ENV-530
OUR NEW MASTER COURSE AT EPFL

Part of the mission of the Laboratory of Sustainability Robotics is to train the next generation of experts in

SUSTAINABILITY ROBOTICS

Prof. Mirko Kovac
Sustainability Robotics Laboratory at Empa-EPFL
Mirko.Kovac@epfl.ch

A huge thank to the team members who have helped shape this course: Kevin Holdcroft, Luca Romanello, Fabian Wiesemüller, Lachlan Orr, Pham Huy Nguyen and Ryo Kanno.

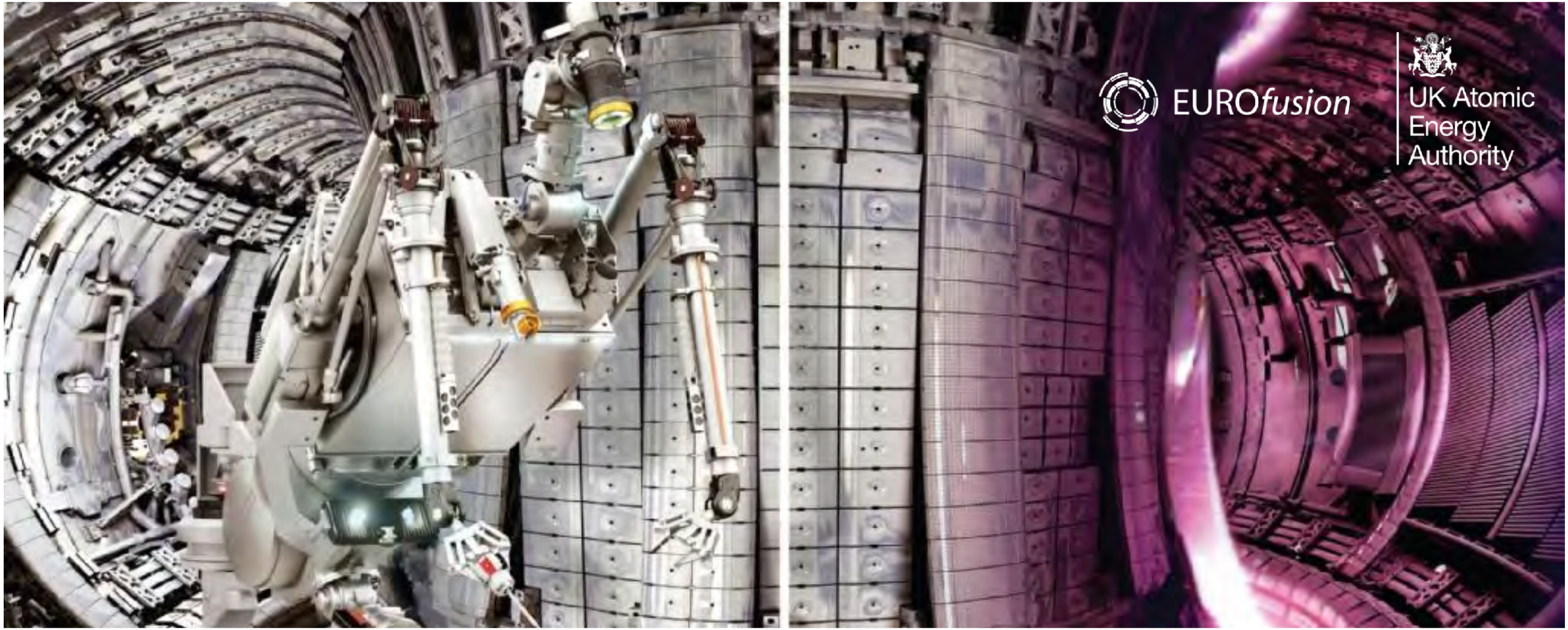
Robotics innovation global trends

Atlas robot Boston Dynamics
(YouTube: https://www.youtube.com/watch?v=-e1_QhJ1EhQ)

Robotics innovation global trends

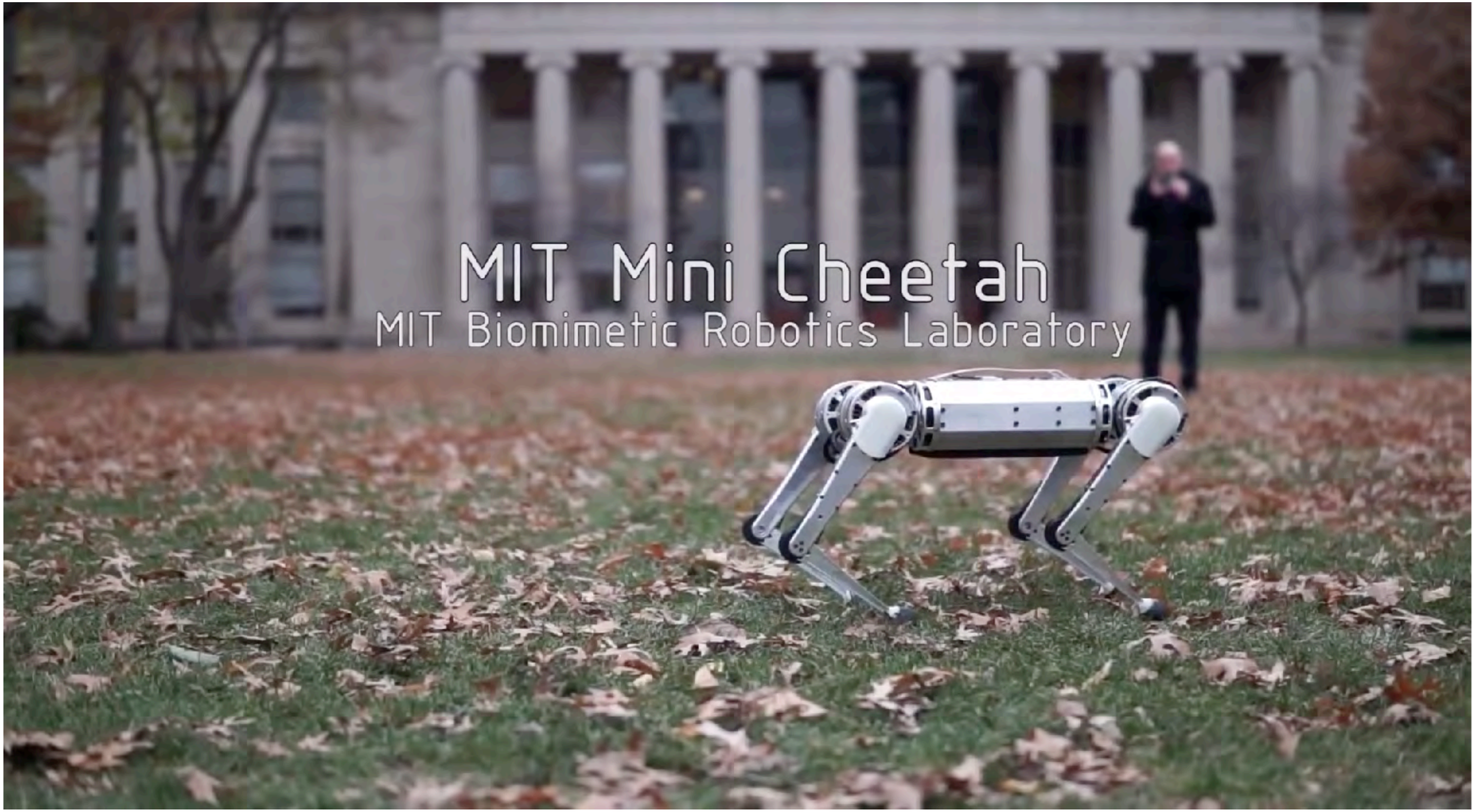
Da Vinci robotic surgery system (Intuitive Surgical)

Robotics innovation global trends



Remote Applications in Challenging Environments (RACE) in Culham Oxford

Robotics innovation global trends



MIT Cheetah robot (Prof. Sang-bae Kim)

Robotics innovation global trends

OceanONE Stanford Robotics Lab (Prof. Ousama Khatib)

Robotics innovation global trends

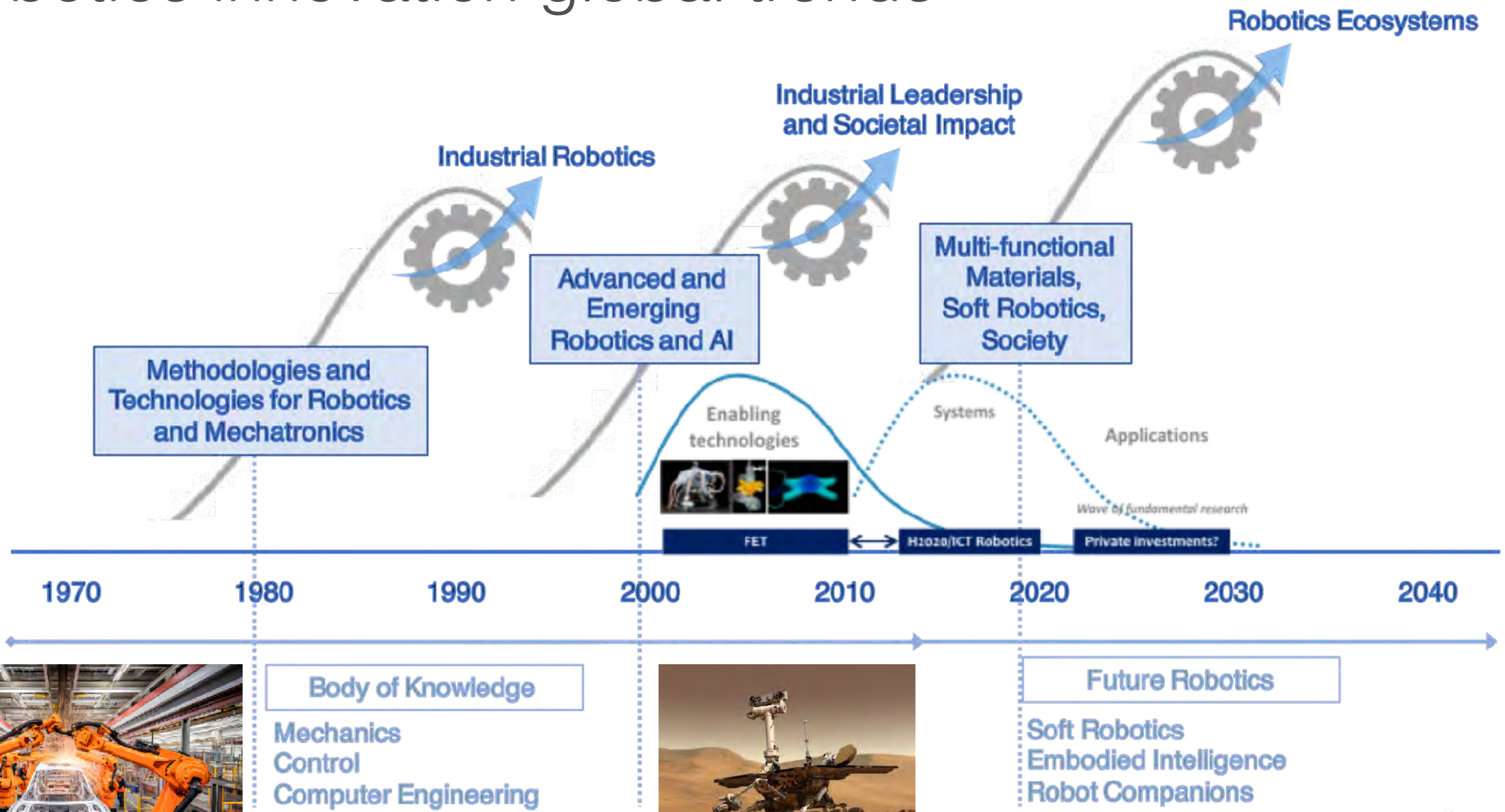


Illustration credit: Laura Margheri

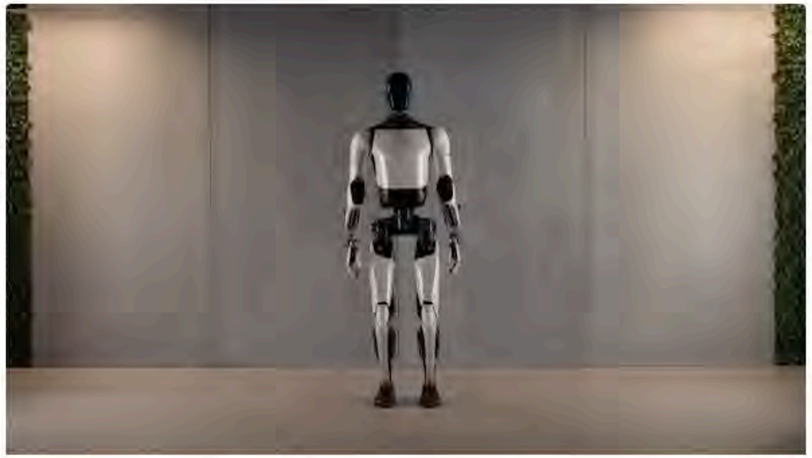
Firstpost. Home Video Shows World Explainers

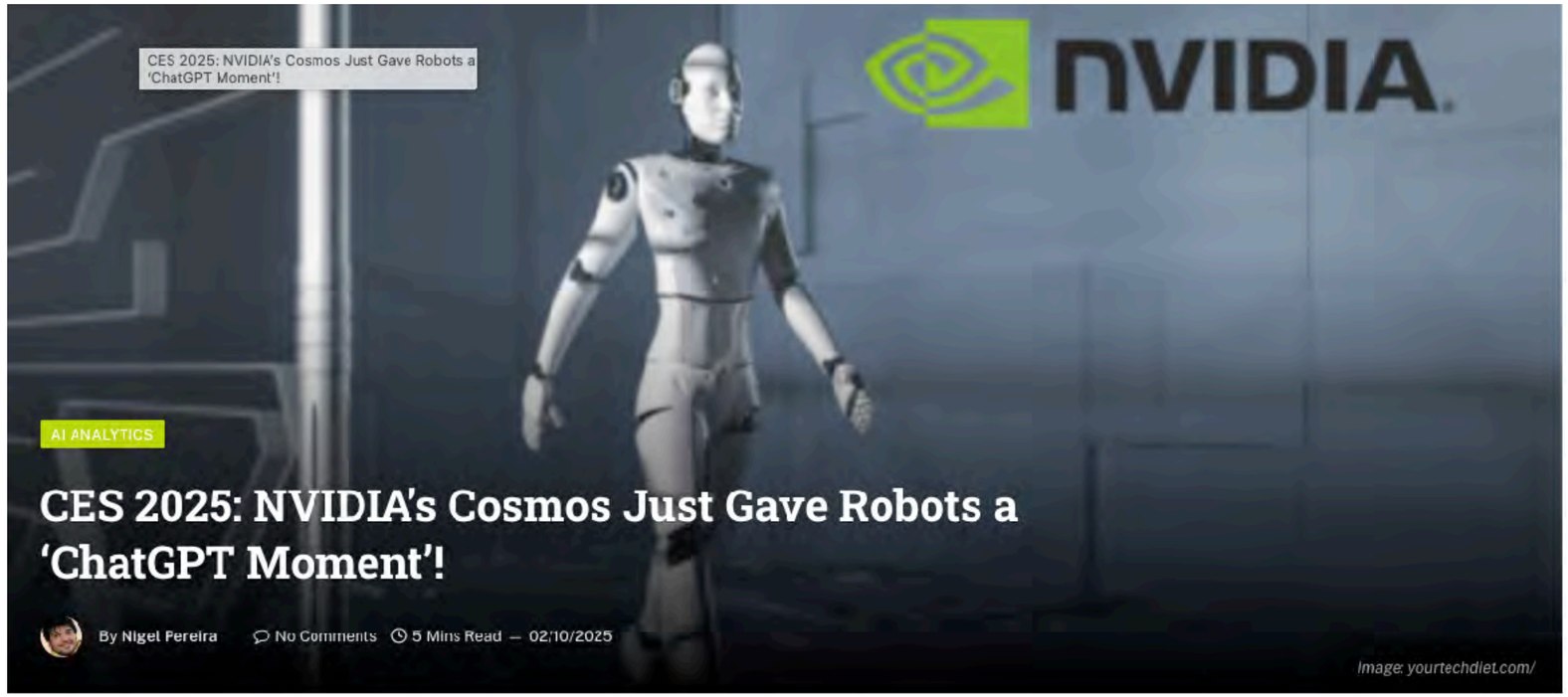
Home / Tech /

Tesla goes on a hiring spree as it begins to ramp up production of Optimus humanoid robot

FP Staff • February 6, 2025, 18:51:57 IST

The large number of open positions indicates that Tesla is accelerating its efforts to boost manufacturing capacity for Optimus. As the company shifts its focus to high-volume production, it appears poised to move closer to making the Tesla Bot a commercially available product





HANS PETER BRONDMO THE BIG STORY SEP 18, 2024 6:00 AM

Inside Google's 7-Year Mission to Give AI a Robot Body

WIRED

Boston Dynamics joins forces with its former CEO to speed the learning of its Atlas humanoid robot

Story by Brian Heater • 1w • 3 min read

Forbes

Meta Is Developing Humanoid Robots; This Has Huge Potential For Healthcare

Dr. Sai Balasubramanian, M.D., J.D. Contributor

Follow

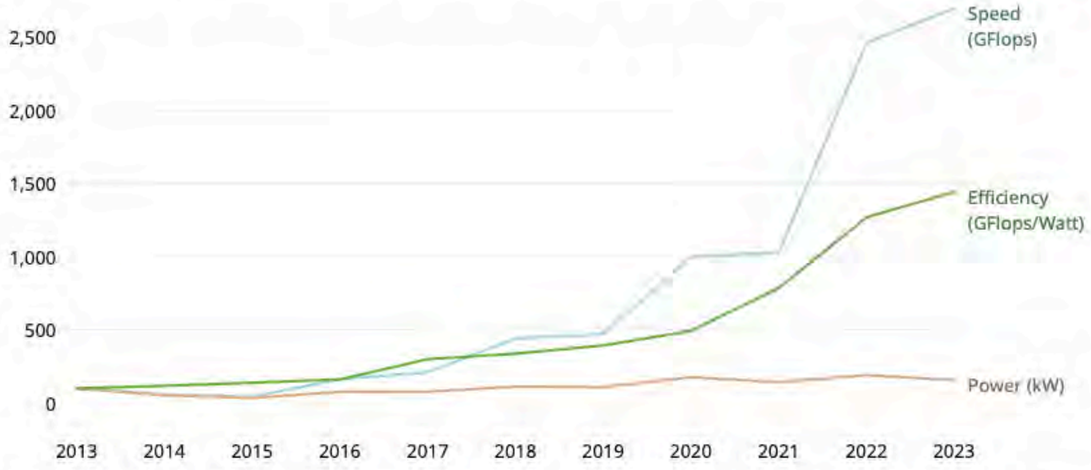
Feb 17, 2025, 09:17am EST

Firstpost. Home Video Shows World Explainers

Apple working on building a humanoid robot, to take on Tesla's Optimus

Manu Ranjan Das • February 17, 2025, 18:06:22 IST

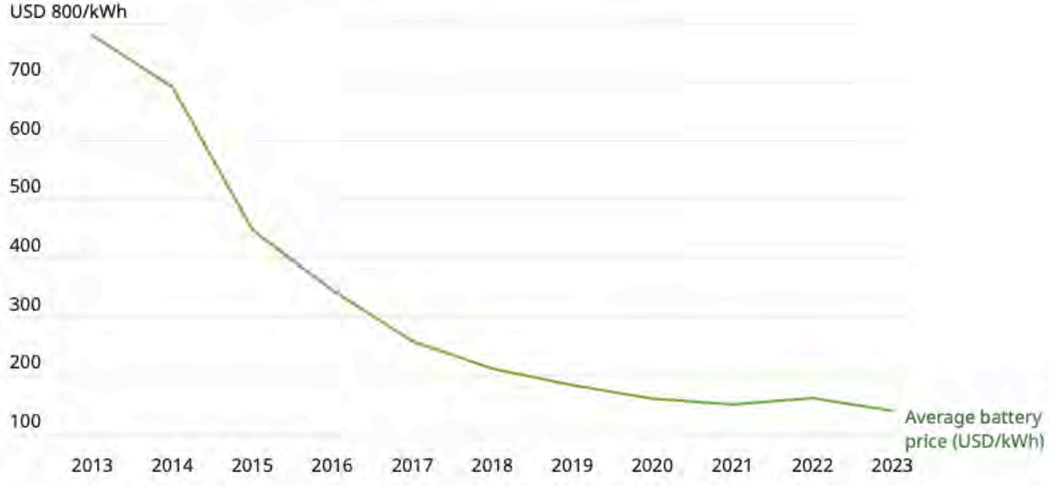
Figure 8 Average speed, power and efficiency of top 50 green supercomputers, 2013–2023



Notes: Average efficiency is calculated as the ratio of average speed to average power for the top 50 green supercomputers. An increase in efficiency can occur even when both speed and power are decreasing. 2013 is the base year and set to 100.

Source: WIPO based on data published by TOP500.

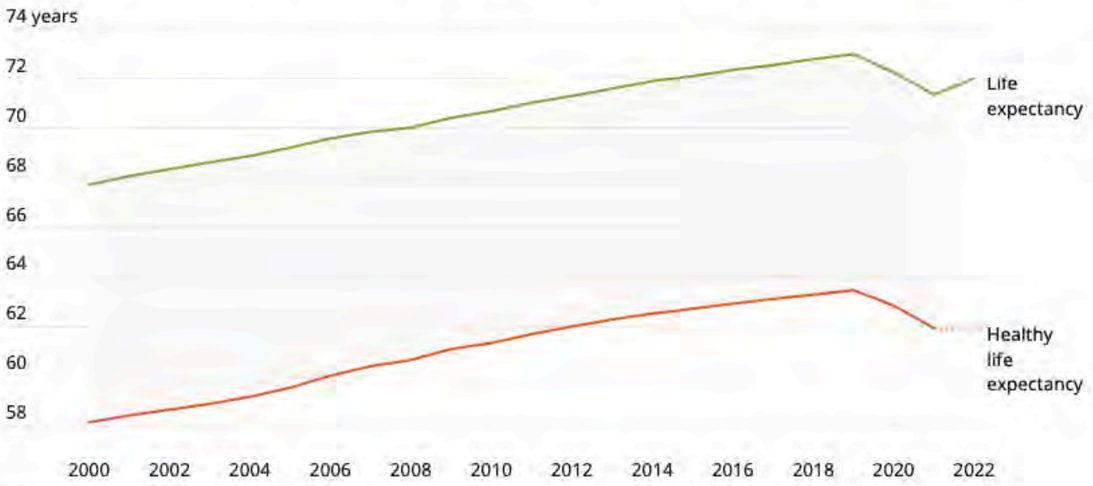
Figure 9 Average lithium-ion battery price, 2013–2023



Note: Prices a shown in real 2023 USD.

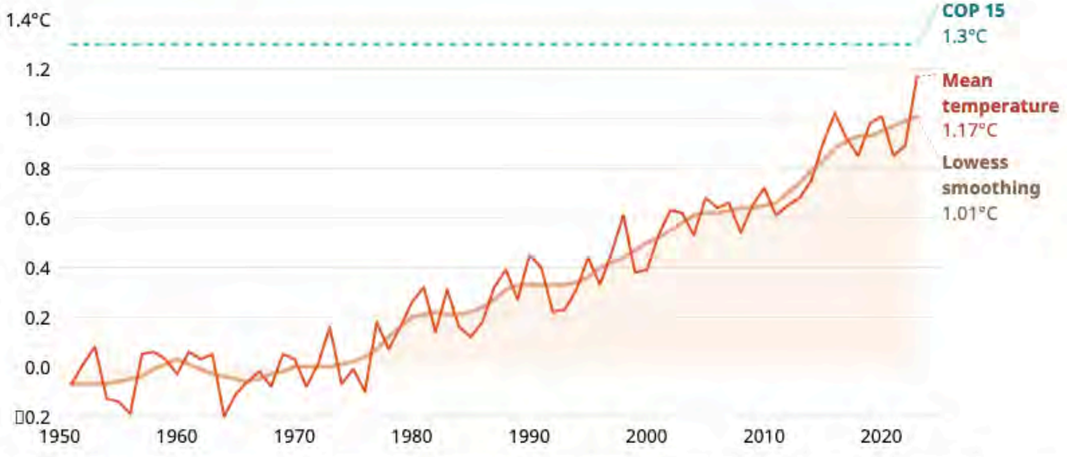
Source: WIPO, based on data published by BloombergNEF.

Figure 13 Life expectancy and healthy life expectancy at birth (years), 2000–2022



Source: WIPO, based on data published by World Bank (LE) and World Health Organization (HALE).

Figure 14 Global temperature anomaly, 1951–2023 land–ocean global mean temperature

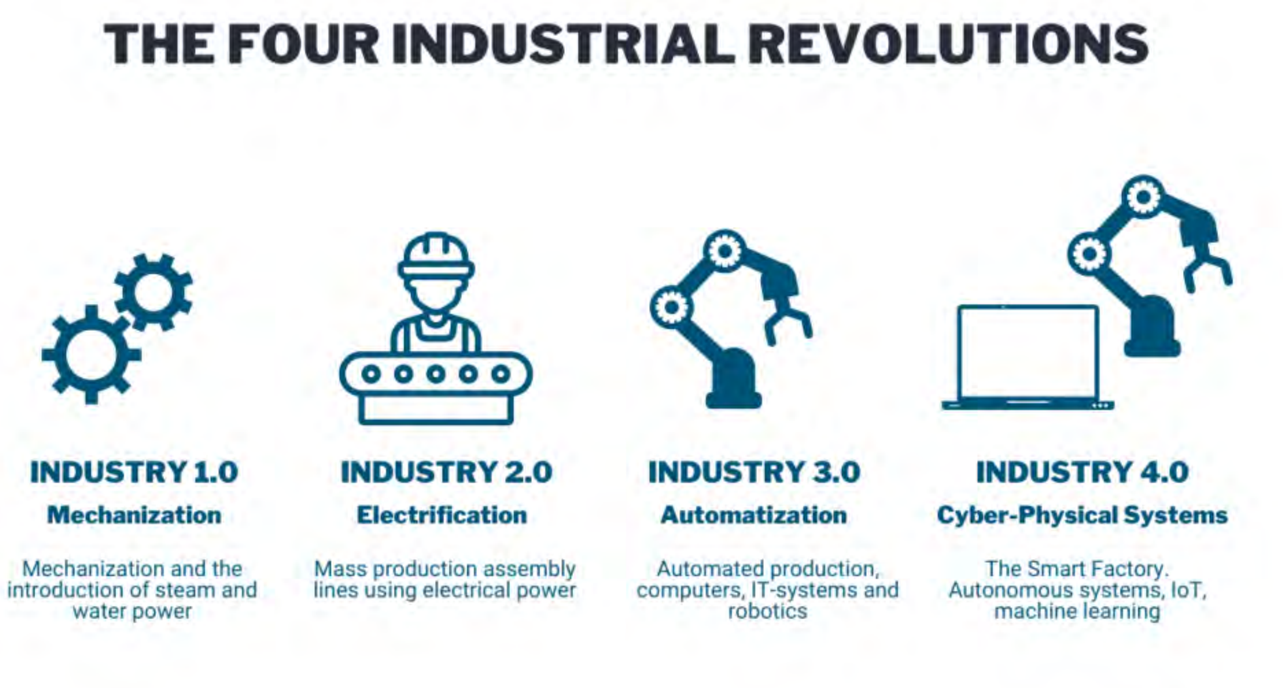


Notes: COP 15 (lower threshold) indicates the lower limit of 1.5°C global warming relative to the pre-industrial temperature. This corresponds to a temperature increase of 1.3°C with respect to the average temperature from 1951 to 1980. Lowess smoothing denotes Locally Weighted Scatterplot Smoothing with a fifth-degree polynomial.

Source: WIPO, based on data published by NASA GISS GISTEM.

What does this mean for you?

- Robotics skills are a must have
  - *All industries becoming more automated / robotic*
  - *“Robotics education [should be] as a mandatory component of other skills training.” (WEF)*
  - “Industry 4.0 will disrupt nearly every industry in every country, creating new opportunities and challenges for people, places and businesses”
- **Next generation needs knowledge, language, network and track record**



1. https://www.weforum.org/stories/2020/10/changes-needed-upskill-workers-robotics-education/
2. https://www.gov.uk/government/publications/regulation-for-the-fourth-industrial-revolution/regulation-for-the-fourth-industrial-revolution
3. https://www.calsoft.com/what-is-industry-4-0/

SWITZERLAND GLOBAL ENTERPRISE

Services | Why Switzerland | Ecosystems | Technologies | About us

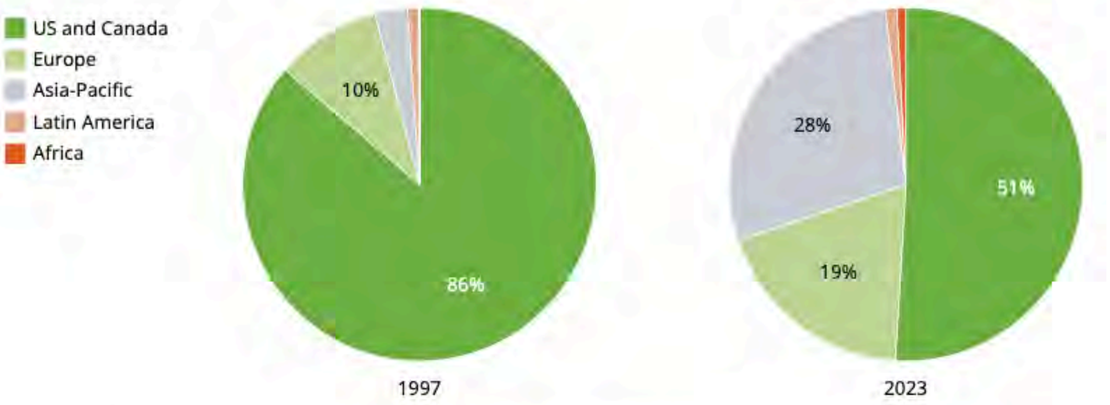
NEWS

SWITZERLAND IS MOST INNOVATIVE COUNTRY ON EARTH FOR 14TH TIME

Oct 03, 2024 16:36 | Switzerland Global Enterprise

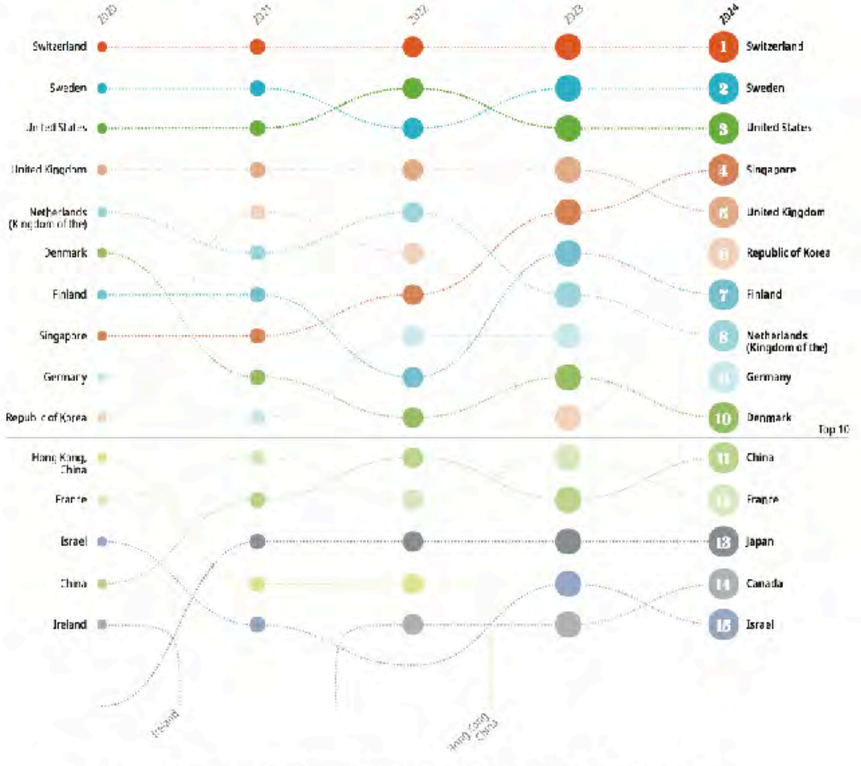
Switzerland has taken first place in the World Intellectual Property Organization's Global Innovation Index 2024 for the 14th time in a row. It takes pole position for scientific, technological, and creative services.

Figure 6 Regional distribution of venture capital deal value, 1997 and 2023



Source: WIPO, based on data published by Refinitiv Eikon (private equity screener), accessed March 2024.

Figure 16 The GII dynamo: The top 15 innovators, 2020-2024



Note: Year-on-year comparisons of GII rankings need to take into account changes to the GII model that have occurred over time, as well as data availability.
Source: Global Innovation Index Database, WIPO, 2024.

GREATER ZURICH AREA

Boston Dynamics AI Institute coming to Zurich

November 03, 2023

Talent & innovation, Sensor technology, Robotics & intelligent systems, Robotics, Process automation, Computer vision, Business environment, Advanced manufacturing

News

Swiss Drone Industry Map

Manufacturers

SWISSDRONES OPERATING AG
senseFly a Parrot company
Fotokite
FLYABILITY
sunflower LABS
VOLIRO
AGRO FLY
Skybotix TECHNOLOGIES
aeroscout unmanned aircraft technology
flying robots
wingtra

Flight Systems

px4 autopilot
MotionPilot
WindShape
weControl
Rapyuta Robotics
DAEDALEAN APPLIED INTELLIGENCE
uaventure

Governance

SCHWEIZERISCHER VERBAND ZIVILER DROHNEN
ZURICH
DroneLogbook
UAWAERO
SGS
Swiss Re

Traffic Management

Global UTM Association
SITA Create success. Together
FLARM TECHNOLOGY
skyguide
skysoft
ONESKY

Defence & Security

Together ahead. RUAG
ViaSat
RHEINMETALL DEFENCE
UMS SKELDAR
Aurora SWISS AEROSPACE
KUDELSKI SECURITY
IDQ

Sensors & Payloads

TERABEE
ublox
DISTRAN SWITZERLAND
FIXPOSITION
SkyAware a product by sunflower
insightness
SENSIRION THE SENSOR COMPANY
SENSIMA technology sa

Electric & Solar Propulsion

Atlantik Solar
H55
EVOLARIS AVIATION
MECAPLEX SWITZERLAND
maxon motor
FAULHABER

Delivery

SWISS POST
Dronistics
MATTERNET
REDLINE
DELDRO

Energy

TWINGTEC WIND ENERGY 2.0
SKYPULL WIND FOR ENERGY

Analytics

picterra
PIX4D
GAMAYA
meteomatics Your Experts in Weather Data Processing.

Entertainment

VERITY studios
AEROTAIN
ANABATIC.AERO
léman tech

Humanitarian

We Robotics
REDOG
FSD
Alarm 0844 441 144
Swiss Fang UAV Search and Rescue Swiss Made

High-Altitude

SOLARSTRATOS TO THE EDGE OF SPACE
Open Stratosphere

Compiled by Simon Johnson, simon@openstratosphere.com, 24th November 2017

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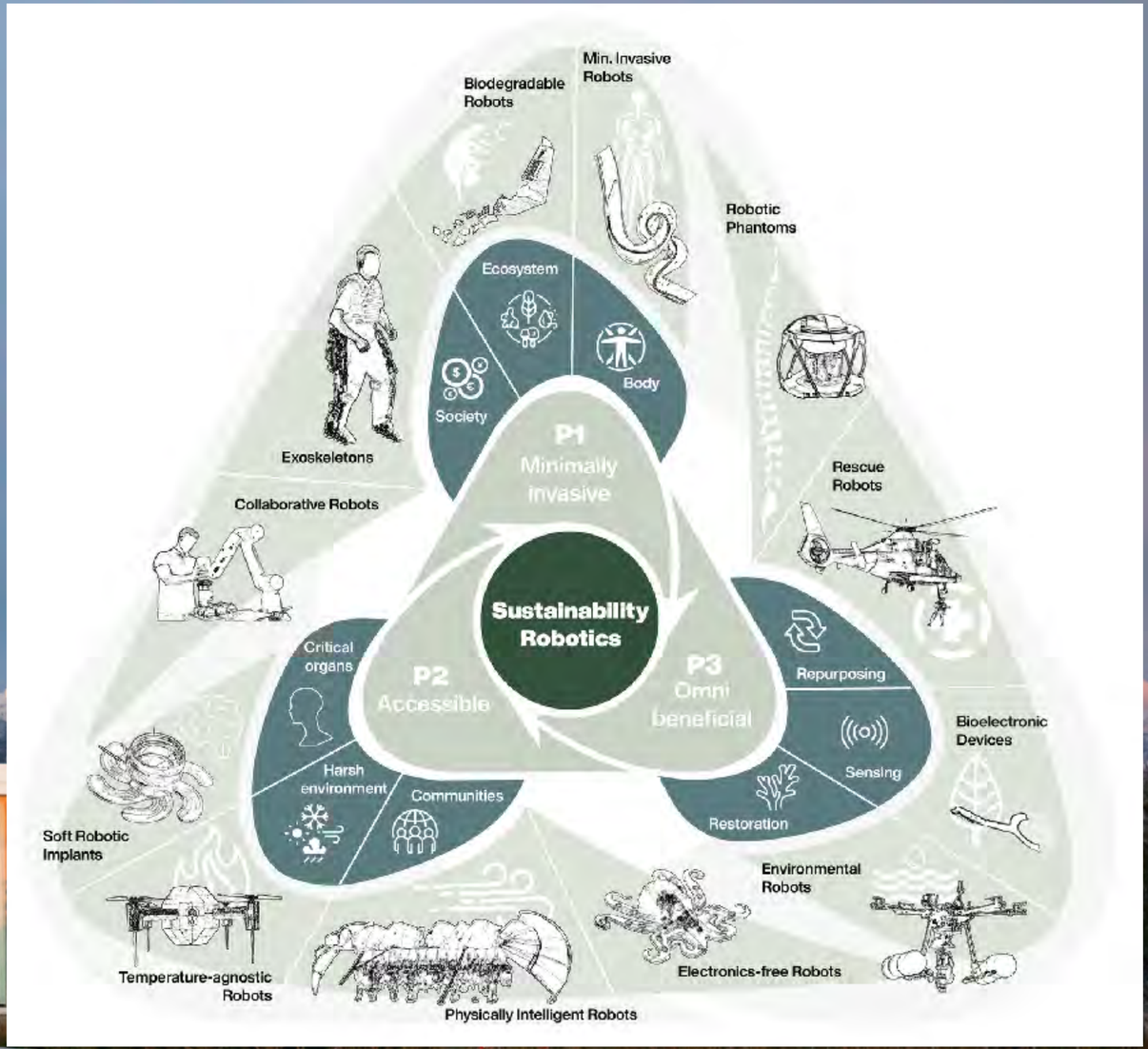
SUSTAINABILITY ROBOTICS



ENV-530 Sustainability Robotics

Motivation

The goal of this course is to provide methods and tools of robotics in promoting sustainable development. The course is a balance between theoretical basics in robotics, associated case studies and project-based learning.

Content

Introduction to Robotics: Introduction to key concepts in Robotics. Application examples include environmental and field robotics and development trends in the academic and industrial community.

Fundamentals of robotic systems: System components of ground based and aerial robots (e.g. hardware, software, sensors, system architecture, microcontrollers). Modeling, scaling and design of aerial robots given operational and payload constraints.

Project on robotics and AI for sustainability: Definition of end user requirements, project planning and contextualisation within the UN Sustainable Development Goals. Group based execution and presentation.

ENV-530 Sustainability Robotics

	Lecture Content	Bonus Content
1	Introduction to Sustainability Robotics	Intro to project development, hypothesis, project pitch (part 1)
	Element 1: EARTH	
2	Agriculture robotics overview (part 1)	Intro to project development, hypothesis, project pitch (part 2)
3	Agriculture robotics overview (part 2)	Guest lecture EcoRobotix
4	Autonomy for agricultural robotics	Guest presentation from Patrick Meier on the innovation pipeline
5	Multi-spectral sensing and data analysis	Tutorial to image processing
	Element 2: AIR	
6	Drone sizing fundamentals	Lecture on sustainable business and economic growth
7	Drone Aerodynamics	Guest lecture from Pix4D
8	Biodegradable drones	Personal tutorial and TA hour
9	Drones for infrastructure monitoring and repair with perching drones	Personal tutorial and TA hour
	Element 3: WATER	
10	Underwater robotics	Training on video editing
11	Aquatic systems innovation (aerial aquatic and soft underwater)	Training on data presentation
	Element 4: FIRE	
12	Search and rescue robotics	Guest lecture from FireDrone
13	Guest lecture and drop in	Guest lecture from Inverto.earth
	Element 5	
14	Final Presentations and Examination	

ENV-530 Sustainability Robotics

Book References

Fundamentals of Agricultural and Field Robotics
https://link.springer.com/book/10.1007/978-3-030-70400-1

Agricultural Robotics: The Future of Robotic Agriculture
https://arxiv.org/pdf/1806.06762

Handbook of Biodegradable Materials
https://link.springer.com/referencework/10.1007/978-3-031-09710-2

Biodegradable Polymers
https://link.springer.com/referenceworkentry/10.1007/978-3-030-83783-9_13-1

Infrastructure Robotics: Methodologies, Robotic Systems and Applications
https://onlinelibrary.wiley.com/doi/book/10.1002/9781394162871

Between Sea and Sky: Aerial Aquatic Locomotion in Miniature Robots
https://link.springer.com/book/10.1007/978-3-030-89575-4

Week 1 learning goals

- Grasp the core philosophical principles of Sustainability Robotics.
- Explore diverse applications at the crossroads of environmental sensing, material science, robotics, and data analysis.
- Learn the development techniques for bio-inspired robot design.
- Learn about the latest trends and advancements in multi-modal robotics.
- Identify the infrastructure requirements for Sustainability Robotics.
- Acquire skills in crafting project narratives and mastering the basics of proposal writing.

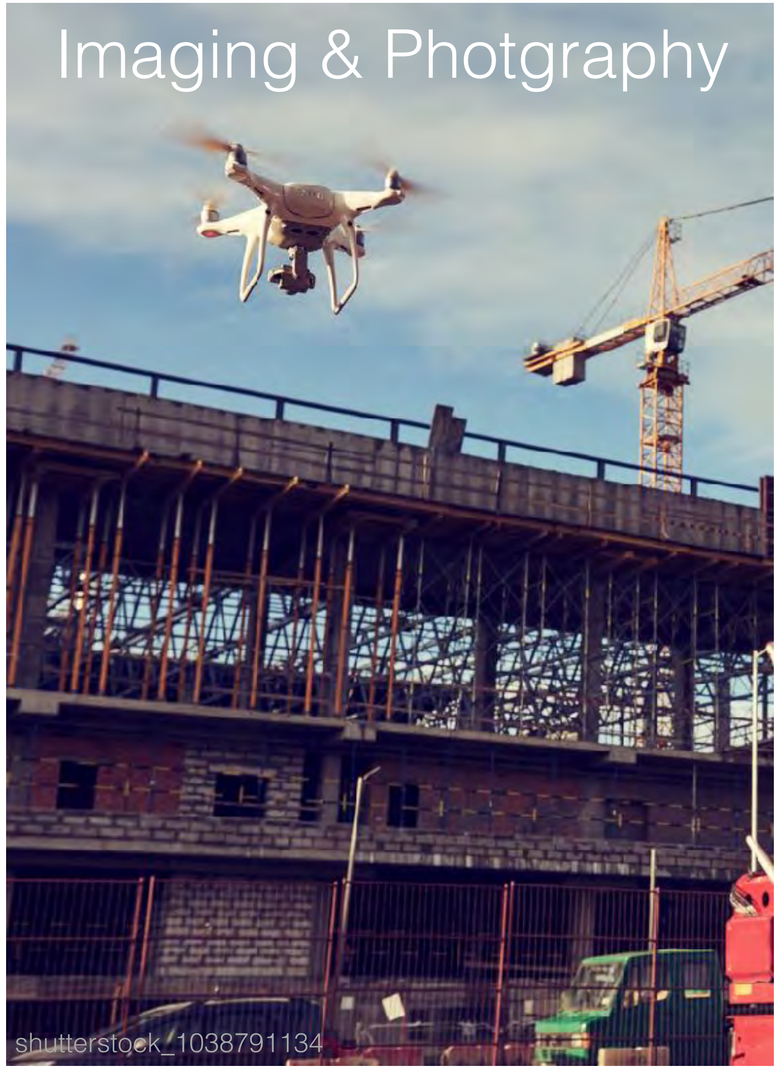
What can drones be used for?

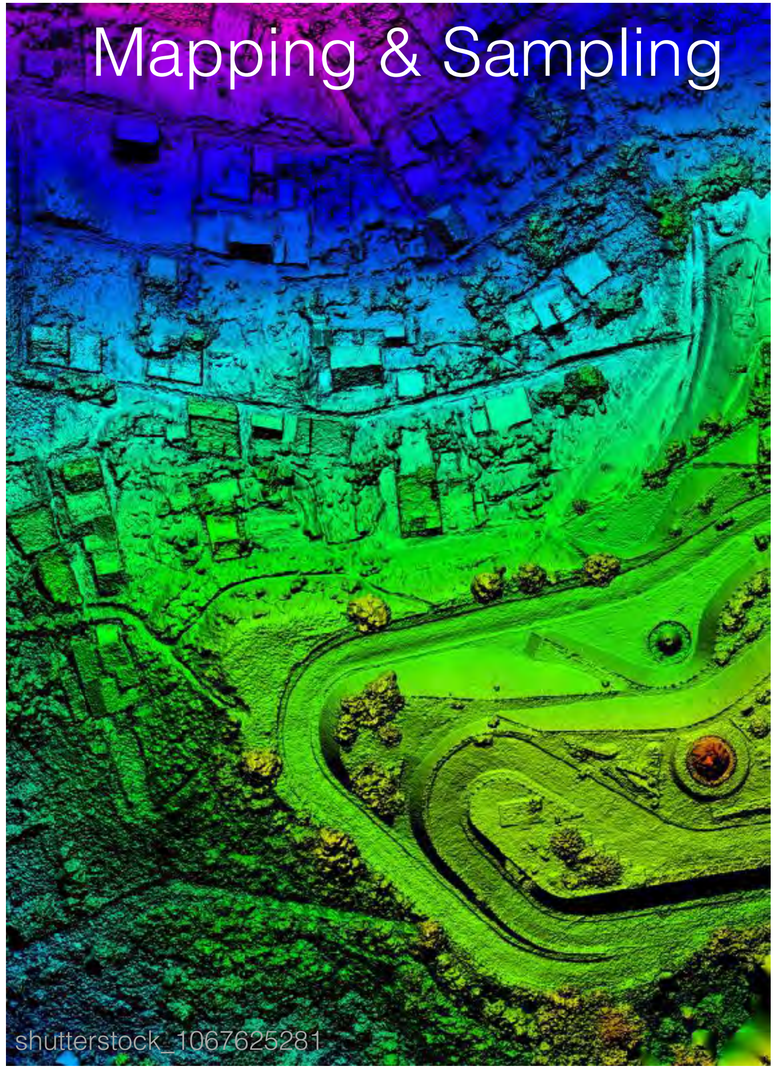
1 Go to wooclap.com

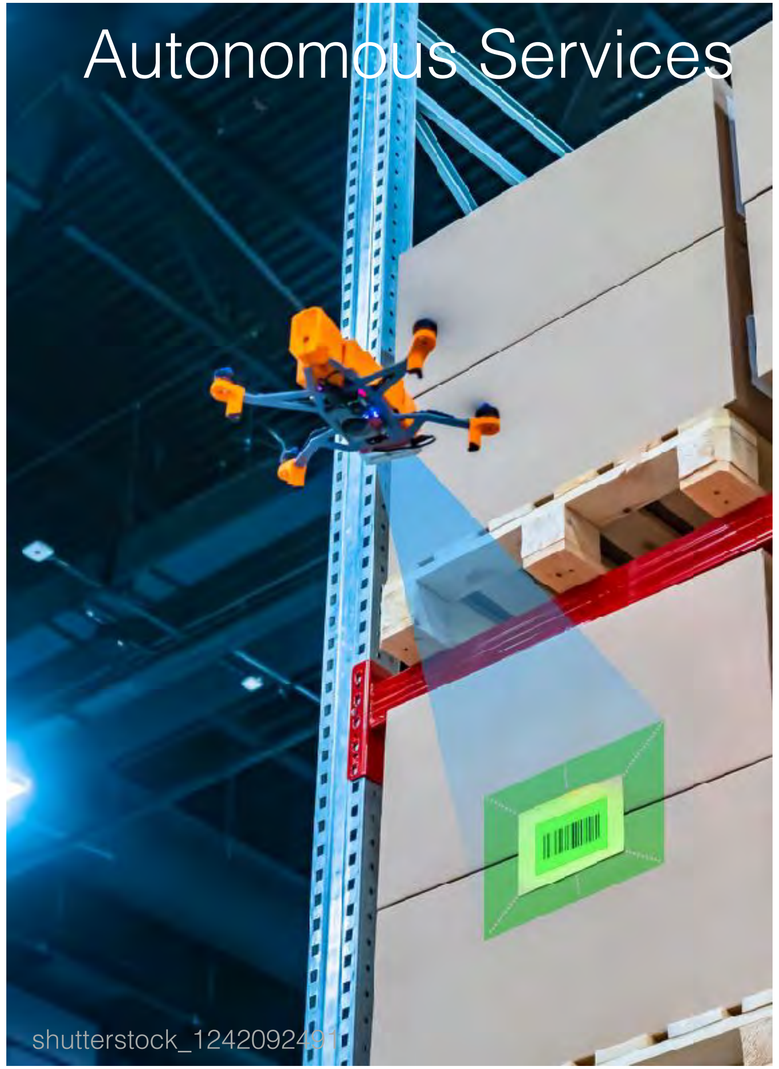
2 Enter the event code in the top banner

Event code
YYNHBJ

Aerial Robotics based value chain - today





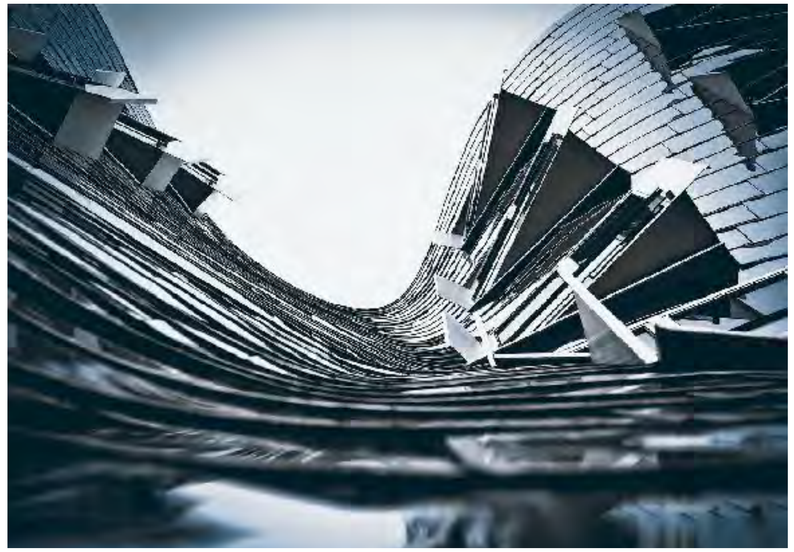


Drones for physical interaction & manipulation

Built environment

Off-shore infrastructure

Environmental health



Construction

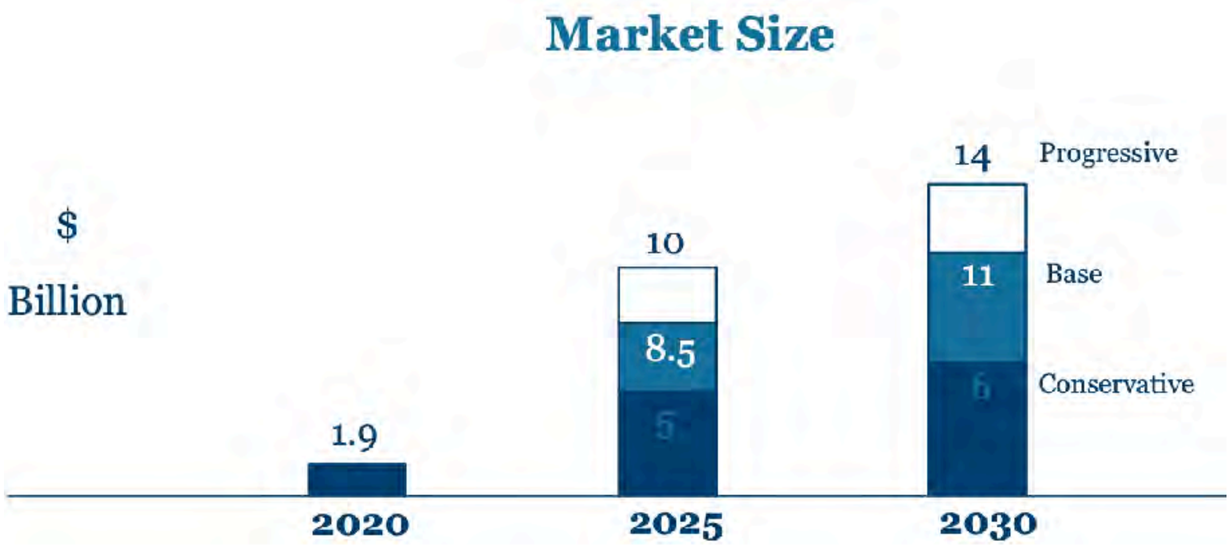
Mining/tunnel infrastructure

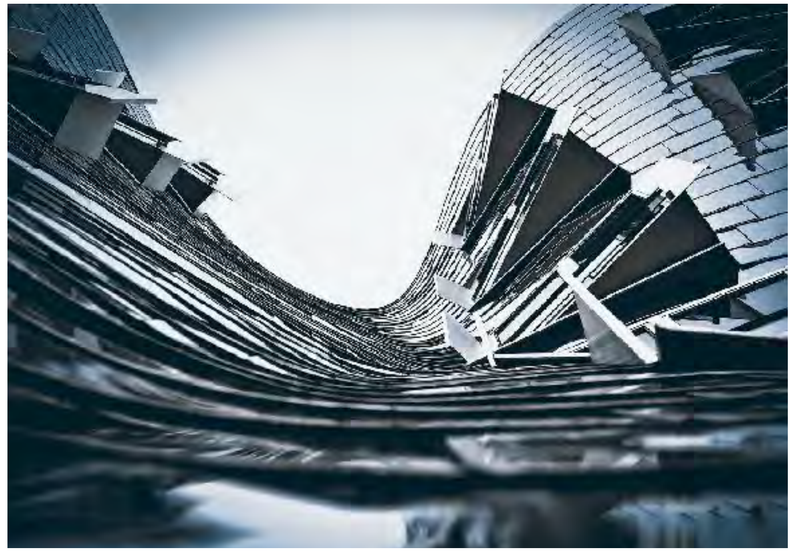
Extreme temperature regions

shutterstock 450441286

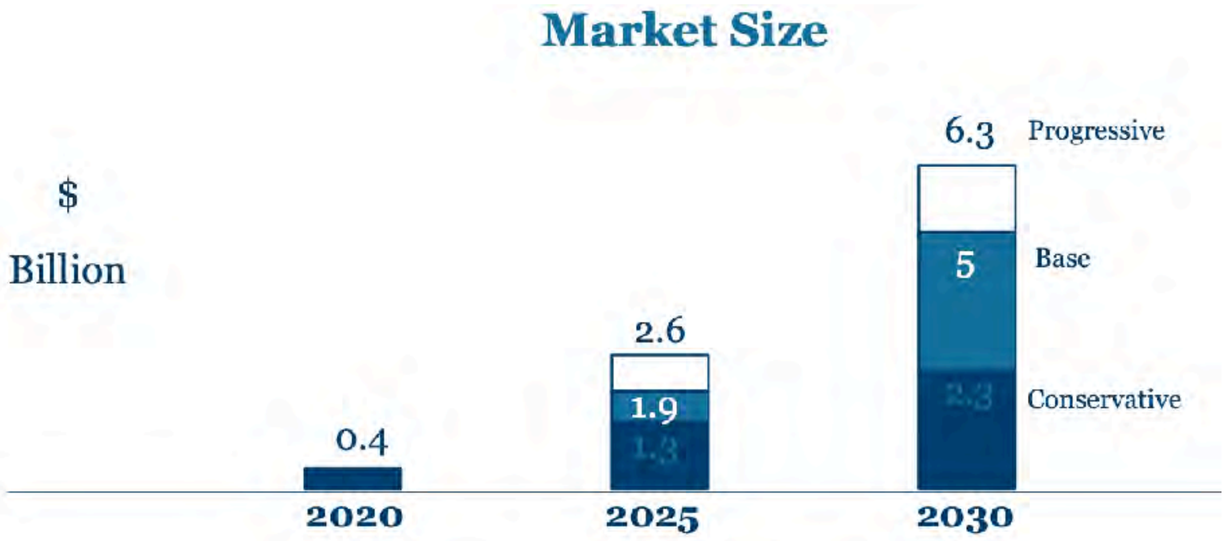
Drones for physical interaction & manipulation

Built environment





Construction



Source: Levitate Capital White Paper Dec. 2020

The Paris moment for biodiversity

Image credit: Ryan Remiorz / AP

Kunming Montreal Agreement Framework (COP 2022)

Conserve

- Near 0 loss of biodiversity
- **Restore 30% of degraded nature**
- **Conserve 30% of land and sea**
- Halt extinctions

Avoid

- Stop use, harvest, trade of species
- Reduce alien species by 50%
- **Reduce pollution impact by 50%**
- Reduce climate change impact

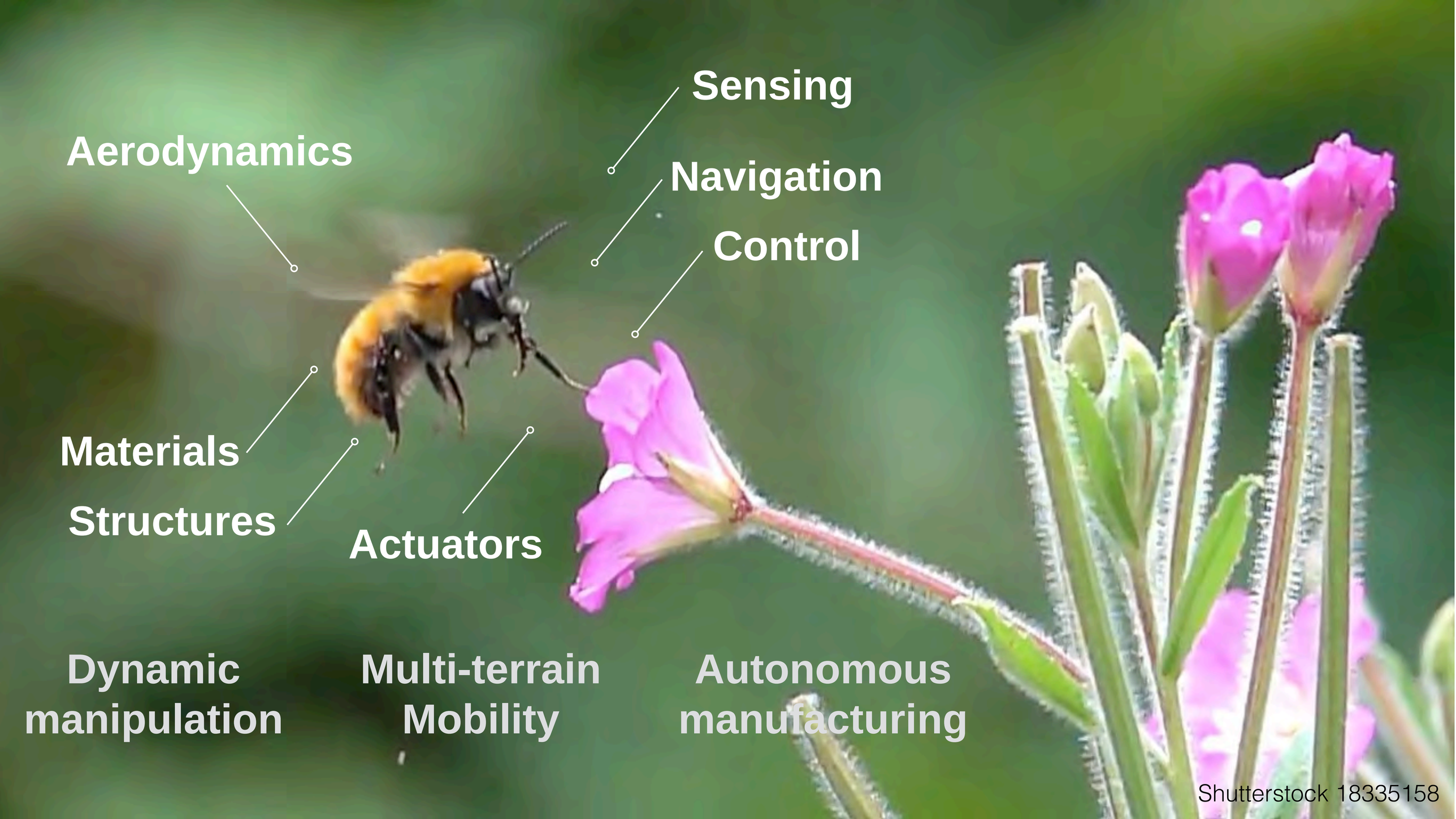
Safe-guard

- **Sustainably manage wild species**
- Sustainable agri/aquacultures, fisheries, forestry
- Restore nature's goods
- Increase urban green/blue spaces
- Fair sharing of genetic resources

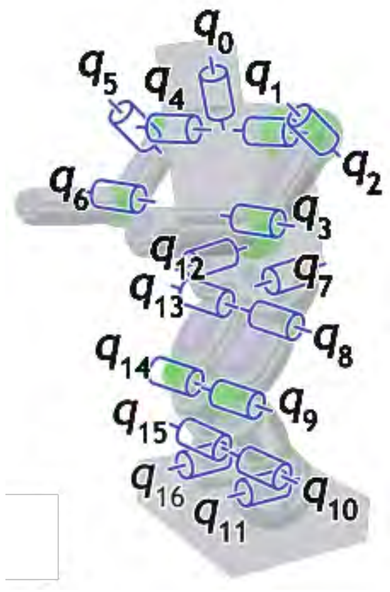
Act

- Mainstream biodiversity into policy, practice
- Businesses to monitor, disclose nature impact
- Reduce food waste by 50%
- **Closing biodiversity finance gap of 700 billion dollars per year**

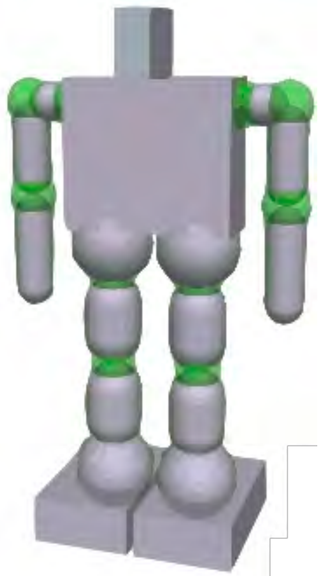
Thomas Creedy, Honduras, 2013


Sensing
Aerodynamics
Navigation
Control
Materials
Structures
Actuators
Dynamic manipulation
Multi-terrain Mobility
Autonomous manufacturing
Shutterstock 18335158

Robotics and AI (the classical paradigm)

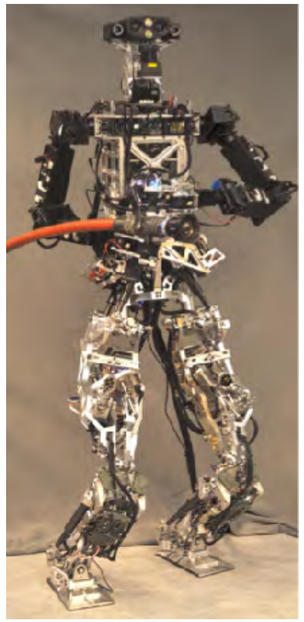


Yamaguchi et al (2013) *AR*



Yamaguchi et al (2013) *AR*

Buschmann et al (2009) *JP*



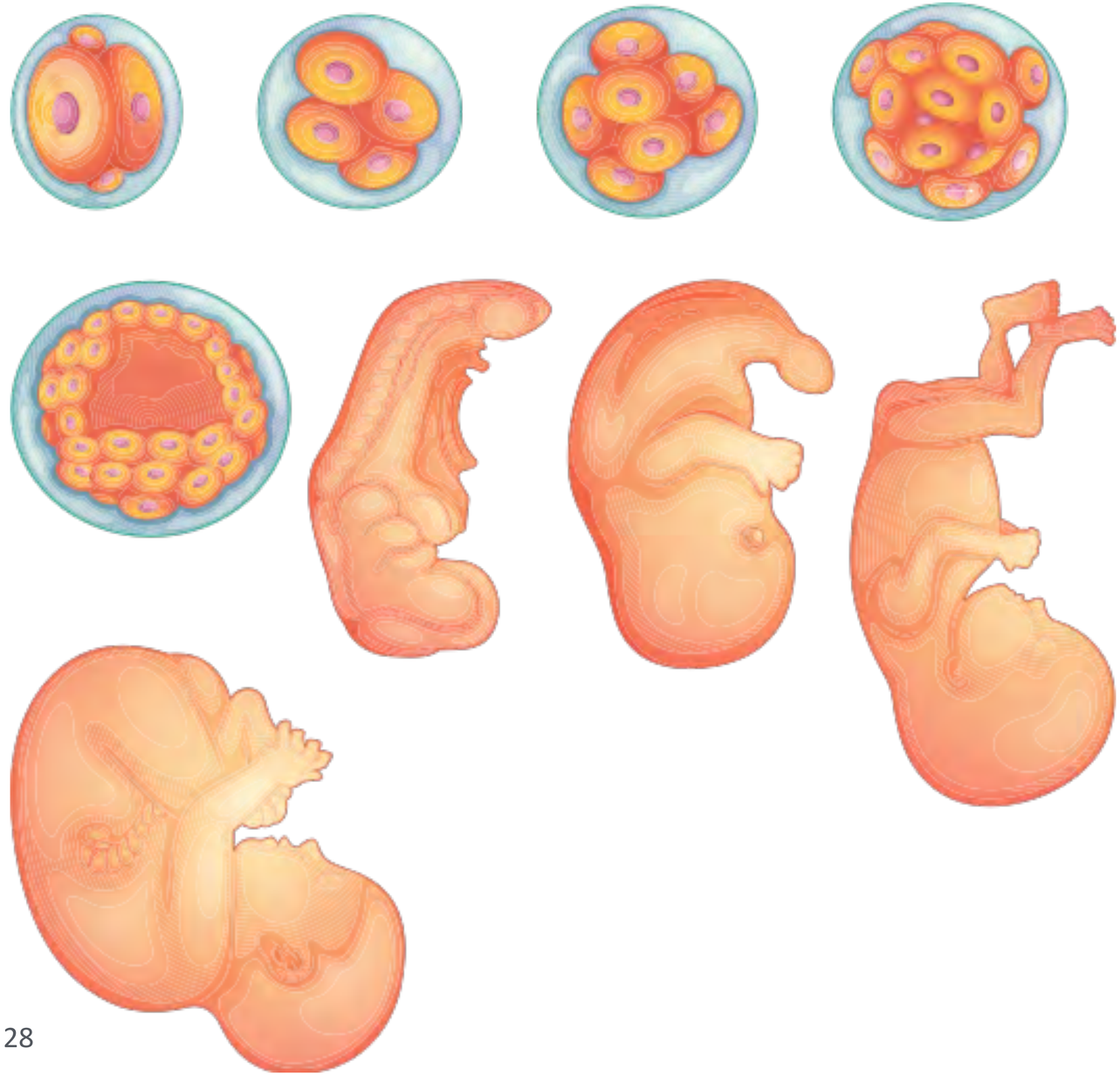
Kim, J. et al (2015) *FSJ*

Image credit: IEEE Spectrum, 2015, Darpa Robotics Challenge (https://www.youtube.com/watch?v=g0TaYhjpOfo)

kin./dyn. Modeling → Simulation → Controller → Components → Assembly → Testing

Linear development with discrete components and development steps

Development in nature (the biological paradigm)



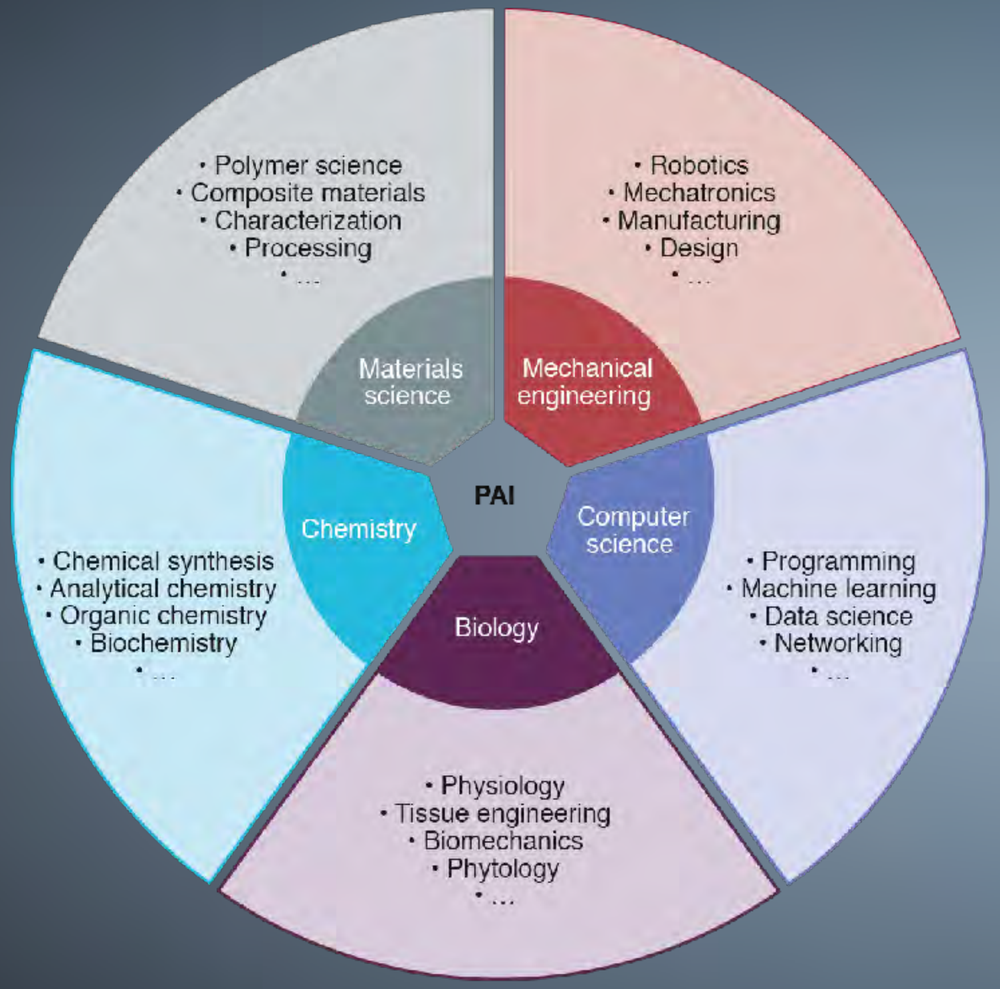
Circular and simultaneous co-evolution and adaptation of materials, sensors, actuators and controllers

shutterstock_131965748

Physical Artificial Intelligence

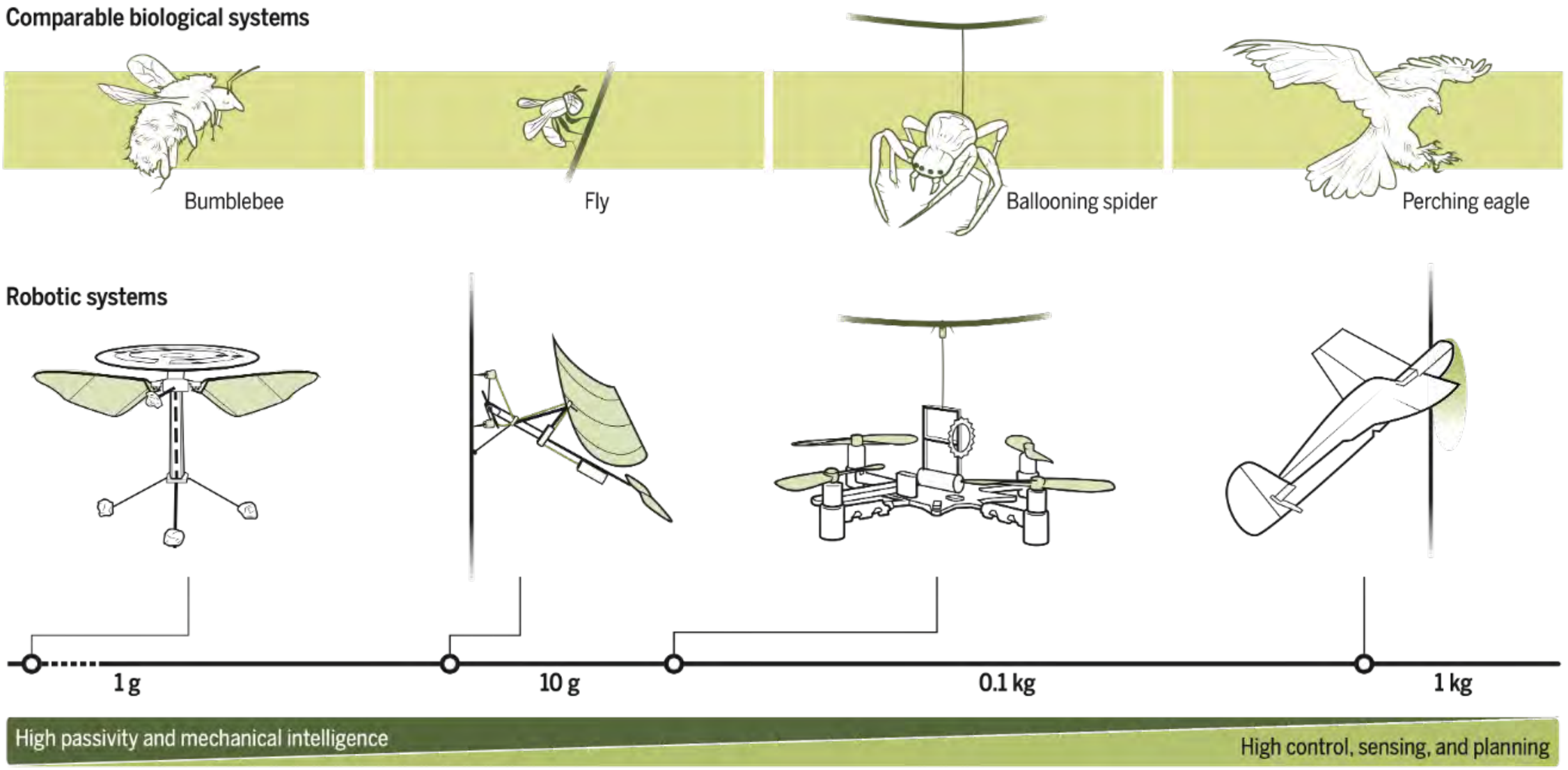
A. Miriyev, M. Kovac, Skills for Physical Artificial Intelligence, *Nature Machine Intelligence*, 2020 (cover)

Physical Artificial Intelligence



A. Miriyev, M. Kovac, Skills for Physical Artificial Intelligence, *Nature Machine Intelligence*, 2020 (cover)

Lifelike aerial capability



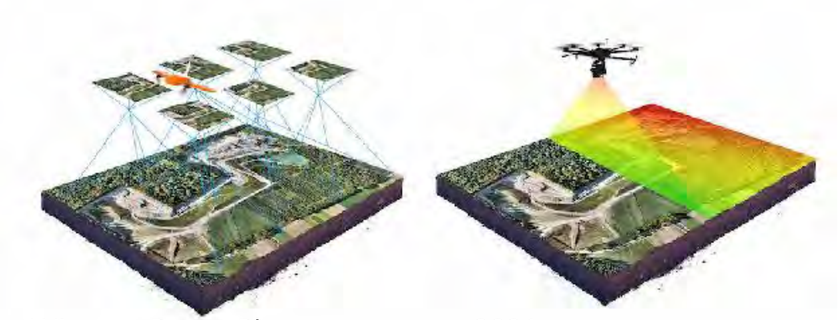
M. Kovac, Learning from nature how to land aerial robots, *Science* (2016)


SUSTAINABLE DEVELOPMENT GOALS
1 NO POVERTY
2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
4 QUALITY EDUCATION
5 GENDER EQUALITY
6 CLEAN WATER AND SANITATION
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
14 LIFE BELOW WATER
15 LIFE ON LAND
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS

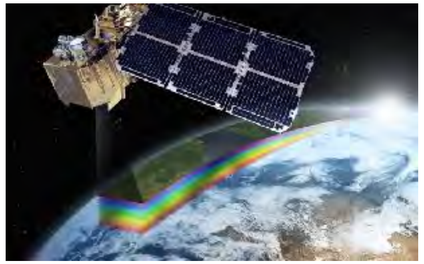
Environmental sensing technologies today

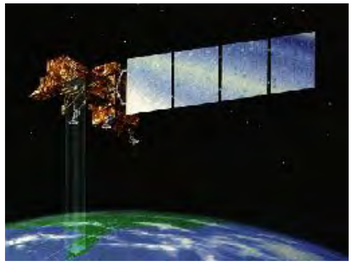
Air

EPFL Helikite, Tethered Balloon, 2021



Wingtra, Drone Photogrammetry, 2021





NASA, Land Remote Sensing, 2017

Land

Treetec, Sensor Installation

Hylio, Crop Spraying Drone, 2018

Soil Sampling Robots, Amrita - 2019; Momaro 2017

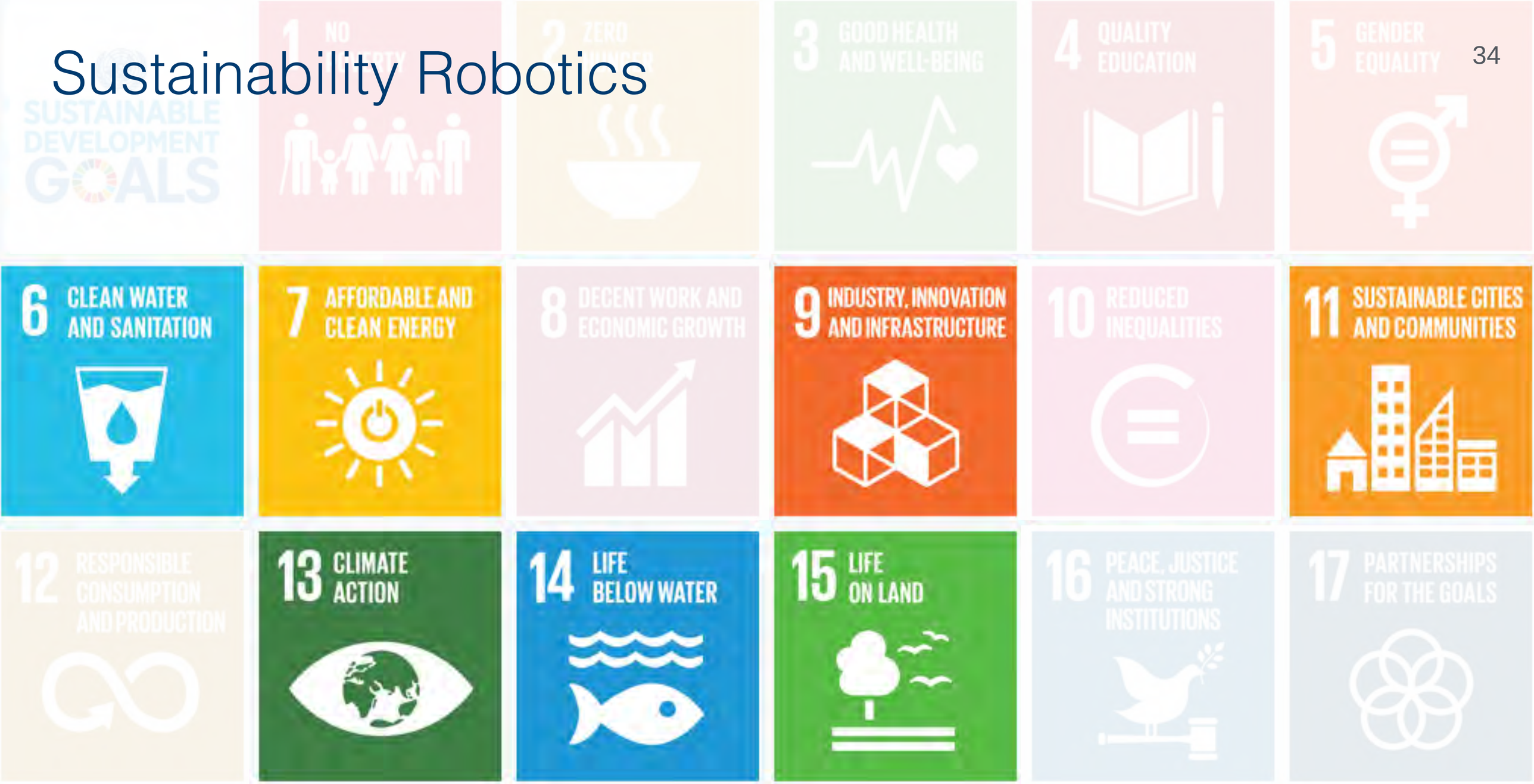
Water

DeepCLiDAR, Floating Buoys, 2016

ASPire, Sailing Platform, 2017

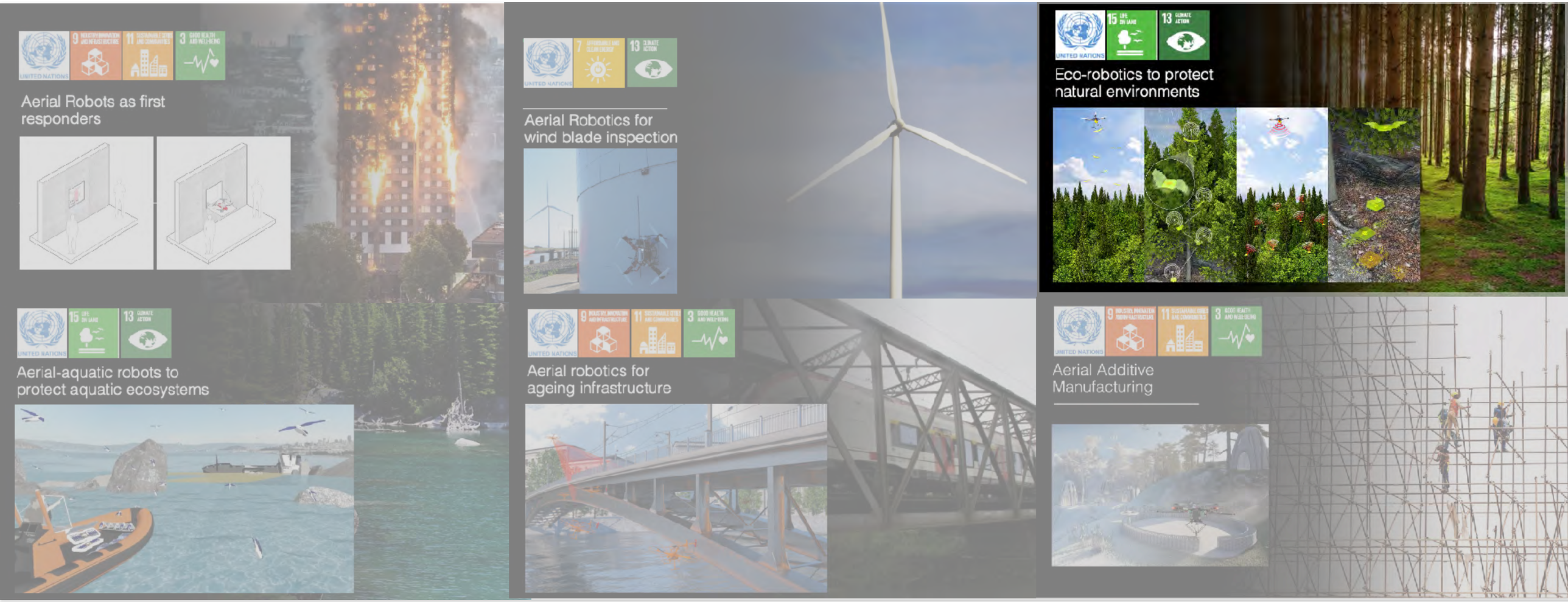
Autonomous surface vehicle: Buscamos-Vigia, 2021

Sustainability Robotics

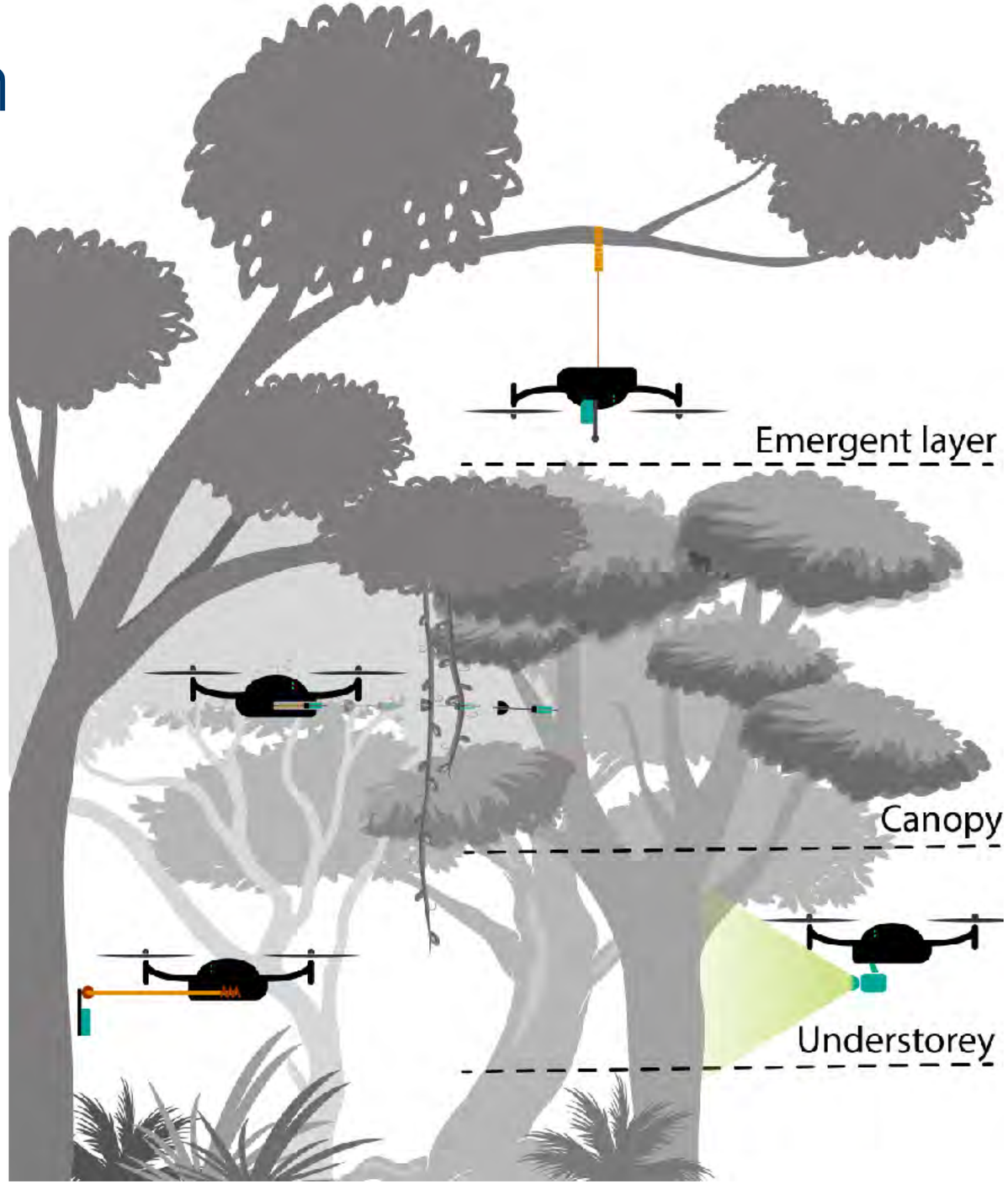


Sustainability Robotics

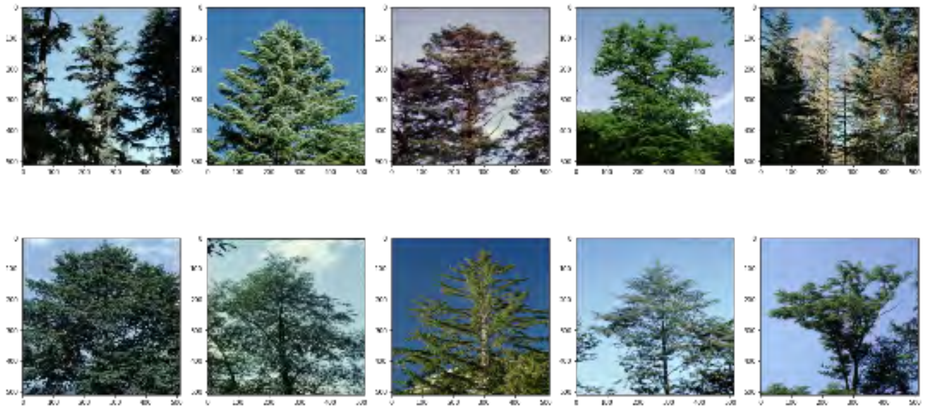
Sustainability Robotics



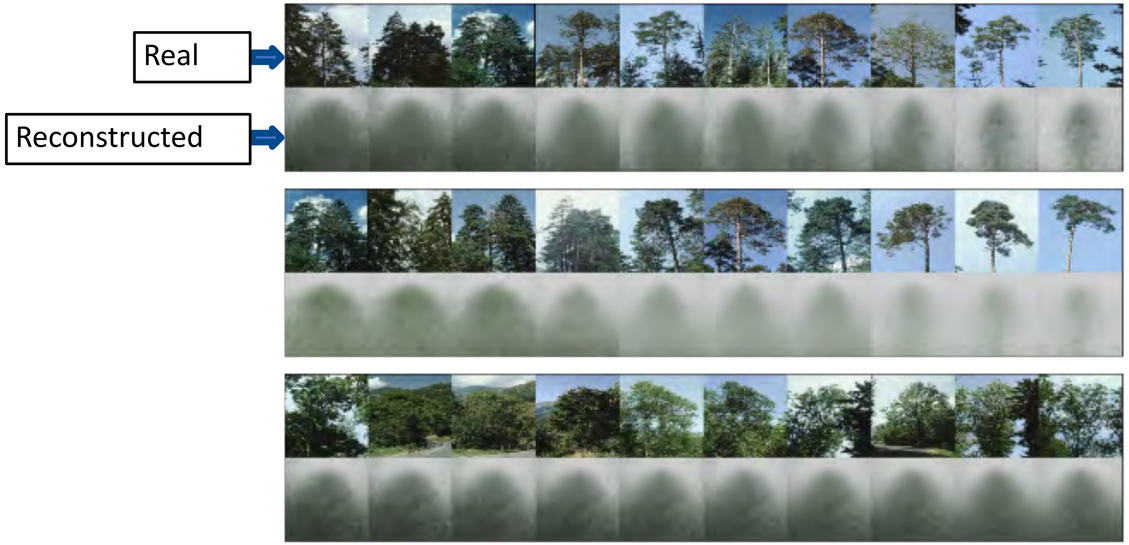
Need for autonomous sensin

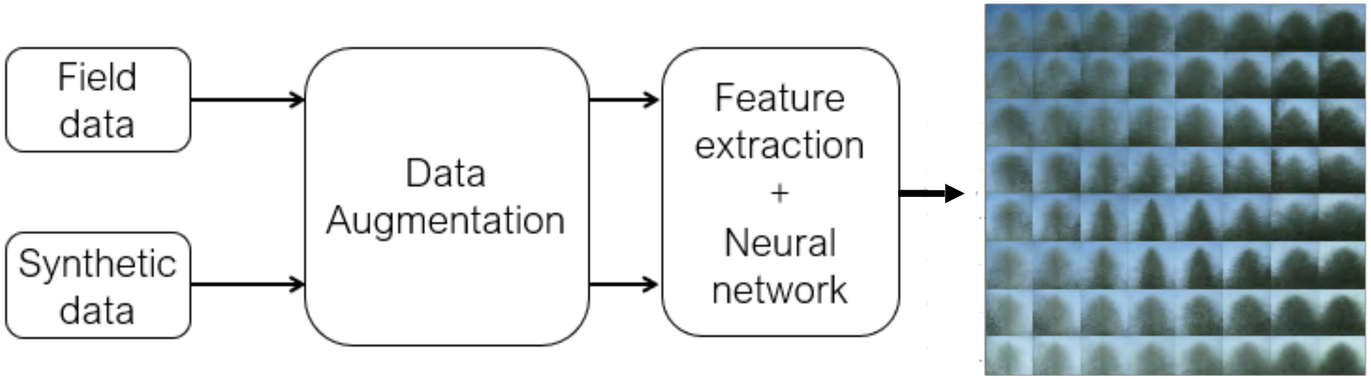


Autonomous crown loss estimation



WSL tree dataset



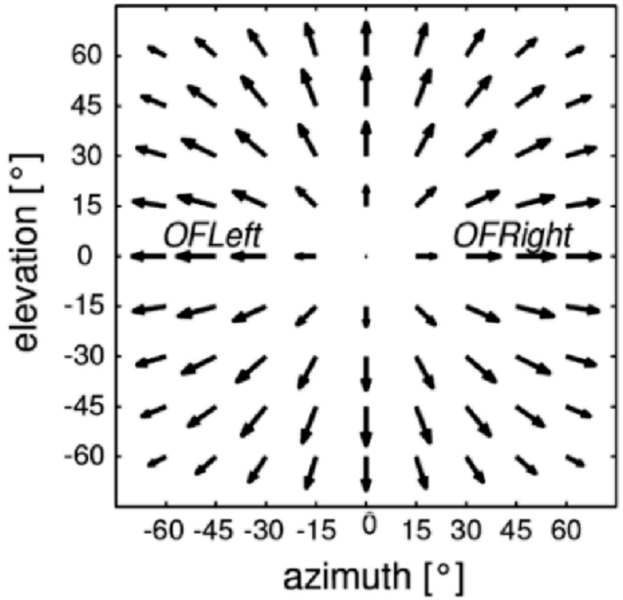


Density map (estimated)

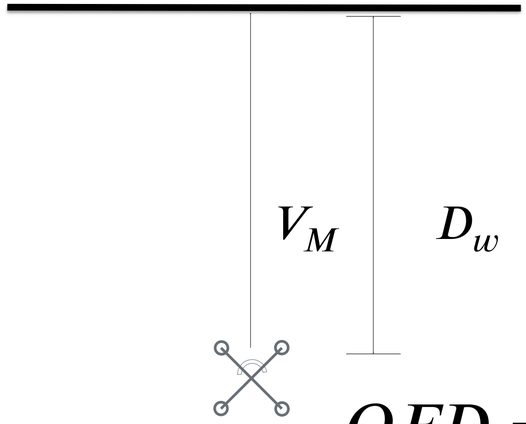
Bo, H., Kocer, B.B. and Kovac, M., 2022. Vision based crown loss estimation for individual trees with remote aerial robots. *ISPRS Journal of Photogrammetry and Remote Sensing*

Bio-inspired forrest flight autonomy

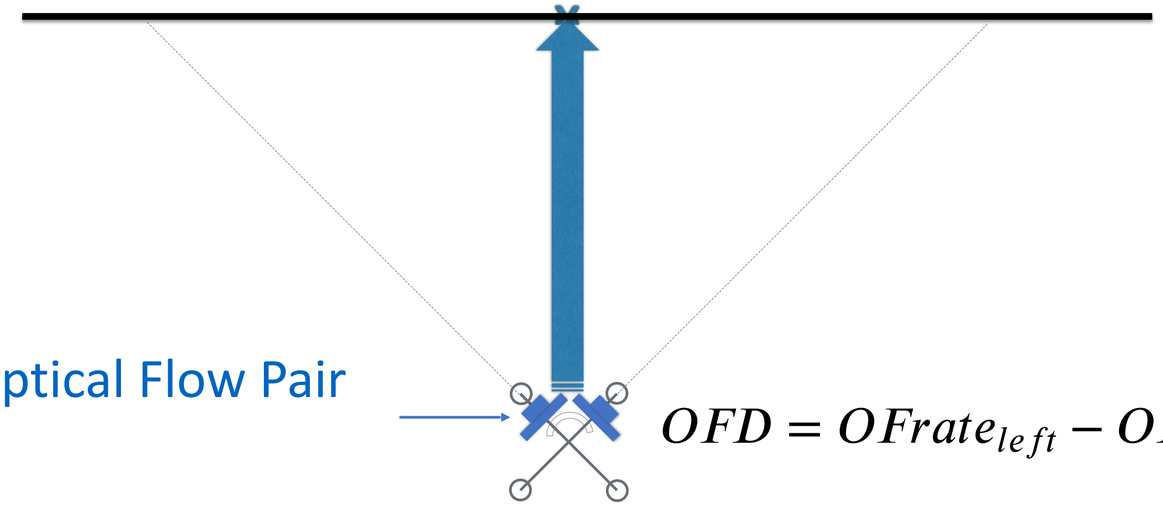
[1]



[2]



$$OFD = \frac{V_M}{D_w}$$



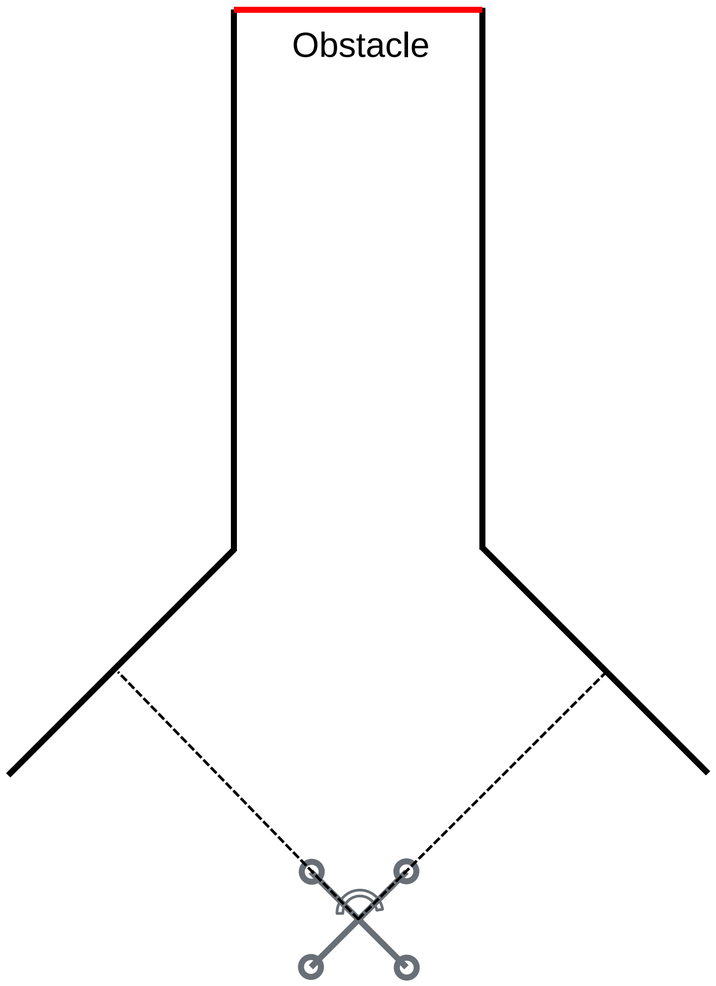
Divergent Optical Flow Pair (DOFP)

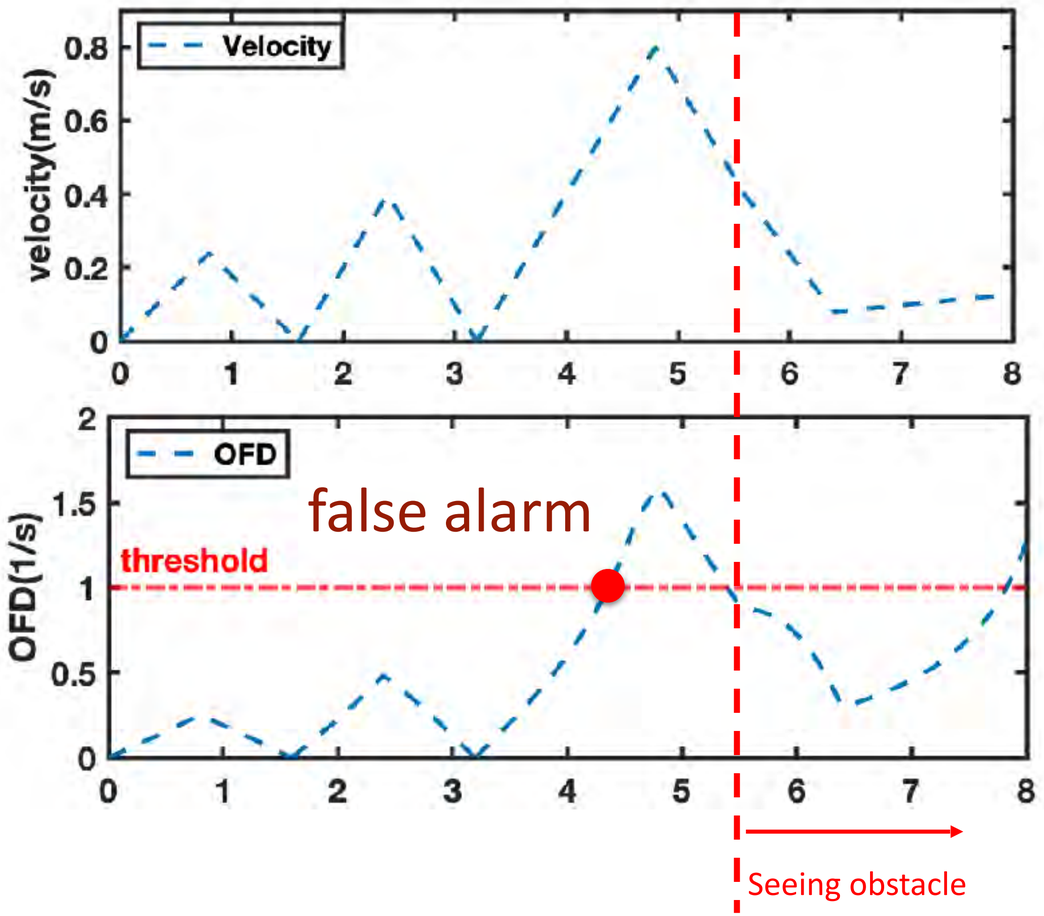
$$OFD = OFrate_{left} - OFrate_{right}$$

[1]Evangelista C, Kraft P, Dacke M, Reinhard J, Srinivasan MV (2010) The moment before touchdown: Landing manoeuvres of the honeybee Apis mellifera. J Exp Biol 213(2): 262–270

[2]J. C. Zufferey and D. Floreano, “Fly-Inspired Visual Steering of an Ultralight Indoor Aircraft,” IEEE Transactions on Robotics, vol. 22, no. 1, pp. 137–146, 2006.

Constant OFD threshold could give false alarm

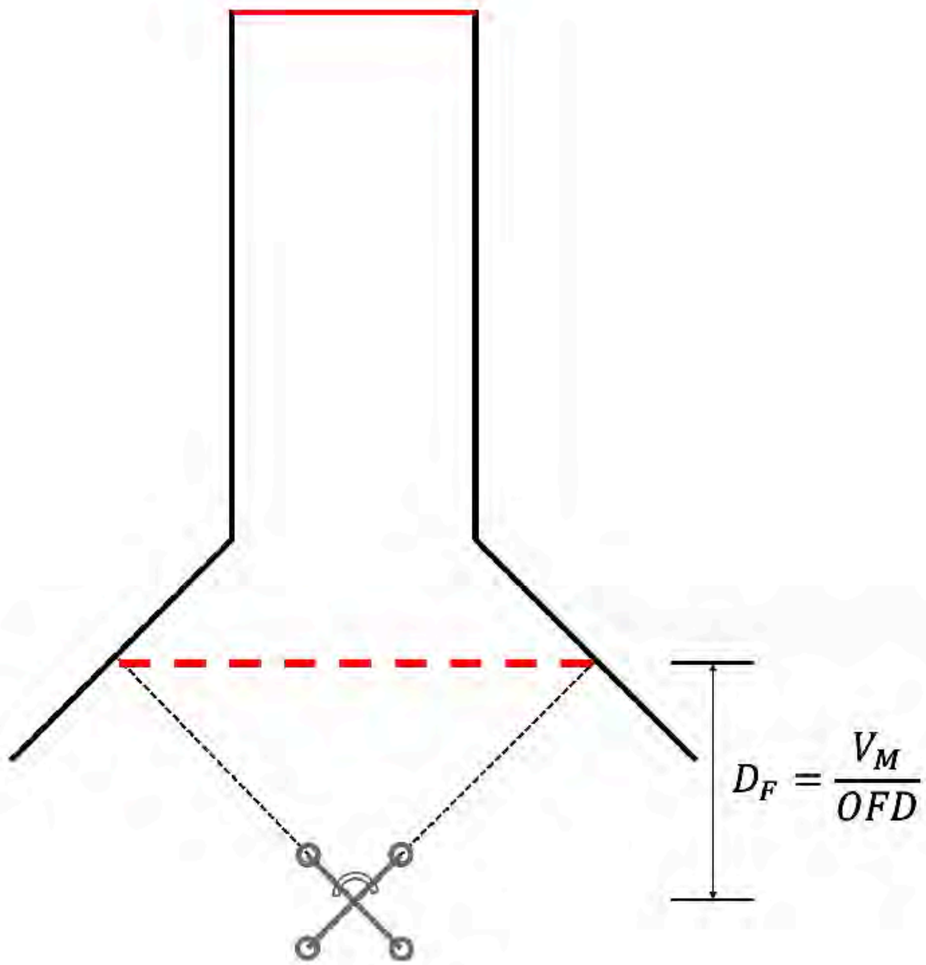


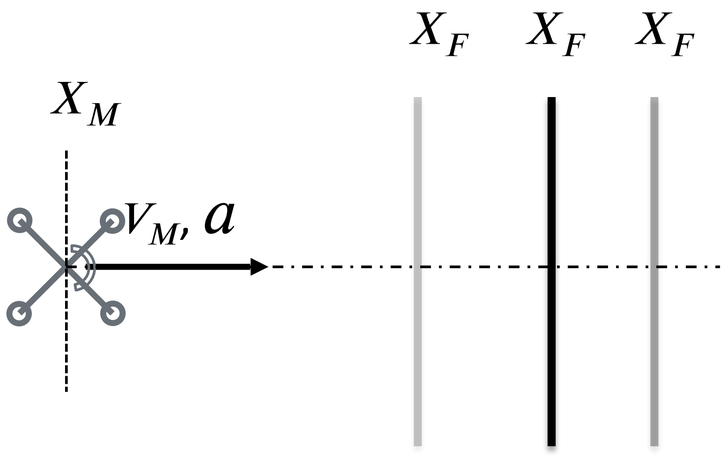


$$OFD = OFrate_{left} - OFrate_{right}$$

Xiao, F., Zheng, P., Tria, J., Kocer, B., Kovac, M., *IEEE ICRA / RAL 2021*

Fictitious wall hypothesis





State vector:

$$x = \begin{bmatrix} X_M & V_M & X_F \end{bmatrix}^T$$

System model: $\dot{x} = \begin{bmatrix} V_M & a & 0 \end{bmatrix}^T$

Observation model:

$$y = OFD = \frac{V_M}{X_F - X_M}$$

OFD observation

a model input → Extended Kalman Filter →

$$\begin{bmatrix} X_M \\ V_M \\ X_F \end{bmatrix}$$

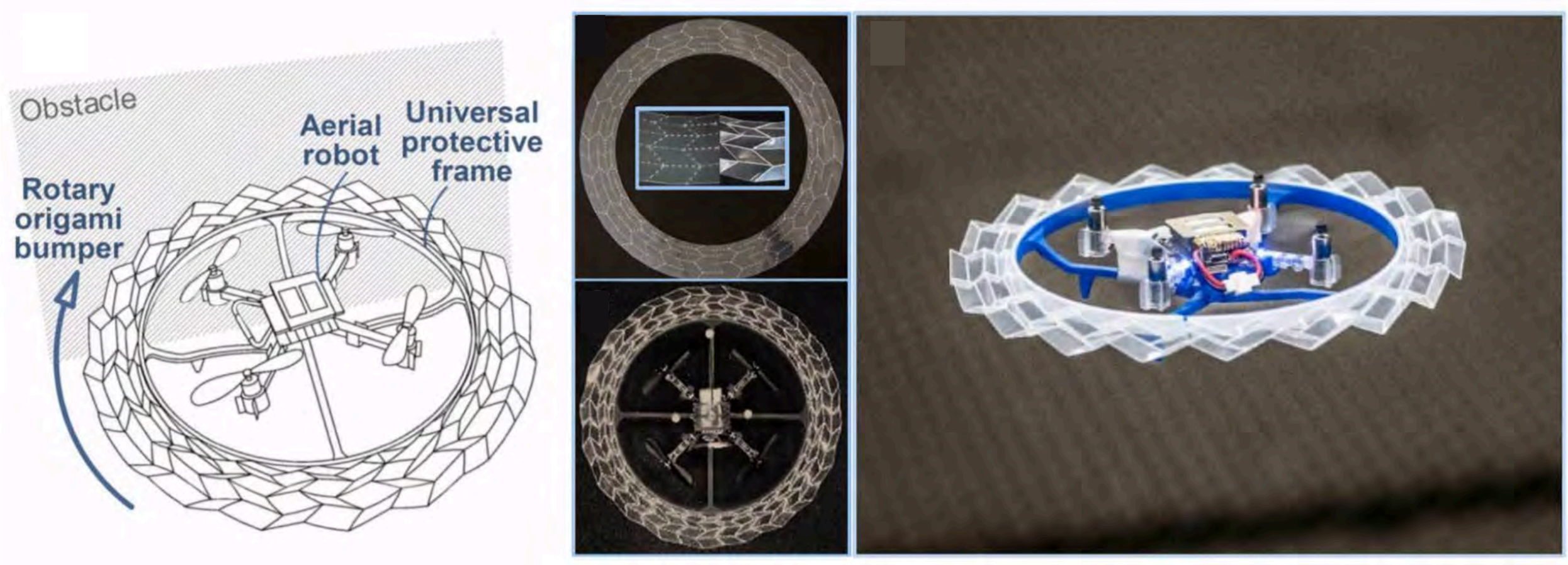
$$Distance:\ D_F = X_F - X_M$$

Xiao, F., Zheng, P., Tria, J., Kocer, B., Kovac, M., *IEEE ICRA / RAL 2021*

Xiao, F., Zheng, P., Tria, J., Kocer, B., Kovac, M., *IEEE ICRA / RAL 2021*

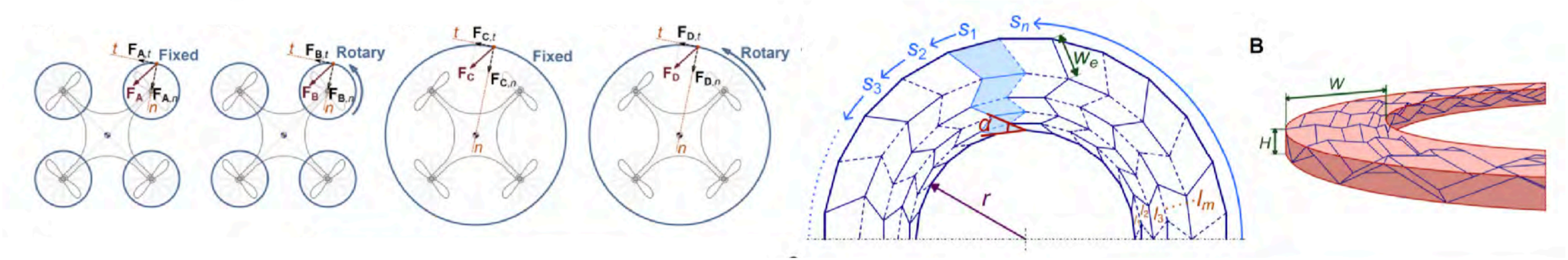
Xiao, F., Kovac, M., et. al. (in revision)

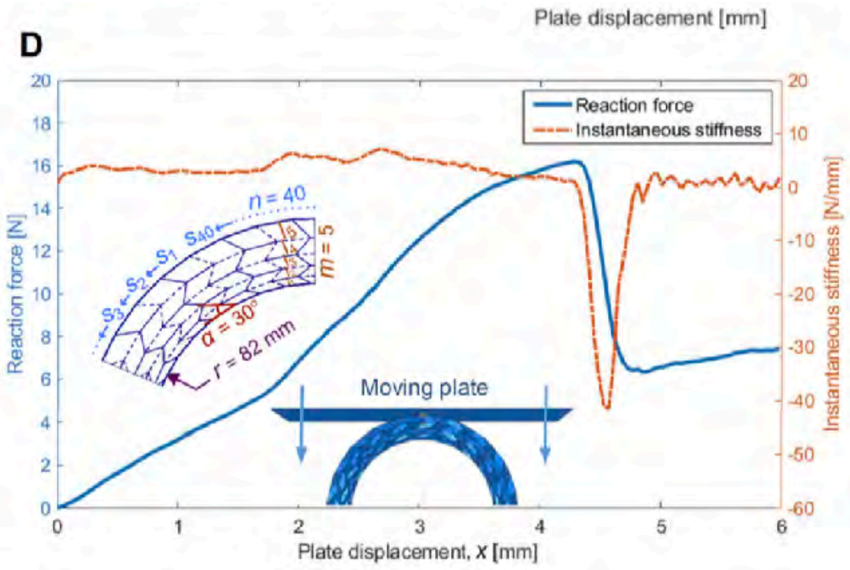
Rotorigami for impact protection

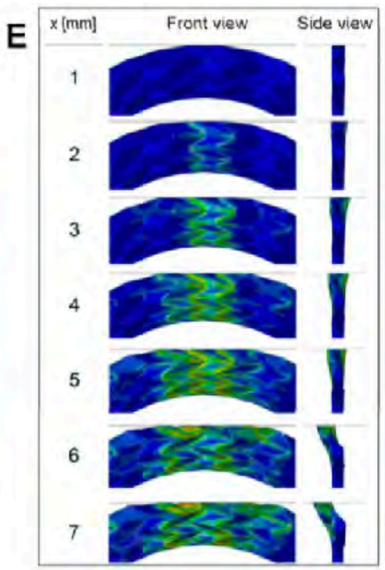


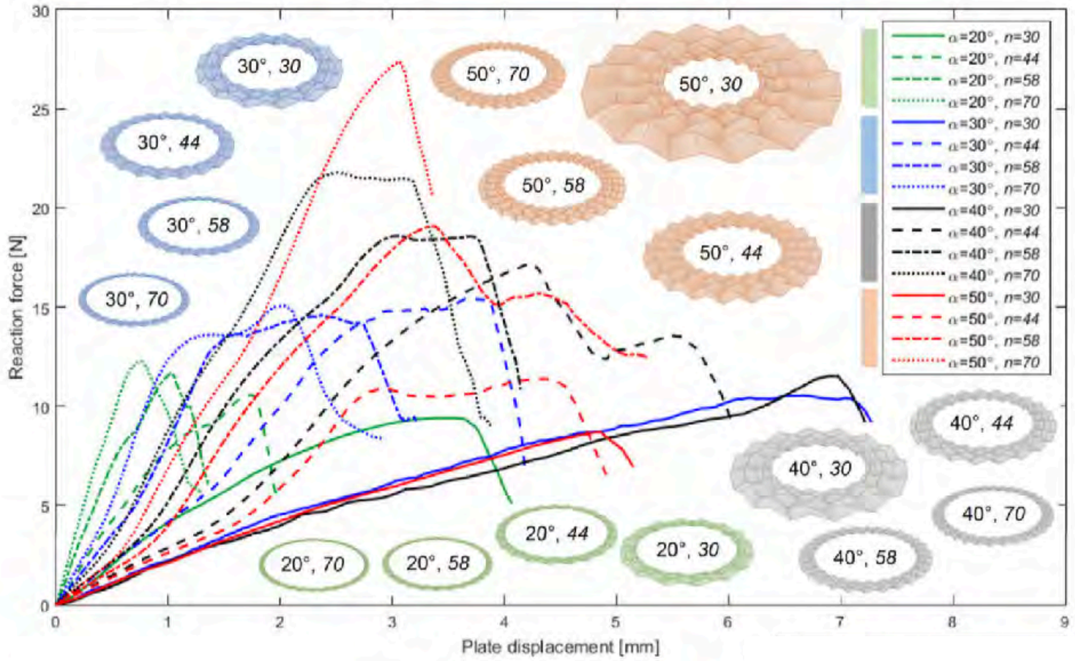
P. Sareh, P. Chermprayong, M. Emmanuelli, H. Nadeem, M. Kovac
Science Robotics (2018)

Rotorigami for impact protection









P. Sareh, P. Chermprayong, M. Emmanuelli, H. Nadeem, M. Kovac
Science Robotics (2018)

Rotorigami for impact protection

Fixed-Naked

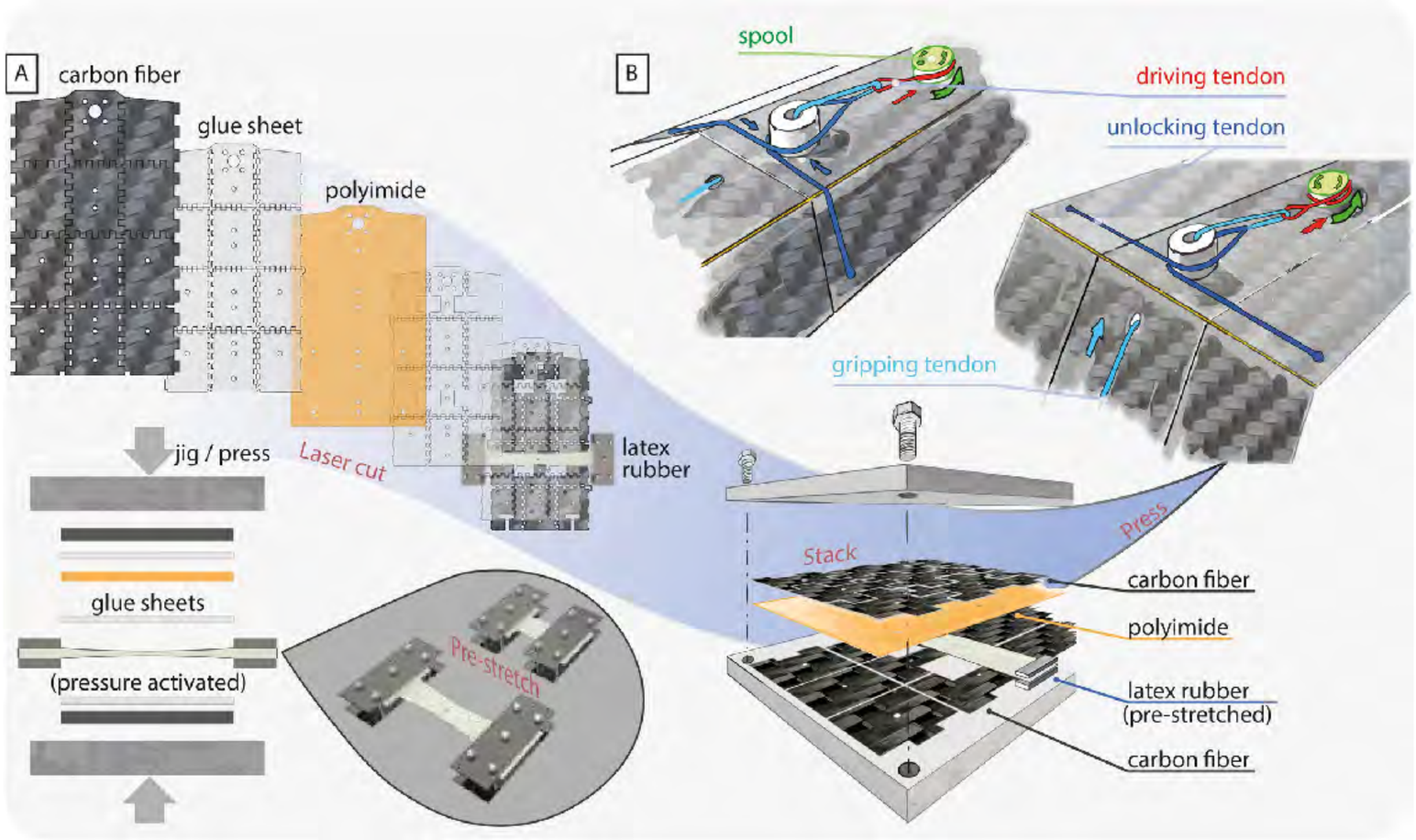
Rotary-Origami

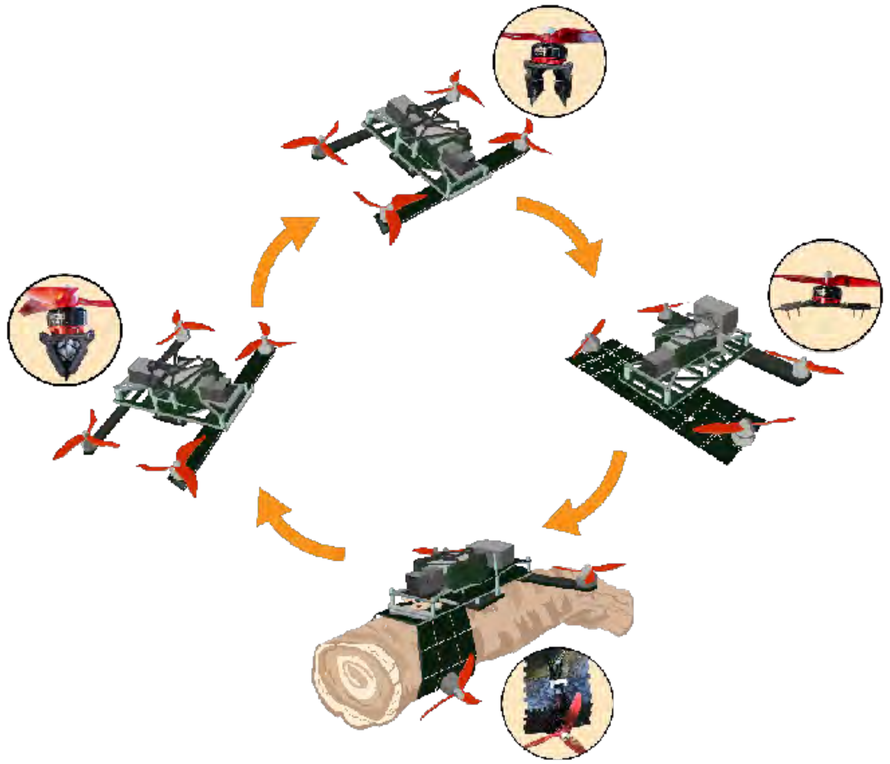
P. Sareh, P. Chermprayong, M. Emmanuelli, H. Nadeem, M. Kovac
Science Robotics (2018)

Meta-morphic full body perching

Zheng, P., Xiao, F., Nguyen, P. H., Farinha, A. and Kovac, M., (2023) Metamorphic Aerial Robot capable of mid-air shape morphing for rapid perching, *Nature Scientific Reports*

Meta-morphic full body perching





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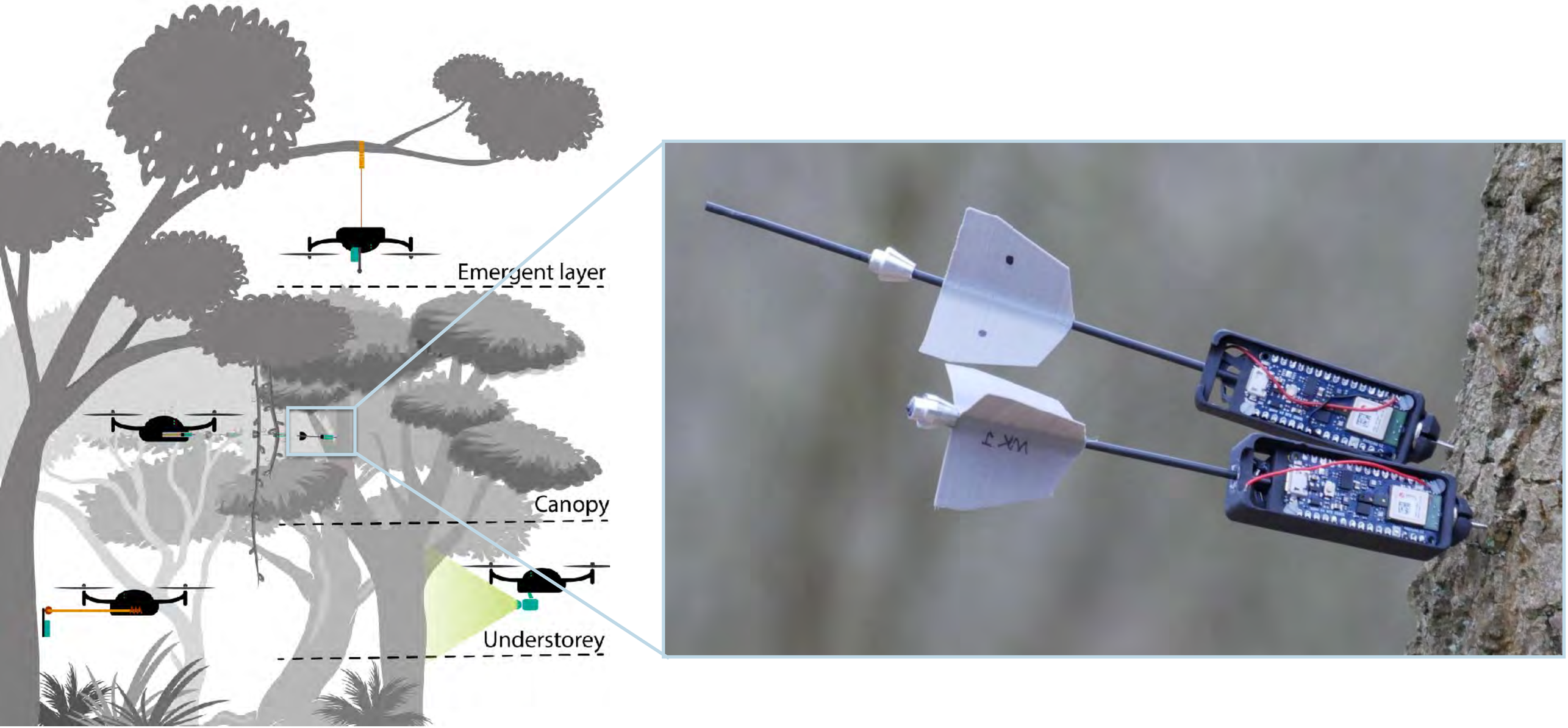
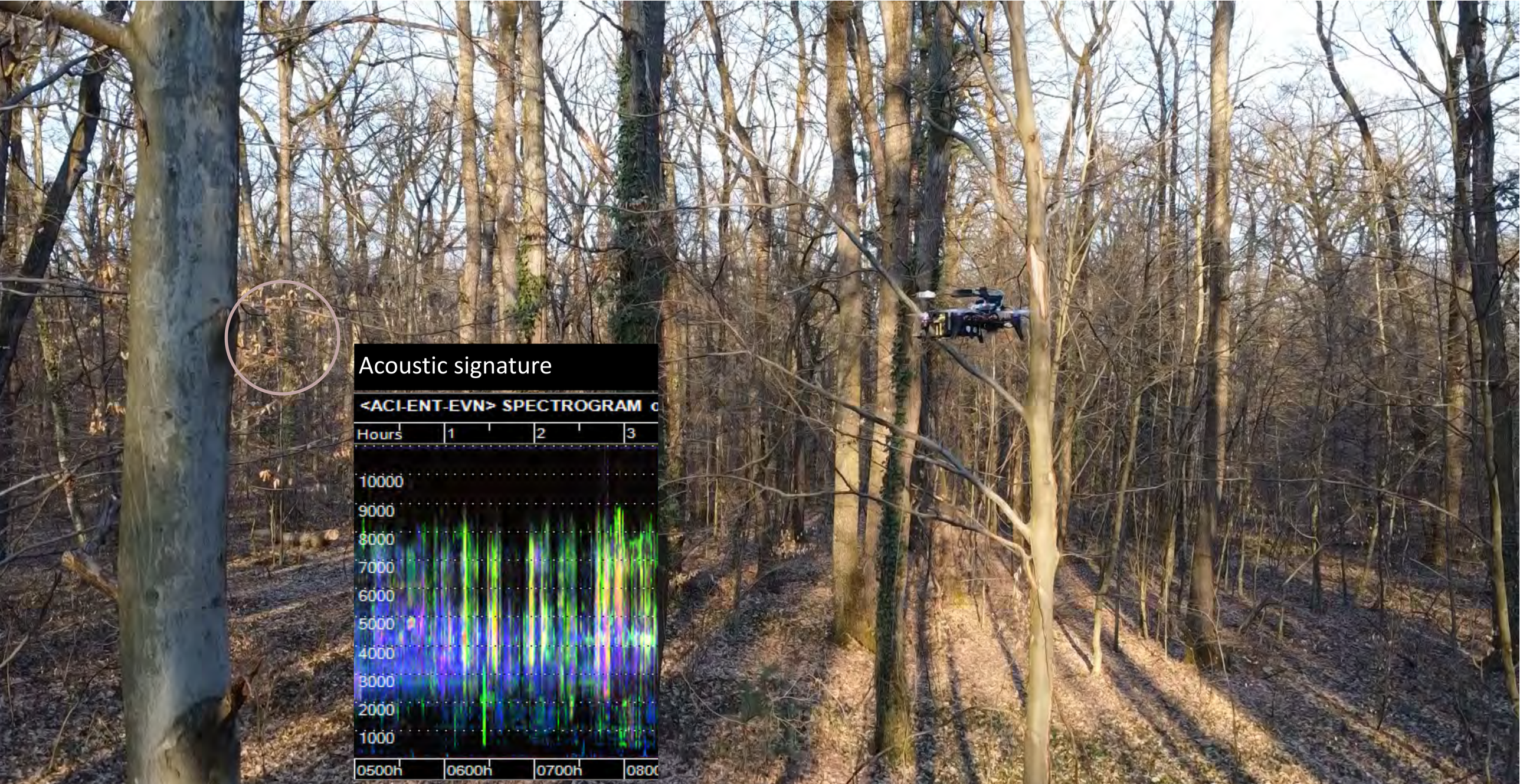


A. Farinha, R. Zufferey, P. Zheng, S. F. Armanini and M. Kovac,
IEEE Robotics and Automation Letters (2020)

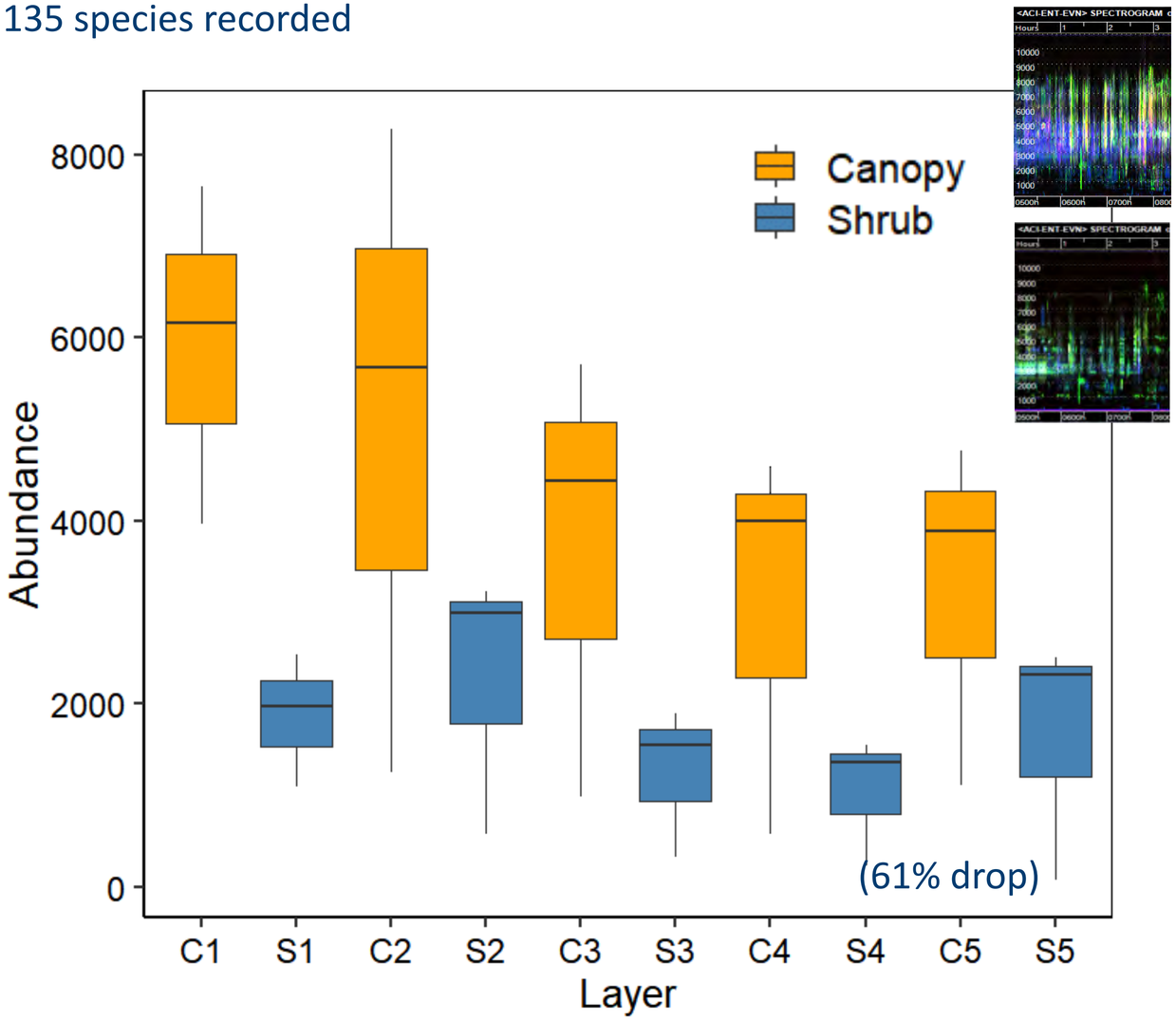


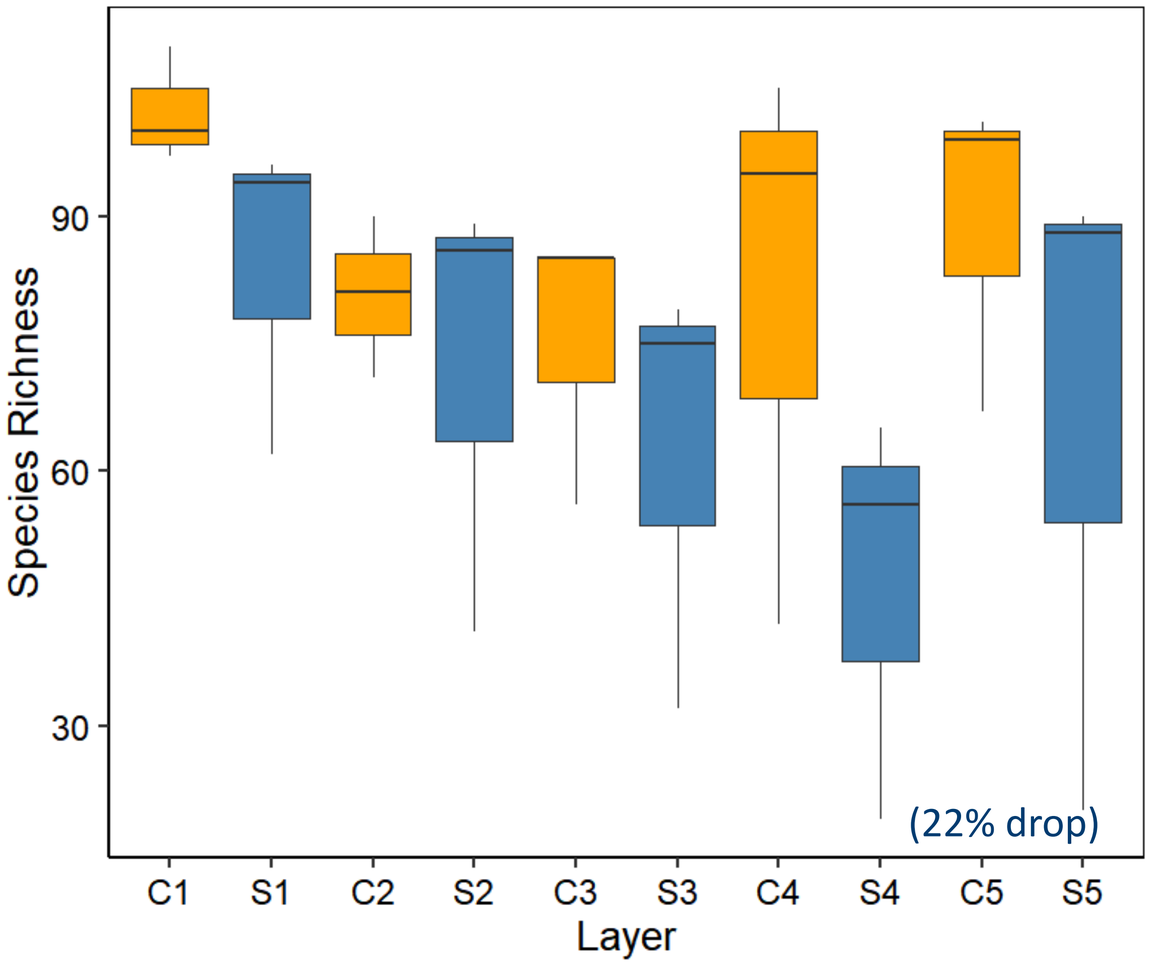
Hamaza, S., Farinha, A., Nguyen, H. N., & Kovac, M. *IEEE IROS, 2020*

A. Farina, M. Kovac et. al *IEEE Robotics and Automation Letters, 2022* and in preparation

Bird abundance and richness differs across layers

135 species recorded

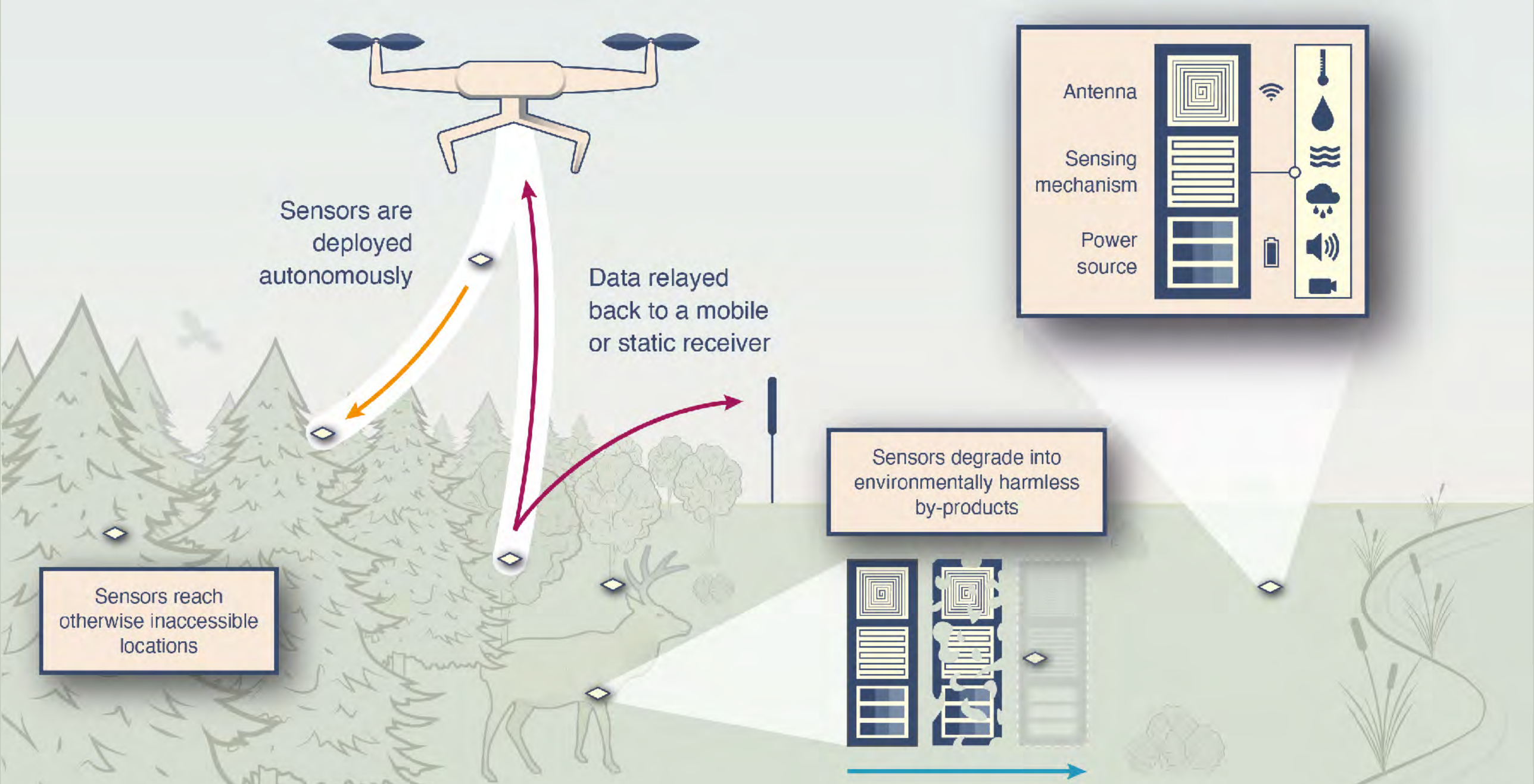




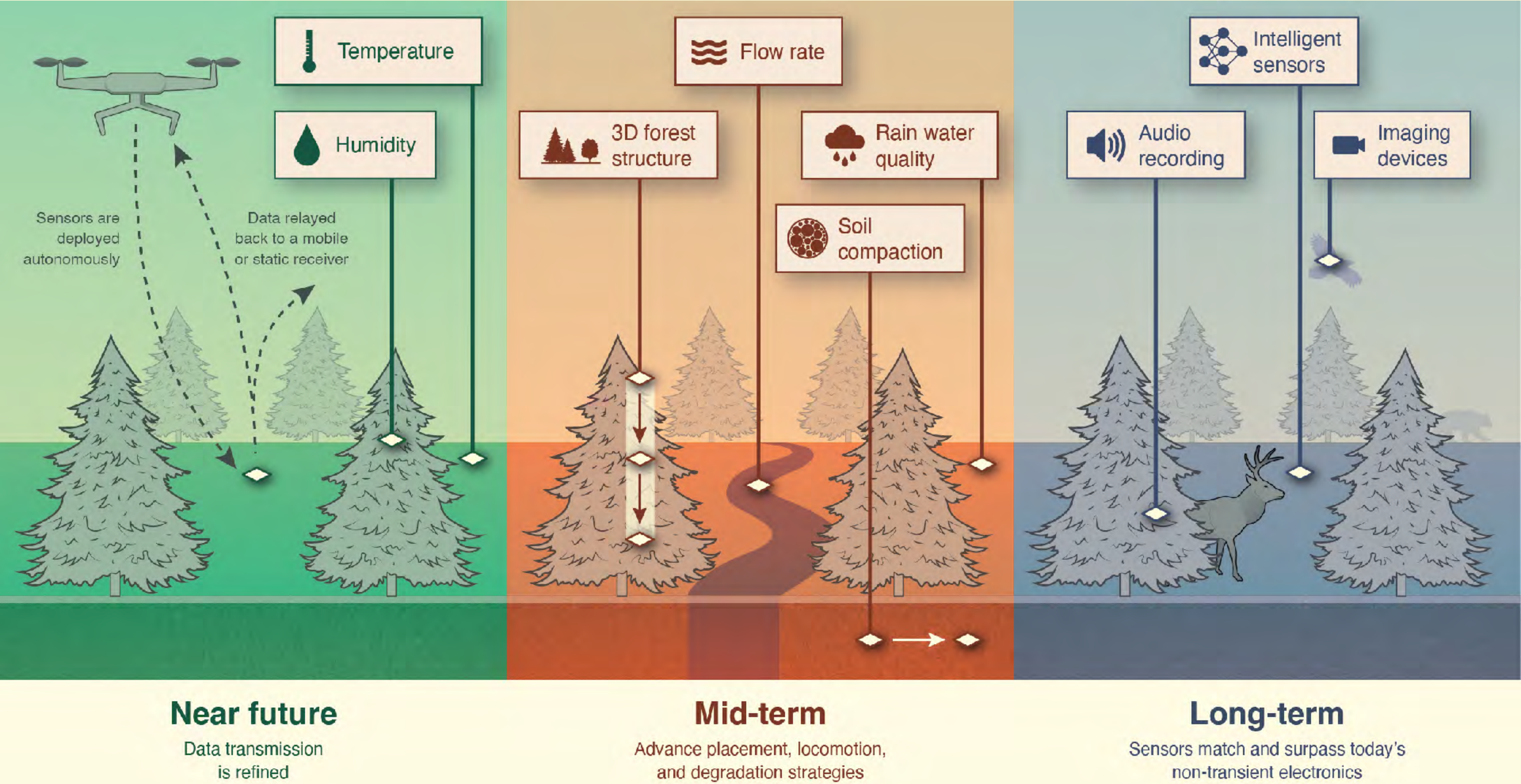
Hamaza, S., Farinha, A., Nguyen, H. N., & Kovac, M. *IEEE IROS, 2020*

A. Farina, M. Kovac et. al *IEEE Robotics and Automation Letters, 2022* and in preparation

Illustration: Yusuf Kaya Furkan



Sethi, S.S., Kovac, M., Wiesemüller, F., Miriyev, A., Viellard-Boutry, C., (2022)
Nature Ecology & Evolution



Sethi, S.S., Kovac, M., Wiesemüller, F., Miriyev, A., Viellard-Boutry, C., (2022)

Nature Ecology & Evolution

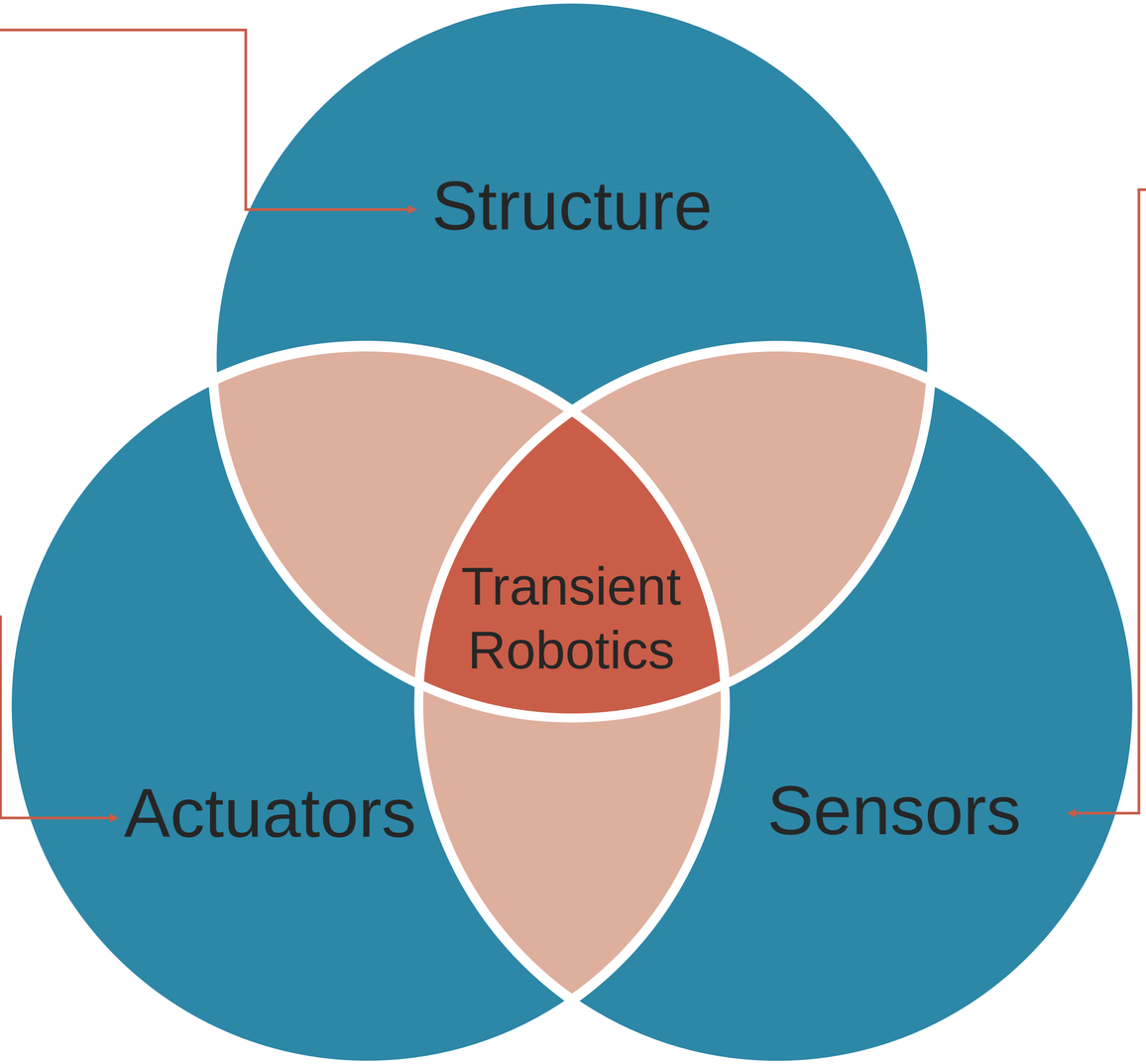
Transient Robotics

Structural materials

- Lightweight, high strength biodegradable structures (cryogels, aerogels etc.)
- Biodegradable polymers (3D printing, casting, moulding)
- Incorporation of living cells

Actuating materials

- Electro thermal actuators
- Humidity responsive composites (swelling, bending etc.)
- Micro-organisms induces shape changes (e.g. bacteria growth)
- Eco-friendly electro active polymers (e.g. polypyrrole)



Sensing materials

- Biodegradable tactile sensors (e.g. strain)
- Biodegradable environmental sensors (e.g. temperature, humidity, UV)
- Carbon or transient metal (e.g. Zn, Mg, Fe) based electronics
- Degradable & eco-friendly chemical sensing (e.g. pH, micropollutants)

Transient Robotics

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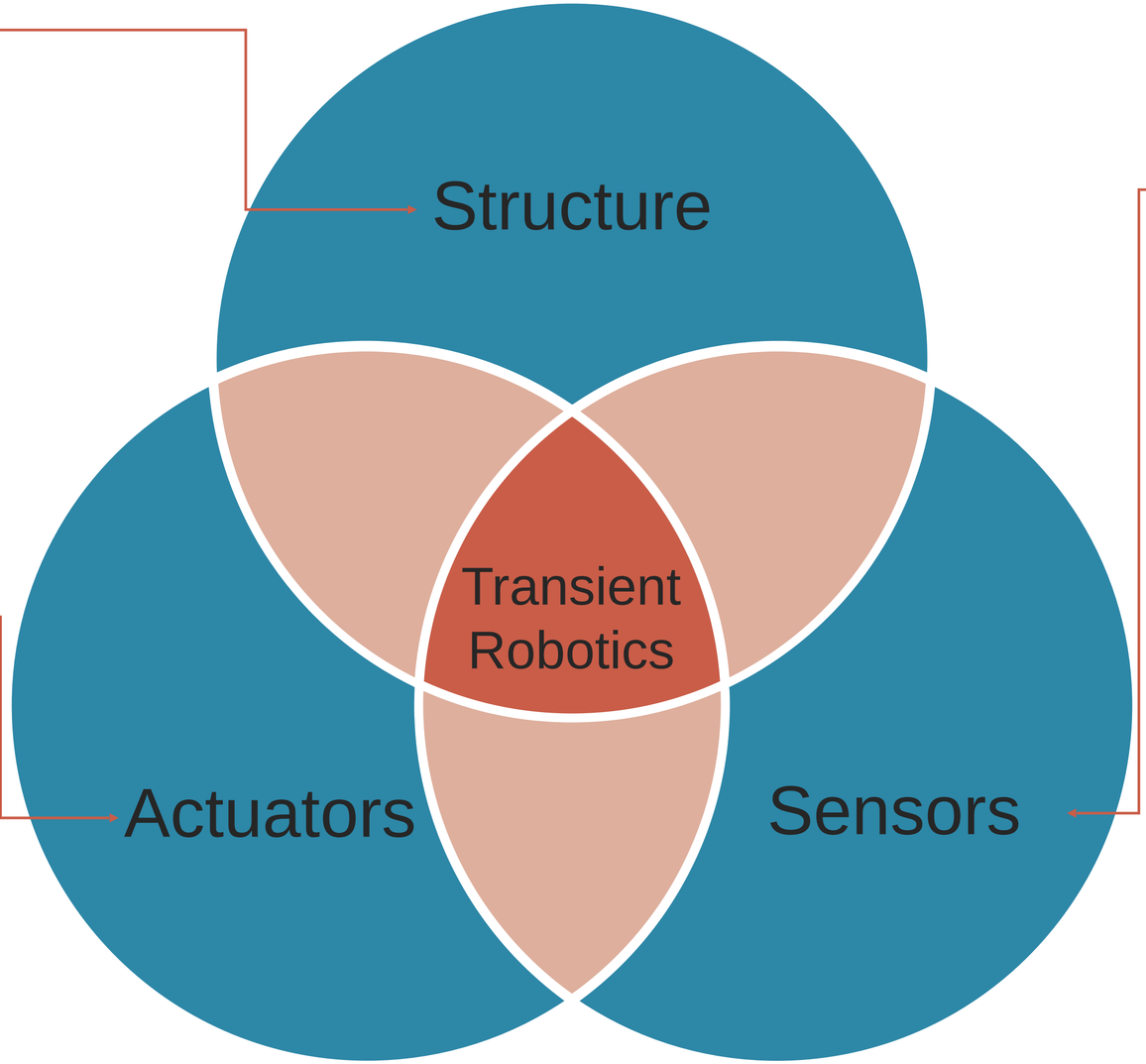

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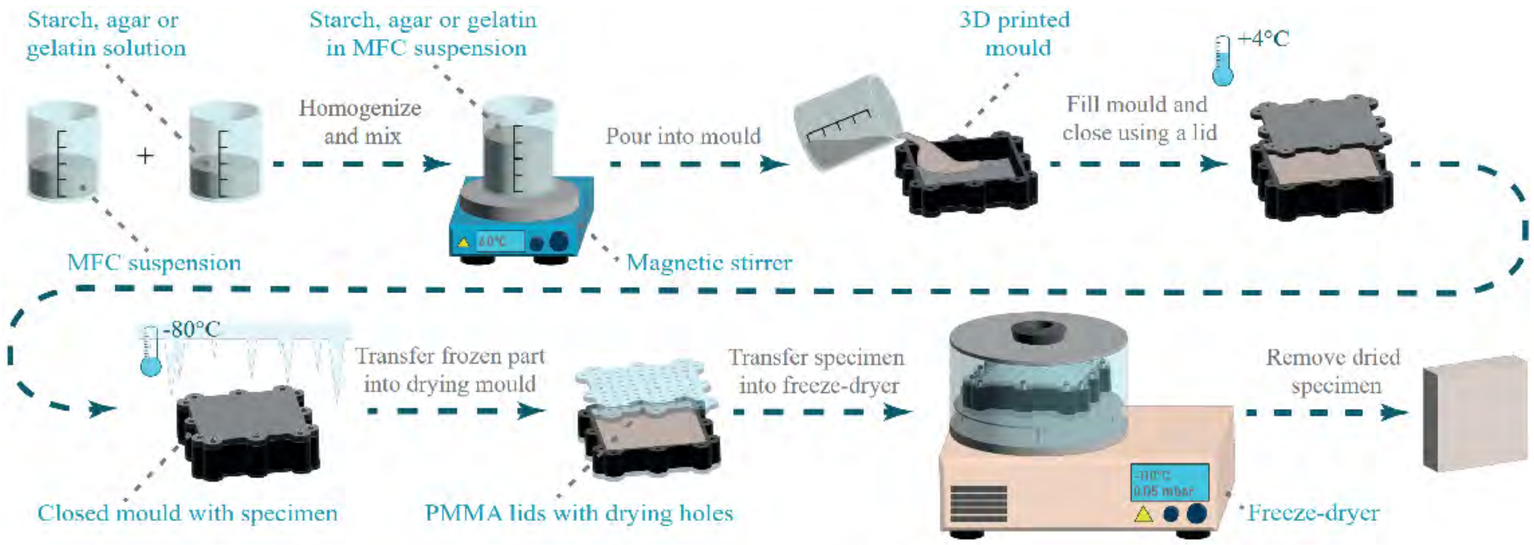
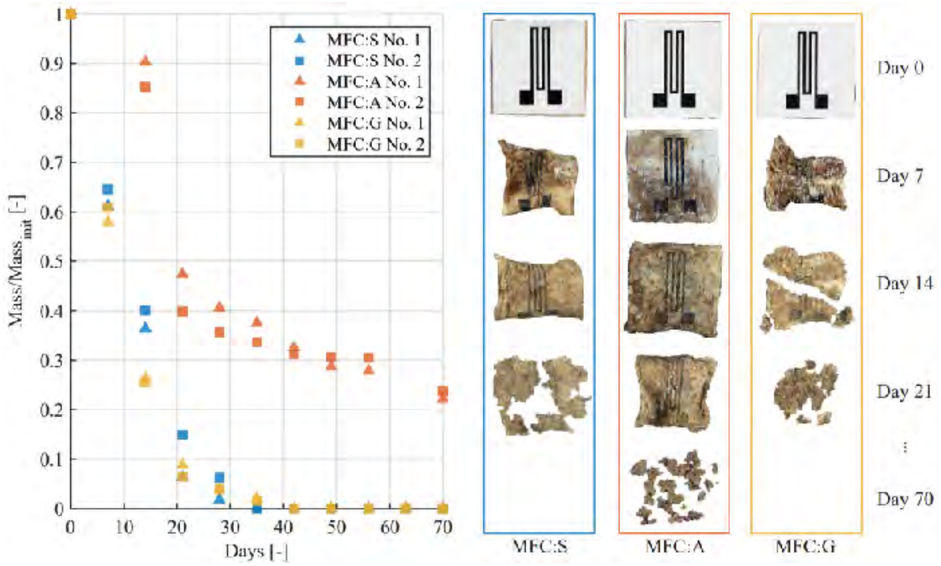
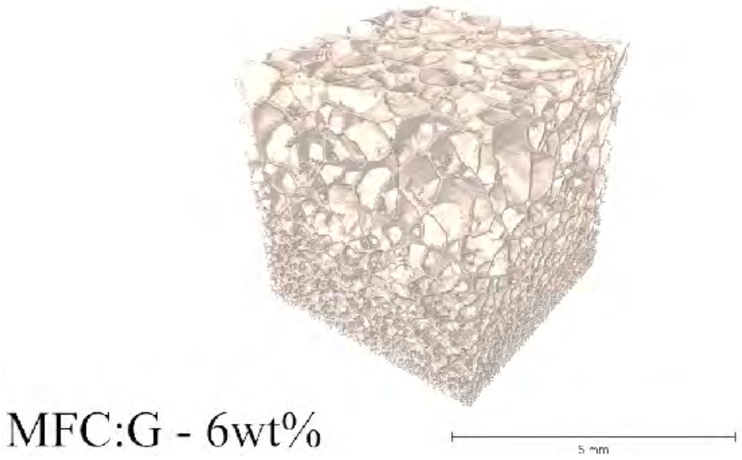
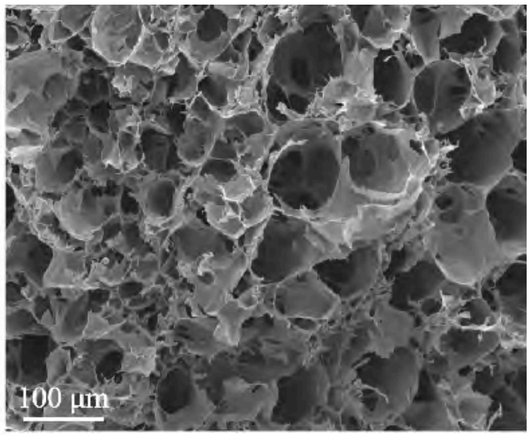
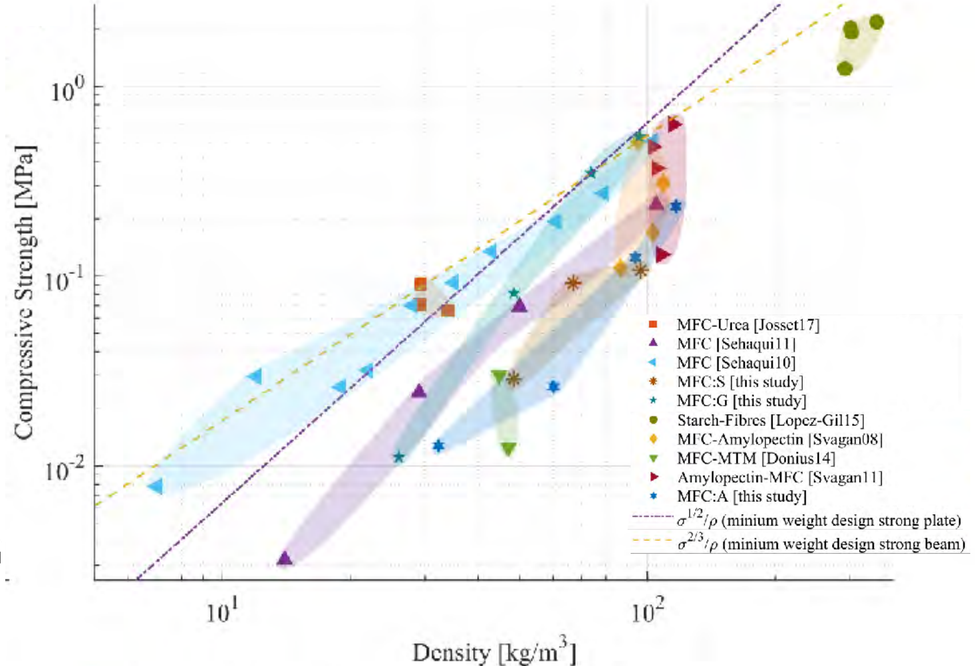
Structure: Cellulose composite cryogels





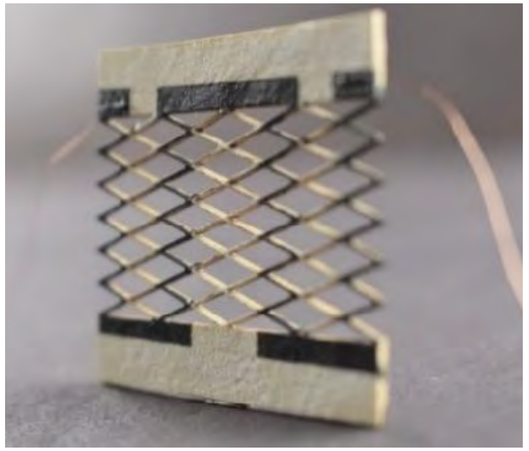


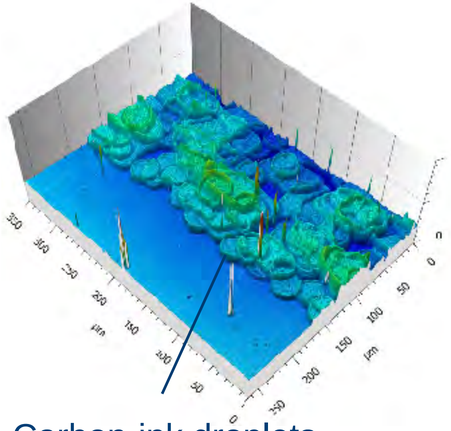


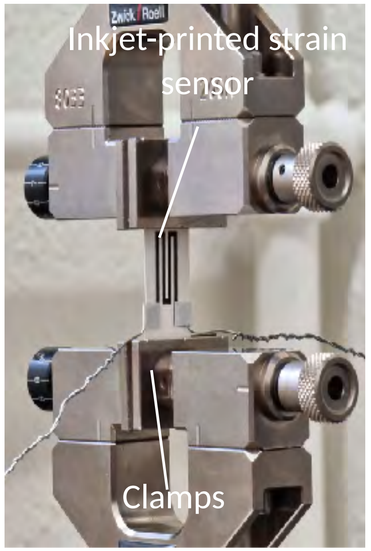


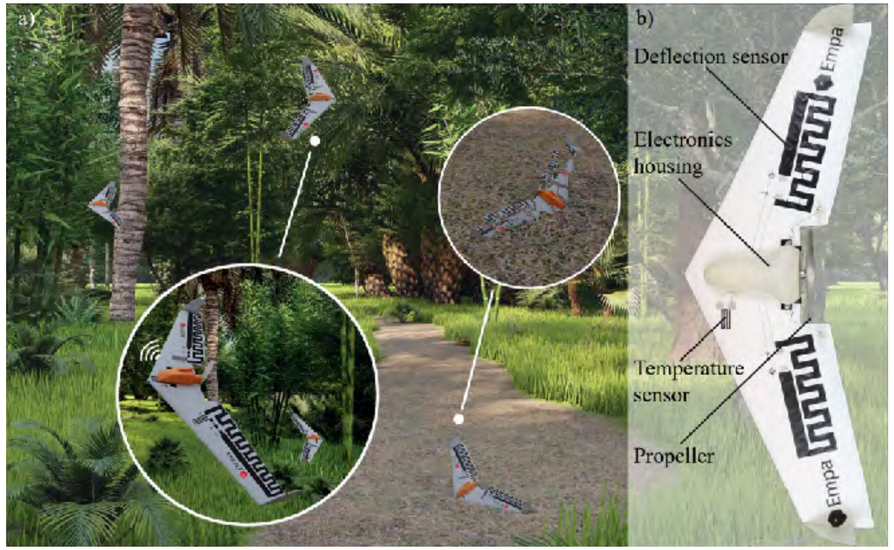
Wiesemüller, F., Meyer, S.,, Hu Y., Bachmann, D., Parrilli, A., Nyström, G Kovac, M., (2023) *Advanced Intelligent Systems*

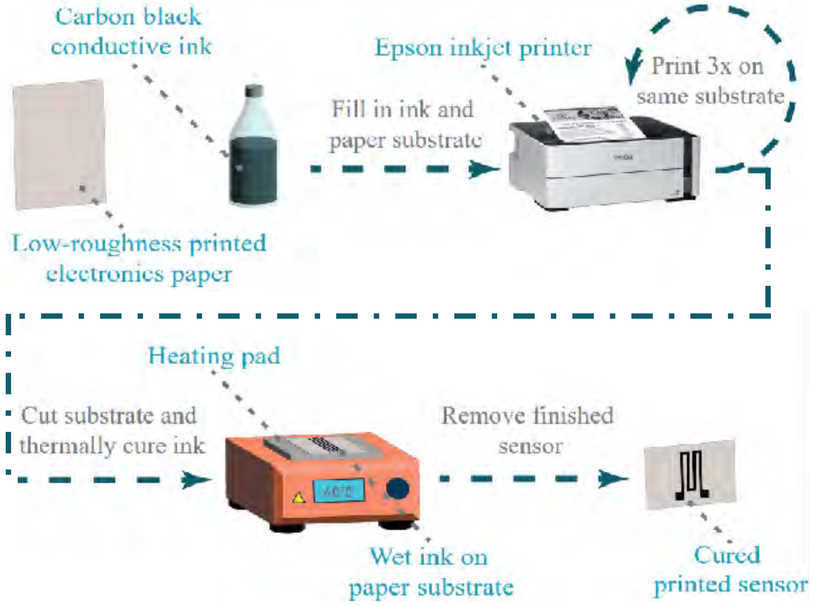
Sensing: Functionalised cellulose substrates

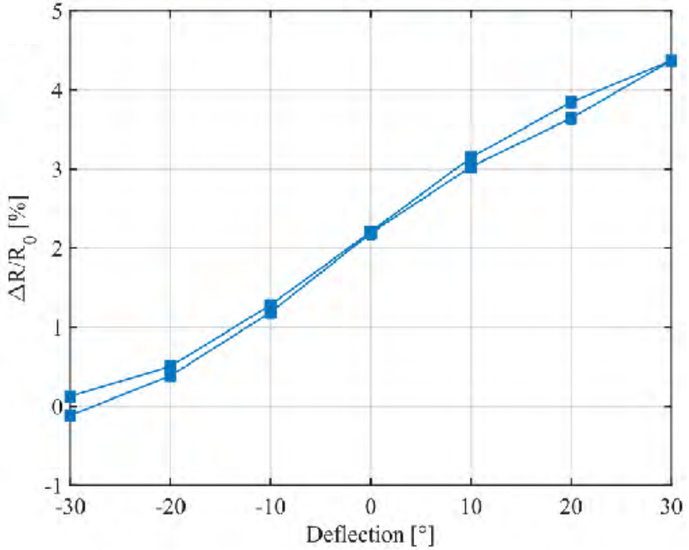


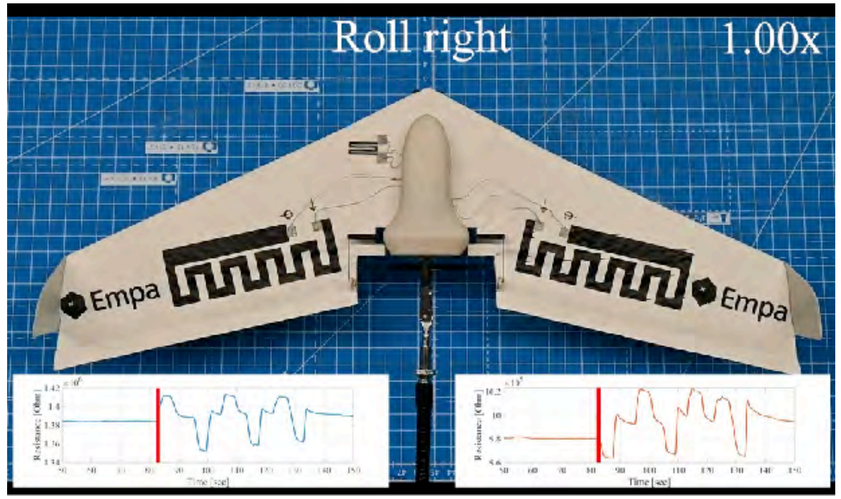






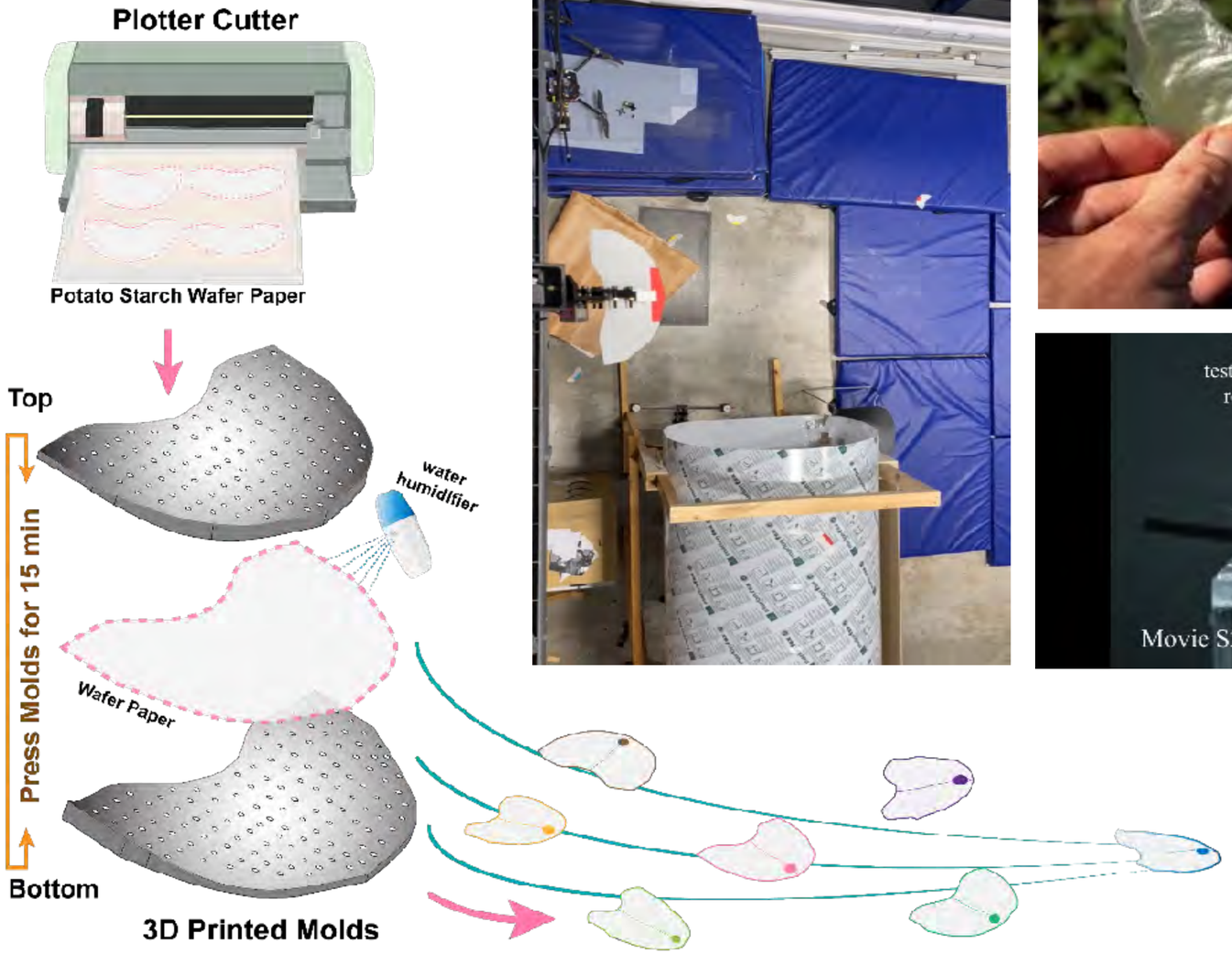


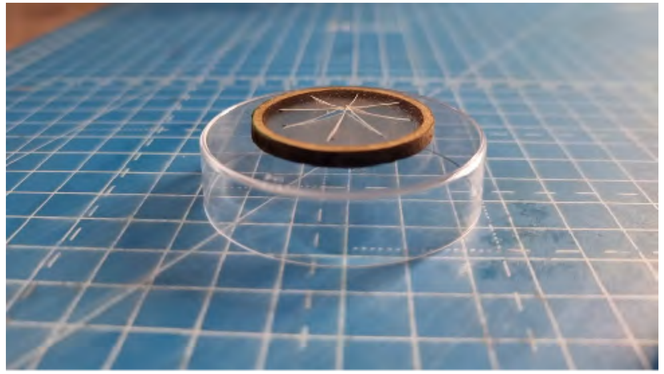


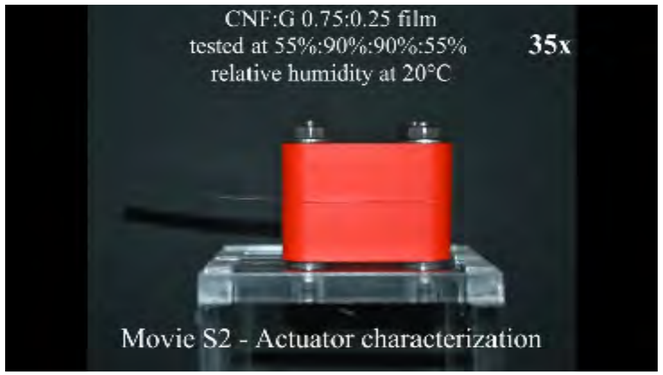


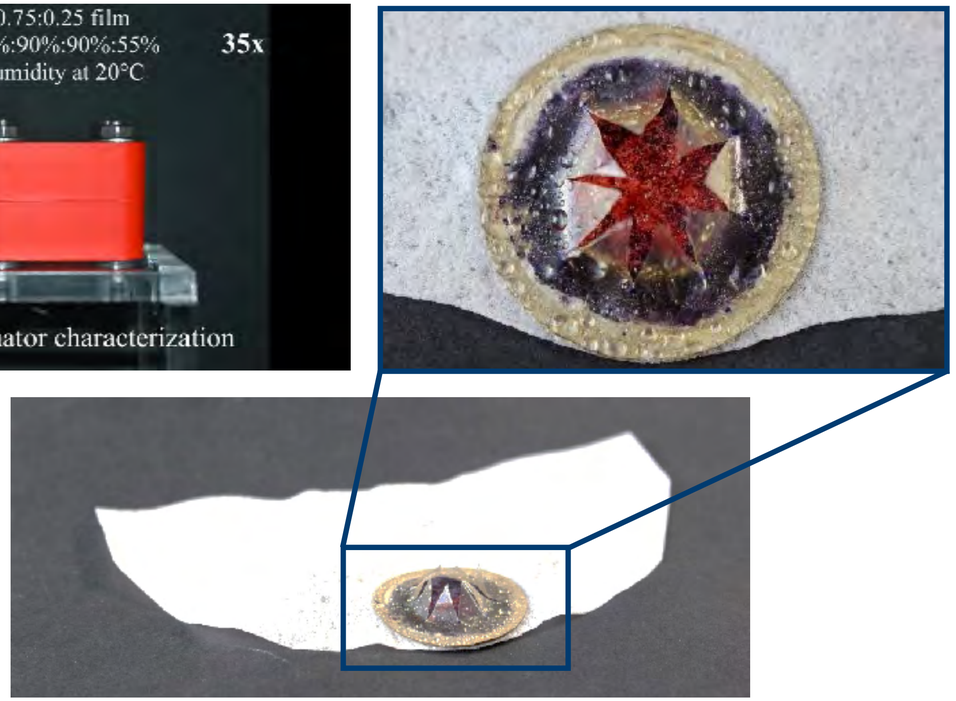
Wiesemüller, F., Nyström, G., Kovac, M., et al.
Advanced Intelligent Systems (2023) & *IEEE Robotics & Automation Letters* (2021)

Actuation: Humidity responsive composites



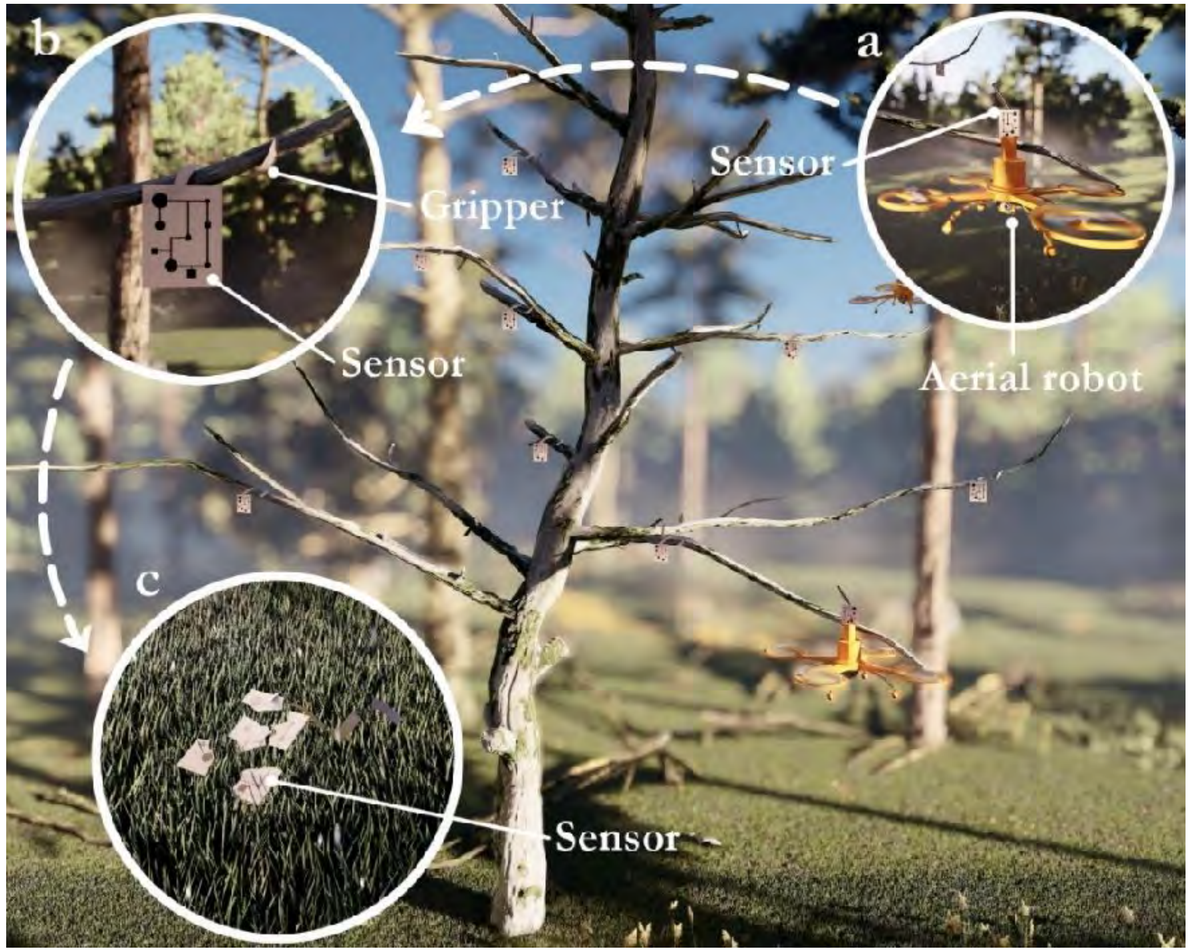


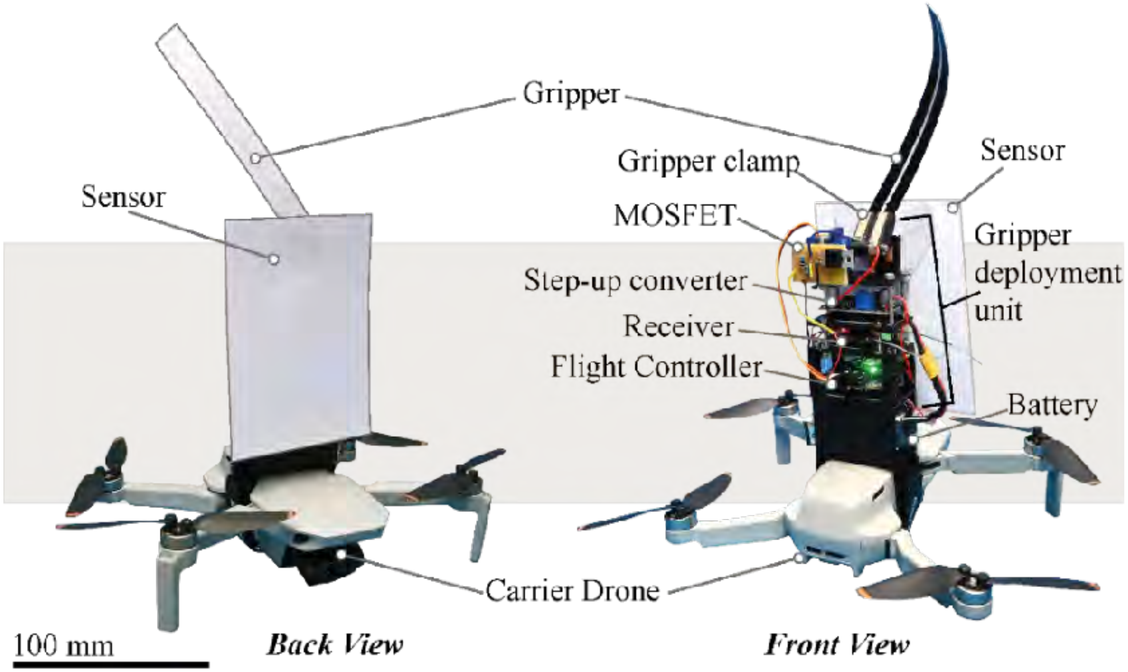




F. Wiesemüller, G. Nyström, M. Kovac et al.,
Frontiers in Robotics & AI (2022) & *N.I.C.E.* (2022)

Hygroscopically-driven transient actuator for environmental sensor deployment

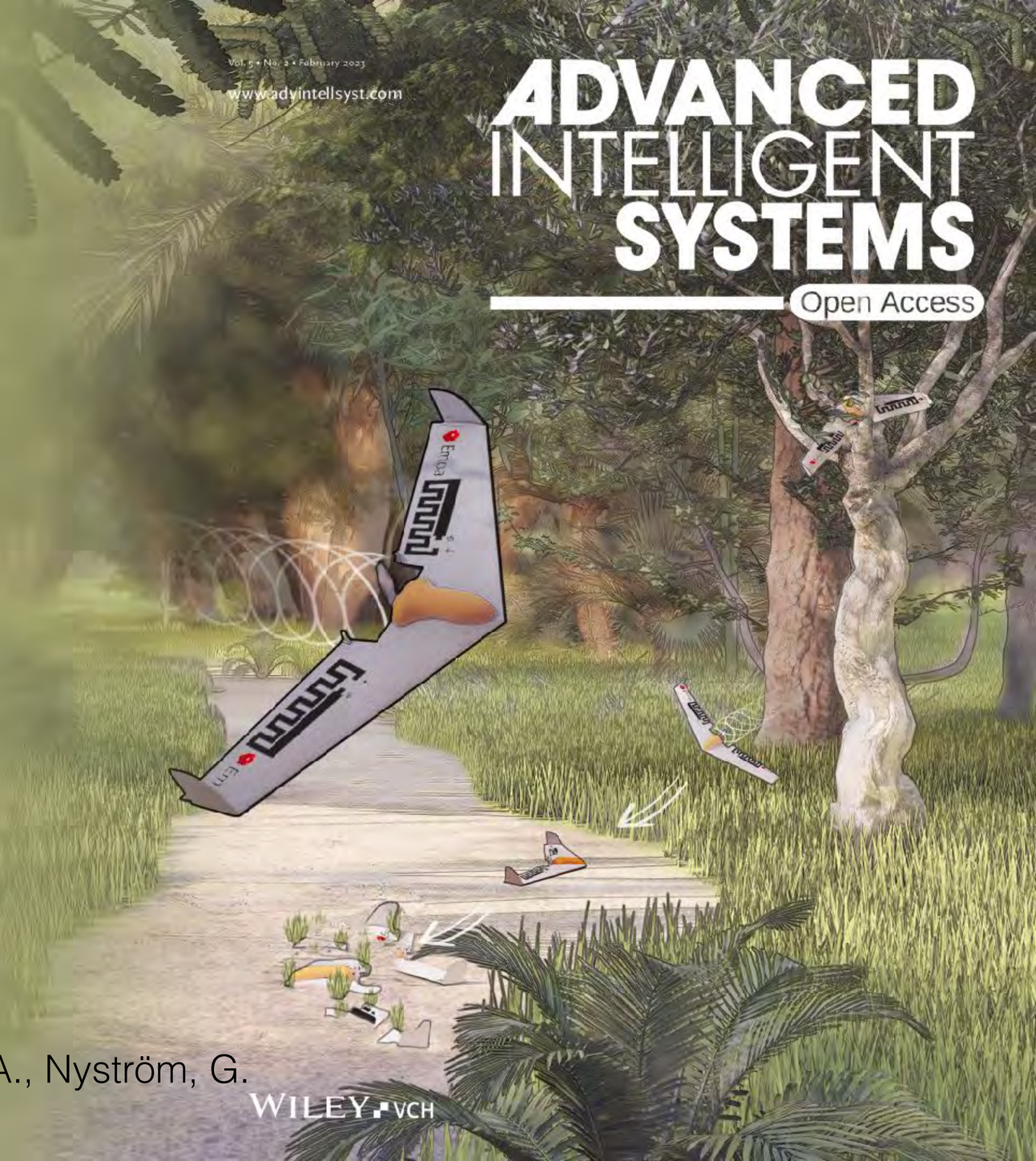




- Development, manufacturing and testing of a transient high-deformation gripper for sensor deployment tasks
- Characterization of time-dependent coiling & maximum payload
- Deployment unit design & gripper integration with quadrotor
- Successful indoor deployment tests of sensing unit

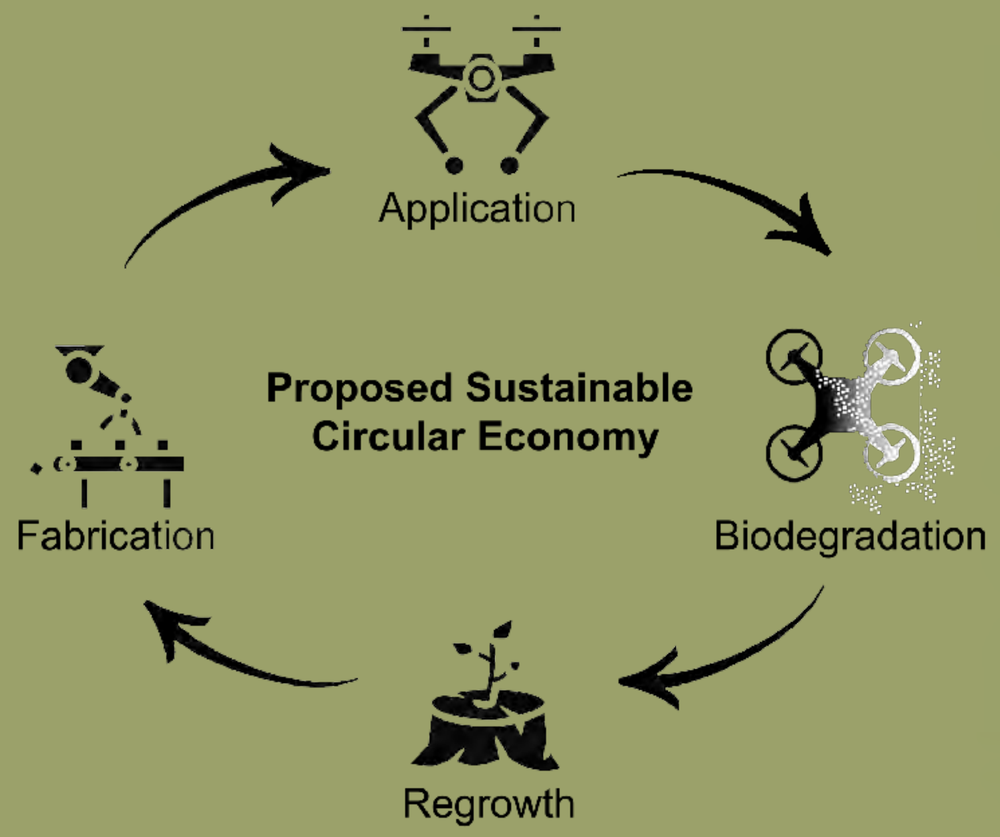
M. Heinrich, F. Wiesemüller, X. Aeby, Y. F. Kaya, D. Sivaraman, P. H. Nguyen, S. Song, G. Nyström, M. Kovac, *IEEE Robosoft* 2023

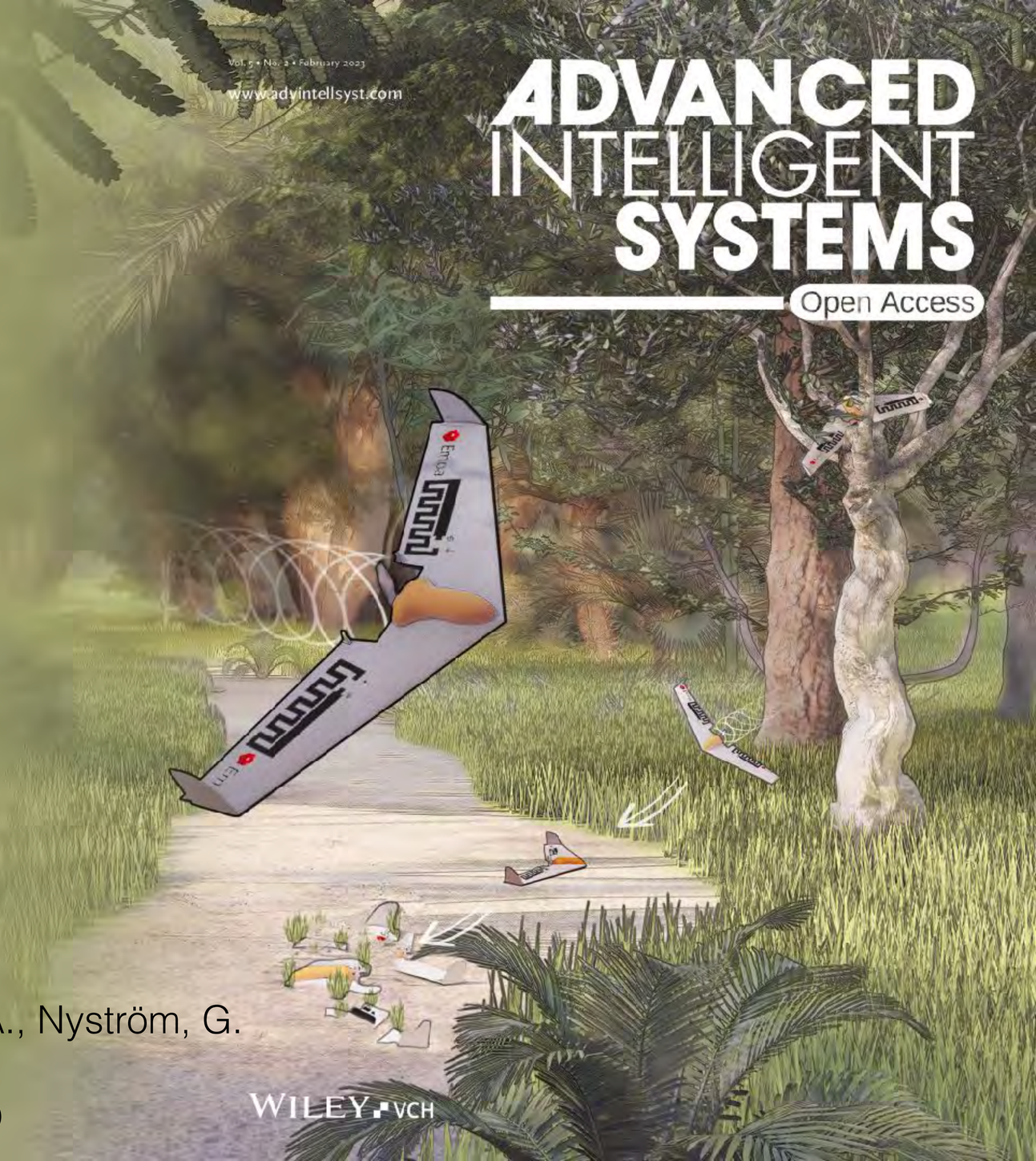
Transient Robotics



Wiesemüller, F., Meyer, S., Hu Y., Bachmann, D., Parrilli, A., Nyström, G. Kovac, M., (2023) *Advanced Intelligent Systems* (cover)

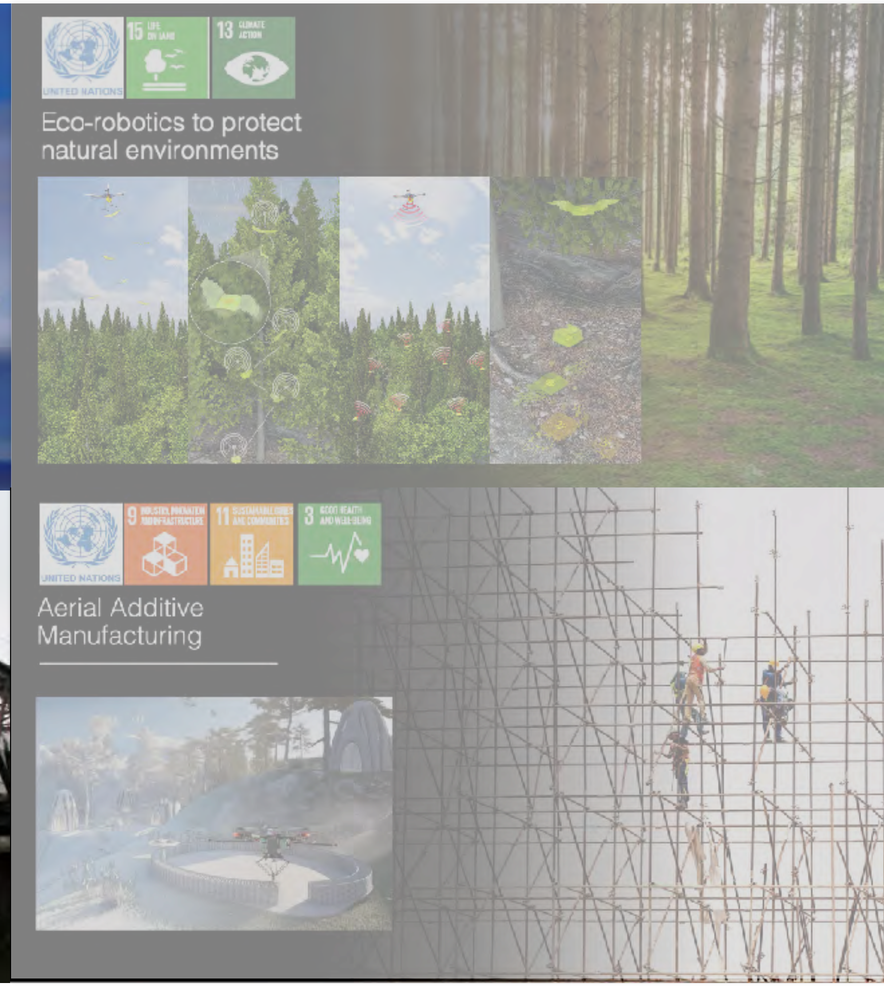
Transient Robotics



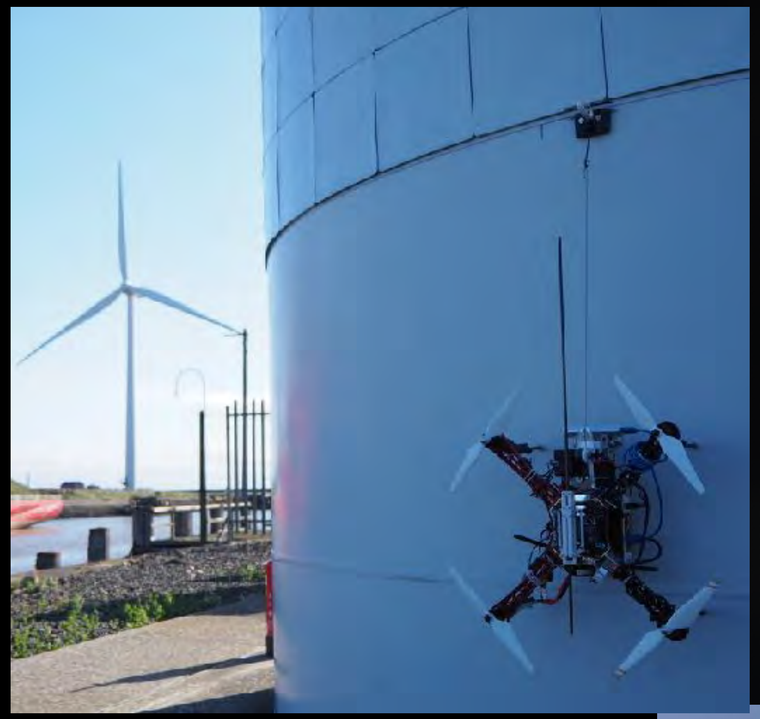


Wiesemüller, F., Meyer, S., Hu Y., Bachmann, D., Parrilli, A., Nyström, G. Kovac, M., (2023) *Advanced Intelligent Systems* (cover)
Wiesemüller, F., Miriyev, A., Kovac, M., (2021) AIRPHARO

Sustainability Robotics



Aerial Robotics for wind blade inspection



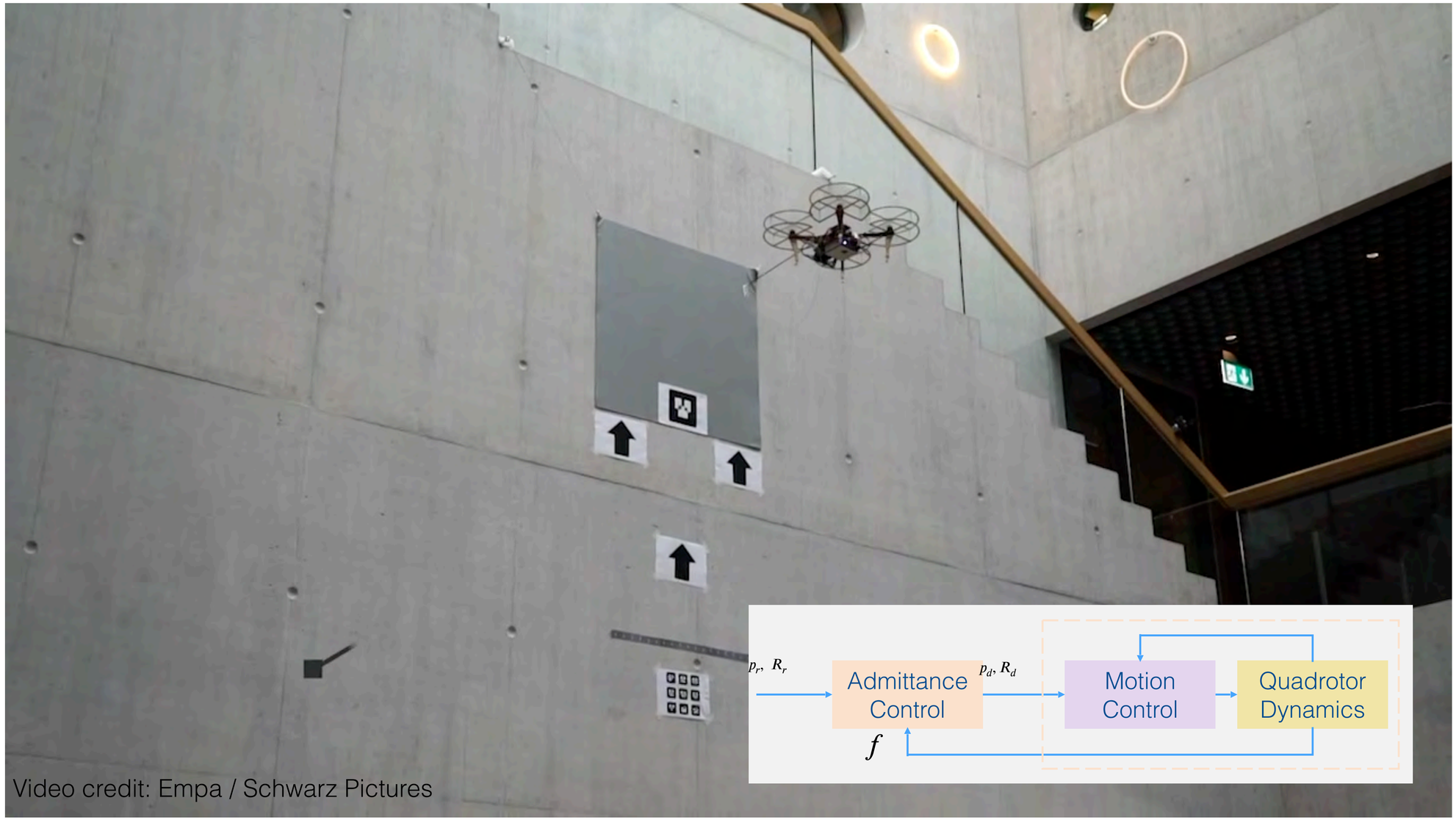
- Tensile perching to save energy
- String as sensing apparatus
- Tethered dynamic movement

Footage credit: Oreon Strusinski www.oreonphotography.com

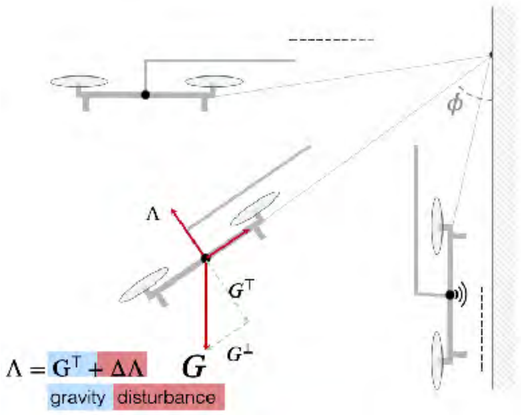
Autonomous Tensile Perching

Braithwaite, A., Alhinai, T., Haas-Heger, M., McFarlane, E., Kovac, M., (2018)
Robotics Research: International Symposium ISRR, Springer International Publishing,

Autonomous Tensile Perching



Video credit: Empa / Schwarz Pictures

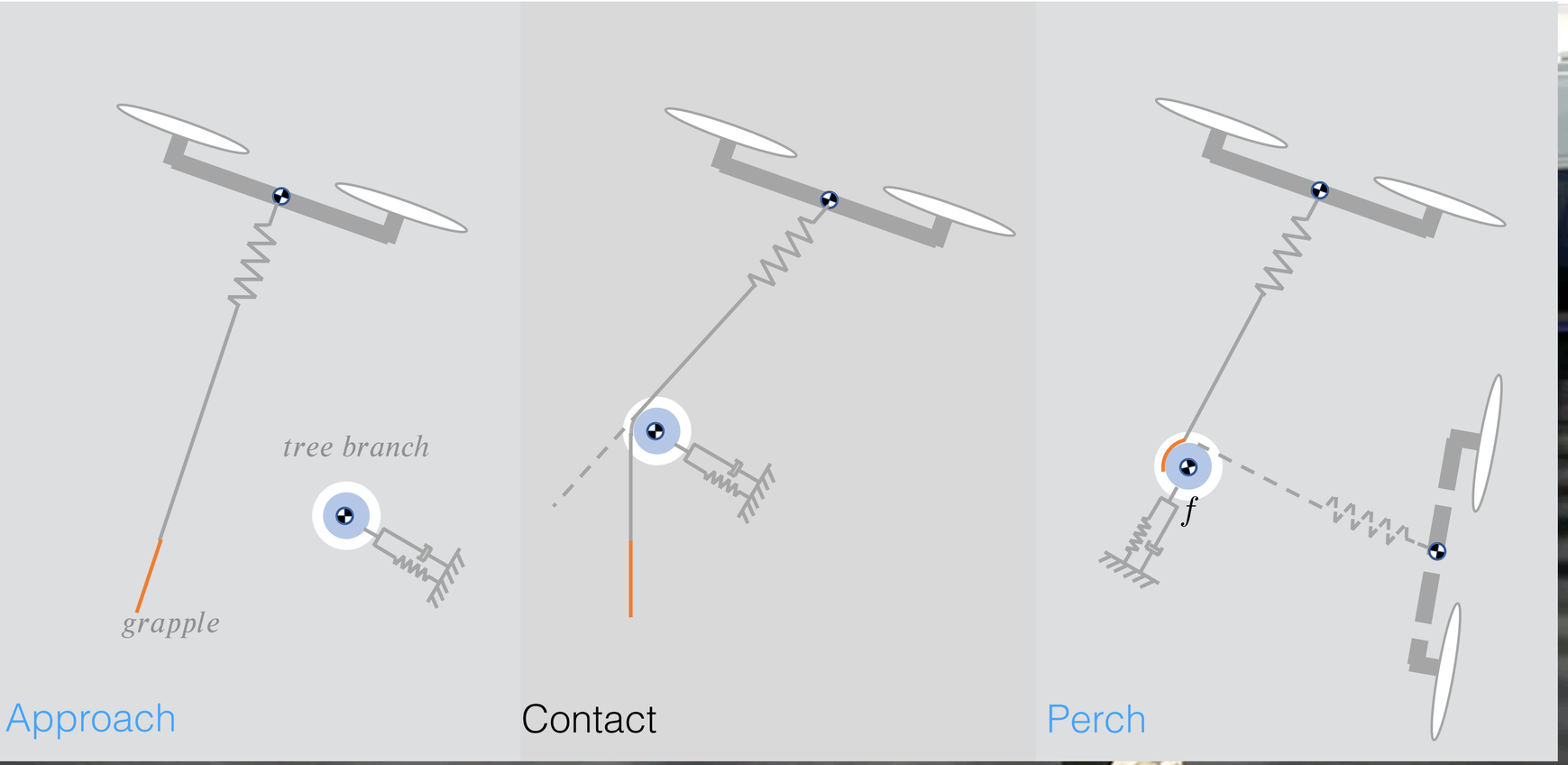


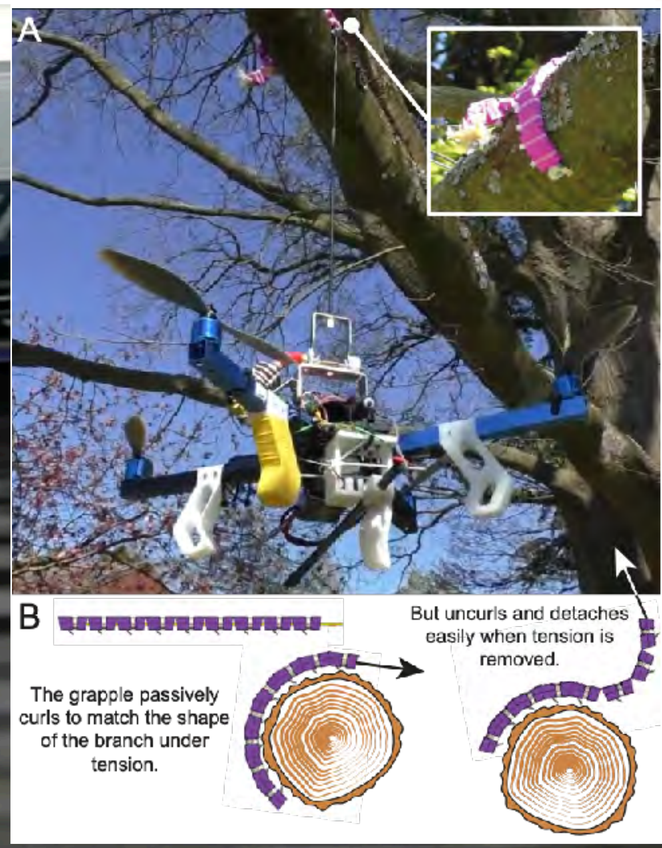
Tethered hovering thrust

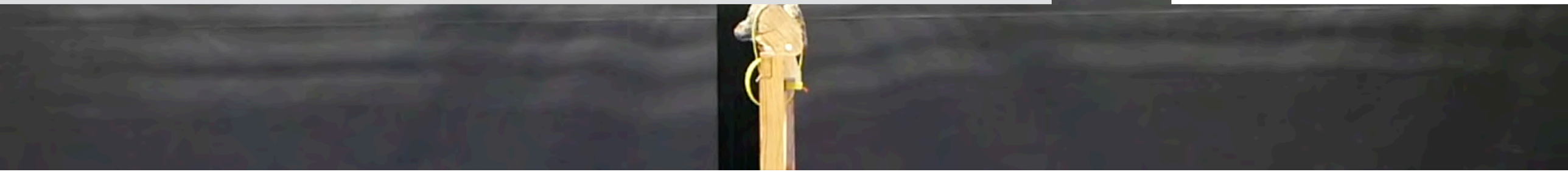
- at 30deg: save 50% the energy
- at 10deg, save more than 80%

Nguyen, H-N, Stephens, B., Kovac, M., *IEEE ICRA* 2019 (video contribution)

Autonomous Tensile Perching

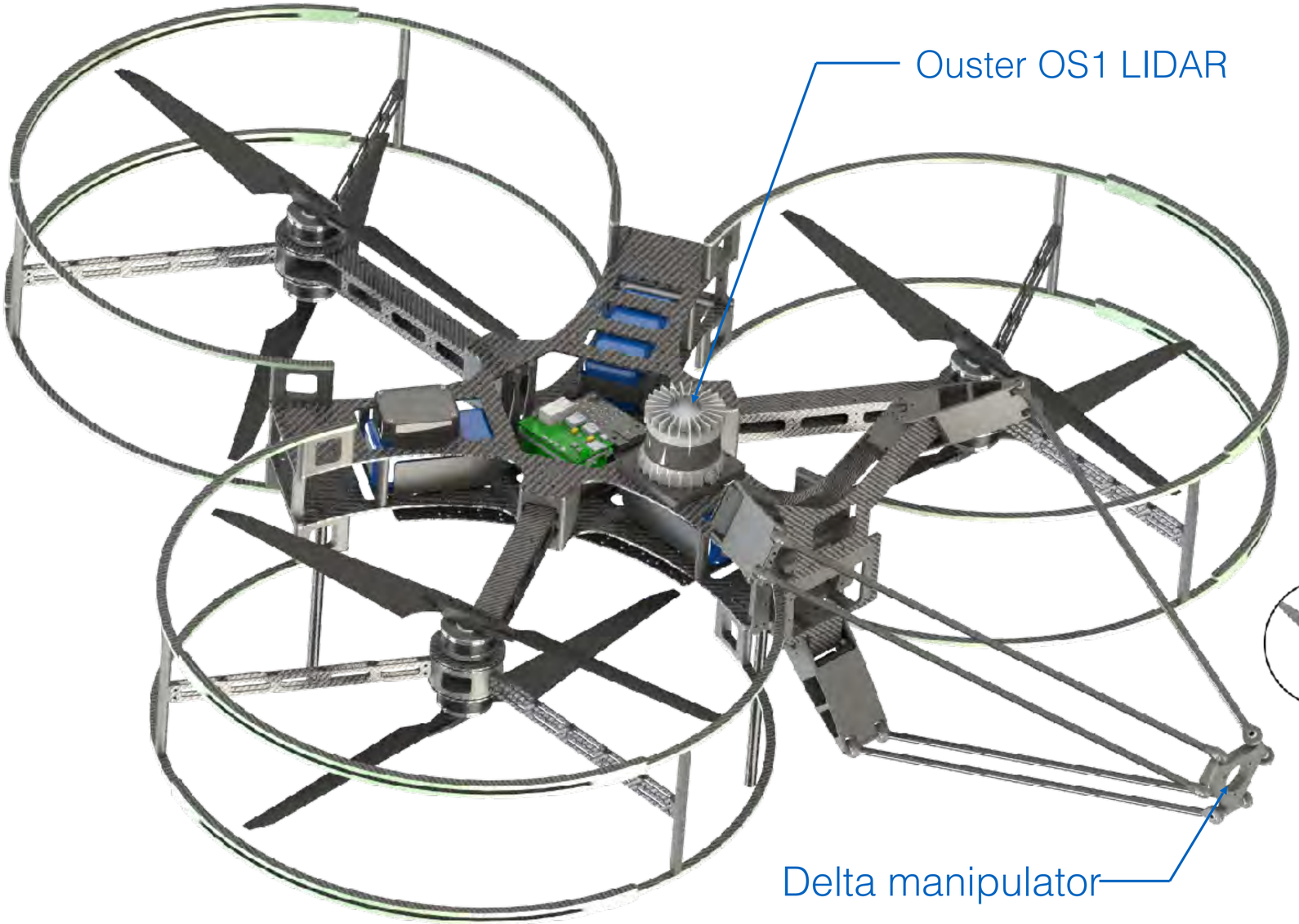




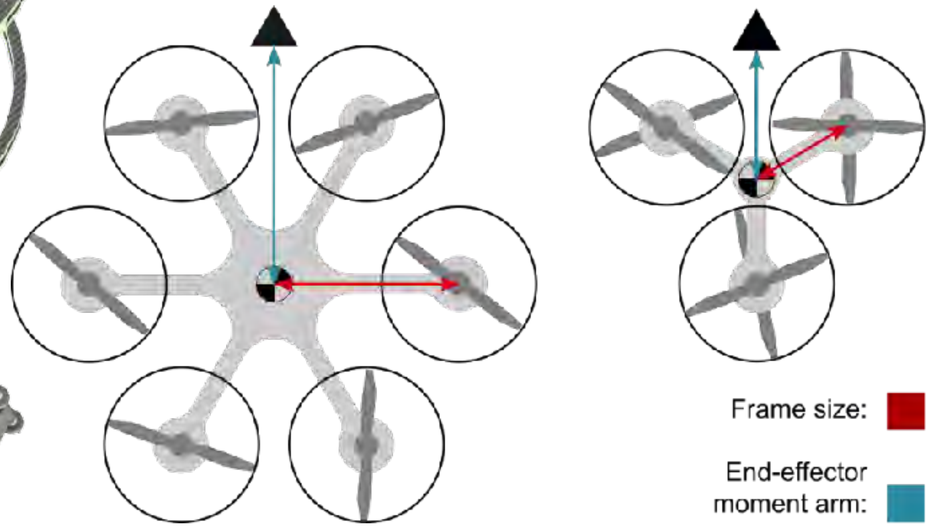


Nguyen, H-N, Siddall, R., Stephens, B., Navarro-Rubio A., Kovac, M., A Passively Adaptive Microspine Grapple for Robust, Controllable Perching *IEEE RoboSoft 2019*

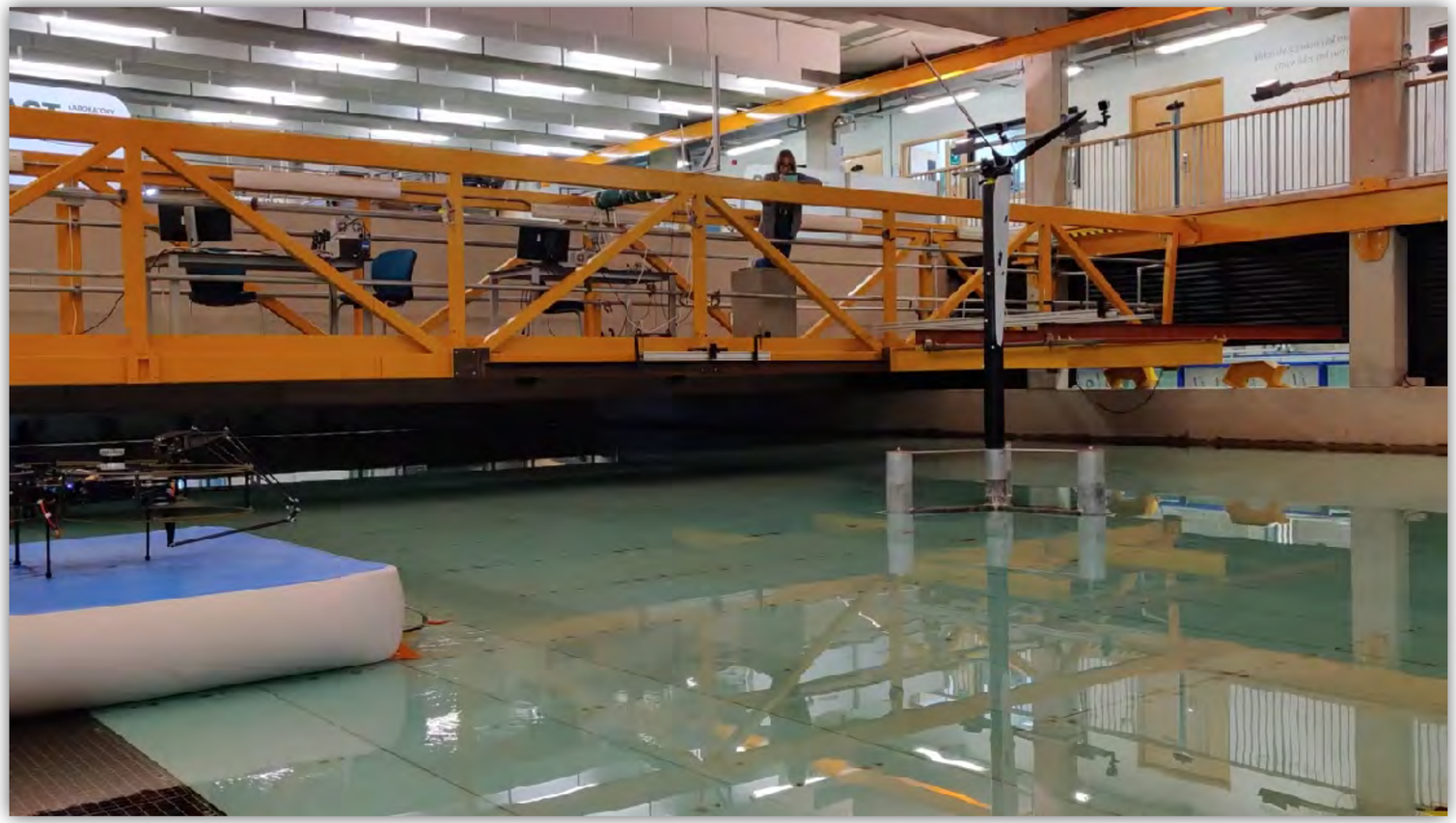
High payload coaxial tri-rotor



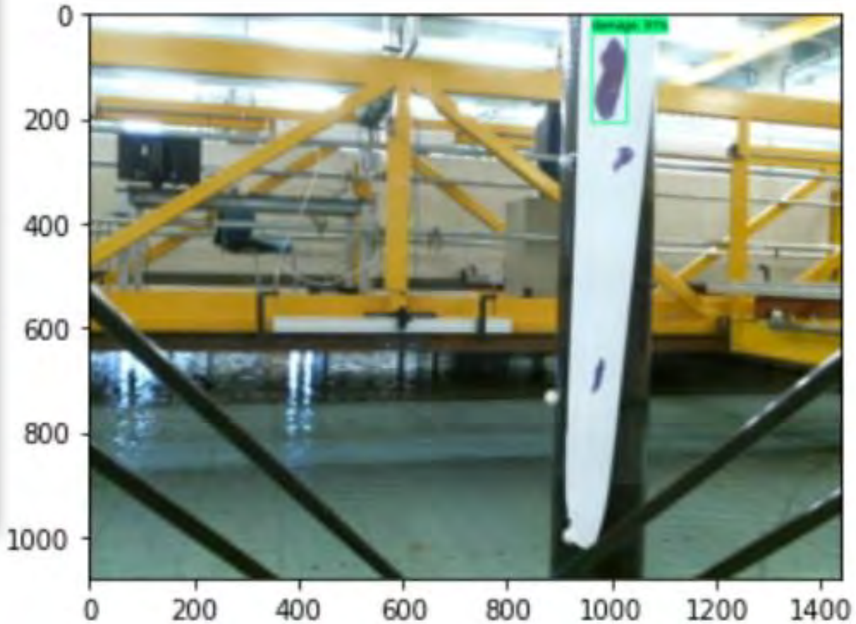
- Max. Take off Mass: 14kg (7kg payload) – 1.3m span
- Frame designed and manufactured in-house at ICL
- Compact coaxial frame layout



Autonomous turbine model inspection

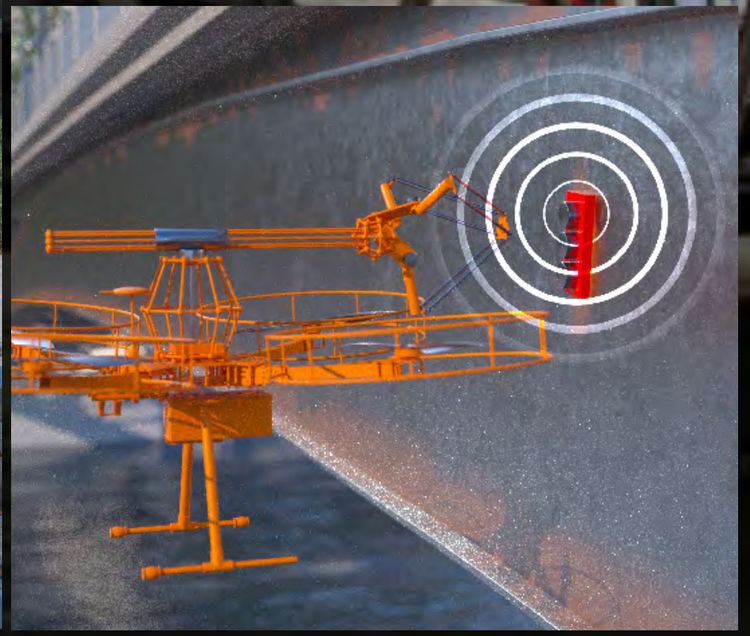


x4 speed

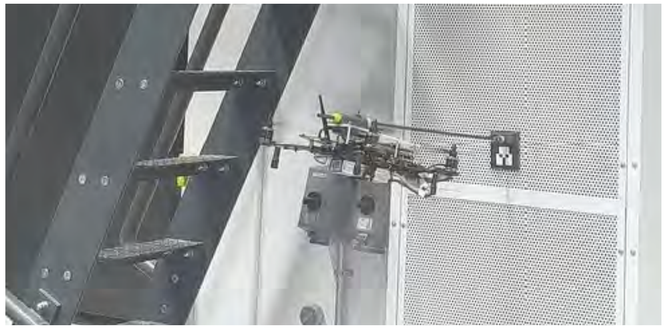


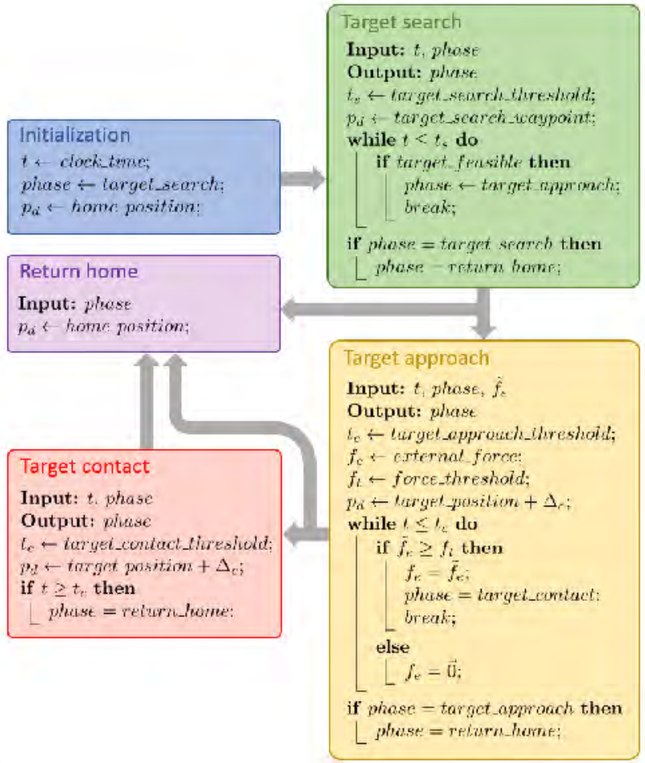
B. Kocer, L. Orr, B. Stephens, Y. Kaya, T. Buzykina, A. Khan and M. Kovac,
UKACC 13th International Conference on Control (2022) (best abstract award)

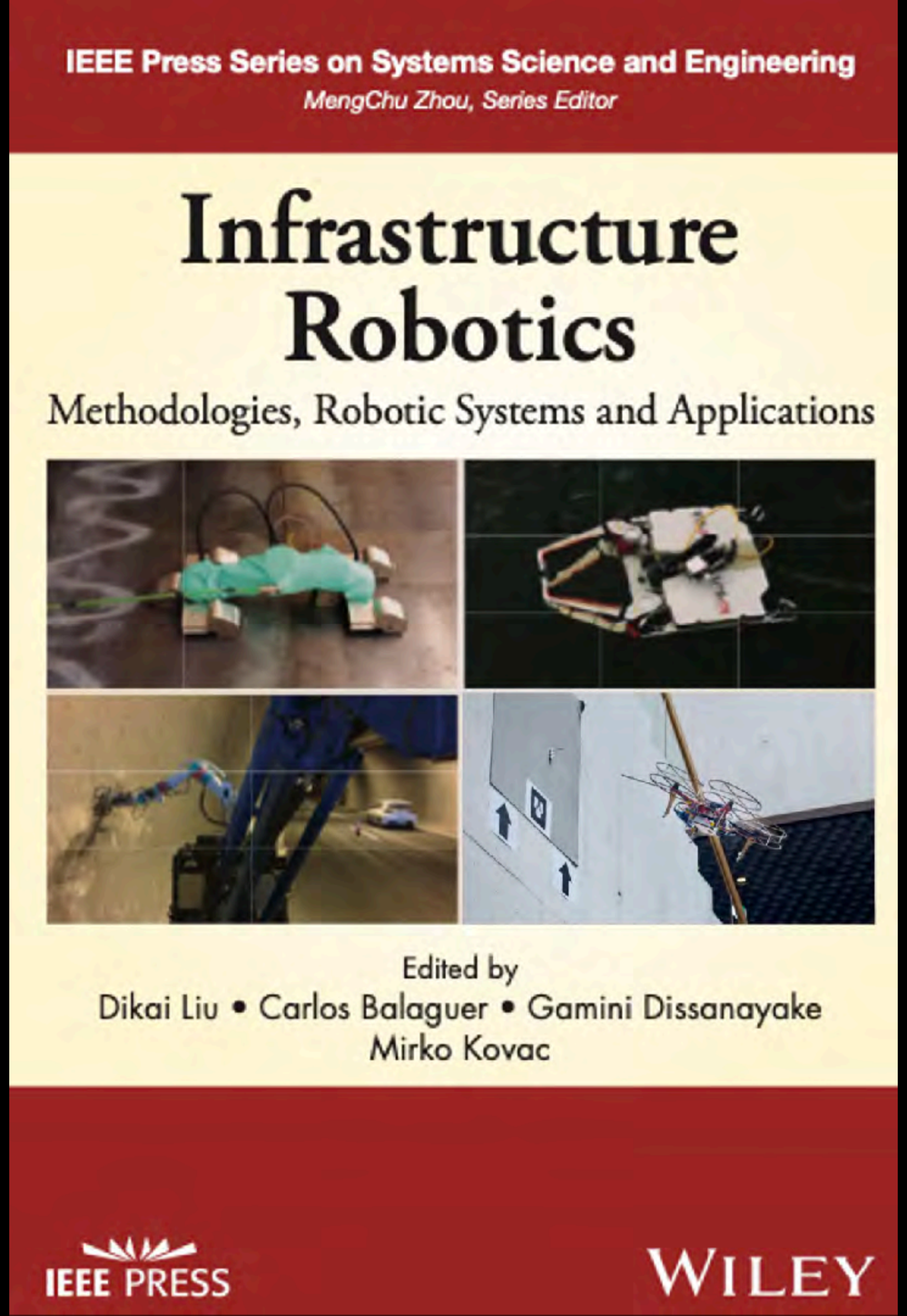
structure



Autonomous sensor placement






IEEE Press Series on Systems Science and Engineering
MengChu Zhou, Series Editor
Infrastructure Robotics
Methodologies, Robotic Systems and Applications
Edited by
Dikai Liu • Carlos Balaguer • Gamini Dissanayake
Mirko Kovac
IEEE PRESS
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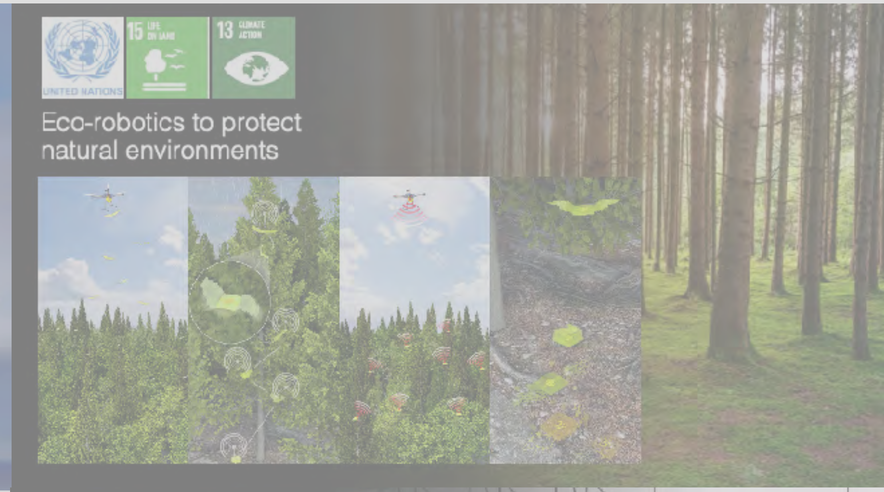
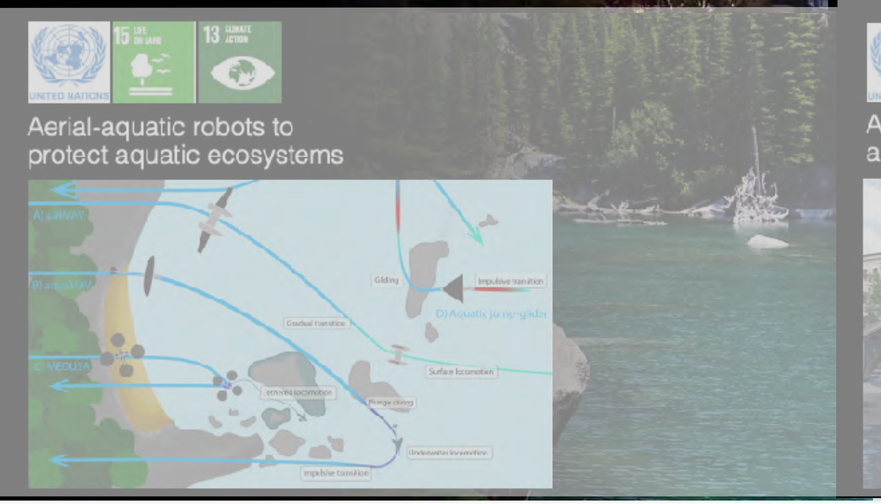
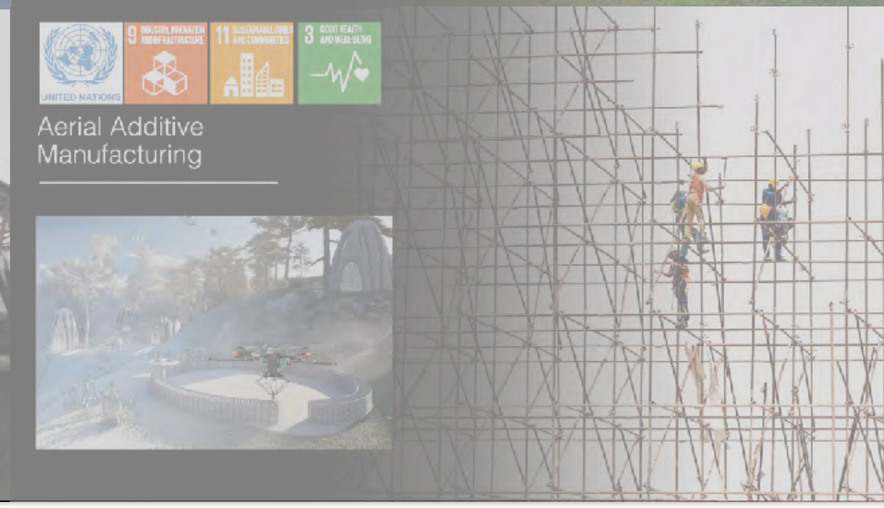
Sustainability Robotics

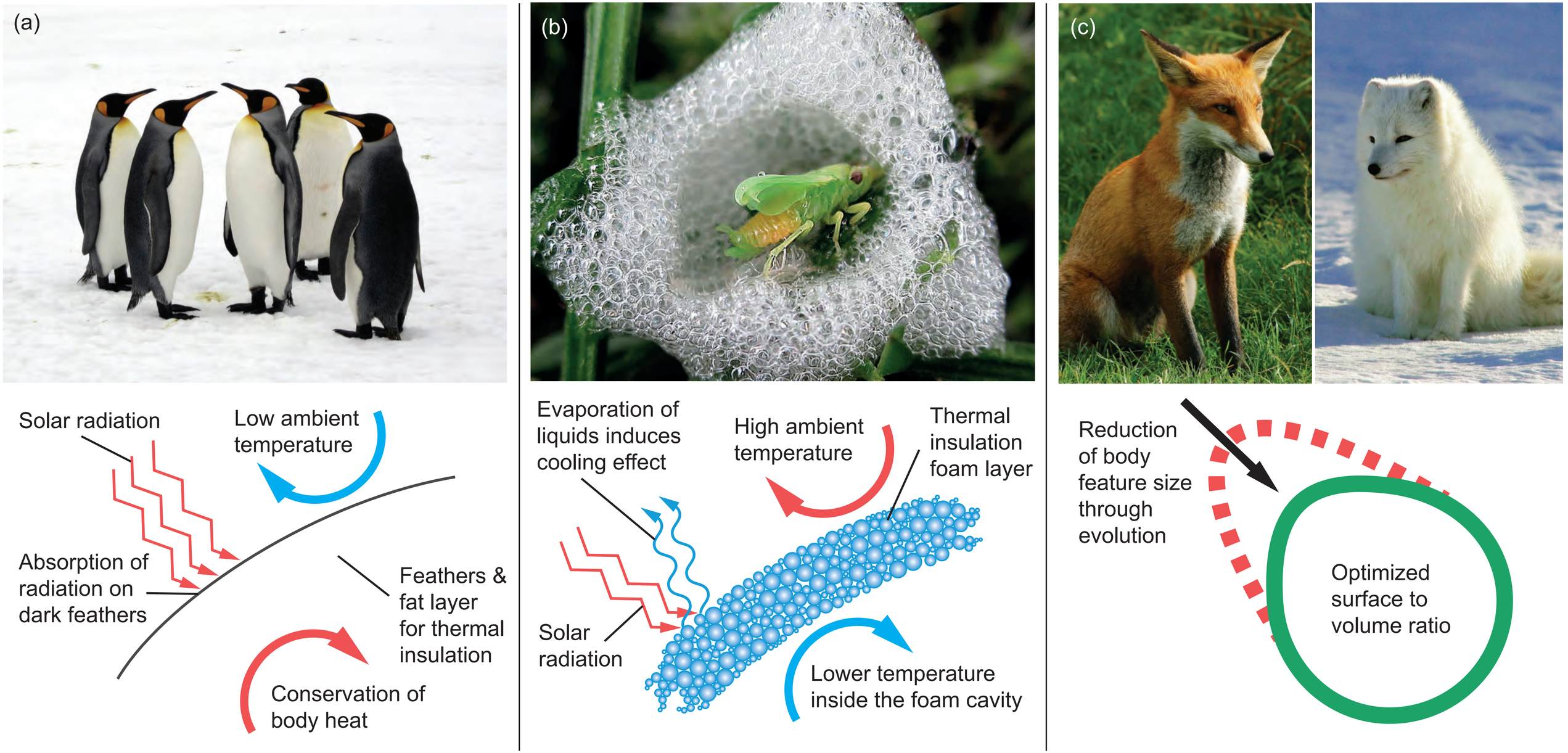






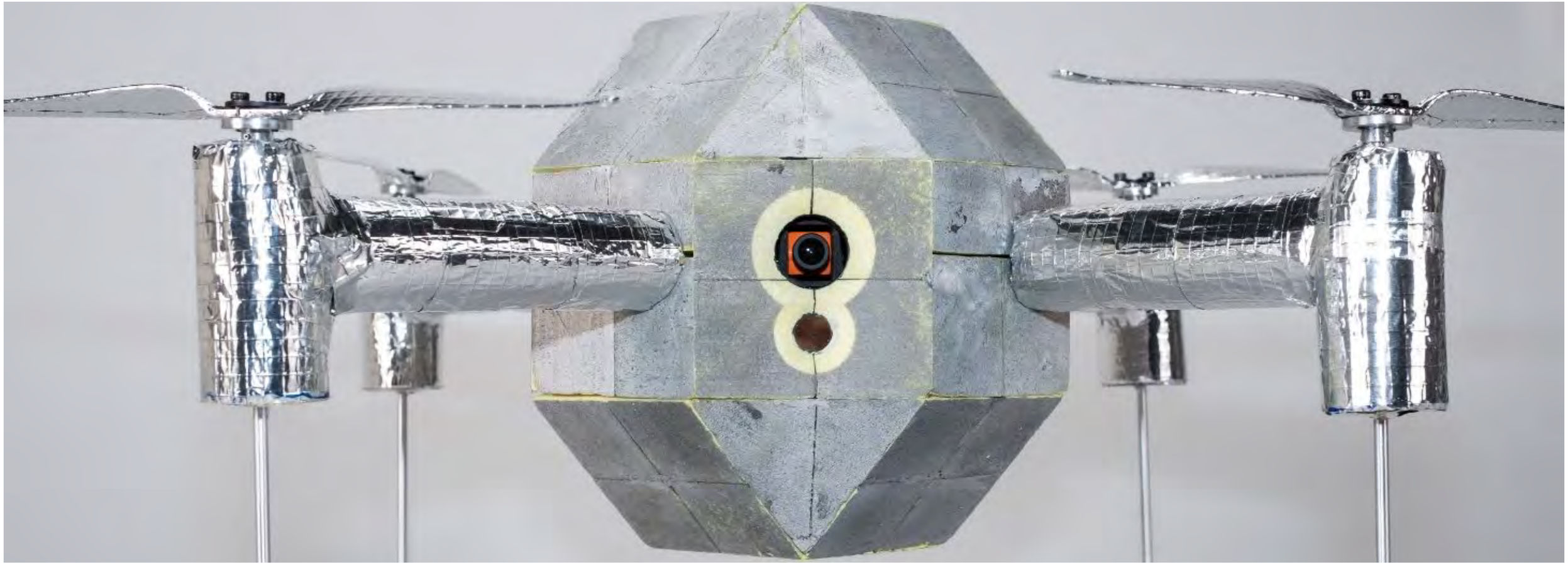
London Greenfell tower fire

Image credit: Natalie Oxford (Wikipedia)



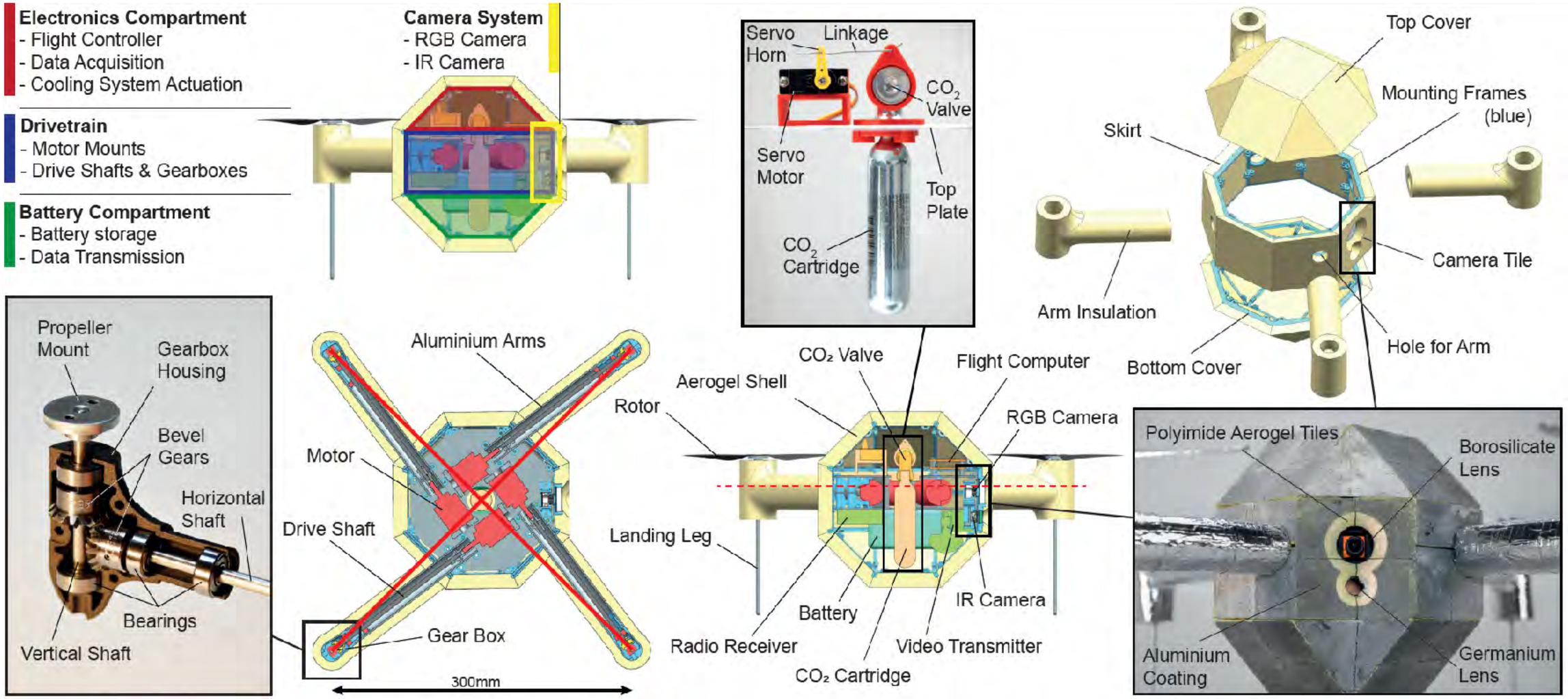
Häusermann, D., Bodry, S., Wiesemüller, F., Miriyev, A., Siegrist, S., Fu, F., Gaan, S., Koebel, M.M., Malfait, W.J., Zhao, S., Kovac, M., (2023) *Advanced Intelligent Systems*

FireDrone - Temperature agnostic aerogel drone



Häusermann, D., Bodry, S., Wiesemüller, F., Miriyev, A., Siegrist, S., Fu, F., Gaan, S., Koebel, M.M., Malfait, W.J., Zhao, S., Kovac, M., (2023) *Advanced Intelligent Systems*

FireDrone - Temperature agnostic aerial robot



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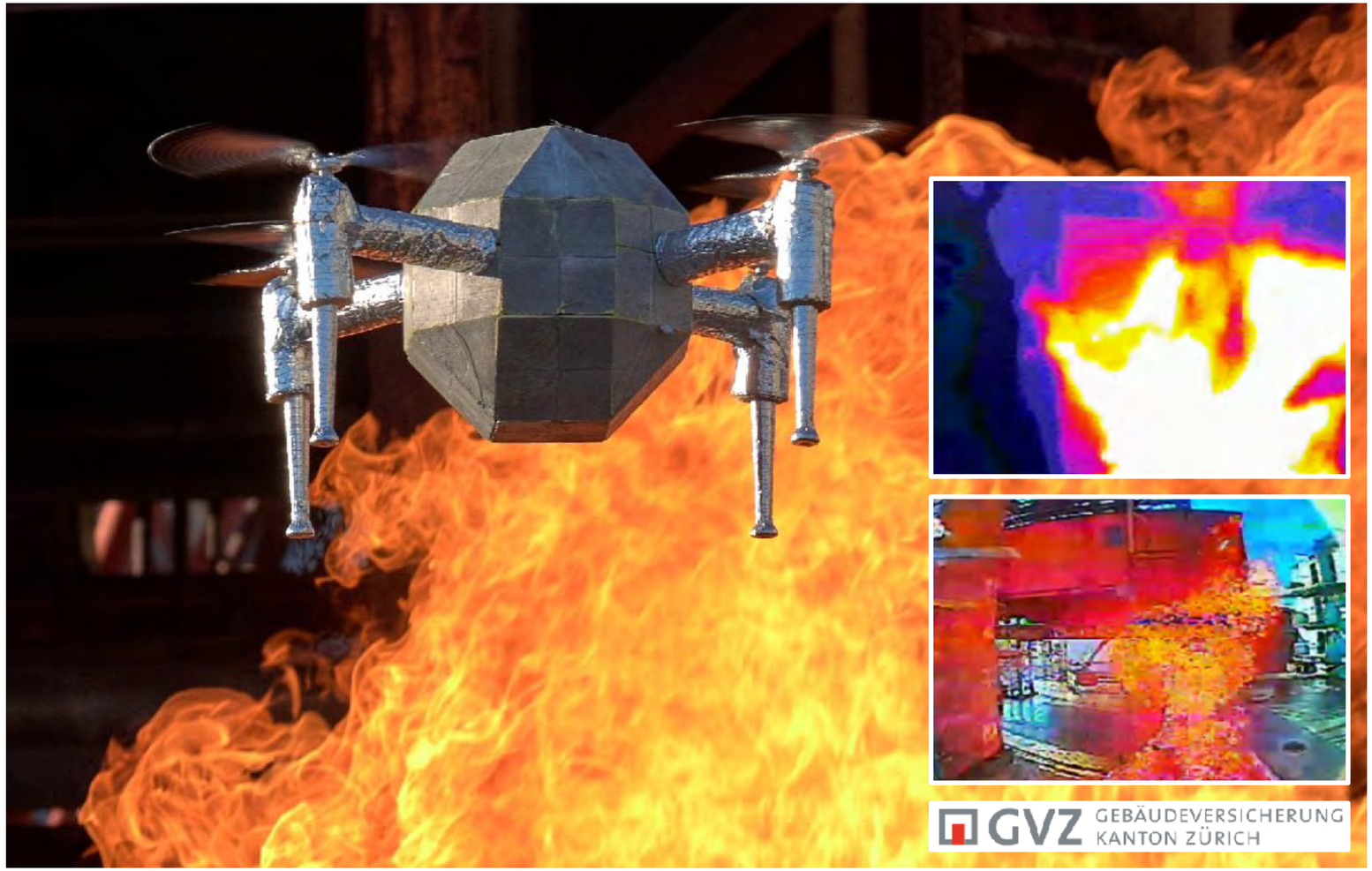
FireDrone - Temperature agnostic aerial robot




Test in glacier tunnel (thank you Prof. D. Farinotti ETHZ/WSL)

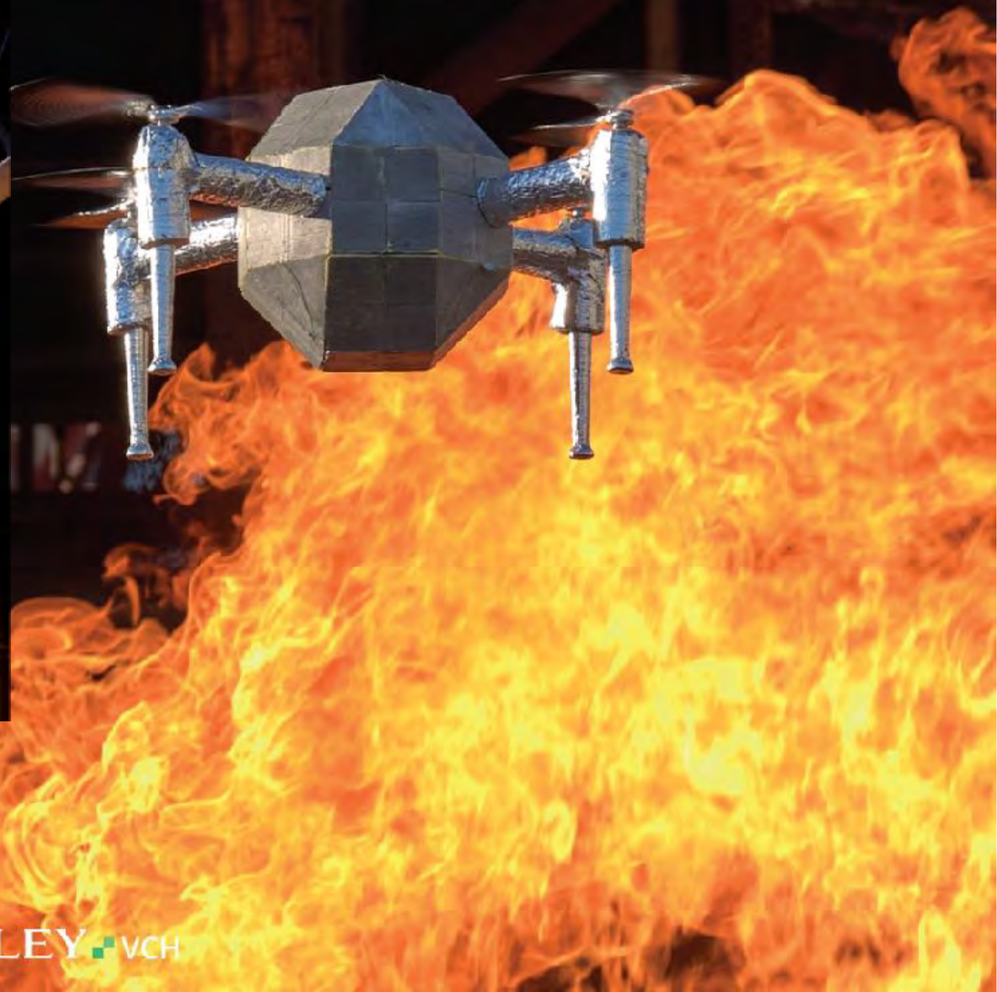
FireDrone - Unmanned aerial vehicle for extreme temperature environments - YouTube

Häusermann, D., Bodry, S., Wiesemüller, F., Miriyev, A., Siegrist, S., Fu, F., Gaan, S., Koebel, M.M., Malfait, W.J., Zhao, S., Kovac, M., (2023) *Advanced Intelligent Systems*

FireDrone
Temperature agnostic aerial robot

Häusermann, D., Bodry, S., Wiesemüller, F., Miriyev, A., Siegrist, S., Fu, F., Gaan, S., Koebel, M.M., Malfait, W.J., Zhao, S., Kovac, M., (2023) *Advanced Intelligent Systems (cover)*

FireDrone
Temperature agnostic aerial robot



ADVANCED INTELLIGENT SYSTEMS
Open Access

Häusermann, D., Bodry, S., Wiesemüller, F., Miriyev, A., Siegrist, S., Fu, F., Gaan, S., Koebel, M.M., Malfait, W.J., Zhao, S., Kovac, M., (2023) *Advanced Intelligent Systems (cover)*

WILEY VCH

Sustainability Robotics

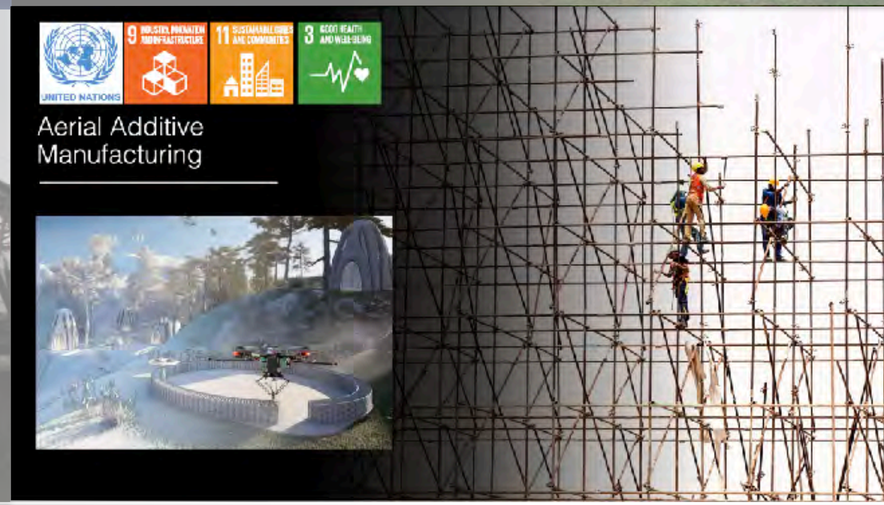


Illustration: Yusuf Kaya Furkan

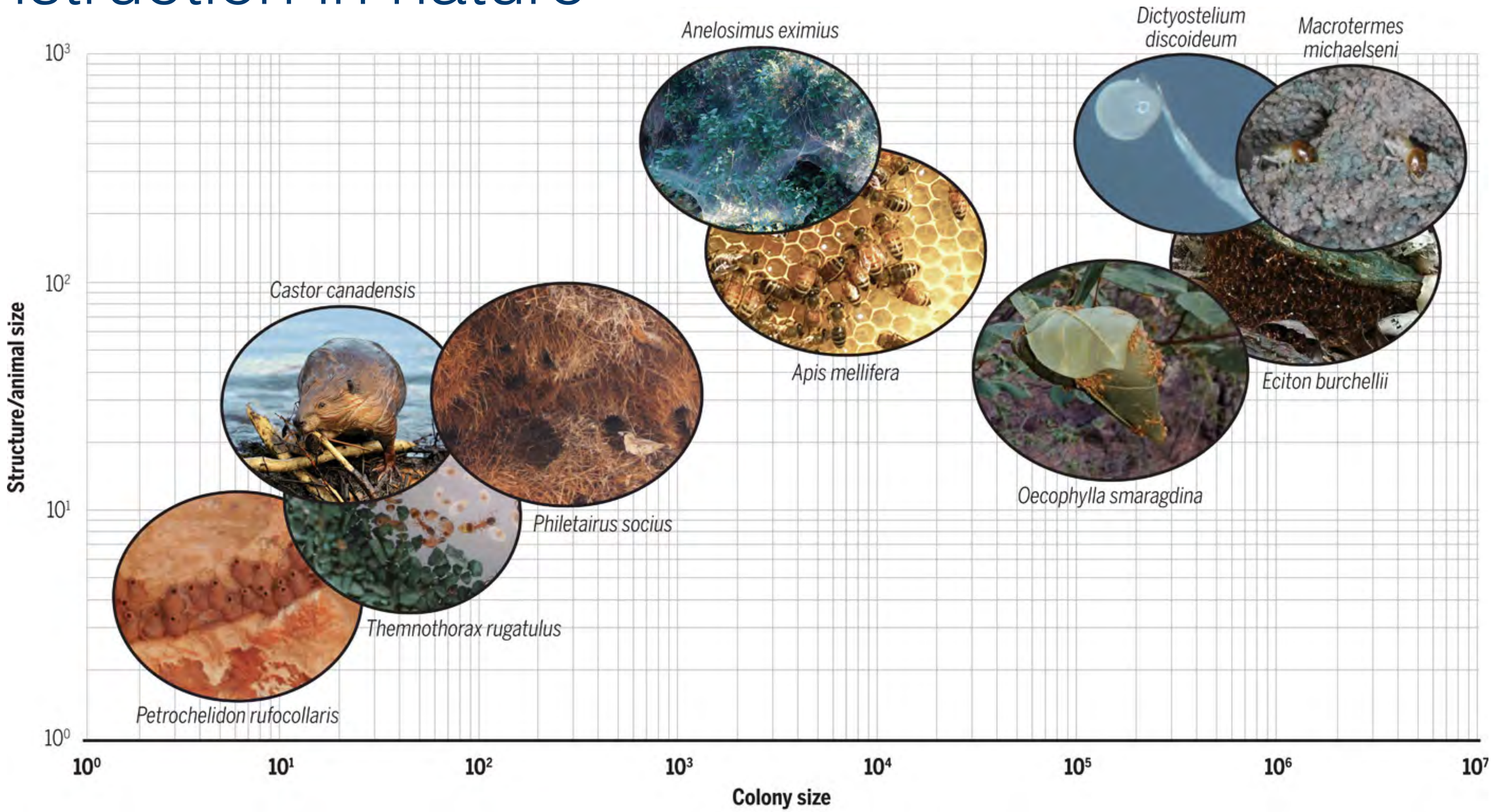
Aerial-AM

AERIAL ADDITIVE MANUFACTURING

3D Printing with Autonomous Aerial Robots

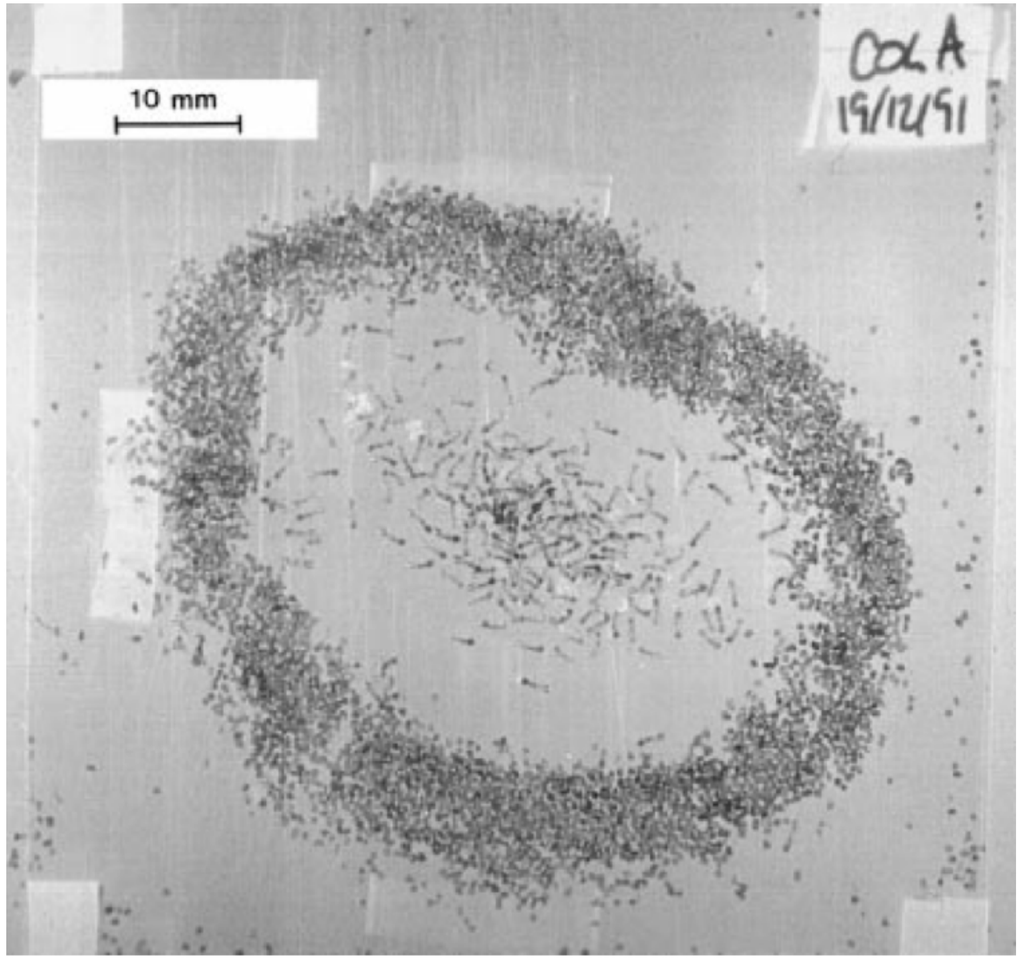
Imperial College London | University College London | University of Bath

Construction in nature



K. H. Petersen, N. Napp, R. Stuart-Smith, D. Rus, M. Kovac, *Science Robotics* (2019)

Bulldozer ants - use of templates



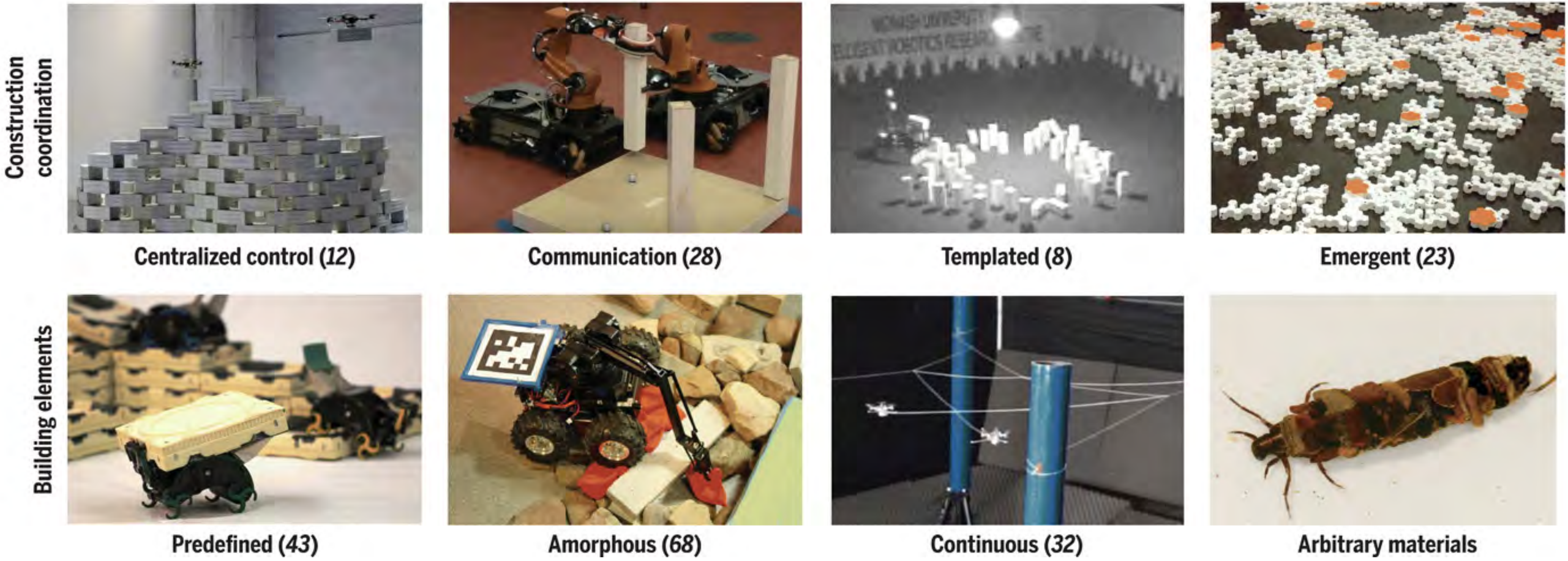
Franks, N. R., & Deneubourg, J. (1997). *Animal Behaviour*

Building process (external workers / internal workers)

1. External workers collect material and return to nest
2. Enter nest and drop material close to cluster of nest mates (carrying time is constant at 21sec after entry)
3. Drop material after direct contact with a cluster of internal workers or stones previously deposited. Release stone only after feeling resistance of stationary stones
4. External workers rarely pick up stones on the inside
5. Internal workers often pick up stones and bulldoze outwards
6. No evidence of pheromone or cement pheromone use
7. Cluster of adult workers around brood cluster (radial symmetry) serves as mechanical template for wall geometry
8. Template is local information and does not provide global knowledge of structure. How is nest entrance built?

K. H. Petersen, N. Napp, R. Stuart-Smith, D. Rus, M. Kovac,
Science Robotics (2019)

Bio-inspired construction principles



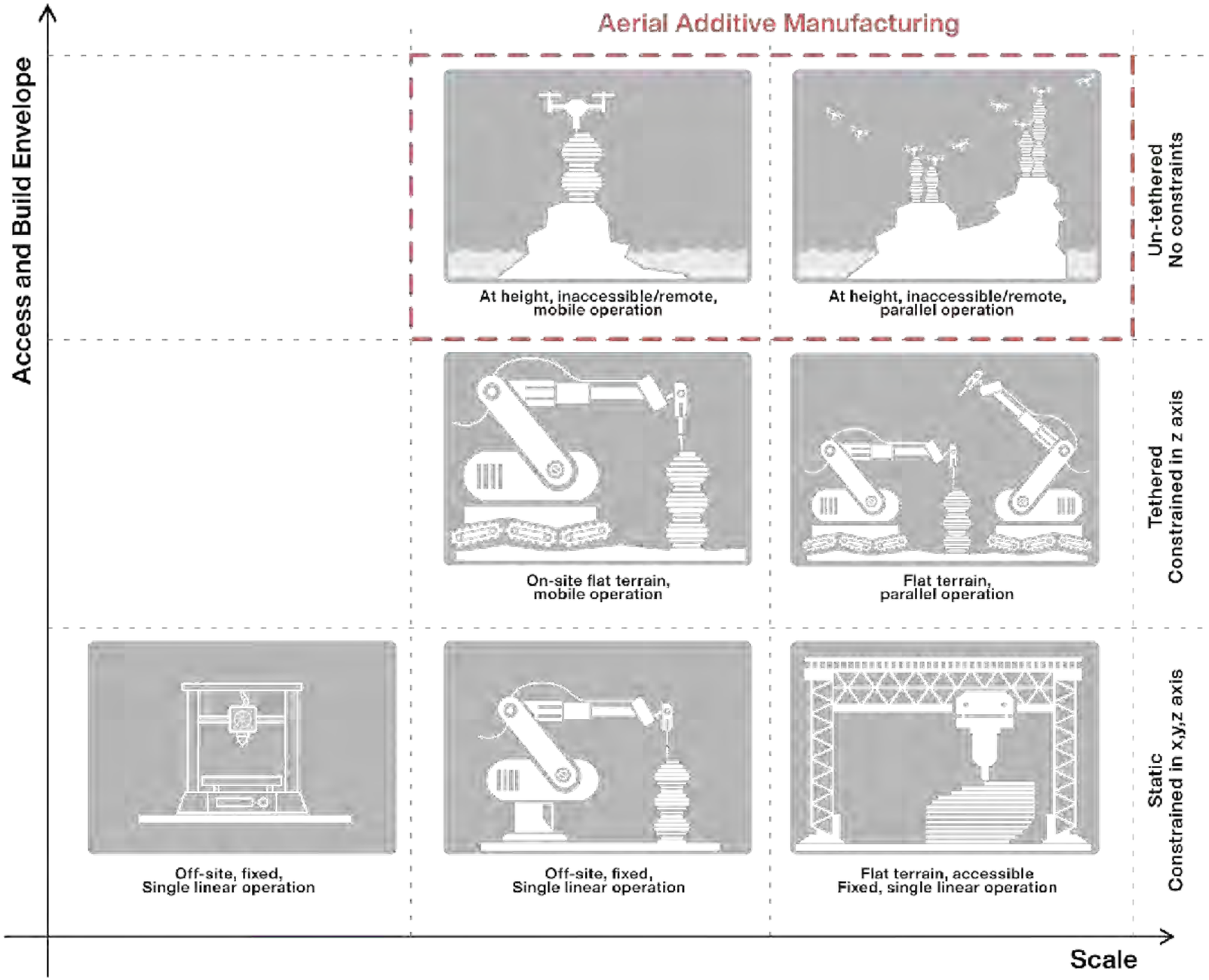
K. H. Petersen, N. Napp, R. Stuart-Smith, D. Rus, M. Kovac,
Science Robotics (2019)

Aerial-AM

AERIAL ADDITIVE MANUFACTURING

3D Printing with Autonomous Aerial Robots

Imperial College London | University College London | University of Bath


Aerial Additive Manufacturing
Access and Build Envelope
Scale
Un-tethered
No constraints
Tethered
Constrained in z axis
Static
Constrained in x,y,z axis
At height, inaccessible/remote, mobile operation
At height, inaccessible/remote, parallel operation
On-site flat terrain, mobile operation
Flat terrain, parallel operation
Off-site, fixed, Single linear operation
Off-site, fixed, Single linear operation
Flat terrain, accessible Fixed, single linear operation

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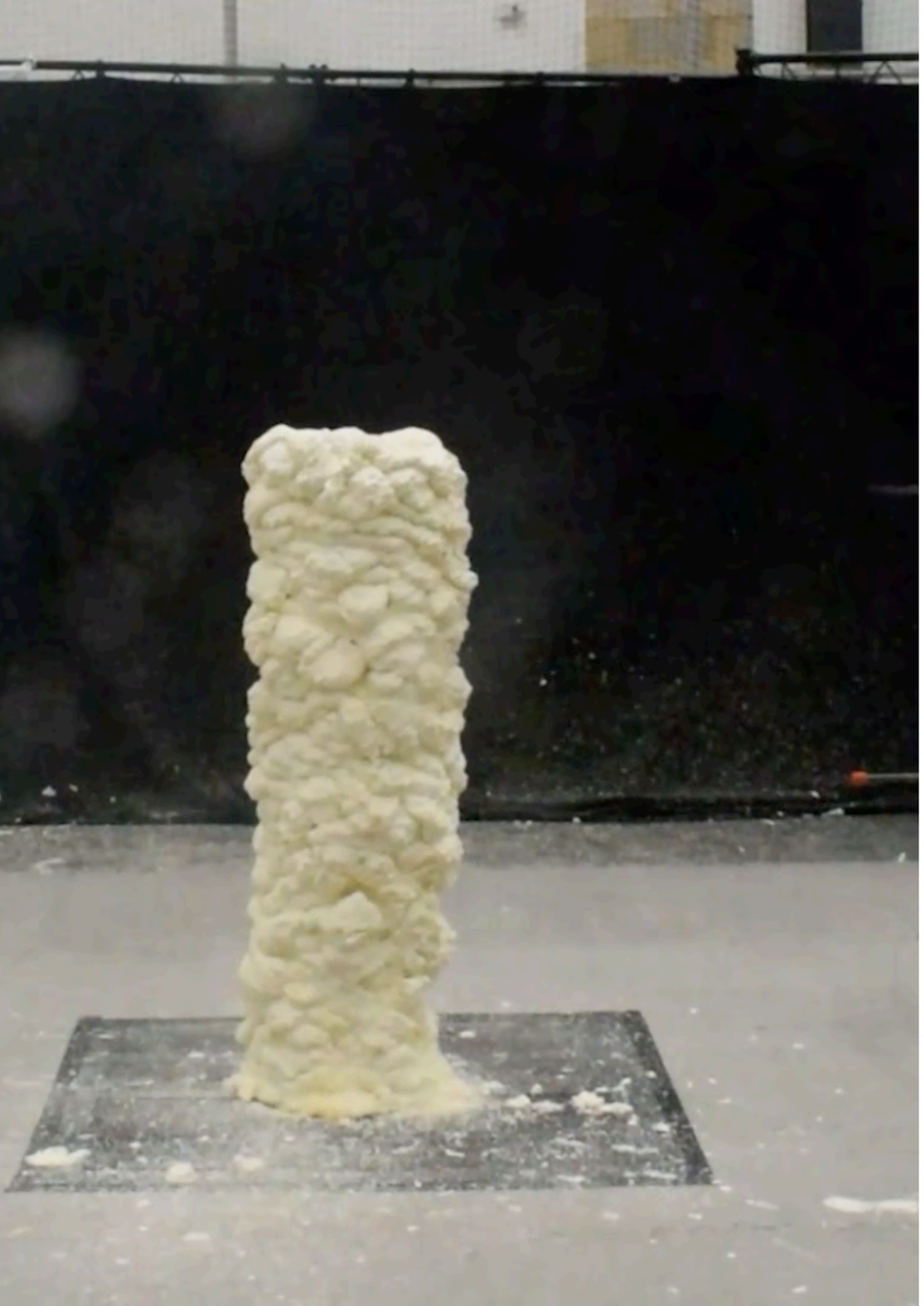
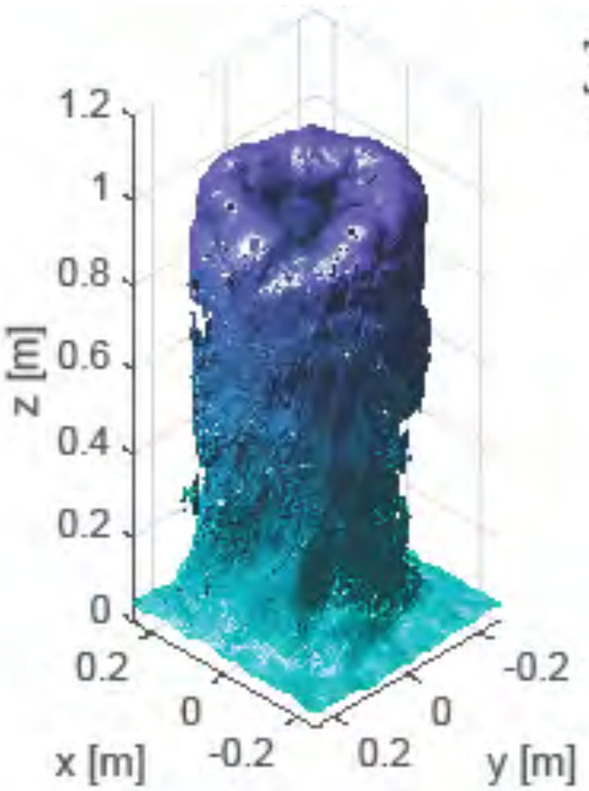



Scan-drone
Build-drone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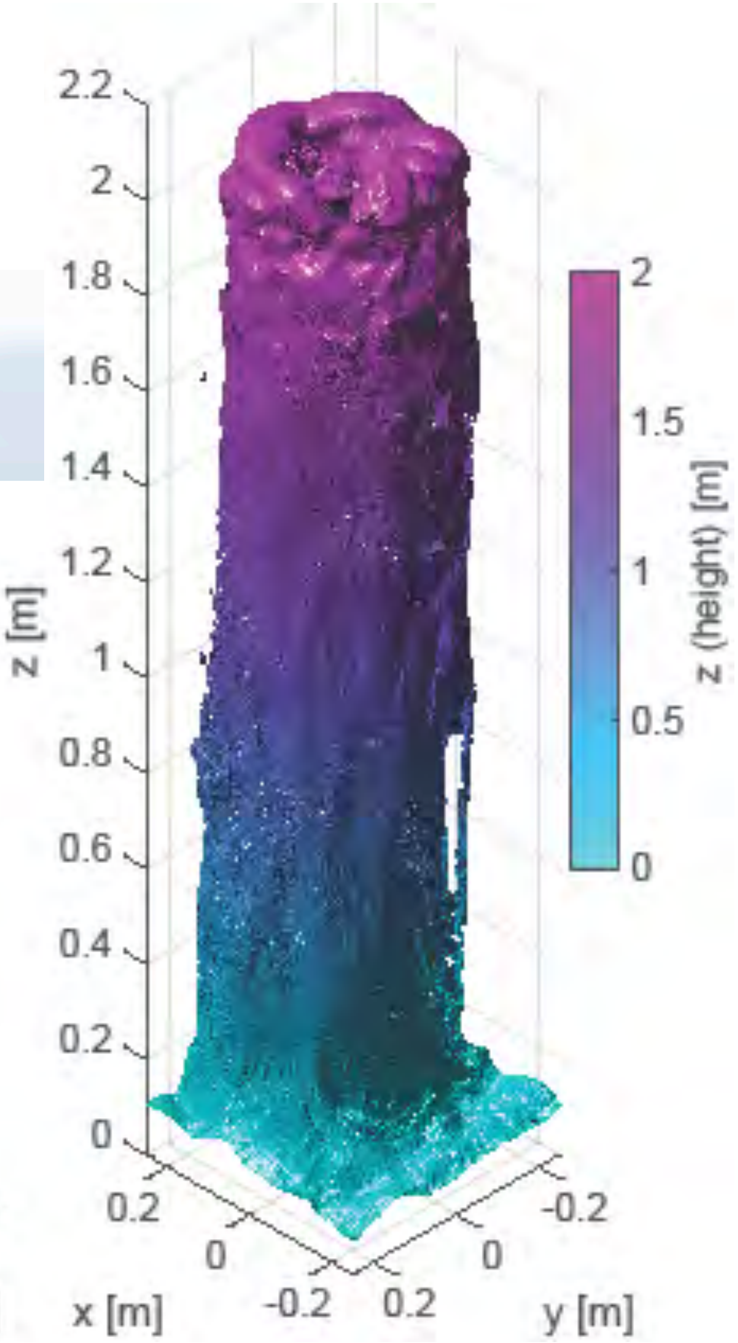
z [m]
x [m]
y [m]
z (height) [m]

Multi-Agent Aerial-AM: Virtual Printing with Multiple Robots

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Aerial Additive Manufacturing

Zhang, K., Chermprayong, P., Xiao, F., Tzoumanikas, D., Dams, B., Kay, S., Kocer, B.B, Burns, A., Orr, L., Choi, C., Darekar, D.D., Li, W., Hirschmann, S., Soana, V., Ngah, S.A., Sareh, S., Margheri, L., Pawar, V., Ball, R.J., Williams, C., Shepherd, P., Leutenegger, S., Stuart-Smith, R., Kovac, M., (2022)
Aerial Additive Manufacturing: 3D Printing with Multiple Autonomous Aerial Robots
Nature 2022 (cover)

Aerial Additive Manufacturing

Zhang, K., Chermprayong, P., Xiao, F., Tzoumanikas, D., Dams, B., Kay, S., Kocer, B.B, Burns, A., Orr, L., Choi, C., Darekar, D.D., Li, W., Hirschmann, S., Soana, V., Ngah, S.A., Sareh, S., Margheri, L., Pawar, V., Ball, R.J., Williams, C., Shepherd, P., Leutenegger, S., Stuart-Smith, R., Kovac, M., (2022)
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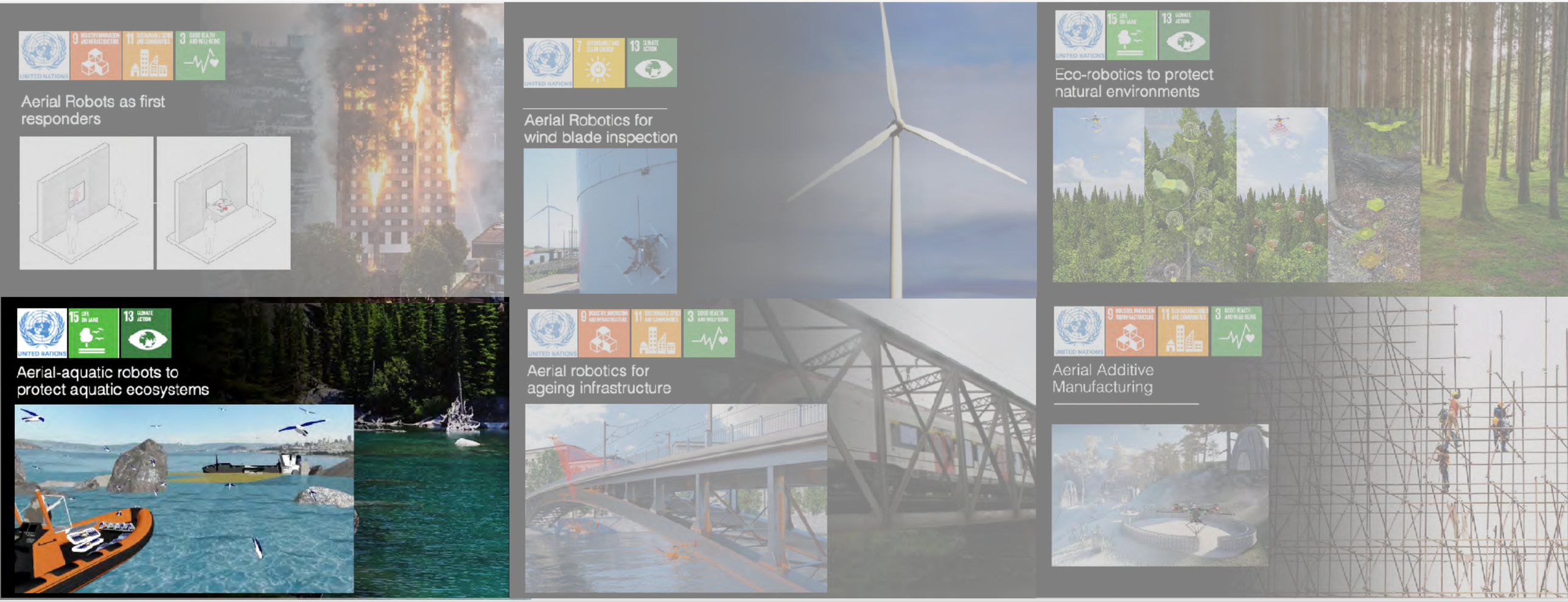
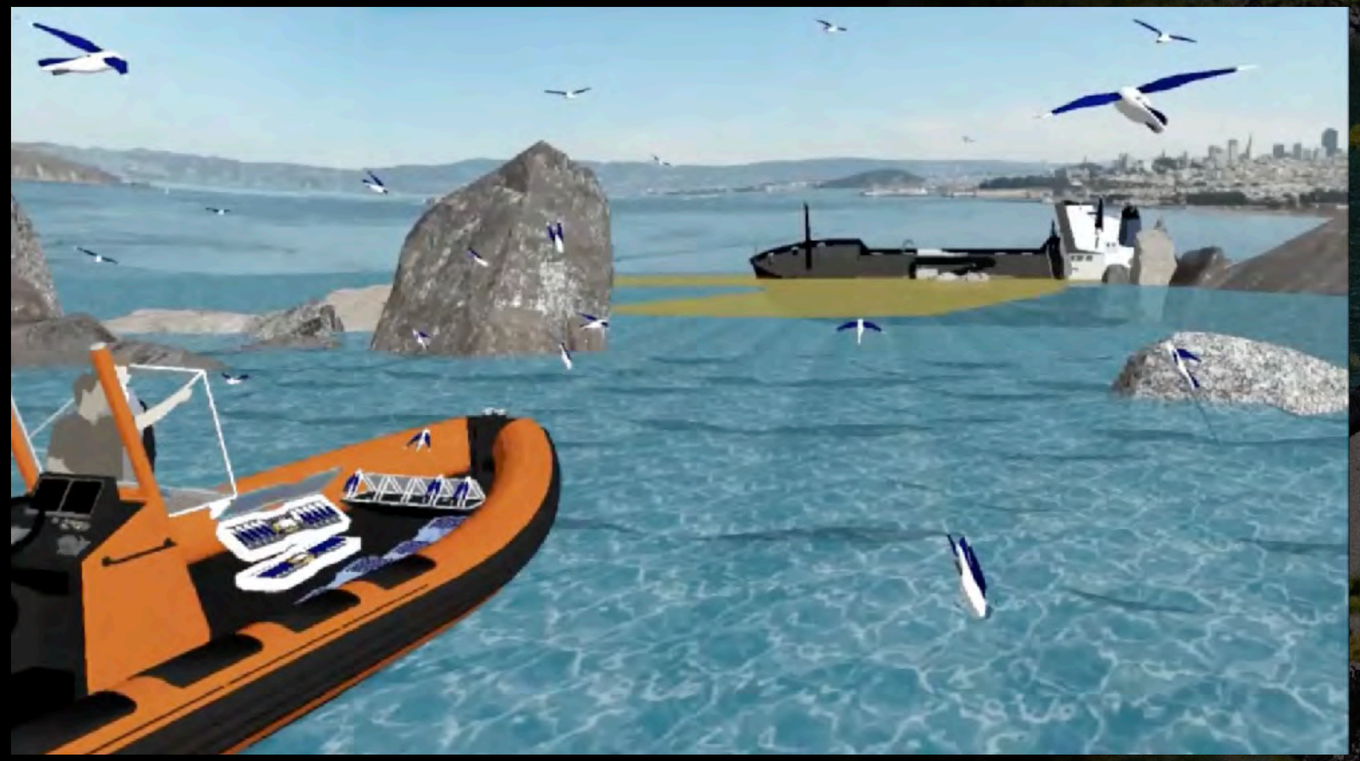
Sustainability Robotics



Aerial-aquatic robots to protect aquatic ecosystems



Use cases:
Water health monitoring (Arctic, coral reefs, lakes etc.)
Catchment area modelling (flooding, sewage spills etc)
Environmental DNA and biodiversity monitoring

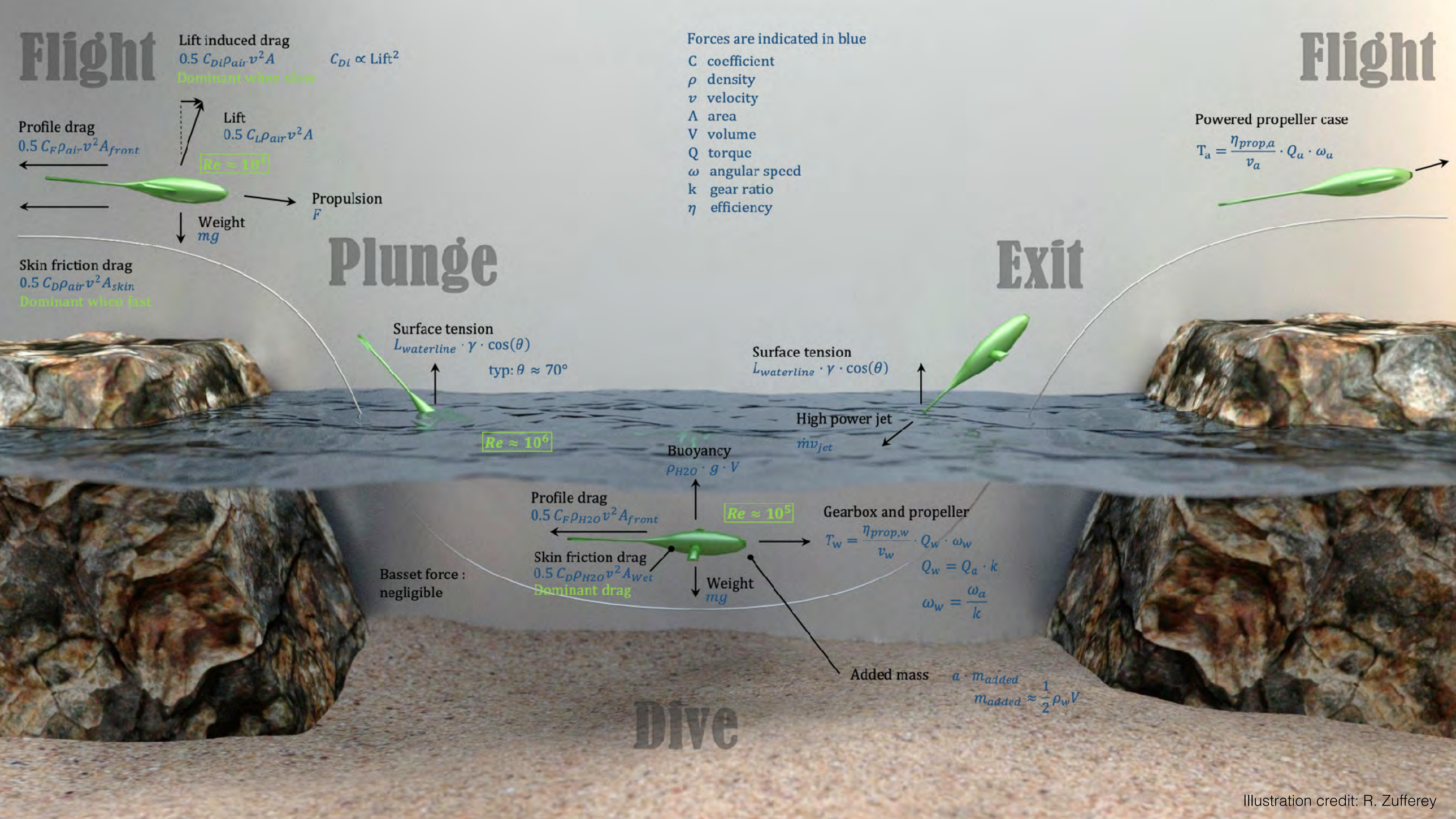
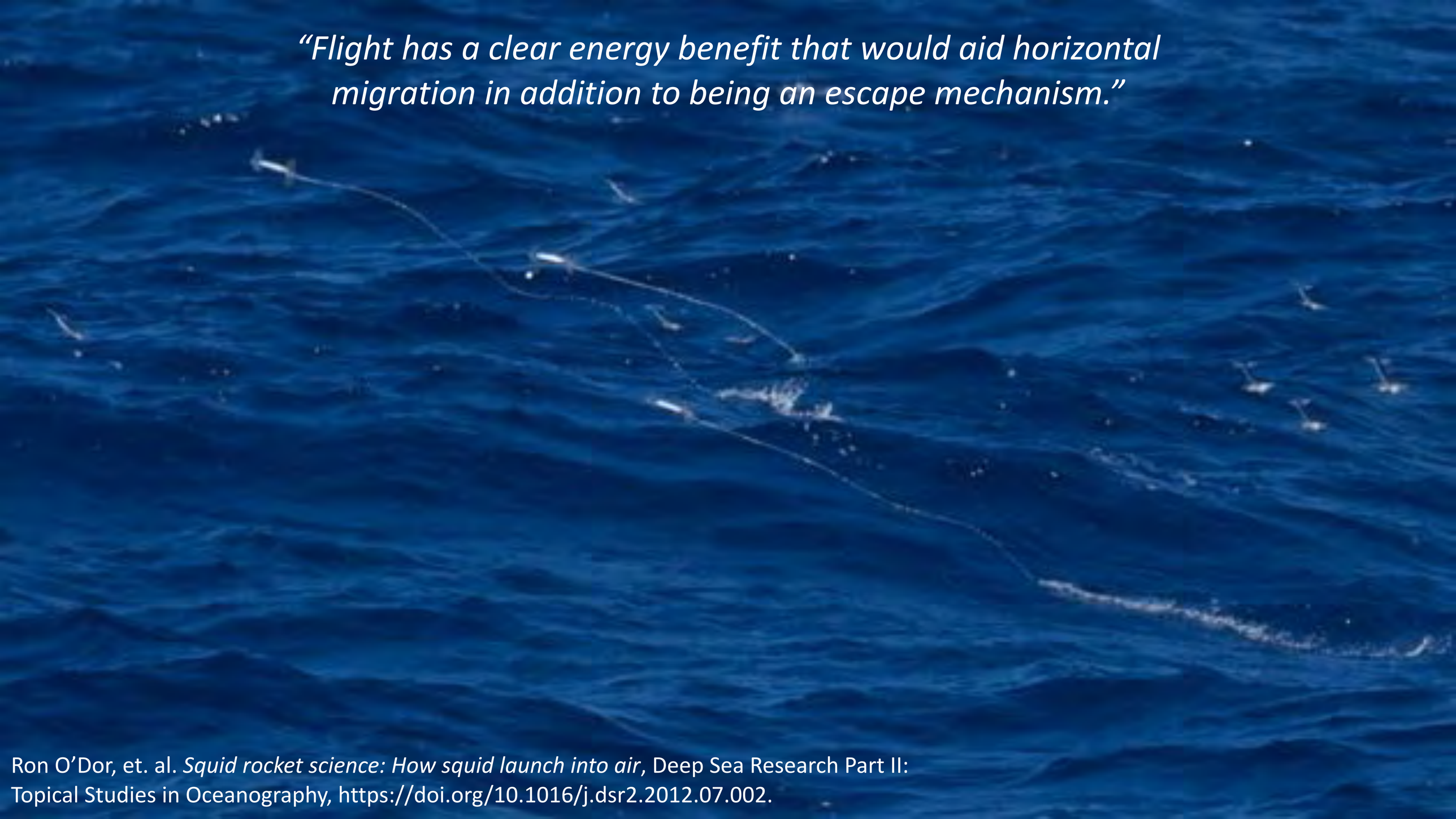


Illustration credit: R. Zufferey

Aerial-aquatic animals

Siddall, Kovac (2014) *Bioinspiration & Biomimetics*

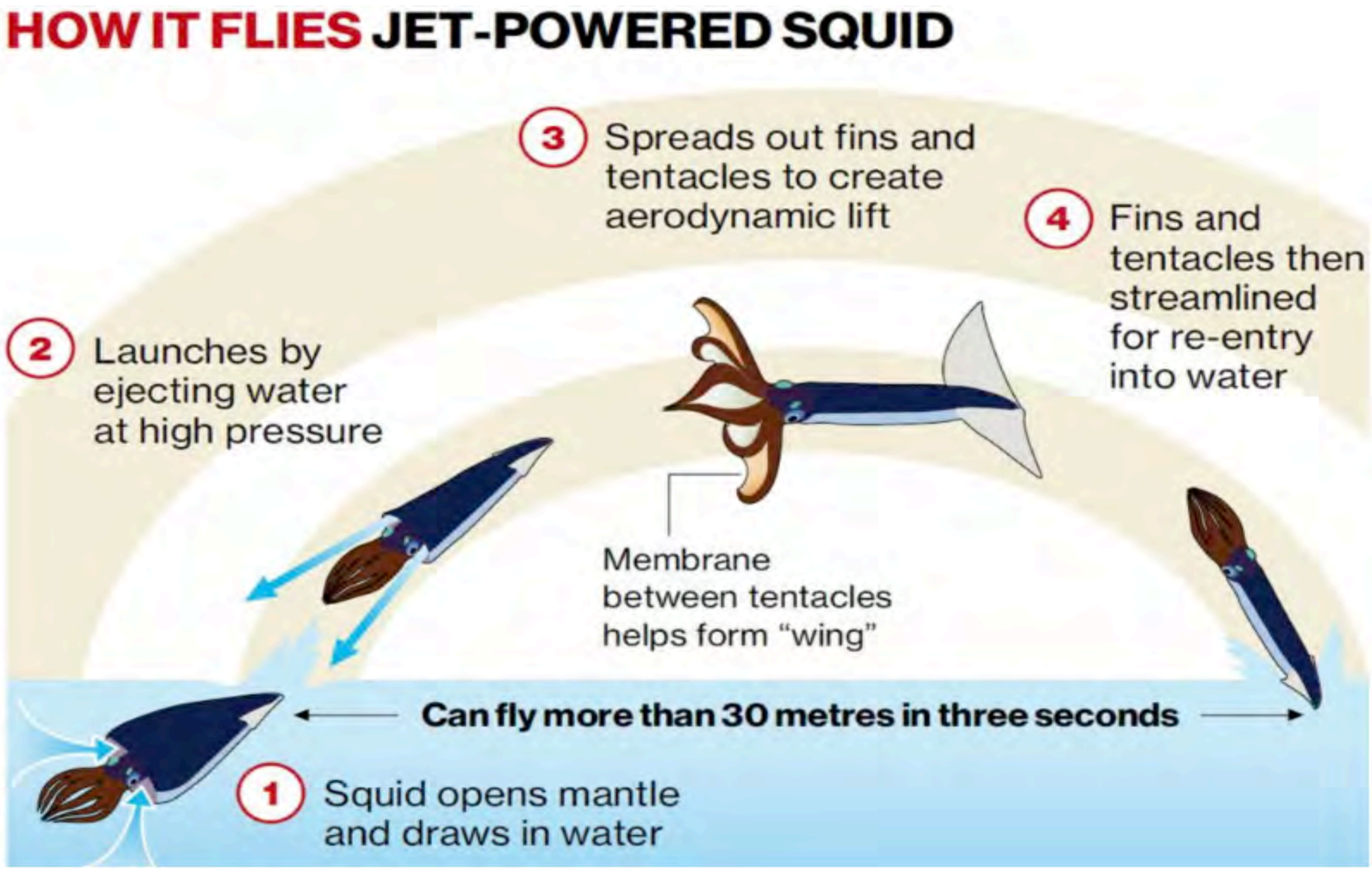
Video: Rainer Bergomaz from Blue Paw Artists https://vimeo.com/107714608

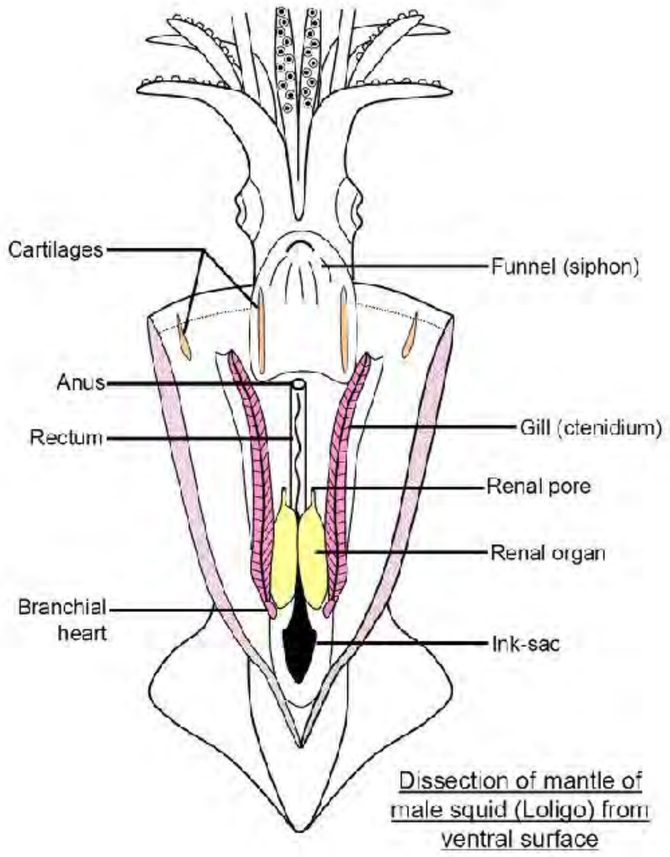


“Flight has a clear energy benefit that would aid horizontal migration in addition to being an escape mechanism.”

Ron O’Dor, et. al. *Squid rocket science: How squid launch into air*, Deep Sea Research Part II: Topical Studies in Oceanography, https://doi.org/10.1016/j.dsr2.2012.07.002.

Flying Squid





Source: *https://ourmarinespecies.com/c-squid/flying-squids/*

Photo credit: "*cephalopods*" on crondon.com

Squid classification

Eukaryota
Domain

Animalia
Kingdom

Mollusca
Phylum

Cephalopoda
Class

Myopsida
Oegopsida
Sepiida
Spirulida
} Order

Species:

Loligo Pealeii

Source: SEFSC Pascagoula Laboratory; Collection of Brandi Noble, NOAA/NMFS/ SEFSC

Loligo Opalescence

Source: Common market squid; Monterey Bay Aquarium, Monterey Bay Aquarium Foundation

Illex Illecebrosus

Source: Getty images

Architeuthis Dux

Source: Don Hurlbert/ Smithsonian Institution

Mesonychoteuthis Hamiltoni

Source: Lee Krystek, unmuseum.org

Squid classification

Species that have been found and photographed / filmed flying

Species:

Loligo Pealeii

Source: SEFSC Pascagoula Laboratory; Collection of Brandi Noble, NOAA/NMFS/ SEFSC

Sthenoteuthis pteropus

(Orangeback squid)

Source: Common market squid; Monterey Bay Aquarium, Monterey Bay Aquarium Foundation

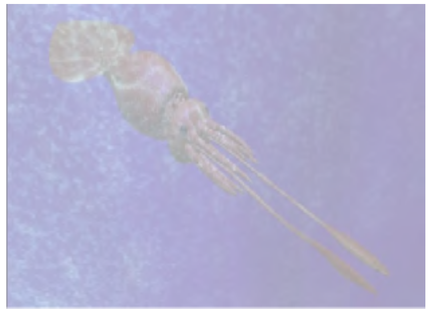
Dodisicus Gigas

(Humbolt squid)

Source: NOAA/MBARI 2006

Architeuthis Dux

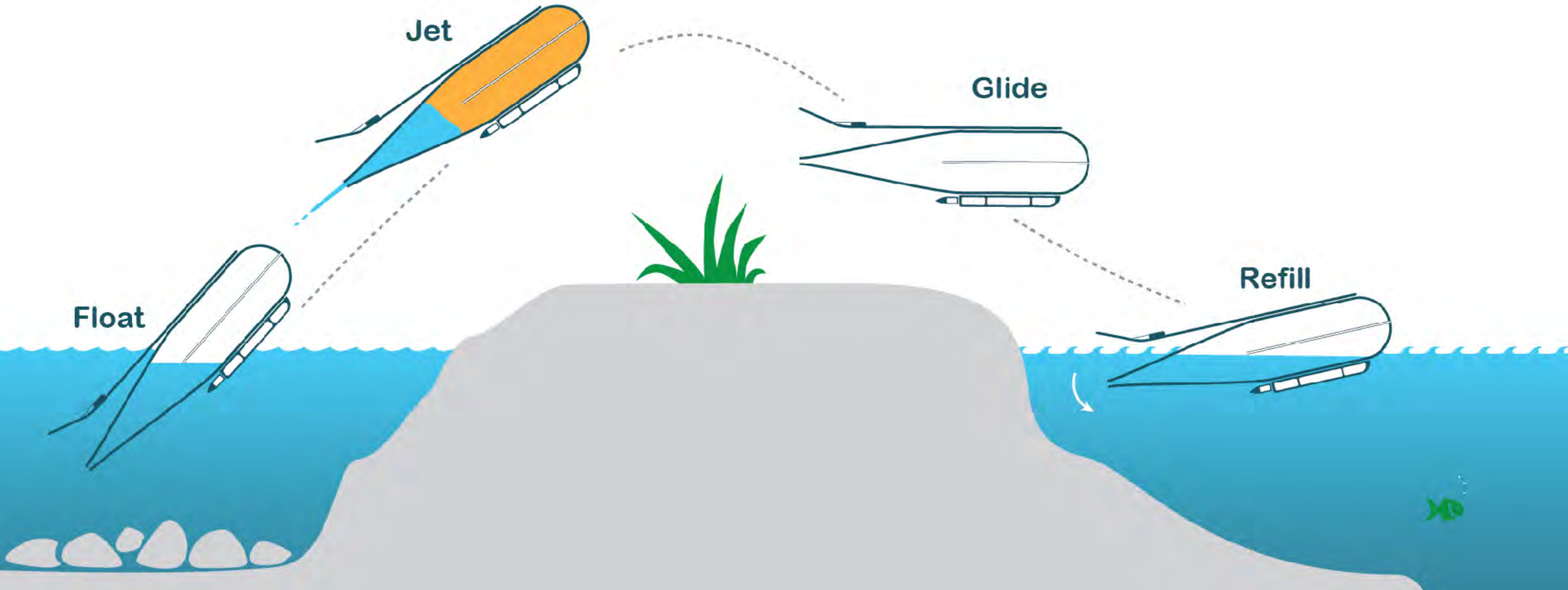
Source: Don Hurlbert/ Smithsonian Institution



Mesonychoteuthis Hamiltoni

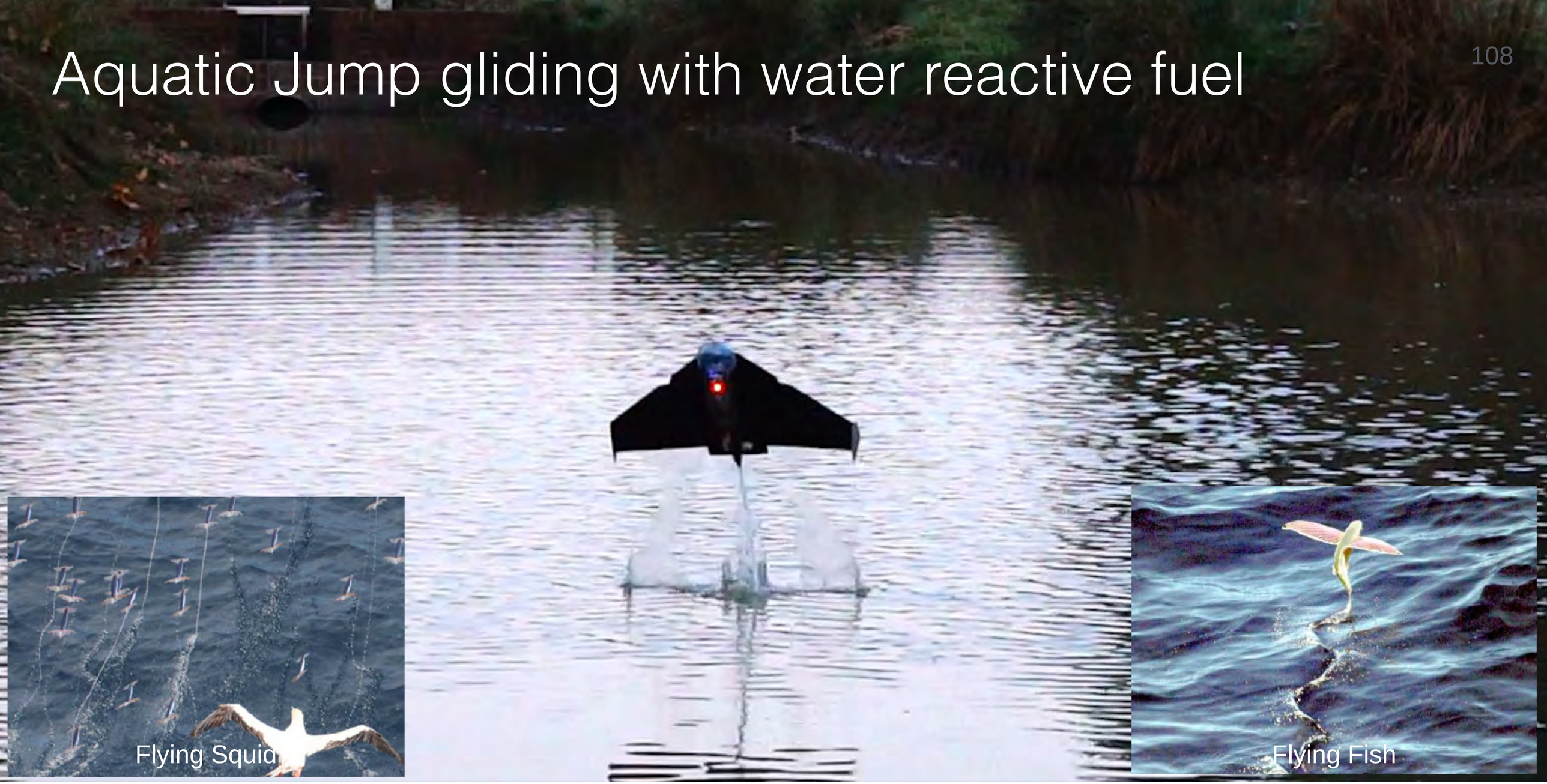
Source: Lee Krystek, unmuseum.org

Mission Cycle



Zufferey, Ortega Ancel, A., Farinha, A., Siddall, R., Armanini, S.F., Nasr M., Brahmal, R. V., Kennedy, G., Kovac, M., *Science Robotics* (2019)

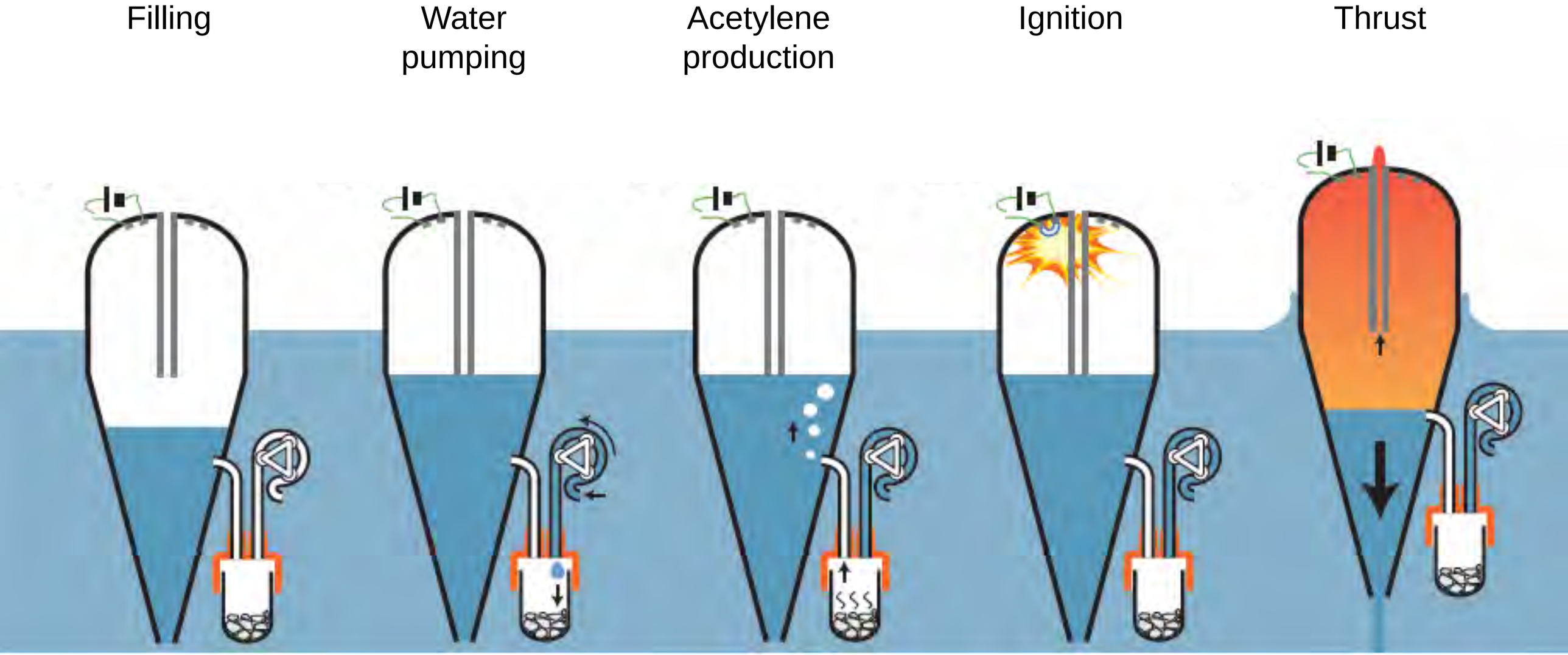
Aquatic Jump gliding with water reactive fuel



Zufferey, Ortega Ancel, A., Farinha, A., Siddall, R., Armanini, S.F., Nasr M., Brahmal, R. V., Kennedy, G., Kovac, M., ***Science Robotics*** (2019)

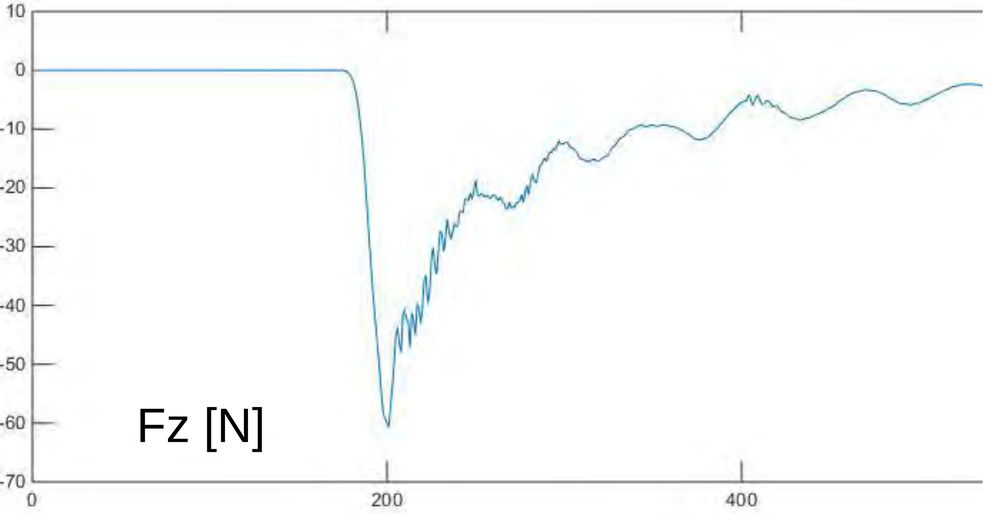
Image Credits (from left): ‘Oceanic Squid do Fly’, Muramatsu et al., Oceans 2013; US NOAA

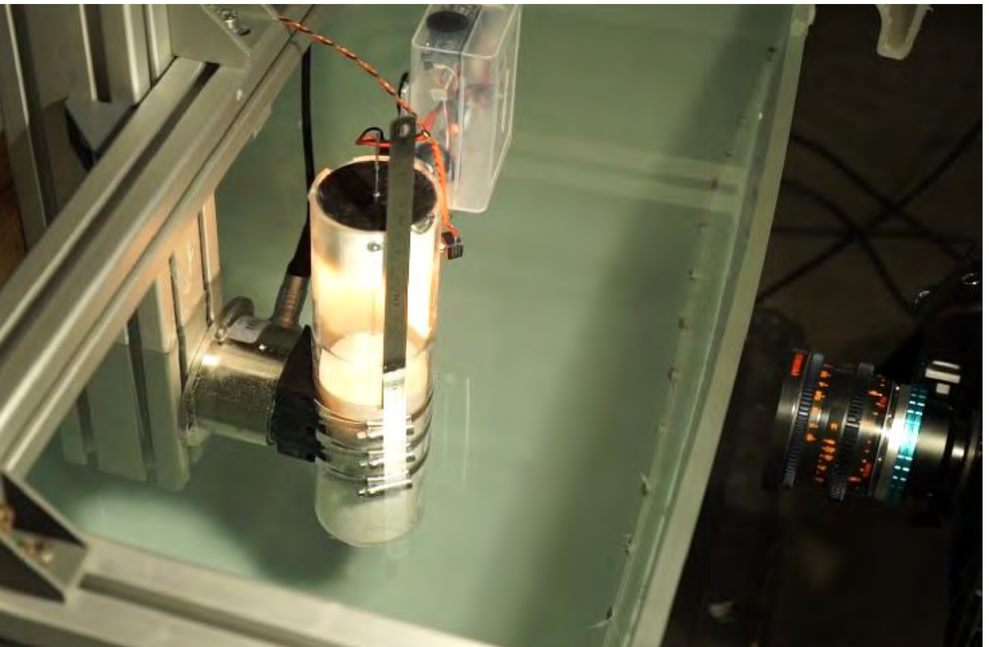
Propulsion System

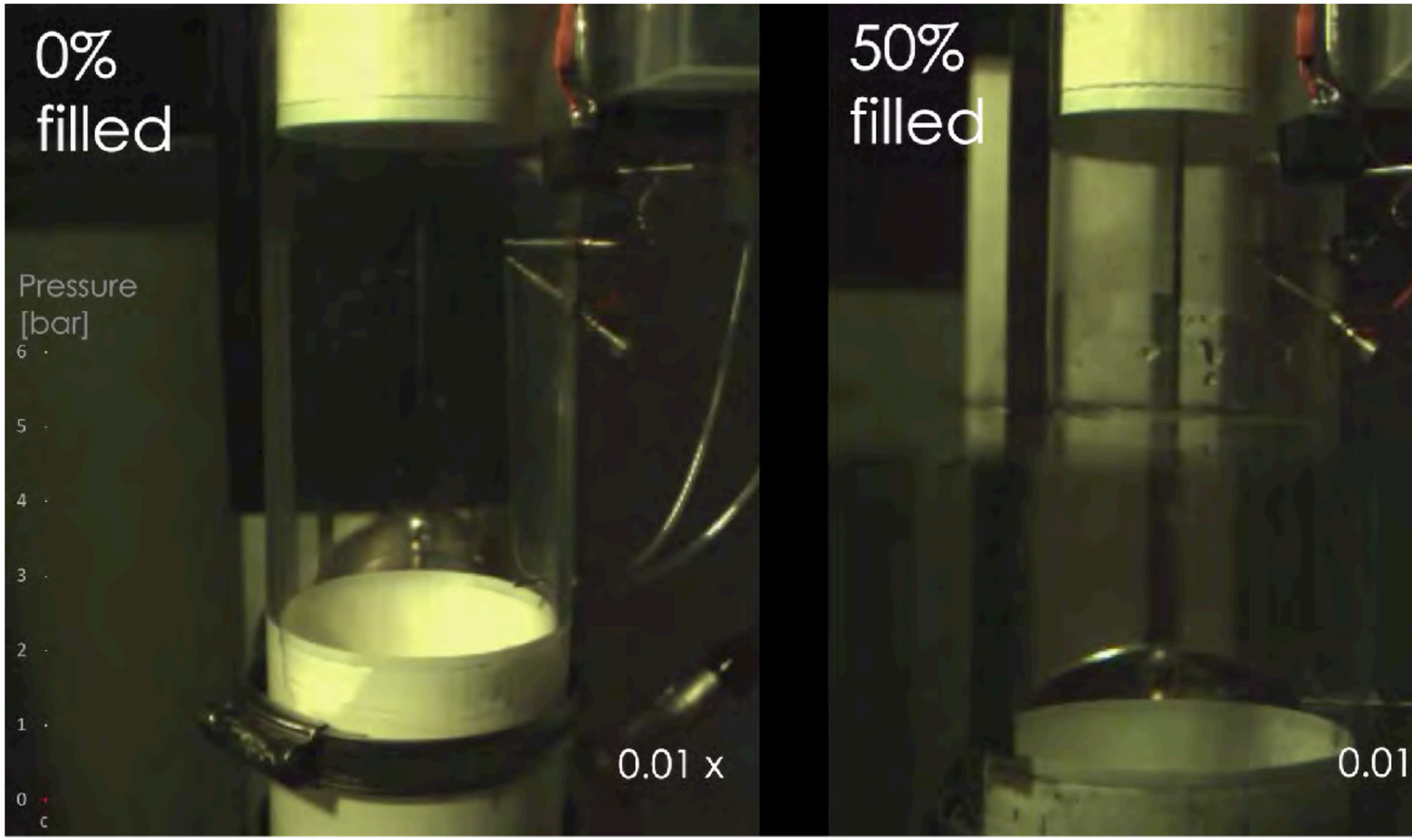


Zufferey, Ortega Ancel, A., Farinha, A., Siddall, R., Armanini, S.F., Nasr M., Brahmal, R. V., Kennedy, G., Kovac, M., ***Science Robotics*** (2019)

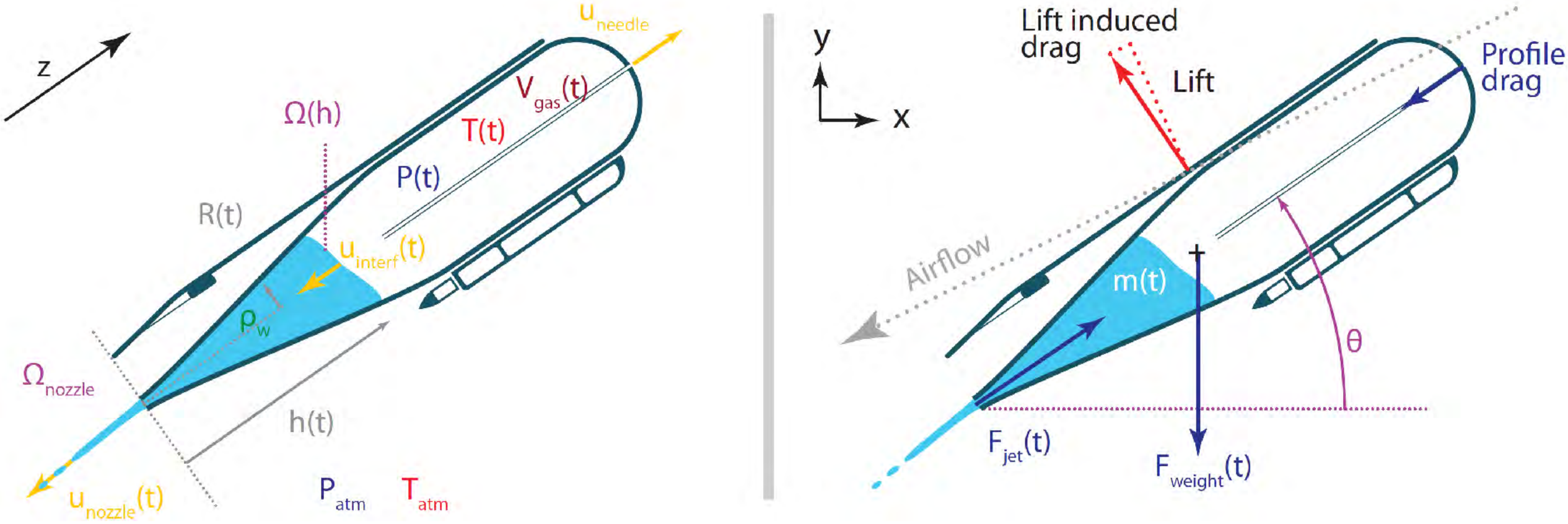
Static Tests





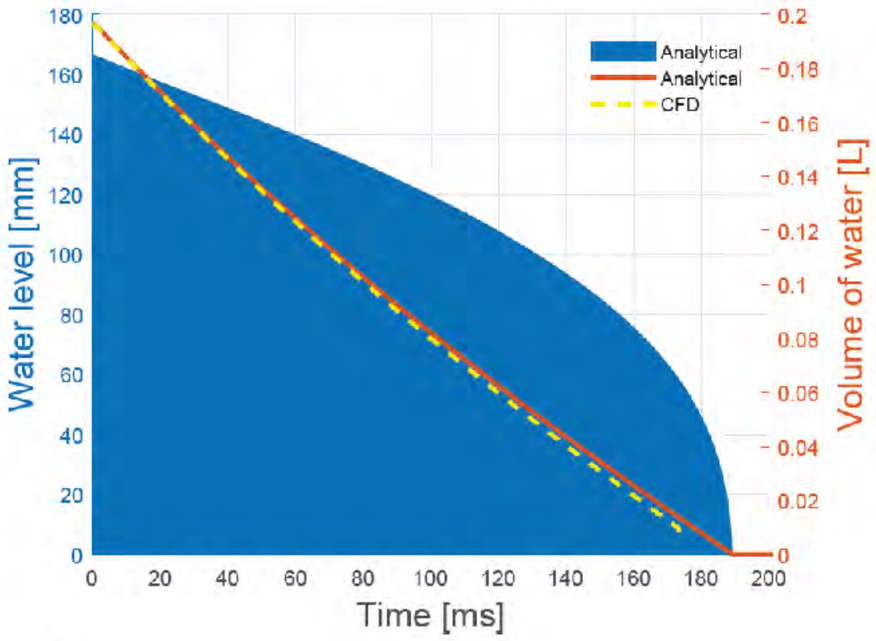


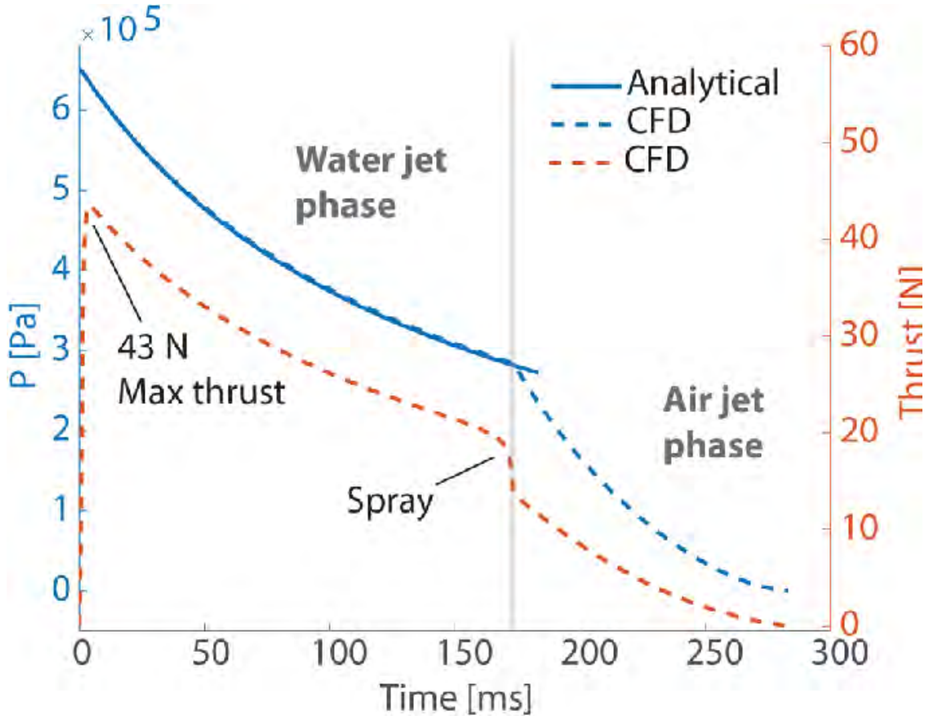
Physics-based development

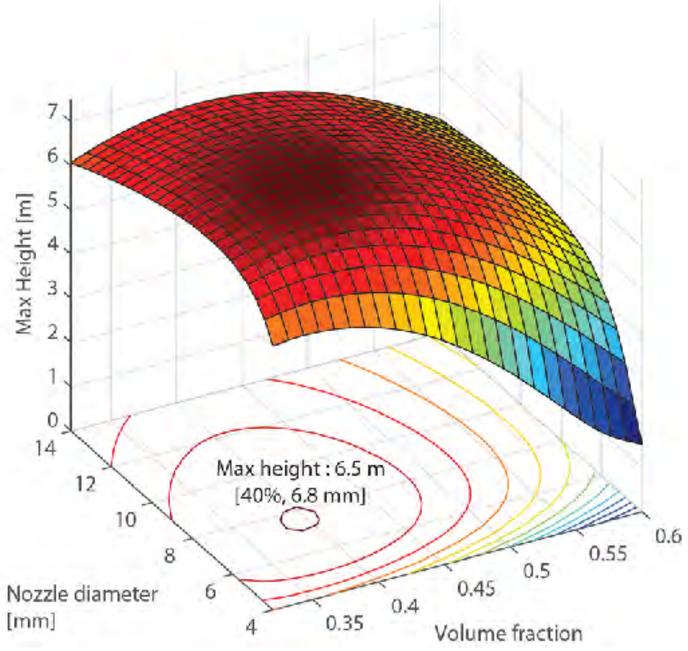


Zufferey, Ortega Ancel, A., Farinha, A., Siddall, R., Armanini, S.F., Nasr M., Brahmal, R. V., Kennedy, G., Kovac, M., *Science Robotics* (2019)

CFD and model analysis

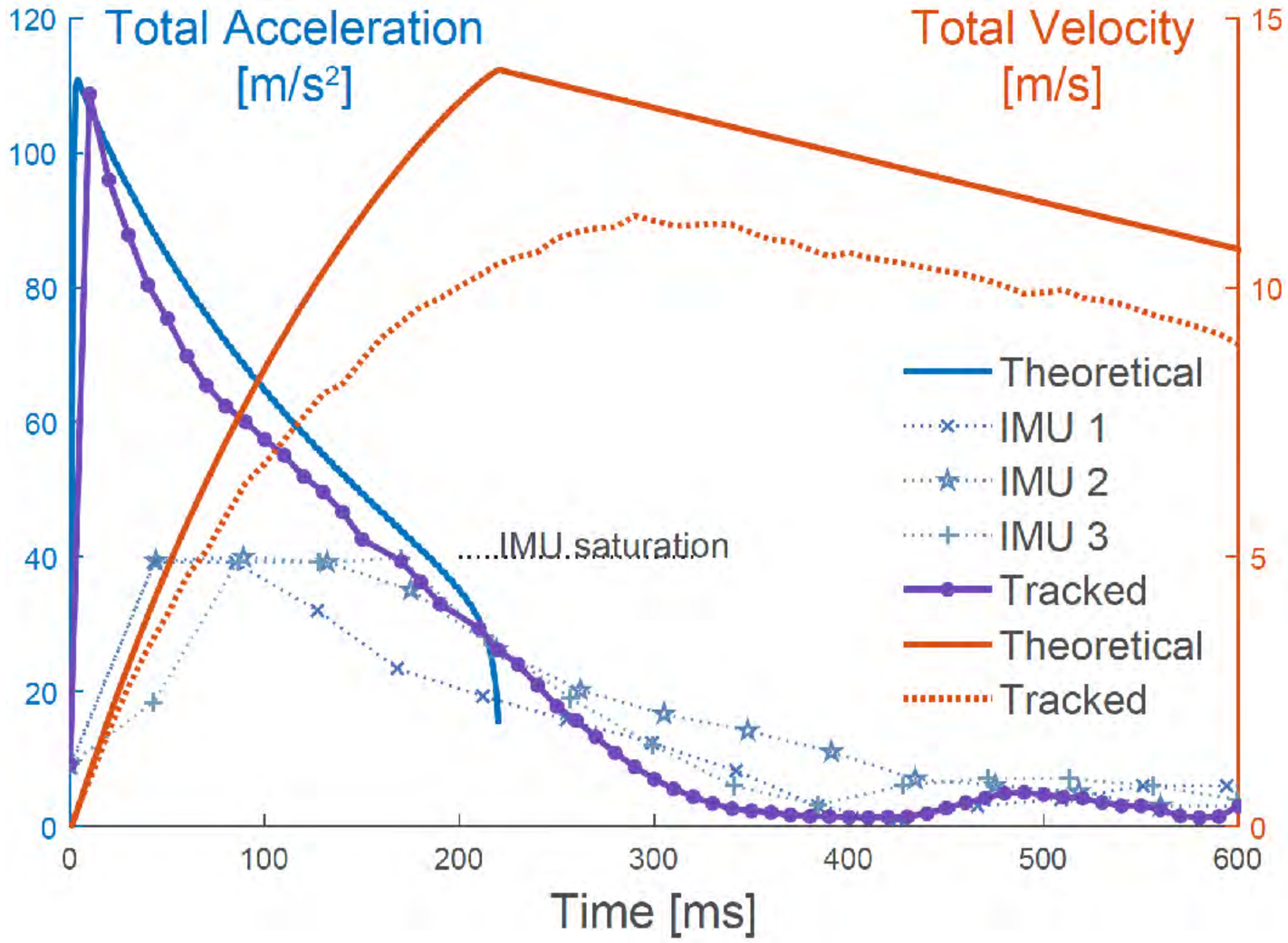






Zufferey, Ortega Ancel, A., Farinha, A., Siddall, R., Armanini, S.F., Nasr M., Brahmal, R. V., Kennedy, G., Kovac, M., *Science Robotics* (2019)

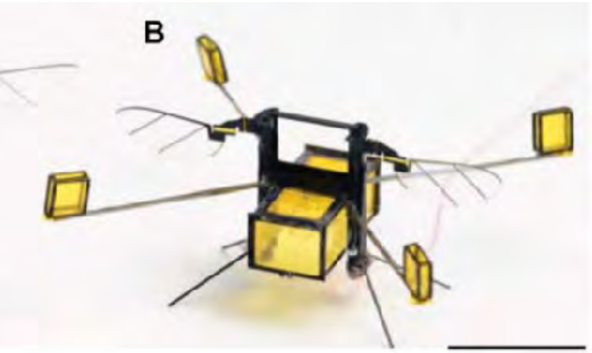
Experimental Comparison

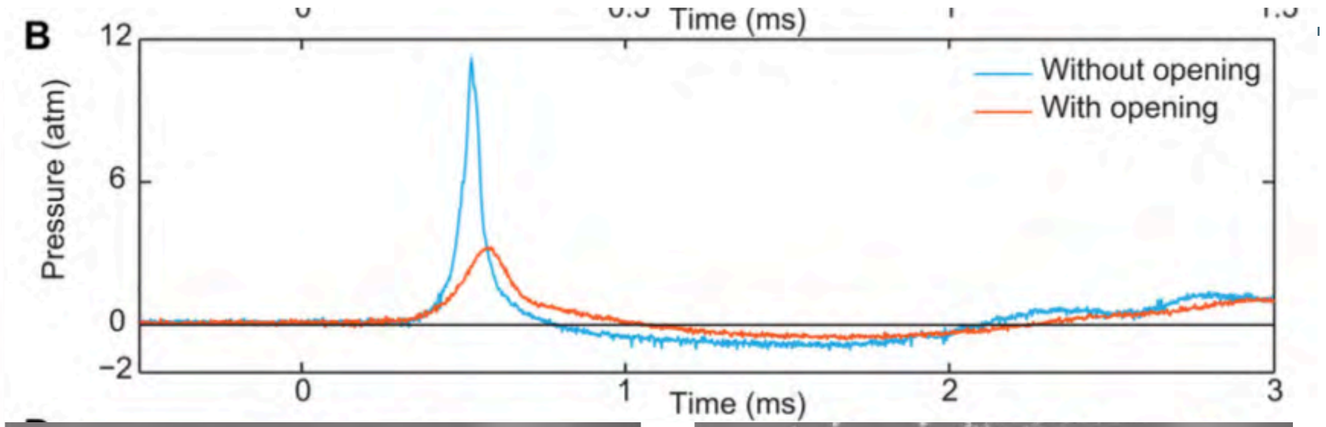


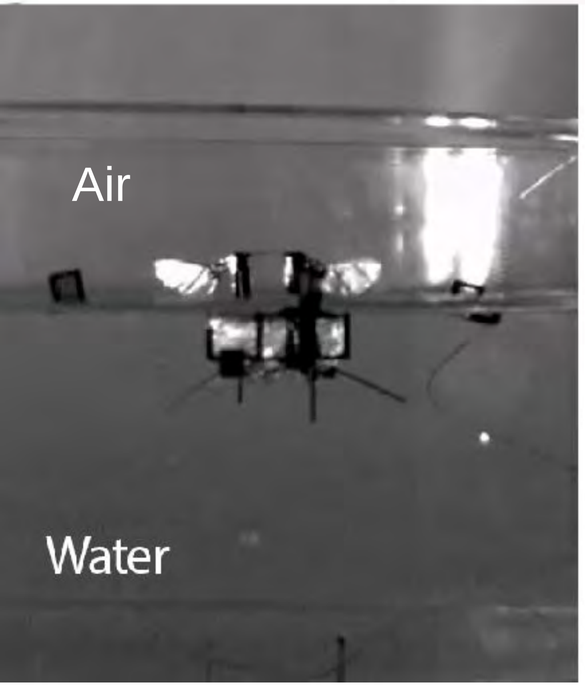
Zufferey, Ortega Ancel, A., Farinha, A., Siddall, R., Armanini, S.F., Nasr M., Brahmal, R. V., Kennedy, G., Kovac, M., *Science Robotics* (2019)

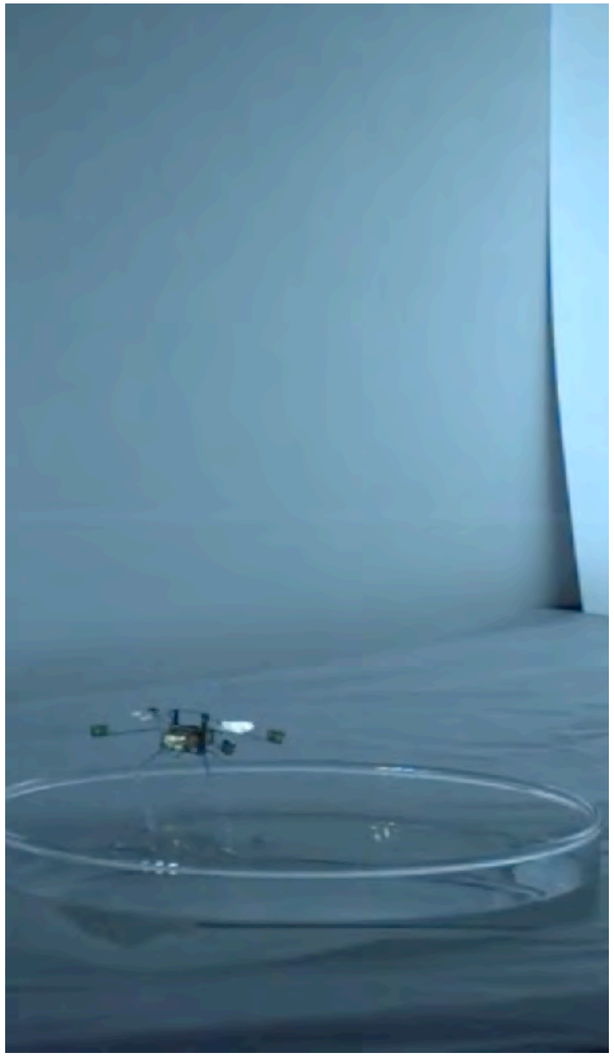

Launch
0.03 x

Aerial-aquatic RoboBee







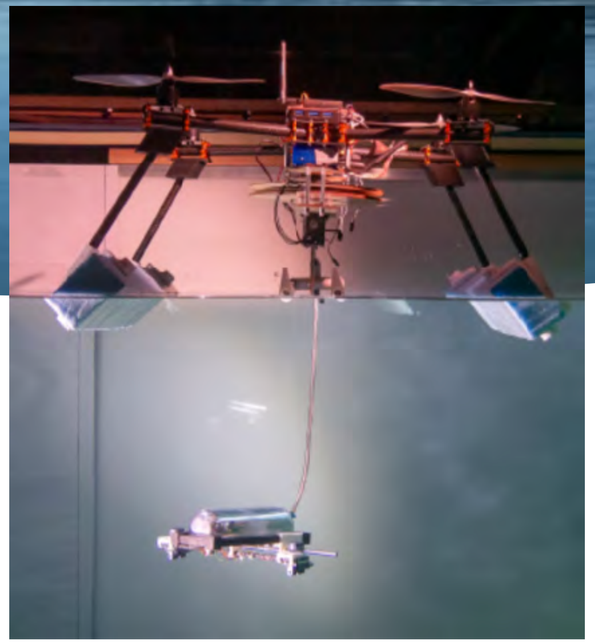


Chen, K., Zufferey, R., Kovac, M., Wood, R. et al.
Science Robotics (2017)

Li, L., Nguyen, P., Kovac, M., Wen, L. et al.
Science Robotics (2022)

Nature (Remora Fish) | Robot

Aerial - Aquatic platforms for biodiversity



MEDUSA:
a Multi-Environment
Dual-Robot

Development of integrated water quality sensing solutions for mobile in-situ sensing

Zufferey, R., Ortega, A., Raposo, C., Armanini, S., Farinha, A., Siddall, R., Barasaluce, I., Zhu, H., Kovac, M. (2019) *IEEE Robotics Automation Letters*

Farinha, A., di Tria, J., Reyes, M., Rosas, C., Pang, O., Zufferey, R., Pomati, F., Kovac, M., *Frontiers in Environmental Science* (2022)

Sailing : Energy efficient locomotion

- Terenius. Windsurfing in Mute Swans (Cygnus olor). *The Wilson Journal of Ornithology*, (2016)
- Hayashi, Morito, et al. "Sail or sink: novel behavioural adaptations on water in aerially dispersing species." *BMC evolutionary biology* (2015)

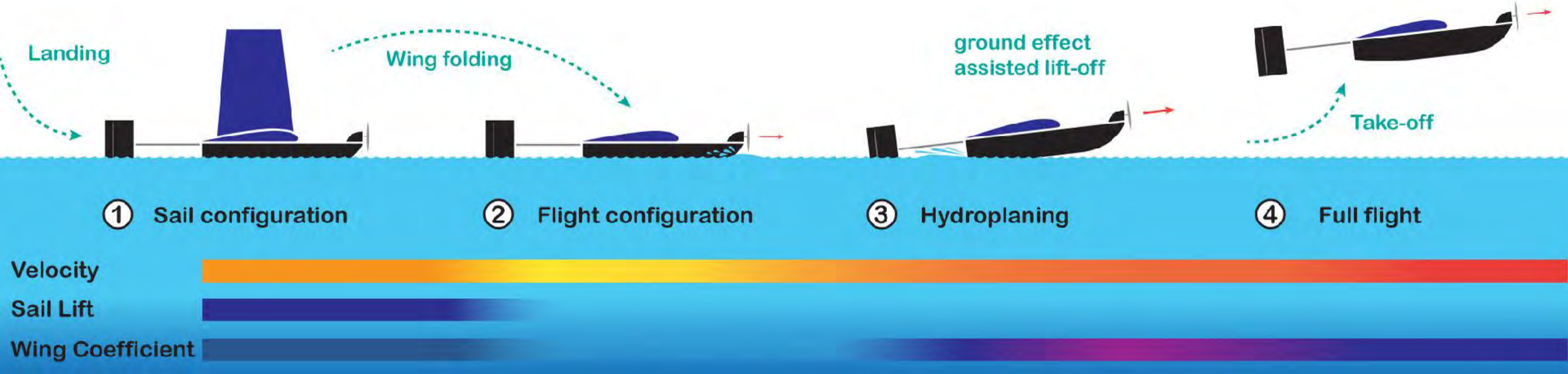
Sailing Micro Aerial Vehicles

Motivation:

Marine Research

Climate change Research

Innacessible area Exploration



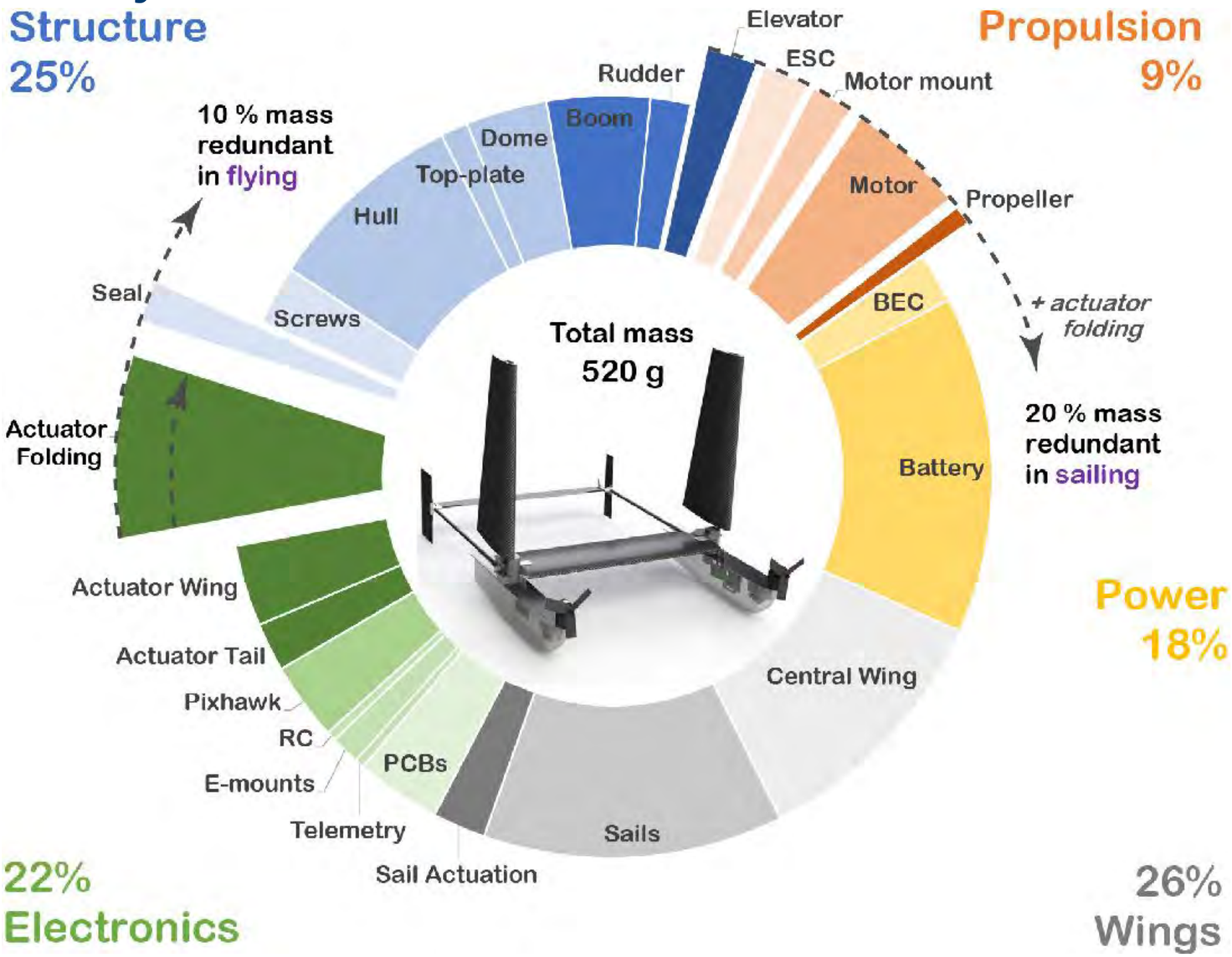
SailMAV: design and implementation of a novel multi-modal flying sailing robot

Raphael Zufferey, Alejandro Ortega, Célia Raposo, Sophie F. Armanini, Andre Farinha, Robert Siddall, Ion Berasaluce, Haijun Zhu and Mirko Kovac

Aerial Robotics Laboratory, Imperial College London

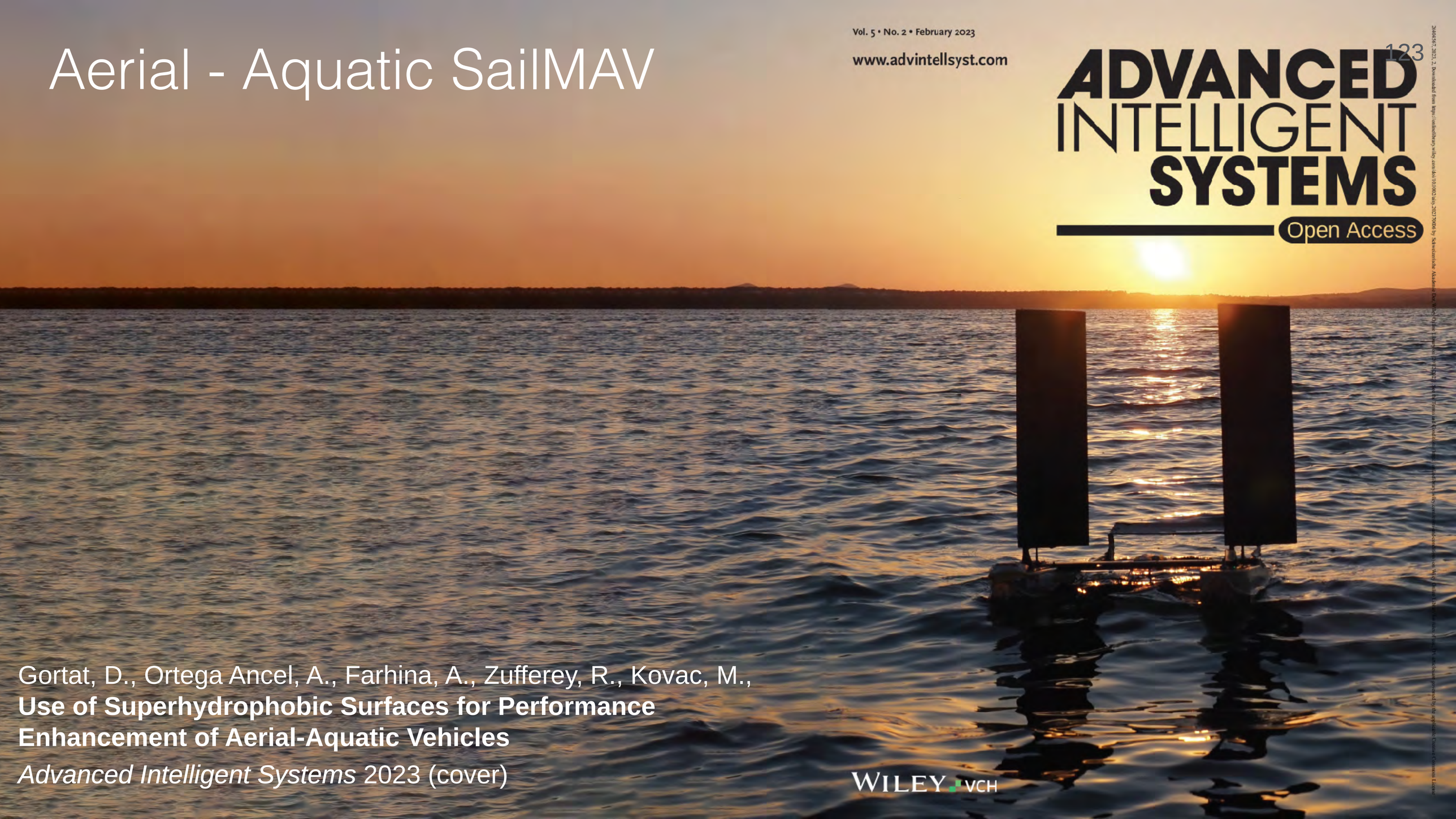
Submitted 24.02.2019 to RA-L

Multi-modality cost



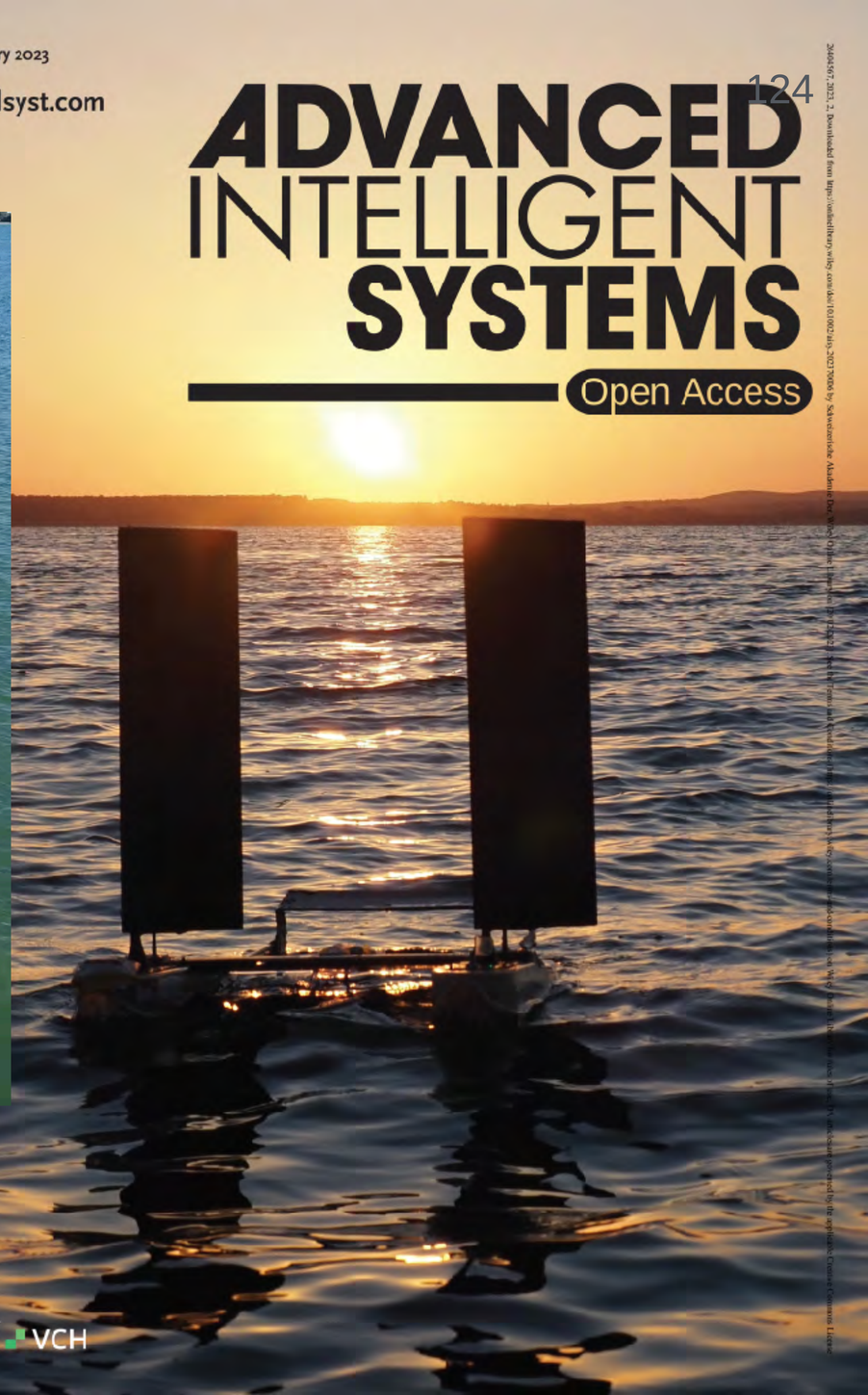
Zufferey, R., Ortega, A., Raposo, C., Armanini, S., Farinha, A., Siddall, R., Barasaluce, I., Zhu, H., Kovac, M. (2019) *IEEE Robotics Automation Letters*

Aerial - Aquatic SailMAV



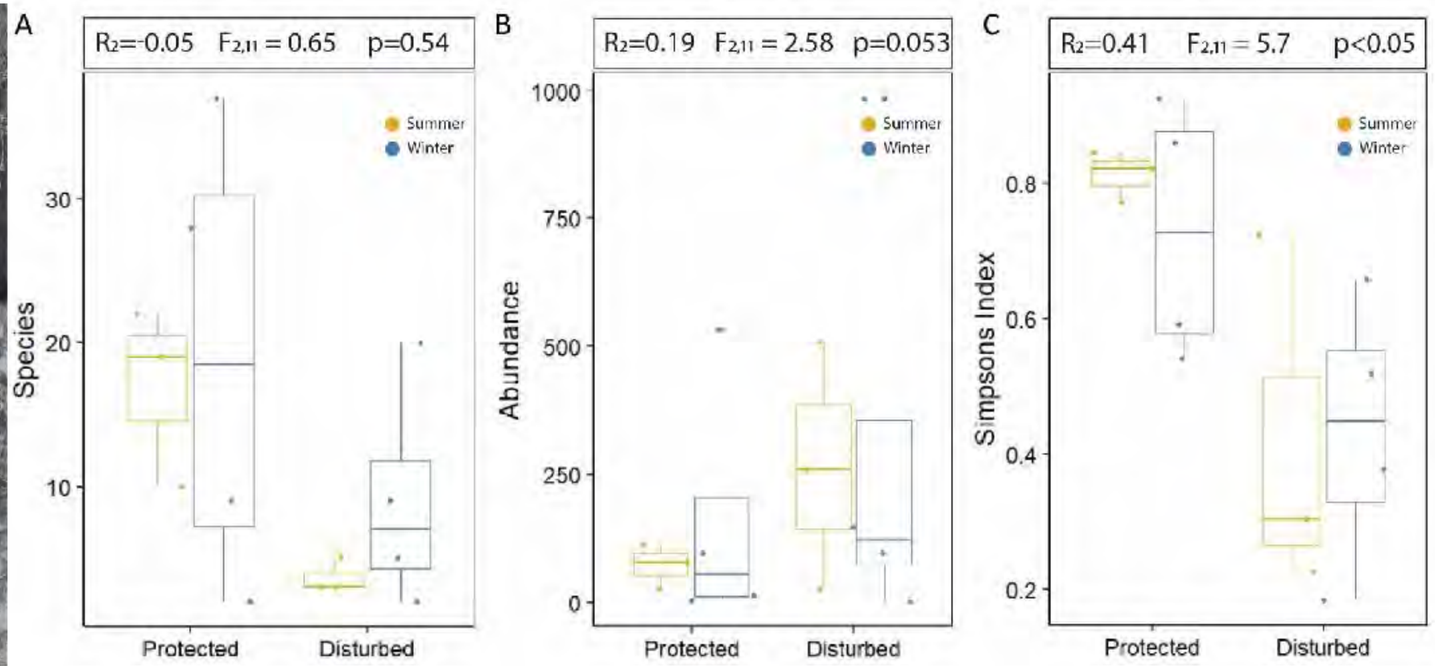
Gortat, D., Ortega Ancel, A., Farhina, A., Zufferey, R., Kovac, M.,
Use of Superhydrophobic Surfaces for Performance Enhancement of Aerial-Aquatic Vehicles
Advanced Intelligent Systems 2023 (cover)

Aerial - Aquatic SailMAV

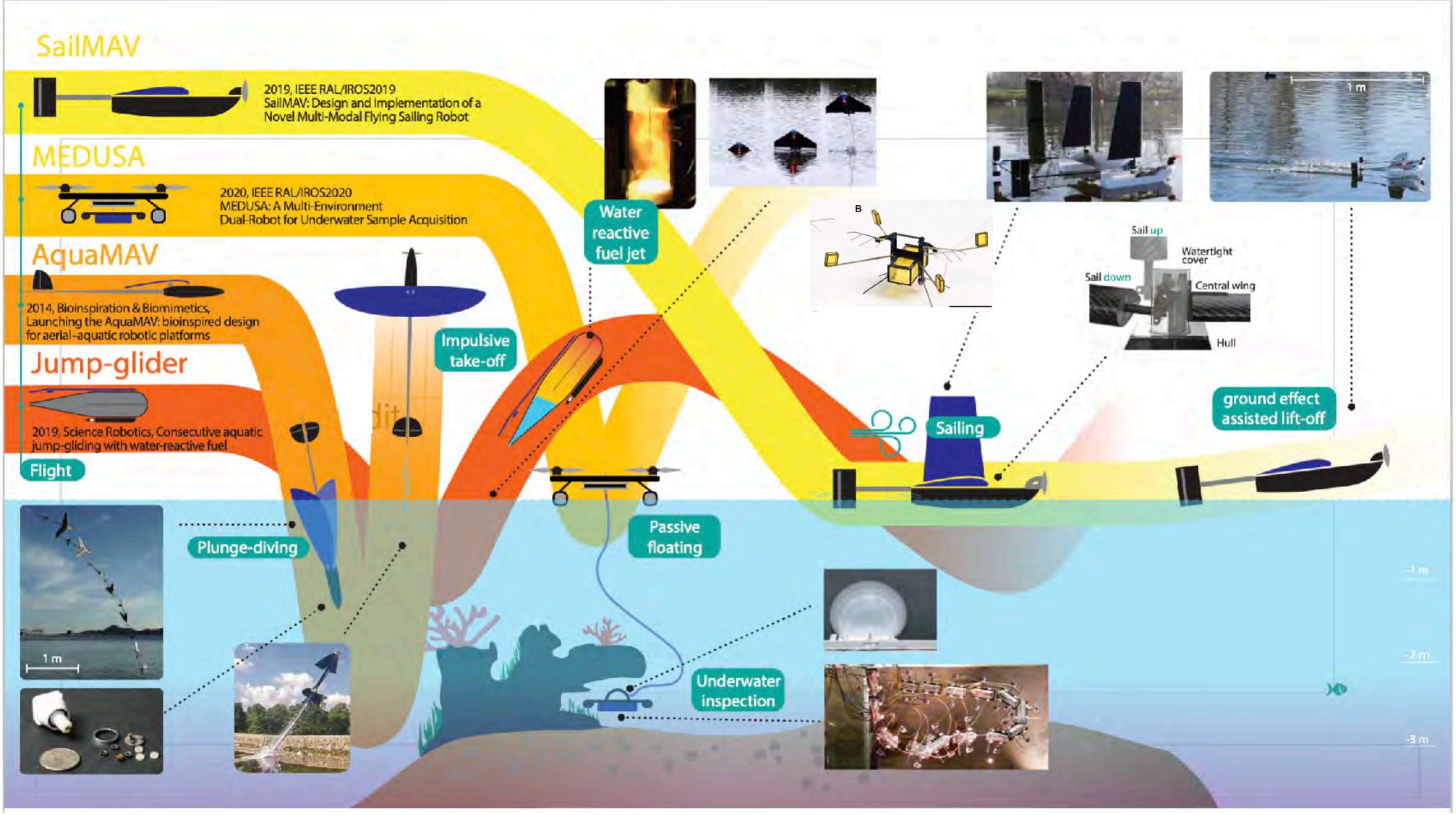


Gortat, D., Ortega Ancel, A., Farhina, A., Zufferey, R., Kovac, M.,
Use of Superhydrophobic Surfaces for Performance Enhancement of Aerial-Aquatic Vehicles
Advanced Intelligent Systems 2023 (cover)

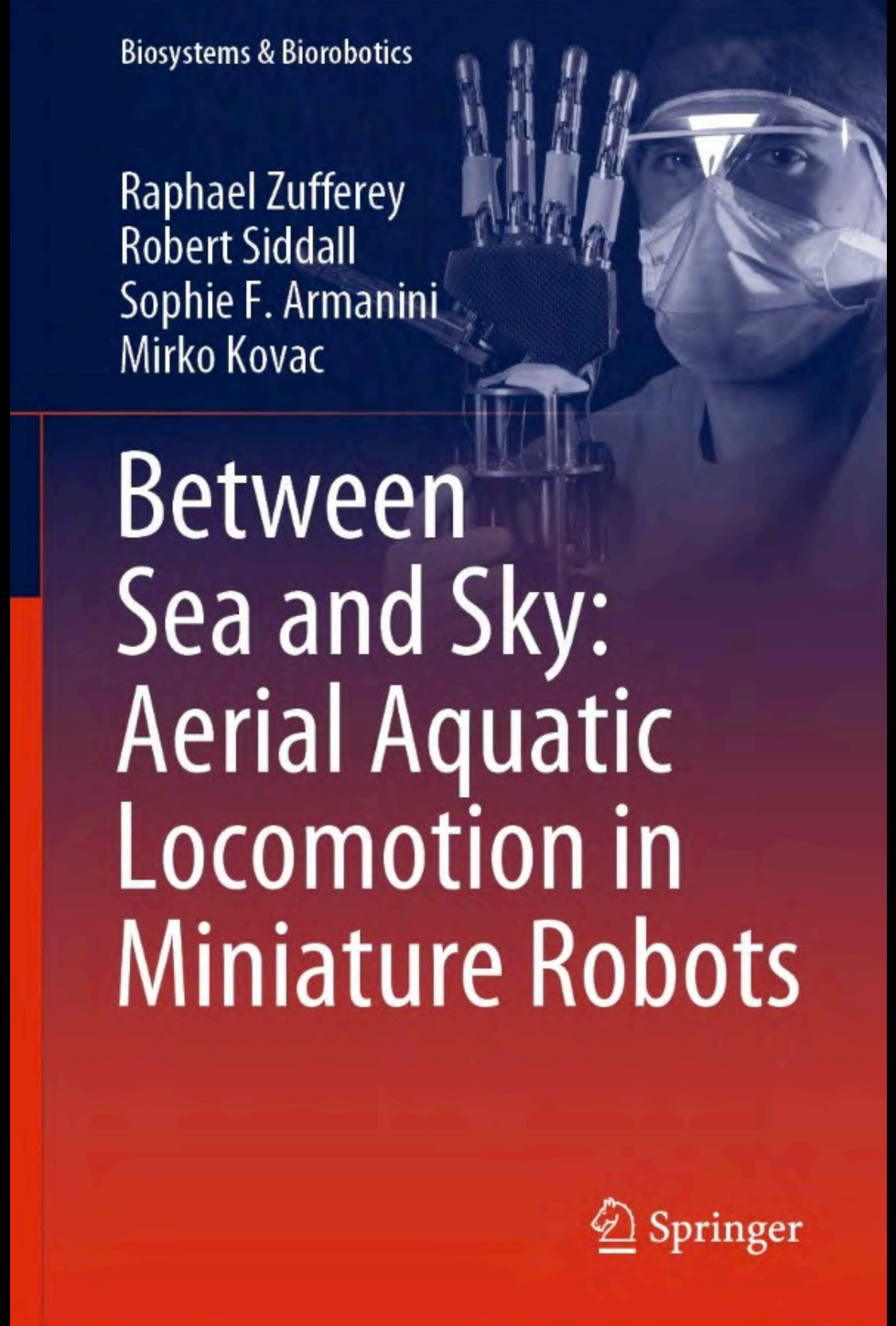
Field testing campaign



In prep.



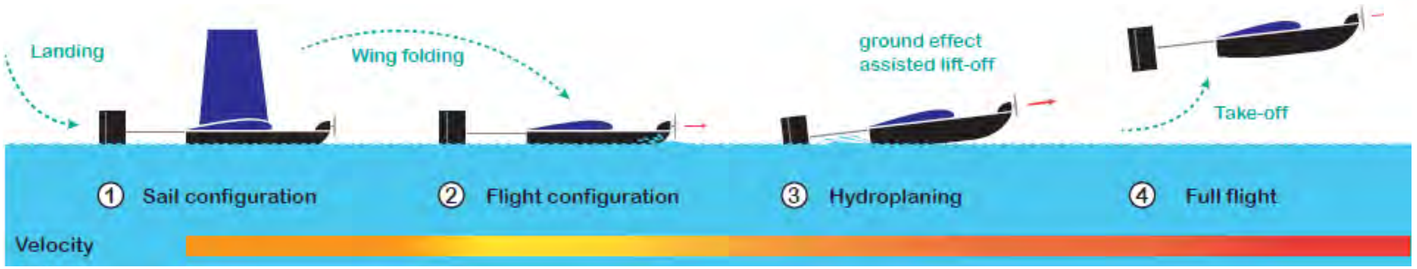
Kovac et al. ***Science Robotics*** 2016, 2019, 2022, ***Royal Society Interface Focus*** 2x 2017, ***ICRA/RA-L*** 2016, 2017, 2019, ***IEEE TMech*** 2016, ***Bioinspiration&Biomimetics*** 2014, ***AIAA*** 2019, *IROS* 2019
Best paper/poster awards at AMAM 2019, TAROS 2015, AAAI 2017, QM best PhD thesis award 2018 & 2020


Biosystems & Biorobotics
Raphael Zufferey
Robert Siddall
Sophie F. Armanini
Mirko Kovac
Between Sea and Sky: Aerial Aquatic Locomotion in Miniature Robots
Springer

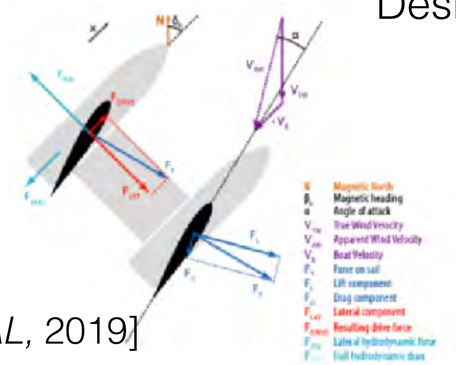
Concept to systems to insights

Empa EPFL

Laboratory of Sustainability Robotics



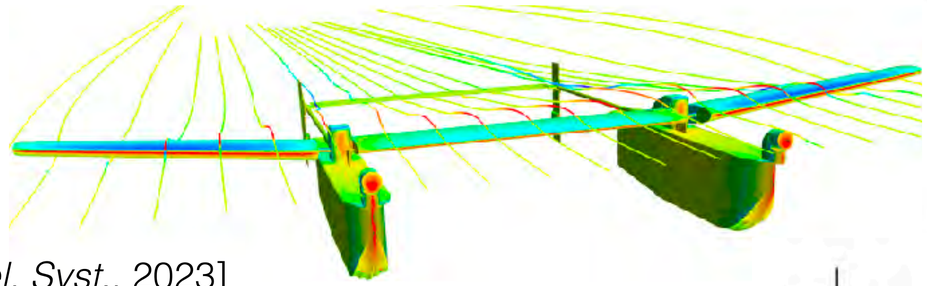
Design

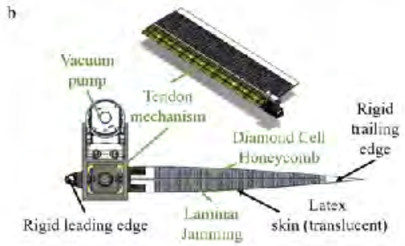


[Zufferey et al *IEEE RAL*, 2019]

Testing

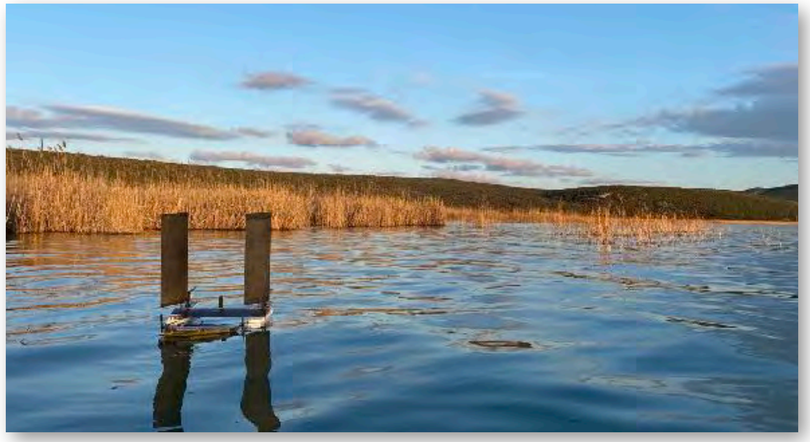
Design iteration





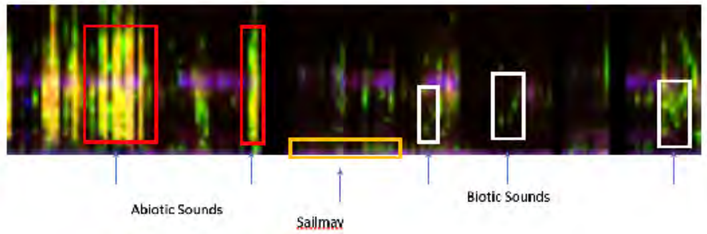
[Gortat et al *Adv. Intel. Syst.*, 2023]

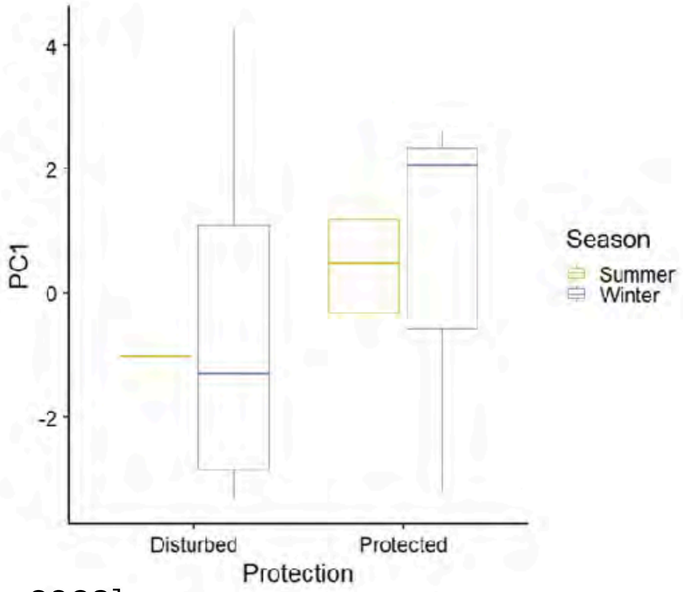
Outdoor validation



Insights

Soundscape Analysis





[Lawson et al *Remote Sensing in Ecology and Conservation*, 2023]

Proteus: Metamorphic sea god

Illustration credit: Generative AI Adobe Firefly

Meta-morphic tri-modal mobility for robotics

European Research Council

Consolidator grant 2023-2028
(funded by SERI)

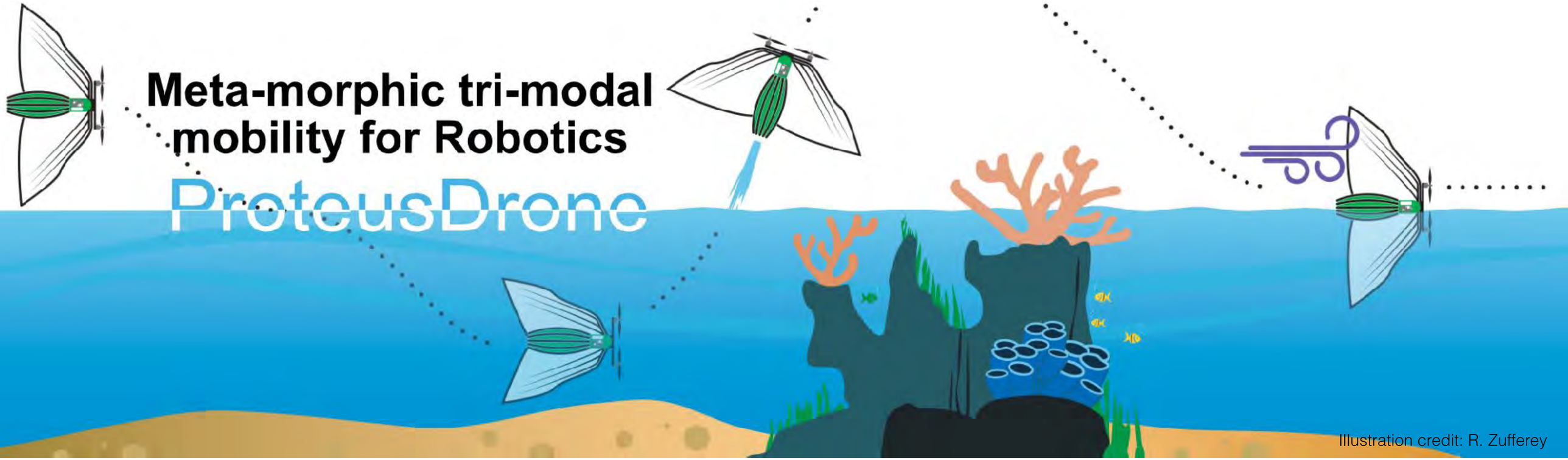
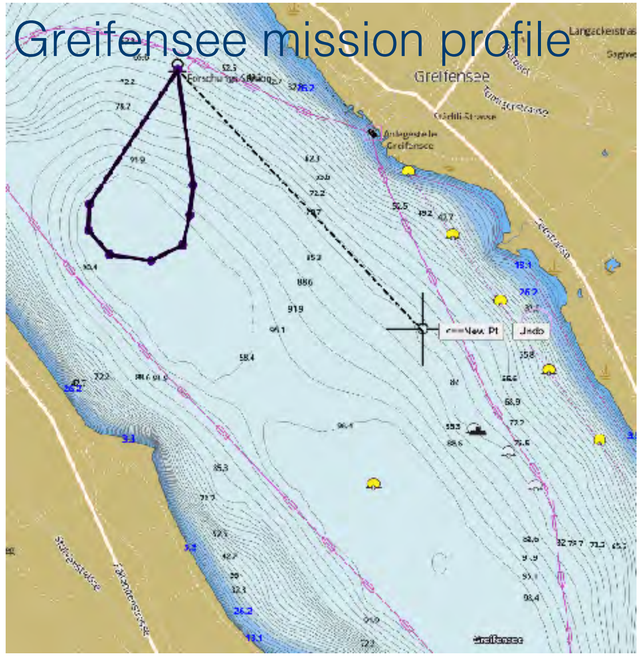
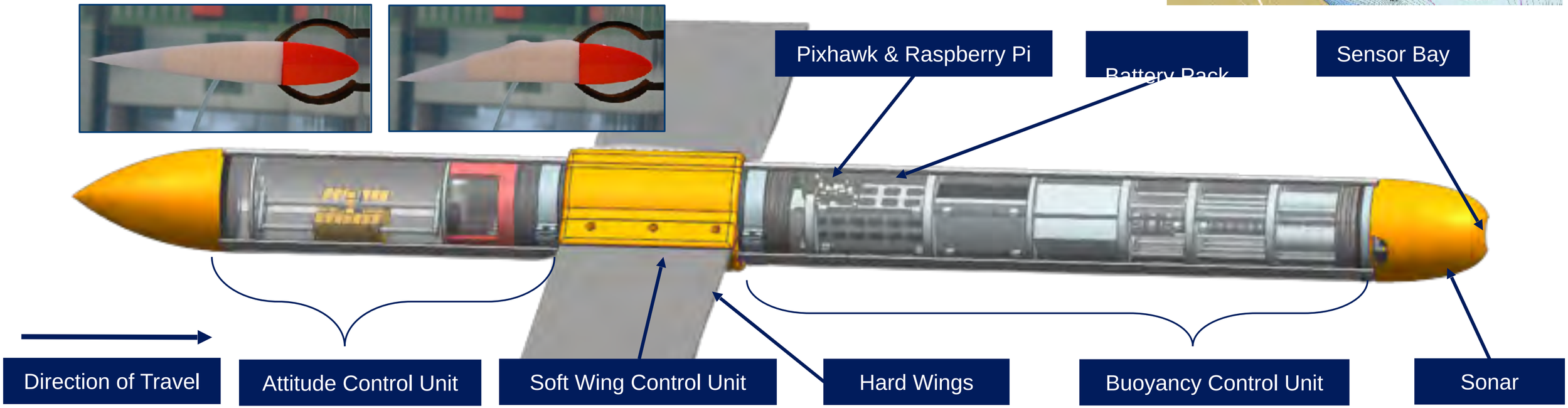


Illustration credit: R. Zufferey

ARIS - Nautilus

- Collaboration with ARIS (Academic Space Initiative Switzerland)
- 20 active contributors, 3 MSc projects
- Development of an Unmanned Underwater Vehicle (Glider) for Planetary Exploration of Icy Moons
- Validation in Greifensee & Aletsch-glacier lake planned





Aquatic research platform in lake Geneva

LéXPLORE eawag aquatic research EPFL UNIVERSITÉ DE GENÈVE Unil UNIL | Université de Lausanne CARRTEL INRAE

Shinrin-yoku (森林浴) – Forest Bathing

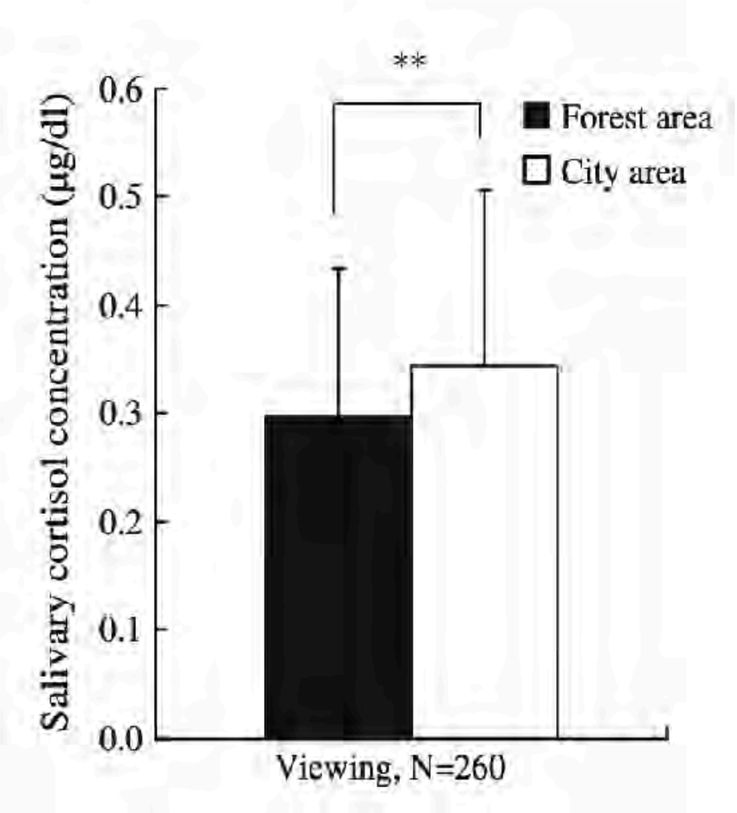
...making contact with and taking in the atmosphere of the forest…

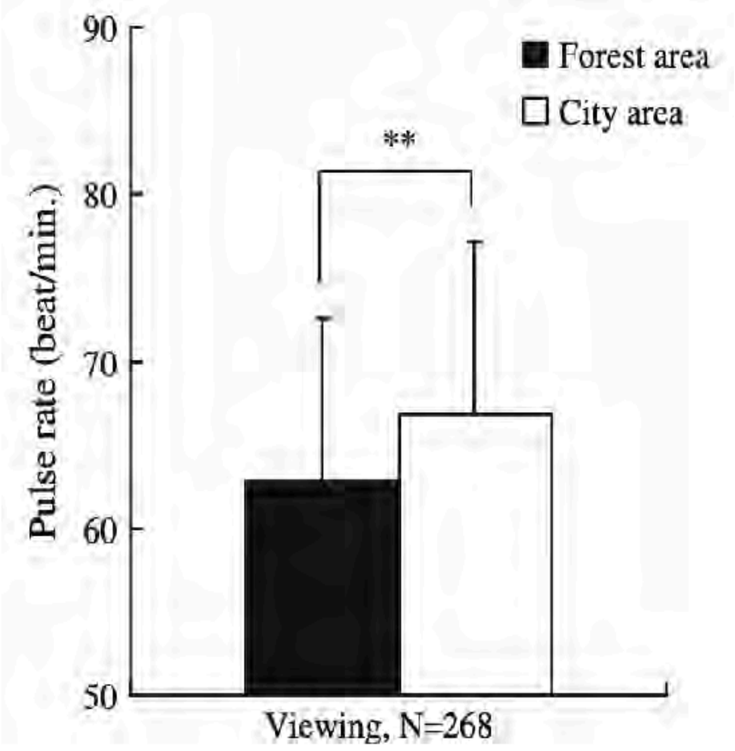
- as defined by the Japanese Ministry of Agriculture, Forestry, and Fisheries in 1982

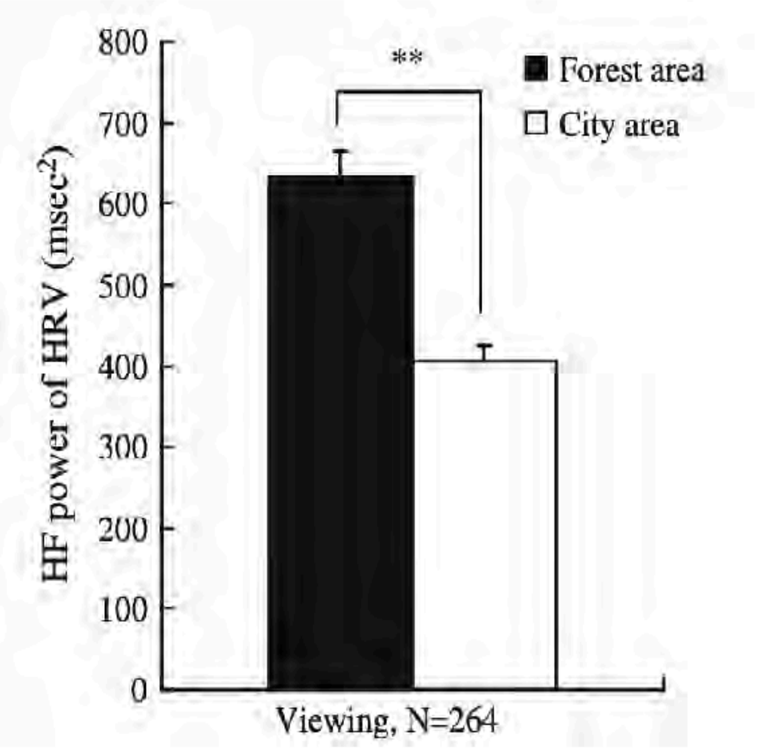
Benefits

- Reduced stress
- Improved mood
- Enhanced relaxation
- Boosted immune system
- Increased focus
- Lowered blood pressure
- Decreased anxiety
- Improved sleep
- Increased energy levels
- Enhanced creativity
- Reduced inflammation
- Improved mental clarity
- Lowered heart rate
- Better cardiovascular health
- Improved overall well-being

Shinrin-yoku – Health Benefits

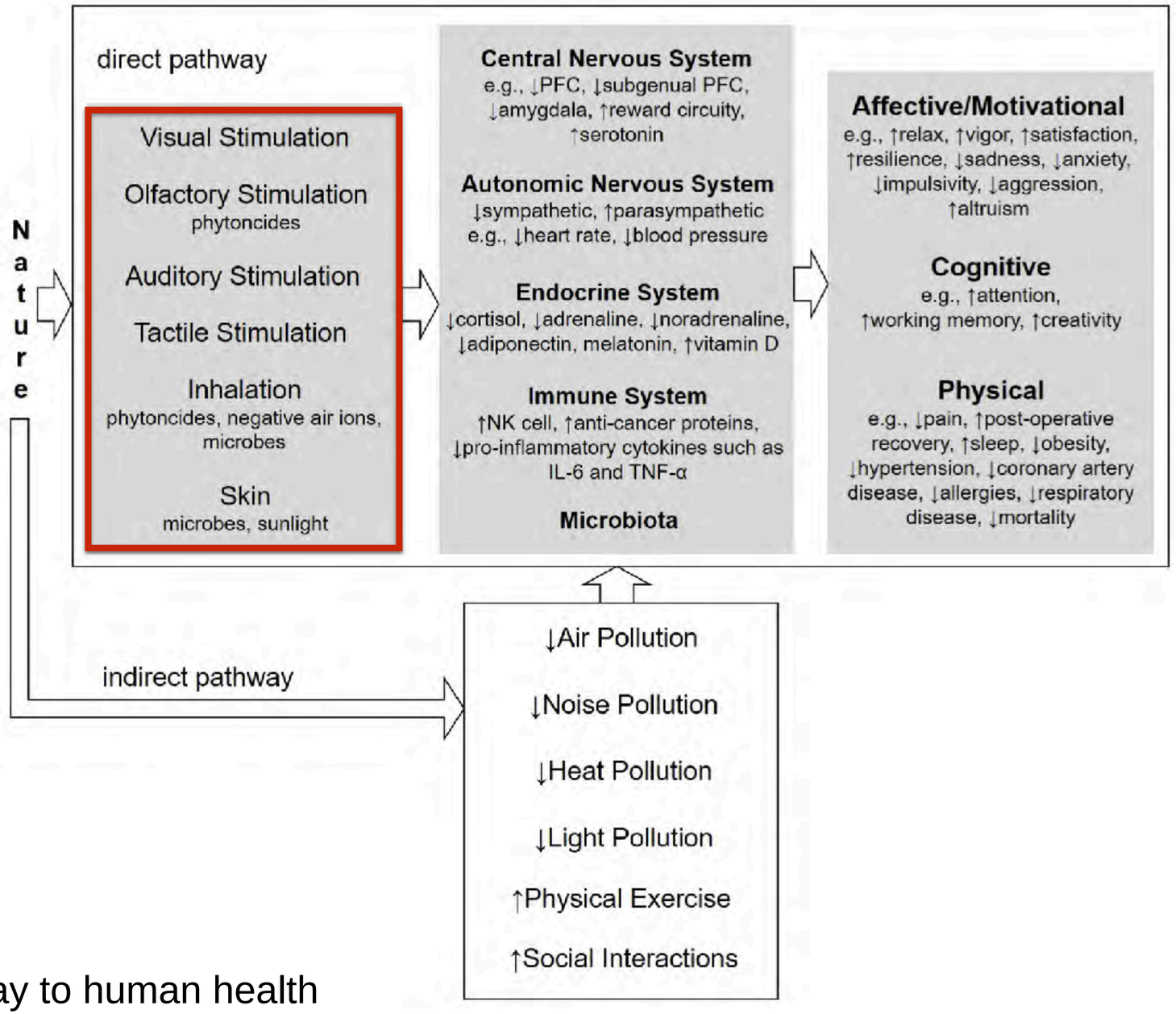






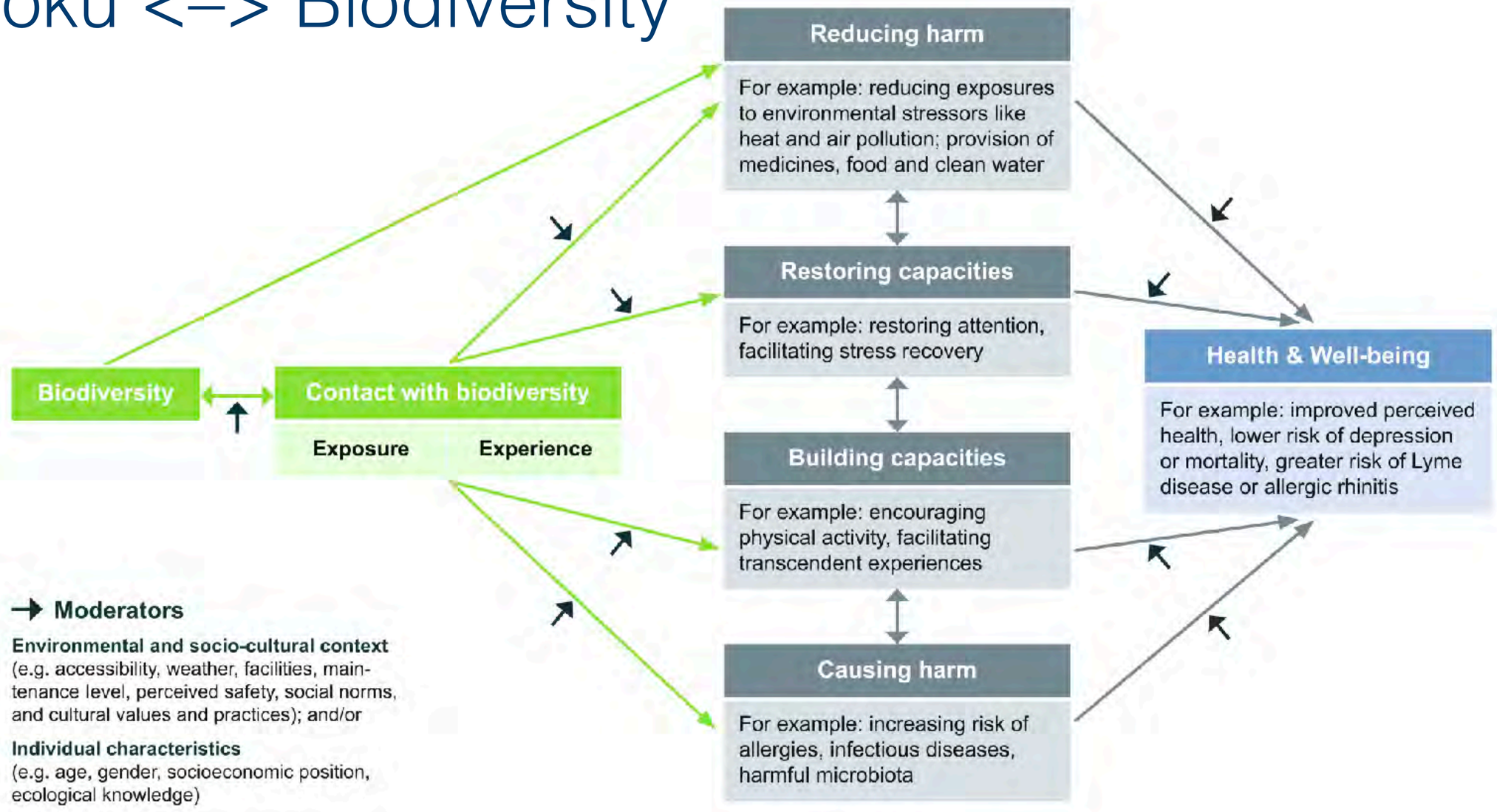
Bum Jin Park, Yuko Tsunetsugu, Tamami Kasetani, Takahide Kagawa, Yoshifumi Miyazaki ***Environ Health Prev Med*** (2010)

Shinrin-yoku



Chen et al. Nature's pathway to human health
International Handbook of Forest Therapy (2019)

Shinrin-yoku <–> Biodiversity

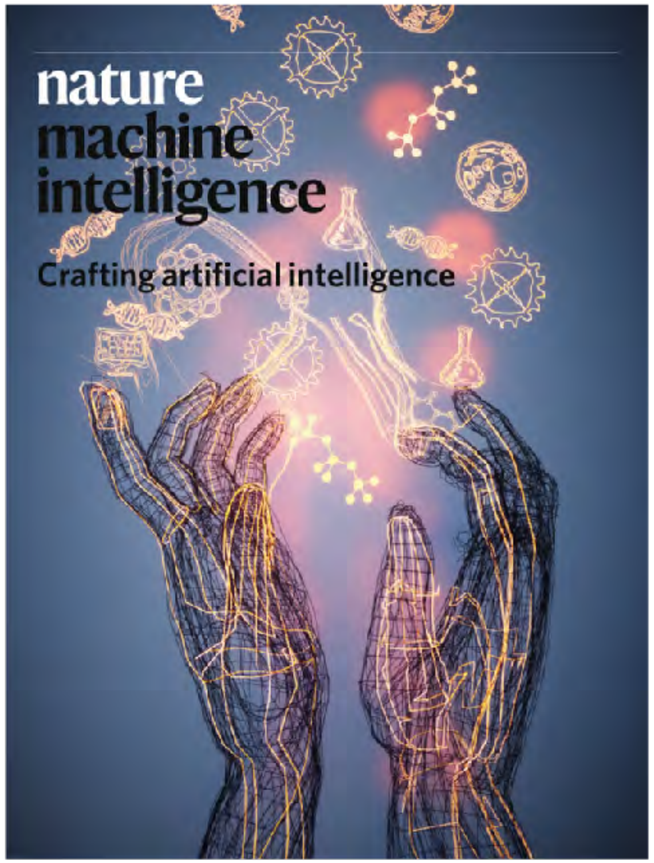


Craig et al. Natural environments, nature relatedness and the ecological theater: connecting satellites and sequencing to shinrin-yoku
Journal of Physiological Anthropology (2016)

Shinrin-yoku <–> Biodiversity

Dimensions of biodiversity at a location		What biodiversity to measure	Measurement Approaches
Actual biodiversity	Biodiversity present at a location.	Individual organism/trait	Ecological field techniques
		Abundance	Count individuals, estimate their spatial and temporal variation
		Richness	Comprehensive monitoring/species assessment
Perceived biodiversity	Biodiversity people think is at a location.	Individual organism/trait	Questionnaires, Eye-tracking, Electroencephalography (EEG), Observational research, Behavioural mapping, Participant photography
		Abundance	
		Richness	

Craig et al. Natural environments, nature relatedness and the ecological theater: connecting satellites and sequencing to shinrin-yoku
Journal of Physiological Anthropology (2016)

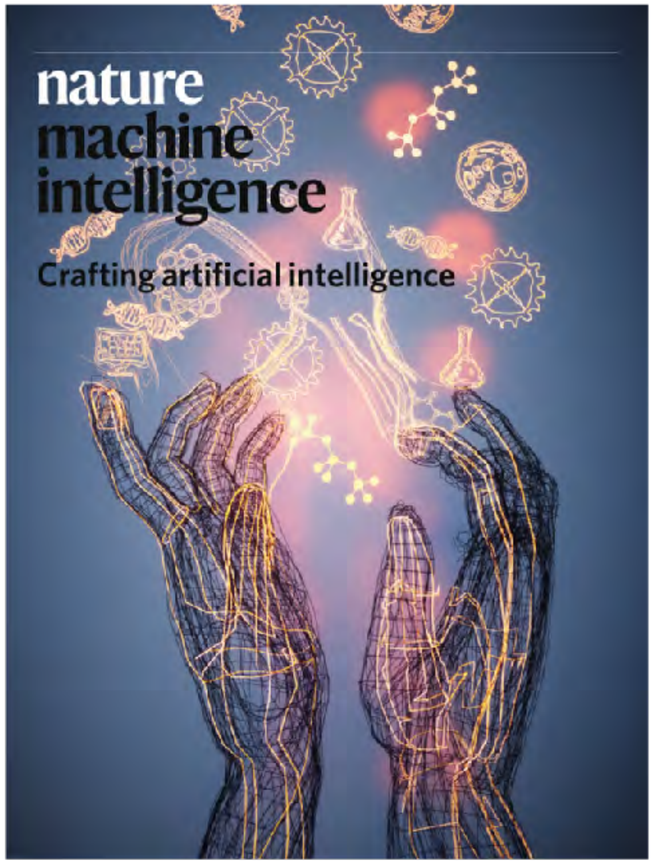


Co-development Method: Physical Artificial Intelligence

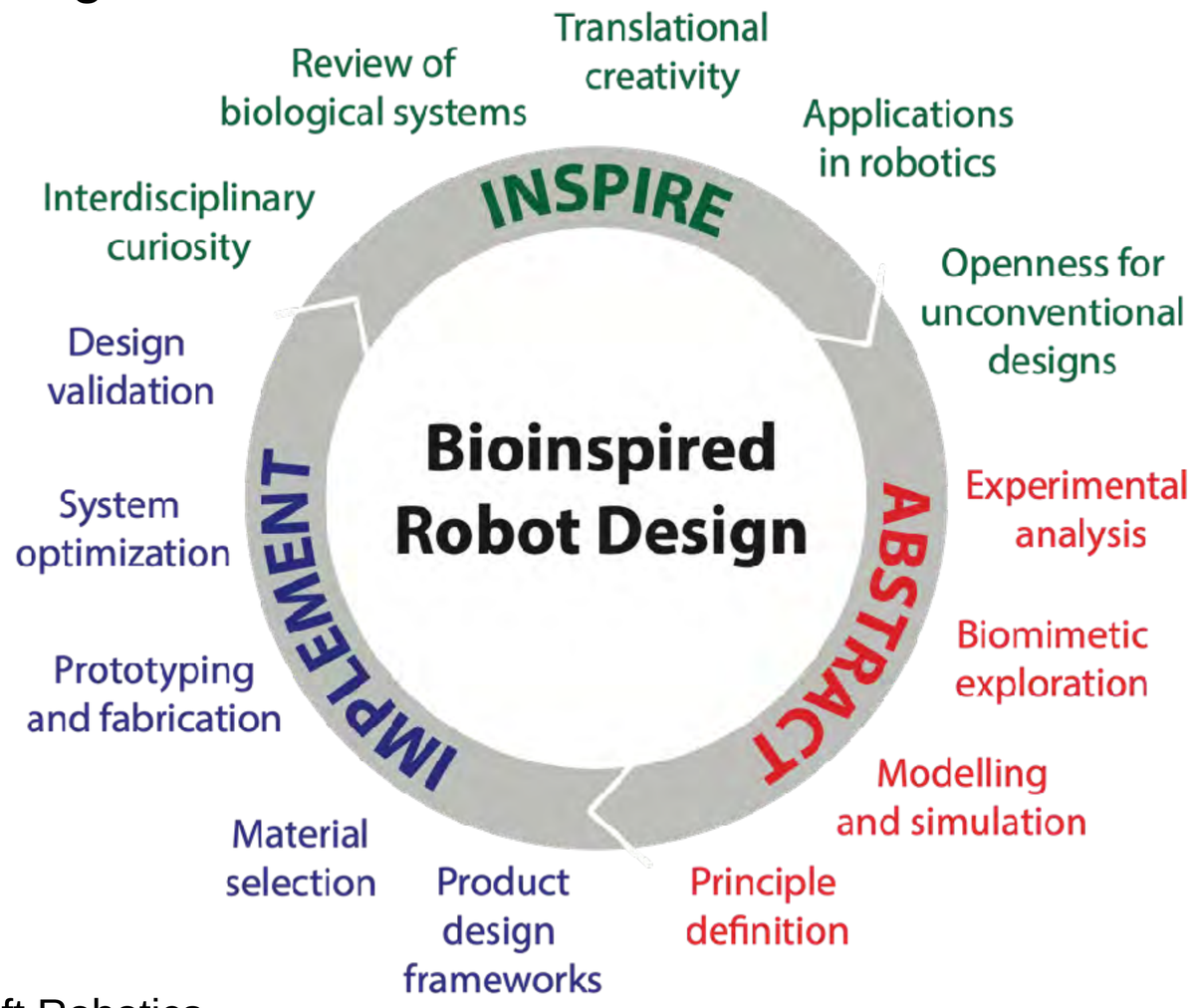
Miriyev, Kovac, Skills for Physical Artificial Intelligence,
Nature Machine Intelligence, 2020 (cover)

Kovac, The Bioinspiration Design Paradigm: A Perspective for Soft Robotics,
Soft Robotics, 2014

Kovac, Learning from nature how to land aerial robots,
Science, 2016



Co-development Method: Physical Artificial Intelligence

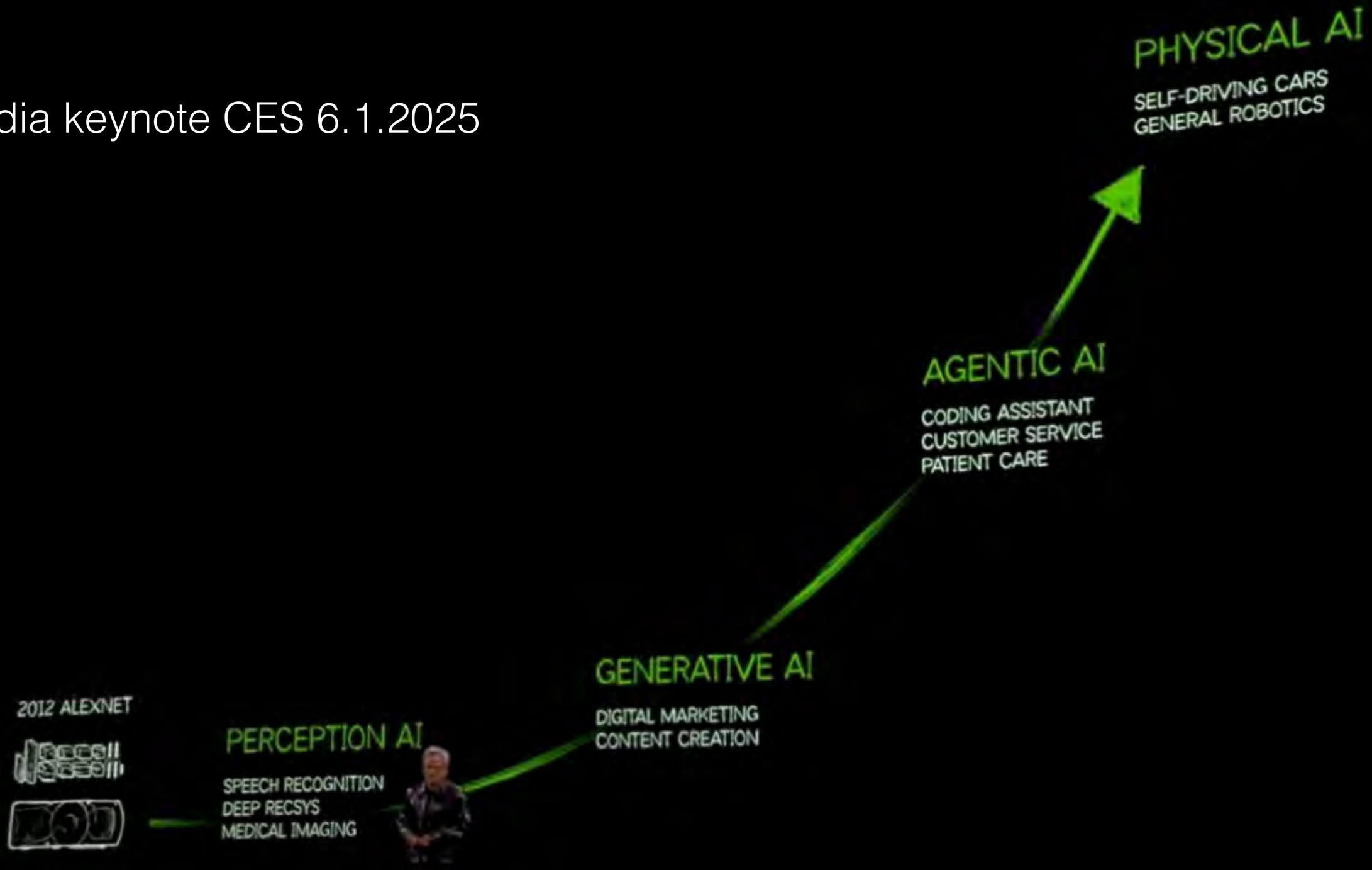


Miriyev, Kovac, Skills for Physical Artificial Intelligence, *Nature Machine Intelligence*, 2020 (cover)

Kovac, The Bioinspiration Design Paradigm: A Perspective for Soft Robotics, *Soft Robotics,* 2014

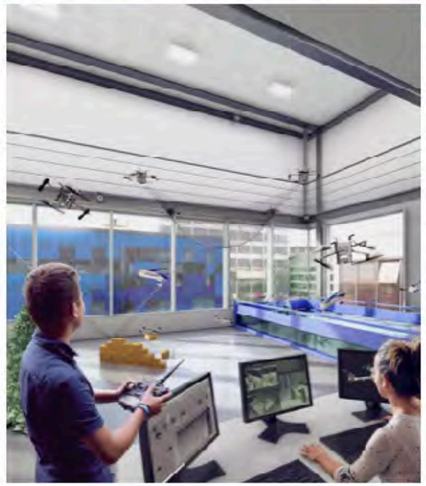
Kovac, Learning from nature how to land aerial robots, *Science,* 2016

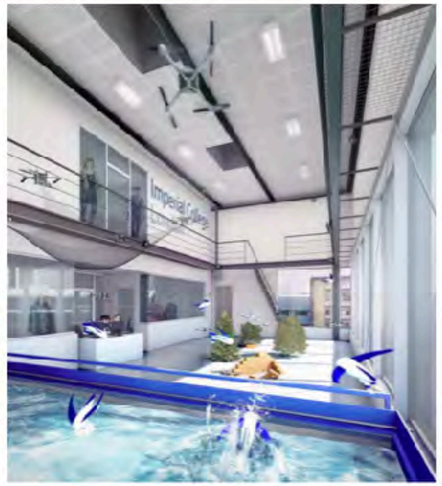
Nvidia keynote CES 6.1.2025



lege

Multi-terrain flight arena in South Kensington





Air/ground/water test areas
-12m long, 10m wide 5.7m high
- integrated workshops, meeting rooms and student spaces

UK's most advanced drone lab to be built at Imperial College London

£1.25m Brahmal Vasudevan aerial robotics lab will allow development and testing of next-generation flying robots

Rise of the drones: how unmanned aircraft took off - video

The new facility in South Kensington will place the UK at the forefront of drone research. Photograph: Jean Pierre Muller/AFP/Getty Images

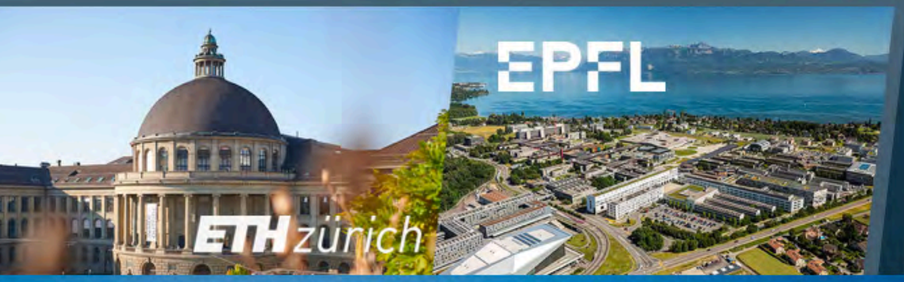
Samuel Gibbs

Thu 6 Nov 2014 06.00 GMT

theguardian

ETH BOARD

Empa - Swiss Federal Laboratories for Materials Science and Technology



Application oriented interdisciplinary material science & technology research

1'000+ Employees

350+ Partners from industry

2 Incubators with **34** Spin-offs and support for Swiss innovation parks

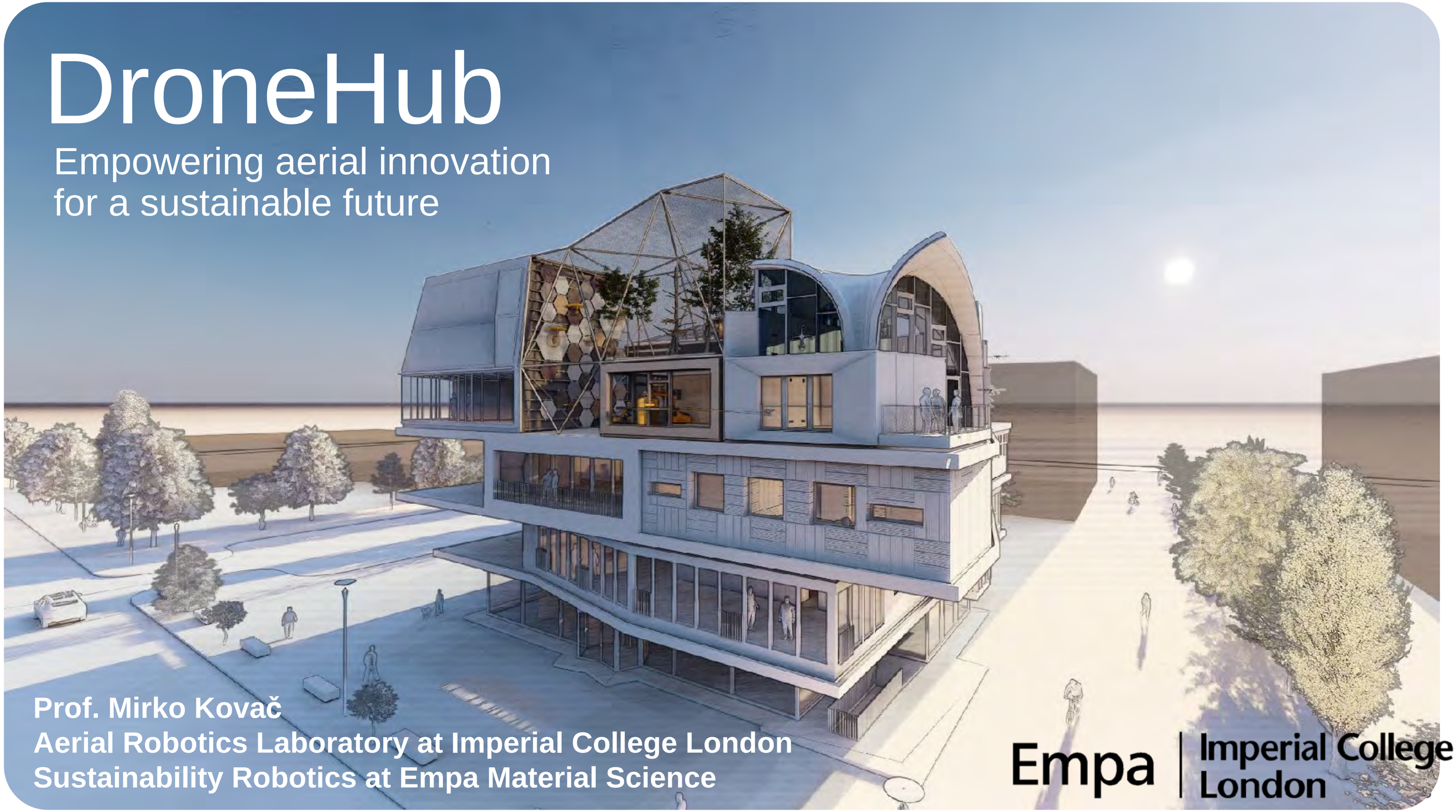
Efficiency

Productivity

Novel applications

DroneHub

Empowering aerial innovation for a sustainable future



Prof. Mirko Kovač
Aerial Robotics Laboratory at Imperial College London
Sustainability Robotics at Empa Material Science

Empa | Imperial College London


Implenia
30
Empa
Imperial College
Lond

Indoor Facilities | **Gap for a transitional research facility** | **Outdoor Facilities**

Indoor Facilities | **Gap for a transitional research facility** | **Outdoor Facilities**

Infrastructure Robotics Facade

- Building interface for logistics
- Drone based Non Destructive Evaluation
- Autonomous recharging

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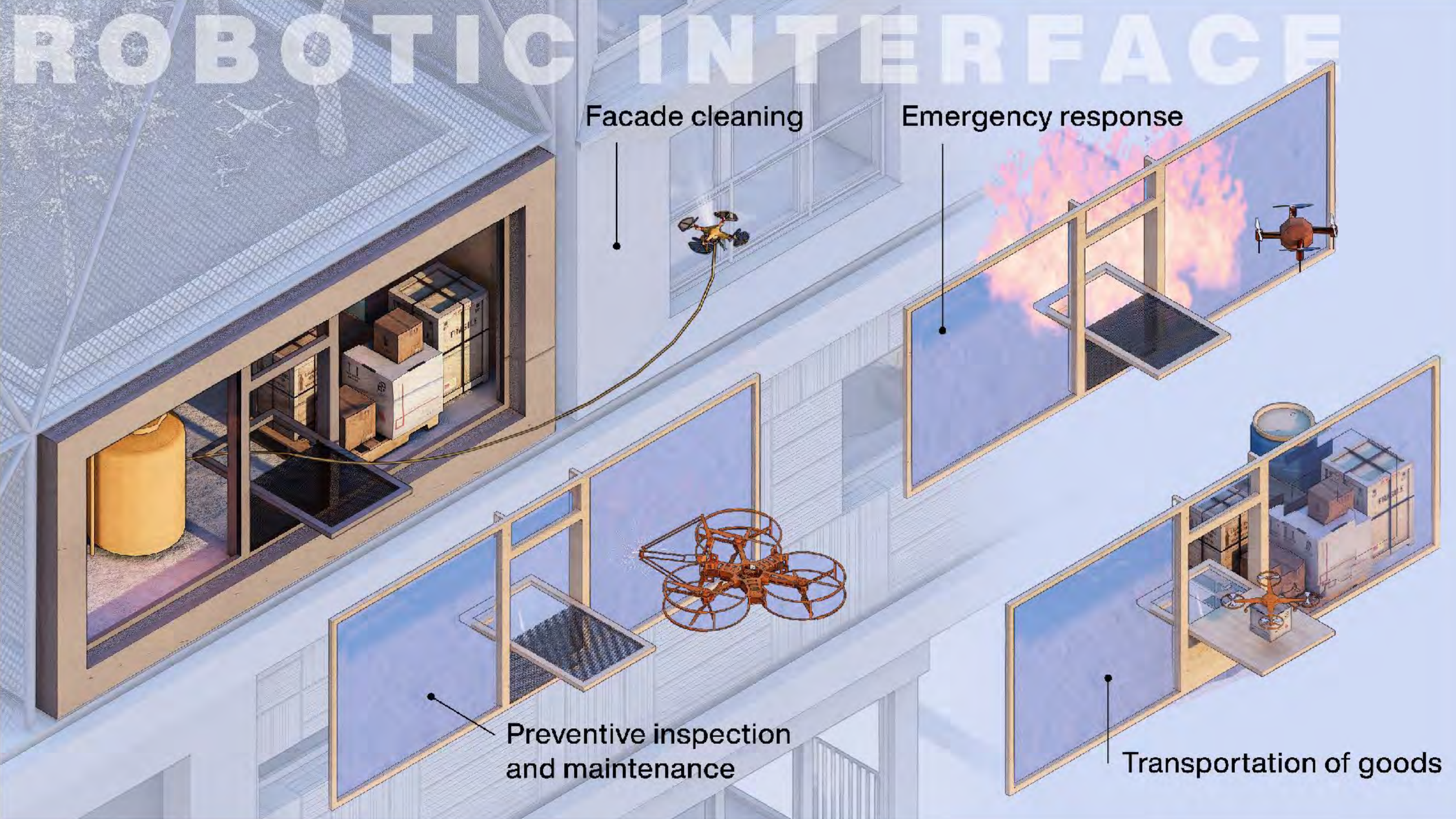
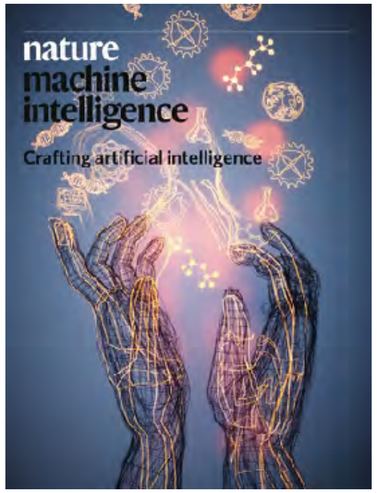
ROBOTIC INTERFACE



Biosphere for environmental sensing

- Transient robots made from bio-polymers
- Long term biodegradability in real-life setting.
- Sustainable circular economy, growing robot structures



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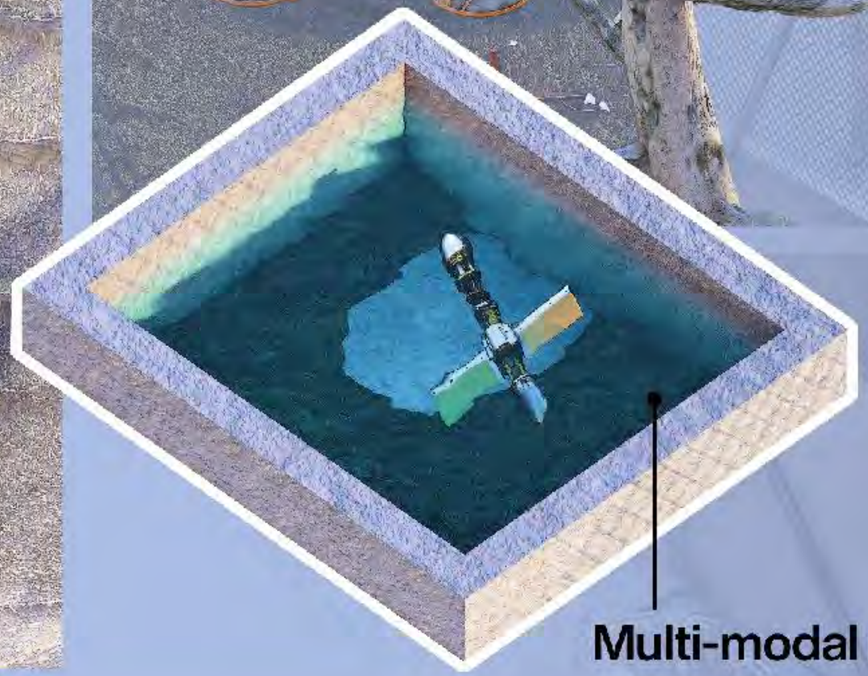
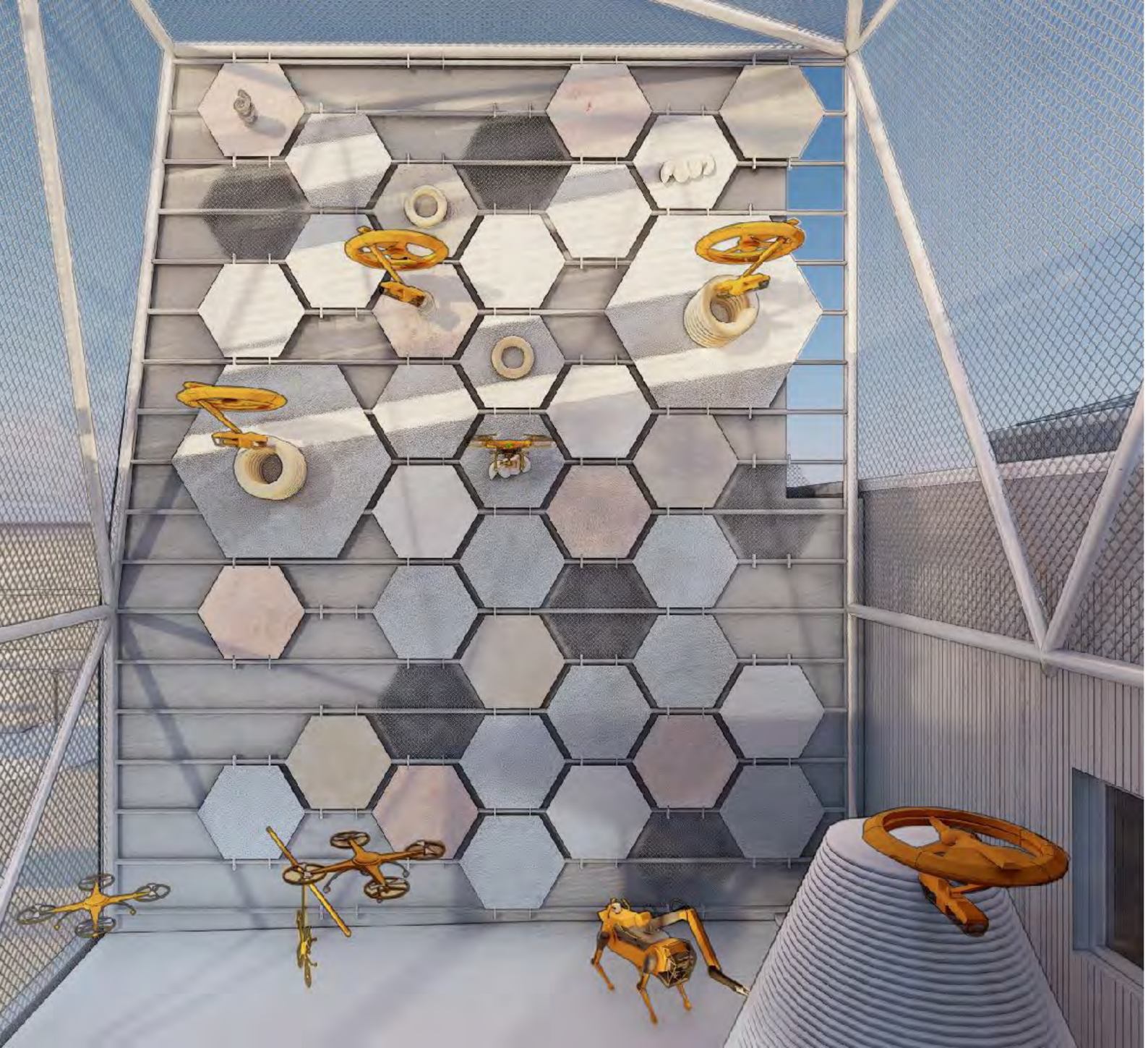
ARTIFICIAL BIOSPHERE



Multi-modal robots



Aerial Additive Manufacturing

- Inspection and repair tasks
- Construction at height
- Modular characteristic
- Safe outdoor flight area

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Infrastructure Drones Testbed @ Empa

The 1000m³ flight arena universal drone testbeds

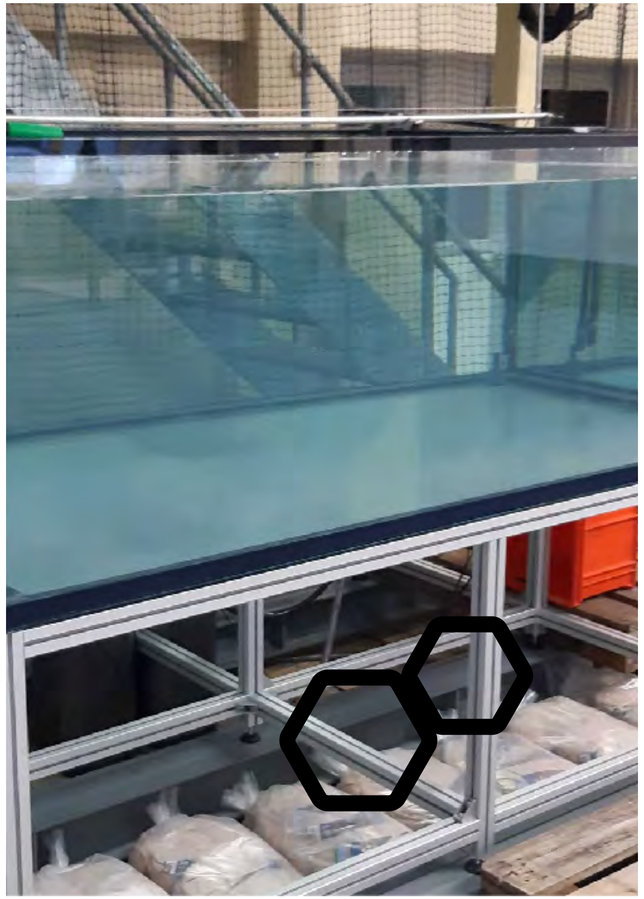
Infrastructure Drones Testbed @ Empa

Wind blade tip (7m)

Wind blade base (6m)

Bridge element (8m)

Water tunnels



Mission statement

Novel Robotics and AI technologies to measure and modify environments and deliver sustainable outcomes

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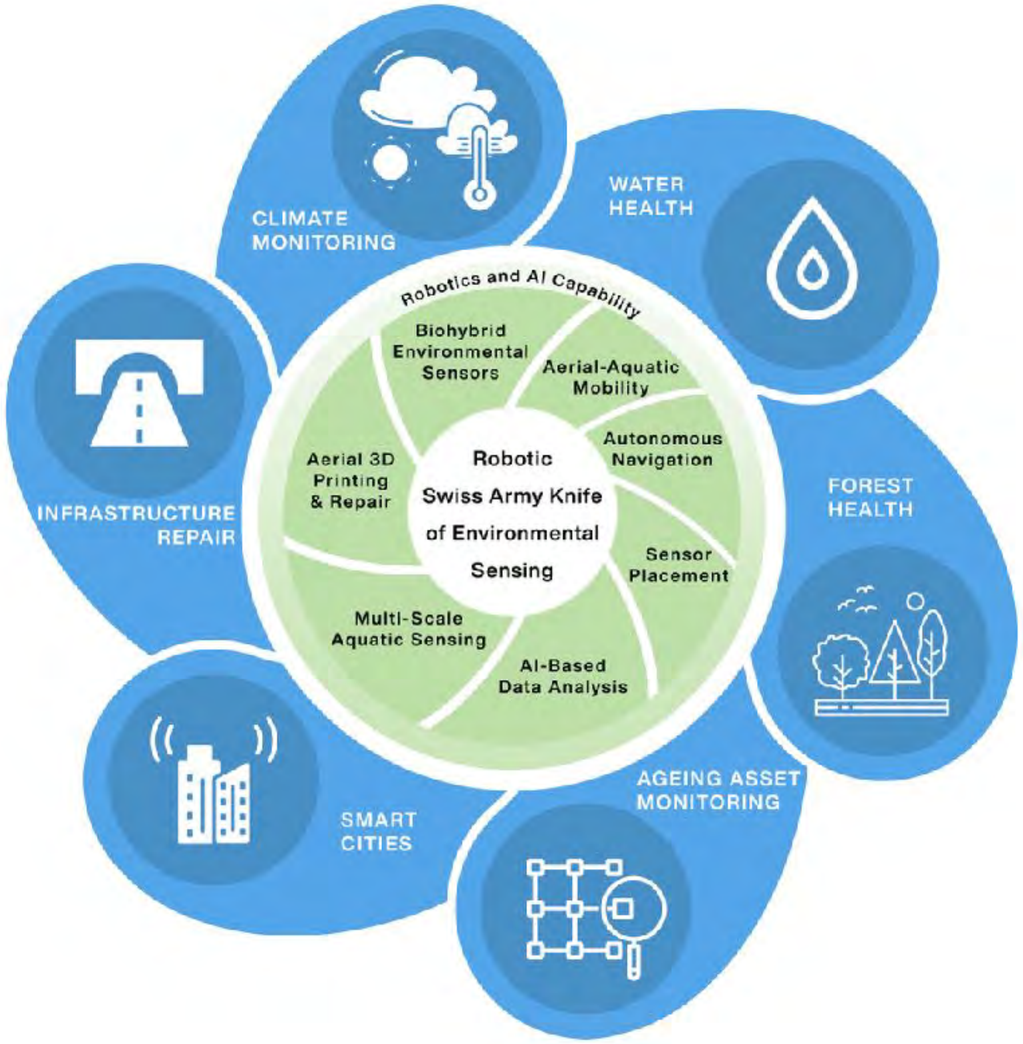
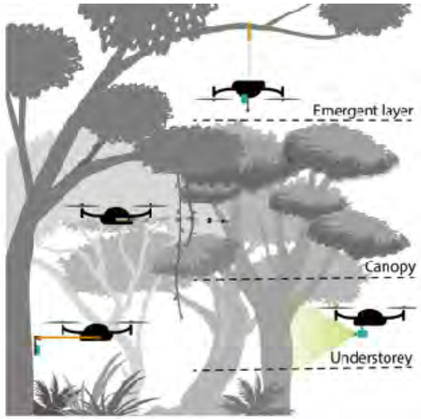
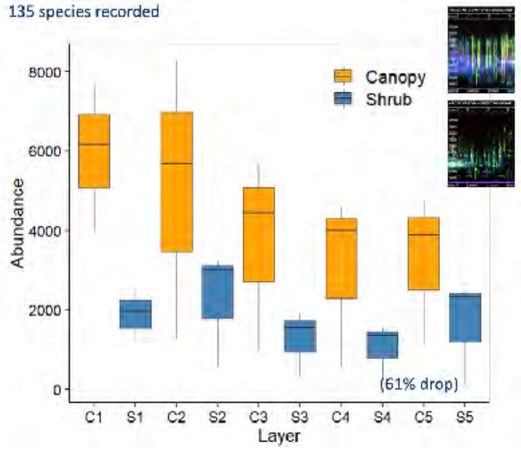
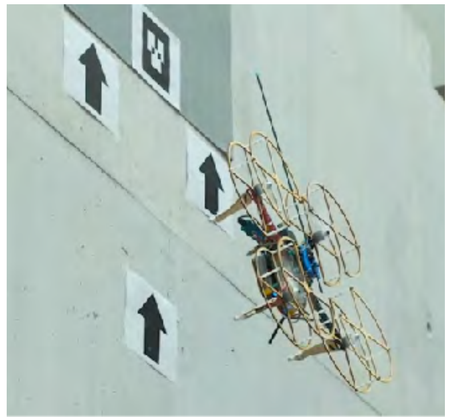


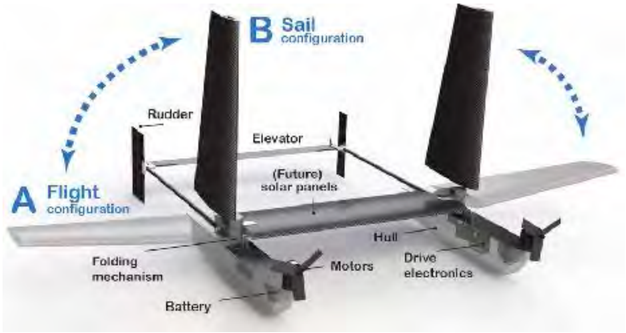
Sustainability Robotics

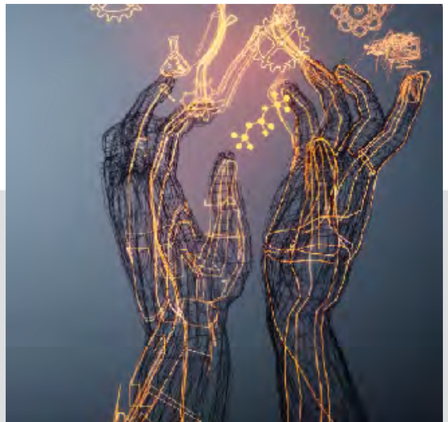
- ✓ **Autonomous drones can quantify biodiversity**
- ✓ **Bio-inspired methods can increase robustness and multi-terrain capabilities**
- ✓ **Meta-morphosis can increase functionality**
- ✓ **Physical AI: Co-eveolution of disciplines for lifelike robots**
- ✓ **DroneHub: Physical AI testbeds for future robotics**
- ✓ **Sustainability Robotics - join us!**







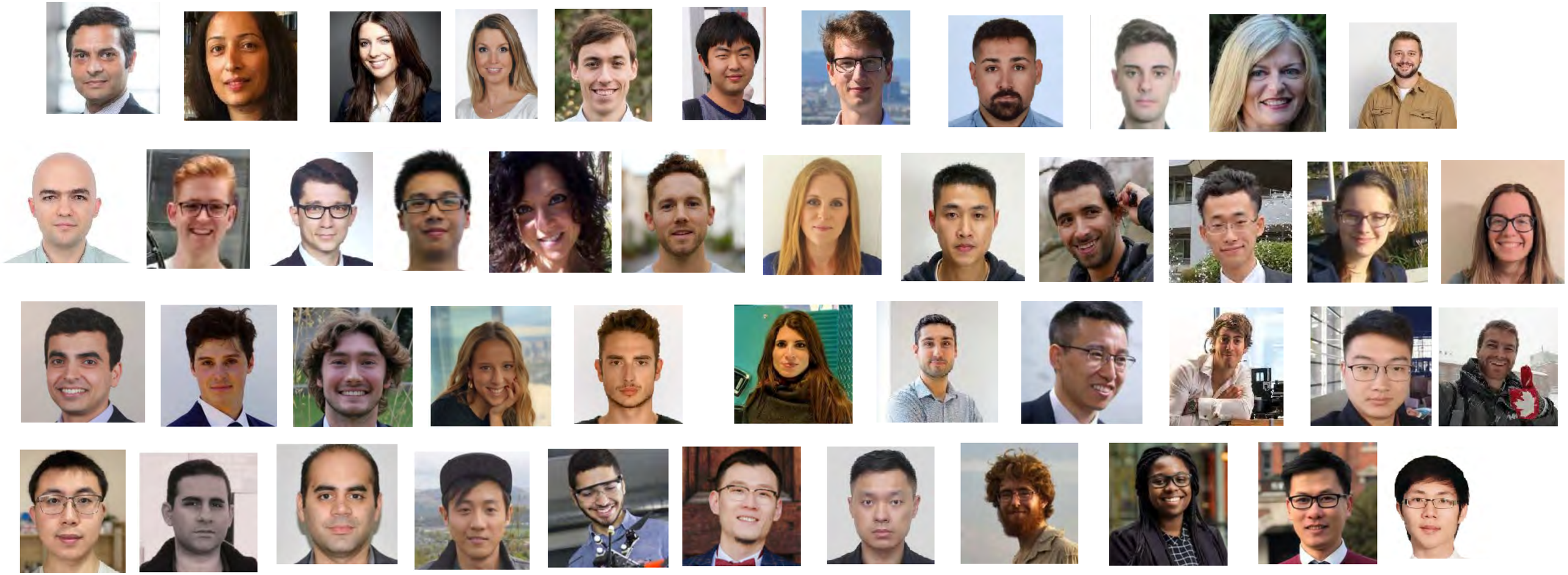




Prof. Mirko Kovac
Aerial Robotics Laboratory at Imperial College London
Sustainability Robotics Laboratory at Empa - EPFL

12 years celebration @ Imperial / Empa / EPFL

Mirko.Kovac@empa.ch



PROFESSORIAL LAB ALUMNI

Raphael Zufferey, Asst. Prof. MIT
Salua Hamaza, Asst.Prof. TU Delft
Sophie Armanini, Senior Lecturer (Assoc. Prof.) Imperial
Basaran Bahadir Kocer, Asst.Prof. (Lecturer) U. of Bristol
Pooya Sareh, Asst.Prof. (Lecturer) U. Liverpool
Sina Sareh, Assoc.Prof. (Reader) Royal College of Arts

Sukho Song, Asst. Prof. DGIST South Korea
Ketao Zhang, Senior Lecturer (Assoc. Prof.) Queen-Mary Uni.
Rob Siddall, Asst.Prof. (Lecturer) University Surrey
Aslan Miriyev, Sen. Lecturer (Assoc. Prof.) B. G. Uni of the Negev
Pisak Chermprayong, Asst.Prof. (Lecturer) Burapha Uni.
Yunus Govedeli Asst.Prof. (Lecturer) Salford Uni.