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Aerial-Aquatic Robotics

Trimodal Locomotion

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Source: theHallofEINAR.com

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Learning goals

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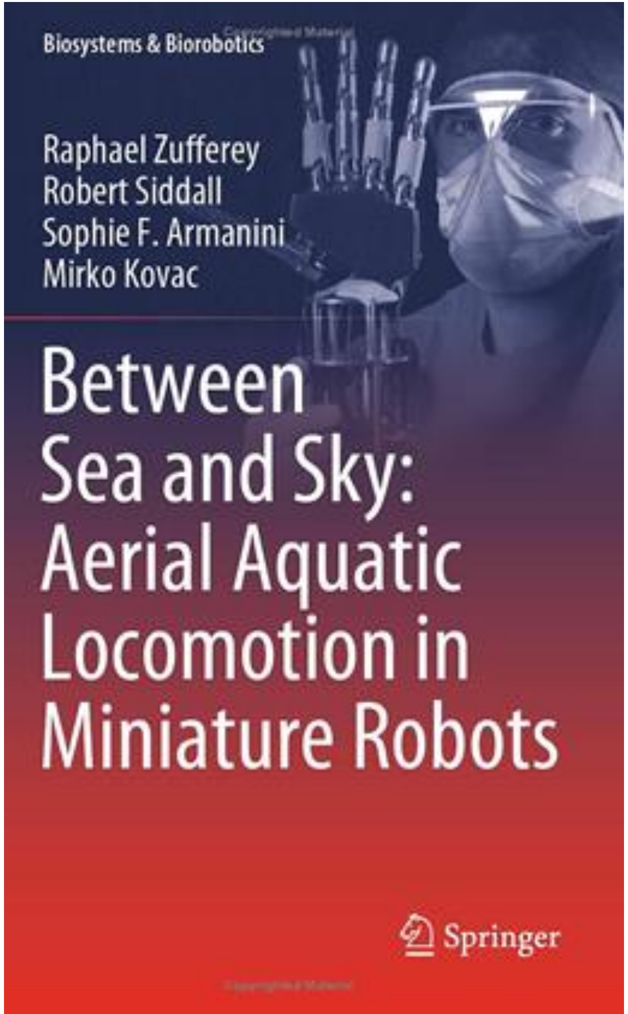
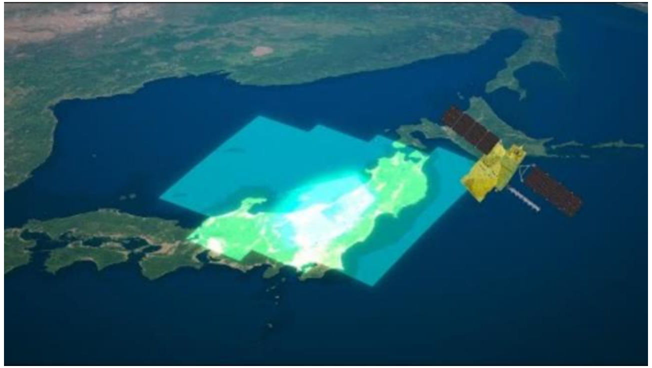
- Understand the reasoning behind robots which operate between air and water.
- Explain how Aerial-Aquatic locomotion is seen in nature.
- Learn the principles of how Aerial Aquatic robots are created.
- Discuss the physical principles of multi-modal locomotion?
- Explain what is trimodality and the cost of transport



Motivation and Objectives

Sattelite for geography mapping

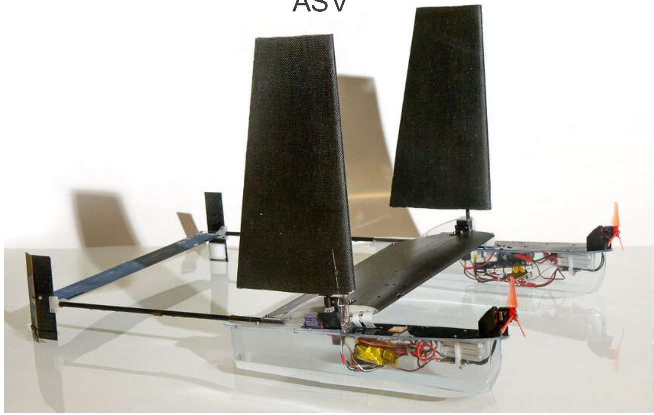


- Source: https://www.youtube.com/@JAXA-HQ

- Challenges in Aquatic Data Collection
  - Rapid global and local environmental changes necessitate precise geospatial and physical data
  - Changing orbit (e.g., low earth, geostationary, polar orbit) are difficult.
  - Current have low spatial and temporal resolution. (3 m x 3 m in 1 pixel)
  - High costs, long mission durations, and water communication limitations hinder effective data collection.

- Solution: Small, Affordable Robotic Vehicles
  - Autonomous Underwater Vehicles (AUVs) and Autonomous Surface Vehicles (ASVs) for aquatic measurements.
  - Low-cost, higher resolution

ASV



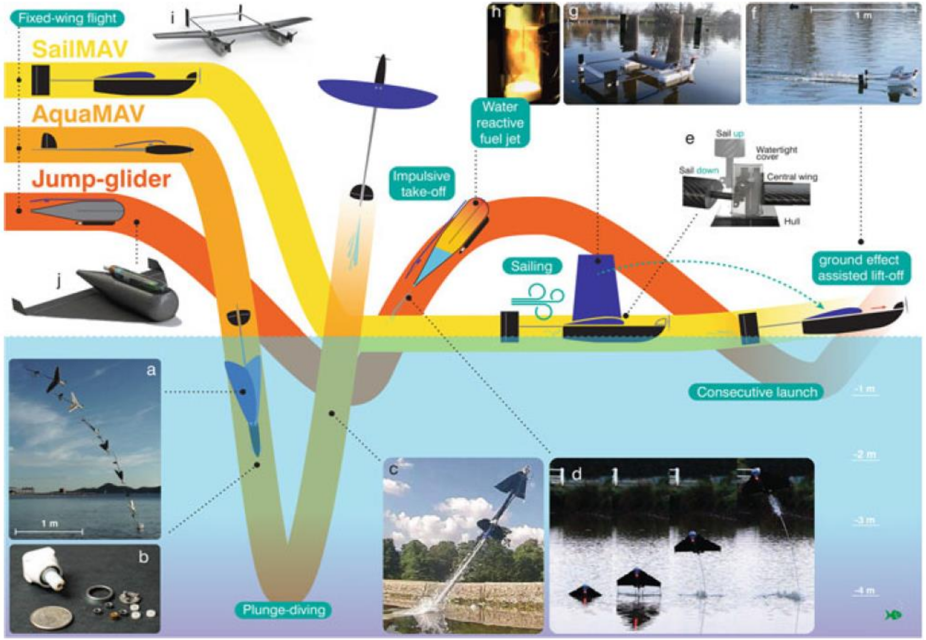
- Source: Zufferey, R., Ancel, A. O., Raposo, C., Armanini, S. F., Farinha, A., Siddall, R., ... & Kovac, M. (2019). Sailmav: Design and implementation of a novel multi-modal flying sailing robot. IEEE Robotics and Automation Letters, 4(3), 2894-2901.

Motivation and Objectives

- Vision for Future Development
  - Transition to flight-capable AUVs/ASVs for
    - Rapid deployment and coverage area can be controlled
    - Obstacle avoidance and transitions between water bodies
    - Elimination of dependency on boats or ports for robot recovery

- Key Benefits
  - Enhanced environmental monitoring
  - Cost-effective and efficient data collection
  - Support for global ecological and disaster management efforts

Overview of existing aerial-aquatic robots



Source: Book

Applications and Opportunities: Remote Sensing

- Role of remote sensing
  - Utilizes satellite observations to detect spatial and temporal ecological trends (e.g., sea surface temperature, photosynthesis rate)
  - Provides a comprehensive view of global environments, essential for climate change policies
- Challenges
  - Satellites need external calibration to link signals to physical measurements on Earth
  - Current methods rely on costly and slow ship-based missions or buoys
  - Limited overlap of clear skies and satellite passes results in high uncertainty
- Aerial-Aquatic Robotics (MEDUSA Platform)
  - Hybrid flying and underwater drive which enable efficient mapping in small areas
  - Provide a scalable alternative to traditional ship and buoyancy methods

MEDUSA
(Multi-Environment Dual-robot for Underwater Sample Acquisition)

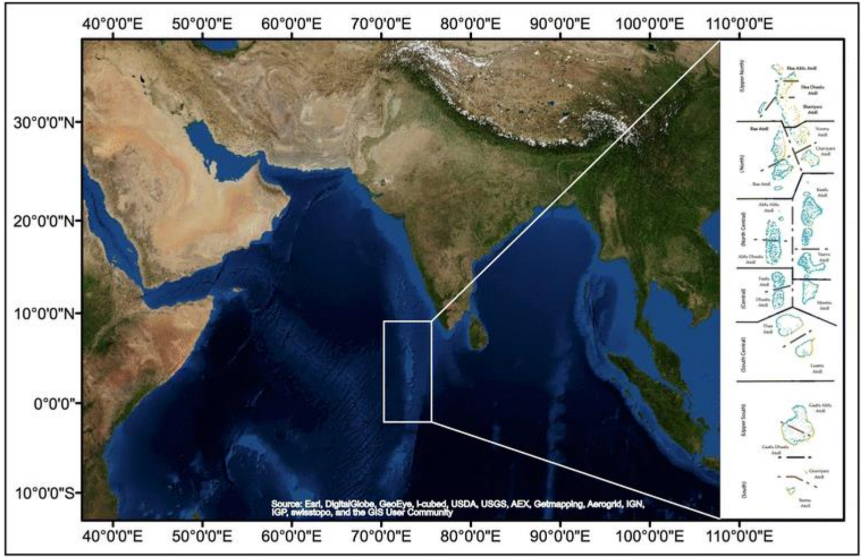
- Source: Debruyn, D., Zufferey, R., Armanini, S. F., Winston, C., Farinha, A., Jin, Y., & Kovac, M. (2020). Medusa: A multi-environment dual-robot for underwater sample acquisition. IEEE Robotics and Automation Letters, 5(3), 4564-4571.

Applications and Opportunities: Marine Conservation

- Challenges
  - Monitoring vast marine areas like the Maldives (comprising 1,200 islands) is logistically difficult
  - Existing drones are limited to surface-level observation, lacking underwater capabilities

- Aerial-Aquatic Robotics
  - Provide both surface and underwater monitoring capabilities
  - Capture underwater noise to estimate species and population numbers
  - Enhance monitoring for marine resources and fisheries

Map of Maldives



- Source: Fallati, L., Savini, A., Sterlacchini, S., & Galli, P. (2017). Land use and land cover (LULC) of the Republic of the Maldives: first national map and LULC change analysis using remote-sensing data. Environmental monitoring and assessment, 189(8), 417.

Applications and Opportunities: Micro-biology and Micro-plastic Analysis

- Microplastic Pollution
  - Widespread presence in aquatic environments
  - Requires better understanding of flows, sources, and accumulation sites

- Aerial-Aquatic Robotics
  - Automated sampling of water for microplastic analysis
  - Increases sampling frequency and reduces costs compared to manned boat operations
  - Equipped with a mechanical micro-filtering system for particulate collection and efficient water filtration

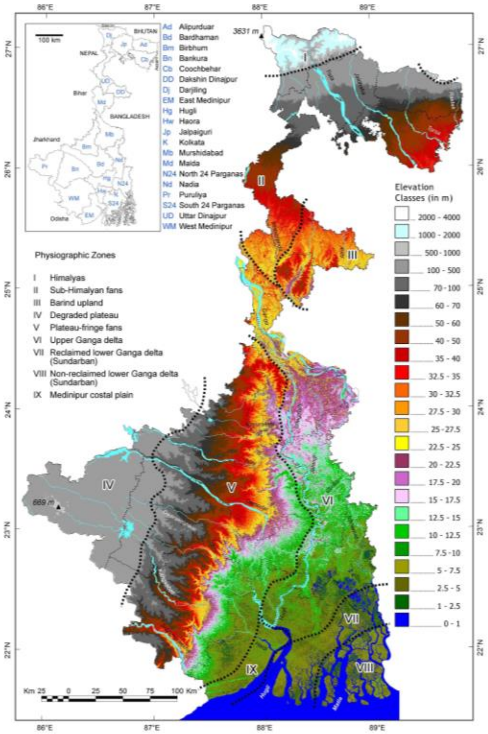
Flow of microplastic pollution

Source: Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G. W., Provencher, J. F., Rochman, C. M., ... & Tekman, M. B. (2022). Plastic pollution in the Arctic. Nature Reviews Earth & Environment, 3(5), 323-337.

Applications and Opportunities: Pollution Monitoring

- Challenges
  - Rising pollutant levels in rivers near the sea require frequent sampling
  - Traditional monitoring methods are labor-intensive, time-consuming, and costly
  - Complex river flows (e.g., in the Bengal region) hinder the use of conventional robotic systems
- Aerial-Aquatic Robotics
  - Automate water quality monitoring for rivers and other water bodies
  - Single-launch, robust designs overcome challenges like surface roughness and currents
  - Jet-powered exit capabilities allow operation in turbulent waters

West Bengal: Physiographic divisions



- Source: Bandyopadhyay, S., Kar, N. S., Das, S., & Sen, J. (2014). River systems and water resources of West Bengal: a review. Geological Society of India special publication, 3(2014), 63-84.

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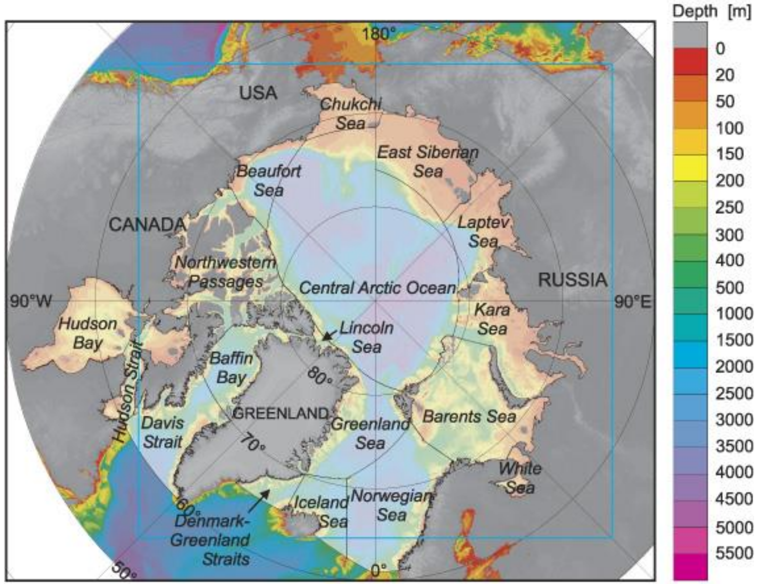
Applications and Opportunities: Arctic Research

- Challenges
  - Remote, hostile, and dangerous environments
  - High cost and time-intensive data collection
  - Difficult access to areas like glacier toes, melt ponds, and sediment-rich glacial flows
- Aerial-Aquatic Robotics
  - Autonomous sampling of remote lakes, glacier toes, and sediment flows
  - Navigation in challenging environments like icebergs and melt ponds
  - Investigate polynyas (open water areas in sea ice)
- Advantages
  - Safe and autonomous data collection minimizes risks to researchers
  - Access to previously unreachable areas (e.g., crater lakes, fjords, edges of glacier terminals)
  - Support long-term preservation of unique environmental data in polar regions

Map of Arctic Ocean



- Source: Jakobsson, M. (2002). Hypsometry and volume of the Arctic Ocean and its constituent seas. Geochemistry, Geophysics, Geosystems, 3(5), 1-18.

Applications and Opportunities: Lake Research

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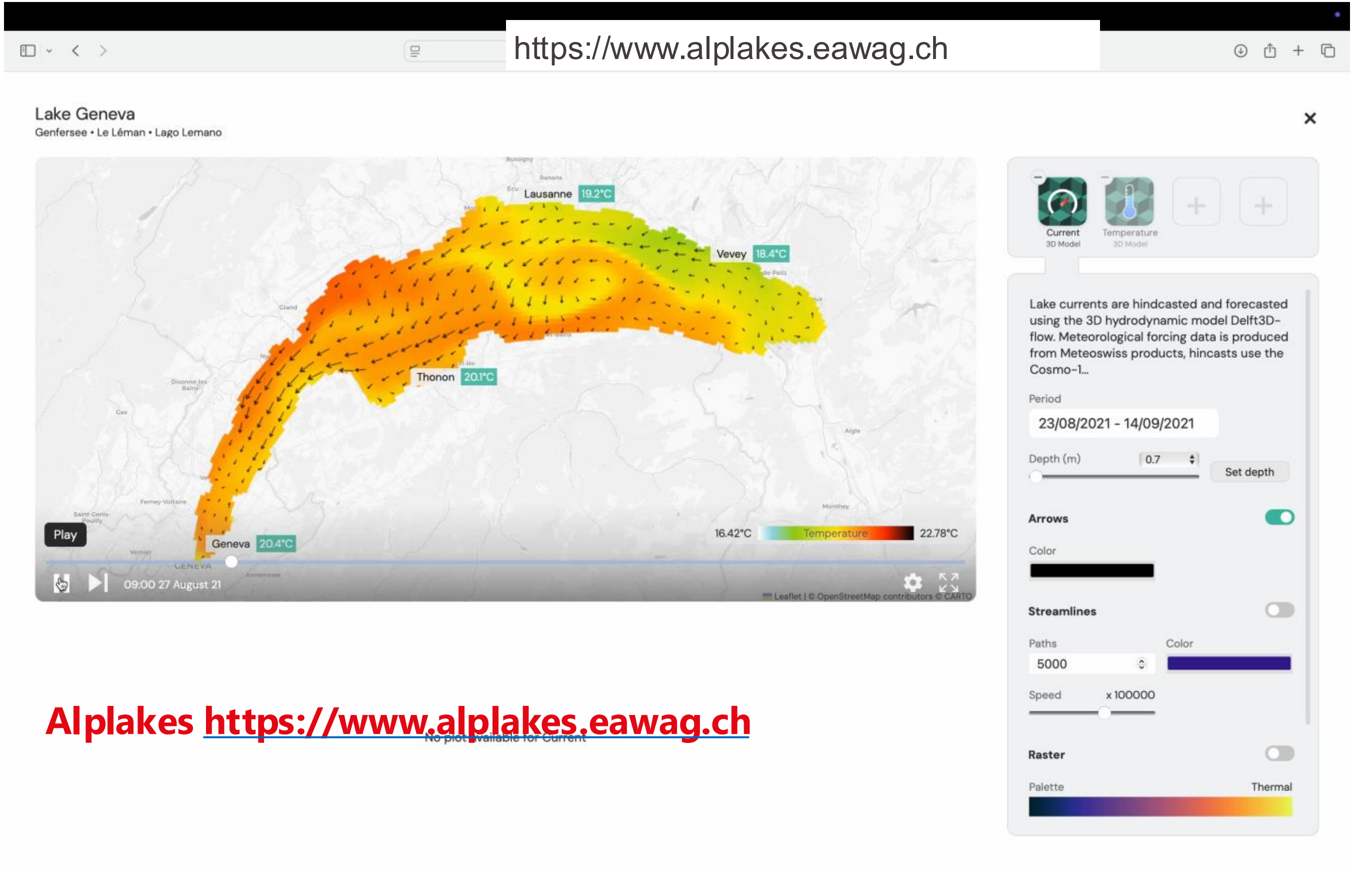


Alplakes https://www.alplakes.eawag.ch

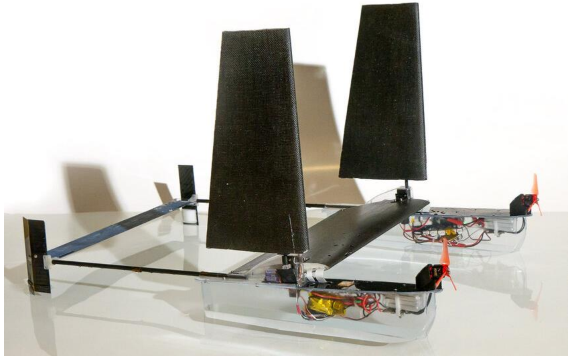
Example of Lake Geneva

- Operational hydrodynamic models (1D & 3D)
- 5 day forecast
- Lake Temperature
- Lake Circulation
- Pollution monitoring

Applications and Opportunities: Marine Wildlife

- Challenges
  - Limited ability to monitor underwater marine life (e.g., fish, plants, whales)
  - Surface-level aerial imaging provides insufficient data for understanding underwater ecosystems
  - High wave resistance and corrosion in salty environments pose design challenges.
- Aerial-Aquatic Robotics
  - Capture downward-facing aerial images for underwater ecosystem monitoring
  - Provide visual data on fish species, sea-weed density, and more
  - Act as a "ground-truth" reference for aerial imaging data-labeling
- Advantages
  - Long operation time allows monitoring of slow-moving subjects
  - Resilient designs (e.g., waterproof and wave-resistant) enable functionality in harsh marine environments
  - Passive hybrid systems (e.g., sailing-flying platforms) are ideal for this mission profile.

Sailing-Flying robot



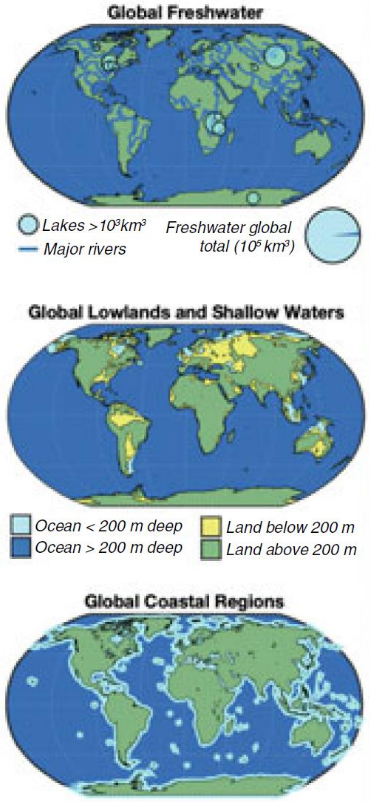
Source: Book, Zufferey, R., Ancel, A. O., Raposo, C., Armanini, S. F., Farinha, A., Siddall, R., ... & Kovac, M. (2019). Sailmav: Design and implementation of a novel multi-modal flying sailing robot. IEEE Robotics and Automation Letters, 4(3), 2894-2901.

Summary

- What Are Aerial-Aquatic Robots?
  - Capable of operating both in the air and underwater
  - Designed to transition seamlessly between environments for diverse applications
- Advantages
  - Multi-Functionality
    - Operates in harsh and inaccessible environments (e.g., Arctic, coastal zones).
  - Efficiency
    - Reduces operational costs and improves data collection frequency.
  - Adaptability
    - Supports diverse missions with integrated sensing and sampling capabilities.
- Key Applications
  - Environmental Monitoring
    - Remote sensing, pollution monitoring, and microplastic analysis
  - Marine Conservation
    - Tracking marine wildlife and mapping coastal ecosystems
  - Industrial Uses
    - Bathymetric mapping, search and rescue missions, and extending research cruise operations

The Pelagic, Pleustonic and Littoral Environments

- Water covers 72% of Earth's surface
  - Most water is saline, frozen, or underground
  - Coastal zones, though small, produce 90% of marine biomass .

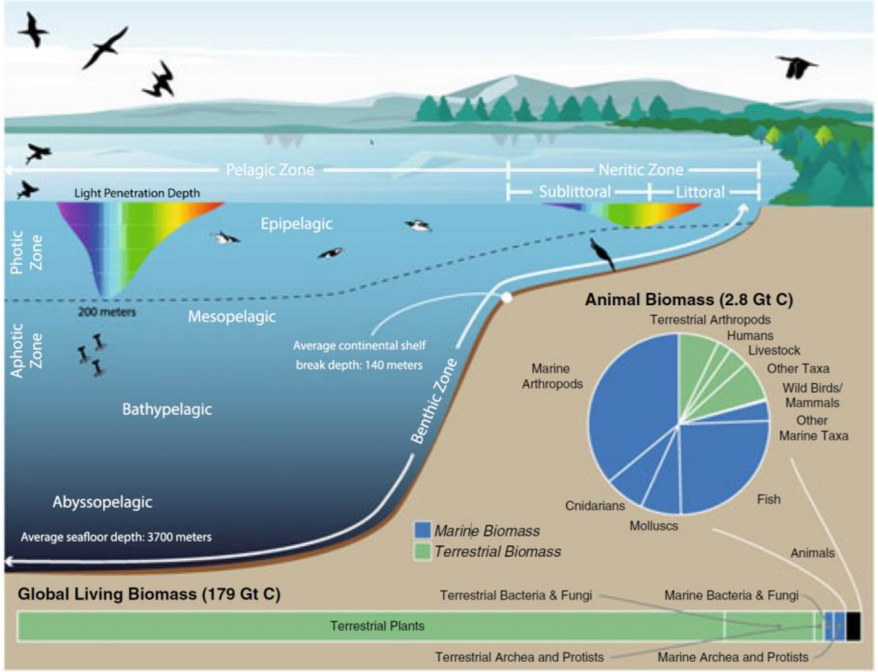


Coasts: 10% of marine area, but 90% of production

- Source: Book

Animal Biomass Distribution

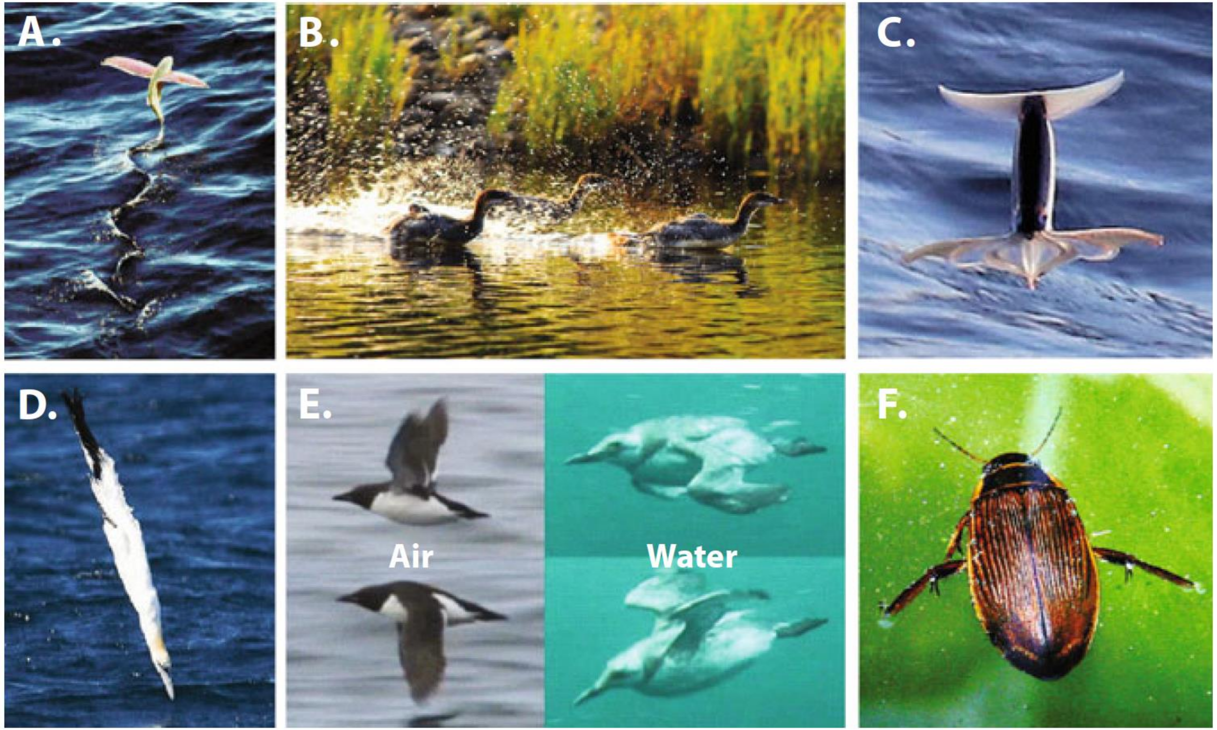
- Marine animals dominate in biomass.
  - Coastal zones are hotspots for predator-prey dynamics.
  - Insights into energy efficiency and locomotion for robotic design.



Source: Book

Swimming in Aerial Animals

- Adaptations for swimming and flying



No.	Strategy	Example
A	Two stage	Flying fish
B	Hydroplaning	Ducks
C	Jet propulsion	Flying squid
D	Plunge diving	Gannet
E	Morphing wings	Guillemot
F	Foot propulsion	Diving beetle

- Source: Book

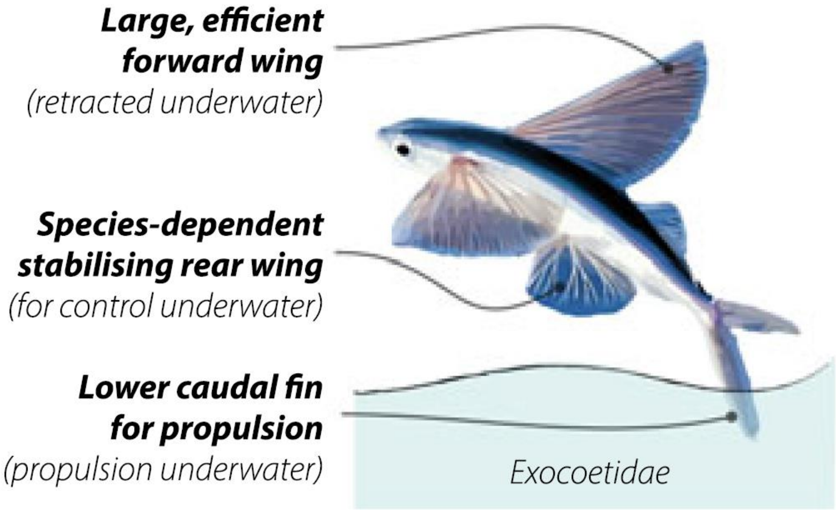
youtube.com/@TEDEd

youtube.com/@bbcearth

Flying Fish

- **Flight Mechanics**
  - Pectoral fins unfold into winds for lift and stability
- **Gliding Performance**
  - Gliding speeds of 15-20 m/s.
  - In flying phase, caudal fin remain in water
- **Other Features**
  - Mucus secretion reduce drag with wing unfolding
  - Exploits ground effect for prolonged flight and increased lift

Flight phase illust of flying fish

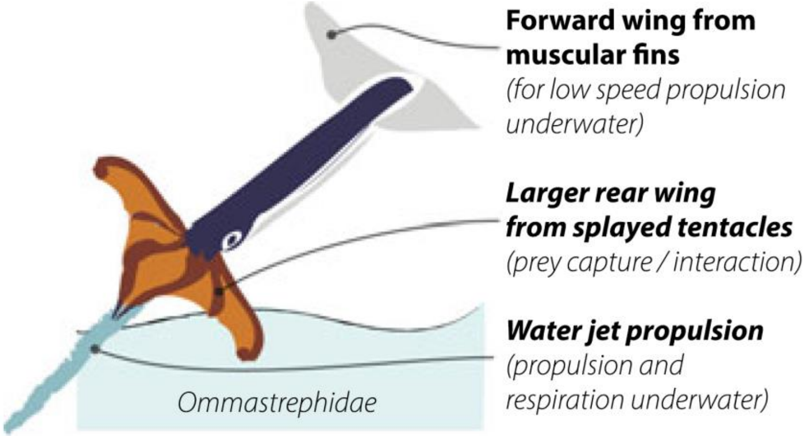


- Source: Book

Flying Squid

- **Overview**
  - Rear wings (Formed by tentacles stretched into a membrane for lift
  - Forward fins: Flap for propulsion underwater and support flight at low speeds
- **Jet Propulsion**
  - Powered by mantle cavity contractions, enabling thrust in air and water
  - Volume change: up to 400% with water pressure reaching 25 kPa
  - Elastic energy stored in collagen fibers enhances power
- **Flight Performance**
  - Short glides lasting 7-8 seconds, reaching 11 m/s
  - Vectoring thrust for directional control by changing orientation of funnel

Flight phase illust of flying squid



Source: Book

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Morphing Wing

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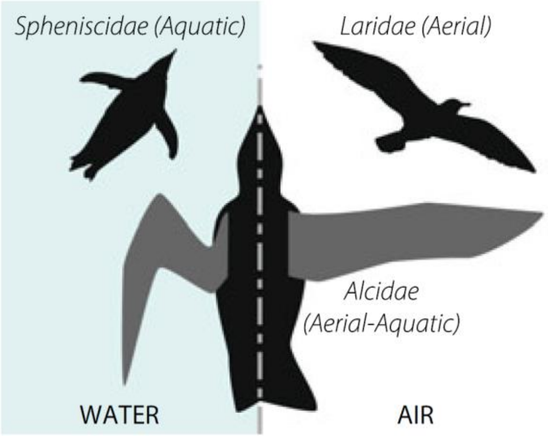
- **Significance of Wing Folding**
  - No fixed-wing animals exist; wing folding reduces drag underwater and lowers structural requirements.
  - Guillemots morph their wings for swimming but do not fully collapse them.

- **Applications in Robotics**
  - Rigid winged underwater gliders are too heavy and inefficient for flight
  - Existing systems include morphing or deployable wings

- Source: Book

Wing Folding Mechanism



Source: Book

Swimming by Wing Folding

Source: phys.org/news/2010-11-seabird-morphing-wings-robots.html#google_vignette

Pursuit Diving

- **Adaptations in Diving Birds**
  - Auks: Guillemots adapt their wings for air and water
    - Smaller, shorter wings with high wing loading (~170 N/m²).
    - Efficient underwater flapping with lower aspect ratio configurations
- **Cormorants: Dive with folded wings and use feet for propulsion**
  - Neutral buoyancy achieved by compressing air in feathers and lungs.
  - Intermittent 'burst and coast' swimming to counteract upthrust.
- **Buoyancy Control**
  - Diving birds carry air for: insulation and respiration and maintaining buoyancy and dry plumage for post-dive flight.
  - Penguins: trapped air under feathers reduces drag by up to 70% during ascent.
    - Enables leaping onto high vertical ice shelves.
    - Example: https://juanvelascoblog.wordpress.com/2012/11/29/emperor-penguins-hit-the-gas/

Guillemots

Source: wikipedia.org/wiki/Guillemot_(oiseau)

Cormorants

Source: wikipedia.org/wiki/Cormorant

Penguin

Source: wikipedia.org/wiki/Penguin

Diving Insects

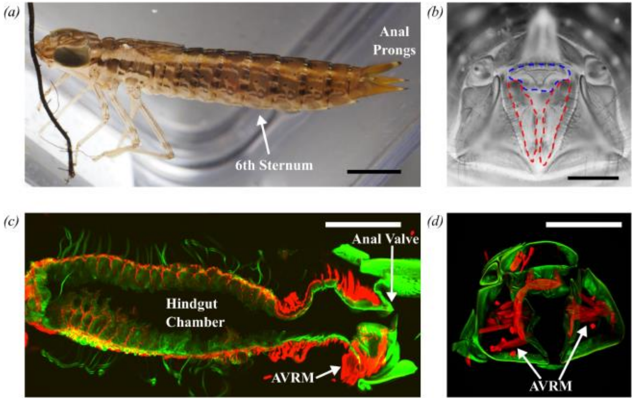
- **General Characteristics**
  - Insects retain wings and swim underwater
  - Use air trapped beneath wings for breathing, balancing buoyancy challenges.

- **Morphological Adaptations**
  - Diving beetles: Streamlined shapes reduce turbulence and allow efficient swimming.
  - Dragonflies: Larvae employ aquatic jet propulsion

Diving beetle

Source: wikipedia.org/wiki/Great_diving_beetle

Body structure of dragonflies larve



- Source: Roh, C., & Gharib, M. (2018). Asymmetry in the jet opening: underwater jet vectoring mechanism by dragonfly larvae. Bioinspiration & Biomimetics, 13(4), 046007.

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Sizing and Energetics

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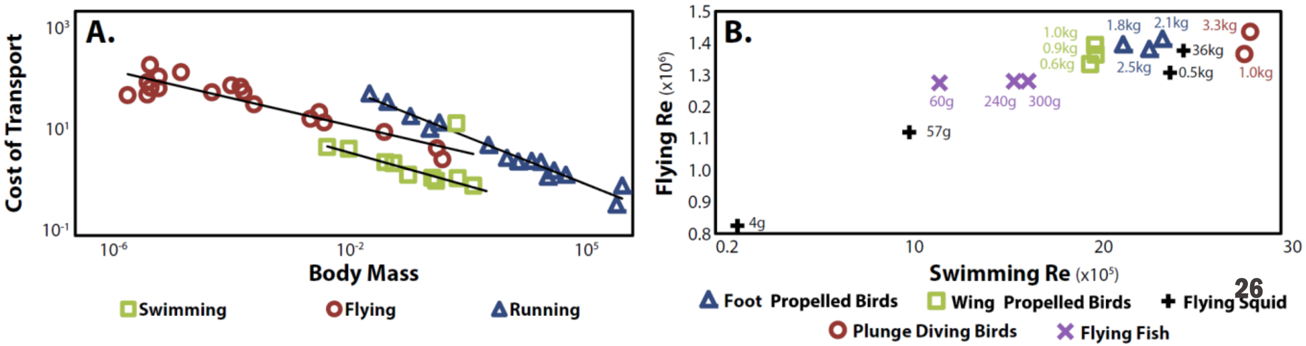
- **Metabolic Costs**
  - Aquatic animals benefit from buoyancy, reducing self-weight transport costs
  - Smaller sizes face increased viscosity and surface tension effects, lowering efficiency
- **Design Considerations**
  - Small size and low weight are crucial for aerial-aquatic vehicles to ensure easy deployment and closer observations
- **Locomotion Dynamics**
  - Flight: Favors low density; restricted by size (e.g., diving birds lose flying ability with size increase)
  - Swimming: Neutral buoyancy supports aquatic locomotion. Variations observed in squid lengths (20 mm to 10 m)
- **Inspiration from Flying Squid**
  - Scalability of flying squid suggests potential for robotic designs

$$\mathrm{COT} \triangleq \frac{E}{mgd} = \frac{P}{mgv}$$

https://en.wikipedia.org/wiki/Cost_of_transport



- Source: Book

Plunge Diving

- **Overview**
  - Gannets sweep wings fully backward at entry
  - Minimal mechanical complexity: no propulsion or neutral buoyancy needed for water entry
- **Advantages**
  - Avoids challenges of soft water landings.
  - Requires minimal landing area—only a GPS waypoint and knowledge of bathymetry
- **Design Insights**
  - Folding wings optimize stability during diving
  - Shifting the center of buoyancy enhances control during the dive and aids post-dive launch readiness

Plunge Diving of Gannet

youtube.com/@bbcearth

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Influence of Philogenesis

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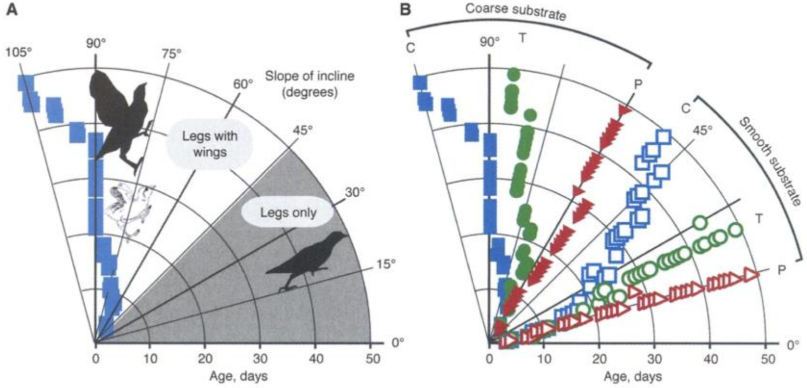
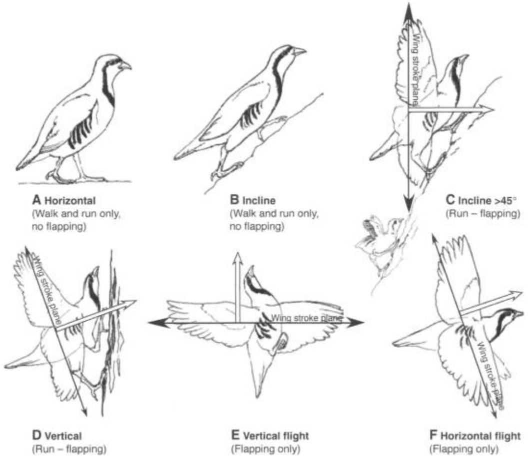


Inclined running performance of Galliform animals with feathered wings



Proposed transitions accompanying WAIR (Wing Assisted Inclined Running) origin of flight hypothesis

Dial, K.P., 2003. Wing-assisted incline running and the evolution of flight. Science, 299(5605), pp.402-404

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Trees-down (arboreal) vs Ground-up (cursorial)

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Source: youtube.com/BBC Earth

Source: youtube.com/BBC Earth

- Dudley et al. 2007 “Gliding and the Functional Origins of Flight” (Annual Rev. Ecol. Evol. Syst.)
  Peterson, Birkmeyer, Dudley & Fearing 2011 “A wing-assisted running robot and implications for avian flight evolution” (Bioinspir. Biomim.)

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Trees-down (arboreal) vs Ground-up (cursorial)

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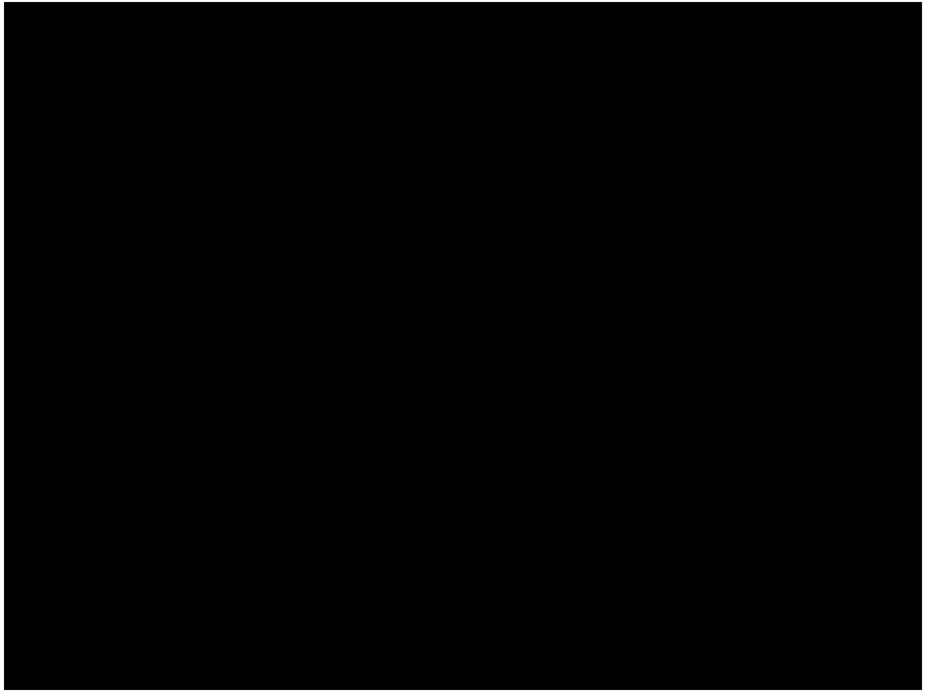
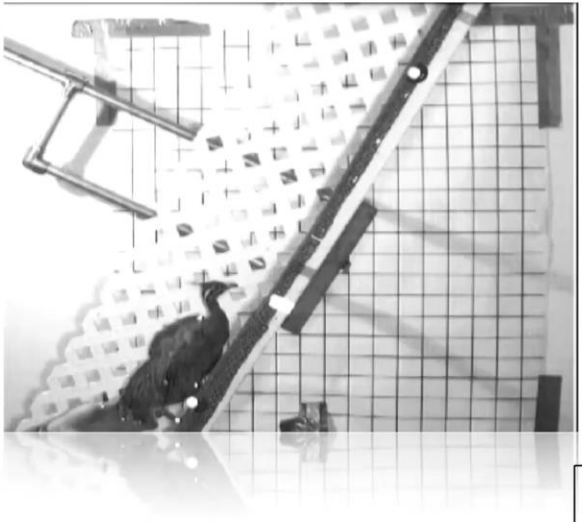
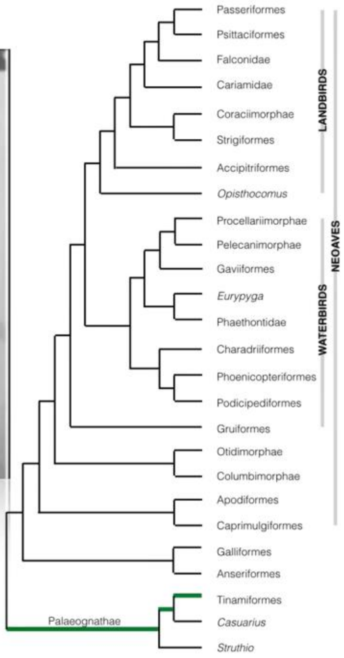


University of Montana Flight Laboratory





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  Peterson, Birkmeyer, Dudley & Fearing 2011 “A wing-assisted running robot and implications for avian flight evolution” (Bioinspir. Biomim.)

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Aerial Aquatic Design Insights in Nature

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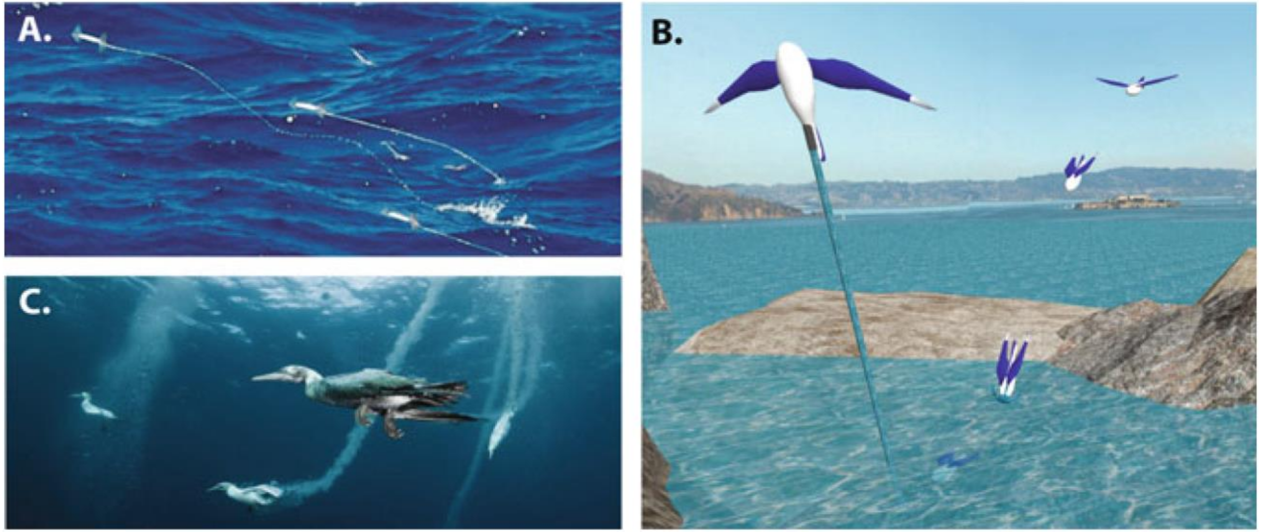
- Flying fish/birds leap directly from water
- Jet propulsion enables efficient, rapid takeoff, reducing drag in air
- Plunge diving is robust for water entry



- Source: Book

Multimodal Robots

- **Key Features**
  - Combines aerial, terrestrial, and aquatic mobility in a single platform.
- **Challenges in design**
  - Increased Mass: Additional subsystems add weight, impacting performance metrics.
  - In flight, increased weight raises power demands for takeoff.
  - In water, buoyancy and density interplay affect locomotion efficiency.
- **Benefits of Multimodal Systems**
  - Enhanced versatility despite added weight.
  - Stabilization during transitions between modes (e.g., crawling to flying).
  - Wings aid in landing orientation and reduce damage by slowing descent.
- **Design Insights**
  - Designing an aerial-aquatic robot with active propulsion is highly complex.
  - Success requires balancing subsystem integration with power and weight trade-offs.

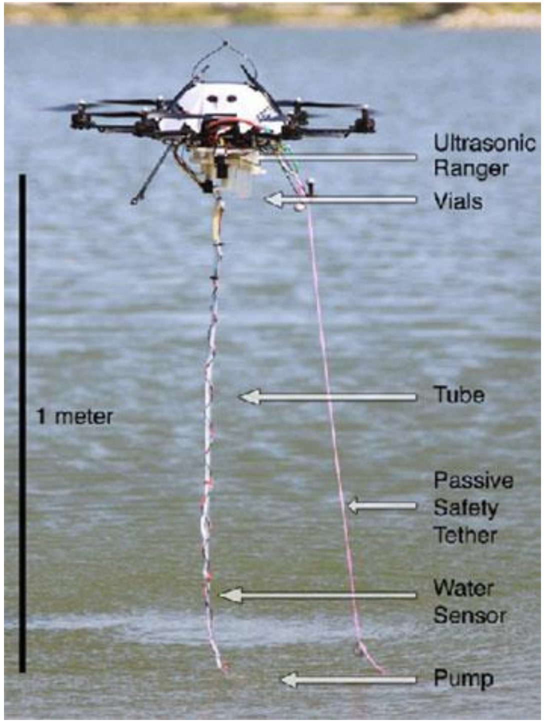
Aerial Water Sampling

- **Key Specifications**
  - Utilization of multirotor UAVs equipped with suction pumps for water sample collection
  - Pumps are suspended ~1m below the UAV for sampling.
  - Precise sensing and control required to maintain stability near ground turbulence.
- **Fixed-wing UAVs**
  - Offer greater range and speed compared to hovering vehicles.
  - Plunge diving UAVs reduce the need for precise control, enabling lower-cost production and scalability
- **Disposable Systems**
  - Deployment of underwater vehicles from air using single-use equipment:
  - Includes parachutes, airbags, and discardable wings
- **Future Possibilities**
  - Aerial-Aquatic Micro Aerial Vehicles (MAVs)
  - Inherent capabilities for air-launched aquatic operations.
  - Address existing demand for air-launched underwater vehicles.

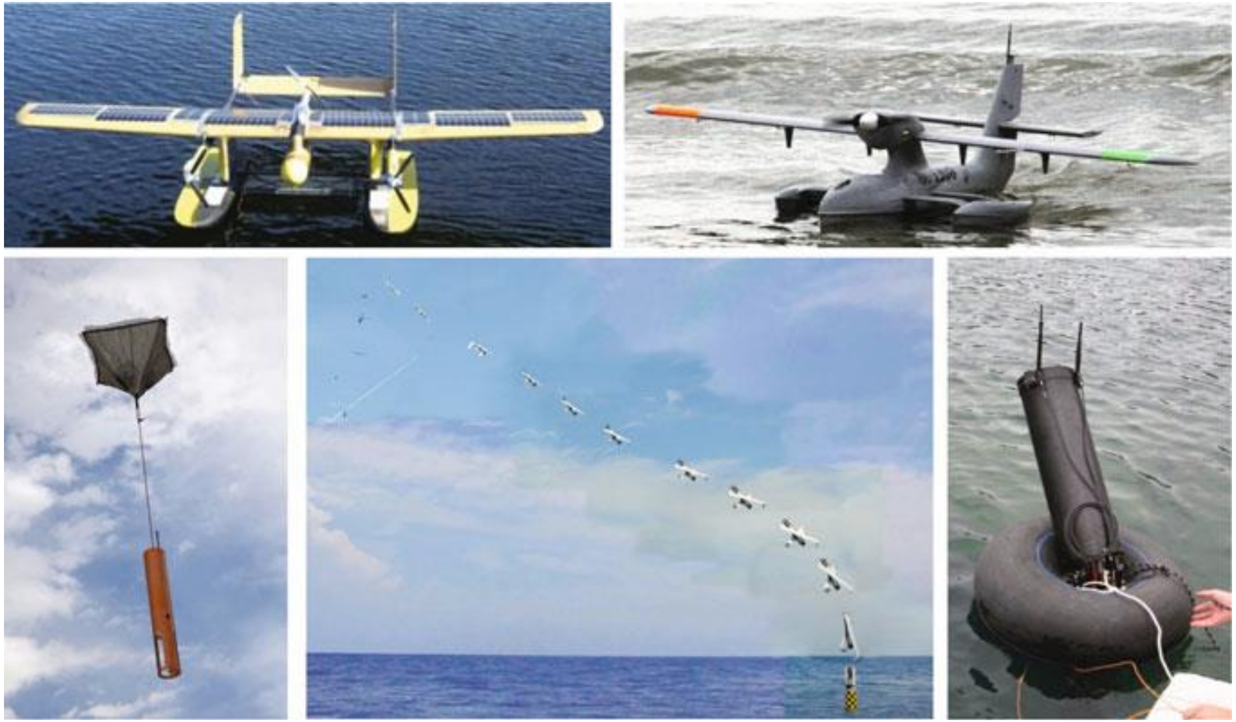
- Source: Book

Aerial Water Sampling

Autonomous Aerial Water Sampler



Aquatic unmanned aerial vehicles

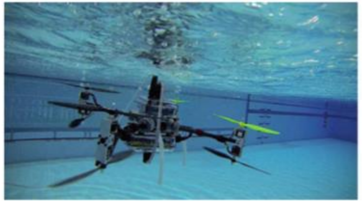


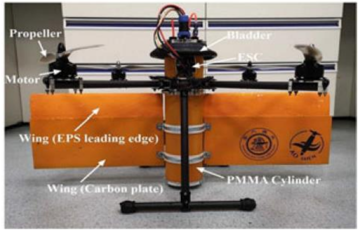
- Source: Book

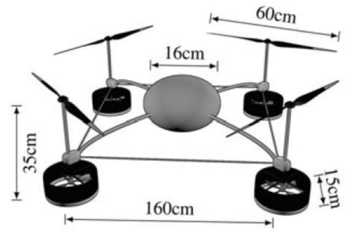
Rotary-Wing Vehicles

- **Key Features**
  - Versatility: Vertical takeoff, landing, and water operations
  - Mission Flexibility: Enables swimming and flying phases in a single mission
- **Challenges**
  - Efficiency
    - Aerial propulsion in water operates at low efficiency
  - Surface Requirements
    - Requires calm water (<10cm waves) for takeoff
- **Performance**
  - Added weight from separate aquatic and aerial systems impacts efficiency
  - Short operational range for underwater missions
- **Notable Innovations**
  - Double-layer propellers ensure thrust for water-to-air transitions
  - Buoyancy control mechanisms allow smooth floating and reorientation
- **Hybrid Concepts**
  - Vertical Take-off and Landing (VTOL) designs enhance aerial efficiency
  - Separate propellers for aquatic and aerial modes reduce inefficiencies

Rotary-Wing Vehicles





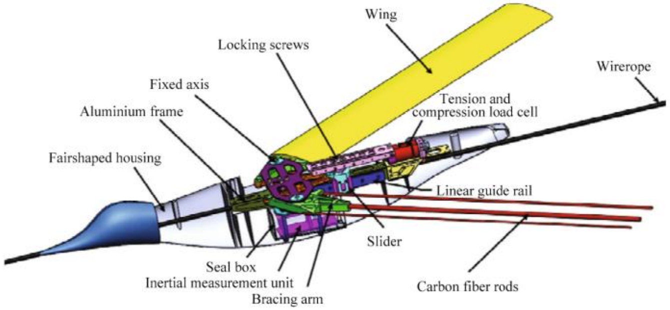


Source: Book

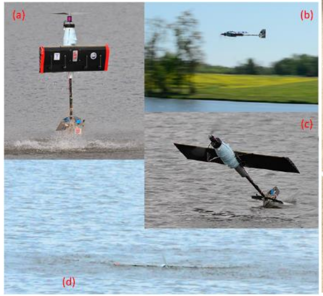
Fixed-Wing

- **Advantages**
  - Efficient for long-distance and extended missions
- **Challenges**
  - Difficult to achieve neutral buoyancy and smooth water-to-air transitions
  - Requires robust structures for water impact
- **Key Innovations**
  - Flying-Wing MAVs: Delta wing design for impact resilience and controlled transitions
  - Rectangular Wing MAVs: Efficient wings with passive drainage for underwater movement
  - Folding Wing MAVs: Foldable wings for plunge-diving and dual propulsion systems

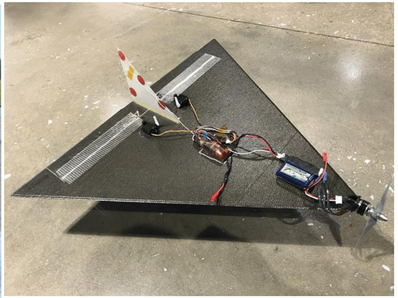
Folding Wing MAVs



Rectangular Wing MAVs



Flying-Wing MAVs



Source: Liang, J., Yang, X., Wang, T., Yao, G., & Zhao, W. (2013). Design and experiment of a bionic gannet for plunge-diving. Journal of Bionic Engineering, 10(3), 282-291., Stewart, W., Weisler, W., MacLeod, M., Powers, T., Defreitas, A., Gritter, R., ... & Bryant, M. (2018). Design and demonstration of a seabird-inspired fixed-wing hybrid UAV-UUV system. Bioinspiration & biomimetics, 13(5), 056013., Moore, J., Fein, A., & Setzler, W. (2018, May). Design and analysis of a fixed-wing unmanned aerial-aquatic vehicle. In *2018 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 1236-1243). IEEE.

Tilting Propeller Configurations

- Overview:
  - Propellor to rotate 90° for efficient water-to-air transitions
  - Eliminates the need for taxing space by accelerating directly into flight

- Key Features
  - Buoyancy
    - Highly buoyant design enables direct water entry and soft landings
    - Rotatable propeller self-rights the vehicle after diving
  - Efficiency
    - Simplified takeoff and landing process with minimal actuators
    - Reliable performance in calm water conditions

- Challenges
  - Limited performance in rough water or adverse conditions
  - Narrow operational envelope for successful launches

- Applications
  - Enhances reliability for aquatic environments with fewer mechanical components

Vertical Lift-Off MAVs

Tilting Propellor MAVs

Source: Tétreault, É., Rancourt, D., & Desbiens, A. L. (2020). Active vertical takeoff of an aquatic uav. IEEE Robotics and Automation Letters, 5(3), 4844-4851., Peloquin, R. A., Thibault, D., & Desbiens, A. L. (2016). Design of a passive vertical takeoff and landing aquatic UAV. IEEE Robotics and Automation Letters, 2(2), 381-388.

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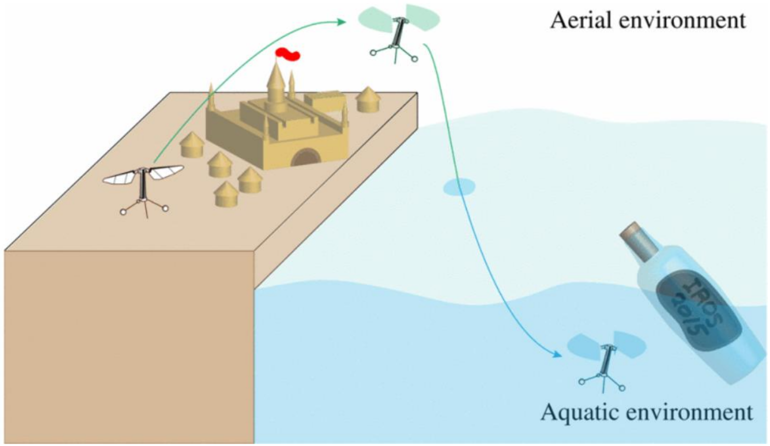
Flapping Wing Vehicles

Empa

- **Advantages**
  - Demonstrated in both air and water; potential for dual-mode operation
- **Key Studies**
  - Guillemot-inspired robots: Optimized for air-water missions but not fully practical
  - Dual-mode propulsion: Efficient thrust demonstrated via kinematic changes
  - Insect-scale vehicles: Demonstrated aerial-aquatic transition using external power and surfactants
- **Aquatic Robobee system**
  - Advanced design using electrolysis for water-air transition
- **Challenges**
  - Energy inefficiency and external power reliance
  - Difficulty transitioning between air and water modes
  - Reduced stroke range on the water surface hinders take-off

Robobee for water-air transition



- Source: Chen, Y., Helbling, E. F., Gravish, N., Ma, K., & Wood, R. J. (2015, September). Hybrid aerial and aquatic locomotion in an at-scale robotic insect. In 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 331-338). IEEE

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Summary: Possible Transition Methods Between Water to Air

Empa

Aerial-aquatic water-to-air transition (WAT)

	Impulsive	Horizontal Lift-off	Vertical take-off
Principle	Fast and large energy release from chemical or elastic element	Aerodynamic surfaces create lift	Propellers create vertical thurust
Cost of methods	Additional on board power storage or production	Take-off distance required	Uncertain transition or floats
Advantages	No control required, insensite to sea-state	Efficient maneuver	Mechanically simple

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Summary: Possible Transition Methods Between Water to Air

Empa

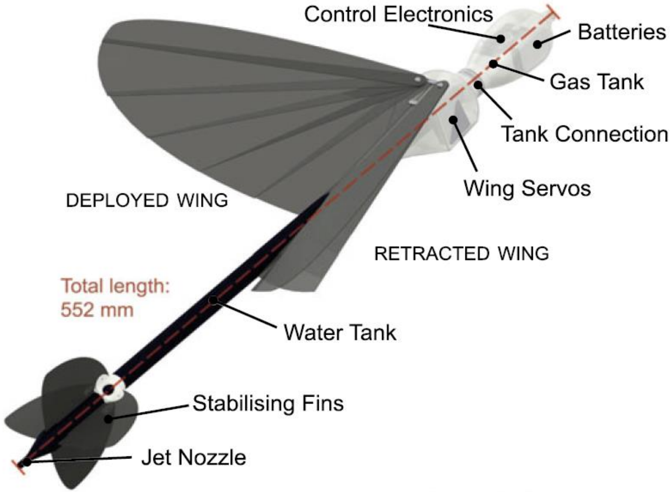
Aerial-aquatic air-to-water transition (AWT)

	Diving	Horizontal Landing	Vertical landing
Principle	High-speed, head-first divie	Horizontal landing	Propellers create vertical thrust
Cost of methods	High structural requirements	High level of control	High power requirement
Advantages	No control required, insensitive to sea-state	Does not require submerging, low forces	Gradual approach, mechanically simple

Compressed Gas Water Jet Thruster

- Technology Overview
  - Jet thruster powered by compressed CO2 (57 bar)
  - Lightweight, modular, and capable of multiple launches
- Performance Highlights
  - Indoor speeds up to 11 m/s; validated with outdoor tests
  - Stable aquatic escape via optimized wing deployment and trajectory design
- Design Features
  - Interchangeable tank sizes and durable CFRP-aluminum construction
  - Deployable wings for stability and glide

Gas Water Jet Thruster MAVs



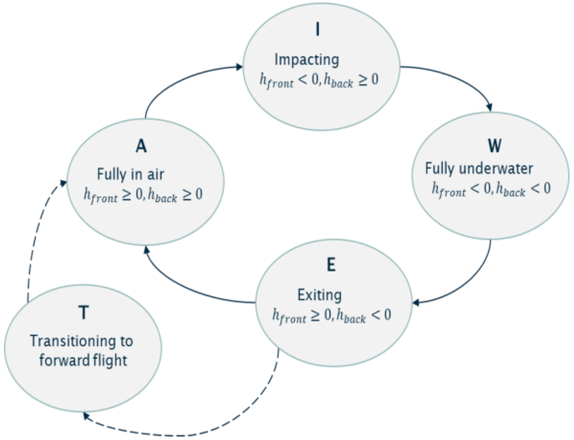
- Source: Siddall, R., & Kovac, M. (2016). Fast aquatic escape with a jet thruster. IEEE/ASME transactions on mechatronics, 22(1), 217-226.

A Jet Propelled Aquatic Jumpglider

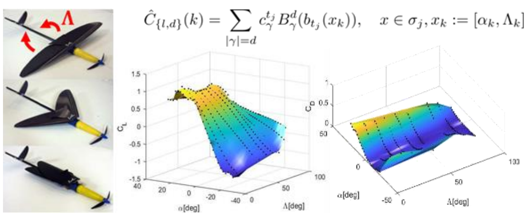
Robert Siddall and Mirko Kovac

Aerial Robotics Laboratory
Imperial College London

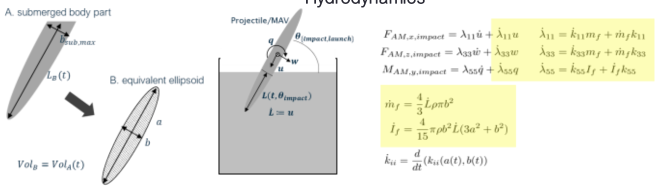
Modelling aerial-aquatic robots

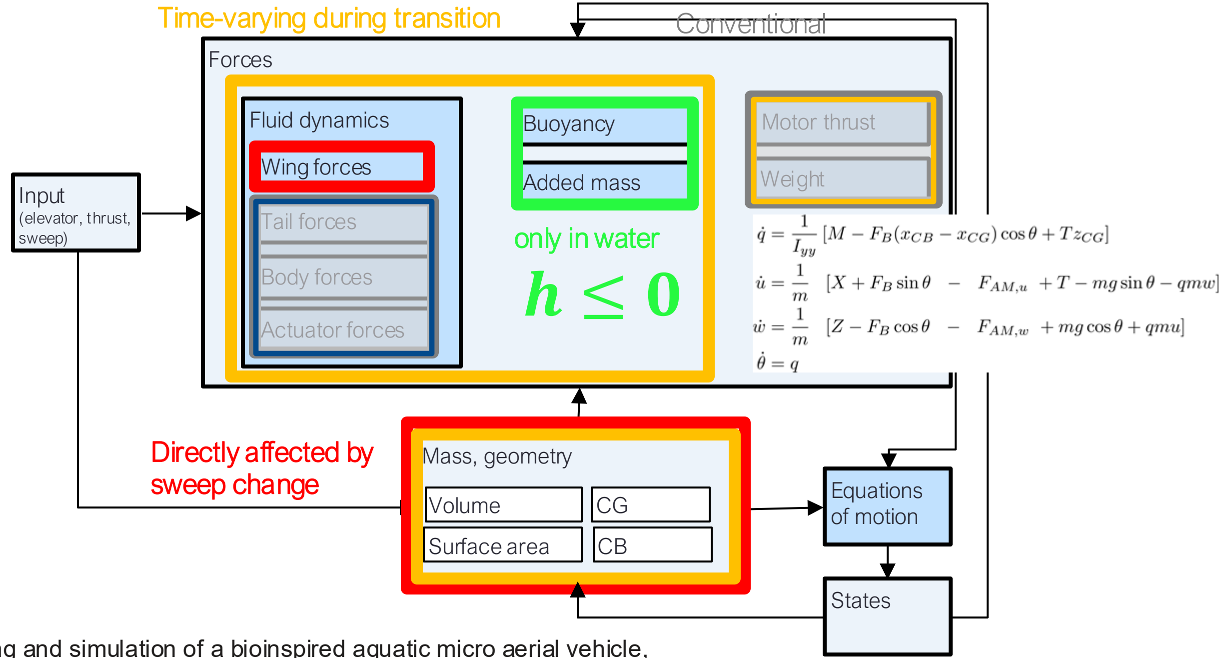


Aerodynamics



Hydrodynamics





Challenges

- Time-varying effects
- Multi-phase aerodynamics
- Hybrid system, transitions
- Unconventional manoeuvres
- Self-manufactured, unique vehicles
- *Waves, wind, ground effect*

Armanini, S.F., Siddall, R., Kovac, M., Modelling and simulation of a bioinspired aquatic micro aerial vehicle, *AIAA Modeling and Simulation Technologies* (2019)

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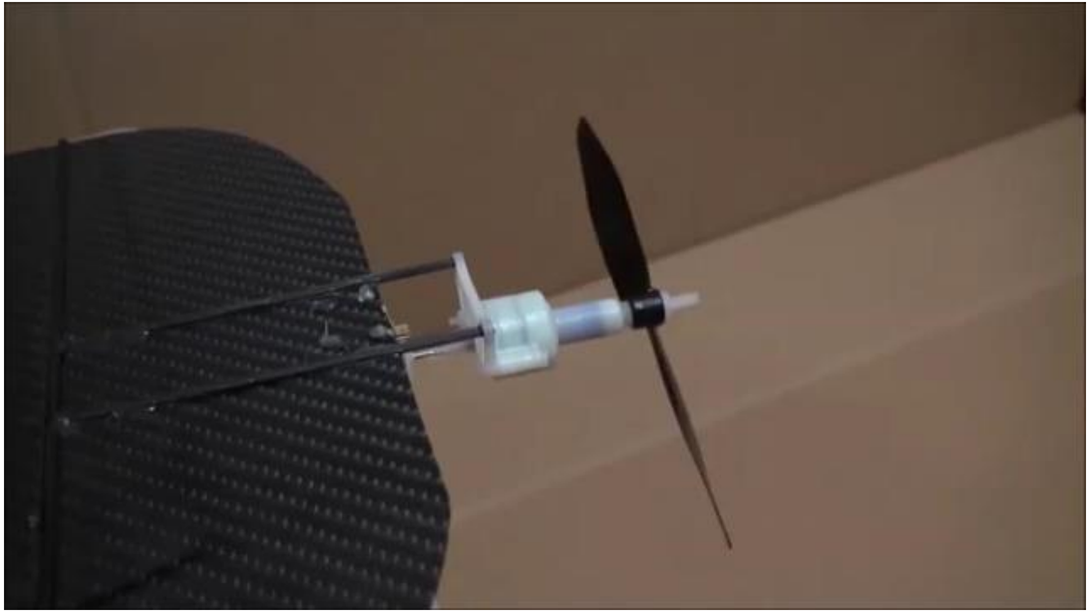
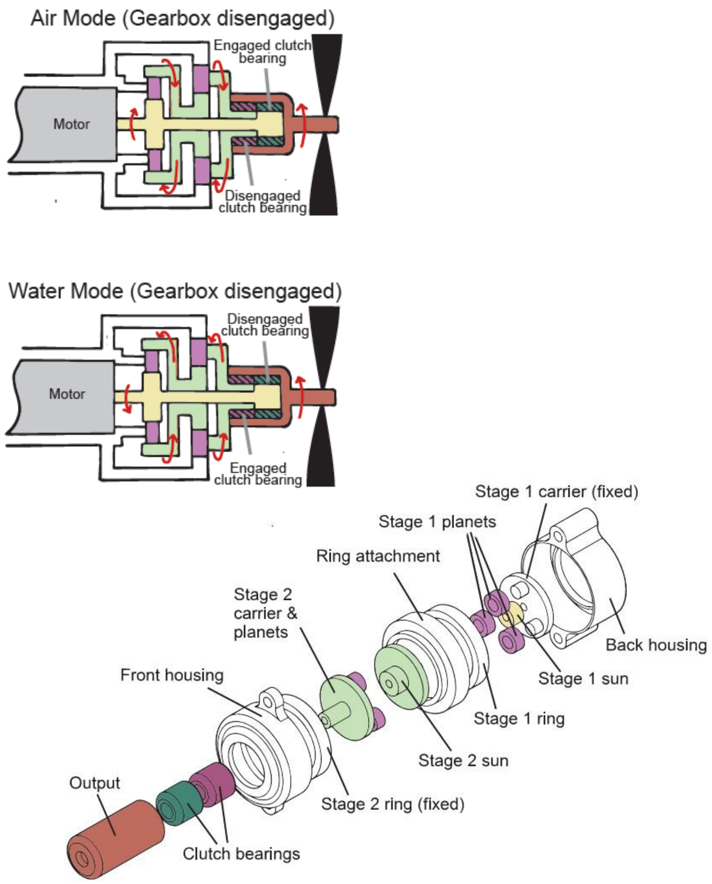
Aerial Aquatic Robot : AquaMAV

Empa





Two modes with ratios: 1:1, 15:1

Clutch bearing for drive mode selection

Compact size — 25 mm diameter

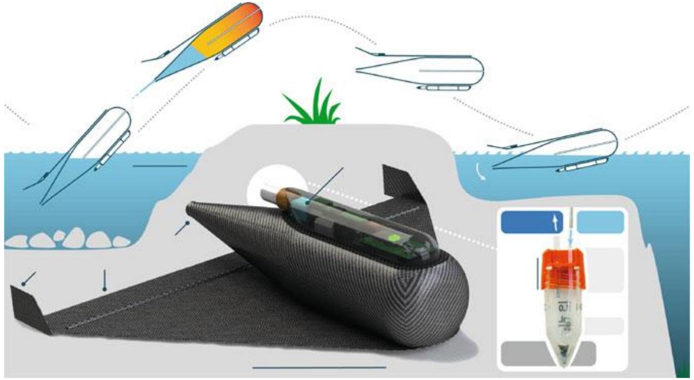
Lightweight — 10 grams

- Tan, Siddall and Kovac, Efficient Aerial-Aquatic Locomotion with a Single Propulsion System, *Robotics and Automation Letters / IEEE ICRA,* 2016

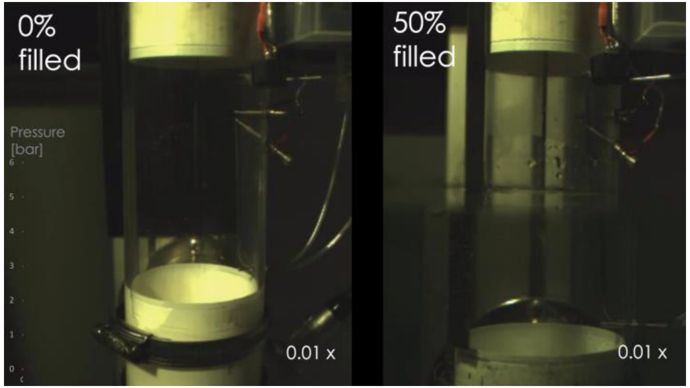
Aquatic Escape with Combustion

- Key Technology
  - Utilizes calcium carbide and water to generate acetylene for combustion
  - Lightweight, modular propulsion system for repeated water-to-air transitions
- Performance Highlights
  - High-power propulsion for turbulent environments
  - Validated with experiments matching simulation results
- Design Features
  - Compact chambers for controlled combustion
  - Automated reaction cycles and nozzle optimization for thrust

Aerial-aquatic escape robot



Aquatic ecape with combustion

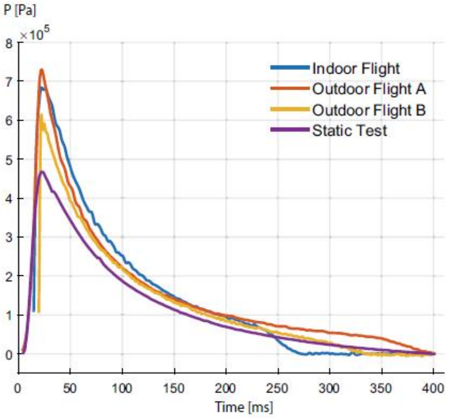


- Source: Zufferey, R., Ancel, A. O., Farinha, A., Siddall, R., Armanini, S. F., Nasr, M., ... & Kovac, M. (2019). Consecutive aquatic jump-gliding with water-reactive fuel. Science Robotics, 4(34), eaax7330.

Aquatic Escape with Combustion

- Applications
  - Ideal for sampling, navigation, and data collection in challenging conditions
  - Applicable in high-turbulence aquatic zones

- Future Focus
  - Miniaturizing systems for broader robot applications
  - Enhancing reliability and safety in propulsion mechanisms.

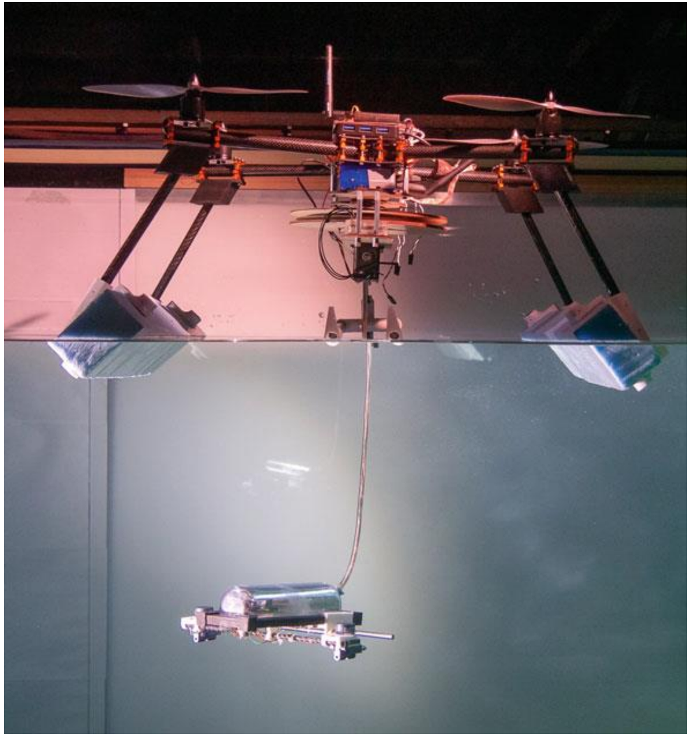


Source: Book, Zufferey, R., Ancel, A. O., Farinha, A., Siddall, R., Armanini, S. F., Nasr, M., ... & Kovac, M. (2019). Consecutive aquatic jump-gliding with water-reactive fuel. Science Robotics, 4(34), eaax7330.

Multirotor Aircraft in Aquatic Environments

- Key Features
  - MEDUSA System: Symbiotic design with a quadrotor and tethered underwater pod
  - Operation: Quadrotor lands on water, deploying the pod for sampling and measurements
- Advantages
  - Minimizes waterproofing needs with above-water quadrotor
  - Lightweight, neutrally buoyant tether provides power and communication
- Applications
  - Coral reef monitoring, water quality testing, and ecosystem mapping
  - Suitable for intricate, shallow aquatic environments

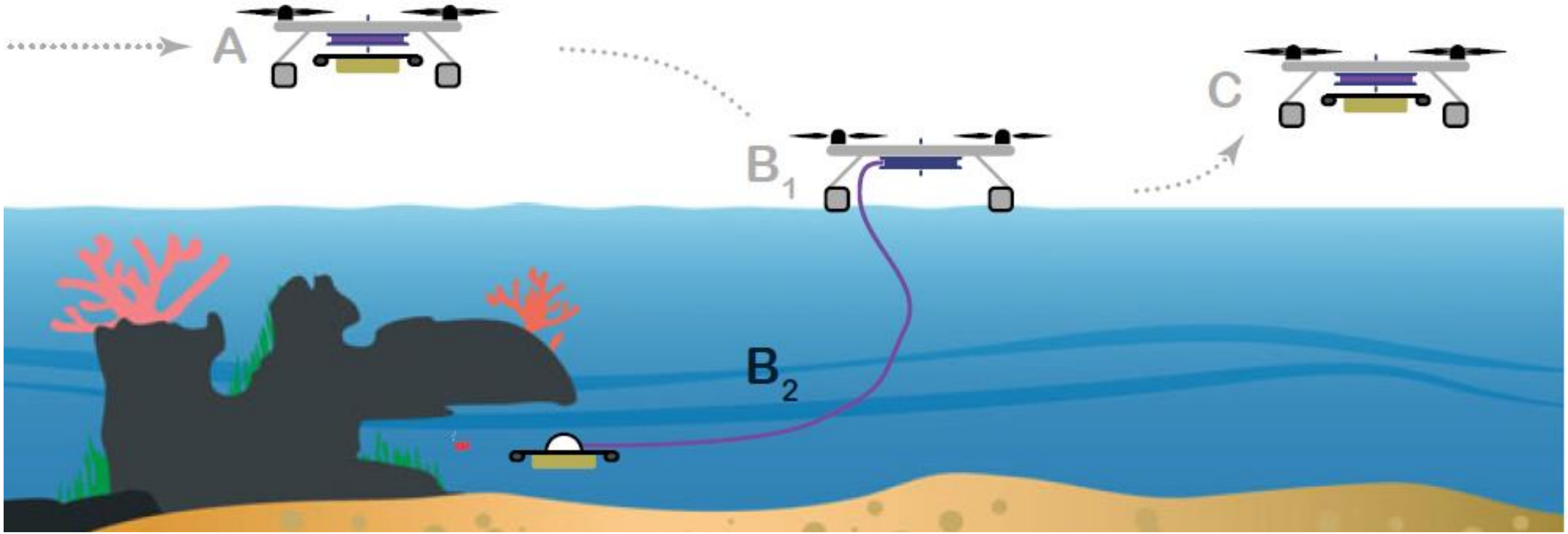
MEDUSA drone



- Source: Debruyn, D., Zufferey, R., Armanini, S. F., Winston, C., Farinha, A., Jin, Y., & Kovac, M. (2020). Medusa: A multi-environment dual-robot for underwater sample acquisition. IEEE Robotics and Automation Letters, 5(3), 4564-4571.

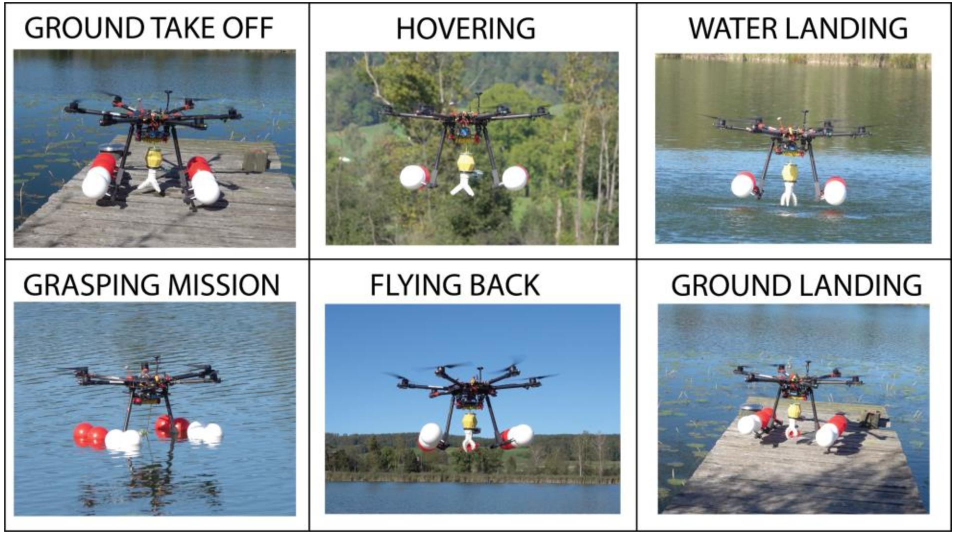
Multirotor Aircraft in Aquatic Environments

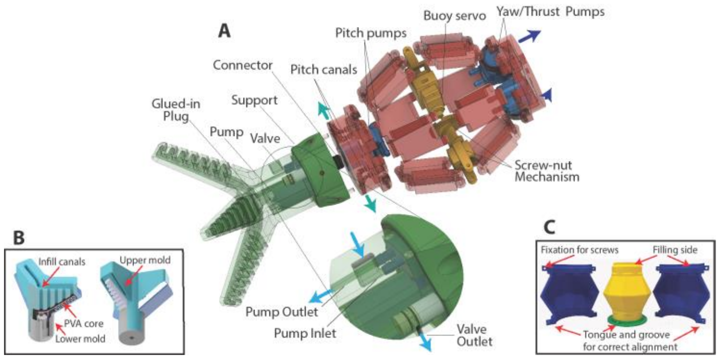
- Innovations
  - Dual-robot approach for enhanced versatility and adaptability
  - Modular designs simplify maintenance and enable customization

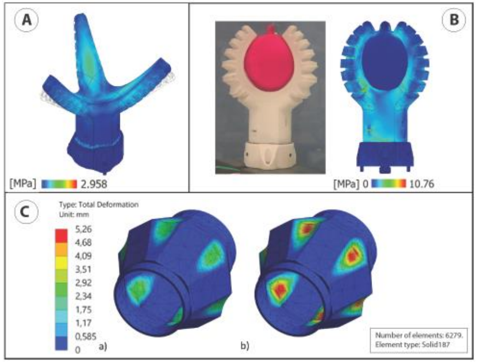


Medusa – Soft Grasping Pod

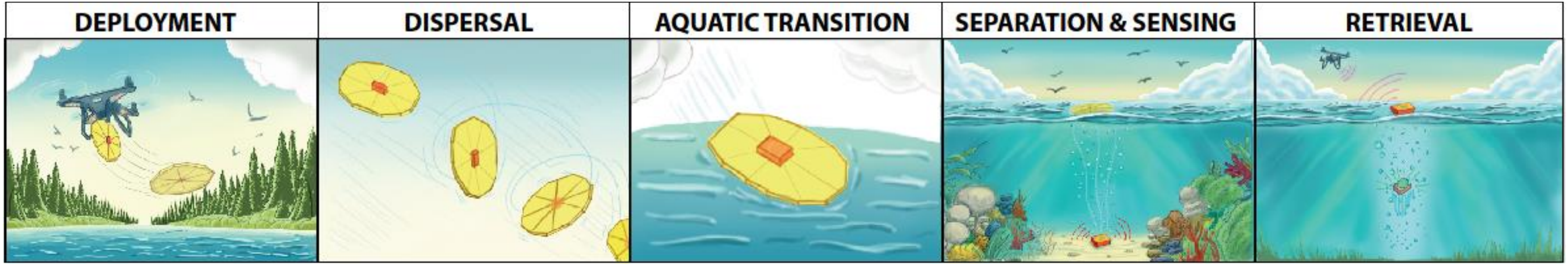
Romanello, L., Amir, D.J., Stengel, H., Kovac, M. and Armanini, S.F. (2024). RoboSoft 2024.

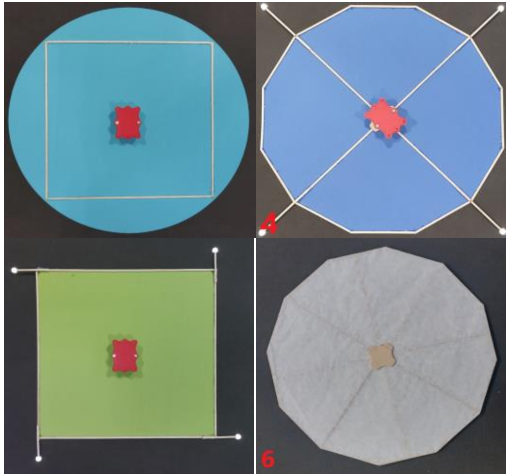


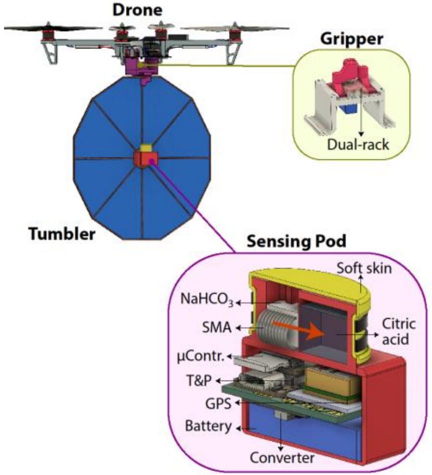


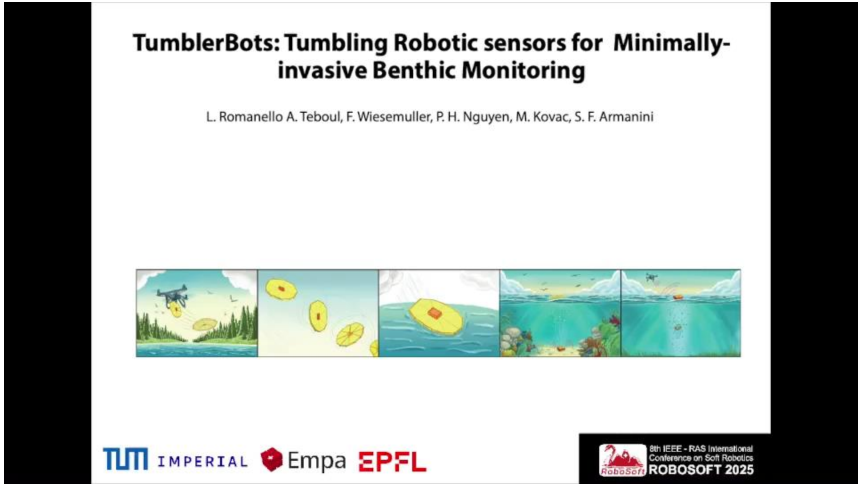


TumblerBots: Tumbling Robotic Sensors for Minimally-invasive Benthic Monitoring









Romanello, L., Teboul, A., Wiesemuller, F., Nguyen, P.H., Kovac, M., and Armanini, S.F. (2024). RoboSoft 2025. [In Review]

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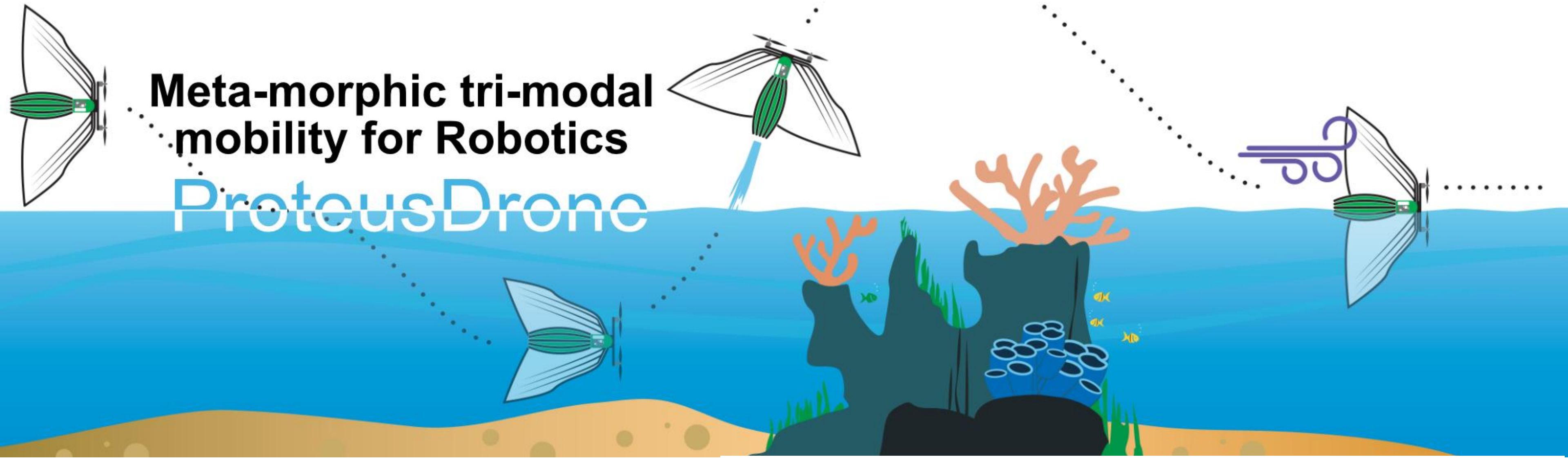
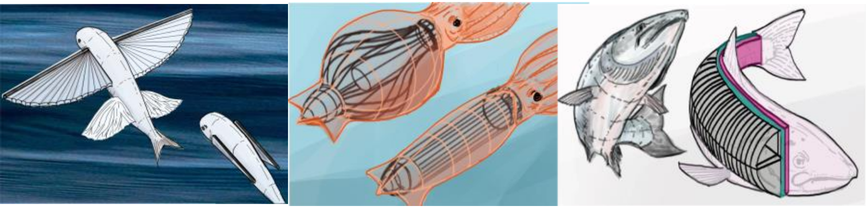
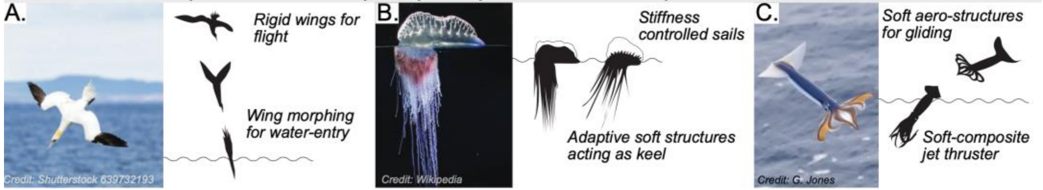
Proteus-X

European Research Council

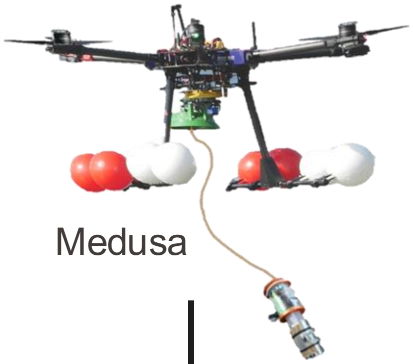




Bio-inspired meta-morphic principles for aerial-aquatic terrain transitions



Previous Work



Medusa

SailMAV

AquaMAV

Proteus

To Fly, Dive, Swim, Transition, and Sail

“How does on-demand body-shape morphing affect the overall energy efficiency, stability, and sensing payload capacity of an aerial–aquatic drone during repeated transitions between flight, surface skimming, and fully submerged locomotion in varying operating conditions?”


Source: Anthony Pierce/SplashdownDirect

The Flying Squid

Aerial Aquatic Transition

Locomotion

Squid locomotion is twofold:

1. underwater jetting;

1) Underwater jetting of a Strawberry squid (*Histiotheutis heteroptus*)

Source: [1] Bujard, T. et al, 2021. A resonant squid-inspired robot unlocks biological propulsive efficiency. *Science Robotics*, *6*(50).

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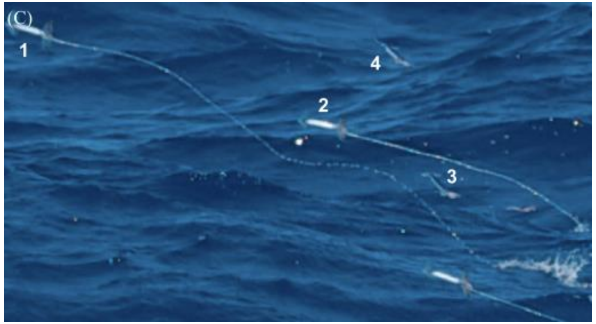

2) Group of 4 flying squids with plotted aerial trajectory

Source: [2] O'Dor, R. et al, 2013. Squid rocket science: How squid launch into air. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *95*, 113–118.

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Empa

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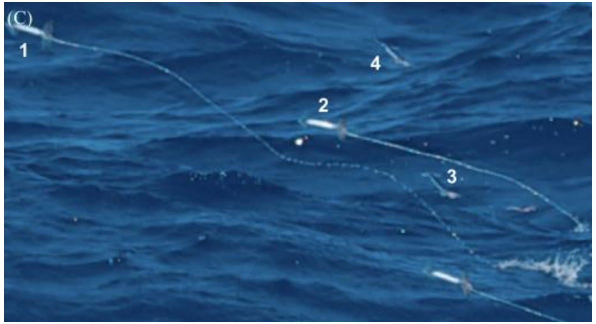

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Research question

“Is aerial aquatic locomotion a *predatory* or a *migration* strategy for squids?”

Predation: fight or flight mechanism, no matter the energetic cost

Migration: long and steady propulsion, energetic cost must be optimized

Research question

“Is aerial aquatic locomotion a *predatory* or a *migration* strategy for squids?”

Predation: fight or flight mechanism, no matter the energetic cost

cost of transport → amount of energy necessary to engage in the chosen type of locomotion

Migration: long and steady propulsion, energetic cost must be optimized

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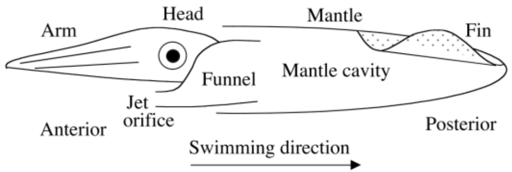
Underwater jetting mechanics

Active propulsion:

- squid eject 90% (40%) of intramantle fluid when swimming fast (slow)
- volume change in mantle cavity implies intramantle pressure change
- cost of transport depends on comparison between $V_{jetting}$ to V_{fluid}



Steering:

- undulating fins
- muscular direction of jet

Refill period:

- crucial for total hydrodynamic efficiency
- shape change and added mass
- mantle elastic properties + antagonistic muscles + flow induced surface pressure

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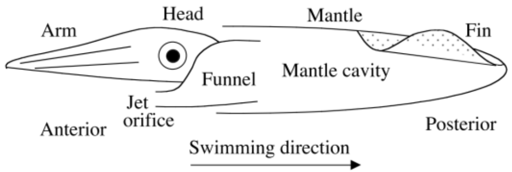

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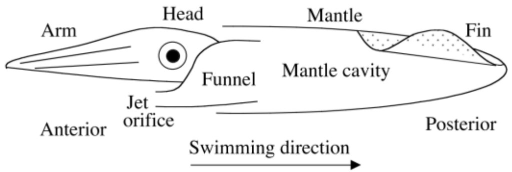

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EPFL

Empa

Underwater jetting mechanics

Froude propulsion efficiency model, analysis found in:

"Anderson, E.J et al. "*The mechanics of locomotion in the squid Loligo pealei: locomotory function and unsteady hydrodynamics of the jet and intramantle pressure*" Journal of Experimental Biology, 203(18), pp.2851-2863.

Propulsive efficiency:
(eq. of Froude for airscrew propeller)

$$\eta = \frac{2V(t)}{V(t)+Vj(t)}$$

V being the upstream flow velocity,
Vj the downstream jetting velocity

V_j is estimated as:

$$V_j(t) = \frac{Q(t)}{A_j(t)}$$

Q being the matle flow rate,
Aj the jetting area

where $A_j(t) = \frac{\pi\, a\, b(t)}{4}$; $Q(t) = -\frac{d\forall_m(t)}{dt}$

a and *b* being geometrical parameters of the squid's mantle;
$\forall_m$ the mantle's volume
(all estimated from pictures of 2 squids flumes @ Woods Hole Oceanographic Institution Rhinehart Coastal Research Center)

Flight mechanics

4 PHASES:

1	2	3	4
LAUNCHING	JETTING	GLIDING	DIVING

Active propulsion:

- rocket powered flight → squids eject fluid underwater & while airbourne
- muscular direction of jet

Steering:

- undulating fins developed accordingly
- attitude control through change of aerial posture

Performance of humbolt squid (Dosidicus Gigas)

- air max speed: 4 m/s
- water max speed: 7 m/s
- hard to extract proper amount of data → measurements taken from pictures & videos

Flight mechanics

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Performance of *humbolt squid* (Dosidicus Gigas)

- air max speed: 4 m/s
- water max speed: 7 m/s
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Aerial mechanics

Further *in situ* observations:

1. scientific community agrees on squids jetting while airbourne
2. 2m to 6m above water surface, flights 4s long at speeds ~ 5 m/s
3. entire squid schools have been observed flying
4. flight observations mainly refer to predation circumstances
5. no flight while squid school chased by dolphing pod

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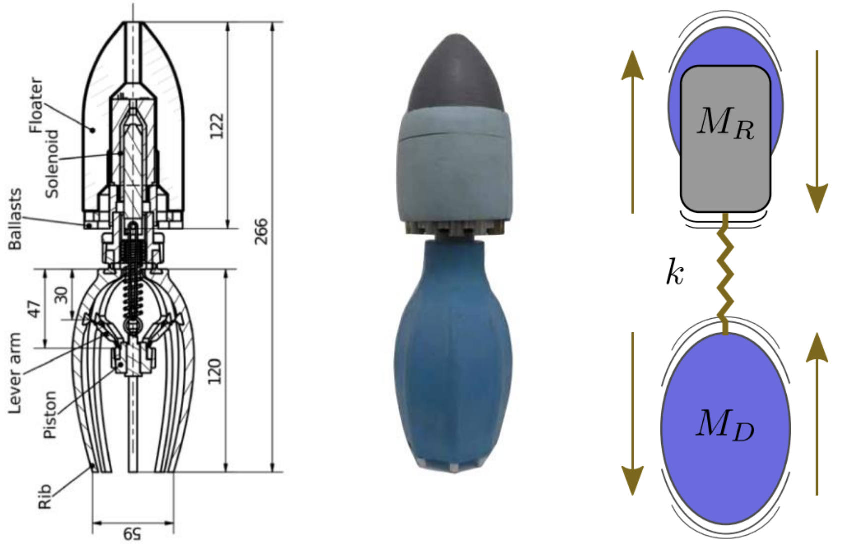
Squid inspired robot

Empa

Resonant squid-like robot, 2021,
[1]

Key elements

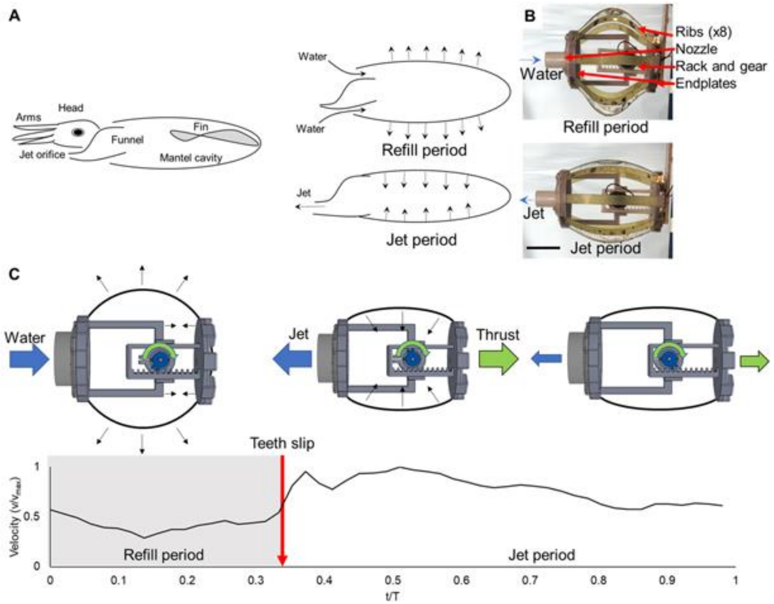
- spring loaded mechanism
- cost of transport low due to pulse syncronization with vortex dynamics
- unable to jump out of the water



Section (left), frontal picture (centre) and physical model of the resonant squid-like robot. The system is actuated by a spring-loaded mechanism.

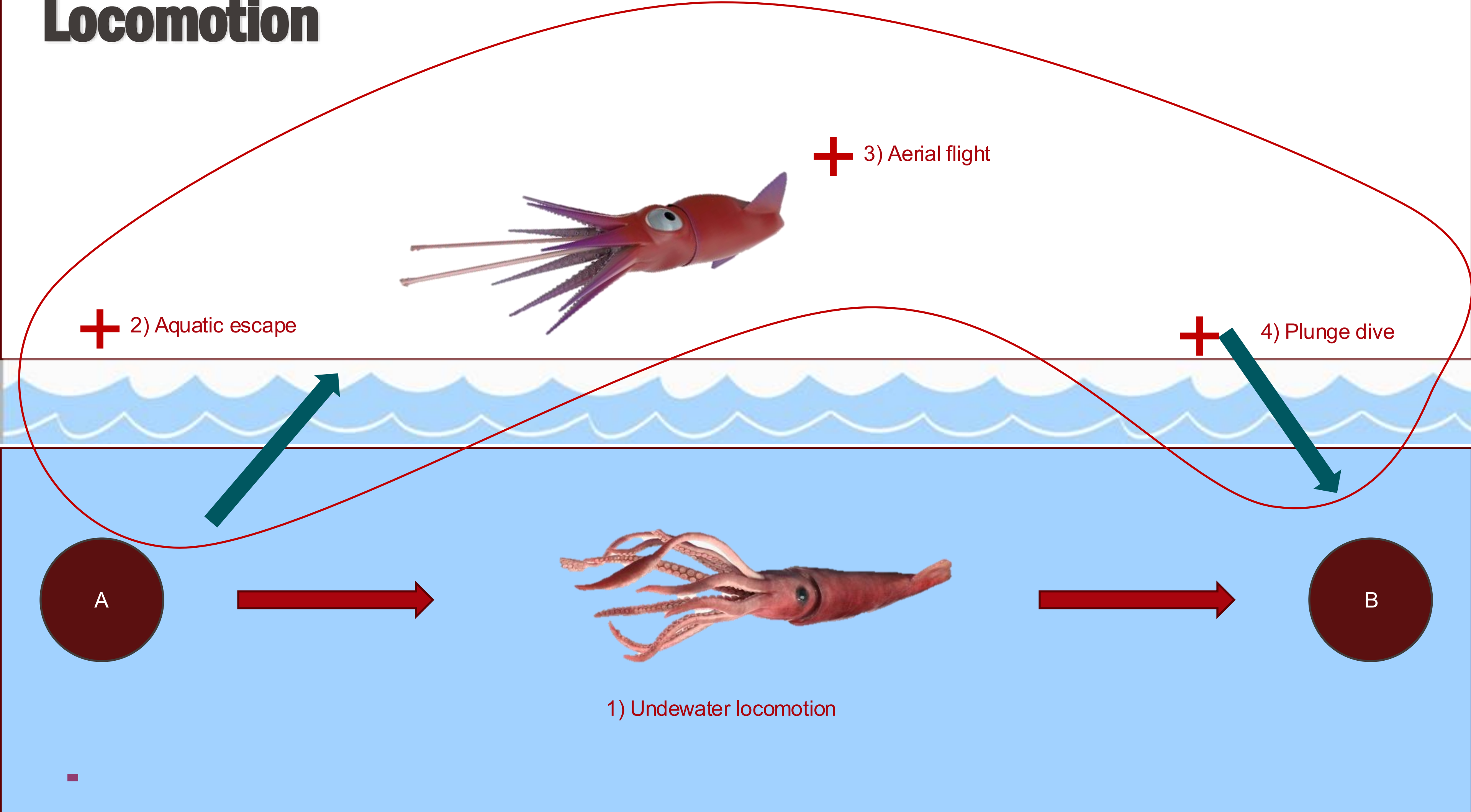
[1] Bujard, T. et al, 2021. A resonant squid-inspired robot unlocks biological propulsive efficiency. *Science Robotics*, *6*(50).

Squid inspired robot

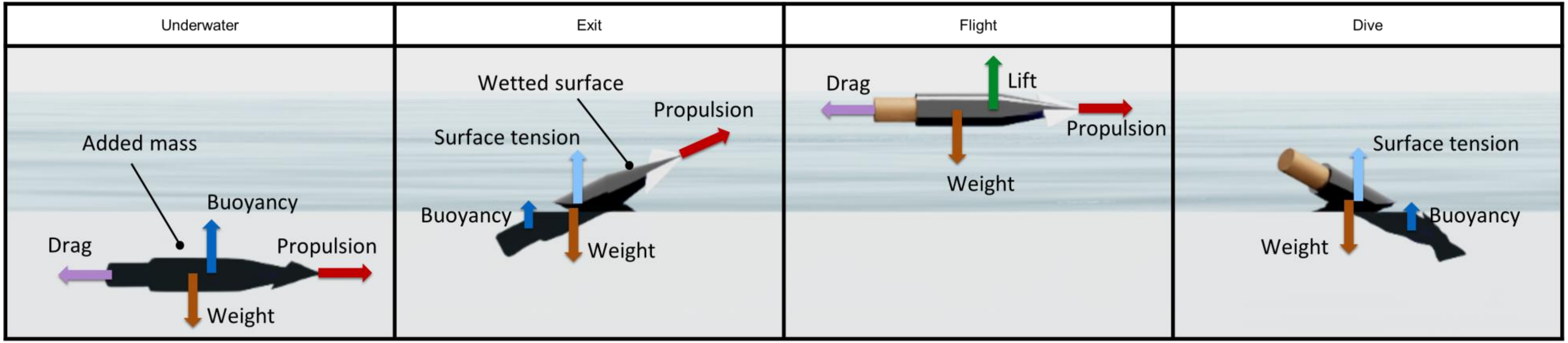


[1] Christianson, C. et al, 2020. Cephalopod-inspired robot capable of cyclic jet propulsion through shape change. Bioinspiration & biomimetics.

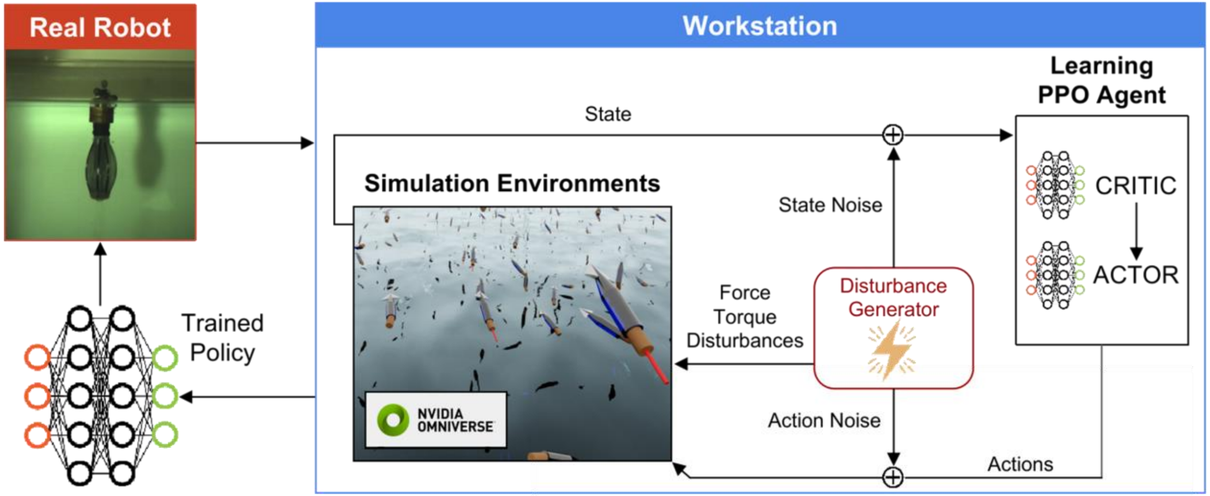
Locomotion


3) Aerial flight
2) Aquatic escape
4) Plunge dive
A
B
1) Undewater locomotion

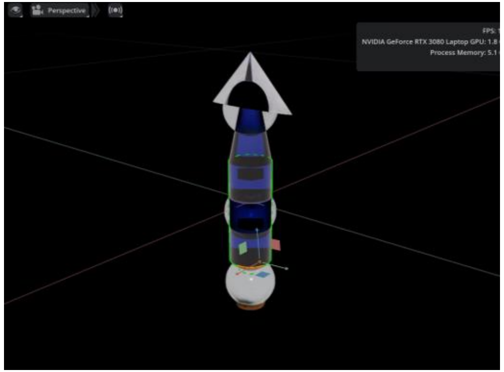
RL Simulation Framework for Squidbot




Flying squid, image taken by Kouta Muramatsu



Distributed Buoyancy

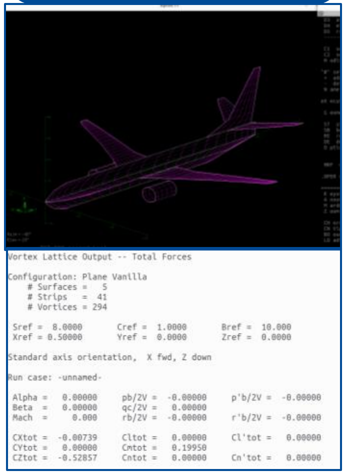


- Collections of spheres
- Simple to calculate the force with elevation
- Attached to each component
- Size could be modified during simulation

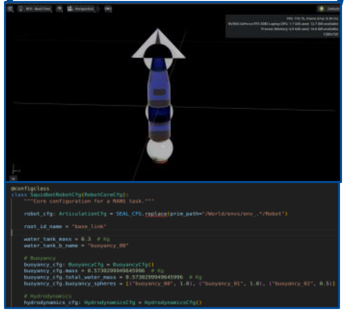
Iterative RL-Driven Design Optimization Loop

Initial Parameter Sets

Flight-Dynamic Analysis(AVL)



Generate Task CFG, .usda model



Reinforcement Learning (IsaacLab)

Mean Reward of each parameter set

Optimization (TuRBO)

Next Parameter Sets to explore

* Eriksson et al., Neurips 2019

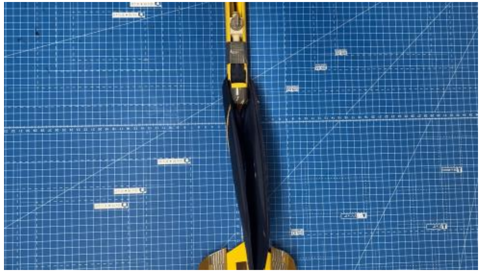

z
x


Source: Image d'illustration - Wikimedia

The Flying Fish

Soft Robot Wings

Soft Pneumatic-Hydraulic Wings



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System Design

Beetle Wing

Dragonfly Wing

Cicada Wing

- ➢ Inspired by a Cicadas wings
- ➢ Network of inflatable veins
- ➢ Heat sealed onto TPU-coated nylon sheets
- ➢ Thick channel at the leading edge provides structural strength
- ➢ Can be reinforced by a carbon fiber rod
- ➢ Ruptures at 200 *kPa*
- ➢ Weight of 5-8 *g*

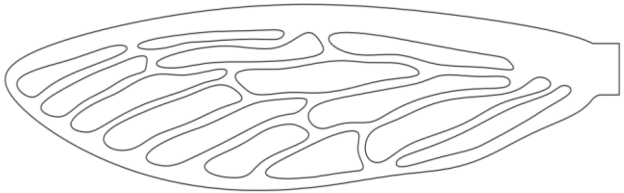
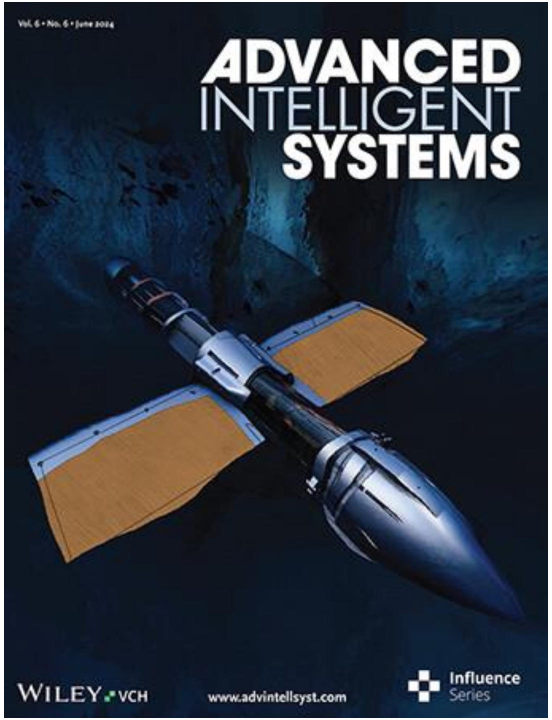
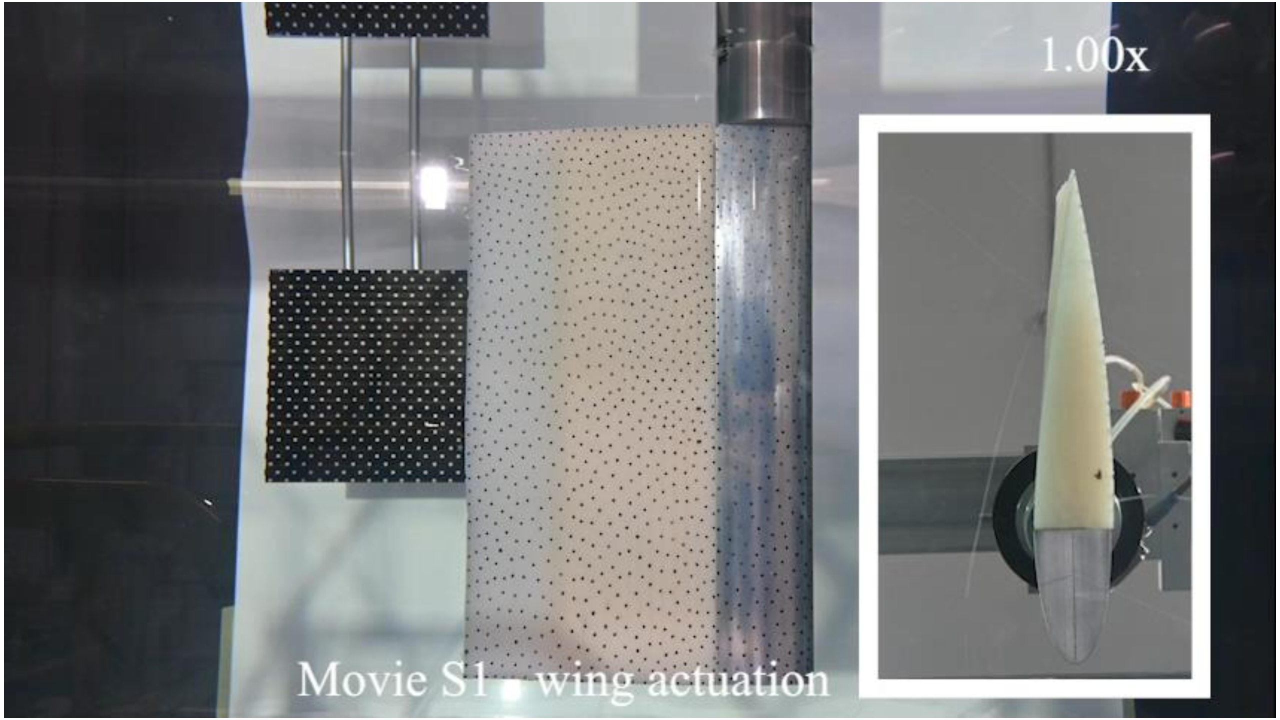


Figure 3: Heat Seal Pattern Inspired by Cicada Wing

Figure 4: Heat Sealed TPU Coated Nylon Wing

Soft Robotic Wing for Underwater Vehicles





Giordano, A., Achenbach, L., Lenggenhager, D., Wiesemüller, F., Vonbank, R., Mucignat, C., Tristany Farinha, A., Nguyen, P.H., Katzschmann, R., Armanini, S.F., Lunati, I, Song, S., and Kovac, M., 2024. A Soft Robotic Morphing Wing for Unmanned Underwater Vehicles. Advanced Intelligent Systems, p.2300702.

Empa | Imperial College London | EPFL

EPFL

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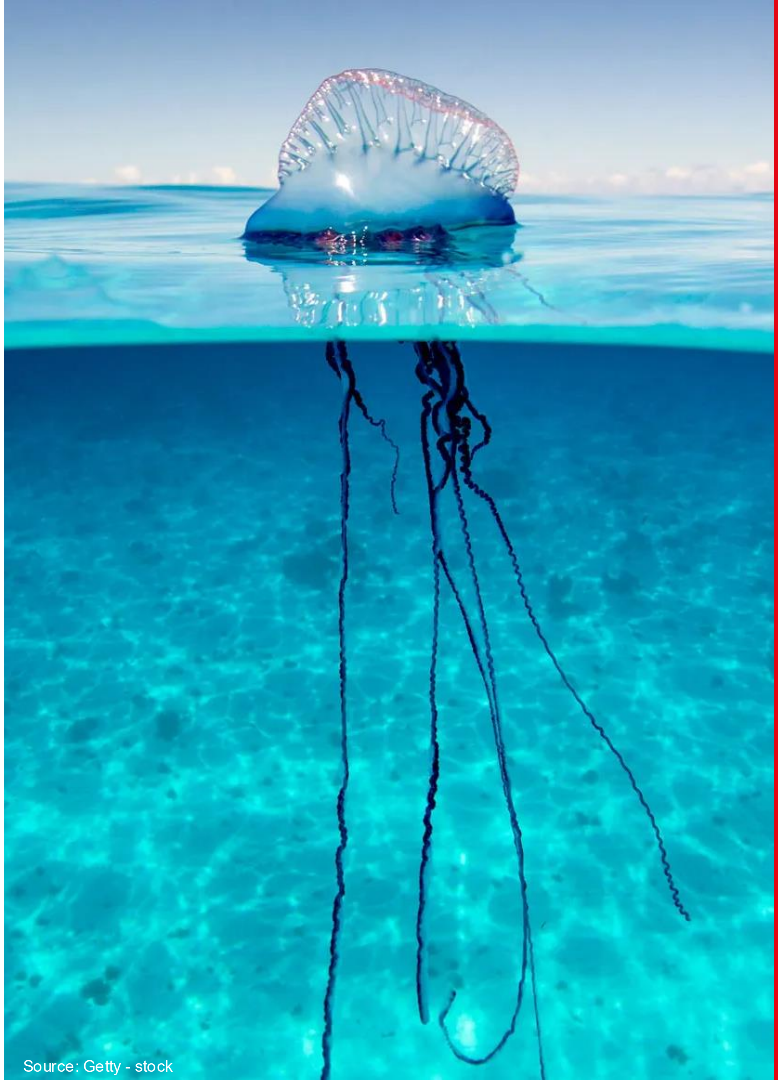

Source: Getty - stock

The Portuguese Man O War

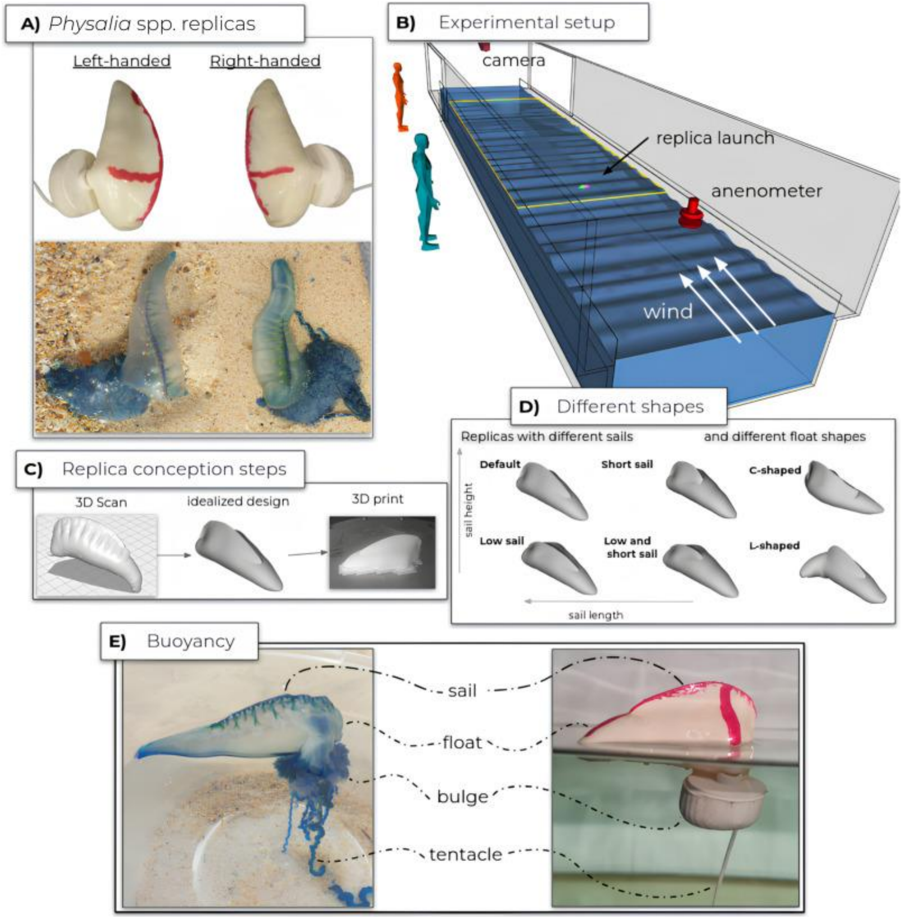
Soft Robot Sailing

Sailing : Energy efficient locomotion

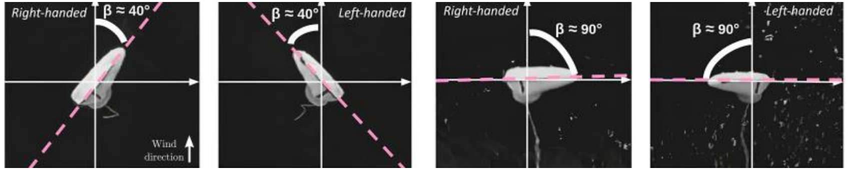
- Terenius. Windsurfing in Mute Swans (Cygnus olor). *The Wilson Journal of Ornithology*, (2016)
- Hayashi, Morito, et al. "Sail or sink: novel behavioural adaptations on water in aerially dispersing species." *BMC evolutionary biology* (2015)

Empa | Imperial College London

Hydrodynamics of Sailing of the *Portuguese man-of-war* (*Physalia physalis*)



- **Symmetrical Drift Patterns:**
  - Left-handed replicas drift to right of the wind
  - Right-handed replicas drifted to the left
- **Drift Angle and Wind Speed:**
  - Under low wind conditions (1m/s), they drifted at angles of 40 deg from wind direction
  - As wind picks up, the drift angle reduces drastically (17m/s => drift angle was 5 deg)
- **Drift Speed and Wind Speed:**
  - Linear relationship between wind speed and drift speed, suggesting that at 10m/s wind speeds the animal could drift approximately 15km daily.



Soft Reconfigurable Sailboat

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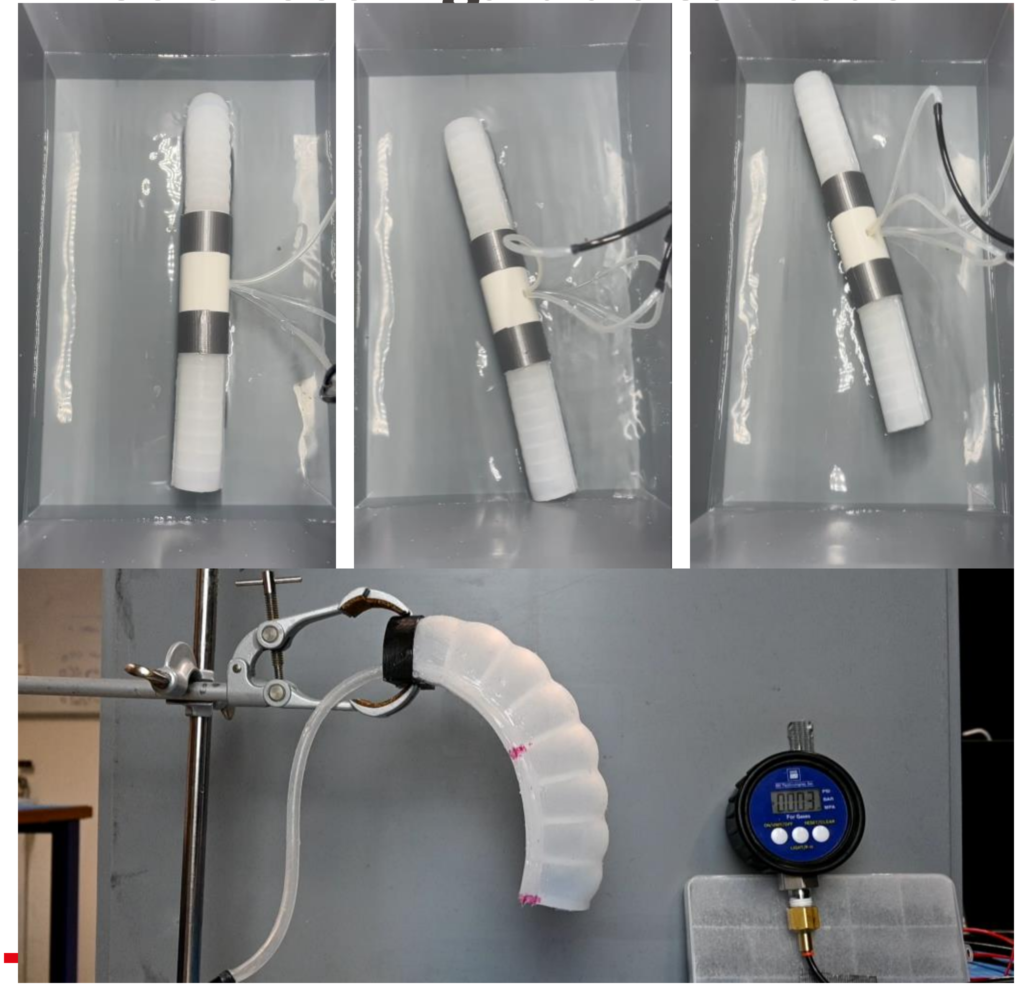
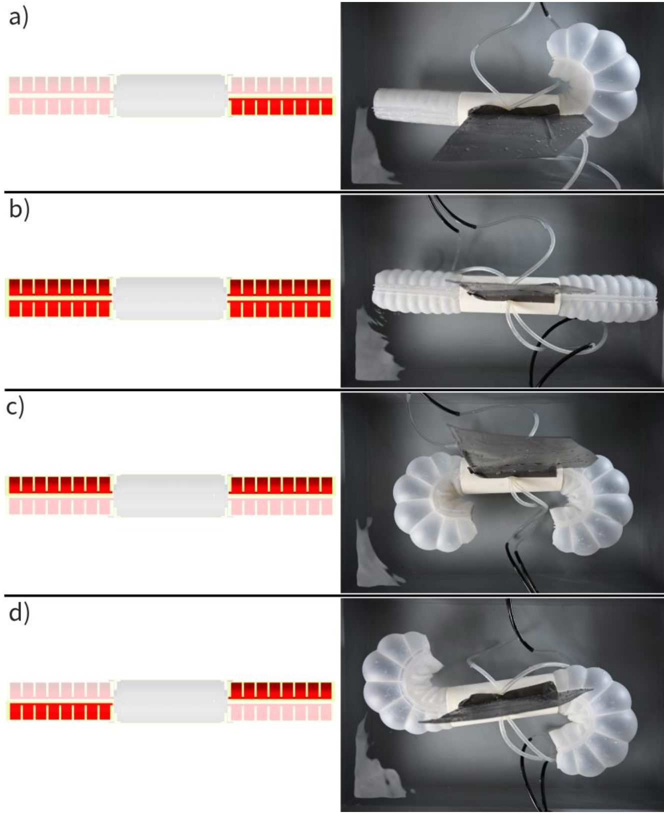


Shape changing



Kovac et.al. 2025 [In Preparation]

EPFL

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Source: Jakob Ziegler/Getty Images/iStockphoto

[Bonus] Remora Fish

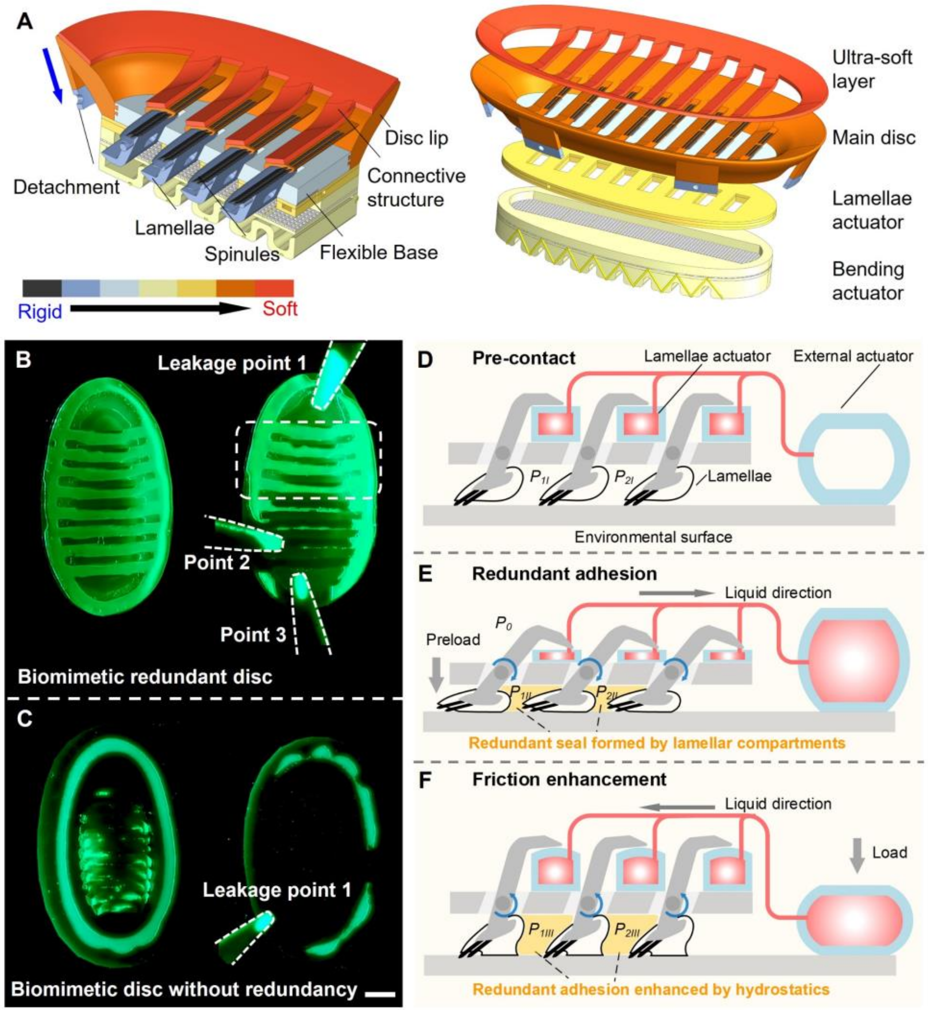
Aerial Aquatic Adhesion and Transition

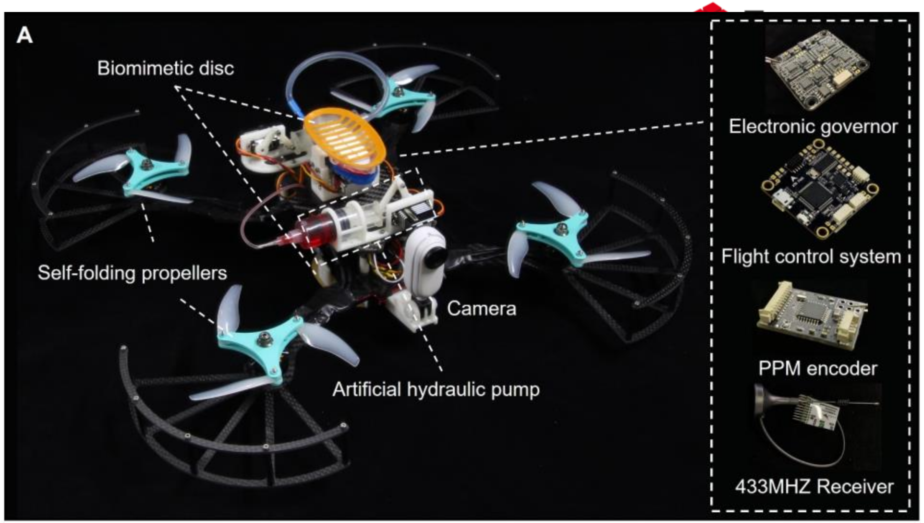
The Aerial-Aquatic Remora

L. Li, S. Wang, Y. Zhang, S. Song, C. Wang, S. Tang, W. Zhao, G. Wang, W. Sun, F. Yang, J. Liu, W. Liu, B. Chen, H. Xu, P. H. Nguyen, M. Kovac, and L. Wen. Aerial-aquatic hitchhiking robots capable of high-performance medium transition and bioinspired redundant adhesion. Science Robotics, 2022.

The Aerial-Aquatic Remora

L. Li, S. Wang, Y. Zhang, S. Song, C. Wang, S. Tang, W. Zhao, G. Wang, W. Sun, F. Yang, J. Liu, W. Liu, B. Chen, H. Xu, P. H. Nguyen, M. Kovac, and L. Wen. Aerial-aquatic hitchhiking robots capable of high-performance medium transition and bioinspired redundant adhesion. Science Robotics, 2022.



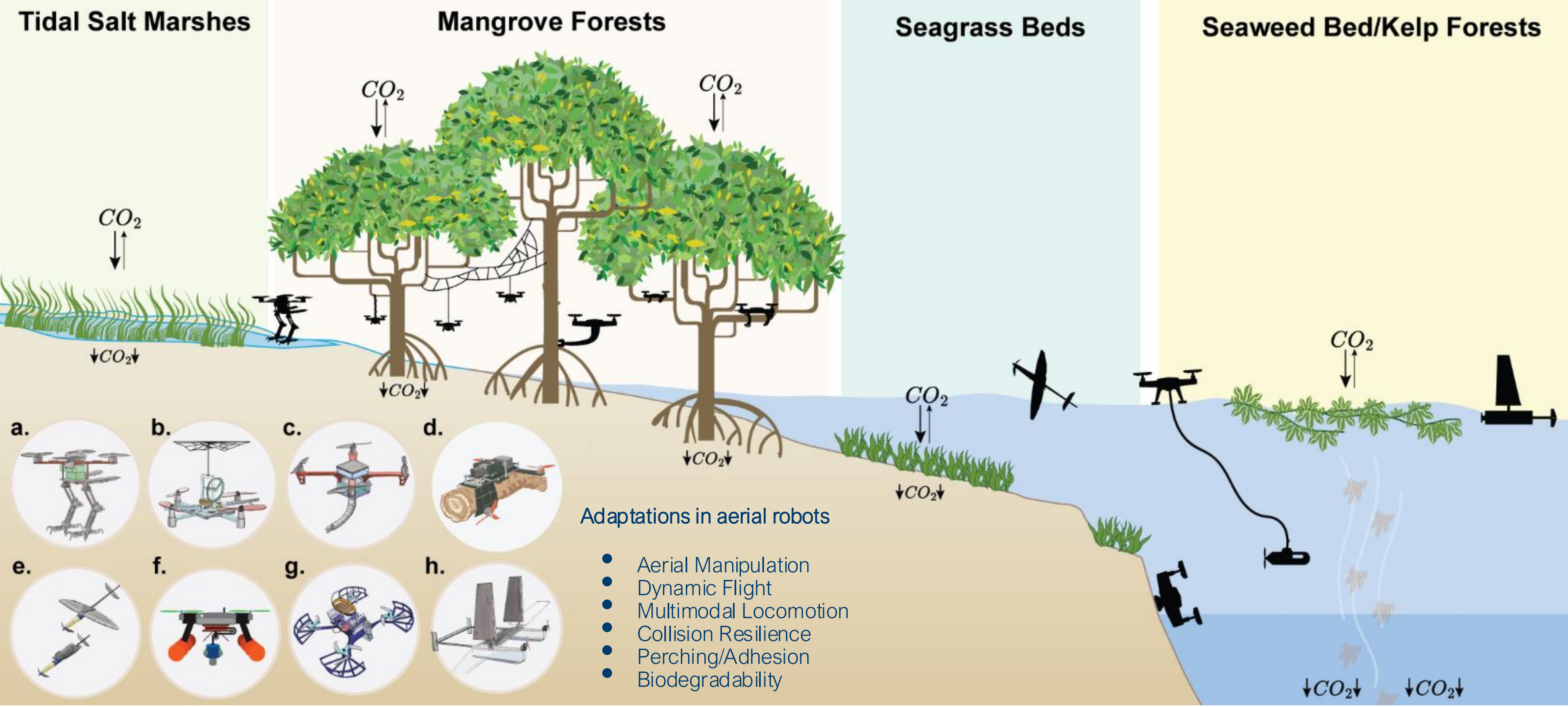


Supplementary Movie 7

Demonstration of lamellae motion, disc bending, and detachment

Biomechanics and Soft Robotics Lab
Beihang University

Future Work: What type of Aerial-Aquatic Robots?



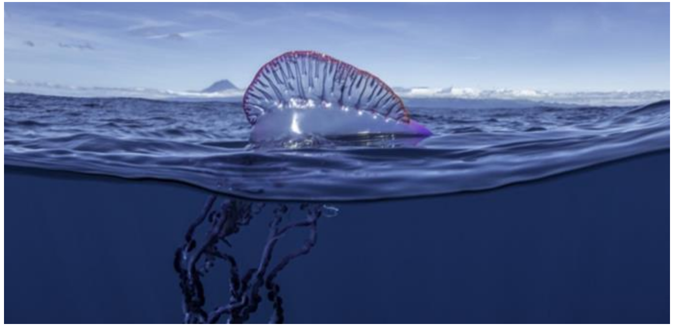
Adaptations in aerial robots

- Aerial Manipulation
- Dynamic Flight
- Multimodal Locomotion
- Collision Resilience
- Perching/Adhesion
- Biodegradability

P. H. Nguyen and Kovac, M. Aerial-Aquatic Robots as a New Paradigm for Blue Carbon Monitoring and Sequestration In the 2024 International Conference on Unmanned Aircraft Systems (ICUAS)

Learning Goals

- *Bioinspirations that lead to robot development for trimodal locomotion?*
- *What are the physical principles of multi-modal locomotion?*
- *Trimodality and the cost of transport*
- *What are the soft-robotic materials and actuation mechanisms to develop these types of robots?*



Source: wildestanimal - gettimages

Portuguese Man O'War

Source: glorytoursbarbados.com

Flying Fish

Source: Anthony Pierce/SplashdownDirect

Flying Squid