# SailMAV, sailing drone for water environmental sensing

Luca Romanello

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PhD with Imperial College London and TUM
PostDoc with EPFL and EMPA Zürich

## SailMAV, sailing drone employed in air/water environmental sensing

Motivation

SailMAV: sailing drone

Autonomous sailing strategy and control

Sailing Results

Acoustic sensing in Lake Vrana, Croatia

Conclusions and Future development

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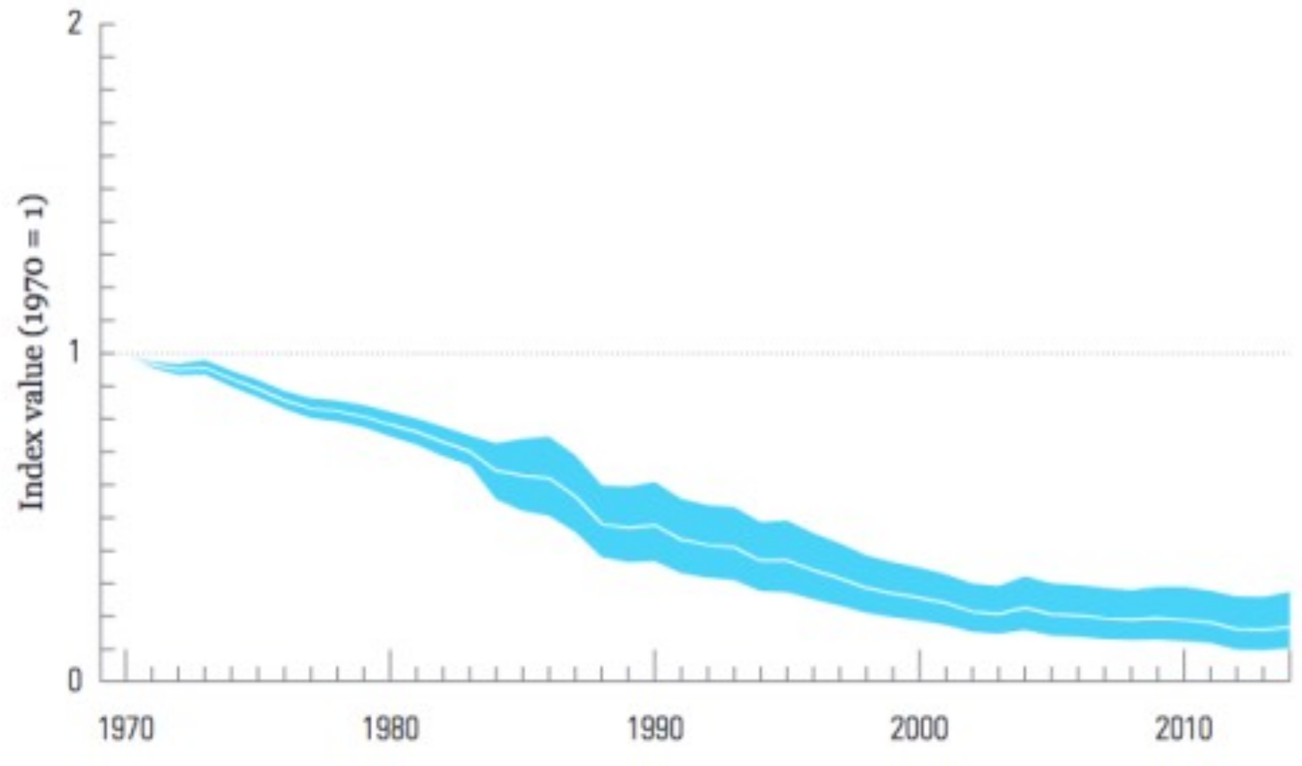
# Motivation

Water biomes are precious but in danger. Freshwater biomes face an 84% species **decline** and 1 in 3 species at risk of **extinction** due to agricultural water use and pollution, while marine ecosystems risk losing up to 90% of coral reefs from overfishing and **climate change** [1]

The plastic pollution crisis, Forbes




Accurate identification of **protected areas** and high-quality **data** are essential for effective **conservation** policies. They help prioritize protection, assess biodiversity **health**, and monitor conservation success.

# Motivation

Is there a **sustainable** way to **sample** water resources?

How can we obtain more functional **data** from water environmental sensing?

Is it possible to design a convenient air/water **vehicle** to make this autonomous?

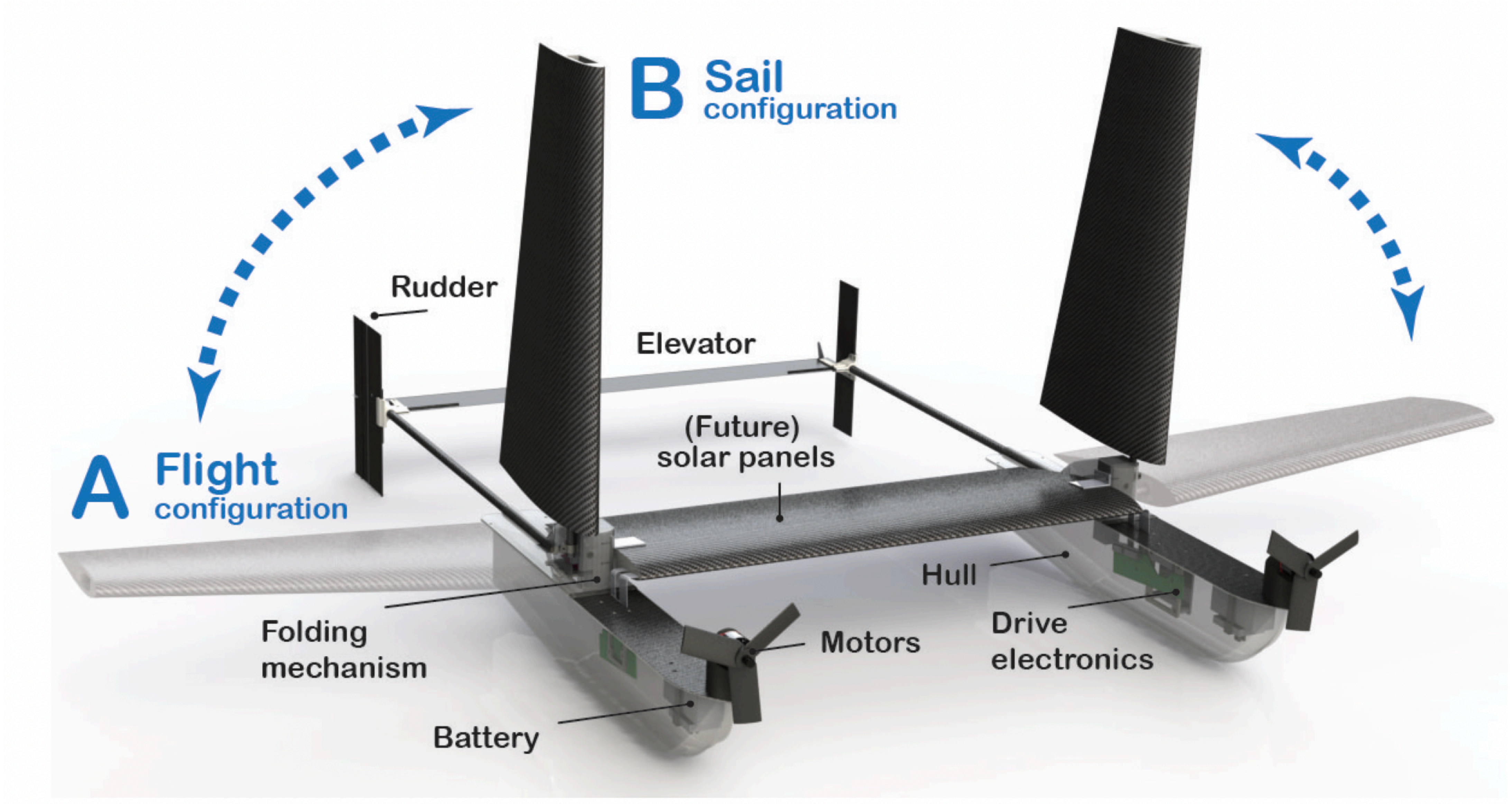

*Stormer Marine BV. Product Information - Stormer Marine BV. https://www.nacuticexpo.com/prod/stormer-marine-bv/product-43082-537199.html.*

Traditional environmental monitoring is **costly**, time-consuming, and logistically difficult, especially in aquatic ecosystems, where changes are hard to detect and **access** is limited.

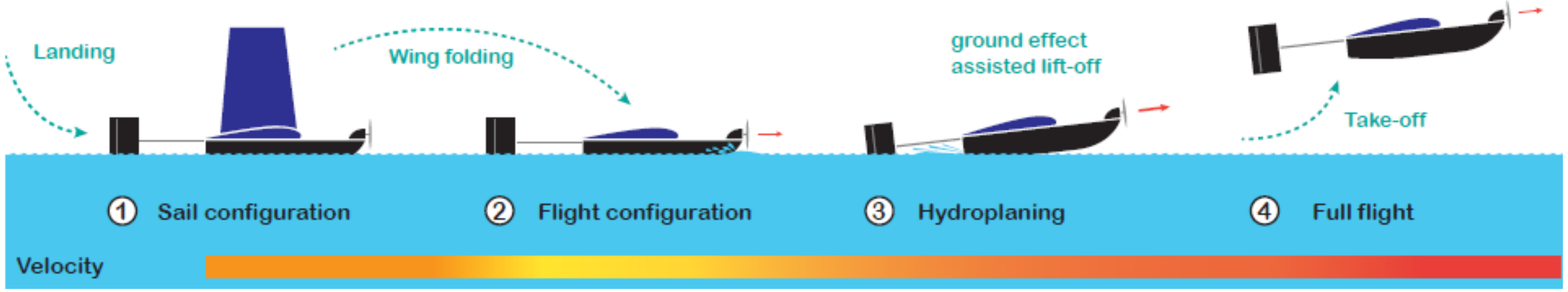
# SailMAV, sailing drone employed in air/water environmental sensing

# Methodologies

## SailMAV: design




- Morphology *adapting* platform (sail and fly)
- The wings can fold to function as sails, working with the **rudder** as control surfaces for *propulsion* and *yaw* respectively during sailing.
- **Elevator** is added on the tail for *pitch* control.
- The same servos used for rotating the sails can also serve as *roll* control surfaces during flight.




**Sailing-flying** cycle

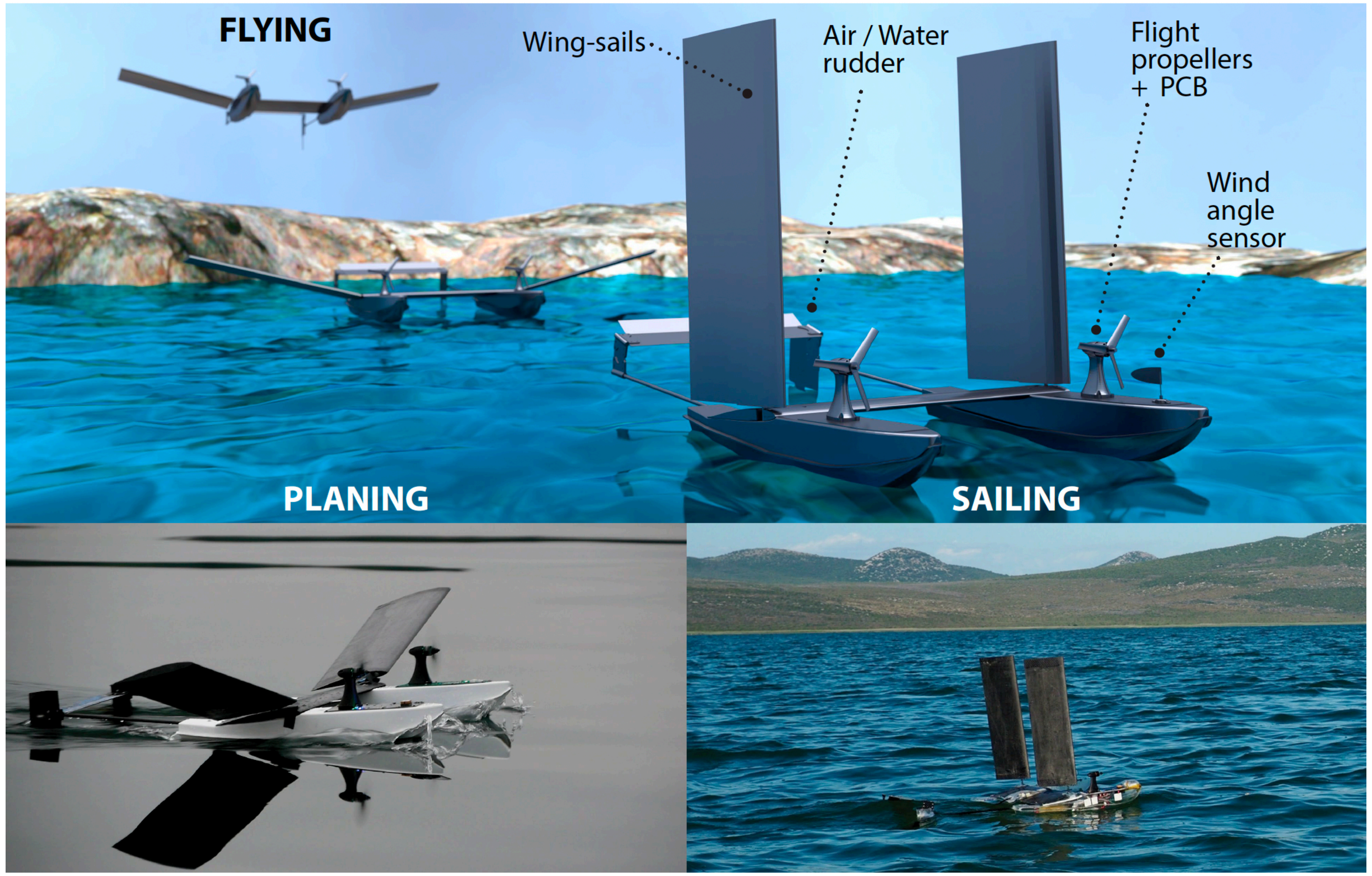




Zufferey *et al.*, "SailMAV: Design and Implementation of a Novel Multi-Modal Flying Sailing Robot," 2019

# Application

- Environmental **sensing** of aquatic ecosystems
- Search and **rescue** in case of disaster
- Efficient **sailing** in case of water sampling
- Autonomously sampling different water sources in one mission **flying** from one to another




## Conflicting requirements

- Waterproofing / mechanical robust
- Buoyancy neutral / low weight
- Water / air propulsion

Farinha* A. and Romanello* L. et al., IEEE Transactions in Field Robotics, 2025



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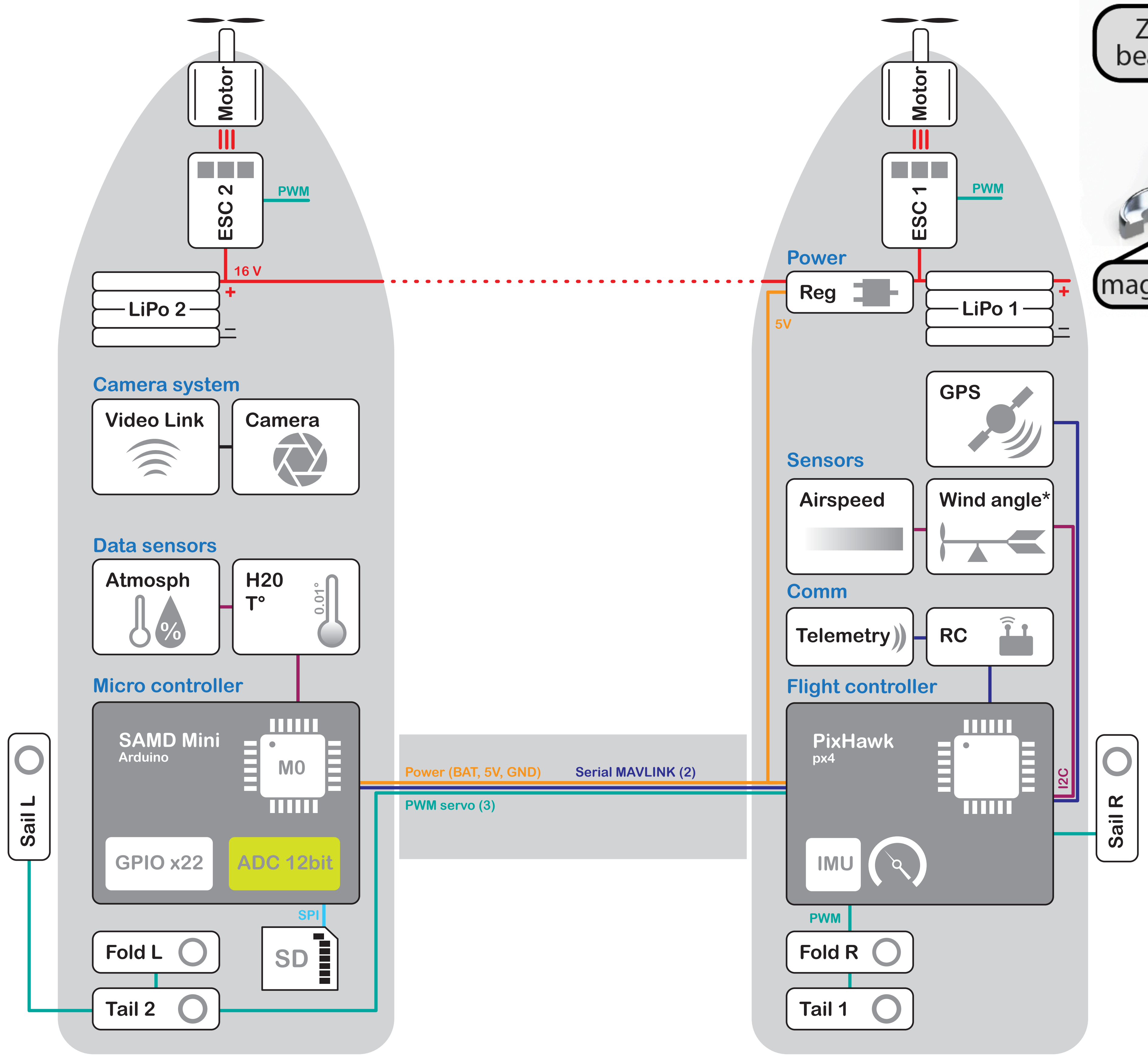
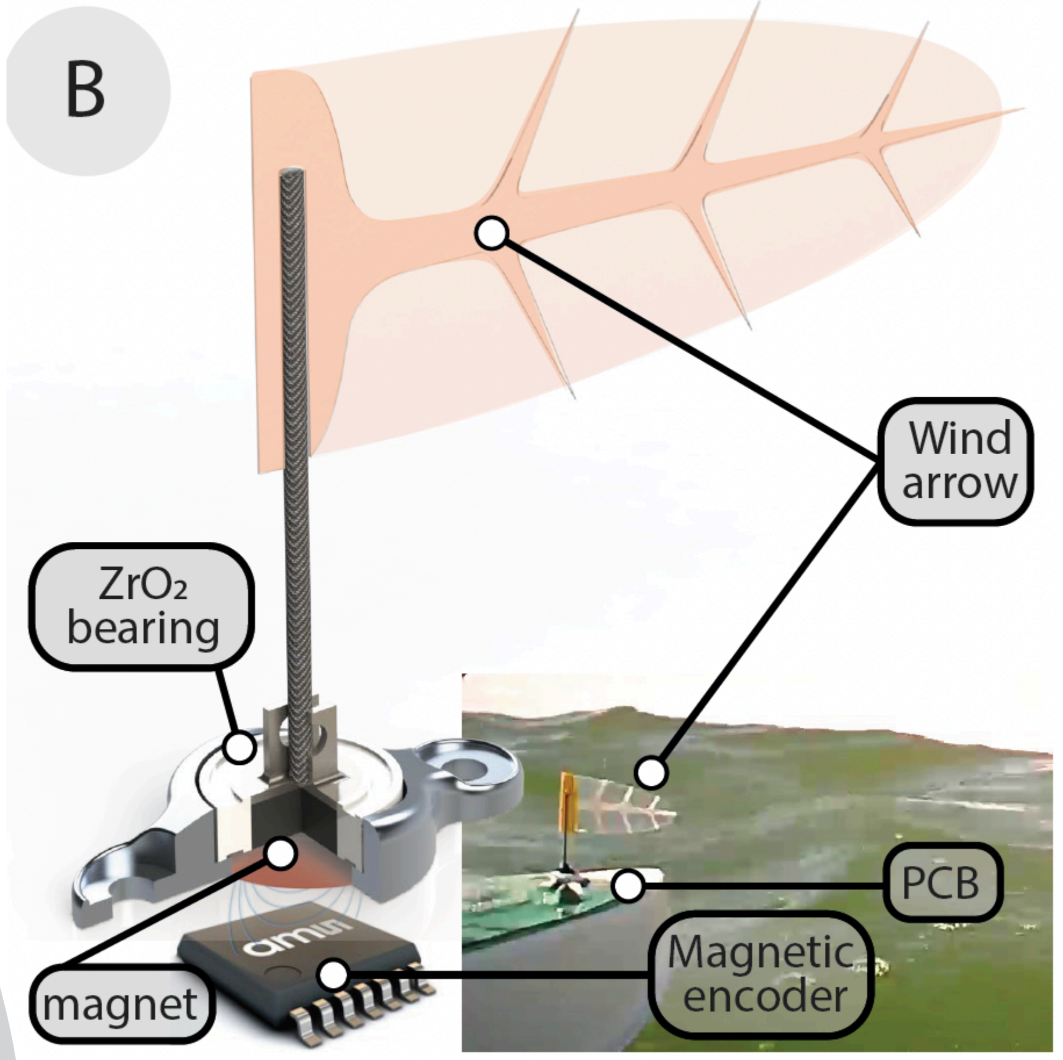
# Electronics

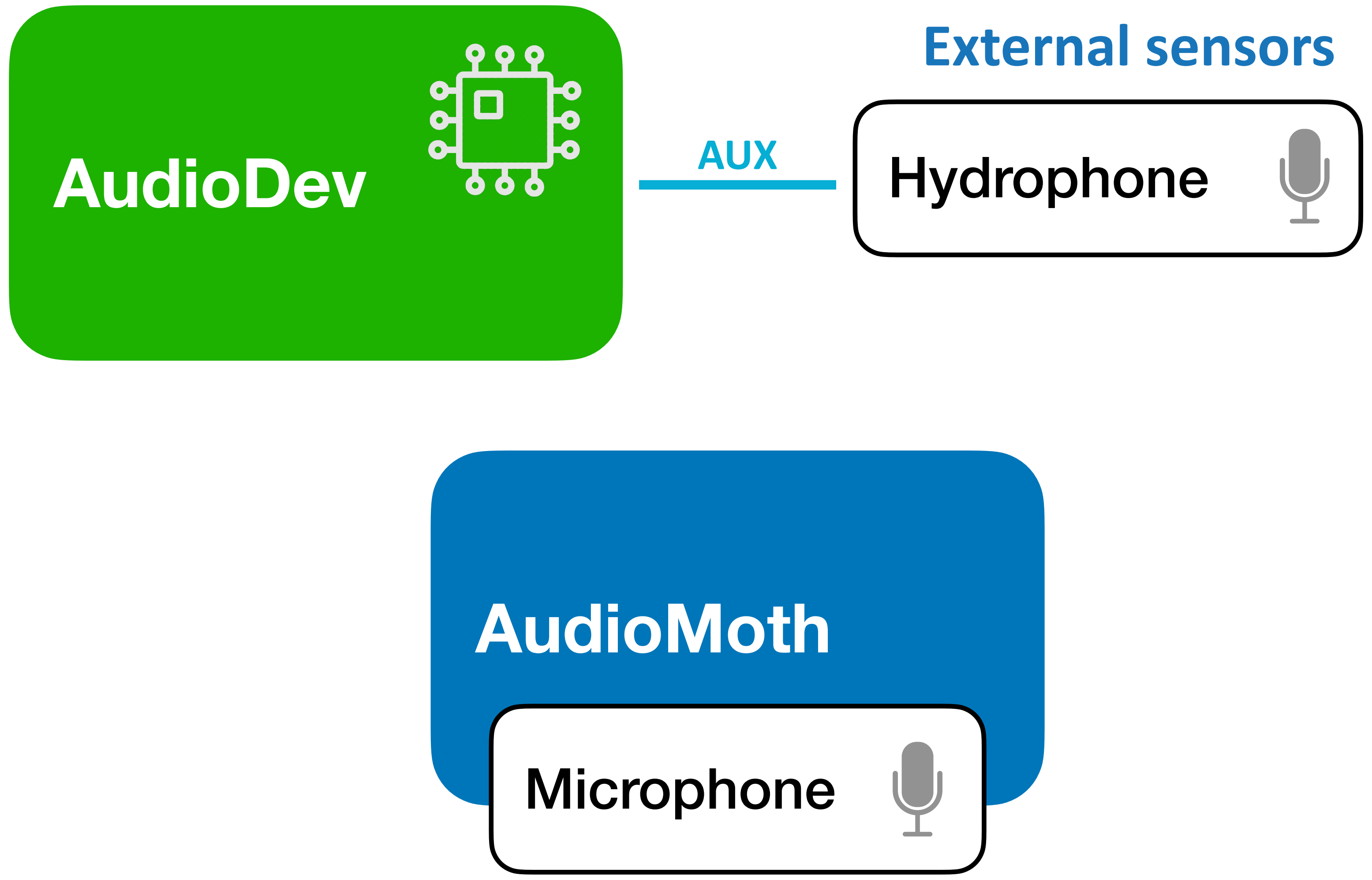
- Control of the drone




Wind direction sensor

- Environmental sensing

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**Autonomous sailing strategy and control**

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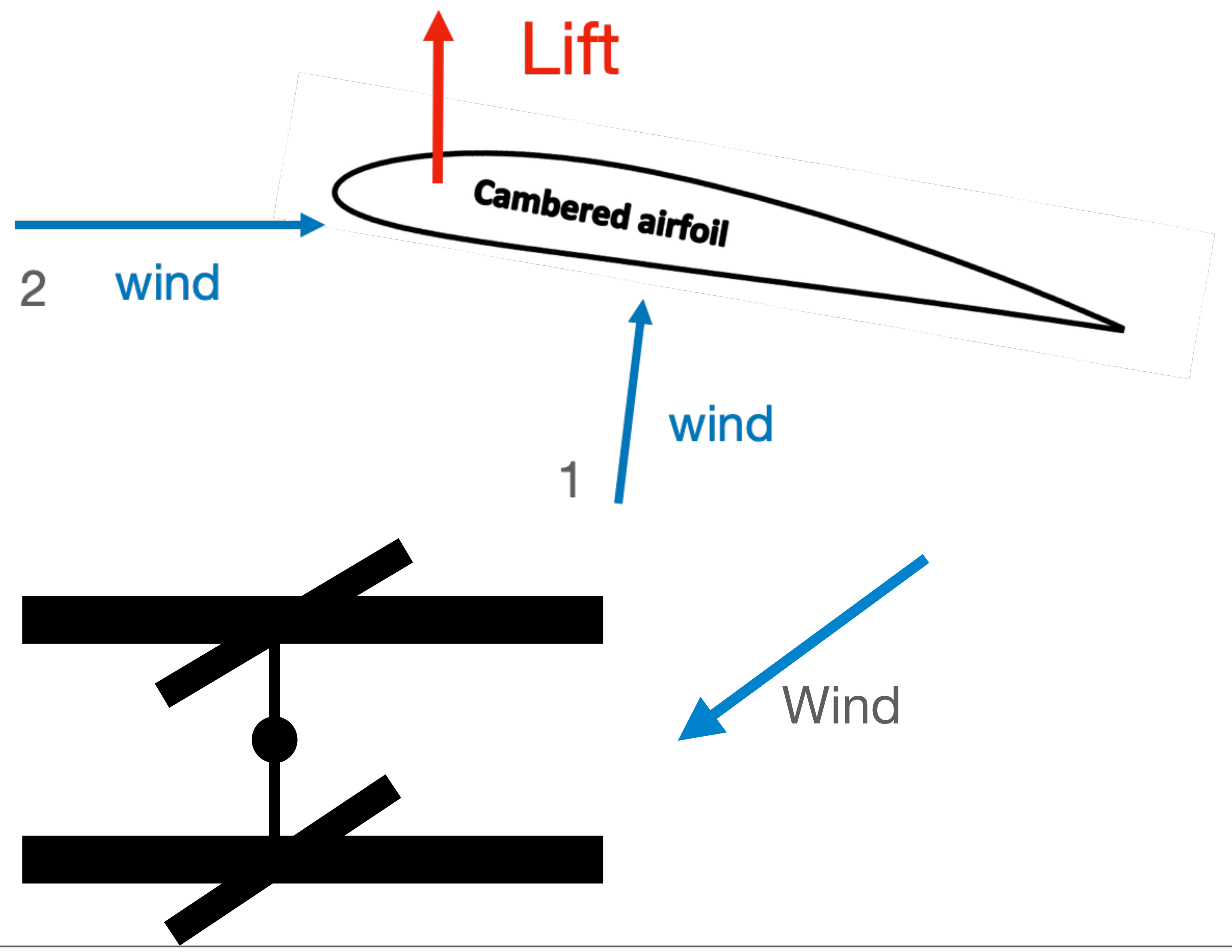
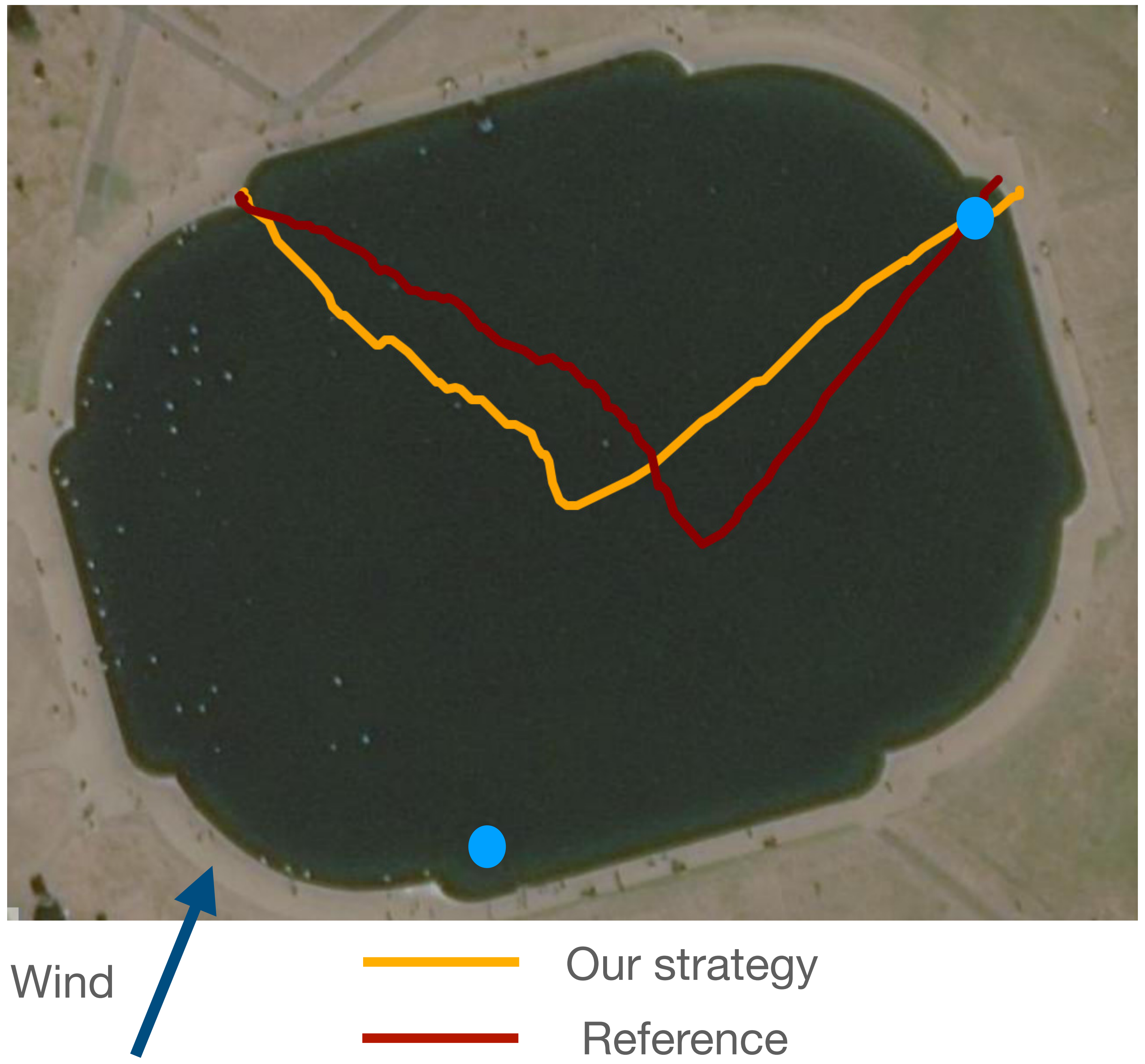
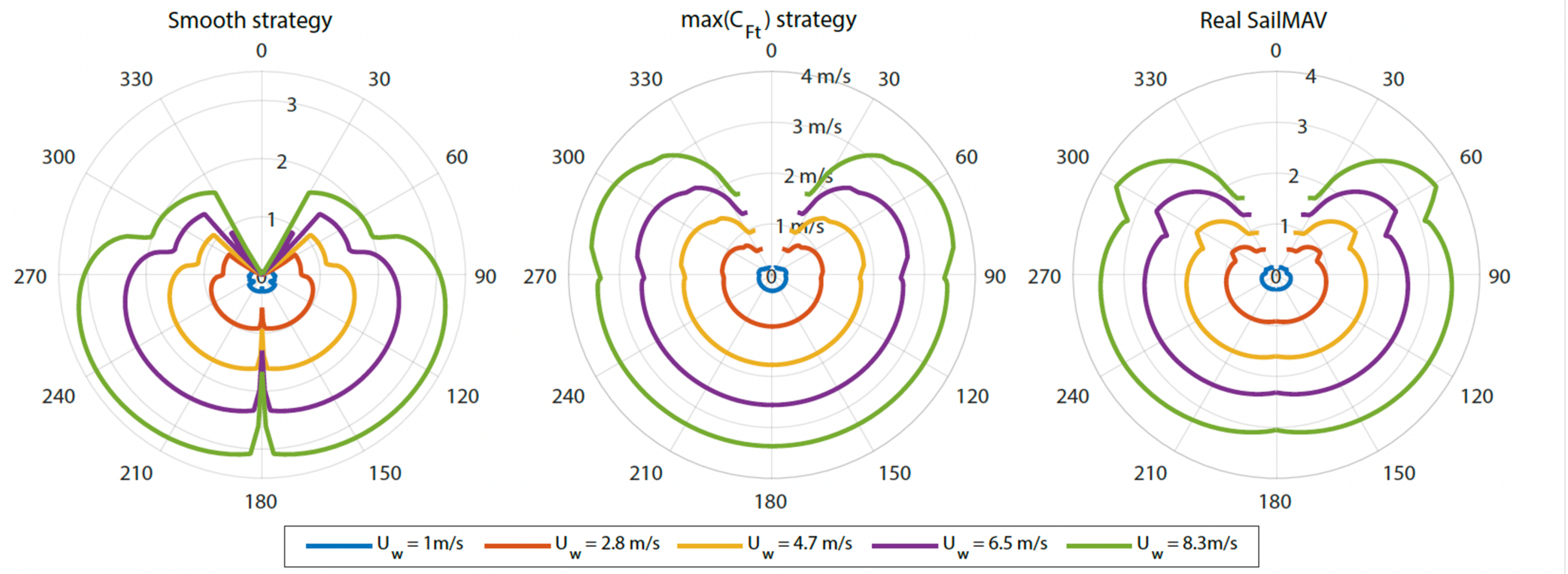
## Sailing strategy

**Objective**: Achieve autonomous sailing capability.

We design a control to harness the **lift** force generated by the airfoil to sail more **upwind**, improving **efficiency** and speed and to have the capability to reach more upwind **directions**.

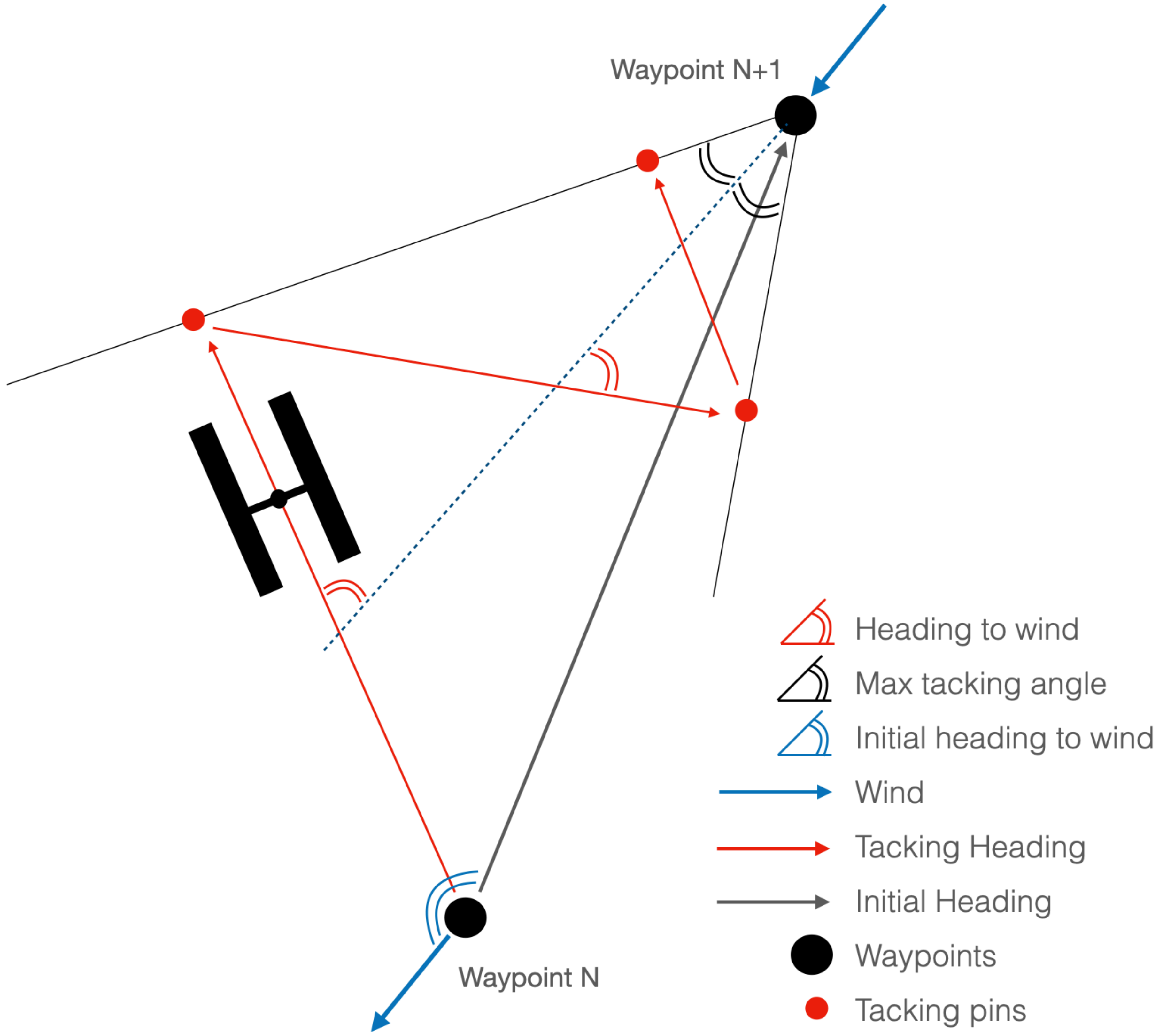


## Sailing strategy

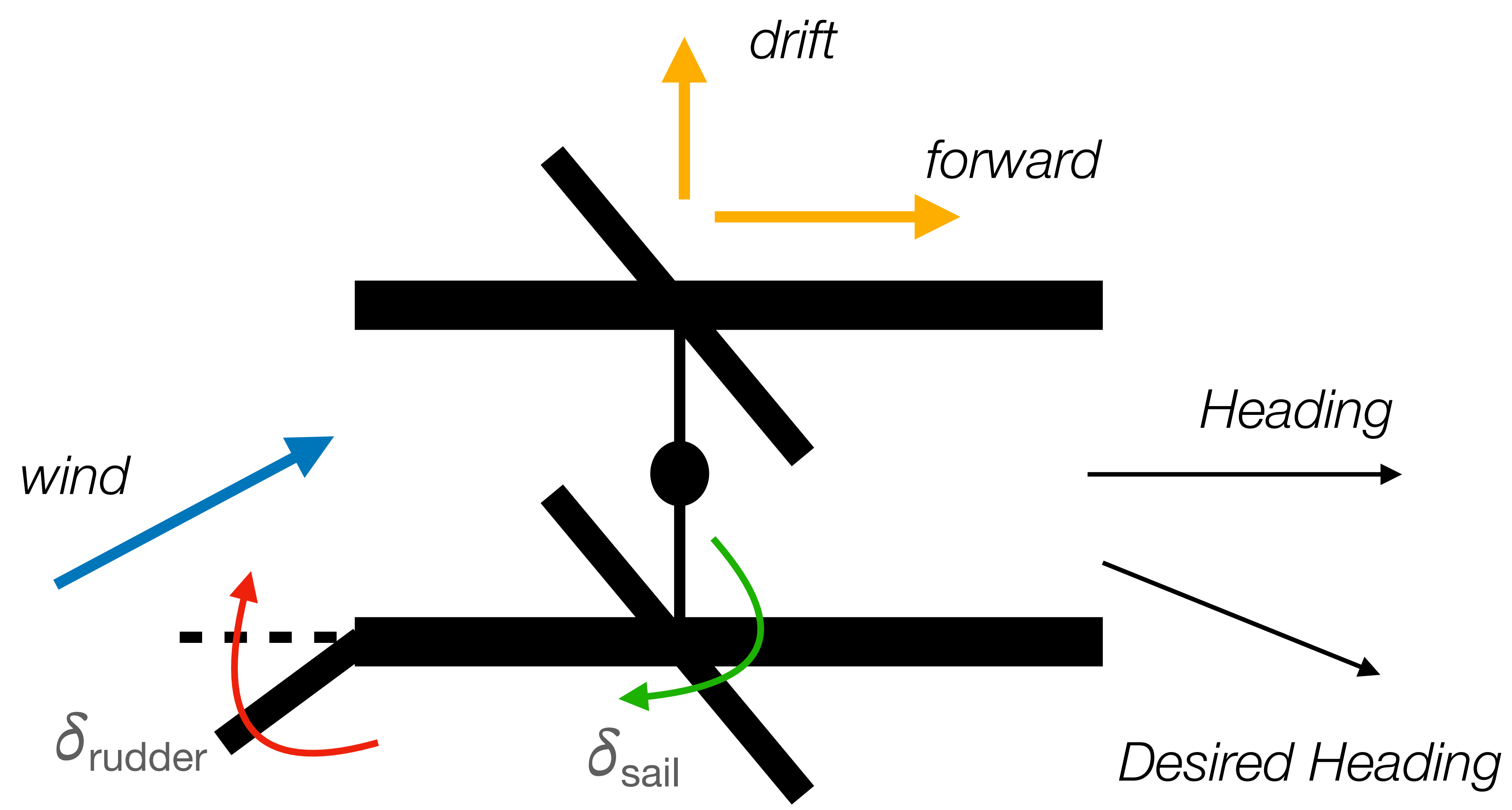
In order to increase the ability of the robot and to potentially reach every possible direction, a **tacking** a strategy has been designed inspired by the actual sailor maneuvers.

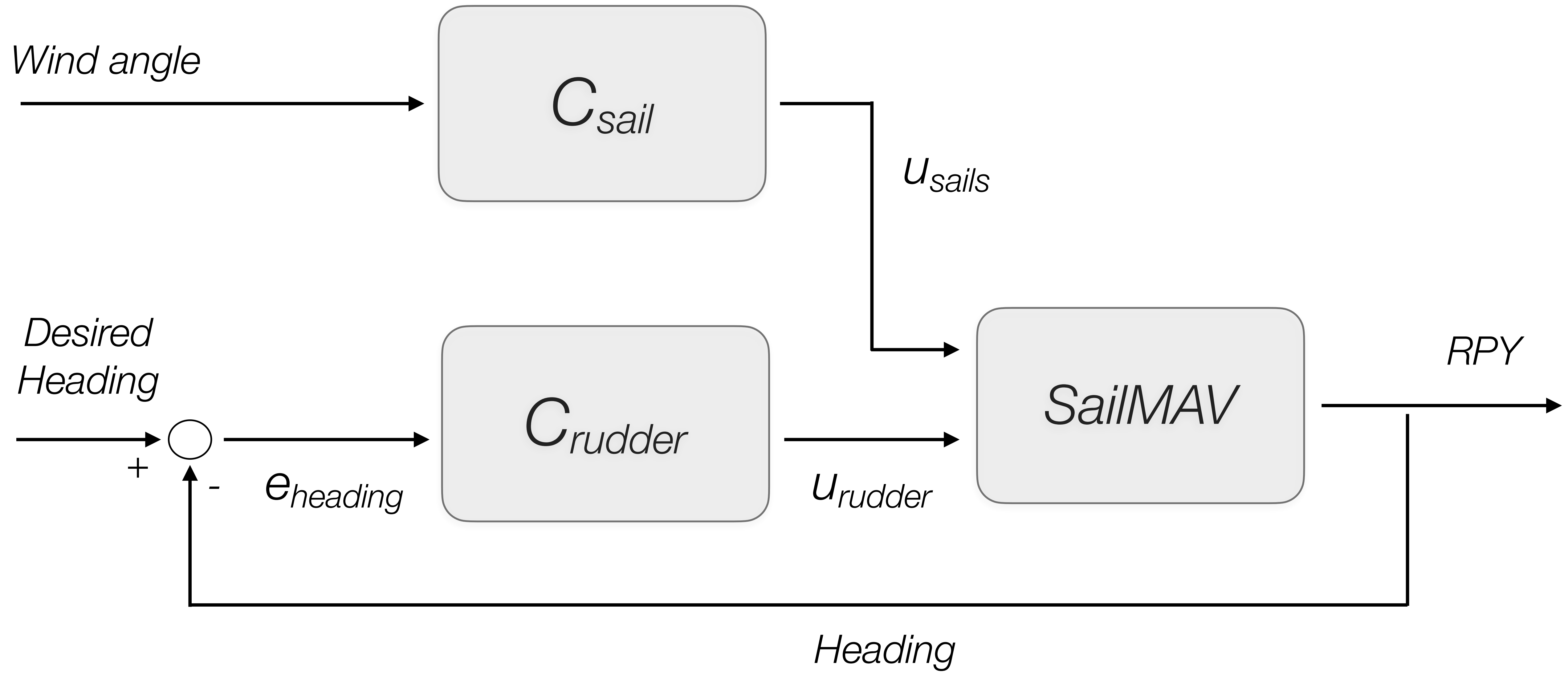



In the case where the course is in the **upwind** region, a tacking strategy was employed that allows the robot to reach the platform with zigzag maneuvers.

## Control

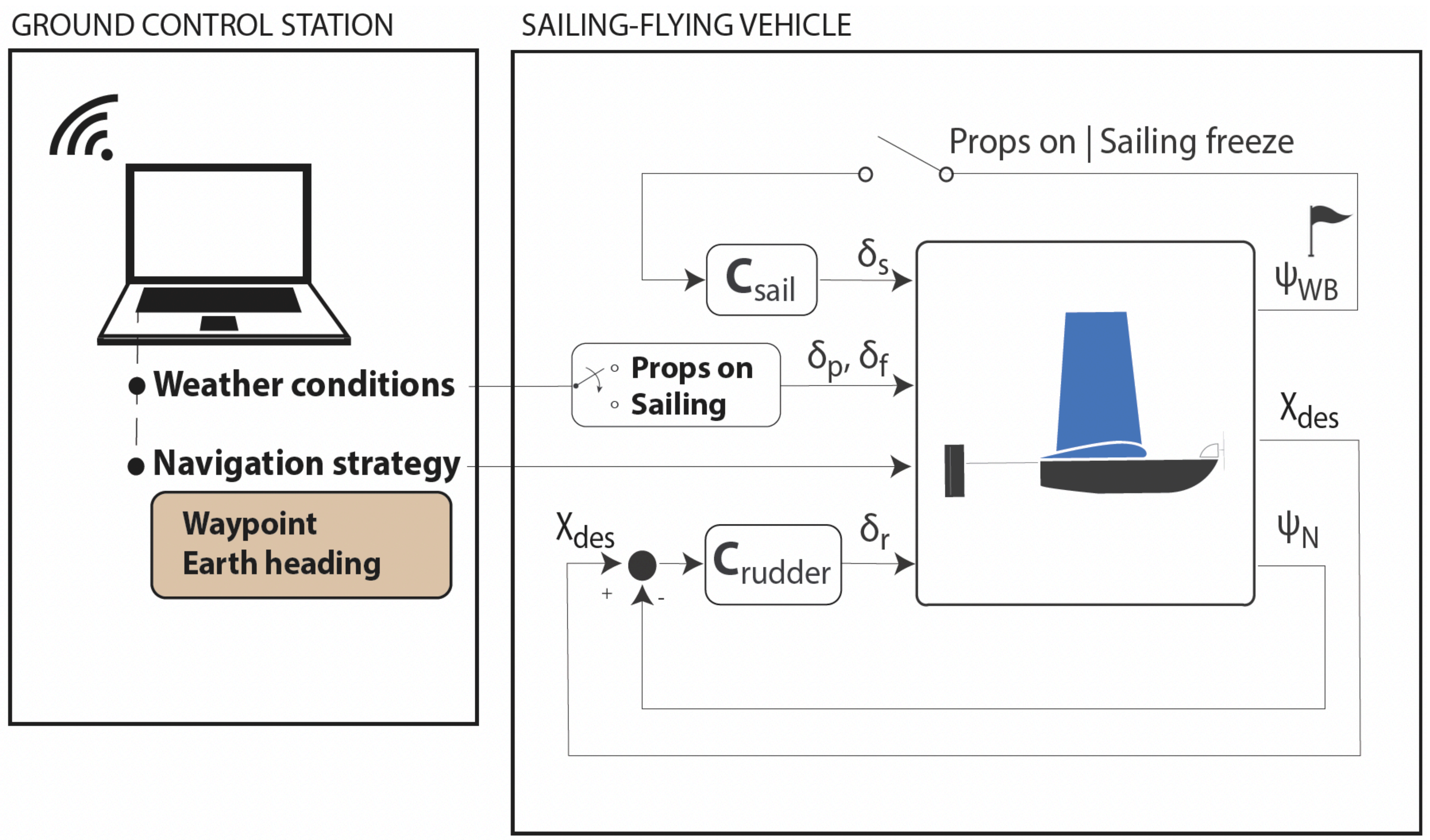
The sail control involves the control of the **sails** for the propulsion and the **rudder** for the direction. Sail control is made of an open loop based on the wind direction, while rudder one is made of a feedback (P based) between desired and actual heading.



# Autonomous sailing

A waypoint mission is pre-set, with **GPS** providing coordinates for direction. When the **distance** to a waypoint (e.g., 30m) is reached, it **updates** to the next until completion.




**Algorithm 1** Switching logic: determine actuator inputs

**Control station:** *Weather conditions, sailing strategy,* $\Psi_W, V_W$
**Input measured:** *GPS position, Attitude,* $\Psi_{WB}$
**if** $Sailing$ **then**:
  $\delta_f = 1$ {Fold up wings}
  **if** $Waypoint$ **then**
    $d = distance(Waypoint_n, GPSposition)$ {Distance from MAV to target}
    **if** $d > d_{min}$ **then** {The des. waypoint has not reached yet}
      $\theta = bearing(Waypoint_n, GPSposition)$ {The angle (NED) between MAV and target}
    **else if** $(n < number\_waypoints)$ **then** {Else: des. waypoint has reached, If: is the last one?}
      $n++$ {Update Waypoint}
      $\theta_1 = bearing(Waypoint_n, GPSposition)$ {Compute 1st bearing, to discriminate for tacking}
      $Tacking = |\Psi_W - \theta_1| > \zeta$ {Check if the first bearing is in no sail-zone}
  $\delta_p = 0$ {Switch off propeller's motors}
  $\delta_s = f(\Psi_{WB})$ {Sail input according to formulation 7b}
**else**
  $\delta_p = 0.1$ {fixed 10 % propeller's propulsion, high enough to move}
  $\delta_s = 0$ {Set sails/wings to 0 position} x
$\delta_d = f(\chi_{des}, \Psi_N)$ {Rudder input according to formulation 10a}
=0

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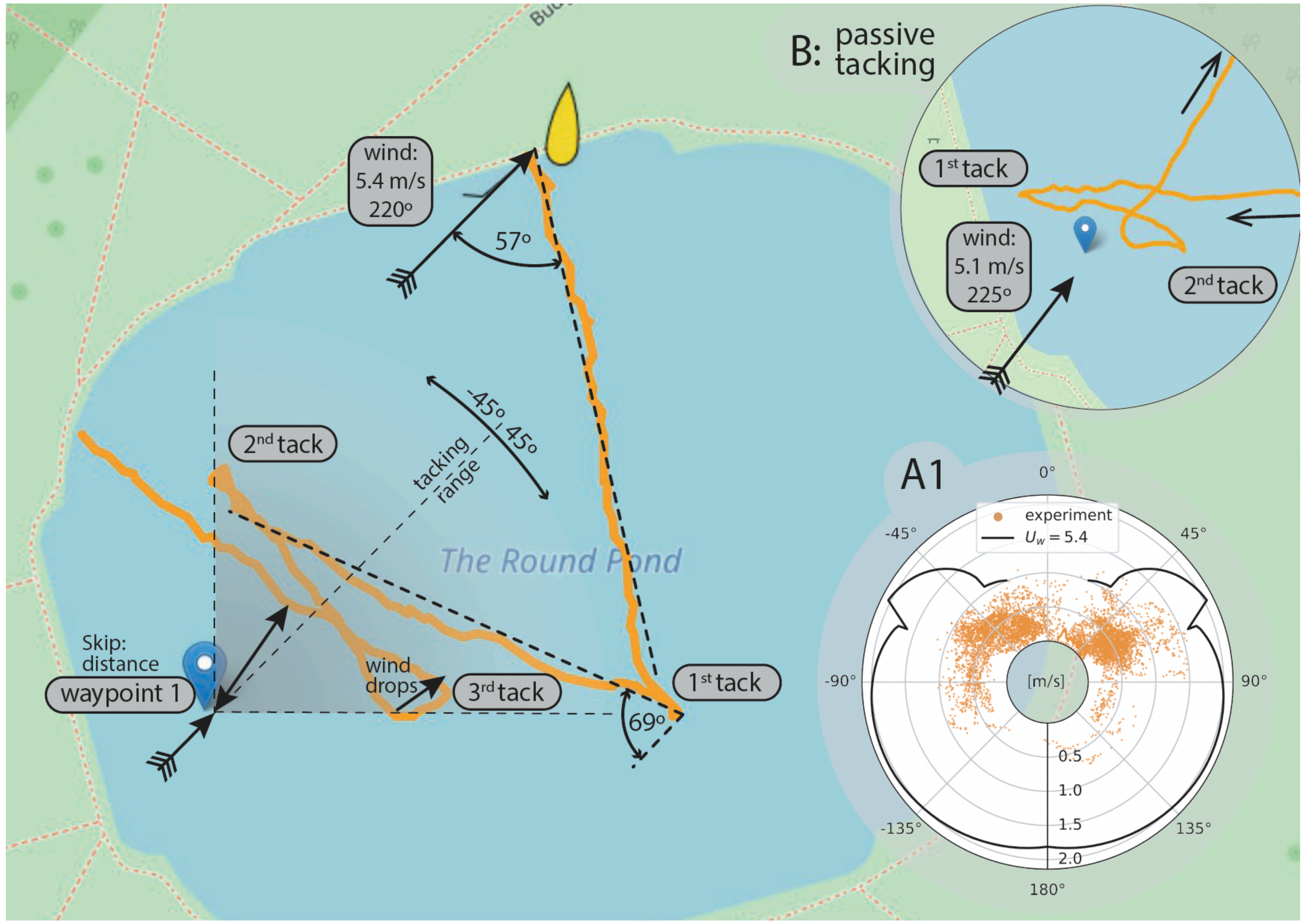
# Sailing results

Successful active and passive tacking in Hyde Park, London, autonomously reaching the upwind point.




A1: Upwind navigation, SailMAV forward speed based on the local wind

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## Water sampling in Lake Vrana, Croatia


Lake Vrana hosts thousands of **migrant birds** coming from North Europe to the South

SailMAV was equipped with a waterproofed PCB for the collection of **acoustic** data from both outside (microphone) and inside water (hydrophone)

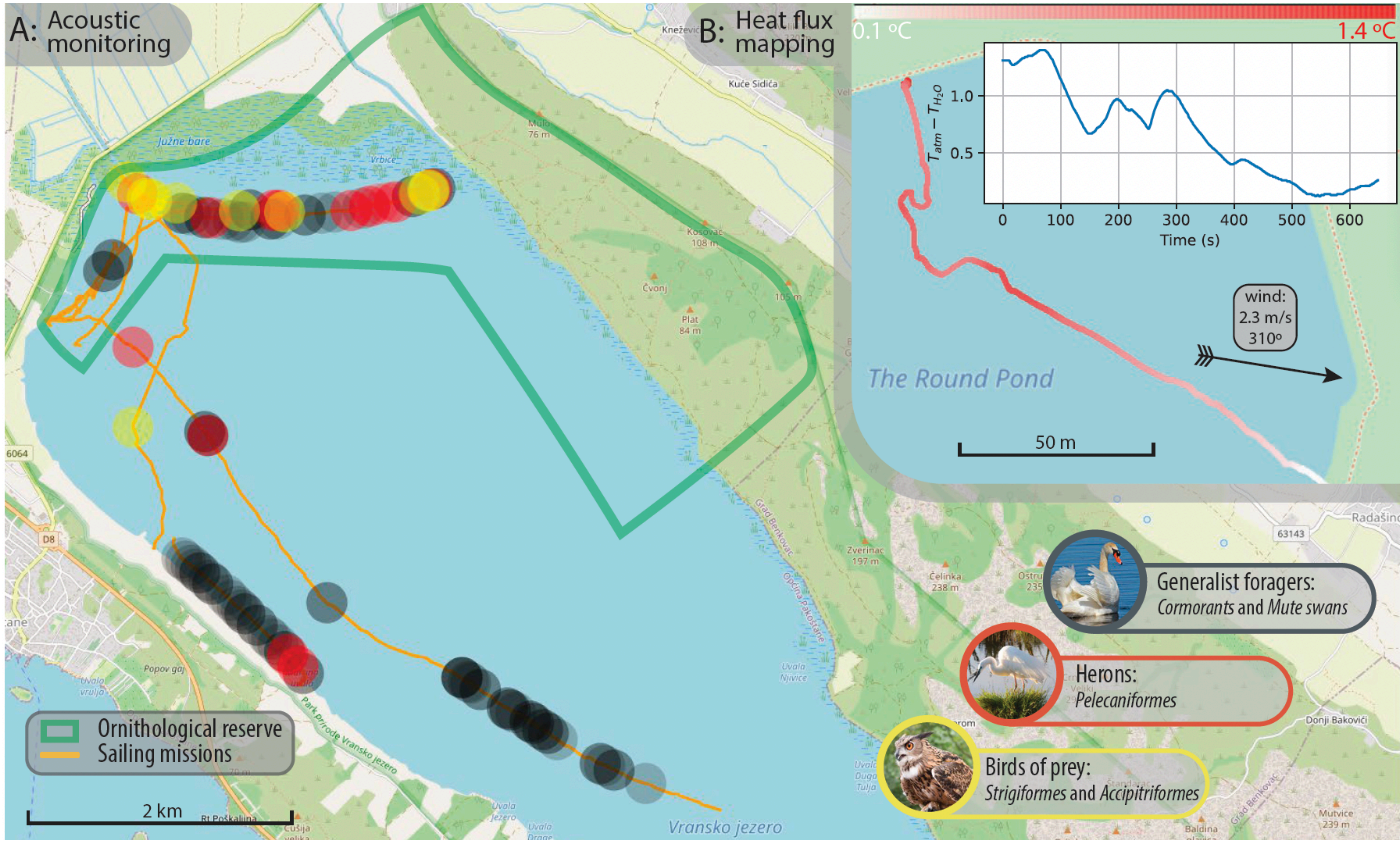
Thanks to the **silent** sailing navigation, the birds were not disturbed by the drone and this allowed to take more **valuable** samples

We scan different parts of the lake to check the species **richness** in case those need to be more protected as in the case of the **ornithological** area.

# Sensing results

With this project, we map the biodiversity of the lake in different periods of the year. It has been compared the data between both in **protected** and **disturbed** areas.

More than **30 different species** have been found during the tests. It was possible also to report the **abundance** of these species thanks to the machine learning algorithms





Farinha* A. and Romanello* L. et al., IEEE Transactions in Field Robotics, 2025
Lawson J., Farinha A., Romanello L. et al., Remote Sensing and Conservation, 2023

Mission Concept
Landing
Wing folding
ground effect
assisted lift-off
Take-off
① Sail configuration
② Flight configuration
③ Hydroplaning
④ Full flight
Velocity
Design
Magnetic North
Magnetic heading
Angle of attack
True Wind Velocity
Apparent Wind Velocity
Boat Velocity
Force on sail
Lift component
Drag component
Lateral component
Resulting drive force
Lateral hydrodynamic force
Hull hydrodynamic drag
Prototyping
Outdoor validation
Sensing result
A: Acoustic monitoring
B: Heat flux mapping
Time (s)
The Round Pond
50 m
2 km
Ornithological reserve
Sailing missions
Generalist foragers:
Cormorants and Mute swans
Herons:
Pelecaniformes
Birds of prey:
Strigiformes and Accipitriformes
Vransko jezero
TUM
Imperial College London
EPFL
Empa

## SailMAV, sailing drone employed in air/water environmental sensing

## Conclusions

This project demonstrated that aerial-aquatic vehicles can achieve concrete **ecology research.**

This project will initiate experiments with various sensors to study flora and fauna, planning missions in **remote**, inaccessible regions like polar areas and dense forests.

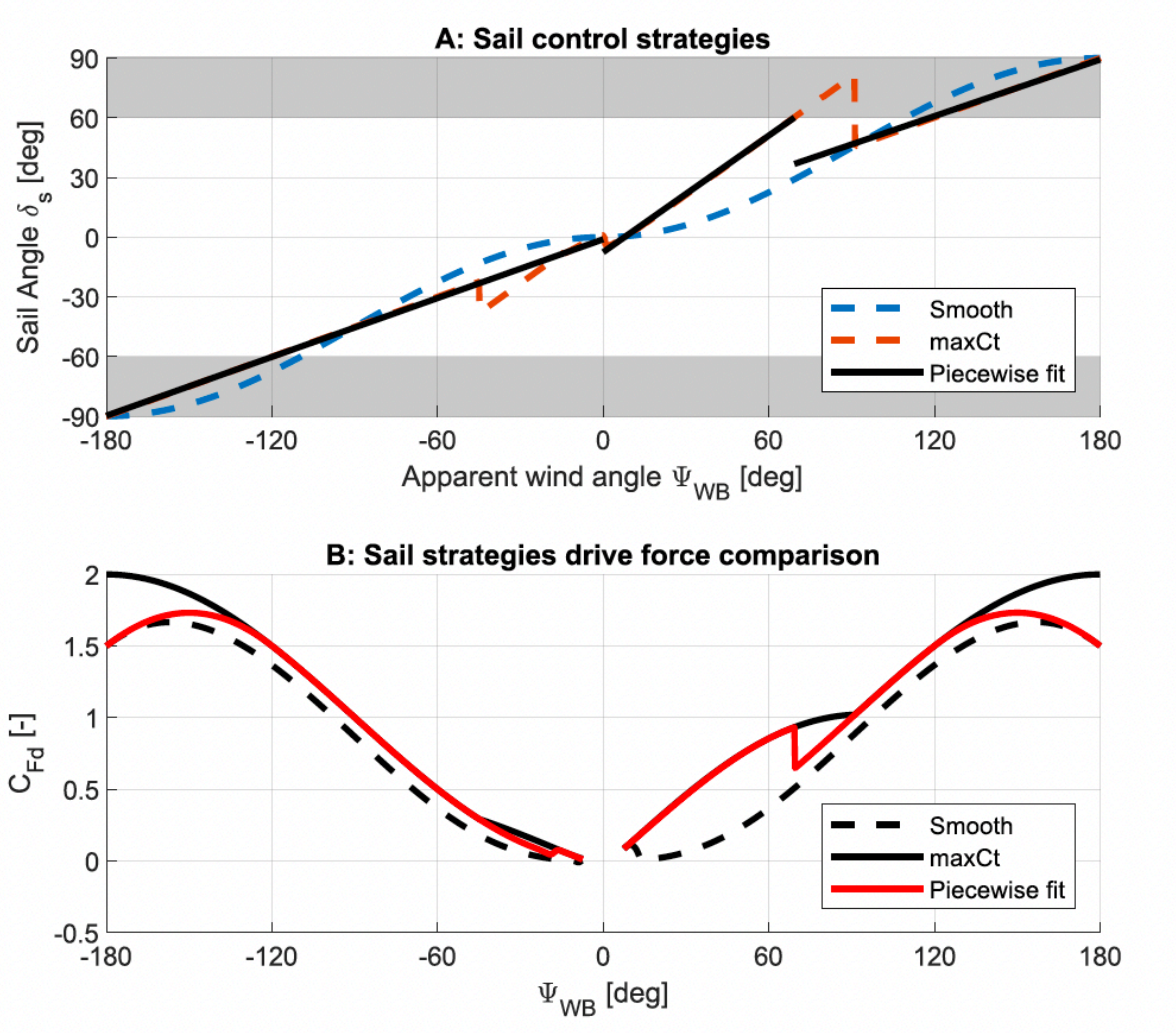
Planning to make the system more autonomous. **VTOL** configuration to improve the controllability of the vehicle

## Thank you for your attention!

**ANY QUESTIONS**

# Contributions

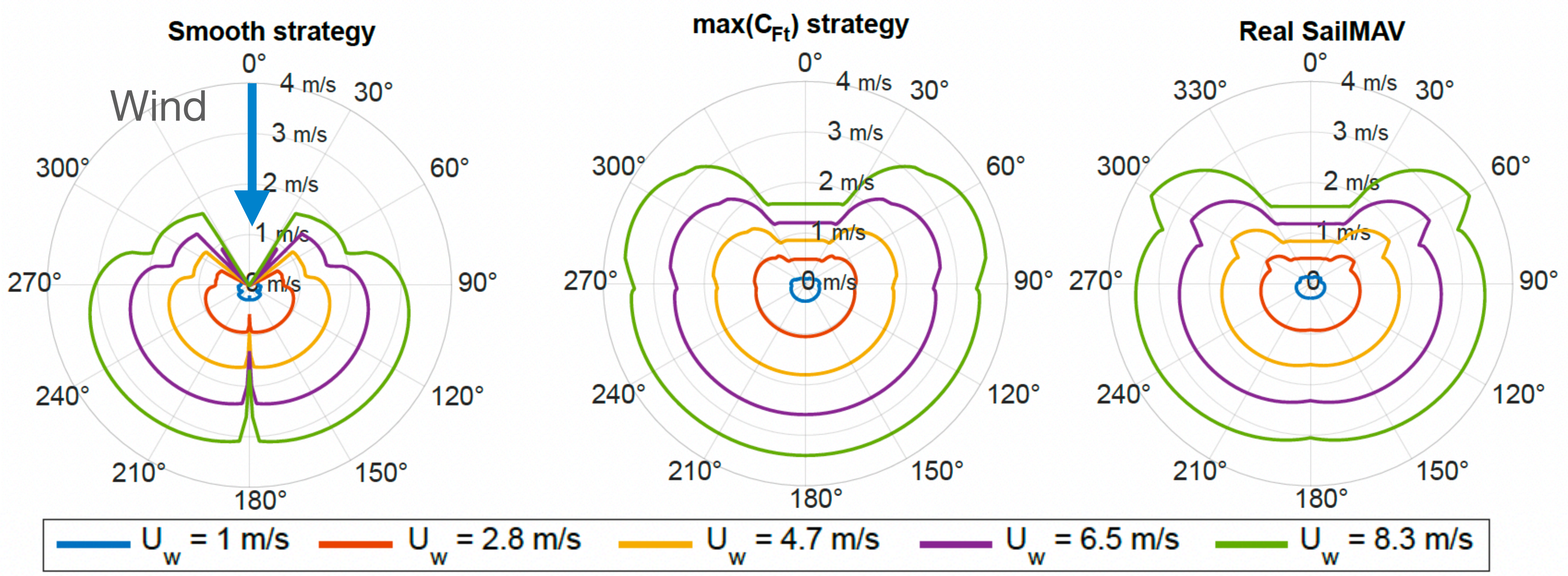
## SailMAV: sailing strategy

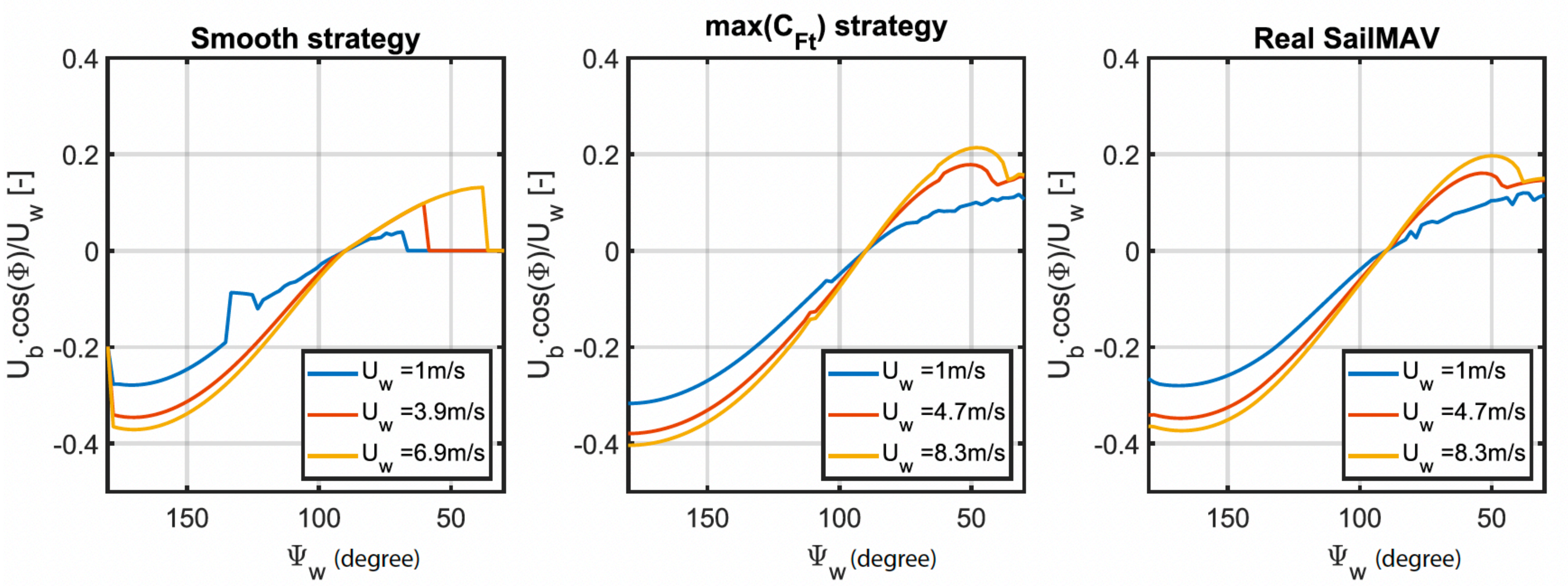



Sail angle

1 $$\delta_s(\Psi_{WB}) = \frac{\pi}{4} sign(\Psi_{WB})(1 - cos(\Psi_{WB}))$$

2 $$\delta_s(\Psi_{WB}) = \begin{cases} 0.4924\Psi_{WB} & \Psi_{WB} \in [-180, 0[ \\ 0.9728\Psi_{WB} & \Psi_{WB} \in [0, 70[ \\ 0.4735\Psi_{WB} & \Psi_{WB} \in [70, 180[ \end{cases}$$

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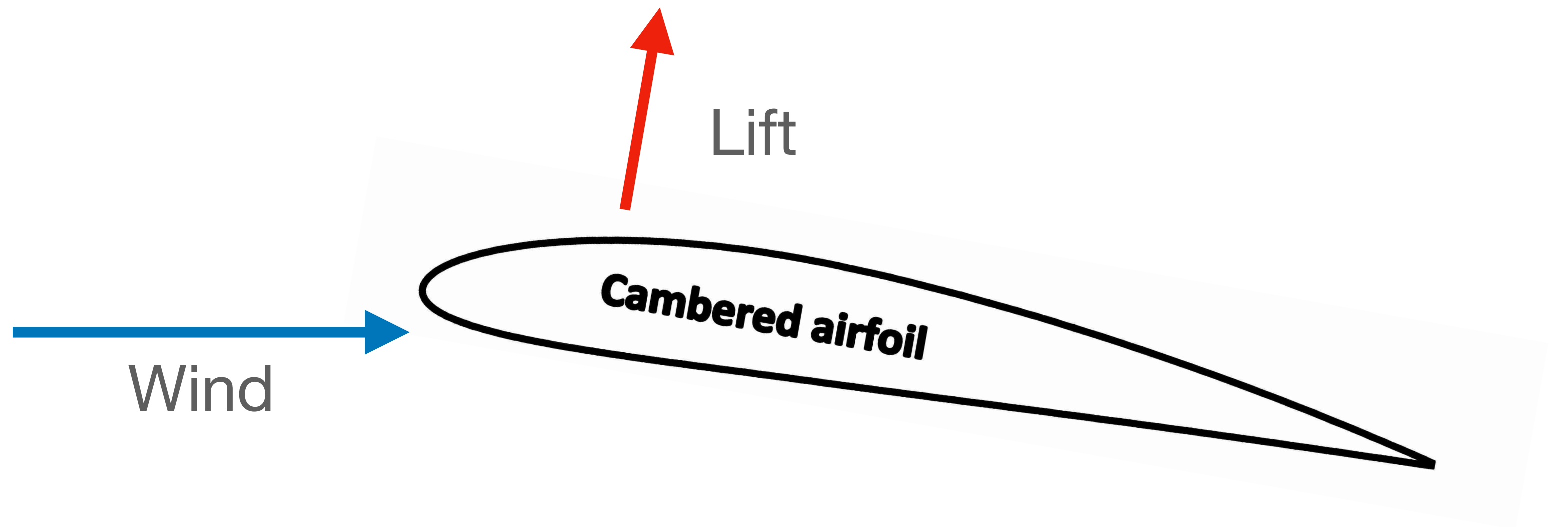



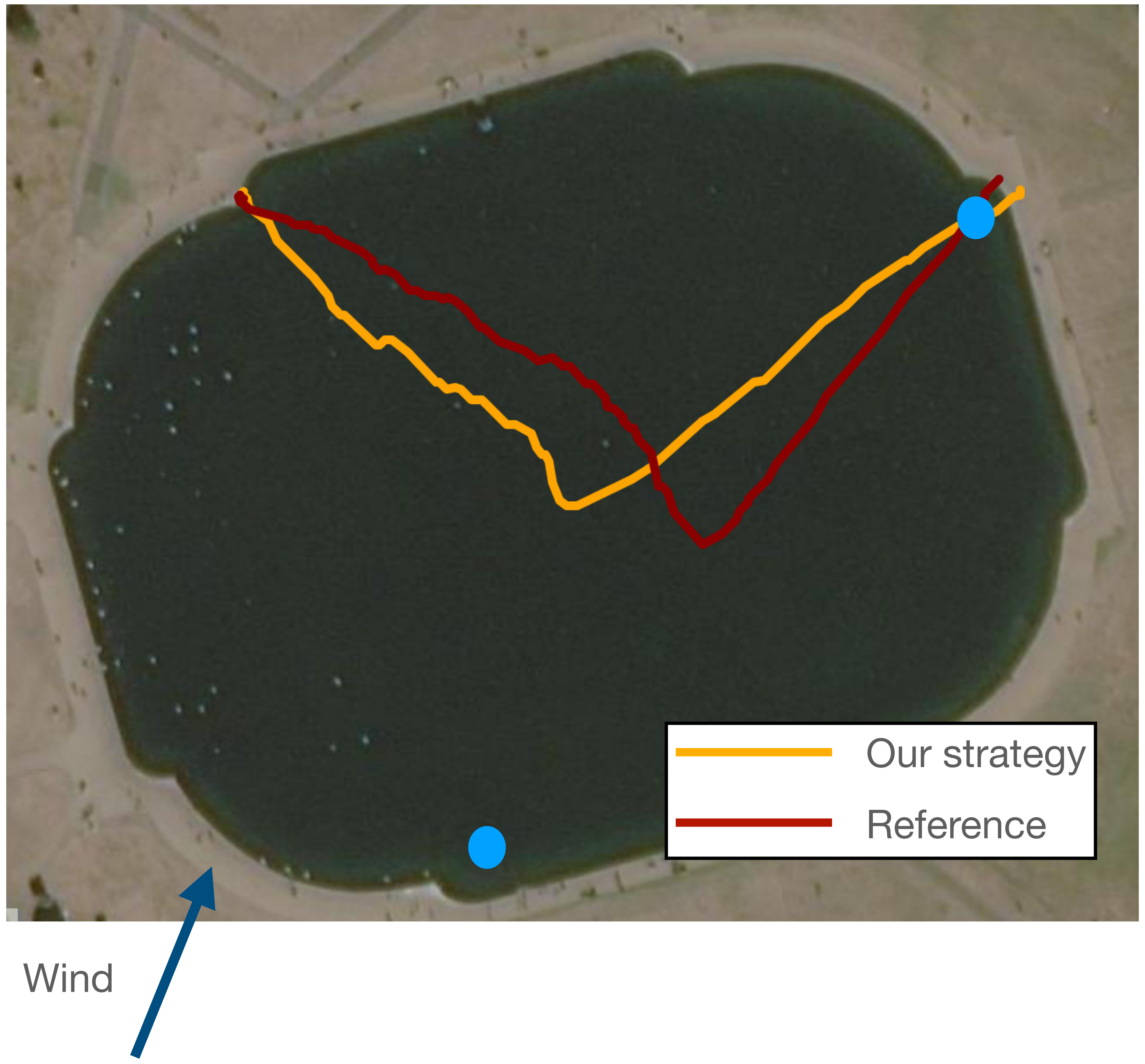


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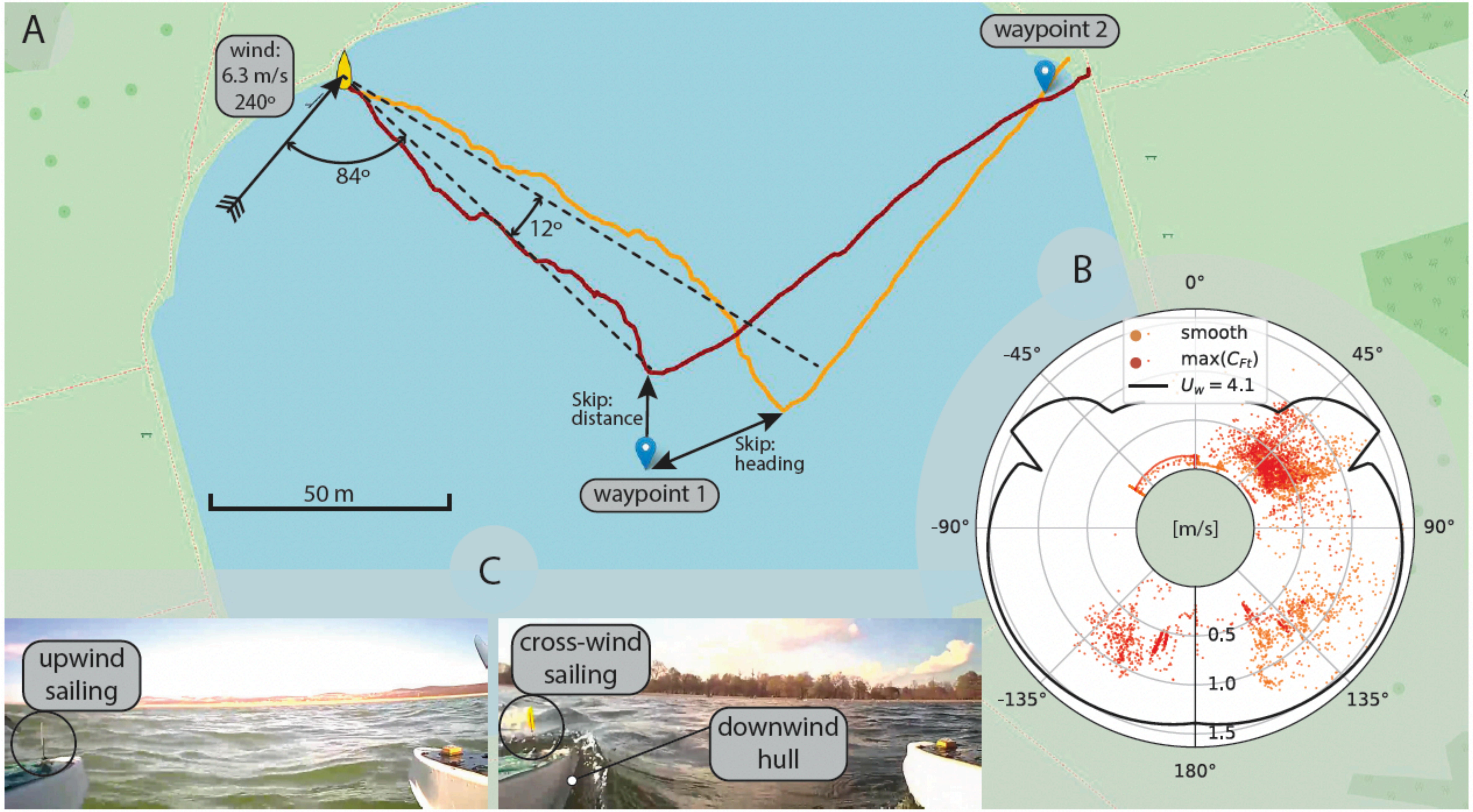


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