidance law is formulated in the relative frame between the UAV and the moving target, where the objective is to stabilize the vehicle onto a time-varying circular set of radius  $r_d(t)$  representing the expanding stand-off distance during reel-out. Let  $\rho = \sqrt{x_r^2 + y_r^2}$  denote the relative distance and  $\delta = \rho - r_d(t)$  the radial error. An arcsine-based shaping function is employed to construct a desired direction  $\chi_d(k_C, \delta)$  that ensures smooth convergence toward the desired set while maintaining bounded curvature. To account for target motion and wind disturbances, the commanded heading  $\psi_c$  is computed by compensating the relative drift, resulting in a feasible air-speed direction. The actual heading dynamics are mod-

eled as a first-order system  $\dot{\psi} = k_\psi \text{wrap}(\psi_c - \psi)$ , enabling stable tracking of the commanded heading.



Results for reeling out phase in AWES (top: Reeling out phase, bottom left: Vector Fields, bottom right: Trajectory).

References:

[1] Shivam, A., and Ratnoo, A., “Arcsine Vector Field for Path Following Guidance,” *Journal of Guidance, Control, and Dynamics*, Vol. 46, No. 12, 2023, pp. 2409–2420. <https://doi.org/10.2514/1.G007562>



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## Development and Testing of an Attitude Estimation Method Based on Infrared Images

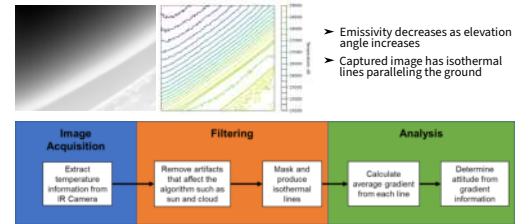
Xintong Deng, Yufei Zhu, Taewoo Nam, Chiming Zhao

Toyota Research Institute of North America

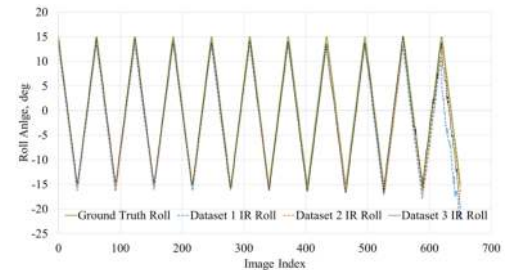
A Toyota Research Institute team is developing an infrared (IR) image-based method for estimating aerial vehicle attitude, with the goal of improving the reliability and safety of the Mothership—a large, tethered, inflatable wing platform designed for high-altitude, long-endurance, stationary missions such as airborne wind energy (AWE) harvesting.

The technique leverages the inherent advantages of infrared (IR) imaging, including robust performance under low-light and variable weather conditions, making it well suited for operation in challenging environments. The proposed approach acquires IR images of the surrounding sky and estimates angular orientation by analyzing isothermal patterns arising from variations in spectral emissivity, using computer-vision-based algorithms. Experimental results demonstrate the effectiveness of the method and highlight its potential for applications such as long-duration navigation and guidance of high-altitude aerial vehicles. In addition, the study examines challenges associated with outdoor IR imaging and proposes mitigation strategies to ensure reliable and accurate attitude estimation.

This presentation will introduce the proposed method and summarize experimental results obtained in both static and dynamic environments across multiple altitudes and environments.



Principle of the Angle Estimation Method [1]



Performance of the Angle Estimation Method in a Static Environment

### References:

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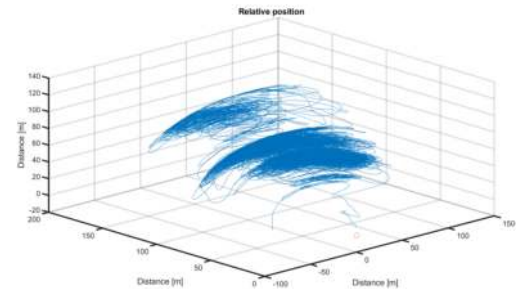
## Experimental Investigation of a Four-Line Ground Steered Soft Kite System to Evaluate Kite Properties and Its Application in a Design Process

**Achim Kuhn, Andreas Strohmayer**  
University of Stuttgart

A central component of airborne wind energy systems is the kite, as it provides the required tether forces, for example, to drive generators. For the design of soft kites based on given requirements the modelling of the flight performance and flight characteristics represents a significant challenge, mainly due to the fluid-structure interaction and permanent deformation of the kite during flight. For kite design, it is therefore useful to have additional experimental data as a reference for modelling or validation.

This work presents the experimental investigation of a four-line ground steered soft kite system and its application in a design process. Therefore a kite-control prototype equipped with a measurement system is used. The dimensions and the design of the prototype system allow static and dynamic flight manoeuvres at different tether lengths and the operation at high tether forces which are representative for airborne wind energy systems. A kite with a wing area of  $15 \text{ m}^2$  is used. The measurement system consists of a sensor unit with air data probe which is integrated in the kite, as well as ground-based measurements such as tether forces, wind speed and wind direc-

tion. The deformation of the kite is not measured directly but is derived from aerodynamic performance data obtained through the airborne and ground-based measurements. The identified kite properties, such as lift coefficient and glide ratio, are compared to the assumptions and modelling used in an iterative design process.



*Measured flight trajectory of the kite during a flight test*



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## Research on a 5000 m<sup>2</sup> Power Generating Parachute Deployment Test and Aerodynamic Performance Verification

**Bixiong Luo, Li Zhang, Kaijun Peng, Zongdong Ren, Haiyang Liu**

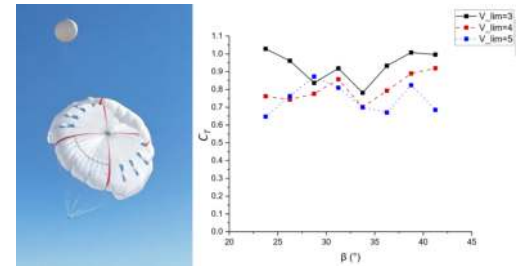
China Power Engineering Consulting Group Co., Ltd

Our research team has investigated parachute-based airborne wind energy systems (AWES) for years. In 2024–2025, we conducted a full-scale outdoor flight test of a large flexible power-generating parachute with a radius of 40 m to support China’s National Key R&D Program “Key Technologies and Equipment for Large-Scale Parachute-based Airborne Wind Energy System (2024–2027)”. The primary objective of this test was to acquire aerodynamic performance data of such structures under real atmospheric wind conditions and to provide core design parameters for a MW-level AWES.

The experiment was conducted at a dedicated location with a well-defined prevailing wind direction. A helium balloon was used to lift the 40 m parachute to an altitude of approximately 500 m, where successful deployment and stable flight were achieved under suitable wind speed range (6–12 m/s). Data was successfully collected after 10 hours of testing covering diverse scenarios such as unopened, incompletely deployed, normally deployed, damaged, and dual-parachute coupled conditions. The following figure shows the variation trends of  $C_T$  with pitch angle under different lower bounds of wind speed with parachute radius of 40 m. The  $C_T$  coefficient reaches its peak within the pitch angle range of 30°–35°, then gradually decreases as the angle increases further. It tends to exhibit low values near 45°, and the variation trend is relatively consistent across different wind speeds, with no trend reversal caused by adjustments to the wind speed threshold. From the experimental data,

our team identified the optimal pitch angle range (30°–35° approximately) for maximum wind energy capture. The results showed that the total tether force could reach up to 90 kN, with the transverse force component accounting for less than 20% of the total load.

Our team plans to conduct multi-parachute flight tests under higher wind speeds, systematically investigating the effects of varying pitch angles and inter-parachute spacing.



Variation trends of  $C_T$  with pitch angle  $\beta$  under different lower bounds of wind speed (parachute radius: 40 m)

References:

[1] Wu-Kuanyu, Zuo Ziiun, Shi-Ziiee, et al.: Aerodynamic principles and modeling of high-altitude wind-harvesting parachute systems [J]. *Acta Aerodynamica Sinica*, 2026, 44(X):1–11



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## **Experimental Validation of an Offshore Floating Airborne Wind Energy Platform Using a Hardware-in-the-Loop Framework**

**Sofia Trombini<sup>1</sup>, Leonardo Cecchin<sup>1</sup>, Alessia Lucarelli<sup>2</sup>, Andrea Bardazzi<sup>2</sup>, Claudio Lugni<sup>2</sup>, Lorenzo Fagiano<sup>1</sup>**

<sup>1</sup> Politecnico di Milano

<sup>2</sup> National Research Council CNR-INM

One of the ultimate goals of AWE systems deployment is installation in offshore environments, particularly in large-scale floating farms. Given the complexity of sea conditions and the inherent challenges of floating platforms, conducting prototype tests in controlled environments such as wave tanks is crucial for identifying and addressing issues that may arise from discrepancies between model predictions and real-world behavior, for instance due to nonlinear hydrodynamic effects.

The presentation describes an experimental activity to test a real floating spar, realized as a scaled-down prototype of the design presented in [1], connected to a virtual autonomous kite, simulated in real-time. The platform is actuated in closed loop through four motorized winches driving cables that reproduce the force reference generated by a simulated kite model, while the measured platform motion is fed back to the simulation. Positions and velocities of the prototype are measured along all six degrees of freedom, providing a comprehensive dataset for the validation of the platform dynamic model. This model, previously adopted in offshore AWE studies, relies on linear potential flow theory, whose assumptions are known to degrade in accuracy under large-amplitude motions.

The comparison between the tank measured platform

motions and the simulated response highlights discrepancies in both the frequency content and the amplitude of the dynamics. An initial parameter identification is performed to refine the effective stiffness of the mooring lines, which is affected by differences between the experimental setup and the real-world configuration. In addition, the dominant source of modelling error is identified as the absence of viscous damping effects. A drag coefficient is subsequently identified from experimental data and incorporated into the equations of motion, leading to a second validation phase with a significantly improved agreement between simulations and measurements.

In conclusion, the experimental results confirm that the adopted modelling assumptions can lead to discrepancies between the predicted and measured platform motions. However, with appropriate identification techniques and modelling choices, accurate motion predictions can be achieved without necessarily incurring a significant increase in model complexity.

### *References:*

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*Rotokite project members from Freiburg (F) and Alicante (A), 2022 in Milan at the AWEC, from left to right: Jakob Harzer (F), Daniel Unterweger (F/A), Jochem De Schutter (F), Christof Beaupoil (A), Moritz Diehl (F).*



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## Multi-Wing AWE Research Project: Goals and Progress

**Jakob Harzer<sup>1</sup>, Kim Selina Polkläser<sup>2</sup>, Moritz Diehl<sup>1</sup>, Dieter Moormann<sup>2</sup>,**  
<sup>1</sup> University of Freiburg, <sup>2</sup> RWTH Aachen University

In existing single-wing airborne wind energy systems, aerodynamic tether drag losses severely limit operation at high altitudes [1]. This problem is mitigated in Multi-wing airborne wind energy systems (MW-AWES), as proposed in [2,3], where two or more tethered flight systems fly crosswind trajectories around a stationary main tether, cf. Figure 1. To date, MW-AWES have only been subject to research in simulation studies.

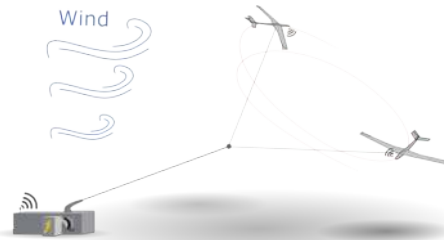


Figure 1: Envisioned MW-AWES

We present the MW-AWES research project where groups from the RWTH Aachen University and the University of Freiburg collaborate to implement a first experimental prototype of an MW-AWES. To this end, the Institute for Flight System Dynamics at the RWTH Aachen University has developed a VTOL flight system called ‘Maverix’ (cf. Figure 2) which will be used to demonstrate the dual-wing system. The System Control and Optimization Laboratory at University of Freiburg is working on numerical methods to compute power-generating flight trajectories that are robustness against external disturbances.



Figure 2: Maverix Flight System, Preliminary Render

The project is structured in multiple phases where we iteratively increase the complexity of the system: We begin with the untethered system to establish a communication workflow between UFR and RWTH. Next, we integrate tether and winch into the system, starting with a single flight system to assess the general feasibility of the tethered operation. Subsequently, we add the second flight system and the Y-configuration. The final phase focuses on tracking optimal trajectories for power generation. Both groups focus on their respective domains while maintaining a continuous collaboration: UFR delivers increasingly complex and robust trajectories, which RWTH validates in experiments. The resulting prototype will establish an experimental foundation for future MW-AWES.

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## Autogyro Pumping Mode Rotary AWE System – Design and Control of a Servo Flap Cyclic Pitch Actuated Rotor

**Christof Beauoil<sup>1</sup>, Felix Weyel<sup>2</sup>,**

<sup>1</sup> someAWE Labs S.L., <sup>2</sup> University of Freiburg

Pumping mode rotary airborne wind energy (AWE) systems have been described in literature [1,2] but despite their potential advantages over single-wing AWE systems, they have not been comprehensively researched or implemented yet. Rotary AWE systems, as illustrated in Figure 1, use a quasi-stationary tether and achieve crosswind motion by orbiting multiple connected wings around a center.

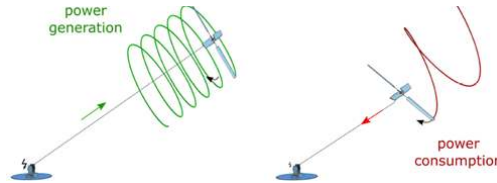


Figure 1: Pumping cycle of a rotary AWE system.

Figure 2 shows such a system using a tethered autogyro. The rotor consists of a) Cyclic and collective pitch mechanisms based on a swash plate with an active rotation compensator [3] and b) Rotor blades with swash plate actuated servo flaps, often referred to as Kaman flaps.



Figure 2: Rotary AWE system developed by someAWE.

The flap control system is being implemented in cooperation with the University of Freiburg. A linear model describing the dynamics of the blade-flap-system was identified based on measurement data and used to design a feed-forward controller that computes the actuation signal for the flaps, such that the blade pitch follows a pre-defined reference signal, as pictured in Figure 3.

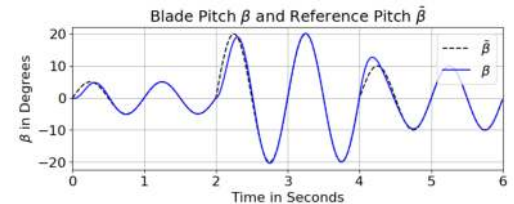


Figure 3: Simulation of the blade-flap-dynamics with controller.

This talk presents the complete system design, its control system and the first results with a functional demonstrator.

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## Identification and Hardware-in-the-Loop Testing of a Tail-Sitter UAV

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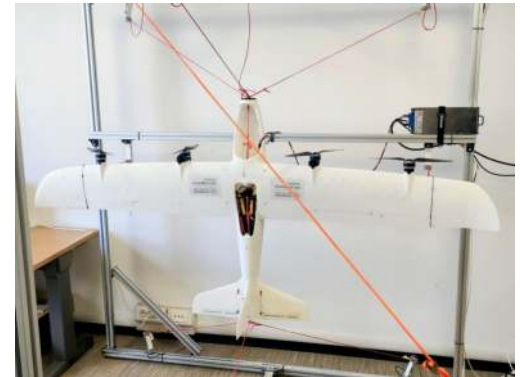
This work presents a testbench for the identification and Hardware-In-The-Loop (HITL) testing of a tail-sitter Uncrewed Aerial Vehicle (UAV) prototype for Airborne Wind Energy Systems (AWES). The platform is used to investigate the take-off and landing phases, which are among the most challenging aspects of AWES operation. Particular emphasis is placed on the characterization of the aerodynamic and actuation models, which represent the main sources of uncertainty for such systems.

The testbench allows the UAV to be rigidly suspended by eight tethers in its hovering position while the actuators can be commanded arbitrarily. Each tether is connected to the rigid structure through a load cell, arranged in a layout that allows to measure the forces and torques generated by the propellers and control surfaces.

This experimental approach allows the direct identification of the actuation and aerodynamic contributions to the vehicle dynamics directly from measurements, while the remaining relevant dynamics are described by the six-degree-of-freedom rigid-body equations of motion. Additionally, the simulation can also incorporate the tether dynamics and the interaction with the ground station.

Beyond system identification, the test bench allows for closed-loop HITL testing of hovering control approaches. In this configuration, the measured forces and moments are fed into a real-time simulation of the aircraft rigid-body dynamics, while the controller operates on the simulated vehicle state applying control inputs directly to the physical prototype.

This proposed methodology enables a safe and comprehensive investigation of the system during take-off, hover, and landing phases. At the same time, it allows the testing of control approaches on the embedded hardware in a secure environment, reducing risks while improving turnaround time. Furthermore, the setup provides a repeatable and scalable framework for benchmarking different control strategies under consistent and well-defined experimental conditions.



*Tail-sitter UAV prototype used for system identification and Hardware-In-The-Loop experiments mounted on the testbench.*

This research has been partially supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).





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## Beyond Technology: The Role of Social Science in Renewable Energy Innovation

**Gerdien de Vries**  
Delft University of Technology

As the global energy transition accelerates, emerging renewable technology is rapidly moving from experimental concepts to implementation in real-world contexts. Airborne wind energy is such an example. Yet the path from technological promise to societal integration is rarely straightforward. Technical performance alone cannot ensure that communities will embrace new energy systems. Instead, broad societal acceptance depends on how individuals and communities perceive, evaluate, and interact with these emerging technologies.

This keynote explores the societal dimensions of airborne wind energy and comparable renewable technologies through the lens of the social sciences. Whereas engineers typically design systems to operate predictably within controlled parameters, human behaviour is shaped by complex psychological, social, and cultural dynamics. Factors such as perceived risk, noise sensitivity, and aesthetics all influence people's responses to energy technologies. Moreover, community dynamics, social norms, and questions of fairness play equally essential roles in shaping acceptance. Often in ways that diverge from purely technical (or financial) expectations. Building on insights from environmental psychology and social-scientific research on renewable energy, this keynote highlights why transdisciplinary research is indispensable for the successful development and integration of emerging energy technologies. Engineers,

policy-makers, developers, and social scientists must collaborate from the earliest stages. Not in a sequential manner but in a truly integrated, iterative process. Such collaboration enables teams to anticipate societal concerns, meaningfully engage stakeholders, co-design solutions with local communities, and ensure that technologies reflect both technical optimisation and human values. While transdisciplinary collaboration can present challenges, ranging from disciplinary language barriers to differing research cultures, it consistently proves essential for developing socially robust, widely accepted energy systems. In the context of the energy transition, overlooking the human factor risks slowing or even halting the deployment of critical innovations.

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## Fusing Model Predictive Kite Control with Vessel Performance Models to Generate Hull-Aware Optimal Trajectories for Ship Propulsion

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CargoKite GmbH

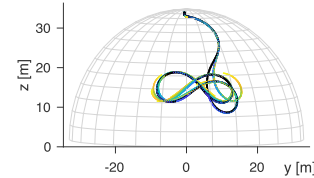
CargoKite aims at bringing Airborne Wind Energy (AWE) to the shipping market. Kite technology has matured to the point where its application in commercial maritime operations is within reach. We are developing an integrated solution optimizing vessel, kite and ship operation together to use its full potential.

One central element for this is our model-based control design: based on simplified kite models [1,2] and methods of physics-informed machine learning, an accurate and at the same time computationally efficient kite model has been developed and validated. This model is embedded in a nonlinear model predictive control (NMPC) scheme, enabling real-time trajectory planning and kite control. By integrating the vessel's hydrodynamic characteristics into the NMPC economic cost function, optimal kite-ship coordination is achieved.

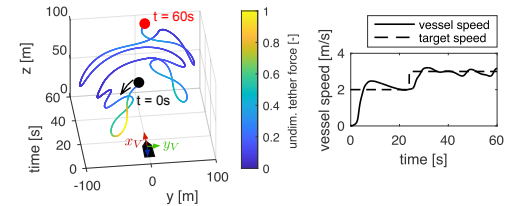
The resulting control architecture allows the kite to pull the vessel not only with maximum thrust, but in its most fuel efficient state, balancing side forces and rudder usage. Simulations with our hull design show performance gains of over 10 % compared to thrust-only optimization, with the largest improvements on close-hauled courses.

The control approach is validated through on-land experiments with simulated vessel courses.

On a 26 m demonstrator vessel equipped with a 60 m<sup>2</sup> kite, performance gains are assessed under real operating conditions. Using the calibrated kite and hydrodynamic models, we derive design requirements for the next-generation kite system in simulation to maximize overall performance with hull-aware trajectories.



*Optimal trajectory planning in an automated land test flight*



*Incorporation of hydrodynamic effects enables functionalities such as cruise control and side force limitation, maximizing the overall efficiency of the kite-propelled vessel*

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- [1] Erhard M., Strauch H.: Control of Towing Kites for Seagoing Vessels. *IEEE Transactions on Control Systems Technology*, 21, 5, 1629-1640 (2013)
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## Design and Educational Implementation of a Transportable Airborne Wind Energy System

**Hiroki T. ENDO**

Formerly Tsuruoka KOSEN

This study presents the development of a transportable ground station for Airborne Wind Energy (AWE), based on a mobile power generation concept. While most Japanese research focuses on flight units, our team focuses on the optimization of ground-based energy conversion and its integration into engineering education.

As part of a graduation project at a National Institute of Technology (KOSEN), students developed a second-generation prototype. The original faculty model, a minimalist aluminum structure designed for weight reduction, achieved 11% efficiency but suffered from structural failure due to low rigidity.

To address this, students designed a revised model using a high-rigidity frame. A key quantitative finding was the trade-off between durability and performance: the reinforcement ensured structural stability during field trials, but the increased vehicle mass, combined with steering constraints, resulted in an energy conversion efficiency of 2%–10%. This provides a clear benchmark for the "mass penalty" in mobile ground stations.

The system incorporates a synchronized measurement unit using an M5Core microcomputer. These results

demonstrate that integrating AWE research into industrial education highlights real-world engineering trade-offs, providing students with critical insights into the balance between structural integrity and system efficiency.



*Experimental trial of the mobile generation vehicle by students at Tsuruoka KOSEN.*

### References:

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## Electrical Conversion and Control System Prototype Using FOC

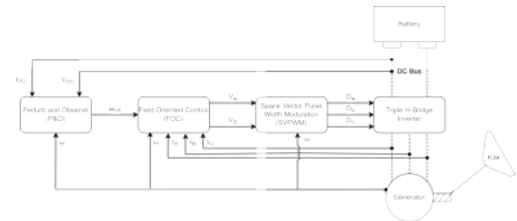
**Jamie Pickar, E Carr Everbach**  
Swarthmore College

Ensuring efficient conversion of energy is crucial for any AWE system [1]. For a tethered kite AWES with a ground-based generator, the energy conversion occurs in two steps: first mechanical energy is extracted from the wind, then converted to electrical energy. Both conversion steps may be optimized using the same control system [2].

The optimal kite reel-out speed changes as wind conditions and kite flight parameters change. We implemented a maximum power point tracking (MPPT) controller for a 660 watt bench scale Permanent Magnet Synchronous Generator (PMSG). The first stage of the MPPT controller uses the perturb and observe (P&O) technique to search for the generator reference speed which maximizes the power exported onto the DC bus. The second stage of the controller uses the field oriented control (FOC) technique to operate the generator at the P&O commanded reference speed under a maximum torque per ampere (MTPA) condition, accounting for both permanent magnet and reluctance torques. The controller was implemented using a commercial ESC from VESC Labs. Such a control architecture allows for the efficient extraction of wind energy by ensuring maximum power operating point is maintained under all conditions, accounting for the efficiencies of the aerodynamic system, generator, and power electronic converters. Generated power is

buffered in a battery for later export to an AC system.

We present the details of the prototype system, the aerodynamic efficiency achieved, the efficiency of the electrical system, and the challenges encountered when using an FOC controlled generator for aerodynamic optimization of an AWE kite.



*Block diagram of implemented control scheme*

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## Nonlinear Dynamics and Bifurcation Analysis of Parachute-Based Airborne Wind Energy Systems

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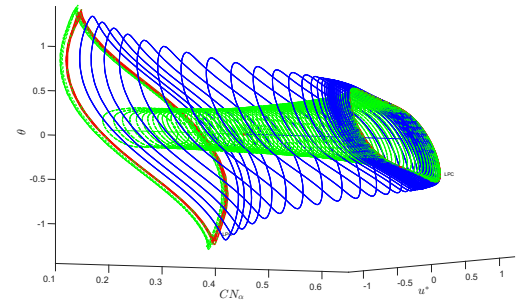
Parachute-based airborne wind energy systems (AWES) have recently emerged as a promising alternative to conventional crosswind kite configurations [1]. By operating in a tether-aligned, pumping (yo-yo) mode and exploiting high aerodynamic drag, these concepts offer distinctive advantages, including simplified control, lower operational speeds, and favourable scalability for large-scale deployment.

Despite this growing interest, fundamental aspects of the system dynamics remain insufficiently understood. Parachute-based AWES often exhibit periodic pendulum motions of the canopy, which reduce the average tether tension and consequently the power generation efficiency [2]. In addition, in clustered deployments, such oscillations may increase the risk of collisions between neighboring units.

This work investigates the nonlinear dynamics of a tethered circular parachute system as a representative model for parachute-based AWES. A reduced-order dynamical model is derived to capture the essential pendulum motion of the system. Using a bifurcation analysis software [3], the influence of aerodynamic force coefficients on the dynamic of the system in phase space is examined. The results show that the observed pendulum motion corresponds to a stable limit cycle. Furthermore, for specific aerodynamic conditions, stable limit-cycle solutions no longer exist, and the system converges to a stable equilibrium state.

The present study provides design-oriented insights for mitigating oscillations and improving power generation

efficiency in parachute-based AWES. The proposed modelling and analysis framework is also applicable to other tethered airborne wind energy systems, including kite- and fixed-wing-based configurations.



Bifurcation diagram of the parachute-based airborne wind energy system.

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# Numerical Simulation on Aerodynamic Characteristics of Wind Capture Structures in an Airborne Wind Energy System

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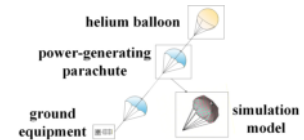
The Parachute-Based Airborne Wind Energy System (PB-AWES) is a new technique for harnessing high-altitude wind energy resources. The system is generally divided into three parts: the airborne assembly, the ground assembly, and the tethers connecting them. The airborne assembly captures wind energy and converts it into mechanical tension, which is then transmitted to the ground assembly via the tether to drive power generation.

The power-generating parachute, as the main structure for capturing wind energy in the system, needs to open and close cyclically during operation. Simulating its dynamic deformation during its opening process provides important support for system design and optimization.

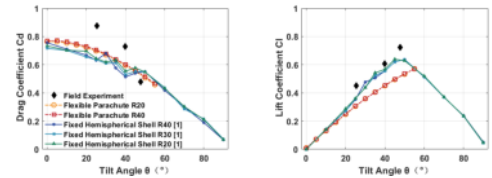
This presentation establishes a fluid-structure interaction model for the large flexible power-generating parachute. In the model, the spring-particle model is used to simulate the flexible structure of the parachute, and the Smoothed Particle Hydrodynamics (SPH) method is employed to simulate wind field. Fluid-structure interaction is established using a dummy particle method. Since the SPH method does not require a mesh, it can essentially avoid numerical errors caused by mesh deformation for such large flexible power-generating parachute structures, thus offering greater advantages.

The opening processes of different parachutes are numerically simulated, considering the opening performance, three-dimensional deformation patterns, and the force variation. The effects of parachute size, incoming

wind speed and direction are provided. The critical conditions for the full deployment of the power-generating parachute are established to assist in determining the optimal opening timing for the parachute-based airborne wind energy system.



(a) Simulation model of the power-generating parachute



(b) Variation of drag and lift coefficients with tilt angle for the parachute. (The flexible parachute fails to fully deploy beyond 60° tilt angle.)

References:

[1] Xinwei Ye, Xiaojing Niu: Numerical Study on Flow Structure and Surface Pressure Distribution of Super-large Round Parachute, National Conference on Hydrodynamics, Harbin, China, 2024.



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# Reinforcement Learning-Based Flux Control for Electrical Efficiency Optimization in Airborne Wind Energy Systems

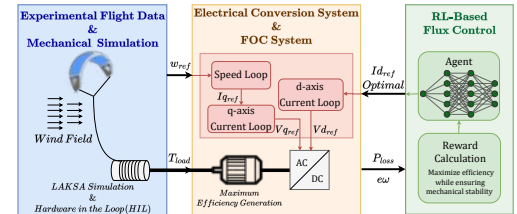
Miguel Alonso-Resta, Carolina Nicolás-Martín, Gabriel Wyatt-Brondel,  
 Jorge González-García, David Santos-Martín  
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Ground-based Airborne Wind Energy Systems (AWES) are characterized by rapid and cyclical variations in mechanical loading. These fluctuations result in significant shifts in the optimal magnetic flux level of the Induction Machine (IM) during the cycle, directly affecting iron and copper losses and, consequently, electrical efficiency. Conventional field-oriented control (FOC) relies on fixed or heuristically tuned flux settings, which are unable to adapt to the highly dynamic conditions of an AWES generation cycle, thereby significantly limiting electrical energy yield [1].

This work proposes a reinforcement learning (RL)-based flux control strategy, for computing the optimal d-axis current value ( $i_{d,ref}$ ) for the induction machine, maximizing total AWES energy generation in each cycle. The RL-agent is trained in a high-fidelity simulation environment combining a six-degree-of-freedom rigid-body kite with elastic tether dynamics framework [2], and a full-order flux-linkage-based three-phase electric machine. This enables countless operating mechanical and electrical conditions to be simulated, allowing the agent to learn how the machine's loss landscape evolves with torque demand, generator speed and power flow direction.

The proposed control strategy was compared against Loss-Minimization and MTPA strategies and validated in a high-fidelity simulation environment, demonstrating its suitability for real-time implementation and to be used in a power-hardware-in-the-loop (PHIL) experimental setup [3], where an electrical machine emulates the torque profile produced by the kite during realistic AWES flight cy-

cles. Obtained results show that the RL-based controller consistently selects flux levels that reduce losses across the entire pumping cycle while ensuring mechanical stability, leading to total energy efficiency improvement of 5-10% for each complete AWES cycle relative to conventional FOC with fixed flux settings. These results highlight its potential as a practical solution for maximizing electrical power generation in next generation AWES.



Proposed RL-based flux control architecture for an efficiency-optimized IM in ground-based AWES.

## References:

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- [2] Sánchez-Arriaga, G., et al. "Modeling and natural mode analysis of tethered multi-aircraft systems." *Journal of Guidance, Control, and Dynamics* 44.6 (2021): 1199-1210.
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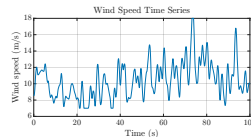


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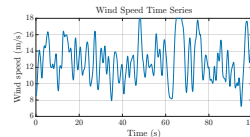
# Comparative Analysis of Classical and Reinforcement Learning-Based Flight Control for Airborne Wind Energy Systems

César Eduardo Perdomo-Díaz, Jorge González-García, Pedro López-Peláez,  
 Carolina Nicolás-Martín, David Santos-Martín  
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Airborne wind energy systems (AWES) commonly rely on cascaded model-based control architectures, where a feedback controller tracks attractor points generated by a guidance system [1]. Although this approach enables autonomous flight, its performance can degrade under non-linear dynamics and varying wind conditions. This work studies a flight-control framework for ground-generation, ground-actuated AWES that combines a continuous-reference guidance system with a reinforcement learning controller based on TD3. The guidance module generates a smooth reference trajectory, while the agent uses flight-state and guidance information to command differential tether length for steering. The reward function promotes trajectory tracking, heading alignment, tether-tension maintenance, and safe operation.



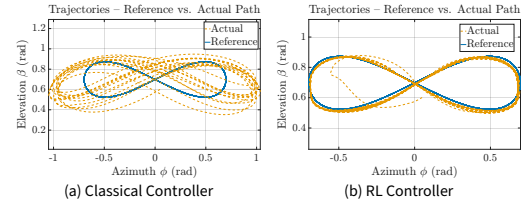
(a) Example 1 of Wind Speed used



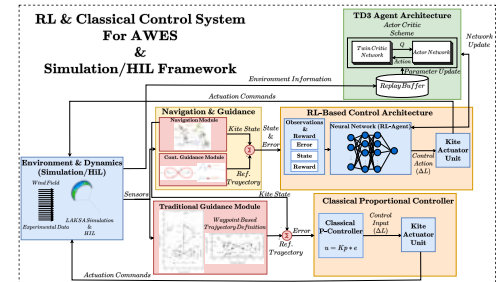
(b) Example 2 of Wind Speed used

Two representative wind speed profiles, obtained experimentally, used for testing during simulation.

The framework is evaluated in the high-fidelity LAKSA simulation environment [2] and compared with a classical controller. Results show that the RL controller achieves more accurate and robust trajectory tracking. The selected RL configuration is then transferred to an experimental setup to assess performance.



Under variable wind, the RL controller shows  $RMSE(\phi)=0.0287$  (rad) and  $RMSE(\beta)=0.0221$  (rad), while the classical controller shows  $RMSE(\phi)=0.9477$  (rad) and  $RMSE(\beta)=0.1911$  (rad).



Control Architecture and Simulation Framework Diagram

References:

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 [2] Sánchez-Arriaga, G., A. Serrano-Iglesias, J., Leuthold, R., Diehl, M., Modeling and Natural Mode Analysis of Tethered Multi-Aircraft Systems.



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## Wind Resource Analysis for Airborne Wind Energy Systems

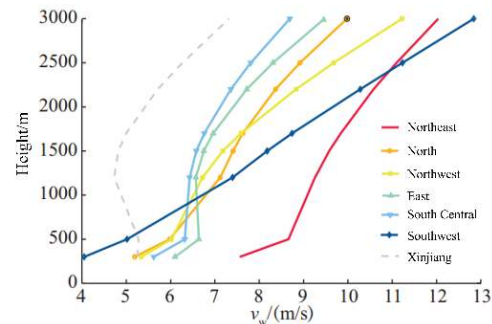
Xiaoyu Li<sup>1,2</sup>, Bixiong Luo<sup>1,2</sup>, Li Zhang<sup>1,2</sup>, Jin Tu<sup>1,2</sup>, Yanfeng Cai<sup>3</sup>

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<sup>2</sup> China-Europe Science and Technology Innovation Center

<sup>3</sup> China Energy Engineering Group Guangdong Electric Power Design Institute Co., LTD.

Focusing on the high-altitude wind energy that could be captured by the Airborne Wind Energy System (AWES), the spatial and temporal characteristics of wind speed and wind power density from 300 m to 3000 m above ground are analyzed and compared between seven regions for China with the ERA5 reanalysis data. The results [1,2] show that the spatial distribution of high wind speed area and high altitude area basically overlap. Wind speed and wind power density continue to increase with the rise of height and the wind profile of Northeast China, North China, Northwest China are more suitable for exploiting high-altitude wind resources. The seasonal variations of wind speed and wind power density also increase with the rise of height. While the daily variation of wind speed gradually decreases and the inter-regional differences narrow. This work suggests that the wind energy utilization potential of the cross-wind mode AWES is lower than Aerostatic AWES. It is necessary to plan for a higher operating altitude for cross-wind mode AWES in considering of the existing status of airspace utilization in China.



Vertical profile characteristics of wind speed

### References:

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*Assembly and calibration of the mechanical and measurement system during field testing.*

*Airborne wind energy system in operation, showing controlled flight and tether interaction in real conditions.*





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## Low-Altitude Airborne Wind Energy as a Density-Driven Power System: Continuous Operation, Compact Architectures and Preliminary Experimental Evidence

**Marco Ghivarello**

GHIVA Progettazione CAD

Airborne Wind Energy (AWE) systems are commonly based on pumping or fly-generator architectures, often requiring complex subsystems and demanding control strategies, limiting deployability and scalability.

This work investigates an alternative AWE design space based on low-altitude operation below 100 m, where compactness, architectural simplicity, and high-frequency operation enable increased areal power density. Rather than maximizing power per unit, the approach prioritizes continuous generation, reduced complexity, and scalability across power classes, including smaller systems, suggesting higher spatial energy density through faster cycles and continuous-operation architectures. A central element of this approach is the adoption of continuous-operation architectures, where energy generation is not organised around discrete reel-in/reel-out pumping phases nor fully airborne generation concepts

By acting on flight trajectories and on the stroke length of a linear ground-based generation unit, power output can be kept non-negative over time, while return motions are mechanically automated without active power input. This architectural choice reduces discrete operational switching and favours system behaviour dominated by continuous dynamics rather than event-driven control.

System simplification does not arise from component reduction alone, but from eliminating distinct operational phases and integrating energy conversion, control and

return dynamics into a single continuous process. The paper analyses the implications of this paradigm for system architecture, control strategy, and mechanical loading.

A fast-pumping, continuous-operation architecture reduces reliance on high-torque bidirectional winches and discrete cyclic load management through a linear generation topology based on reduced dependence on actively coordinated control actions and increased use of passive mechanical elements such as inertia and elastic compliance. While quantitative load reductions still require experimental validation, the reduced need for actively driven phase inversions and the high-frequency operation suggest a pathway toward milder load transients compared to conventional pumping-based systems, potentially suggesting the possibility of resonance-like system behaviour under specific conditions.

These concepts are illustrated through KGM1, a low-altitude AWE system developed using an independent experimental approach. Preliminary observations from a small-scale prototype show non-negative power output over time, with mechanically automated return phases, under variable low-wind conditions and without automatic control.

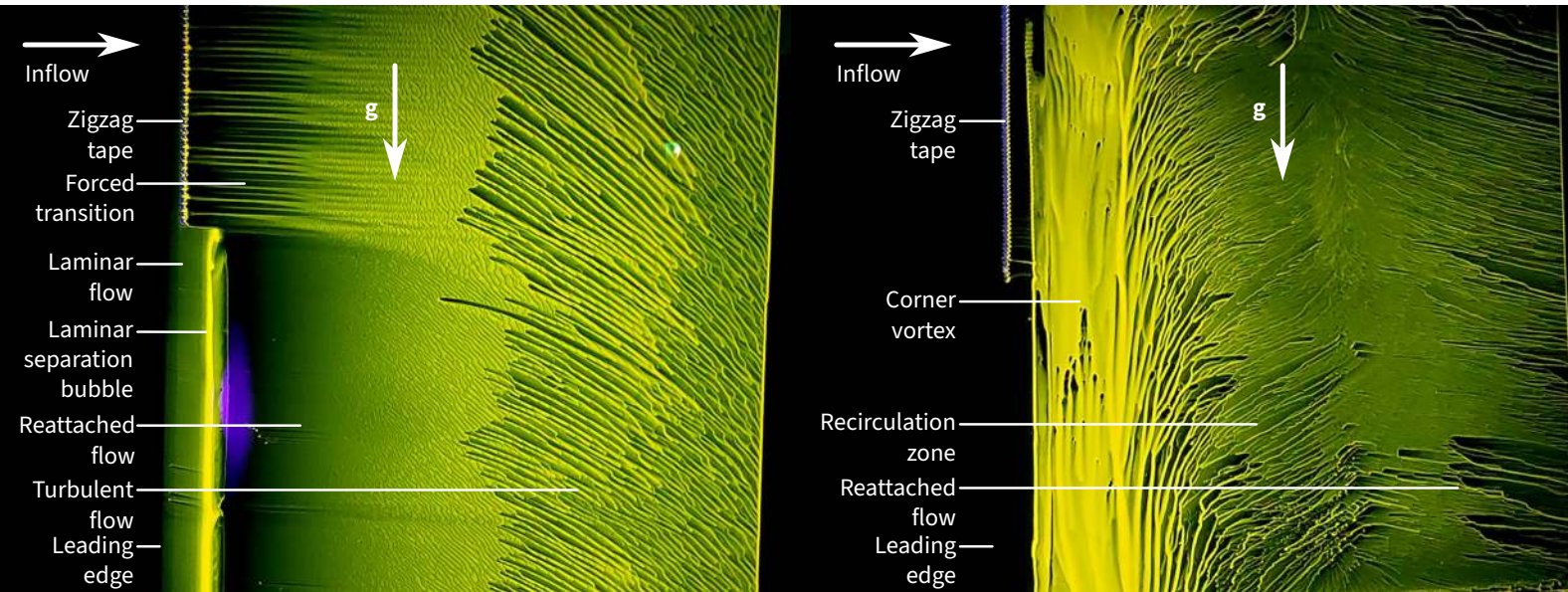
Although not intended to demonstrate performance optimisation or scalability, these time-resolved measurements provide evidence supporting the feasibility of continuous-operation AWE architectures at low altitude.



*Two-dimensional, rigid scale model of the TU Delft leading edge inflatable (LEI) V3 kite mounted with a high angle of attack in the low turbulence tunnel (LTT) of the university (Thijs van Lith: Aerodynamic analysis of a 2D rigid LEI airfoil. MSc Thesis, TU Delft, 2025. <https://edu.nl/fqp3y>).*

## Suction side

## Pressure side



*Oil flow visualisation of the two-dimensional aerodynamics of the TU Delft LEI V3 kite. Parts of the leading edge are fitted with zigzag tape shortly downstream of the stagnation line, on both the suction and pressure sides of the airfoil. On the suction side (left), the tape trips the boundary layer into turbulent flow. Without tape, a laminar separation bubble is visible. Further downstream, the flow reattaches and eventually transitions into turbulent flow. The pressure side (right) exhibits a corner vortex with low flow speed, where the oil predominantly flows down due to gravity. Further downstream, the recirculation zone drives the oil flow towards the leading edge. Once the flow reattaches, the oil flow is again driven to the trailing edge. The result is a Christmas tree-like oil flow pattern on the pressure side (Thijs van Lith: Aerodynamic analysis of a 2D rigid LEI airfoil. MSc Thesis, TU Delft, 2025. <https://edu.nl/fqp3y>).*



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## Aerodynamic Analysis of a Two-Dimensional Rigid Leading Edge Inflatable Airfoil

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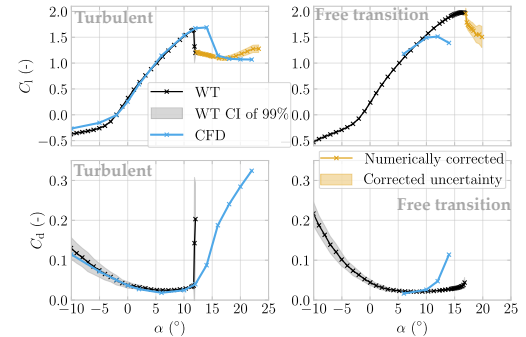
To increase understanding of the complex aerodynamic flow phenomena around leading-edge inflatable (LEI) kite sections, Reynolds-averaged Navier–Stokes (RANS) computational fluid dynamics (CFD) predictions and wind-tunnel (WT) measurements were compared.



Rigid LEI airfoil model representing an extruded mid-span section of the TU Delft V3 kite; pressure side (left) and suction side (right).

The LEI airfoil was tested in the TU Delft low-turbulence wind tunnel at  $Re=10^6$ . Lift was obtained from wall-pressure integration, and drag was determined from wake-rake momentum-deficit measurements. A forced transition was imposed using zigzag (ZZ) tape on either the suction or pressure side of the leading-edge tube. The measured polars show that forcing the suction-side transition reduces the maximum lift coefficient by 15.3%, shifts stall to a lower angle of attack  $\alpha$ , whereas ZZ tape placed at  $45^\circ$  on the tube's pressure side improves low-angle-of-attack performance by mitigating the pressure-side separated region behind the tube.

Agreement was closest in the linear-regime for fully turbulent simulations, while deviations increased near and beyond stall, consistent with the sensitivity of separation onset and reattachment to modelling assumptions. The correlation-based  $\gamma\text{-}\tilde{Re}_{\theta,t}$  transition model did not converge reliably across the investigated angles of attack, which limited quantitative assessment of transition-modelling fidelity for this geometry.



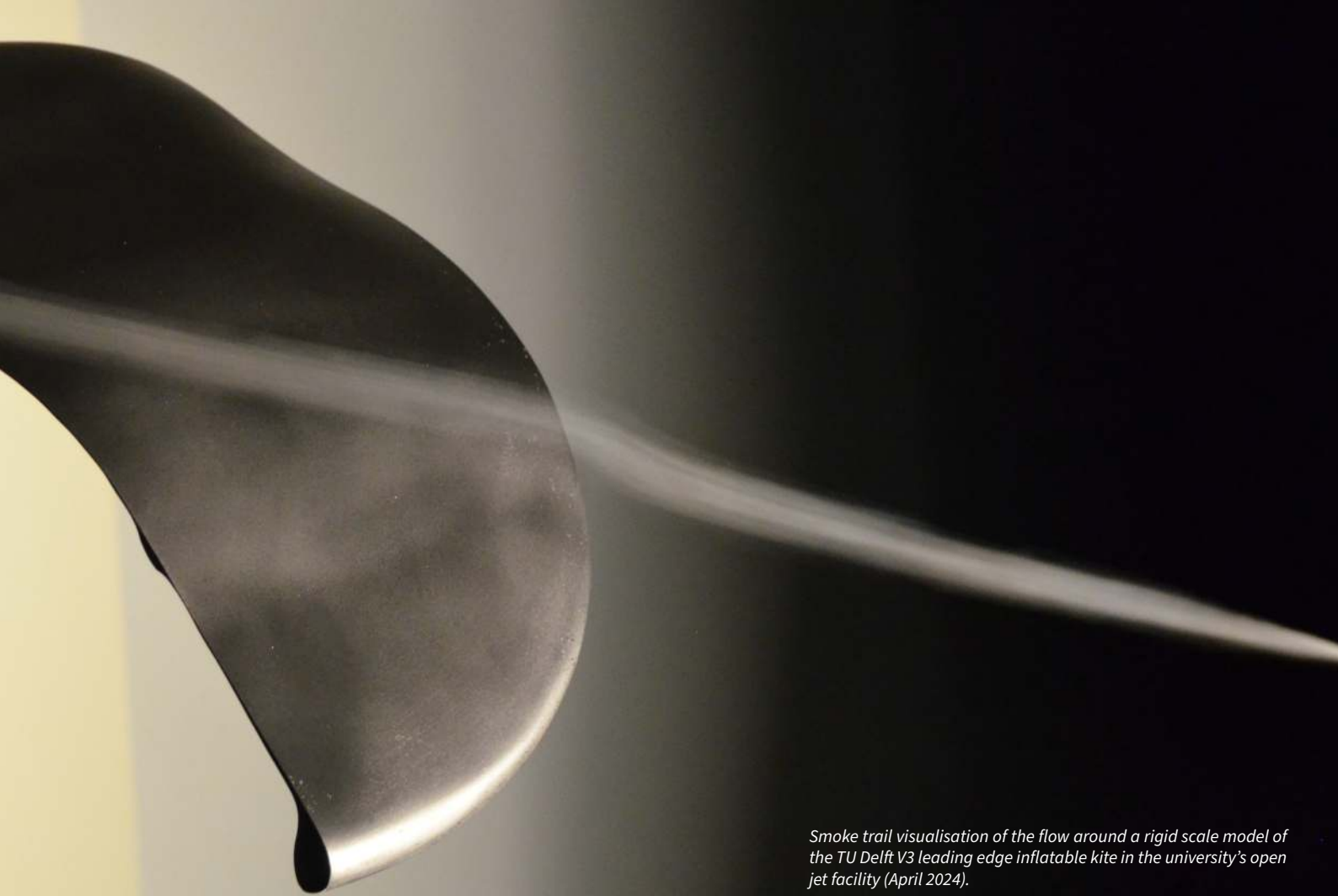
Comparing WT measured polars to RANS CFD predictions.

Oil-flow visualisation and infrared thermography were used to identify boundary-layer transition and flow separation, confirming the presence of a laminar separation bubble on the suction side and an extended pressure-side recirculation zone. These measurements demonstrated how forced transition modified the size and location of these flow features, directly explaining the observed changes in lift, stall behaviour, and low-angle-of-attack performance. It was also concluded that, under a fully turbulent assumption, RANS CFD can predict the lift and drag of LEI airfoils with high accuracy.

### References:

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This research has been supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).



*Smoke trail visualisation of the flow around a rigid scale model of the TU Delft V3 leading edge inflatable kite in the university's open jet facility (April 2024).*



*Smoke trail visualisation of the flow around a rigid scale model of the TU Delft V3 leading edge inflatable kite in the university's open jet facility (April 2024).*



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## Machine Learning for Leading-Edge Inflatable Kite Profile Aerodynamics

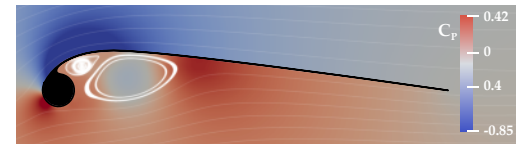
**Jelle A. W. Poland, Kasper R. G. Masure, Roland Schmehl,**  
Delft University of Technology

This study (a subset of [1]) presents a regression model for leading-edge inflatable (LEI) kite airfoil aerodynamic coefficients, trained on Reynolds-averaged Navier-Stokes-derived two-dimensional aerodynamic data spanning Reynolds number, angle of attack, and profile configuration. The simulations resulted in lift, drag, and pitching moment coefficients, subsequently used to train a machine learning (ML) surrogate able to provide rapid and accurate aerodynamic predictions in 2D, for subsequent 3D aerodynamic analysis. Because soft-wing kites substantially deform spanwise and chordwise, the low computational cost is key in enabling fluid-structure interaction simulations, especially within iterative optimisation loops.

Profile-geometry parameterisation underpinned the automated CFD toolchain: a circular leading-edge tube was blended with a membrane canopy represented by front- and rear-cubic Bézier splines with tangent continuity, yielding a shape family governed by six chord-normalised parameters. Finite canopy thickness and an LE fillet were introduced to ensure robust meshing and numerical stability.

The RANS simulations used the  $k-\omega$  shear stress transport (SST) turbulence model implemented in OPENFOAM, with structured O-grid meshes generated in POINTWISE. A fully turbulent assumption was adopted, as seam-induced roughness at the LE tube-canopy connections was assumed to enforce forced boundary-layer transition close to the leading edge, such that any remaining laminar flow region is expected to be negligible. Within the linear regime (from approximately  $\alpha = -1^\circ$  to  $10^\circ$ ), the average percentage errors of mid-span TU Delft V3 kite simu-

lations compared to 2D wind tunnel measurements were 4% in lift and 16% in drag [1]. Extensive mesh-sensitivity studies ensured grid-independent force and moment predictions. In addition to integral force and moment coefficients, surface pressure and skin-friction distributions were extracted to characterise load distributions relevant for subsequent structural and fluid-structure interaction analyses.



RANS CFD predicted flow field of the LEI airfoil, the mid-span section of the TU Delft V3 kite, at  $\alpha = 8^\circ$ .

The ML model type that predicted lift, drag and moment coefficients closest to the CFD predictions was an extremely randomised trees model. Coefficients of determination, relative to CFD predictions, of  $R^2 = 0.987$ ,  $0.988$ , and  $0.989$  for  $Re = 1 \times 10^6$ ,  $5 \times 10^6$ , and  $2 \times 10^7$ , were found.

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This research has been supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).

*Kitemill's Manoj Mandru and Marius Dyrseth working at the Lista test facility in Norway (February 2025).*



*Trond Hammerstad, Exact Aircraft AS, at Kitemill's Lista test facility in Norway (January 2026).*





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## UniSimAWE: Kitemill's Airborne Wind Energy Simulator

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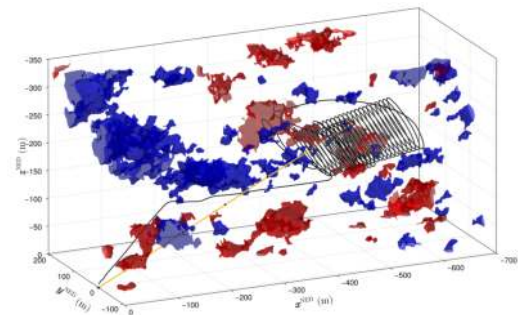
<sup>2</sup> Technical University of Denmark

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The Universal Simulator for Airborne Wind Energy (UniSimAWE) is an in-house airborne wind energy simulator developed by Kitemill AS over the last two years. Originally, Kitemill maintained a multitude of different simulators created by PhD students and engineers for various purposes - for example, a Simulink simulator used to validate flight control algorithms [1-3], another software-in-the-loop (SIL) simulator, and both a VBA-based and a Julia-based power-curve estimator. With several different simulators serving overlapping purposes, maintenance quickly became challenging, and it was decided to unify them into what is now known as UniSimAWE.

UniSimAWE is a Julia-based simulator environment built from the ground up. It includes rigid-kite aerodynamics, an advanced tether model, wind-shear and turbulence models, vertical take-off and landing (VTOL) capabilities, live visualization, an interface towards Kitemill's KM1 flight code, and an environment for developing control algorithms directly in Julia. Additionally, UniSimAWE is connected to an Influx database where live lidar data is retrieved and integrated into the simulator - enabling flights using real-time wind data from Farsund Airport, where Kitemill operates.

This presentation will outline the core capabilities of UniSimAWE, describe its high-level architecture, and discuss future directions for the framework. In particular, it will highlight how UniSimAWE accelerates development, reduces testing costs, and improves the reliability of Kitemill's flight-control system.



Example visualization from UniSimAWE. Black lines are kite trajectory, yellow line is the tether, red and blue blobs are positive and negative turbulence eddies.

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- [3] Nguyen, D. H., M. H. Lowenberg and E. Oland (2026). Improving Power Generation in Rigid-Wing Groundgen Airborne Wind Energy Systems Using Feedback Control - A Parametric Study. *In Wind Energy*, Vol. 29, No. 4, pp. 1-13.

*View from the onboard camera of Kitemill's Spark 15 (March 2026).*





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## Floating Airborne Wind Energy Farms with Shared Mooring Lines

**Andrea Bertozzi<sup>1,2</sup>, Francesco Niosi<sup>2</sup>, Bruno Paduano<sup>2</sup>, Mattia Alborghetti<sup>1</sup>, Lorenzo Fagiano<sup>1</sup>, Giovanni Bracco<sup>2</sup>**

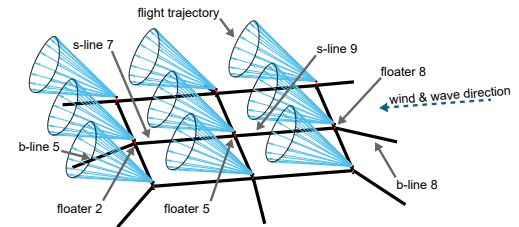
<sup>1</sup> Department of Electronics, Information and Bioengineering, Politecnico di Milano

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Airborne wind energy (AWE) has the potential to complement conventional wind power and accelerate the transition to renewable energy. Realizing this potential will require offshore farm-scale deployments, where mooring systems represent a consistent share of capital expenditures [1,2]. This study integrates three emerging technologies: floating AWE systems, shared-line mooring configurations to reduce material costs, and taut mooring systems employing synthetic ropes. While this combination offers significant advantages, shared-line designs remain not commercialized due to the complexity of mooring-induced platform-to-platform interactions. Furthermore, the inherently nonlinear behavior of synthetic taut lines is often neglected despite its known influence on system dynamics.

This study addresses these critical research gaps by numerically investigating the role of nonlinear tensile stiffness in shared-line moorings for floating AWE systems. A fully nonlinear stiffness model, based on industrial rope characteristics, is integrated to capture realistic behavior of the nylon mooring lines. The dynamics of a nine-platform shared-line farm are compared against a baseline single-device configuration under critical loading conditions. The evaluation assesses motions, line tensions, and hourly fatigue damage rates. Results show that while horizontal offsets remain within safe operational limits, even simple single-mooring configurations experience strong dynamic effects from material nonlinearities. In shared-line arrangements, high-frequency load components significantly accelerate fatigue damage. These findings underscore the critical importance of nonlinear mooring modeling in the design and assess-

ment of shared-moored floating renewable energy systems.



Three dimensional view of the nine-element AWES farm.

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This study is supported by the Italian Ministry of University and Research through the European Union – NextGeneration EU fund, project P2022927H7 “DeepAirborne – Advanced Modeling, Control and Design Optimization Methods for Deep Offshore Airborne Wind Energy”, and by the AWETRAN MSCA Doctoral Network project, which receives funding from the European Union’s Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101168734.



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## awesIO: A Standard Input/Output Framework for Airborne Wind Energy Systems

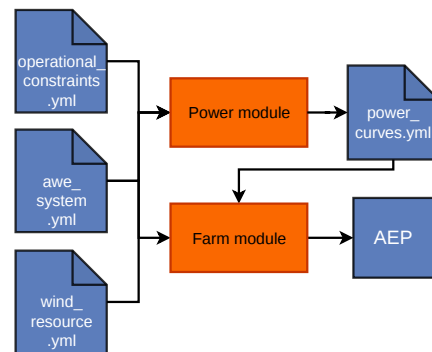
Joren Bredael, Oriol Cayon, Roland Schmehl  
Delft University of Technology

Airborne wind energy (AWE) research is advancing rapidly, but the diversity of system concepts, modelling approaches, and data formats makes it difficult to compare results or reuse models across research groups and industry. The lack of a common, standardized interface reduces transparency, hinders reproducibility, and slows collaborative progress in the field.

awesIO [1] is an open-source, standardized data specification and validation framework for airborne wind energy research. It defines a structured and human-readable representation of AWE system configurations, simulation inputs, and results using YAML files, enabling consistent data exchange between modelling tools, research groups, and industry. Implemented as an open-source Python package with accompanying documentation, awesIO provides schema-based validation to ensure clarity, transparency, and reproducibility, while remaining flexible enough to evolve alongside the fast developing AWE field.

While awesIO is inspired by windIO [2], which is used in conventional wind energy, it will be developed as a separate standard to accommodate the fundamentally different and rapidly evolving nature of AWE systems. In contrast to windIO, which emerged after many tools and conventions were already established, awesIO is introduced at an earlier stage of the field, where common interfaces can still meaningfully shape modelling practices.

Unlike conventional wind turbines, where system architectures are relatively similar and well aligned, airborne wind energy concepts differ substantially in configuration, operation, and modelling focus.



Example awesIO use case for a toolchain predicting annual energy production (AEP) of a farm.

This diversity is a challenge for awesIO, as it is difficult to develop the AWE system schema in isolation to cover the full range of AWE systems. It, therefore, strongly motivates collaborative development, where input from research groups working on different concepts is essential to ensure that awesIO remains both flexible and broadly applicable.

References:

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## A Preliminary Techno-Economic Evaluation of AWE for Offshore Applications in Italy

**Alessandro Croce, Francesca Neri, Umberto Nobile**

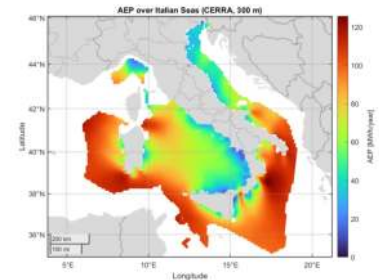
Department of Aerospace Science and Technology, Politecnico di Milano

This work presents a preliminary techno-economic evaluation of offshore airborne wind energy (OAWE) applications in the Italian maritime domain. The analysis combines an offshore wind resource assessment with an economic evaluation based on the Levelized Cost of Energy (LCoE). Wind conditions at altitudes relevant to AWE systems are analysed using two atmospheric reanalysis datasets, ERA5 and CERRA, which are compared in terms of wind speed distributions and resulting Annual Energy Production (AEP). A reference ground-generation AWE system (SkySails PN-14) is adopted to estimate site-specific energy yields and to map the large-scale offshore energy potential across Italian seas, after excluding environmentally and legally constrained areas.

The comparison between ERA5 and CERRA at 100 m shows strong temporal coherence offshore, with correlation coefficients around 0.98 and only small deviations in monthly mean values. Differences increase in coastal areas, where CERRA resolves local gradients induced by land-sea interactions, while ERA5 exhibits a smoother spatial and temporal evolution. Results show that, when extrapolated over the entire Italian offshore domain, the theoretical energy potential ranges between about 340 and 450 TWh/y. The techno-economic analysis is based on an offshore-adapted cost framework, building on the model developed in [1] and extended with a cost model for floating platforms derived for conventional floating offshore systems [2]. This analysis highlights the dominant role of offshore infrastructure and operation and maintenance over the plant lifetime in the total expenditure, accounting for more than half of the capital cost.

Despite the reduced structural mass of airborne systems, offshore deployment requires floating platforms, mooring systems, and marine operations of a magnitude comparable to those of conventional floating wind.

Despite several limitations of this preliminary analysis, the work provides a foundation for future assessments of offshore AWE and opening new avenues of investigation.

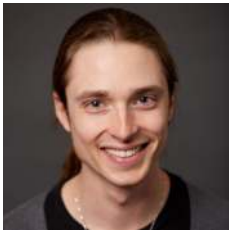


AEP density map based on the CERRA dataset at 300 m altitude [3].

References:

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This research has been supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).



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## Using Experimental Measurements of Annular Wakes to Validate Wake Models for Airborne Wind Energy Systems

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University of California, Santa Barbara

Several novel wind energy systems produce wakes with annular cross-sections (as illustrated in Figure 1), which are qualitatively different from the wakes with circular cross-sections commonly generated by conventional horizontal-axis wind turbines and by compact obstacles. Since wind farms use arrays of hundreds of turbines, good wake models are essential for efficient wind farm planning. Although circular-wake models have long been established, models for annular wakes constitute a recent development [1] and, so far, have had to rely on limited computational datasets for validation [2]. The lack of experimental data for turbulent annular wakes presently constitutes a limit to the validation and further development of wake models. To address this issue, we perform wind tunnel measurements of annular wakes. We generate wakes by suspending annular discs of varying center-opening size and porosity in a wind tunnel (as shown in Figure 1), and we report detailed measurements of mean flow velocity across each wake, for multiple locations

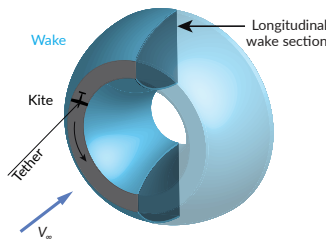


Figure 1: Left: Schematic of an annular wake. Right: example of a porous disc used for wake generation in a wind tunnel.

downstream (an example is shown in Figure 2). We find that the wake of a disc with geometry and thrust coefficient matching the AWE system simulated in [2] shows excellent agreement with said simulation results and the model of [1]. Our results provide a dataset for the development and validation of AWE wake models.

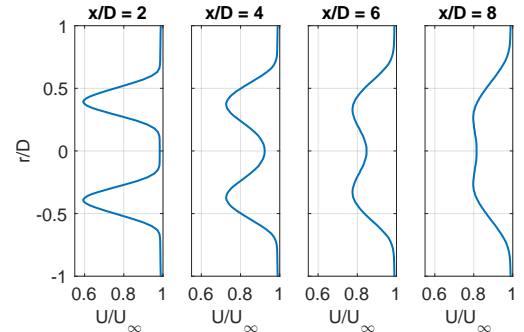


Figure 2: Wake velocity measurements for a disc with 58% solidity, and center opening equal to 64% of the diameter.

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## Data-Driven Prediction of Critical Load Events in Airborne Wind Energy Systems

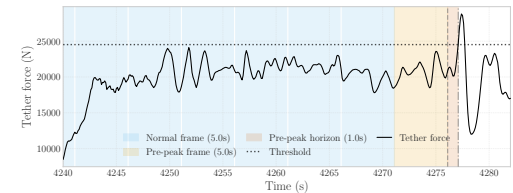
Monika Pasquali<sup>1</sup>, Roland Schmehl<sup>2</sup>, Spilios Theodoulis<sup>2</sup>, Christophe Farges<sup>1</sup>,  
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Predicting and avoiding high tether force events is crucial for the reliable autonomous operation of AWE systems. These can lead to reduced steering capability of the kite control unit (KCU) and increased structural loads, eventually resulting in long-term degradation of the kite, tether and ground-station components [1]. To address this problem, the present study explores a data-driven approach for the prediction of rare critical load events, defined as instances where the force exceeds a threshold imposed by the winch controller. The method is developed using a large-scale experimental dataset from the Kitepower leading-edge inflatable V9 kite, consisting of 12 autonomous flights, 26 hours of kite operation and more than 1000 pumping cycles, covering a wide range of wind and operating conditions. Tether force peaks are detected and used to extract pre-peak time frames that capture the system behavior before each threshold exceedance. From these frames, statistical, temporal and spectral features are computed from multiple kite, tether and ground-station measurements. A supervised classification model based on Logistic Regression is trained to distinguish normal operation from pre-peak dynamics. The proposed approach predicts critical load events up to 1 s in advance, achieving an F1-score of 81% (precision 71.2%, recall 94%) for the faulty class on in-domain data, and 90.9% (precision 97.2%, recall 85.4%) on out-of-

domain data, demonstrating strong generalization capability [2]. Moreover, the extracted features provide insight into pre-peak dynamics, enabling preventive control actions and improving AWE system reliability.



*Tether force signal segmented into 5 s frames. Exceedance of the force threshold (dashed line) defines a pre-peak horizon 1 s and preceding 5 s pre-peak frame (red). Blue frames correspond to normal operation. Identical framing is applied to all measured signals to capture the full system dynamics.*

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## Experimental RPAS-Based Vertical Wind Profiling for Wind Resource Assessment in Remote Mountainous Regions

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A deployable system for measuring wind velocity vertical profiles was developed to support the preliminary assessment of renewable wind energy resources, particularly in remote rural mountainous regions where significant wind potential remains untapped, such as the north-eastern region of Peru, as indicated by available wind resource maps.

The system developed in this study provides a flexible and cost-effective alternative for wind resource prospecting, enabling a more robust identification of areas with sufficient potential to justify the subsequent installation of a formal meteorological mast.

To address these limitations, a lightweight RPAS-based platform was designed to measure vertical wind velocity profiles using a LI-COR ultrasonic anemometer, which has been applied in similar studies [1]. Appropriate CFD analyses and laboratory tests were conducted to ensure reliable wind measurements, following similar methodologies reported in the literature [2].

Field campaign was carried out near a meteorological mast in Bayovar–Piura, Peru, to evaluate system performance and data reliability. Wind velocity was measured during stationary hovering using two setups: (1) 2.5 minutes at every 20 m between 60 and 200 m; (2) 10 m intervals at 120 and 200 m. Measurement duration was limited by RPAS battery capacity. Although not the main focus, the high-resolution sampling demonstrates potential to characterize turbulence, supporting applications in AWEC.

The results indicate that the developed system provides

a flexible, reliable, and cost-effective approach for acquiring vertical wind velocity profile data particularly for wind resource assessment. The system is suitable for preliminary, early-stage site evaluation and for comparison with other wind measurement techniques, such as tethered balloon systems, which are also considered within the funded project.



*Experimental measurements with developed system*

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Project is funded in Peru under the the expansion of English "Applied Research Projects", Contract N° PE501083423-2023-PROCIENCIA.



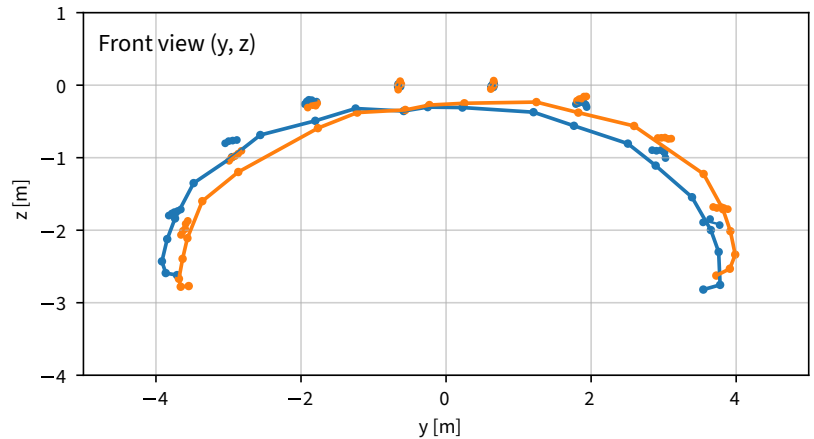
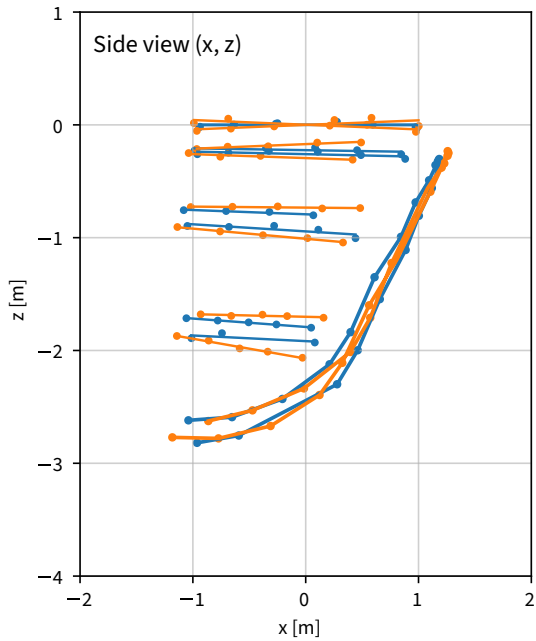
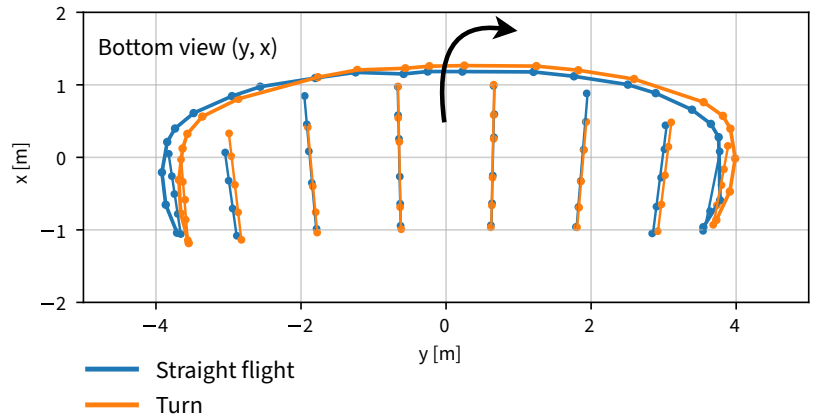
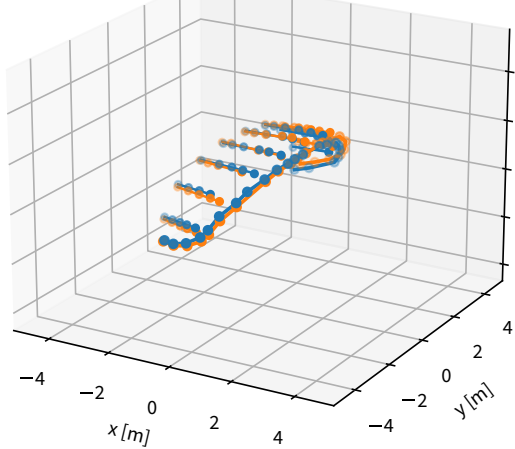
*Preparing Kitepower's V3 kite for launch at Bangor Erris, Ireland, on 9 October 2025. The kite is instrumented with a stereoscopic photogrammetry system and several other sensors for in-flight deformation measurements.*

*Kitepower's V3 kite instrumented with stereoscopic photogrammetry system and several other sensors for in-flight deformation measurements (9 October 2025).*





*Kitepower's V3 kite with marker indexing on the wing during flight. The distinction between the leading-edge (LE) markers and the strut markers is indicated, with the strut markers numbered from 0 to 7. Some markers remain unidentified, either because they do not pass the detection filters or because they are occluded in either of the camera views. Pim J. Haanen: In-flight experimental measurements of large-scale deformations on a leading-edge inflatable kite using stereoscopic photogrammetry and UWB modules. MSc Thesis, Delft University of Technology, the Netherlands (2026). [edu.nl/ke9kq](https://edu.nl/ke9kq)*



Measured shape change of Kitepower's V3 kite during a turning manoeuvre in the wing reference frame. Pim J. Haanen: In-flight experimental measurements of large-scale deformations on a leading-edge inflatable kite using stereoscopic photogrammetry and UWB modules. MSc Thesis, Delft University of Technology, the Netherlands (2026). [edu.nl/ke9kq](http://edu.nl/ke9kq)



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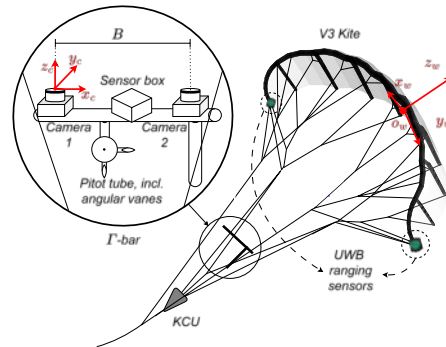


## In-Flight Experimental Measurements of Large-Scale Deformations on a Leading-Edge Inflatable Kite

Pim J. Haanen<sup>1,2</sup>, Jelle A. W. Poland<sup>1</sup>, Roland Schmehl<sup>1</sup>

<sup>1</sup> Delft University of Technology, <sup>2</sup> Kitepower BV

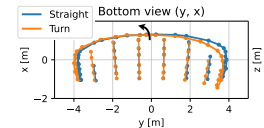
Quantitative in-flight deformation data are required to validate aero-structural models of soft-wing kites. This work presents a measurement framework that combines stereoscopic photogrammetry with wireless ultra-wideband (UWB) ranging to reconstruct large-scale wing deformations under operational conditions [1].



*Experimental setup.* A rigid  $\Gamma$ -bar mounted in the bridles carries the cameras and sensors. Tip-mounted UWB tags provide wingspan  $b$ .

The integrated assembly contains a stereo camera pair, UWB sensors, and air-data sensing on a rigid,  $\Gamma$ -shaped bar mounted in the bridles, enabling repeatable flight-test acquisition on a full-scale LEI kite. Marker tracking creates a 3D point cloud that is transformed to a wing-fixed frame to isolate rigid-body motion from shape change. Photogrammetry is fused with UWB span data to correct camera misalignment, achieving centimetre-level 3D errors, enabling comparison across manoeuvres.

Deformation states are quantified for depowering and turning and compared against a CAD reference shape. First, we observed that the in-flight projected span and area are substantially lower than the CAD shape, indicating that the CAD shape overestimates the effective lifting geometry under load. Second, depowering is captured mainly as an attitude change, with a measured pitch decrease, accompanied by modest symmetric wing curvature changes while tether force drops. Third, steering manoeuvres show the expected antisymmetric response of differential tip incidence (twist) and wing shear, inducing a coupled yaw and roll moment, turning the kite.



*Measured wing shape in straight vs turning flight.*

The resulting dataset improves the quantitative characterisation of soft-wing deformations and provides validation input for aero-structural models, supporting improved kite design and providing a pathway towards deformation-aware monitoring and real-time control.

### References:

[1] Haanen, P. J., Poland, J. A. W., Schmehl, R.: In-flight measurement of large-scale deformations of a soft-wing kite. [Manuscript in production], TORQUE (2026).

This research has been supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).



*Overview of the mobile Parachute-Ladder AWE system at the Gobi Desert test site, illustrating the complete system architecture: a helium balloon tethered to a winch truck on the right side of the photo, with the power generation unit on it, and the support vehicle on the left side. The photo was taken in Xinjiang Gobi desert in the winter 2024.*



*A helium balloon anchored to the ground in the Gobi Desert test site, with the ground support vehicle positioned in the distance. The photo was taken in Xinjiang Gobi desert in winter 2024.*

*A tethered helium balloon of the Parachute-Ladder AWE system at sunset in the Gobi Desert, with ground support equipment and marker flags visible on the desert floor. The photo was taken in Xinjiang Gobi desert in winter 2024.*



*The parachute opened in the air and captured the wind energy.  
The photo was taken in Shannxi desert in summer 2025.*





*The Parachute-Ladder AWE system in operation, featuring a helium balloon and a parachute aloft against a cloudy sky, with the ground-based winch truck with power generation unit installed visible in the lower right. The parachute opened and captured wind energy to drive the ground generator via tether rope. The photo was taken in Shannxi desert in summer 2025.*





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## A Mobile Airborne Wind Energy Prototype Utilizing Parachute-Ladder System

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The parachute-ladder AWE technology was first proposed by Guangdong High-Altitude Wind Power Technology Co.,Ltd, which is a subsidiary of Zhonglu Co.,Ltd. The parachute-ladder AWE system basically consists of a UHMWPE rope, a helium balloon connected to the top of the rope, parachutes and their opening/closing switch controllers installed on the rope, a ground winch for winding the rope, a PMSM, a 4-quadrant inverter, and an energy storage system. The helium balloon lifts the parachutes into the air via the rope. When the wind reaches a certain speed, the parachutes will open and harness wind force to drag the rope, driving the winch to rotate and generate power via the PMSM. When the rope is paid out to the limit, the parachutes are closed by the switch controllers to minimize wind resistance. Thus, the PMSM can drive the winch to retract the rope and then repeat the power-generation process.

The parachute-ladder AWE technology features the following advantages:

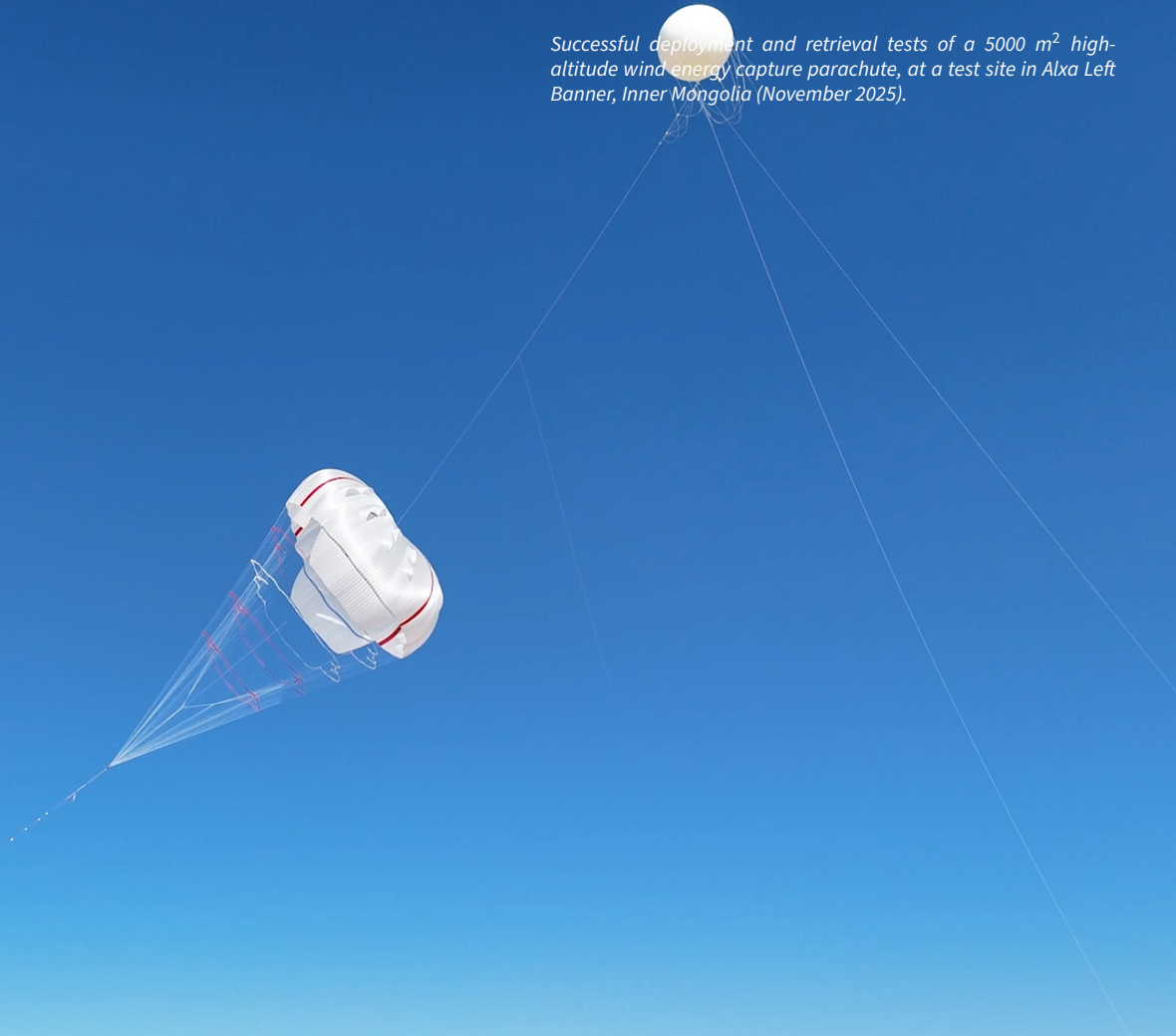
- 1.Flexible setting on number and size of multiple parachutes makes a potential prospect on power output to MW scale available
- 2.System operation up to 2km height with better and more stable wind resources
- 3.System can adjust its operating altitude according to the wind resource profile at various heights
- 4.The absence of heavy components in the parachute-ladder system makes it a safer and more economical investment.

The team has developed a mobile AWE prototype to rapidly deploy testing devices as required, verify the feasibility of parachute-ladder AWE technology, and test the system's performance in sites with diverse landscapes and wind conditions. The size of the prototype is 12m (L)×2.5m (W)×4m (H), including the vehicle. This prototype can operate outdoors in harsh conditions with temperatures ranging from -20°C to 40°C, as well as in rainy and snowy weather. Multiple series of tests have been conducted on this prototype in Shanxi and Xinjiang desert. The tests covered the entire process of lifting, static load (suspension), and dynamic load (power generation and retrieval) under different wind conditions. Data including force, power, rope speed, system efficiency, and others were recorded to optimize engineering and modeling, analyze the coefficient ( $C_p$ ) at different parachute angles, and assess industrial execution potential.



Overview of the mobile AWE prototype(left) Parachute opened in the air(right).

Successful deployment and retrieval tests of a 5000 m<sup>2</sup> high-altitude wind energy capture parachute, at a test site in Alxa Left Banner, Inner Mongolia (November 2025).



*Flight tests of a 5000 m<sup>2</sup> high-altitude wind energy capture parachute, at a test site in Alxa Left Banner, Inner Mongolia (November 2025).*





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团队 进取 真诚 务实

## Ground Power System of Parachute-Based Airborne Wind Energy System

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<sup>1</sup> Northwest Electric Power Design Institute of China Power Engineering Consulting Group Co., Ltd.

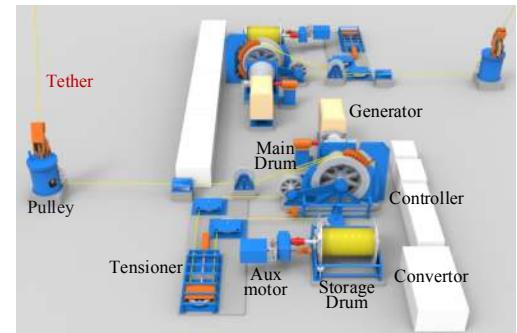
<sup>2</sup> China Power Engineering Consulting Group Co., Ltd.

Parachute-Based Airborne Wind Energy System (PAWES) is a technological pathway that enables the scaling up of AWES. The ground power system of PAWES mainly includes a universal pulley, main drum, mechanical transmission system, motor-generator, and converter. For PAWES with large amounts of tether, additional components such as tether storage drum, tensioner, auxiliary drum, and auxiliary motor are also needed. A typical ground generation configuration of PAWES is illustrated in the figure.

The airborne and ground components of PAWES can be configured as “one-to-one” or “many-to-one” manner. The “one-to-one” configuration involves one set of airborne parachutes corresponding to one set of ground component. In this setup, the overall power generation capacity of the AWES is primarily limited by the maximum wind-capturing capability of the airborne components. According to publicly available data, the maximum power of a single fixed-wing ground-based or flexible-wing ground-based AWES prototype is unlikely to exceed 1 MW, whereas the estimated maximum power generation of a PAWES prototype can reach 5 MW [1].

The “many-to-one” configuration involves multiple sets of airborne parachutes corresponding to one set of ground component. This can be implemented through two specific structural schemes. One is the mechanical power combining scheme, which uses a split-and-combine gearbox to merge the mechanical power from multiple main drums. However, this mechanical combining method only supports synchronous operation where all parachutes ascend and descend simultaneously.

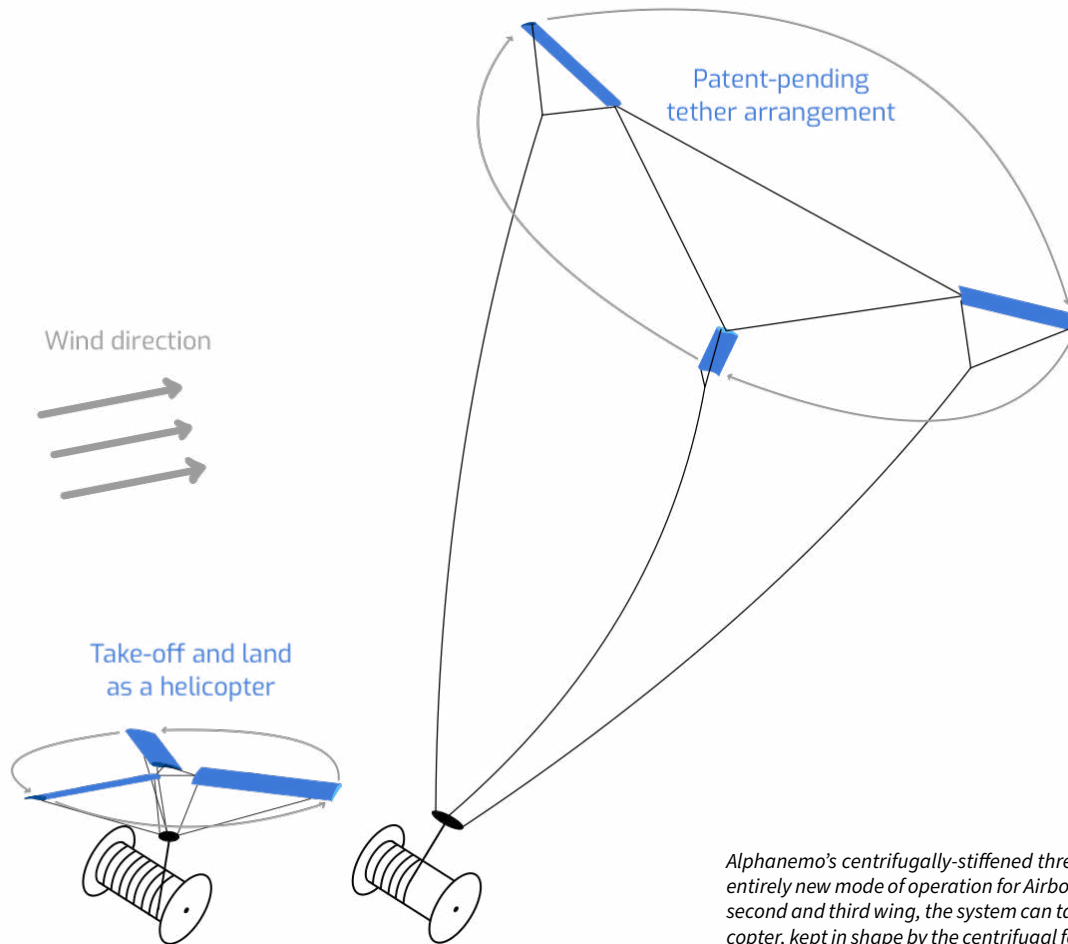
The other scheme is the electrical power combining scheme. In this approach, each main drum is connected to a generator in a modular configuration, with one converter per generator. The converters can adopt a “common DC bus” electrical topology, which includes multiple rectifier units and one inverter unit. This scheme imposes no restrictions on the input circuits, allowing connected units to operate either synchronously (“same up, same down”) or asynchronously (“free up and down”). It offers flexible control and operational modes, making it a promising solution.



3D visualization of ground power system of PAWES (2×5 MW)

### References:

[1] Wu Kuanyu, Zuo Zijun, Shi Zijie, et al.: Aerodynamic principles and modeling of high-altitude wind harvesting parachute systems. *Acta Aerodynamica Sinica*, 2026, 44(X): 1–11. doi:10.7638/kqdlxb-2025.0103



*Alphanemo's centrifugally-stiffened three-wing design unlocks an entirely new mode of operation for Airborne Wind Energy. Adding a second and third wing, the system can take-off and land like a helicopter, kept in shape by the centrifugal forces of their own weights.*

# Passive Stability in Centrifugally-Stiffened Airborne Wind Energy Systems

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Centrifugally-stiffened Airborne Wind Energy Systems (AWES) consist of multiple kites constrained to circular orbits around a common center by one or more cross-kite tethers. This configuration effectively transforms the kite ensemble into a symmetric rotor, reducing aerodynamic drag in long ground tethers while avoiding the control and coordination complexity typically associated with multi-kite systems.

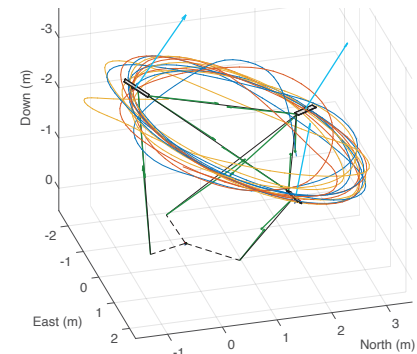
We present a novel AWES architecture that is passively stable by design. Stability is achieved without onboard control systems or actuators, substantially reducing system complexity and mass. Passive stability arises from specific parameters for tether geometry, kite inertia, and system rotational speed, which together provide restoring forces against perturbations.

We identify key design parameters and constraints necessary for passive stability. These findings are supported by high-fidelity numerical simulations and extensive experimental validation using small-scale physical prototypes. Insights from the experiments informed the development of the simulation framework, while simulation results guided subsequent experimental design, enabling iterative refinement.

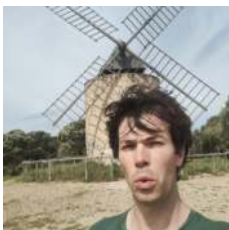
Experimental results demonstrate the feasibility of passively stable centrifugally-stiffened AWES and confirm the predicted stability regimes. We further extract the underlying mechanical principles and scaling laws governing system behavior. Finally, we discuss how this architecture can be applied to both torsion-based and pumping-cycle power generation, highlighting its potential for scalable and robust airborne wind energy harvesting.



*Experimental prototype in operation.*



*Matlab simulation showing the trajectories of the three kites.*



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## Benchmarking the KEEEP Project Rocking Arm Using AWEbox

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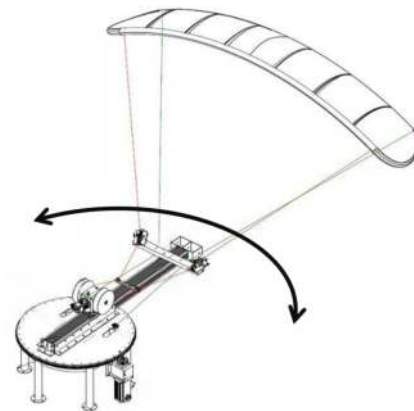
<sup>2</sup> University of Freiburg.

Airborne wind energy (AWE) is currently experiencing a rapid increase in the diversity of harvesting methods and architectural designs. While some of these technologies have reached the stage of experimental field testing, many promising concepts remain within the realm of numerical simulation. To evaluate these disparate approaches on a level playing field, unified modeling frameworks are essential for ensuring that comparisons of aerodynamic performance and power output are consistent.

In this study, we utilize AWEbox [1], a high-level optimal control framework, to perform a comparative performance analysis across three distinct production modes. Specifically, we benchmark the established lift-mode and drag-mode — both of which are already implemented in the software — against a novel approach developed within the KEEEP project [2]. This new method relies on a ground-based rocking arm to convert the kite's mechanical energy into electricity. The arm is put into motion by having the kite fly a lemniscate trajectory (horizontal figure-eights), generating alternating lateral forces and rocking the arm left and right. As shown in the sketch, this configuration allows for a kite that is entirely controlled from the ground and features no electrical components, eliminating the airborne electrical wires. The simplicity of the design should prove advantageous in situations where portability and reliability are key.

By integrating the rocking arm's kinematics into AWEbox, we are able to solve complex trajectory optimization problems under identical wind profiles and physical constraints for all three systems. This research provides a direct quantitative assessment of the potential of the

rocking arm concept, highlighting its efficiency and structural requirements in relation to industry-standard AWE modes.



*Schematic of the KEEEP device. The arrow illustrates the oscillatory motion used to transfer wind energy to a generator.*

### References:

[1] De Schutter, J., Leuthold, R., Bronnenmeyer, T., Malz, E., Gros, S., Diehl, M.: AWEbox: An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems. *Energies* **16**(4), 1900 (2023)

[2] Bavoil, A., Caillau, J.-B., Dell'Elce, L., Nême, A.: Airborne wind energy: the KEEEP project. <https://hal.science/hal-05366391> (2025)



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## Airborne Wind Energy

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These technologies still require further research, testing, and industrial development before they can be deployed commercially, but precisely for this reason they represent a strategic opportunity for Europe: a chance to lead from knowledge and innovation.

The European Union has already laid solid foundations through its R&D programmes, such as Horizon 2020 and Horizon Europe, which support pioneering innovation projects. In addition, under the new Renewable Energy Directive, which sets minimum national targets of 5% of new renewable capacity coming from innovative technologies by 2030, Europe is turning innovation into tangible solutions for our energy future.

It is essential to continue supporting research while at the

same time building industrial and human capacities to innovate, design, and manufacture within our own borders. This technology opens up new opportunities in rural areas, islands, or maritime environments where conventional wind power is not viable.

To turn this promise into industrial and energy reality, Europe must act on three fronts: fit-for-purpose regulation, sustained financing, and a long-term strategic vision. Airborne wind energy encapsulates the ambition of a Europe capable of flying higher, combining energy sovereignty, industrial leadership, and environmental sustainability.





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**POLITECNICO  
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## From Towers to Tethers: Lessons Learned, Lessons Ahead

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Over the past two decades, research and innovation in wind energy have been extraordinarily intense, transforming wind power from a niche renewable option into one of the most economically competitive sources of electricity. Continuous advances in aerodynamics, materials, structural design, control systems, and large-scale manufacturing have dramatically reduced the cost of energy (CoE), particularly for onshore wind. Today, onshore turbines compete directly with fossil-based generation in many markets, a result achieved through systematic optimization, upscaling, improved reliability, and an increasingly mature supply chain. Offshore wind, while still facing significant economic and logistical challenges, is following a similar path. Although cost reduction and industrial consolidation are ongoing, the technological roadmap is relatively well defined.

Airborne wind energy (AWE), on the other hand, is at a much earlier stage of development. The prospect is appealing: access to stronger, more consistent winds at higher altitudes, potentially lower material consumption, and new deployment scenarios. However, the industry is still exploring its fundamental architectures, operational concepts, and scaling strategies. Many of the questions that were central to wind turbines decades ago—structural durability, load mitigation, control robustness, certification, maintainability, and bankability—are re-emerging in a new and more complex dynamic context.

The experience gained with conventional wind energy offers both guidance and reasons for caution. The systematic approach that has enabled turbine costs to be re-

duced (rigorous modeling, validation campaigns, incremental scalability, industrial standardization) provides a methodological roadmap. At the same time, the challenges of the past remind us of the risks of premature scalability, underestimating operational complexity, or neglecting reliability in the pursuit of performance.

The key question, therefore, is whether the AWE community can learn from this adjacent technological history: can it replicate the virtuous circle of innovation and cost reduction while avoiding the mistakes made in the past? The journey from towers to tethers is not a simple transfer of technology, but it can benefit greatly from the lessons learned in over twenty years of wind energy evolution.



*A personal research path [Graphic design by Elisa Croce]*



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## Synergies between Terrestrial and Airborne Wind Energy

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The Horizon Europe MERIDIONAL project [1] is developing tools to better predict the performance and loads of both conventional wind turbines and airborne wind energy systems. The aim of the project is to develop a tool chain that can be used to model a range of wind inflow conditions to help better estimate annual energy production and fatigue. The tool chain is underpinned by a new knowledge and data hub called WindLab [2] developed with sister projects FLOW and AIRE and which is available to the wider wind energy community.

This presentation will provide highlights from this project, particularly with regard to the synergies between terrestrial turbines and airborne wind energy systems. For example, kite power systems give an opportunity to measure wind inflow and temperature profiles up to heights which are of relevance to both types of systems. Results will be presented which will show how kite power systems can measure wind speeds with comparable accuracy to ground-based lidar systems [3].

Furthermore, the combination of airborne wind energy systems with terrestrial turbines has the potential to provide firmer wind power generation given that airborne systems can harvest wind speeds at multiple heights. A case study will be presented of how this synergy can be exploited for an offshore wind farm.

Finally, some of the tools developed by the project for assessing the performance of terrestrial and airborne wind energy systems will be summarised.

### References:

[1] <https://meridional.eu>

[2] <http://windlab.hlr.de>

[3] Cayon, O., Watson, S., and Schmehl, R.: Kite as a sensor: wind and state estimation in tethered flying systems, *Wind Energ. Sci.*, 10, 2161–2188, doi:10.5194/wes-10-2161-2025, 2025.

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## Energy-Optimized Control of a Magnus-Effect Winged Quadcopter

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This work investigates the energy performance of a Magnus-effect winged quadcopter (MWQ) through an optimization-based control allocation framework and explores its potential for tethered airborne wind energy systems (AWES). The MWQ combines a multirotor platform with rotating cylindrical wings that generate aerodynamic lift through the Magnus effect. Unlike conventional lifting surfaces, this lift is actively modulated through cylinder spin ratio rather than angle of attack, providing additional aerodynamic control authority.

A nonlinear optimization-based control allocation strategy is developed to distribute the required control forces between the quadcopter rotors and the Magnus cylinders in order to minimize total onboard energy consumption while preserving trajectory-tracking performance [1]. Experimental results obtained on a 1.766 kg MWQ prototype with a total Magnus-cylinder surface area of 0.0308 m<sup>2</sup> show that Magnus-assisted flight reduces the thrust demand on the propellers, achieving approximately 9% net power saving, including the power required to spin the cylinders, at wind speeds above 5 m/s. These gains translate into improved endurance and demonstrate that actively generated lift can compensate for some of the operational limitations of conventional multirotors.

Building on these results, the proposed framework is extended to tethered AWES operation. In this context, the MWQ architecture is particularly attractive because Magnus-based lifting surfaces can generate high lift with a compact surface area, offer robust control through active cylinder rotation, and are less sensitive to wind variations and tether drag effects. The adapted approach for AWE applications is validated through a series of indoor and outdoor tests conducted under no-wind and

turbulent wind conditions [2]. Indoor experiments enable precise evaluation of the control strategy and energy performance in a controlled environment, while outdoor tests demonstrate the feasibility of the approach in real-world conditions. The results highlight the potential of the MWQ platform as an energy-efficient airborne system and a promising building block for future AWES architectures.



MWQ flying outdoors.

### References:

[1] Z. Azaki, et al. "Magnus-Effect Winged Hybrid UAV System: Improved Energy Efficient and Autonomy Through Control Allocation Strategy," *IEEE Transactions on Aerospace and Electronic Systems (TAES)*, vol. 61, no. 2, pp. 1610-1629, 2024. DOI: [10.1109/TAES.2024.3464569](https://doi.org/10.1109/TAES.2024.3464569).

[2] Z. Azaki, et al. "Advanced Control Strategies for Tethered Magnus-Effect Quadcopter Systems: Optimization-Based Control for Safe Takeoff and Landing under Wide Wind Range," **submitted at IFAC World Congress with Journal option to Mechatronics**, 2026. SSRN: [ssrn.5954631](https://ssrn.com/abstract=5954631)



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## Optimisation and Control in Airborne Wind Energy Systems: A PRISMA Systematic Review

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Research groups and startups have led to a sharp rise in the number of scientific papers on Airborne Wind Energy Systems (AWES), showing how quickly this technology is moving from concept to large-scale experiments. This growth makes it important to organise the existing work on optimisation and control in a structured way.

In this work, a systematic literature review is proposed with the aim of addressing the following research question: Which optimisation and control methods have been applied in the scientific literature to the modelling, design, and operation of Airborne Wind Energy Systems?

We follow the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology which offers a set of reporting items and a flow diagram, Fig. 1, that help authors explain why the review was done, how it was carried out, and what the main findings are [1]. The study focus on peer-reviewed journal articles and conference proceedings indexed in SCOPUS and Web of Science only. Search queries combine Airborne Wind Energy keywords with terms related to optimisation, control, and system design, using the same strategy in both databases.

The main goal is to identify the optimisation methods used in AWES research. These include optimal control formulations, nonlinear programming, mixed-integer approaches and heuristic or metaheuristic algorithms. For each selected paper, the review document how the optimisation problem is formulated, including the objective functions and constraints, and the used methodologies.

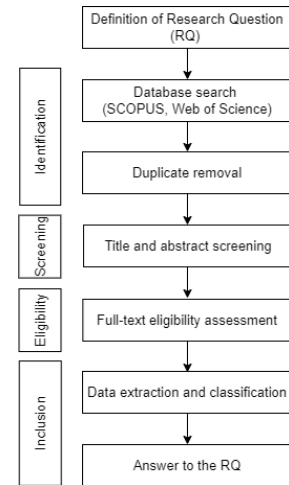
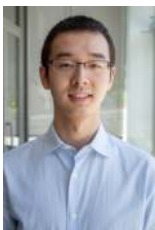


Figure 1: The PRISMA methodology scheme.

### References:

[1] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., Moher, D. *The PRISMA 2020 statement: an updated guideline for reporting systematic reviews*. *BMJ Publishing Group* **372**(71) (2021).



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## Wind Adaptive Path Planning for Airborne Wind Energy System

**Yufei Zhu, Taewoo Nam, Xintong Deng, Chiming Zhao**

Toyota Research Institute of North America

A Toyota research team is advancing fundamental technologies for Airborne Wind Energy (AWE) systems to overcome key technical challenges in real-world applications. A primary challenge is the continuously shifting wind direction, requiring constant realignment of the kite's flight path.

To address this, we refined our Figure-8 path-tracking approach by incorporating Fechner's two-waypoint scheme [1], enhancing robustness. In the outer control loop, we implemented wind-adaptive path planning that dynamically adjusts the azimuth angle of target waypoints based on asymmetries in kite velocity or tether tension between the two diagonal segments of the Figure-8 pattern, requiring no lidar wind sensor.

The algorithm was first validated through simulations using a detailed flight dynamics model and then tested in flight with a small-scale proof-of-concept (POC) kite. Preliminary results show the system's ability to maintain smooth Figure-8 trajectories, laying the foundation for integrating a velocity-based, wind-adaptive path planner to support long-endurance power generation.

Further testing confirms the algorithm effectively realigns the kite's target path in response to changing wind directions. The Toyota team plans additional experiments,

including parametric studies of key variables, to deepen understanding and optimize performance. Additional findings from these tests will be presented at AWEC2026.



*Flight testing of the AWE kite system to validate the wind-adaptive path planning method, Romney, IN, Dec/9/2025.*

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## Disturbance-Learning MPC for Wave-Induced Motion Rejection in Offshore Airborne Wind Energy Systems

Syed Hassan Ahmed, Lorenzo Fagiano

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Deep-offshore airborne wind energy systems (AWES) are subject to significant platform motions induced by ocean waves. These motions introduce disturbances affecting the relative alignment between the floating platform and the airborne vehicle [1]. These effects are particularly critical during takeoff and landing phases, where misalignment can lead to degraded performance or collision risks.

This work proposes the application of a disturbance-learning model predictive control (DL-MPC) framework [2] to mitigate wave-induced platform motions in offshore AWES. The approach exploits the predominantly periodic nature of wave disturbances, by learning a data-driven disturbance model online from measured system responses and embedding it directly into the MPC prediction model. The learned disturbance model enables the controller to anticipate future platform motions and proactively compensate for their effects, while preserving constraint satisfaction and robustness properties through a tube-based MPC structure.

The proposed method builds upon a recently developed DL-MPC framework for periodic disturbance rejection [2] and extends it to the AWES context. Simulation results on a floating platform AWES model show that the proposed controller significantly improves relative positioning and alignment compared to standard MPC formulations, while effectively reducing motion-induced tracking errors and enhancing operational safety. These results highlight the potential of disturbance-learning MPC as a promising control technique for reliable and safe offshore

deployment of airborne wind energy systems.

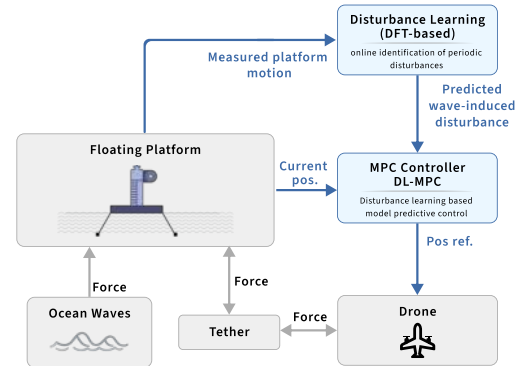


Illustration of the DL-MPC approach applied to an offshore flyGen AWES.

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## Development and Testing of an Airborne Wind Energy System

**Taewoo Nam<sup>1</sup>, Yufei Zhu<sup>1</sup>, Xintong Deng<sup>1</sup>, Chiming Zhao<sup>1</sup>**  
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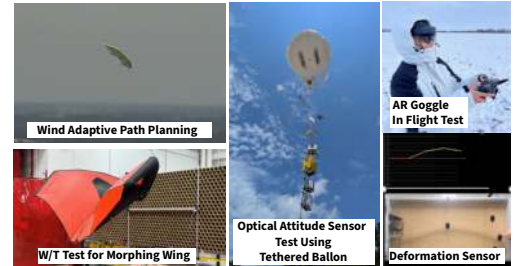
A Toyota research team is developing the “Mothership,” a large tethered wing [1] designed for high-altitude, long-endurance, stationary missions such as airborne wind energy (AWE) harvesting. They created a small-scale proof-of-concept AWE system featuring a 6,m<sup>2</sup>, 4,kg kite equipped with a flight computer, four leading-edge control surfaces, and pitch control. The system also includes a winch with a 1.5,kW generator and a ground station for real-time monitoring and control. Following the successful demonstration of the first fully automated pumping cycle test in 2022, the team has been advancing new technologies for AWE systems:

- A morphing mechanism for an inflatable wing that improves lateral stability during landing.
- A wind-adaptive path planning algorithm that continuously adjusts the flight path based on changing wind conditions.
- An optical attitude sensor estimating the kite’s pitch and roll as a backup to IMU sensors.
- A deformation sensor measuring in-flight wing deformation.
- Augmented reality goggles that overlay critical data onto the pilot’s view to enhance situational awareness, efficiency, and safety.

The presentation will provide a concise introduction to these technologies, share key insights from our recent integration efforts within an AWE prototype system, and outline our future plans.



Images superimposed to depict the Figure-8 flight path of the AWE kite during Phase 2 test in March 2023



Technologies progressing in 2025 to support AWE systems, developed by Toyota Research Institute of North America

References:

[1] Eiji Itakura.: "High Altitude Aerial Platform 'Mothership' Project Vision and Progress", AIAA SciTech 2024. doi:10.2514/6.2024-2094



*Wind Fisher team in front of the MAG prototype.*



*Wind Fisher MAG prototype flying with a plane in the background.*

*Wind Fisher MAG prototype on the ground.*



*From left to right, Wind Fisher CEO Stephane Vidaillet, Transpolis CEO Philippe Lamoine, Wind Fisher President Garrett Smith, Saint-Maurice-de-Rémens mayor Eric Gaillard and Wind Fisher CSO Armand Tardella celebrating MAG prototype official launch.*





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## **Development and Flight Testing of a Magnus-Effect Airborne Wind Energy System**

**Camille Marrel, Yacine Boucheriguene, Estéban Carvalho, Aurélien Carriquiry, Garrett Smith, Armand Tardella**

Wind Fisher SAS, 38000 Grenoble, France

At Wind Fisher, we are currently undertaking the development of a unique airborne wind energy system based on the Magnus effect. Since July 2025, Wind Fisher's operational team has been familiarizing itself with the MAG15, Magnus Airborne Generator, the company's first lighter-than-air prototype with a wingspan of 15 meters. It is composed of two cylindrical balloons filled with helium, that are rotated from the ground by eight drums and electric motors, which are also used to generate electricity. This flying laboratory allows the operational team to learn a great deal without risking damage to the prototype in the event of loss of control or unforeseen circumstances. This campaign proved that take-off and landing are easy and practically risk-free.

The MAG15 offers a crosswind aerodynamic performance that is considered a good compromise between that of a rigid wing and a soft wing, with a better gust response.

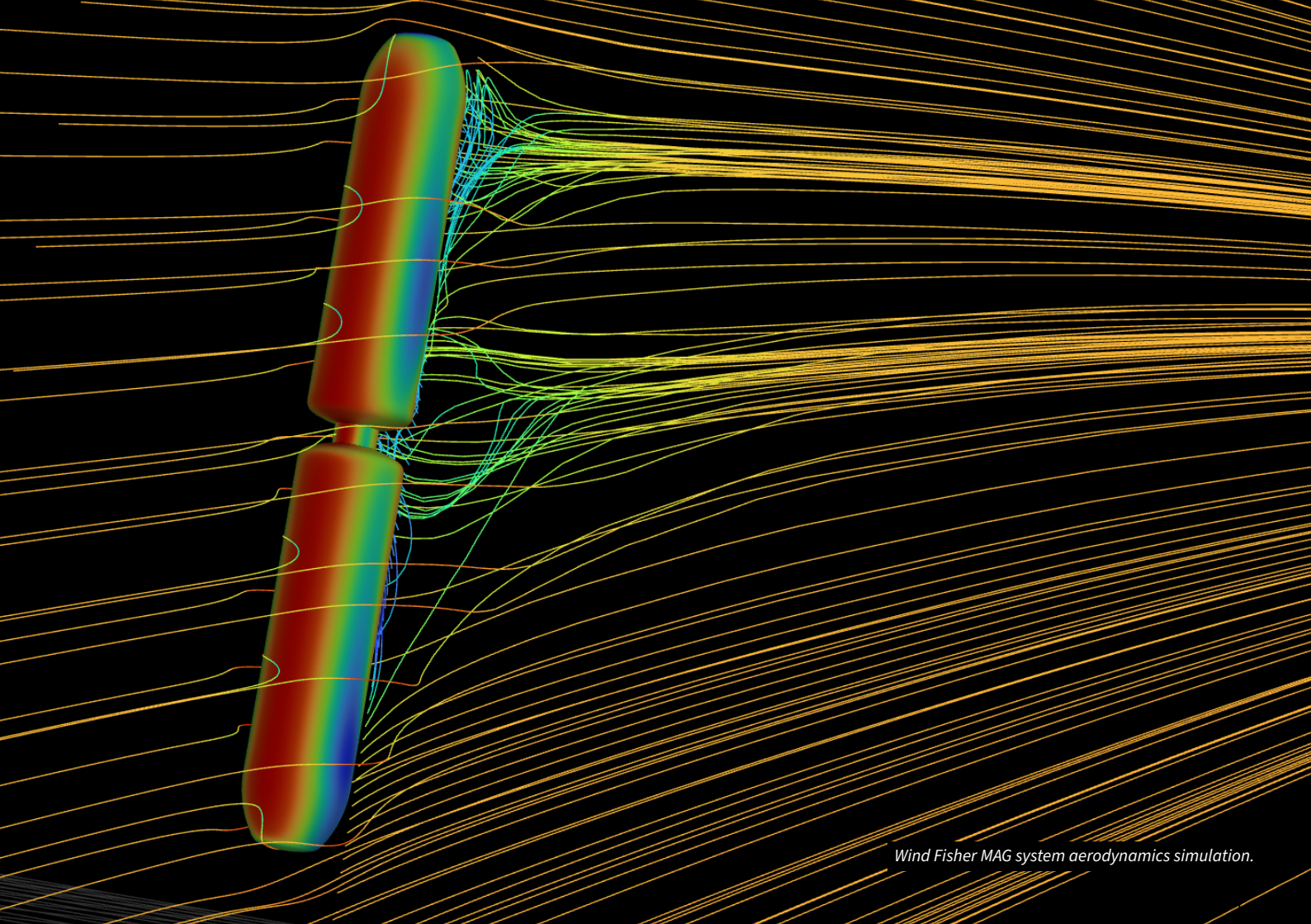


*MAG15 landing on it's ground station, Transpolis, Fr.*

The test campaign is taking place at the Transpolis test center, in France, a suitable site that offers numerous advantages, including a constant wind direction and a large safety area. After validating the take-off and landing procedures, the operational team conducted flight tests at heights of between 100 and 120 meters, compared to the 40 meters with the previous prototype.

The MAG15 is fully equipped with numerous sensors for data collection using either onboard or ground based measurements. One of its main objectives is to produce as much data as possible about the kite behavior, the apparent wind speed and direction, Magnus effect coefficients and performance, etc.

The presentation will provide an overview of the latest test campaign, including the results obtained and feedback from the operational team, such as lessons learned regarding "positive lead-out" on small rope diameters, the ability to take off and land safely, prototyping challenges related to fabric creep, and the initial aerodynamic data collected during the latest test phase.



*Wind Fisher MAG system aerodynamics simulation.*



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## Iterative Development and Field-Testing of a Compact AWES Prototype: Design Upgrades, Operational Challenges, and Performance Improvements

Filip Korzekwa, Paweł Konieczny

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Developing small-scale Airborne Wind Energy Systems requires addressing tightly coupled challenges spanning aerodynamics, mechatronics and automation, system integration, and operational safety under outdoor test conditions. This paper reports experiences from an industrial R&D process at Njord Energy aimed at building and commissioning a 3.5 kW ground-generation AWES demonstrator based on an LEI kite. The system is operated using radio control via an RC transmitter, and the work focuses on iterative engineering development and validation under realistic outdoor test conditions.

The contribution is structured around an iterative development methodology consisting of identification of limitations during testing, formulation of an engineering hypothesis, implementation of a bounded modification, and verification under controlled conditions. The system architecture is described from a functional perspective, separating the airborne segment, tether subsystem, and ground infrastructure. The ground infrastructure is treated as an energy interface and operational platform providing measurement and telemetry, data logging, and safety and operational layers. Key classes of issues typical for small-scale development platforms are discussed, including multi-domain integration constraints, sensitivity to environmental disturbances, robustness of the measurement and telemetry chain, repeatability of operational procedures, and design-for-test and design-for-maintainability considerations.

The paper further highlights how successive design upgrades and operational adjustments led to measurable

improvements in test readiness and operational robustness, including reduced telemetry failures and an increased successful test completion rate, thereby making the engineering contribution more explicit. The main conclusion is that sustained progress in demonstrator maturity is primarily driven by systematic risk reduction enabled by modularity, instrumentation, and staged verification, from bench and ground tests to outdoor trials. This approach shortens the learning loop and supports stable increases in system readiness even when experimental datasets remain limited. The findings are relevant for organizations building AWE capability from early prototype level, where engineering learning speed and experimental robustness are critical.



*Njord's AWE prototype system*



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## KITELab: A Low-Cost Mobile Iron Bird for Test and Evaluation of Tethered-Kite Systems

Kartik Anand Pant<sup>1</sup>, Yufei Zhu<sup>2</sup>, Xintong Deng<sup>2</sup>, Chiming Zhao<sup>2</sup>, Taewoo Nam<sup>2</sup>, Inseok Hwang<sup>1</sup>  
<sup>1</sup> Purdue University  
<sup>2</sup> Toyota Research Institute of North America

Our team at Purdue University, in collaboration with Toyota Research Institute of North America, has developed *KITELab*, a low-cost, lightweight, and modular iron bird designed for the rigorous test and evaluation of guidance, navigation, and control (GNC) architectures for tethered-kite systems [1], as shown in Fig. 1. The goal of this platform is to improve the reliability of airborne wind energy (AWE) harvesting systems by enabling rapid prototyping and benchmarking of onboard sensors, actuators, and flight control units in a controlled environment.

The proposed ironbird design enables three levels of testing: *tabletop evaluation*, *ground-based hardware-in-the-loop (HIL) experiments*, and *UAV-mounted flight testing to simulate kite-like flight conditions*. It features a compact electronics stack based on a Raspberry Pi 5 (as shown in Fig. 2) and a 3D-printed ergonomic structure optimized for mobility.

Experimental results demonstrate the effectiveness of the method through a comparative analysis of VectorNav VN-200 and VN-300 inertial navigation systems, identifying the dual-antenna VN-300 as better suited for high-altitude navigation. Additionally, the study validates a figure-of-eight path-planning and control architecture that uses *bio-inspired flaps* as control effectors, demonstrating the testbed's ability emulate changing wind conditions. Overall, the study highlights the potential of *KITELab* to significantly reduce the manpower and weather dependencies traditionally associated with full-scale flight campaigns for tethered-kite development.



Fig. 1: Overview of proposed *KITELab* iron bird. The image on the left shows a fully inflated tethered-wing system with bio-inspired flaps as a control effector. On the right side, we have our *KITELab* testbed with a compact placement of the flight control unit and the control effectors.

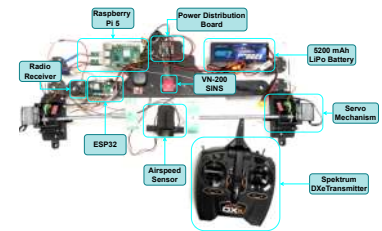


Fig. 2: Components of *KITELab* testbed, including a flight computer, sensors and servo systems for a tethered-kite system compactly placed for HIL experiments.

### References:

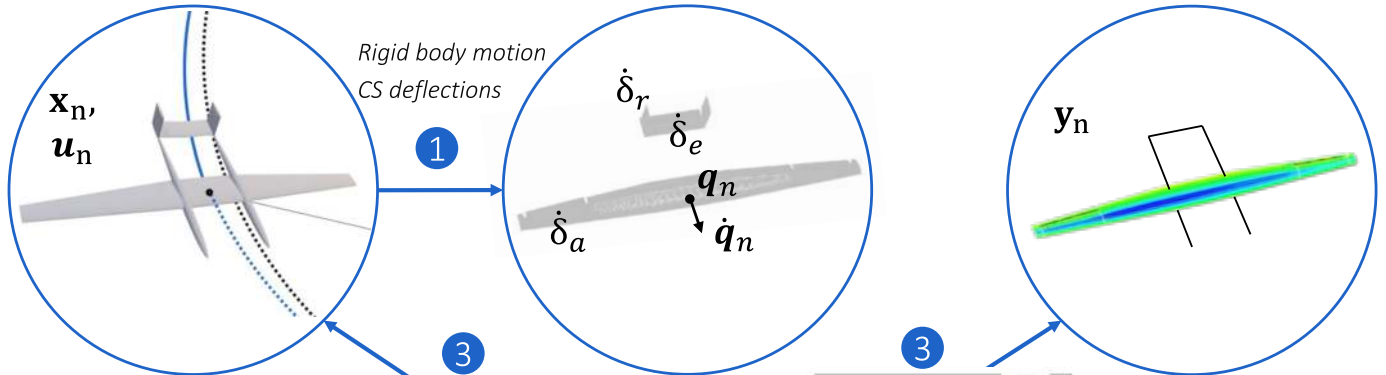
[1] Y. Zhu, X. Deng, R. Gupta, and T. Nam, "Navigation and flight control for airborne wind energy kite," in *AIAA SCITECH 2024 Forum*, p. 2097, 2024.

# Dynamics & control

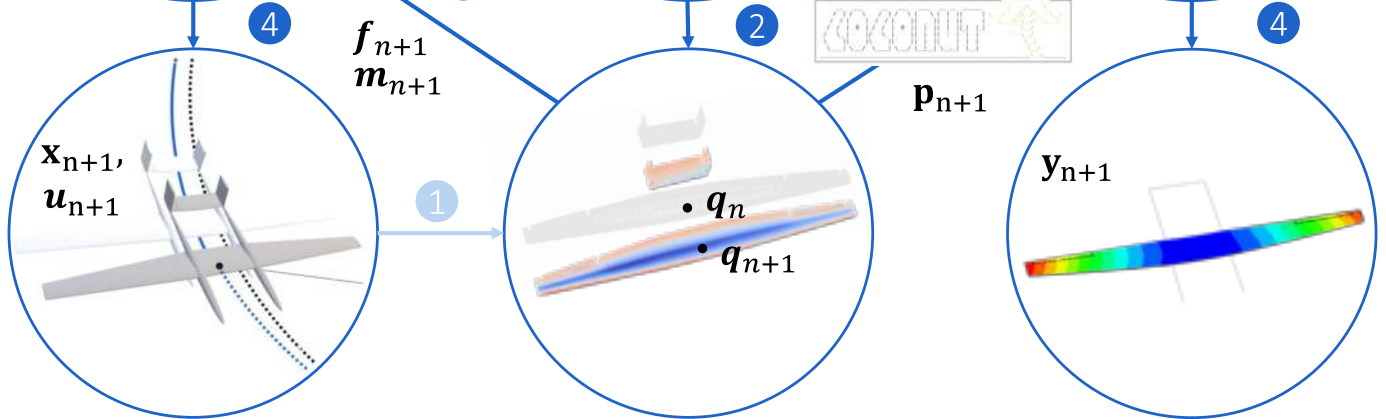
# Virtual wind environment

# Structural dynamics

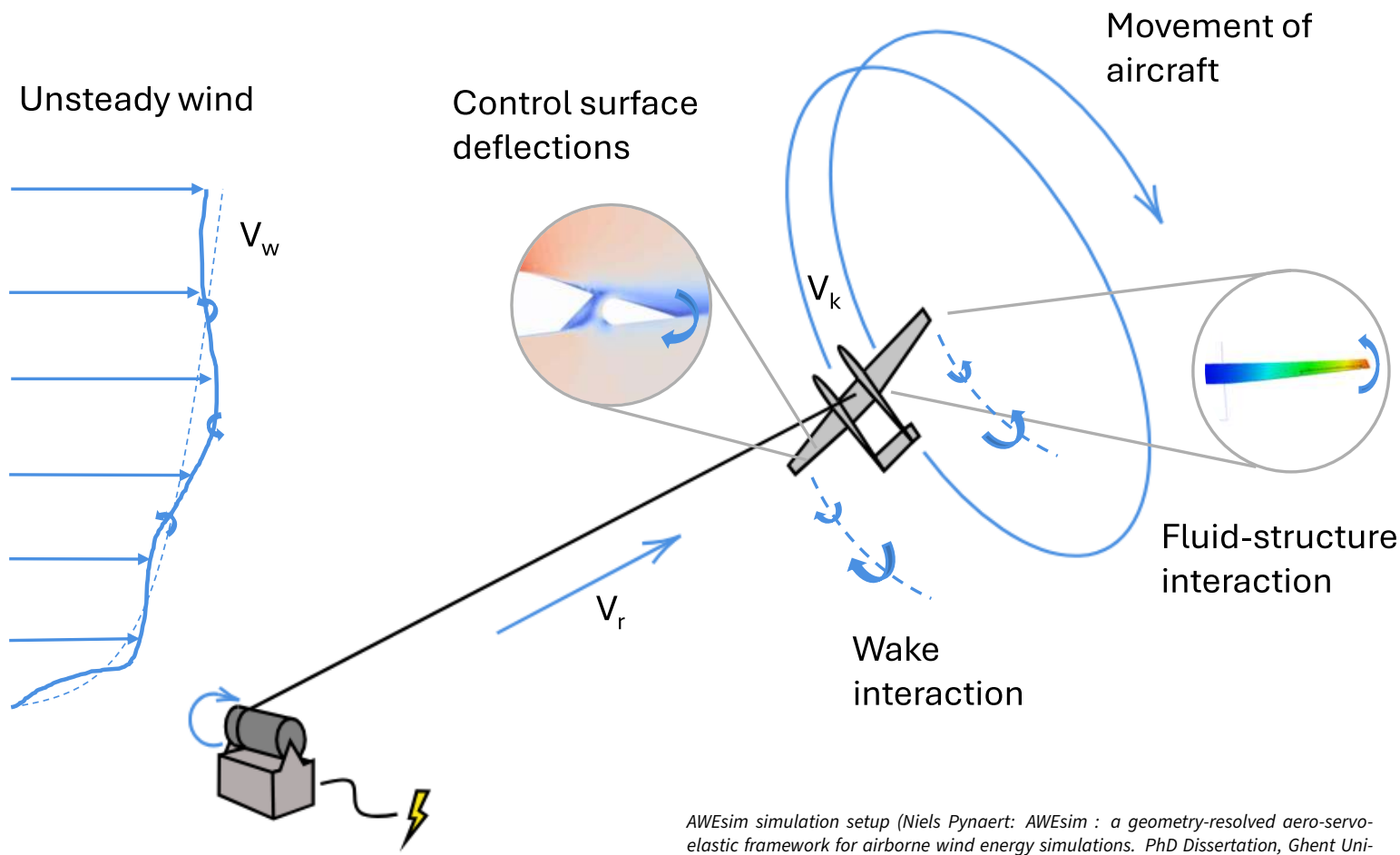
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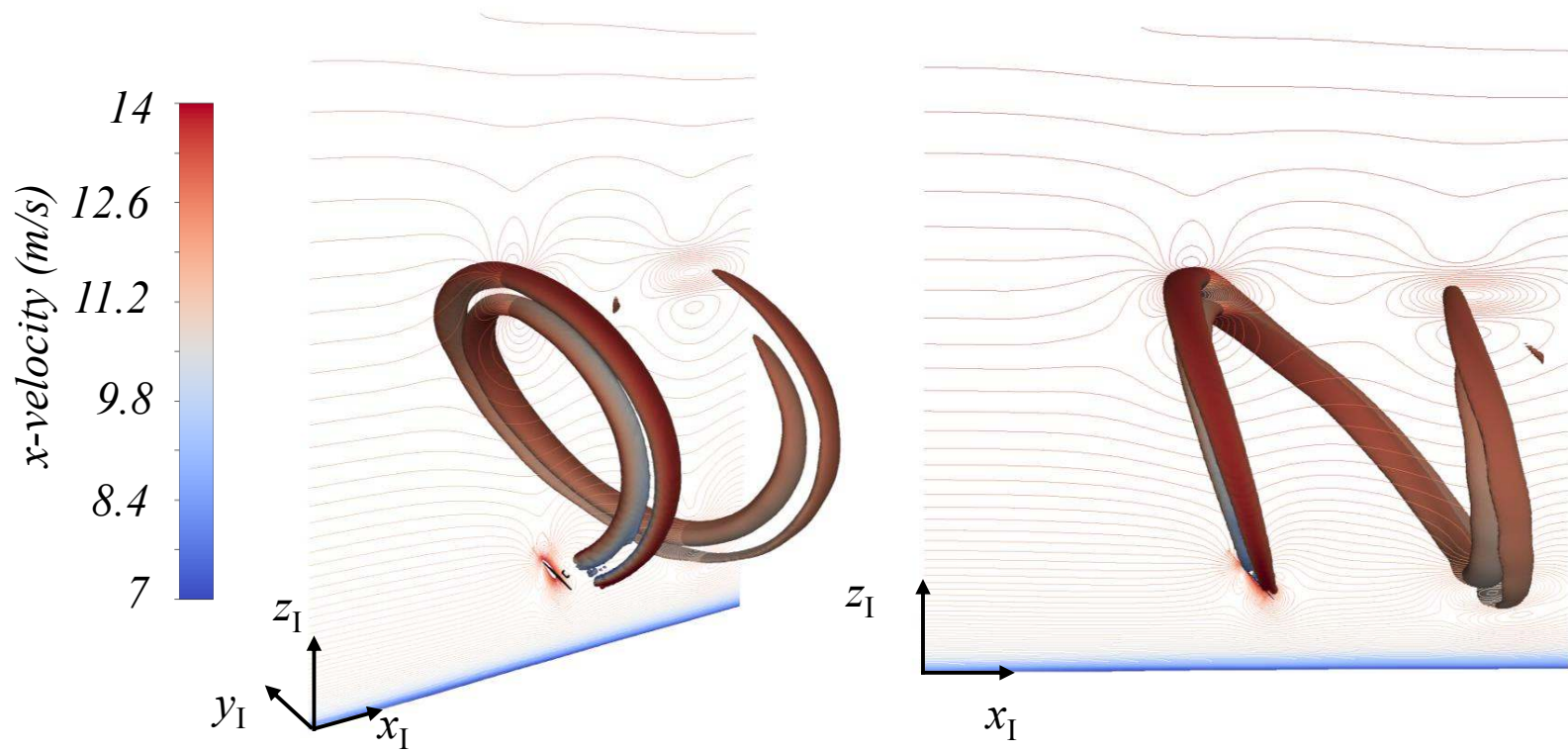
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*AWEsim coupling steps (Niels Pynaert: AWEsim : a geometry-resolved aero-servo-elastic framework for airborne wind energy simulations. PhD Dissertation, Ghent University, 2026. <http://hdl.handle.net/1854/LU-01KJSKYBQ1DBMN7WAJY1K9GW83>).*



AWESim simulation setup (Niels Pynaert: AWESim : a geometry-resolved aero-servo-elastic framework for airborne wind energy simulations. PhD Dissertation, Ghent University, 2026. <http://hdl.handle.net/1854/LU-01KJSKYBQ1DBMN7WAJY1K9GW83>).



Wakes created by the kite (Niels Pynaert: *AWESim : a geometry-resolved aero-servo-elastic framework for airborne wind energy simulations*. PhD Dissertation, Ghent University, 2026. <http://hdl.handle.net/1854/LU-01KJSKYBQ1DBMN7WAJY1K9GW83>).



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## AWEsim: A Geometry-Resolved Aero-Servo-Elastic Framework for Airborne Wind Energy

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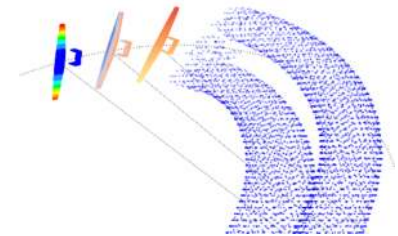
<sup>2</sup> MIRO core lab, Flanders Make @ UGent

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Airborne wind energy (AWE) aircraft experience strong unsteady aerodynamics driven by the coupled interaction of aerodynamics, structural deformation, flight dynamics, and control. Understanding this aero-servo-elastic behavior is essential for achieving both safe operation and high power output. This work presents AWEsim, a geometry-resolved aero-servo-elastic framework for simulating AWE systems. The framework couples three disciplines: a virtual wind environment (VWE), evaluated by computational fluid dynamics, flight dynamics and control, and structural mechanics, using CoCoNuT. The VWE resolves all lifting surfaces using incompressible unsteady RANS with overset grids. For flight dynamics and control, AWEbox [1] is used, relying on 6 Degrees of Freedom dynamics and model predictive control. Structural deformations are computed using a finite-element model of the aircraft. The VWE and AWEbox are two-way coupled by aerodynamic forces and moments, rigid-body motion, and control surface deflections, while aerodynamic pressure is one-way coupled to the structural model.

The framework is applied to the MegAWES reference aircraft [2] flying a 20-second power cycle in a logarithmic wind field. The VWE highlights several complex aerodynamic effects, including limited aileron authority due to flow separation and three-dimensional effects in the lift distribution that simplified models do not capture. Structural analysis reveals a cyclic and asymmetric wing deformation, demonstrating the importance of including the full power cycle in the design.

AWEsim provides a powerful framework for analyzing AWE system design and operation. Ongoing work is directed towards incorporating hybrid turbulence modeling to study more dynamic wind-aircraft interactions and simulating other aircraft, such as the AP2. This work was conducted as part of the ETF project BORNE, funded by the FPS Economy.



*AWEsim outputs: reference trajectory, aircraft velocity distribution, wake development, pressure distribution, and wing deformation.*

### References:

[1] De Schutter J., Leuthold R., Bronnenmeyer T., Malz E., Gros S., Diehl M.: *AWEbox: An optimal control framework for single- and multi-aircraft airborne wind energy systems*. *Energies* (2023)

[2] Eijkelhof D., Schmehl R.: *Six-degrees-of-freedom simulation model for future multi-megawatt AWES*. *Renewable Energy* (2022)



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## Fuselage Influence on Aerodynamic Coefficients Captured with Geometry-Resolved Computational Fluid Dynamics

Maxim Notable<sup>1</sup>, Niels Pynaert<sup>1</sup>, Jolan Wauters<sup>2</sup>, Guillaume Crevecoeur<sup>1,3</sup>, Joris Degroote<sup>1,3</sup>

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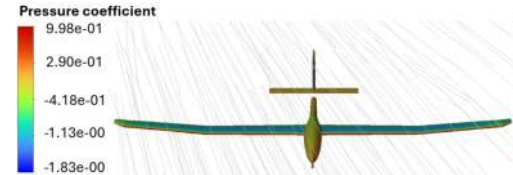
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Fixed-wing airborne wind energy systems (AWES) often operate at high sideslip angles during crosswind flight, as sideslip is typically not actively controlled. This behavior has been observed in simulations using the AWE-box control toolbox [1] and in experimental AP2 flights [2], where sideslip angles around  $10^\circ$  are common. At such sideslip angles, fuselage aerodynamics significantly affect performance through interaction with other components. While neglecting the fuselage may be acceptable for conventional aircraft flying mostly straight, this assumption does not hold for AWES regimes.

This work presents a geometry-resolved computational fluid dynamics (CFD) study of AP2 to quantify the influence of fuselage aerodynamics on AWES performance. The overset technique is employed to include all aircraft components: wing, tail, control surfaces and fuselage. A larger gap than in reality is introduced between fuselage and tail, as well as between control surfaces and their main components, to improve the overset connectivity. Aerodynamic derivatives, based on the model by Malz et al. [2], are calculated both with and without fuselage.

The comparison indicates that fuselage effects on aerodynamic coefficients are minimal at zero sideslip angle, resulting in negligible influence on angle of attack derivatives. However, as sideslip angle increases, fuselage aerodynamics become increasingly important. Including the fuselage raises the sideforce derivative with respect to sideslip by 25%, affecting lateral and directional stability.



Pressure coefficient on all components of AP2 and streamlines during flight at  $-10^\circ$  sideslip angle and  $0^\circ$  angle of attack.

This study demonstrates that accurate aerodynamic modeling of AWES requires the explicit inclusion of fuselage effects. Neglecting the fuselage can lead to a misrepresentation of stability and control behavior, particularly at high sideslip angles. Incorporating fuselage geometry in CFD-based derivative calculations therefore provides a more reliable foundation for flight dynamics analysis, controller development and the design of robust AWES.

### References:

[1] De Schutter J., Leuthold R., Bronnenmeyer T., Malz E., Gros S., Diehl M.: AWEbox: An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems. *Energies*, **16**, 1900 (2023)

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## Aerodynamic Shape Optimization of Box-Wing Crosswind Kites

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The paper presents ongoing research on two-dimensional aerodynamic shape optimization of box-wing crosswind kites. The configuration consists of two airfoils of comparable chord lengths, separated by horizontal and vertical offsets. The optimization framework employs the Improved Geometric Parameterization (IGP) method for airfoil shape representation, uses MSES to compute the aerodynamic forces, and applies the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to generate and evolve candidate airfoil geometries.

Although aerodynamics is critical to crosswind kite power generation, the literature on the aerodynamic shape optimization for such systems remains sparse. Ref. [1] developed an optimization framework for single airfoils, where the optimal airfoils were reminiscent of flapped airfoils, suggesting multi-element airfoils design. Ref. [2] addressed the optimization of multi-element airfoils for airborne wind energy applications. Ref. [3] performed aerodynamic simulations of parameterized box-wing configurations and conducted an optimization study to identify a box-wing configuration that maximizes the lift coefficient while minimizing structural weight.

In the present study, in addition to horizontal ( $H$ ) and vertical ( $V$ ) offsets, the geometry of the upper and lower airfoils are also treated as optimization variables. The IGP method significantly reduces the computational burden and increases the versatility of the design and optimization framework. Pareto-optimal fronts are obtained considering maximizing two conflicting objective functions, namely power output and structural strength. For example, the figure presents the optimal box-wing configuration with a total maximum thickness ratio of 40%.

The vertical offset between the airfoils was set to one chord length  $c$  while the horizontal offset was set to zero. As seen, the lower airfoil is nearly symmetric, with a maximum thickness ratio of 24%, whereas the upper airfoil is positively cambered, has an almost flat lower surface and a maximum thickness ratio of 16%. Both airfoils have sharp trailing edges, which help promote attached flow. This configuration indicates a predominantly structural role for the lower airfoil and a primarily aerodynamic role for the upper airfoil. Similar observations can be made from other configurations in the Pareto-optimal front. The methods and results presented in this study provide valuable guidance for the development of more efficient crosswind kite systems.

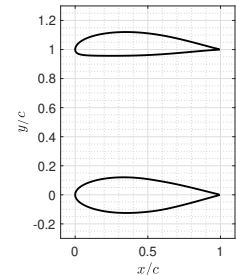


Fig. 1 Optimal box-wing configuration ( $H = 0$ ,  $V = c$ ) with a total maximum thickness ratio of 40%.

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- [3] Eijkelhof, D., Buendía, G. and Schmehl, R., 2023. Low-and high-fidelity aerodynamic simulations of box wing kites for airborne wind energy applications. *Energies*, 16(7): 3008.



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## Holding Capacity Method: An Engineering Approach for Bending Fatigue in an Airborne Wind Energy Tether

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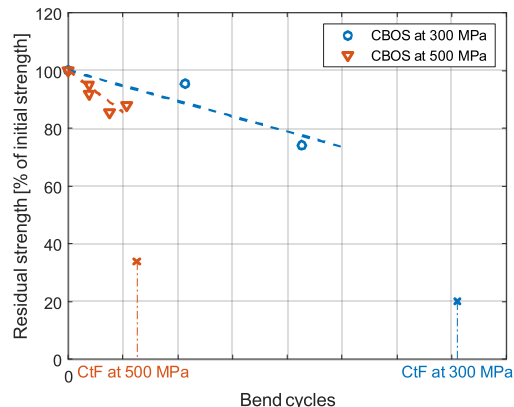
RIGO Ropes

Current research indicates that the tether contributes for a large part to the LCOE of an airborne wind energy (AWE) system [1]. At the same time it is a single point of failure that must perform with minimal risk to failure. Controlling and mitigating failure modes will lead to a lower LCOE. To assure the performance of the tether and to determine the point of safe discard, methods need to be put in place to determine its health condition. The AWE tether is subjected to many failure mechanisms that need to be mitigated or controlled by proper design, engineering, production and monitoring. Next to UV, particle ingress and external damage, the bending fatigue has an important contribution to the rope performance degradation.

For the rope bending fatigue, Meuwissen et al. [2] introduced the Holding Capacity (HC) method to conservatively determine the rope bending fatigue health over usage. The HC is defined as the strength of the rope on the system during operations. The HC method is based on residual strength measurements in Cyclic Bending Over Sheave (CBOS) testing. For the HC method a conservative linear strength reduction as a function of the bending cycles is assumed (see figure). This results in a Holding Capacity Reduction Rate (HCRR) that depends on the actual load and the change of shape of the rope during operations (from bent to straight or straight to bent).

The diameter of the rope ( $d$ ) and of the sheaves ( $D$ ) have a big impact on the rope bending lifetime. It is represented by the ratio  $D/d$  and it is observed that with a newly introduced parameter, the Normalized Sheave Pressure ( $NSP = \sigma/(D/d)$ ), AWE systems can be compared with a equivalent bending performance.

The HC method is already being used to support AWE developers to come to an optimised tether system design. Also monitoring systems have been developed to attribute local damage to tether segments pending on actual loads. Putting alarms on damage levels this will result in inspection and discard actions.



Measurements of residual rope strength after a CBOS tests at different loads. The drawn lines are conservative with respect to the measured values [2].

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## Navigating the Innovation Phase: A Technological Innovation System Analysis of Airborne Wind Energy

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Airborne Wind Energy (AWE) represents a radically new technology capable of exploiting stronger and steadier high-altitude wind resources inaccessible to conventional wind turbines. However, despite these inherent advantages, the transition of AWE from a technical prototype to a profitable mainstream energy source faces a distinct “valley of death.” Success requires more than just technological refinement; it demands the maturation of an entire socio-technical system.

This paper presents preliminary findings from a comprehensive literature review that evaluates the systemic readiness of the AWE sector using the Technological Innovation Systems (TIS) framework developed by Ortt and Kamp [1]. Specifically, this study addresses three research questions: (1) What is the historical evolution of AWE technology? (2) What characterizes the current phase of AWE technology? (3) What is the status of the TIS building blocks for AWE, and how is that status shaped by influencing conditions?

Our preliminary analysis situates AWE in the later stage of the innovation phase. We identify a recurring pattern of “systemic disconnects” where critical building blocks, notably customers, complementary products and services, and institutions, are missing, incomplete, or incompatible. Furthermore, we explicitly link these barriers to underlying influencing conditions, including limited knowledge and awareness of the technology, intense

competition, and constrained natural, human, and financial resources. We demonstrate how these adverse conditions create a feedback loop that hampers direct competition with established renewables and fossil fuels [2].

By systematically diagnosing the interplay of influencing conditions and building blocks, this paper provides a foundation for evaluating strategic pathways for AWE commercialization and large-scale diffusion. These insights are directly relevant to the development of AWE technology, offering a roadmap for policymakers, utility companies, financiers, and AWE developers to navigate the “valley of death” toward mature energy market integration.

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## Enhanced Power Generation and Reliability of AWES Through Active Exploitation of Turbulence Eddies

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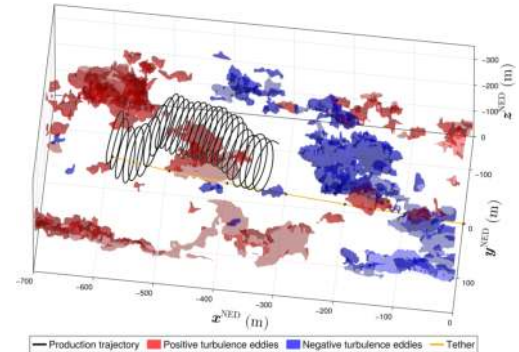
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Airborne wind energy systems (AWES) encounter significant wind velocity fluctuations due to atmospheric turbulence. If unhandled, these can degrade both power production as well as the reliability of AWES. This work presents a control strategy that actively exploits turbulence eddies to provide an increase in performance, contrary to limiting the system's performance. The control strategy has been implemented in the Universal Simulator for Airborne Wind Energy (UniSimAWE)<sup>1</sup>, where atmospheric turbulence is modeled through the Mann model<sup>2</sup> combined with high-fidelity kite and tether models.

The approach relies on the fact that the helical trajectory of the AWES in production phase sweeps the same region of the YZ plane after each loop, enabling the kite to sense the same turbulence eddies multiple times. Thus, the turbulence fluctuations sensed by the kite along a loop can be employed to actively modify the lateral component of the following loops to pursue the positive eddies, achieving higher local wind speeds. This results on an increase of power output and higher margin towards stall in low wind conditions.

The effectiveness of the proposed control strategy is dependent on the turbulence intensity, the eddies scale and location relative to the production cylinder and the rate at which the flight path can be adapted.



Example of an AWES flight trajectory in production phase where the lateral component of the helical path is adapted for active exploitation of turbulence eddies.

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## Towards Full Autonomy in Airborne Wind Energy

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To boost their commercial success, Airborne Wind Energy Systems (AWESs) must be capable of operating fully autonomously over long periods of time with minimal human interaction [1]. Achieving such a high level of autonomy requires control systems that go beyond simple tracking and regulation tasks [2]. In addition to low-level flight stabilization, AWESs must autonomously decide when to take off and land, adapt their operational modes, and reconfigure their behavior based on continuous monitoring and estimation of the wind field. To address these challenges, a hierarchical control architecture is usually adopted, in which increasing levels of autonomy are associated with higher-level decision-making capabilities. While lower layers rely on numerical and algorithmic methods, higher layers require symbolic approaches, for example based on logical Discrete Event System (DES) models [2]. Finite State Machines (FSMs) have been proposed as well as a practical solution for implementing high-level supervisory control of AWES, see Figure 1. Despite these advancements, full autonomy has not yet been achieved, as FSM transitions were commanded manually during testing [3]. To guarantee safe, autonomous operation, systems must be capable of reaching a safe state at all times. To achieve this goal, drawing on successful applications in related fields like drone navigation [4], we investigate high-level decision-making via multi-trajectory Model Predictive Control, considering fly-gen Airborne Wind Energy Systems (AWES). By planning the system behavior under the constraint of having persistently a safe backup trajectory, and requiring a moderate computational load, the proposed approach moves AWESs closer to reliable, long-term autonomy.

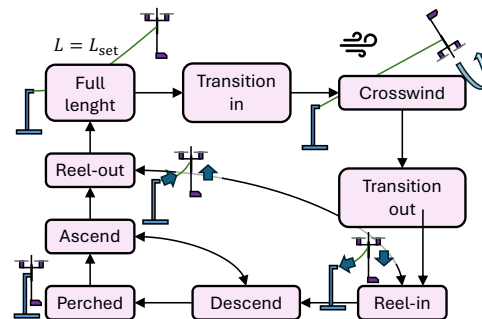


Figure 1: Illustration of the operational state machine of a fly-gen AWES in healthy nominal conditions, depicting the cyclic transitions between launch, power generation, and recovery phases.

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## Socio-Political Acceptance and Legitimacy of AWE: An Institutional Perspective

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Airborne wind energy (AWE) is a novel technology which does not fit neatly into existing institutions, consisting of the rules, standards, expectations and norms that govern how a technology is understood, regulated, accepted and utilized. Operating at high altitudes using tethered kites [1], AWE differs from traditional energy systems, lacking the precedents and shared understandings which typically develop around more mature technologies. This raises the question of how acceptance and legitimacy, which directly influence the technology's investment, adoption, and expansion prospects, can be built in the absence of established institutional frameworks [2, 3]. Earlier research on social acceptance has largely focused on local acceptance and public opinion [3], often measured through surveys [4, 5]. Later work has shown that acceptance cannot be reduced to attitudes alone, as local acceptance is only one dimension of a broader political and dynamic process [4], encompassing socio-political, community, and market acceptance. Furthermore, how institutions shape technological acceptance and legitimacy has received limited attention [2]. Legitimacy, which is understood as the perceived appropriateness and trustworthiness of a technology within institutional frameworks, has been studied mainly for developed technologies, leaving legitimacy-building in regard to emerging [2] and alternative technologies underexplored. As AWE is a novel technology, the limited existing research has focused solely on community acceptance [1], with socio-political and market acceptance still unmapped. This research aims to address this gap through an initial review of grey literature, to be presented at

AWEC, as the first stage of a PhD project. This will later be followed by document analysis and semi-structured interviews with governance and industry actors, examining how regulatory interpretations and actor perceptions in a pending choice of European countries with test and demonstration sites, and varying regulatory environments, enable or constrain the adoption and expansion of AWE, through a lens of institutional work theory.

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## System-Ready Techno-Economic Inputs for Airborne Wind Energy in Pan-European Electricity System Optimization

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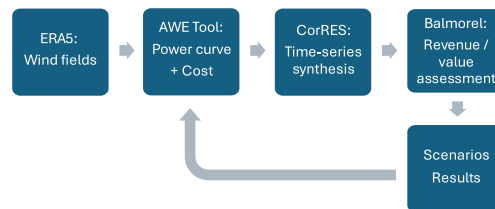
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Airborne Wind Energy (AWE) is new technology that has not yet achieved large scale deployments in Europe and beyond. So, there is some uncertainty on the economic potential of this technology. Additionally, since it harvests high altitude wind, it may have a different temporal and geographical behaviour than conventional wind [1]. This presentation will outline a new PhD project with the aim to i) identify the economic potential ii) identify regions within Europe that are most favourable to AWE and iii) how AWE can compete with existing technologies on the grid.

As shown in the figure, ERA5 reanalysis wind fields are used to characterize the high-altitude wind resource. These data are processed by an AWES system-engineering tool that outputs (i) power curve for selectable operating altitudes and (ii) a harmonized techno-economic input set (CAPEX, fixed/variable O&M, availability, and simplified operational constraints). Then the result passed to CorRES [2] to generate scenario-consistent renewable time series and preserve spatial and temporal correlations structures needed for system studies. Finally, these inputs are evaluated in Balmorel [3], where the value of novel wind technology can be assessed on continental scale.

The project will consider a range of different scenarios for 2026–2050, like early off-grid deployments, niche grid services and eventually broader utility-scale integration. That latter will consider additional grid scenarios with varying energy storage, power-to-X and transmission expansion. The research analyses high-altitude wind conditions, including wind shear, low-level jets, and at-

mospheric stability, to refine AWE power curves for selected sites and assess impacts on annual energy production. Preliminary results also include early LCOE estimates and, where possible, revenue estimates based on Balmorel electricity prices. Overall, the presentation highlights early findings, next research steps, and how the value of AWE can be assessed for both asset owners and the broader energy system.



Schematic overview of modelling framework applied in this work.

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## Operational and Grid Integration Framework for Airborne Wind Energy Systems

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Airborne Wind Energy (AWE) is in a transition phase, moving beyond validated simulation models and demonstrators toward early deployment in more operational settings. Current AWE models capture power dynamics associated with the electrical processes at varying levels of resolution. These dynamics become more relevant as AWE systems (AWES), particularly ground-generation pumping-cycle systems, begin to integrate into utility and microgrid environments. Additional constraints arise from the interaction between ground station operations and these grid environments, shifting focus toward external dynamic behaviors at the AWES-grid interface.

Studies have shown ongoing progress in optimizing ground-station performance and in integrating AWES with hybrid energy systems. Work has been conducted on the modeling and control of ground station dynamics for stable power delivery and robust disturbance control [1], and on sizing frameworks for off-grid hybrid AWES configurations with integrated photovoltaic (PV), battery energy storage, and diesel generation systems [2]. A gap emerges in the synthesis of these two approaches, with an emphasis on system-level operational dynamics for grid compliance. Bridging this gap will require developing control strategies directed towards operational deployment and identifying relevant grid-based performance metrics.

The main objective of this study is to develop a framework for stable grid-serving operations for AWES, with direct focus on the operational handling of system dynam-

ics at the grid interface. The framework aims to enable controllable power injection across various grid-serving applications, addressing compliance metrics such as frequency stabilization, power factor, and low-voltage ride-through (LVRT), while respecting operational constraints. Existing reference models will be built upon and integrated across kite, ground station, and power system domains to generate operational strategies that address the dynamic interactions at the AWES-grid interface. Operational data from Kitepower B.V., together with data from power system simulations, will be used to capture subsystem dynamic behaviors and validate the overall performance of the framework against the defined compliance metrics across different operational scenarios using a simplified system model. The results will provide a foundation for the further development of integrated AWES control strategies in utility, microgrid, and hybrid system environments.

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# Optimal Scaling and Clustering for Airborne Wind Energy

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Realizing the potential of airborne wind energy (AWE) requires understanding how system-level design choices affect farm-level performance. While recent studies have developed physics-based and techno-economic frameworks for single systems [1,2], and others have examined life-cycle assessment [3] or farm-level techno-economics [4], an integrated farm-scale model that simultaneously optimizes physical, economic, and environmental performance remains a challenge.

Building on the quasi-steady model for bridled kites of Cayon et al. [5] and integrating aspects of the single-system optimization and scaling methodology of Joshi et al. [1], developed for fixed-wing systems, this research focuses on soft-wing, ground-based generation systems and extends current methods in two ways: first by refining single-system scaling analyses with environmental metrics, and second by modelling and optimizing farm-level systems. A key contribution is using high-fidelity ASKITE simulations [6] for multiple kite sizes to extract scaling laws which calibrate the quasi-steady model into a fast digital twin, enabling thousands of simulations needed for farm-level optimization while preserving physical accuracy.

Component-level life-cycle assessment is coupled with techno-economic models, linking design parameters to energy yield, levelized cost of energy (LCoE), material use, emissions, and end-of-life impacts. Farm-level interactions influence trade-offs between deploying fewer large systems versus multiple smaller units. Mass scaling, particularly of the wing, is critical at both the single-

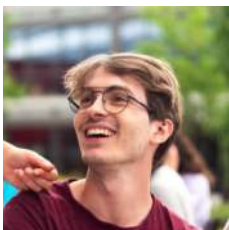
system and farm levels to ensure physically consistent performance and environmental assessment.

Collaboration with industry partners, including Kitepower B.V. [7], provides operational data to refine assumptions and bridge industrial-scale deployment.

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## Robust Autonomous Control of Onboard-Generation AWE Systems

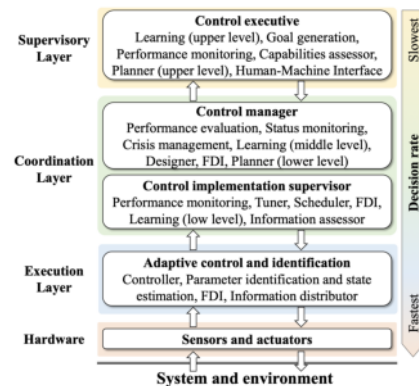
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The transition of Airborne Wind Energy (AWE) to an established, industrial-grade power generation solution will require high standards of flight-critical reliability. For onboard generation systems, this challenge is further complicated by the strong coupling between energy harvesting and aerodynamic stability. Moreover, addressing this issue requires control architectures that can cope not only with turbulent wind conditions but also with failures in sensors, actuators, onboard computation, and the ground-based winch system [1].

This presentation outlines a research program to develop a robust and fault-tolerant control framework for AWE onboard-generation systems, targeting catastrophic failure probabilities of the order of  $10^{-9}$  per hour. The approach adopts a modular cascade architecture [2], combining conventional feedback control schemes and non-linear ones. In such architectures, control actions and decisions are spread across various system layers, from fast low-level execution to higher-level supervision and fault management. The project investigates how robustness can be achieved through a careful design and optimization of safety-related redundancies across sensing, actuation, and computation, specifically targeting the lower layers. As a first step, actuation redundancy are explored through a four-propeller distributed propulsion system on a fixed-wing airframe. The work also considers off-nominal operating conditions relevant to AWE operation, like partial loss of thrust in one of the propellers during the transition or hovering phases. These scenarios are evaluated using a Python-based simulator, with experimental validation conducted on a custom test bench.



Typical hierarchical structure of autonomous systems like AWE [3].

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## AWE Wind Farm Optimization and Operation

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Operating multiple airborne wind energy (AWE) systems as a coordinated plant is a key requirement for achieving grid-scale power generation [1]. Increasing plant density (i.e., the number of aircraft per unit area) is essential to improve land-use efficiency and reduce plant-level costs; however, it also introduces significant challenges related to collision avoidance, wake interactions, turbulence, and wind direction variability. These effects can strongly influence both flight trajectories and power production [2]. Unlike conventional wind turbines, AWE systems offer additional degrees of freedom through adaptable flight paths and operating altitudes, creating new opportunities to mitigate adverse flow interactions using plant-level control strategies.

This research focuses on the development of low-fidelity, plant-level simulations for AWE systems operating under dynamic wind conditions and wake interactions. Particular attention is given to understanding wake formation and its evolution from near-field to far-field regions, and to quantifying its impact on downstream kites at varying separation distances. This limiting factor decides upcoming clustering configurations and collision avoidance strategies

Generic plant configurations are used as a testbed to study coordination and control strategies across a range of plant densities, with particular emphasis on collision avoidance and wake-aware operation. Furthermore, siting optimization is applied alongside these regulation strategies to explore feasible plant layouts under varying density and environmental conditions. The overall objective of this research is to establish a modeling and

control framework suitable for assessing the operational challenges associated with dense AWE plants and to support future investigations on scalability and reliability.



*Conceptual illustration of the research objective: a high-density AWE farm (Author's own illustration, created using AI-based tools).*

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## Investigation of the Impacts of Unsteady Atmospheric Conditions on Airborne Wind Energy Systems

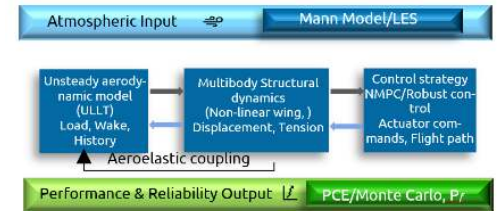
Sanya Shabir Rather, Mac Gaunaa, Mark C. Kelly, Michael K. McWilliam  
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At higher altitudes, airborne wind energy systems (AWES) offer access to stronger and more persistent winds [1]. However, during operation, the system may encounter flow environments that include various transient structures, inducing unsteady loads and driving an AWES toward unstable flight regimes. Thus, their deployment is constrained by challenges in reliability, stability, control, and production [2]. Understanding the interactions between atmospheric flow phenomena, aircraft dynamics, and control remains a significant research challenge. The PhD research aims to study unsteady aerodynamic and aeroelastic behavior of rigid-wing tethered airborne systems in realistic atmospheric flows, with the overarching goal of improving the reliability and robustness of AWE systems. The research will employ an iterative approach to identify stochastic atmospheric flow features, especially low-level jets, coherent structures, discrete synthetic gusts, and operating conditions that are most critical for load amplification, loss of control, and failure risk.

At this early stage of the PhD project, the exact methodology to conduct the research is still being explored. The research aims to exploit a moderate fidelity Aero Servo Elastic simulation framework that couples an unsteady aerodynamic solver with a non-linear multibody structural model of the wing and tether. To map these atmospheric variabilities onto the failure probabilities, the research will employ UQ methods to provide a rigorous reliability analysis of the system's operational envelope. The research further aims to employ control strategies to dynamically optimize the flight paths while respecting the

structural and aerodynamic constraints to ensure stable operation.

At the conference, we plan to present the plan for this research in hopes of stimulating a fruitful discussion on this work. Any preliminary results available at the time of the conference, supporting the analysis of how unsteady atmospheric conditions and system parameters influence reliability, will be presented as well.



Systematic modelling framework for rigid-wing AWES

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## Reliable and Functional Electrical Systems for AWE

**David Tapia Pino, Christoph M. Hackl**

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Airborne Wind Energy (AWE) presents itself as a promising option within the realm of renewable energies; however, its adoption by the industrial energy system and widespread deployment remain limited. To further advance this integration, it is a key prerequisite to improve the reliability of the device itself.

This work focuses on the electrical subsystems of AWE systems (AWES), such as electrical machines, machine and grid side power converters, and grid filters, aiming to make them more robust against endogenous events by implementing fault tolerant control, reconfiguration strategies, fault detection and diagnosis, as well as implementing predictive maintenance to avoid internal faults. In addition, the work aims to extend AWES functionality with grid-supporting, grid-forming, or black start capabilities to meet future grid requirements for frequency and voltage stability while also implementing safety features to protect the AWE subsystems and make them resilient against external faults in the grid without compromising their proper operation and functionality.

To enhance transparency and support certification in safety-critical operations, the project further investigates explainable AI methods as part of the modeling and decision-making pipeline, avoiding opaque “black-box” solutions. Using interpretable surrogate models such as Kolmogorov–Arnold Networks (KANs) [1] or Explainable Predictive Maintenance (XPM) [2] methods can provide traceable, auditable evidence for maintenance and reconfiguration policies, facilitating root-cause analysis, while also strengthening confidence for investors and regulatory authorities.

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## Optimizing Pumping Cycle Energy Yield in Airborne Wind Energy Systems Using Deep Reinforcement Learning

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Renewable energy will play a pivotal role in meeting future energy needs and strengthening energy independence. However, the widespread deployment of today's renewable energy systems is often limited by geographic suitability and environmental constraints. Airborne Wind Energy (AWE) systems offer a compelling alternative, with the potential to access stronger, more consistent winds aloft and deliver higher power generation at lower cost than traditional wind turbines.

We propose a model-free deep reinforcement learning (DRL) framework that maximizes the energy harvested per pumping cycle in a kite-based AWE system operating along a predefined figure-eight orbit. The controller maps a 93-dimensional state vector to two tension-force commands for the reel-out and reel-in phases, respectively, without requiring explicit wind measurements. The reel-out states consist of 15 variables (i.e., the kite's position, velocity, attitude angles, angular rates, tether tension, tether length, and reel-out speed), recorded at each of the six waypoints of the most recently completed figure-eight orbit shown in Figure 1(a). Reel-in states include the initial tether length, average reel-in velocity, and total reel-in time duration. The action vector includes the desired tether tension forces for both the reel-out and reel-in phases, respectively. The reel-out action space is defined as  $A_{RO} \triangleq \{400, 600, 800, 1000, 1200, 1400\}$  N, and the reel-in action space as  $A_{RI} \triangleq \{50, 75, 100, 125, 150\}$  N. The reward is defined as the average power generated over a pumping cycle, as illustrated in Figure 1(b). Maximizing this objective promotes higher overall energy yield.

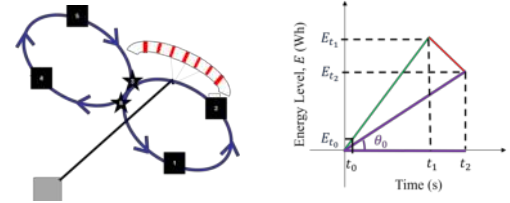


Figure 1: (left) Six sequential waypoints define the figure-eight trajectory: four square waypoints (1, 2, 4, 5) for the path-following controller and two star waypoints (3, 6) added for the RL framework. (right) Energy harvested versus cycle duration, where  $t_0$ ,  $t_1$ , and  $t_2$  mark the start of reel-out, transition to reel-in, and end of reel-in, respectively;  $E_{t_*}$  denotes energy at time  $t_*$ .

The DQN agent was trained in a MATLAB simulation environment under wind magnitudes ranging from 6 to 12 m/s using replay buffers generated through exhaustive behavior-policy exploration. Results demonstrate that the agent recovers optimal actions and average power with high fidelity at low wind speeds. While some performance degradation is observed at higher wind speeds, the agent consistently maintains low error and accurately captures the overall trend of the optimal policy. Across all evaluated wind conditions, the relative error ranges from approximately 3.3% to 16.4%, with the smallest errors observed at 9–10 m/s and the largest (16.42%) occurring at 12 m/s.



uc3m

UC3M team and technology demonstrator.



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## A Unified Dynamic Simulation Framework for Electromechanical Efficiency Analysis of AWES

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 Osmany Pérez-Aballe<sup>2</sup>, David Santos-Martín<sup>1</sup>,

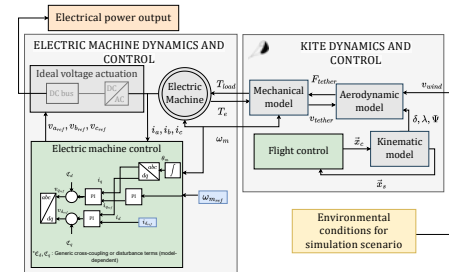
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This work presents a comprehensive Simulink-based simulation environment for integrated analysis of ground-generation airborne wind energy systems (AWES), combining mechanical and electrical subsystems within a unified framework. The model integrates a 6-degree-of-freedom rigid-body kite with elastic tether dynamics—originally implemented in the LAKSA AWES environment [1]—with a 5th-order flux-linkage-based three-phase electrical machine model, configurable as an induction, permanent-magnet synchronous, or reluctance synchronous generator with closed-loop speed control.

This integrated model enables the evaluation of AWES trajectories not only from a purely mechanical energy-extraction perspective, but also by accounting for electromechanical energy conversion from the kite to the electrical machine. Due to the specific torque and speed profiles encountered during each AWES pumping cycle, the electrical machine must operate alternately as a generator and a motor, often at operating points far from its nominal ratings, where efficiency characteristics differ significantly. Consequently, trajectories and reel-out velocities that appear optimal in mechanical terms may not correspond to the most effective configurations for net electrical power generation, with observable deviations in optimal operating points and net energy output.

The environment provides a valuable tool for developing control strategies that optimize both flight trajectories and electrical conversion efficiency. Extending previous studies [2], the proposed model novelly enables full dynamic simulation of both the kite system and the

electrical machine within a unified framework, capturing transient behaviours across a wide range of kite sizes and wind speeds. This facilitates deeper insight into the coupled aero-electromechanical dynamics of AWES and supports the development of optimization algorithms targeting true end-to-end energy efficiency, leading to improved optimization outcomes compared to purely mechanical criteria.



Unified AWES simulation framework coupling kite and electrical machine dynamics and control for net electrical power evaluation under varying wind conditions.

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## Design, Iterative Correction, and Integration of Airborne Wind Energy System Models for Hardware-in-the-Loop Testing

**Uwe Fechner, Roland Schmehl**  
Delft University of Technology

Dynamic models of airborne wind energy systems can be used for deriving a power curve, designing a controller, and optimizing the flight path. This study presents an overview of how a generic model for pumping kite power systems [1,2] can be adapted to a real system and integrated with its control system for Hardware-in-the-Loop (HIL) testing.

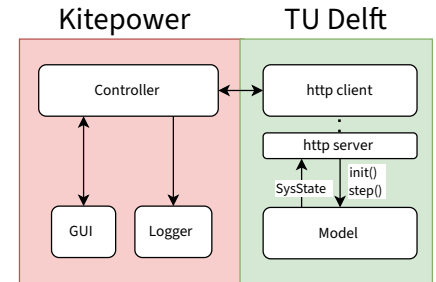
Model design is an iterative process. It starts with gathering available physical data, such as the mass and size of the kite, ground station, tether, and suspended airborne kite control unit. We added a new winch model using torque control and, in addition, a more generic model of the kite control unit. The aerodynamic polars and steering sensitivity are usually unavailable and must therefore be determined iteratively. As a starting point for the polars, the CFD simulation results of a similar kite can be used. For the iterative correction of the model, the following steps are required:

- Determine the polars  $C_L(\alpha)$ ,  $C_D(\alpha)$ , where  $\alpha$  is the wing's angle of attack.
- Plot and match the aerodynamic side force coefficient  $C_S(u_s)$ , where  $u_s$  is the normalized steering input.
- Perform a steering test to determine the coefficients  $c_1$  and  $c_2$  of the turn-rate law,  $\dot{\psi} = c_1 v_a u_s + \frac{c_2}{v_a} \sin \psi \cos \beta$ , where  $\dot{\psi}$  is the turn rate,  $v_a$  is the apparent wind speed,  $\psi$  is the heading angle, and  $\beta$  is the elevation angle.
- Perform a parking test (kite in static flight mode) at different depower settings to iteratively correct the polars.

Finally, the model is integrated with the real-time con-

troller of the kite power system. For the coupling, HTTP messages were used to exchange data in real time, the simplest and sufficiently performant approach, allowing hardware-in-the-loop testing of the airborne wind energy control system.

The figure shows the integration of the dynamic model [1,2] with Kitepower's control system.



Integration of the model with the real-time control system of a commercial kite power system, in this case, Kitepower's system.

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- [3] <https://thekitepower.com>

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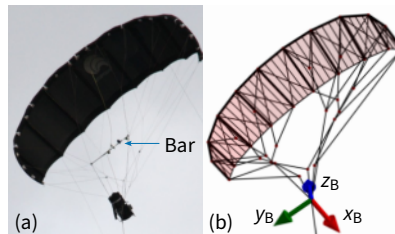
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## Dynamic Aero-Structural Coupled Circular Flight Simulations of Soft Kites

Jelle A. W. Poland, Bart van de Lint, Roland Schmehl,  
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Dynamic aero-structural coupled simulations of a soft-wing kite for airborne wind energy generation were investigated to reduce reliance on costly prototype campaigns and empirical controller tuning. An aerodynamic vortex-step method was coupled to a reduced-order structural particle system model of a leading-edge inflatable kite, and the coupled equations were symbolically integrated in time to yield a dynamic aero-structural model [1].



TU Delft V3 kite. (a) In-flight photograph during 2025 campaign [2] with the bar used for photogrammetric measurements and (b) a snapshot of a dynamic simulation [1,3].

Without gravity, the simulations converged to a pseudo-quasi-steady circular flight state around the wind vector under a constant steering input. It is considered a pseudo-quasi-steady state because the velocity magnitude remains constant, but the direction changes. Furthermore, when observing from a kite-fixed rotating reference frame, the shape and forces remained constant.

To validate the predicted steering response, flight campaigns in 2019 and 2025 were analysed using a sensor-fusion approach [4]. The steering response, commonly considered linear, was quantified by the turn-rate gain

$g_k$ . The gains were obtained from fitting the turn-rate law,  $\dot{\psi} = g_k v_a u_s$ , where  $\dot{\psi}$  denotes the yaw rate,  $u_s$  denotes the (normalised) steering input and  $v_a$  denotes the apparent airspeed. The turn-rate response was approximately linear for the 2019 flight but non-linear for the 2025 flight. The non-linearity occurred primarily during downward flight and coincided with substantially lower tether forces prior to the down-loop. The differences between the two campaigns were attributed to variations in depower setting and bridle geometry, which alter the aerodynamic force production and thereby the relative importance of gravity; hence the differences between upward and downward flight.

Circular-flight simulations reproduced the steering response from the 2019 flight and the steering response of the 2025 campaign during upward-flight. More powered configurations (shorter depower tapes) produced comparatively higher apparent wind speeds, smaller turn radii, and larger steering gains.

References:

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This research has been supported by the MERIDIONAL project, which receives funding from the European Union's Horizon 2020 program (grant agreement no. 101084216).



The 5 m span Toyota Mothership/TRINA test wing.



The 5 m span Toyota Mothership/TRINA test wing.



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## Taking Off: Shapewave Inflatable 3D Printing Technology for Wing Design and Manufacturing

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The shapewave project, first presented to the public at the AWEC 2021, is now ready for commercial exploitation.

The transition from concept to fully implementing the shapewave toolchain for building components has been a fantastic journey, from software development to the design and construction of the wavemaker01.



Sean Carslaw Tricot hunching over the wavemaker01, watching as the tapes are placed and welded between the membranes.

Several wings have already been built for both flight and propulsion, and now that the first field data is coming in, we are working on modular designs for single-head and multi-head machines.

Research is underway to build morphing profile wings by

integrating spanwise pneumatic actuators into the membranes.



CAD screen shot of the 5 m span Toyota Mothership/TRINA test wing<sup>1</sup>, with an inflatable main section and a stitched rip-stop trailing edge, with triple functionality: (1) housing for electronics; (2) light-weighting and aerodynamic improvement; (3) integrated control surfaces.

The technology is being made available for licensing under the “shapewave® inside” logo.

<sup>1</sup>Wing design provided by Taewoo Nam, Toyota Research Institute of North America (TRINA)



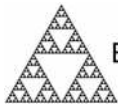


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## Comparing Airborne Wind Energy Systems with Tilt-Tower Wind Turbines in Hurricane/Typhoon Prone Locations

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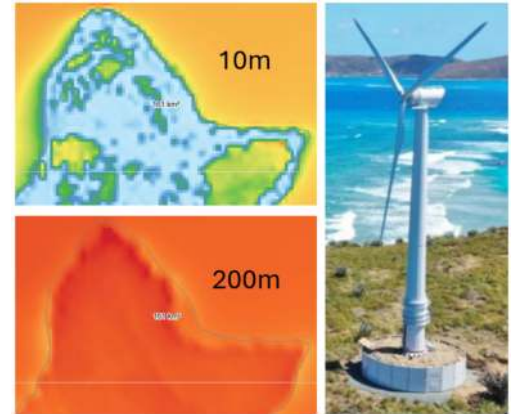
<sup>1</sup> E3-Design, LLC

<sup>2</sup> Sandia National Laboratories

Remote locations such as islands often have expensive electricity. Their microgrid energy systems often rely on diesel generators. Fuel supply disruptions pose serious energy security risks. Many islands, especially those in tropical or subtropical locations, use solar energy to supplement fuel-based energy generation and to diversify their energy supply thereby increasing energy security and saving costs. For example, both Hawaii and Guam have extensive solar farms.

Traditional towered wind energy systems are usually not installed in regions prone to hurricanes or typhoons because the risk of a single storm destroying the entire wind farm is too great. One strategy to reduce the risk of destructive storms to wind turbines is to use wind turbines that have tilt towers so that the wind turbine can be lowered during storms to avoid damage. The figure shows a 100kW wind turbine with a ballasted base and a tilt tower. AWES can also be lowered during storms to avoid damage.

This paper compares the relative advantages and disadvantages of tilt-tower wind turbines and AWES in terms of levelized cost of energy using real world pricing. Special attention is given to how wind shear leads to an improved wind resource for AWES potentially counteracting higher capital and O&M costs. Economic and renewable energy resource conditions necessary for wind to be competitive with solar and diesel generation, and the role of energy storage vs matching load with generation are explored.



Average Wind Speed at 10m & 200m, Northern Guam (Left) NPS 100kW Turbine on 25m Tilt-up/down Tower (right)

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*EnerKite EK100-10P in launch configuration (April 2026).*







*Kitedynamics' ship propulsion system in operation.*



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## Kite Dynamics – Going Offshore

**Sander Schroeder, Fabian Stölzle**

Kite Dynamics AG

Kite Dynamics' vision is to develop innovative energy ships that use kites to harness wind energy on the open sea. These ships are designed to gain and store wind energy. The conversion of wind energy into electrical energy and the storage in the form of hydrogen take place directly on board. Once the tanks are full, the hydrogen is unloaded at terminals.

As an intermediate step to reach the vision, Kite Dynamics contributes to maritime decarbonization by the development of wind-assisted propulsion systems for various sizes of vessels. Our Kite Drive development (4-lines, ground-gen, soft wing) is ideal to apply high traction forces to relieve the main engine and reduce fuel consumption and CO<sub>2</sub> emissions.

We would like to give an insight into our testing campaign on land and offshore.

On land the automated flight controller is developed, and trajectories are optimized with respect to the traction force. The kites are equipped with a sensor box, which captures position and orientation data of the kite in motion. The acquired signals are used as the input of the flight controller, to analyze the flights and to estimate parameters. Prior to experimental validation on the large systems, the automation approaches are validated in simulation, and experimental test flights are con-

ducted on a small-scale version of the kite control system.

In 2025, Kite Dynamics did the first offshore test on the North Sea shore of Denmark. A crew transfer vessel was used to demonstrate the handling of a 15 m<sup>2</sup> kite on a moving platform. This contained launch, power flight and landing maneuvers.

Kite Dynamics would like to present the results of the first offshore test campaign.



*Experimental trial of Kite Drive in 2025*



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## Design of a 1.5 kW ground station for autonomous takeoff and landing

Nasouh AlRayyes, Tanguy Simon

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We present the design of a low cost airborne wind energy prototype aimed at developing control and observation methods, notably for takeoff and landing phases with soft wing kites.

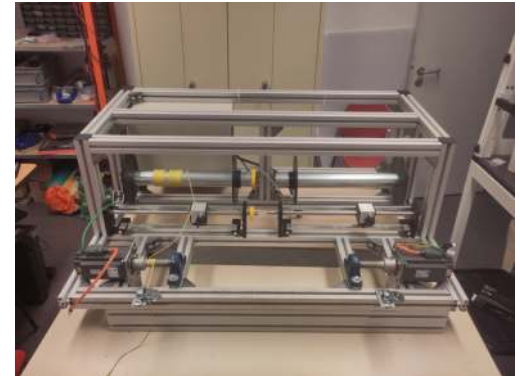
It is a two-line, ground actuated system [1] with a mast and reefing line to allow for autonomous takeoff and landing experiments. By using a dual capstan system [2,3], it can stow up to 900m of 3mm Dyneema line at a constant, low tension. The spools are powered by small DC motors.

The ground station can be powered both via the AC or lead batteries via a reversible boost converter, which allows testing in remote areas. A discharge resistor ensures the dissipation of the energy produced. It is designed for a max power of 2kW (two 1kW permanent magnet synchronous machines in parallel).

Each electrical machine has the dual role of power generation and steering control. The small radius, aluminium capstan system leads to low inertia and allows for rapid actuation.

Each motor is controlled by an open source Owntech inverter, and the automatic control laws will be implemented on a Raspberry Pi with RTOS [3]. A portable HMI allows for manual control of the kite. The whole system transforms into a bicycle trailer for a cheap and easy dispatch.

The CAD files, documentation and code will be provided in open access.



Experimental testbed under construction (mast not shown).

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## A Small-Scale and Low-Cost Testbed for the Control of Multi-Wing AWE Systems

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University of Freiburg

We present a testbed for tethered-flight experiments built around the Crazyflie 2.1. Replacing the wings of AWE systems with quadcopters, we can quickly design, implement and evaluate control approaches, because they are easier to actuate than aerodynamic wings. Instead of a costly motion-capture system, we use the Lighthouse tracking system [1], thus keeping the cost below 1000€.

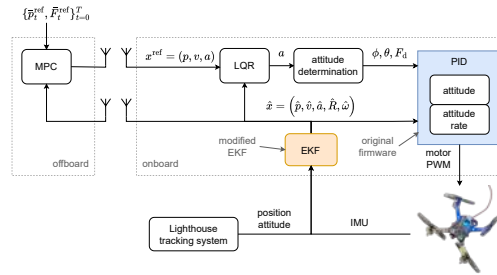


Figure 1: proposed control approach

To investigate the dynamics of a multi-wing Y-shape configuration in particular, we developed the following control scheme, as visualized in Figure 1: A given reference is tracked by a hierarchical controller: an off-board model-predictive controller (MPC) running at 25 Hz computes a feasible state-control trajectory, while an onboard linear-quadratic regulator (LQR) operating at 100 Hz follows that trajectory and outputs an acceleration command. The acceleration is mapped to the quadcopter's attitude-and-thrust setpoints for the existing low-level Crazyflie controllers. Both the MPC and the LQR are based on a simple linear triple-integrator model of the quadcopter (jerk

as input, position, velocity and acceleration as states). By controlling the jerk, we ensure continuous, piecewise-linear acceleration commands that ensure smooth trajectories in flight. For reliable state estimation during tethered flight, we extend the Crazyflie's extended Kalman filter (EKF) to include linear accelerations and a global attitude measurement. Experimental flights, cf. Figure 2, demonstrate accurate tracking without any expensive external motion-capture infrastructure.



Figure 2: example of tethered flight

References:

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**POLITECNICO  
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## Control Co-Design for Takeoff and Landing of Tailsitter VTOL AWES

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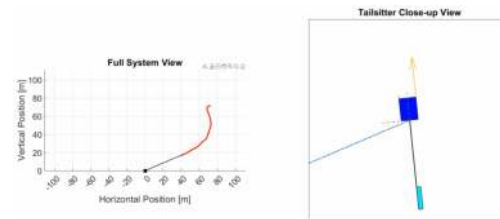
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This research proposes a Control Co-Design (CCD) framework for the optimization of wind-planes (Fly-Gen Airborne Wind Energy systems) based on a tailsitter configuration, focusing on resolving the critical design conflict between the power generation and hover phases. While aerodynamic principles suggest that positioning generation turbines at the wingtips maximizes power harvesting efficiency [1], the requirement for Vertical Take-Off and Landing (VTOL) authority necessitates placing additional propulsion units closer to the fuselage to allow precise pitch control during this critical phase. The proposed framework optimizes the distribution of this installed power—specifically the positioning of motors along the wing, the propeller dimensions, and the wing dihedral angle—to mediate this trade-off between optimal energy extraction and takeoff feasibility.

The co-design problem is formulated using a simulation-based optimization approach that couples the plant geometry with a Linear Quadratic Regulator (LQR) control system, regulating motor speeds to generate the necessary thrust and moments. The modeling framework focuses the analysis to the longitudinal plane (pitch, surge, and heave), leaving lateral dynamics, roll/yaw coupling and downwash on control surfaces as accessory effects.

The cost function in this study is constructed from direct simulation measures and control stability quantities.

This approach allows for a rigorous examination of the dynamic stability margins and power efficiency penalties incurred by the forced relocation of motors from the ideal wingtip location to the fuselage. The result is a specialized tailsitter design that sacrifices a quantified degree of harvesting efficiency to guarantee robust VTOL capabilities within a strict longitudinal control envelope.



Ground station approach path and Tailsitter attitude visualization

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[1] Trevisi, F., Cassoni, G., Gaunaa, M., and Fagiano, L. M.: Concurrent aerodynamic design of the wing and the turbines of airborne wind energy systems, *Wind Energ. Sci.*, 11, 195–216, <https://doi.org/10.5194/wes-11-195-2026>, 2026

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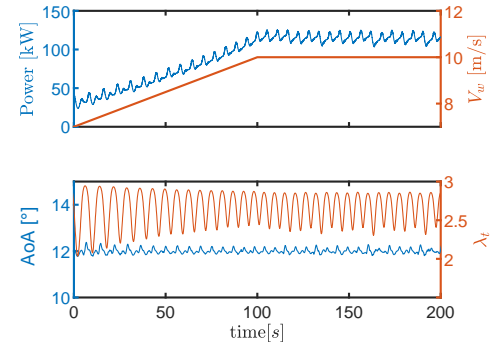
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## A Mid-Level Feedback Control Strategy for Crosswind Fly-Gen AWES

Mattia Alborghetti, Filippo Trevisi, Lorenzo Fagiano  
Politecnico di Milano

Achieving fully automatic operation of airborne wind energy systems (AWES) is essential to ensure safety, reliability, and cost-effectiveness. Despite the variety of approaches proposed in the literature (e.g. [1,2]), a broadly accepted reference control strategy for crosswind power production has yet to emerge. This work proposes a mid-level feedback control strategy for Fly-Gen AWES operating in crosswind conditions along circular trajectories. The approach defines an inclined reference flying plane (similar to [3]), characterized by desired mean azimuth and elevation angles. From this plane, a set of reference attitude angles describing the aircraft orientation for circular flight is derived. The control inputs are chosen as the attitude angles, the deflection of the elevator, and the turbine tip-speed ratio [4], resulting in a mid-level control architecture that assumes low-level attitude controllers with known dynamics. The adopted flight strategy relies on yaw-based turning, aligning the wing nearly radially with respect to the trajectory centre. The elevator is controlled to track a reference angle of attack via a proportional-integral (PI) controller. The roll is controlled to compensate for gravity, combining an analytical approximation with cyclically modulated PI control loops based on average azimuth and elevation angles. To mitigate power fluctuations, the turbine tip-speed ratio is regulated around its optimal operating point using an approximate model inversion combined with feedback on the average power in memory.

Numerical simulations demonstrate the effectiveness of the proposed strategy in achieving limited power variability during crosswind operation from cut-in to rated wind speeds, while preserving the same control tuning.



*Numerical simulation of the proposed control strategy applied to a 6 DOF model. Evolution of electrical power under a varying wind speed  $V_w$  and controls: angle of attack (AoA) and turbine tip-speed ratio  $\lambda_t$ .*

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- [2] J. De Schutter et al., “AWEbox: An optimal control framework for single- and multi-aircraft airborne wind energy systems,” Energies, 2023.
- [3] M. Tareg, “Automatic control solutions to enhance the reliability of airborne wind energy systems,” Phd Thesis, 2023.
- [4] F. Trevisi et al., “Concurrent aerodynamic design of the wing and the turbines of airborne wind energy systems,” Wind Energy Science, 2026.

*This research has been supported by the project “DeepAirborne” (NextGenerationEU fund, grant no. P2022927H7); and by the MERIDIONAL project, which receives funding from the European Union’s Horizon Europe Programme (grant agreement no. 101084216).*



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## Offshore Airborne Wind Energy: Resonance Aware Control for Vibration Resilient Operation

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Offshore airborne wind energy (OAWE) systems harvest stronger high-altitude winds using tethered wings and floating platforms, avoiding fixed-bottom foundations and enabling deployment in deep-water environments. In pumping-based AWE systems, periodic tether reeling induces force oscillations whose dominant frequencies may interact with platform natural modes, potentially leading to resonant responses, amplified motions, and increased structural fatigue.

Based on the frequency domain analyses of kite-platform interactions [1], this work develops a resonance-aware control framework that actively shapes the spectral content of tether forces. The approach introduces two key components: (1) a real-time modal frequency estimator that identifies dominant platform natural frequencies from measured motion and tether force signals; and (2) an online frequency-feedback adaptive trajectory planner that adjusts the figure-eight angular span  $\Delta\phi$  to maintain the excitation frequency outside resonance bands, thereby modifying the dominant excitation frequency through changes in flight speed and reel-out dynamics. These components are integrated within a dual-timescale control architecture, where the outer loop performs low-frequency resonance avoidance via trajectory adaptation, and the inner loop for fast tether tension regulation.

High-fidelity coupled simulations, incorporating a point-mass kite model, nonlinear tether dynamics, and a 6-DOF spar platform under JONSWAP wave conditions, fully coupled through tether-force interaction and plat-

form motion feedback, demonstrate that the proposed strategy reduces platform sway peak displacement by 63–73% and resonance amplification by more than 50% compared to baseline fixed-trajectory control, with only a marginal reduction ( $\approx 2 - 3\%$ ) in average traction-phase power output.

These results show that extending frequency-domain analysis to a closed-loop, real-time adaptive control framework significantly enhances the vibration resilience and operational robustness of offshore AWE systems without additional hardware.



Offshore AWE System

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## Trajectory Tracking in AWE Optimal Control with a Rigidly-Convected, Lifting-Line Vortex Model

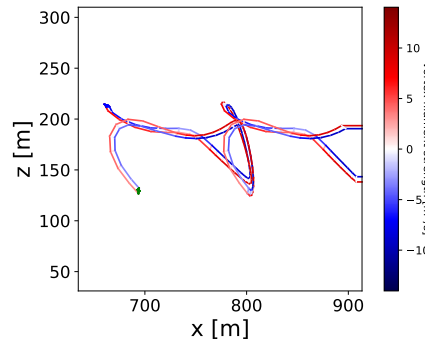
Rachel Leuthold<sup>1</sup>, Curran Crawford<sup>2</sup>, Sébastien Gros<sup>3</sup>, Moritz Diehl<sup>1</sup>

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Licitra et al. [1] compared optimal control-generated predictions of an AWE system's power to real-world experimental values, and suggested several real-world effects that might cause discrepancies. Among these, were sources of 'model-plant mismatches' such as the relationship between the kite aerodynamics and the wind field, which would include wake effects that were not included in the optimal control problem (OCP).



An example of the vorticity distribution within the flow behind a two-kite, lift-mode, power-maximizing AWE system, using a partially-resolved, rigid-wake lifting-line vortex model, as formulated and solved in the *awebox*[3].

This leads to a question: how difficult is it to fly the optimal trajectory found by solving a power-maximization OCP without a wake model (baseline OCP) in a real - and therefore, momentum conserving - flow? In order to keep the degree of complication low, we might simplify that question as asking: how difficult is it to follow the optimal trajectory found with the baseline OCP, using a tracking OCP that includes a mid-fidelity wake model, such as a rigidly-convected lifting-line vortex model[2]?

To answer this question, we'll consider a lift-mode AWE system with two Ampyx AP2 kites. To approximate the achievable power generation with different tracking priorities, we'll parametrize the ratio of the power-relevant variable weights to the path-following variable weights. And, we'll solve all of these specified OCPs using the *awebox* [3].

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## Experimental Test Results on Rotational Launch and Recovery for a Fixed Wing Kite

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At Swift Airgen we are developing a fixed wing kite AWE system. Current experimental work is focusing on the launch and land of the kite and the pathway to autonomous operation. Rotational launch methods avoid the mass of kite vertical take-off motors, and the runway infrastructure of horizontal take-off. We outline progress made in the build and testing of our rotational launch method, transition from launch to wind driven flight and recovery back to stationary. Some rotational launch systems use multiple control lines from the base station whereas we use a single tether line.

We describe the control architecture for launch and recovery and our progress to achieving autonomous operation. Our current system includes a base station rotational launcher, a kite, a user control handset and a radio comms network. In autonomous mode the base station acts as the master coordinator whilst the handset currently enables the user to issue simple 'launch now' and 'land now' type commands.

Our launch sequence is described. 1) The kite is initially held in 'park' on the rotator arm. 2) The rotator spins up to the initial launch rate. 3) The reel releases tether allowing the kite to move outward. 4) The rotator rate gradually reduces (maintaining a constant kite airspeed). 5) The kite achieves controlled aerodynamic flight in an orbit around launcher. 6) The rotator motion stops with the arm pointing downwind. 7) The kite transitions to a cross-wind flight path. The landing sequence is the reverse. At

short tether lengths, centripetal force dominates in setting the kite position, but this gradually transitions to aerodynamic control as both the kite airspeed and tether length increase. Forward thrust of the kite is achieved through a combination of the rotational arm 'pulling' it forward (at shorter tether lengths) coupled with thrust from the kite's own propeller (longer tether lengths).

We present our recent experimental results and discuss some of the control challenges and their potential solutions.



*Kite and launcher system*



*UC3M single skin kite in flight.*



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## Benchmarking NASA Parafoil, Single-Skin Foil, and Leading Edge Inflatable Kites for Airborne Wind Energy Applications

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Over recent years, a variety of ground-generation yo-yo airborne wind energy (AWE) machines have been developed by universities and private companies [1,2]. In terms of aircraft, they exhibit a diverse range of solutions, encompassing rigid wings, ram-air kites and leading edge inflatable (LEI) kites. Experimental and computational fluid dynamic analysis provided fundamental information about their aerodynamic performance [3]. However, a fair, i.e. using the same ground station and number of tethers, comparison of AWE aircraft under real operational maneuvers has yet to be conducted.

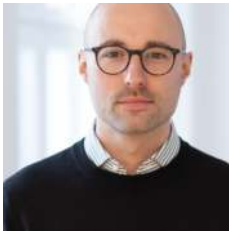
This work compares key performance indexes of (i) a 5 m<sup>2</sup> NASA parafoil soft wing, (ii) an 11 m<sup>2</sup> single-skin foil kite, and (iii) a 10 m<sup>2</sup> leading-edge inflatable kite. To make a fair comparison, the three kites were tested by using the same hardware, i.e. the versatile AWE Ground Station (GS) developed at Universidad Carlos III de Madrid and CT Ingenieros [4]. It allows to test a ground-control configuration by connecting the aircraft with 2 or 3 tethers to the GS and also fly-control by using one tether and a kite control unit to actuate on the kite's bridle. In this study, the experiments were conducted for similar wind conditions and equivalent figure-of-eight maneuvers. Key performance variables for AWE applications were measured, including tether-tension, actuator power consumption, and commanded control inputs. Control handling qualities of the three aircraft are also discussed based on the results of the flight tests.



Kites and ground station used in the experiments.

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## Harnessing Higher Altitude Winds for Mobile Renewable Energy Systems

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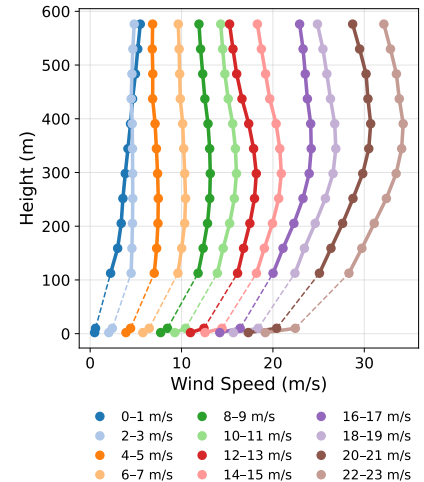
<sup>3</sup>III. Physics Institute B, RWTH Aachen

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Airborne wind energy systems (AWES) are particularly suitable for remote applications that require mobility and flexible deployment. This study investigates their potential use for mobile research missions at Neumayer Station III in Antarctica. The work is conducted within the framework of the project Technologies for Rapid Ice Penetration and subglacial Lake Exploration (TRIPLE), which is part of the Explorer Initiative of the German Space Agency at DLR (Deutsche Raumfahrtagentur im DLR). LiDAR wind measurements up to 500 m above ground level are analyzed, with a focus on low-level jets.

The energy yield of a 30 kW AWES is compared with that of a conventional wind turbine of equal rated power. The analysis is based on wind speed time series at the respective operating heights and the power curves of both systems. The AWES is assumed to operate at an average harvesting height of 300 m, while the conventional turbine has a hub height of 18 m. Uncertainties regarding assumptions about operating heights and power curves exist, but they are sufficient for an initial extrapolation.

Two scenarios are considered. Scenario A covers the Antarctic summer mission period from November 2024 to February 2025, during which the AWES generates about 10% more energy. Scenario B considers only wind speeds below 12 m/s, suitable for fieldwork, where the AWES produces approximately 40% more energy.



*Tall wind speed profiles, determined by LiDAR measurement, combined with ground-based anemometer in 2 and 10 m height. Averaged measurements of the Antarctic summer months Jan, Feb, Nov, Dec 24 and Jan, Feb 25 are represented. The bins refer to the corresponding wind speed at 10 m height.*

*Drum and tether guidance mechanism of Kitepower's 100 kW ground station (October 2025).*





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## Validation of a Coupled Aero-Structural Kite Model Using SymbolicAWEModels.jl

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We present validation of an aero-structural simulation for the TU Delft V3 kite (25 m<sup>2</sup> flat area, leading-edge inflatable, LEI) [1]. The simulation requires no flight data inputs, enabling use in the design phase and reducing reliance on costly test campaigns. The model combines a vortex step method for aerodynamics with a structural model of 44 mass points and 95 spring-damper segments, using ModelingToolkit.jl for symbolic ODE generation. All tools are open source.

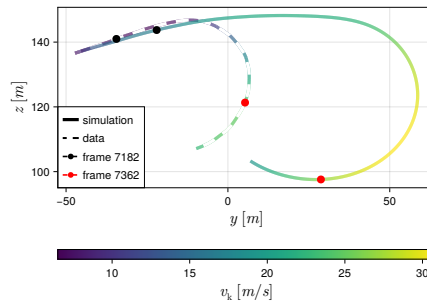


Fig. 1: Open-loop trajectory colored by kite velocity. Markers indicate photogrammetry frames: 7182 (straight flight) and 7362 (right turn).

Validation uses an open-loop simulation of a straight-to-right-turn segment from the 2025 test flight of the V3 kite operated by Kitepower (~9 s). Tether length, reel-out velocity, steering and depower inputs, wind speed, and wind direction are prescribed from flight data; the trajectory, velocity, tether force, and wing shape evolve from the physics. Drag underestimation causes the simulation

to accelerate to higher velocity and tether force than measured (Fig. 1) [1]. The turn rate gain [3]  $g_k = \dot{\psi}_m / (v_a u_s)$  agrees well between simulation and flight data ( $g_k = 0.19$  vs.  $0.24$ ). Photogrammetry [2] confirms the spanwise twist distribution is well matched during straight flight and turns (Fig. 2). Shape comparison with photogrammetry shows good agreement, although some adjustments were needed; billowing pulls struts closer together (~5% reduction [2]), so we reduce TE length by 5%. Wingtip bridle length is reduced by 0.2 m to compensate for LE tube stiffness absent in the model. Pitch matching required a -9% depower offset, possibly due to higher simulated aerodynamic forces reducing bridle slack, or discretization of the bridle system.

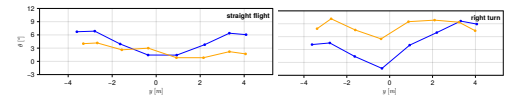
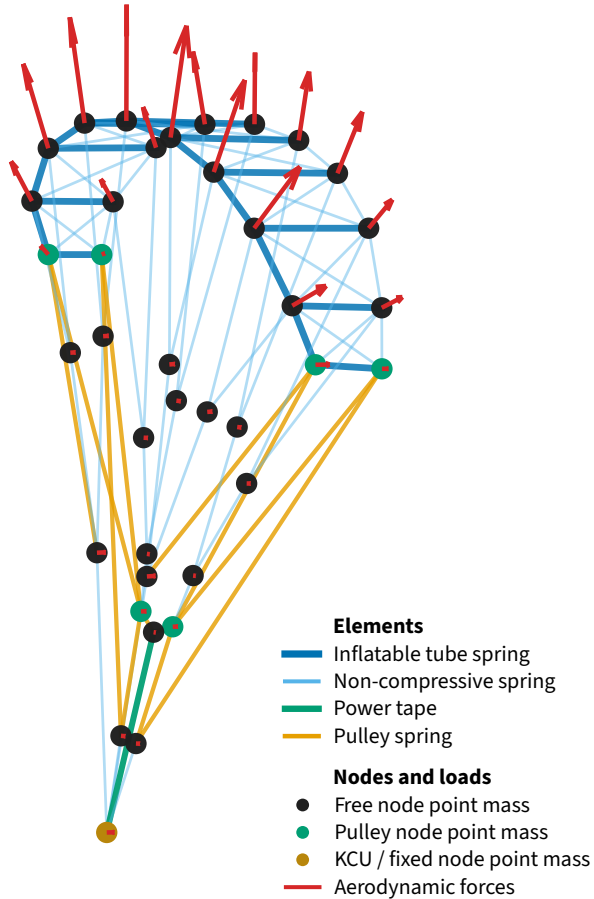


Fig. 2: Twist distribution along the span at frames 7182 (straight flight) and 7362 (right turn).

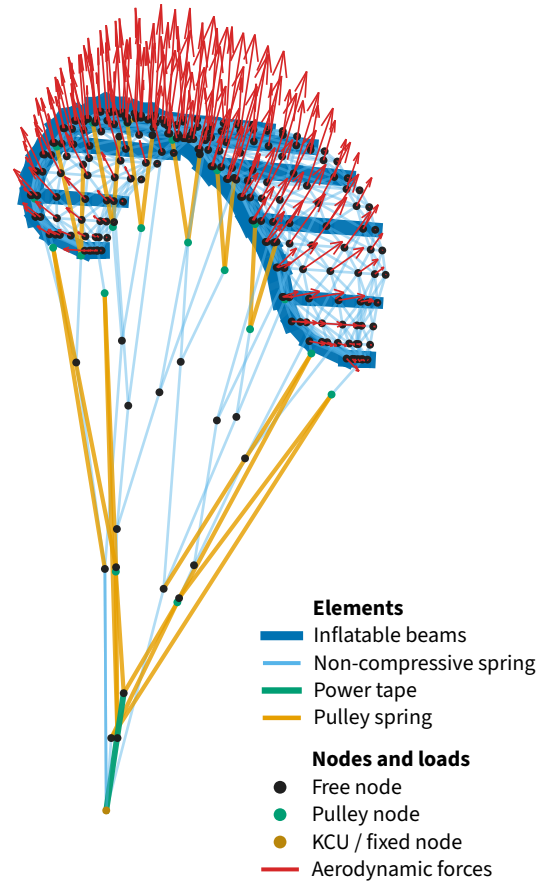
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## PSM: Particle System Model



## FEM: Finite Element Model



*Aero-structural models of the TU Delft V3 kite ([github.com/awegroup/ASKITE](https://github.com/awegroup/ASKITE)).*



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## Fast finite element modelling of bridled leading-edge inflatable kites

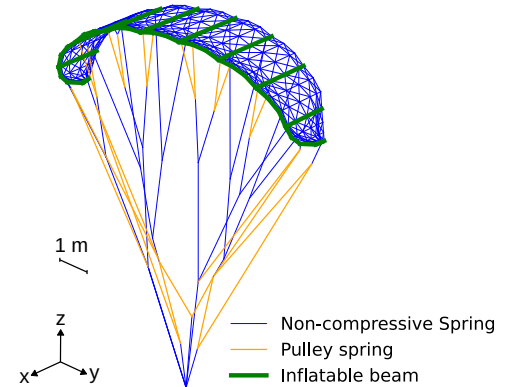
**Patrick I. H. Roeleveld, Jelle A. W. Poland, Roland Schmehl**  
Delft University of Technology

Accurate aero-structural modelling of leading-edge inflatable kites is key for the upscaling of airborne wind energy systems. Existing structural modelling approaches typically introduce simplifications in either the wing structure [1] or the bridle line system [2]. This work presents a finite element framework that models the wing structure and bridle line system within a single, unified formulation.

The framework accounts for material and geometric non-linearities through a Newton–Raphson solution scheme combined with a co-rotational formulation. The bridle line system is represented using non-compressive spring elements, which are also employed to model pulley effects. The inflatable leading edge and struts are modelled as Timoshenko beam elements, with their beam properties iteratively tuned to match experimentally obtained relations for inflatable beams [3]. The canopy is represented using non-compressive spring elements.

The structural modelling framework is applied to the TU Delft V3 kite, and validation is performed using stereoscopic photogrammetry measurements obtained from static load tests under varying internal pressures and external loading conditions [4]. The results show good agreement between the simulated and measured kite geometries for most test cases, demonstrating that the model captures the dominant structural behaviour of leading-edge inflatable kites.

The proposed framework provides a foundation for aero-structural analysis in kite design and enables future coupling with aerodynamic models for steady and quasi-steady kite simulations.



Finite element framework applied to the TU Delft V3 kite [5]

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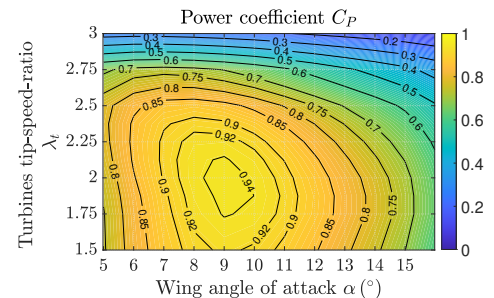
## Concurrent Aerodynamic Design of the Wing and the Turbines of AWE Systems

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The aerodynamic design of the fly-gen AWE system aircraft, named windplane here, is a largely unexplored yet crucial problem for improving power production. To this end, an engineering model for the interactional aerodynamics of the onboard turbines and the wing is developed and coupled to a steady-state model of the windplane flying circular crosswind trajectories and a far-wake model. This novel comprehensive model is then used for the aerodynamic design of a windplane with wingspan of 10 m. Initially, a design space exploration study reveals that placing the turbines at the wing tips and rotating them inboard down increases the power production compared to other locations and rotation direction. This improvement arises because the turbines wake swirl reduces the wing induced drag, which increases flight speed and consequently the generated power. Moreover, airfoils with high lift-to-drag ratio are found to be optimal for windplanes. As a consequence, NACA4421 airfoils are used for the design of the wing and the tip-mounted turbines. The trapezoidal wing with constant twist which maximizes power production has an aspect ratio of 5.1 and a taper ratio of 0.60. The onboard turbines operate at a design low tip speed ratio of 1.9 to increase the wake swirl. The results from the vortex models of the wing, the turbines, and their interaction show very good agreement with the lifting line, the vortex lattice method, and the vortex particle method implemented in the well-established code DUST. Finally, the windplane is studied with DUST at different wing angles of attack and at different turbine tip speed ratios to characterize its behavior

away from the design point. The maximum in power coefficient, defined as the ratio between the onboard turbines shaft power and the wind power passing through a disk with radius equal to the windplane wingspan, is observed near to the design point, well separated from the stall regions of both the wing and the turbines.



Windplane power coefficient  $C_P$  as a function of the wing angle of attack  $\alpha$  and the turbine tip speed ratio  $\lambda_t$  evaluated with DUST.

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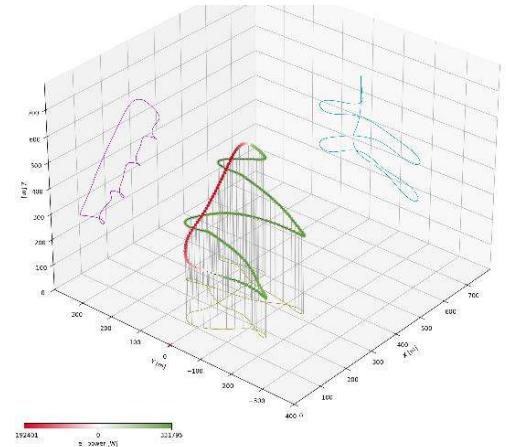
## Faster, Smarter, Safer: SkySails' End-to-End Simulation Tool Chain for Airborne Power

**Thorben Bartsch, Xaver Paulig, Lukas Schmidt, Andreas Höhl, Paul Thedens, Benjamin Karg, Christoph Heeckt, Mahmoud Soliman**  
SkySails Power GmbH

Airborne power systems have already demonstrated their strong potential for efficient, low-material clean energy generation. Advanced simulation capabilities further accelerate and robustify the development process while reducing costs by avoiding field errors. This talk presents SkySails' end-to-end simulation tool chain, which empowers faster development cycles for kite, autopilot and ground station. The tools enable precise performance predictions for scaled up systems and are the foundation for fatigue analyses. Central components include a coupled aero-structural model of the kite [1], simple model-based closed-loop flight dynamics simulation [2], deriving efficient flight control patterns through optimization [3], a simulation of flight in wind conditions with defined turbulence, FEM simulations of the structural components, and an efficiency model of the ground station. Besides, we will present recent improvements of the simple model [4] to describe tether slack and free flight situations.

Furthermore, we demonstrate how CasADi-based trajectory optimization combined with load results from flight simulation in turbulent conditions, can generate a fatigue-spectra. Using it as a load case for the mechanical design process, we can improve the lifetime of key components.

SkySails simulation workflows advance the field towards more robust and efficient airborne power extraction, paving the way for innovation and greater system reliability.



CasADi-based trajectory optimization for high wind conditions.

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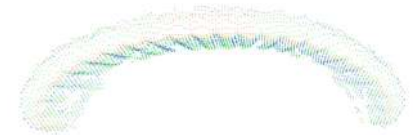
## 3D LiDAR Assisted Validation of the SkySails Aero-Structural Kite Model

**Paul Thedens**  
SkySails Power GmbH

SkySails Power GmbH has developed a custom ram-air kite for wind energy generation. To support its design and to better understand the interplay between canopy deformation and the bridle system's layout and kinematics, a comprehensive simulation environment modeling the kite's aero-structural behavior has also been created [1-2]. Previous attempts to validate this aero-structural model have mostly relied on point measurements taken from load cells and wind speed sensors positioned at specific spots on the kite.

Although these measurements provide valuable insights into the kite's performance, they lack the spatial detail required to fully assess the complex interactions between aerodynamics and structural dynamics. To overcome this limitation, a 3D solid-state digital LiDAR scanner has been employed to capture detailed point cloud data of the kite in flight. This approach allows for the acquisition of high-resolution, real-time representations of the kite's surface and deformations. Furthermore, each point in the cloud contains both distance and reflectivity data. By applying special reflective tape to key locations on the canopy, specific features can be easily identified during post-processing. Comparing the LiDAR-generated point clouds to the simulated kite shapes from the coupled

aero-structural model enables a more thorough validation of the model's accuracy.



*3D Point Cloud of the ram-air kite during flight captured by the LiDAR scanner.*

### References:

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## Scaling airborne power: SkySails' Venyo (PN-14) industrialization and functional risk assessment

**Thorben Bartsch, Izabela Lewandowska, Gerrit Fischer**  
SkySails Power GmbH

The field of airborne wind energy encompasses a wide diversity of technology concepts [1,2]. For all power-generating concepts, the power curve remains the key step in demonstrating the viability of the product [3]. Beyond this milestone, further steps are required to industrialize the technology demonstrators into commercially viable products.

Reliable and accurate production processes, as well as quality assurance mechanisms, must be implemented. Moreover, cost-optimized designs are essential to offer competitive alternatives to conventional renewable energy sources with acceptable OPEX and CAPEX [4].

Besides these commercial needs, CE declaration is a central requirement for trading products in the European market [5]. The basis of the CE declaration is the safe operation of the product, ensuring it does not pose unreasonable risk [6]. Therefore, the product development requires accordance with relevant EU directives and state-of-the-art standards. Key aspects include functional risk assessment and corresponding adaption of product design to avoid all risks emanating from the product to operators and others.

This talk presents the latest steps on SkySails' road to industrialisation. Moreover, we present the formalisms, as well as the key results of functional safety assessment that we have accomplished in 2025.



*Results of CasADi based trajectory optimization for high wind conditions. Note: Results are based on an imaginary system.*

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## Author index

- Afonso, Gabriel V. C., 33  
Ahmed, Syed Hassan, 138  
Airimitoiaie, Tudor-Bogdan, 112  
Alborghetti, Mattia, 108, 184  
Aldana, Yajaira, 113  
Alonso-Resta, Miguel, **92**, 168  
AlRayyes, Nasouh, **27**, 179  
Astolfi, Daniele, 27  
Azaki, Zakeye, 25, **135**  
Bah, Oum Selema Hind, **25**  
Bardazzi, Andrea, 79  
Barre, Stéphane, 52  
Bartsch, Thorben, **196**, **198**  
Bavoil, Antonin, **131**  
Beaupoil, Christof, **83**  
Bertozzi, Andrea, **108**, **157**  
Bordignon, Matteo, **183**  
Bosman, Rigo, **154**  
Boucheriguene, Yacine, 144  
Bracco, Giovanni, 108  
Bredael, Joren, **109**  
Breipohl, Florian, **46**  
Brouillon, Jean-Sébastien, **130**  
Burrell, Inigo, 29  
Cai, Yanfeng, 94  
Cappellari, Alessandro, **162**  
Carriquiry, Aurélien, 144  
Carroll, James, 26  
Carvalho, Estéban, 144  
Cassoni, Gianni, 195  
Castelino, Roystan V., **58**  
Cayon, Oriol, **57**, 109  
Cecchin, Leonardo, 79, **84**  
Chatelain, Philippe, 53  
Chen, Wenbo, 125  
Chen, Ziwei, 26, **28**  
Crawford, Curran, 186  
Crevecoeur, Guillaume, 67, 151, 152  
Crismer, Jean-Baptiste, 53, **65**  
Croce, Alessandro, **110**, **133**, 162, 163, 183  
da Costa, Conrado Guimarães, **34**  
da Costa, Rui C., **33**  
De Schutter, Jochem, 23, 131  
de Vries, Gerdien, **86**  
Degroote, Joris, 151, 152  
DeLosRíos-Navarrete, Francisco, 189  
Deng, Xintong, **76**, 137, 139, 147  
Dief, Tarek N., 31  
Diehl, Moritz, **23**, 81, 180, 186  
Ding, Jinsong, 125  
dos Santos Rocha, Dario, **160**  
Dumon, Jonathan, 25, 135  
Duponcheel, Matthieu, **53**, 65  
Dyrseth, Marius, 49  
Endo, Hiroki T., **88**  
Enserink, Rudo, **173**  
Espe, Clemens, 190  
Everbach, E Carr, 89  
Fagiano, Lorenzo, 79, 84, 108, **138**, 157, 162, 183, 184, 195  
Farges, Christophe, 112  
Farmani, Amirhosein, **159**  
Fechner, Uwe, **169**  
Feldmann, Marco, 190  
Fernandes, Gabriel M., **35**, 74  
Fernandes, Manuel C. R. M., 33, 74, 75  
Fernandez, Guillermo, 64  
Fine, Jacob B., **85**  
Fischer, Gerrit, 198  
Fontes, Fernando A. C. C., **7**, 33–35, 74, 75  
Francke, Gero, 190  
Galarza-Morales, Nico E., 174  
Garg, Srishti, 111  
Gaunaa, Mac, 164, 195  
Genoni, Alessandro, **52**  
Ghezzi, Andrea, 180  
Ghivarello, Marco, **97**  
González Casares, Nicolás, **132**  
González-García, Jorge, 92, 93, 168, **189**  
Gros, Sébastien, 186  
Gu, Xing, 125  
Hårklau, Thomas, **49**  
Haanen, Pim J., **118**  
Haas, Thomas, **66**  
Hably, Ahmad, 25, 27, 135  
Hackl, Christoph M., 165  
Harzer, Jakob, 23, **81**, 180  
He, Tianyu, 185  
Heeckt, Christoph, 196  
Heinen, Dirk, 190  
Heutelbeck, Dirk, **190**  
Heydarnia, Omid, **67**  
Houchens, Brent C., 174  
Hu, Jun, 90  
Hua, Zhen, **125**  
Huang, Weixi, 125  
Huang, Yidi, **30**  
Hwang, Inseok, 147  
Höhl, Andreas, 196  
Itakura, Eiji, **60**  
Jansen, Theo, **22**  
Jondeau, Kaoane, 64  
Jones, Colin N., 73  
Kamp, Linda M., 155, 158  
Kamra, Mohamed M., 31  
Karg, Benjamin, 196  
Kaufman-Martin, Sam, **111**  
Kazemi, Abbas, 28  
Ke, Jianxu, 30  
Kelly, Mark C., 156, 164  
Kennedy Scott, Will, **187**  
Keplinger, Jonas, **180**  
Khalil, Nathalie, 33  
Kheiri, Mojtaba, **153**  
Khurshid, Yahya, **31**  
Koivisto, Matti, 159  
Konieczny, Pawel, 146  
Korzekwa, Filip, **146**  
Kosmopoulos, Panagiotis, 98  
Kou, Yilin, 111  
Kuhn, Achim, **77**  
Lang, Eric J., **174**  
Lanusse, Patrick, 112  
Lefebvre, Tom, 67  
Leuthold, Rachel, **186**  
Lewandowska, Izabela, 198  
Li, Leming, **32**  
Li, Xiaoyu, **94**  
Liu, Haiyang, 78  
Liu, Huilin, **155**  
Lolies, Tom, **64**  
Lowenberg, Mark, 29, 68  
Luca, Andrei, 40  
Lucarelli, Alessia, 79  
Lugni, Claudio, 79  
Luo, Bixiong, **78**, 94  
Luzzatto-Fegiz, Paolo, 111  
Løno, Asgeir, 49  
López-Peláez, Pedro, 93  
Marrel, Camille, **144**  
Measure, Kasper R. G., 103  
McWilliam, Michael K., **62**, 159, 164  
Meslem, Nacim, 25, 135  
Moormann, Dieter, 24, 81  
Mota, Alzira, 136  
Nam, Taewoo, 76, 137, **139**, 147  
Neri, Francesca, 110  
Nguyen, Duc H., **29**, **68**, 106, 156  
Nicolás-Martín, Carolina, 92, 93, **168**, 189  
Niosi, Francesco, 108

Niu, Xiaojing, 32, 91  
 Nobile, Umberto, 110  
 Notable, Maxim, **152**  
 Offermann, Alexis, 135  
 Oland, Espen, 29, 68, **106**, 156  
 Ortt, J. Roland, 155  
 Paduano, Bruno, 108  
 Paelinck, Reinhart, **63**  
 Paiva, Luís Tiago, 34, 35, **51**, 136  
 Pang, Yan, **185**  
 Pant, Kartik Anand, **147**  
 Pasquali, Monika, **112**  
 Paulig, Xaver, 196  
 Peng, Kaijun, 78  
 Perdomo-Díaz, César Eduardo, **93**,  
 168, 189  
 Petrick, Kristian, **36, 59**  
 Pickar, Jamie, **89**  
 Pinedo, Henry, **113**  
 Poland, Jelle A. W., 100, **103**, 118, **170**,  
 192, 194  
 Polkläser, Kim Selina, **24**, 81  
 Porta Ko, Agustí, 29, 68, 106, **156**  
 Pusch, Manuel, 183  
 Pynaert, Niels, **151**, 152  
 Pérez-Aballe, Osmany, 168  
 Qu, Zijie, 30  
 Rand, Kevin, 63  
 Rangriz, Sina, 153  
 Rather, Sanya Shabir, **164**  
 Read, Rod, 28  
 Ren, Zongdong, 78  
 Reuchlin, Sweder, 40  
 Riboldi, Carlo, 162  
 Roeleveld, Patrick I. H., **194**  
 Roque, Luís A. C., 33, **136**  
 Rudolph, David Philipp, 158  
 Runacres, Mark, 66  
 Santos-Martín, David, 92, 93, 168, 189  
 Saving, Anastassia, **158**  
 Schmehl, Roland, **7**, 57, 100, 103, 109,  
 112, 118, 160, 161, 169,  
 170, 190, 194  
 Schmidt, Lukas, 196  
 Schoettler, Fabian, 190  
 Schorbach, Vera, 190  
 Schroeder, Sander, **178**  
 Schulze, Timon, **87**  
 Schuster, Florian, **176**  
 Selje, Robert, **166**  
 Sella, Giorgio, **50**  
 Serres, Ulyess, 27  
 Shivam, Amit, **75**  
 Sicot, Christophe, 52  
 Simon, Tanguy, 27, **179**  
 Singh Grewal, Karanvir, **163**  
 Smith, Garrett, 144  
 Soliman, Mahmoud, 196  
 Song, Shiyi, 30  
 Strohmayer, Andreas, 77  
 Stölzle, Fabian, 178  
 Sun, Liang, 166  
 Sánchez-Arriaga, Gonzalo, 189  
 Tapia Pino, David, **165**  
 Tardella, Armand, 144  
 Thedens, Paul, 196, **197**  
 Theodoulis, Spilios, 112  
 Thirumaligai, Raaghav, 111  
 Thoms, Stefanie, **7**  
 Tinianov, Riley, 111  
 Trevisi, Filippo, 183, **184, 195**  
 Trombini, Sofia, **79**  
 Tu, Jin, 94  
 van de Lint, Bart, 170, **192**  
 van Lith, Thijs L. B., **100**  
 Vergara, Claudio, 160  
 Vermillion, Chris, 85  
 Vinha, Sérgio, **74**, 75  
 Waibel, Johannes, **73**, 130  
 Wang, Junhao, 32, **91**  
 Wang, Lipo, 30  
 Watson, Simon, **134**  
 Wauters, Jolan, 67, 151, 152  
 Wei, Yuan, **128**  
 Weyel, Felix, 83  
 Wiebusch, Christopher, 190  
 Willems, Pieter, **40**  
 Winckelmans, Grégoire, 53, 65  
 Wyatt-Brondel, Gabriel, 92  
 Yang, Wolong, 128  
 Yousef, Hanna, **161**  
 Yu, Jianqiao, 90  
 Yu, Yong, 90  
 Yue, Hong, 26, 28  
 Zhang, Li, 78, 94  
 Zhang, Yue, 125  
 Zhao, Chiming, 76, 137, 139, 147  
 Zhao, Lihao, 125  
 Zhou, Hongmiao, **90**  
 Zhu, Yufei, 76, **137**, 139, 147  
 Zierke, Simon, 190  
 Zou, Chenghao, 185  
 Zulfazli, Muhammad Mutthanna Am-  
 jad, **26**

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Beaupoil, Christof, 82  
Brouillon, Jean-Sébastien, 129  
CPECC, 126, 127  
Dura Vermeer, 41  
EnerKite, 44, 45, 175  
FEUP, 6  
Ghivarello, Marco, 95, 96  
Haanen, Pim, 114, 115, 116, 117  
Jansen, Theo, 15, 16, 17, 18, 19  
Kitedynamics, 177  
Kitemill, 47, 48, 104, 105, 107  
Kitepower, 37, 38, 39, 42, 43, 54, 56, 61, 191  
Klis, Loek van der, 21  
Lith, Thijs van, 98, 99  
Lousberg, Jorrit, 41  
Oosterling, Rob, 11  
Pereira, Tiago, 8  
Politecnico di Milano, 181, 182  
Poland, Jelle, 98, 99  
Pynaert, Niels, 148, 149, 150  
Rijkswaterstaat, 40  
Schmehl, Roland, 13, 14, 55, 101, 102  
Studio Retouched, 40  
Toyota, 171, 172  
UC3M, 12, 167, 188  
University of Freiburg, 80  
Wind Fisher, 140, 141, 142, 143, 145  
Yousef, Hanna, 193  
Zhonglu Co., 119, 120, 121, 122, 123, 124  
Zwinkels, Marco, 20

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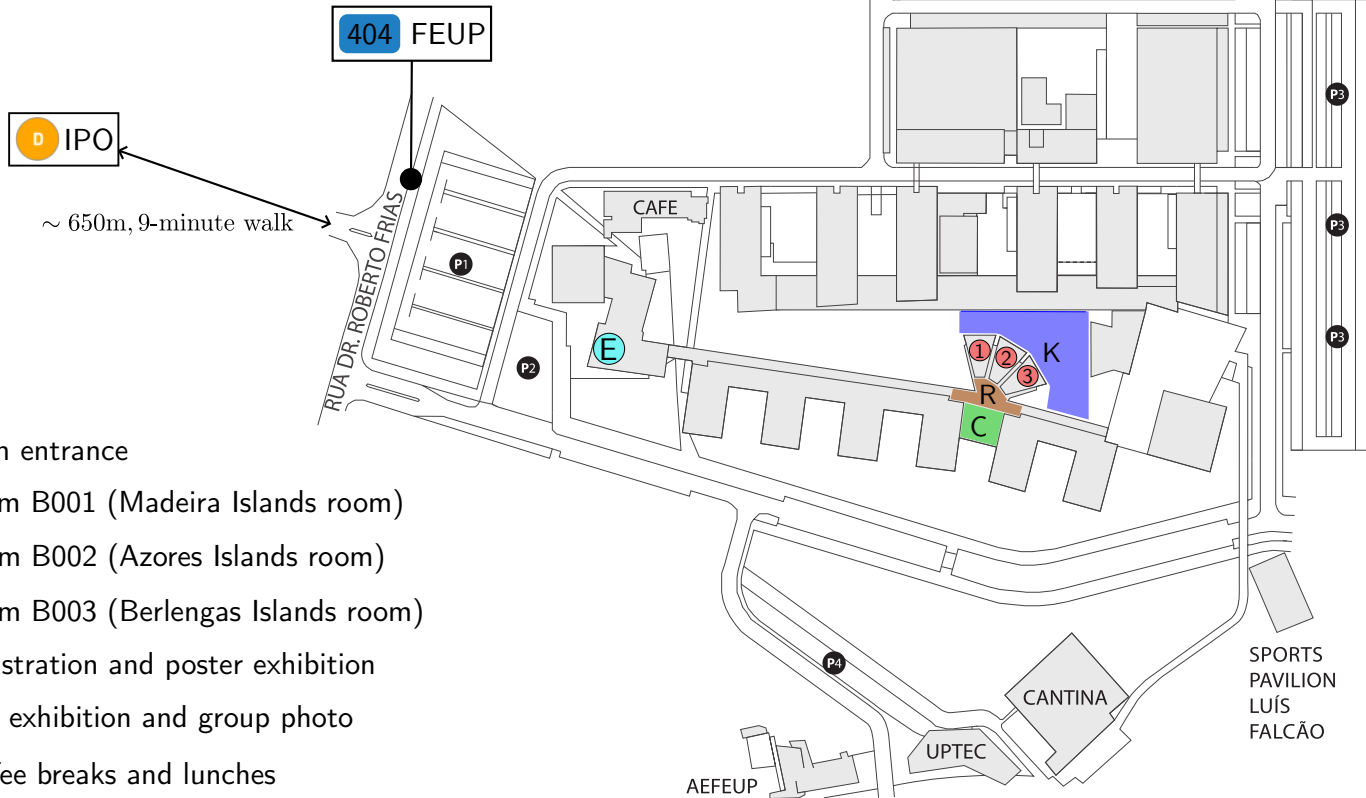
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