Assignment 1: Computational Modelling of an Autonomous Sail Drone

25% Unit Weighting – Main Deadline: 16:00, Fri 5 Dec

Figure 1: Small, autonomous sailing vessels have the potential to revolutionise ocean observation. Examples include: [left] the American "*SailDrone*"[1] and [right] the Australian "*Bluebottle*"[2].

1 Outline

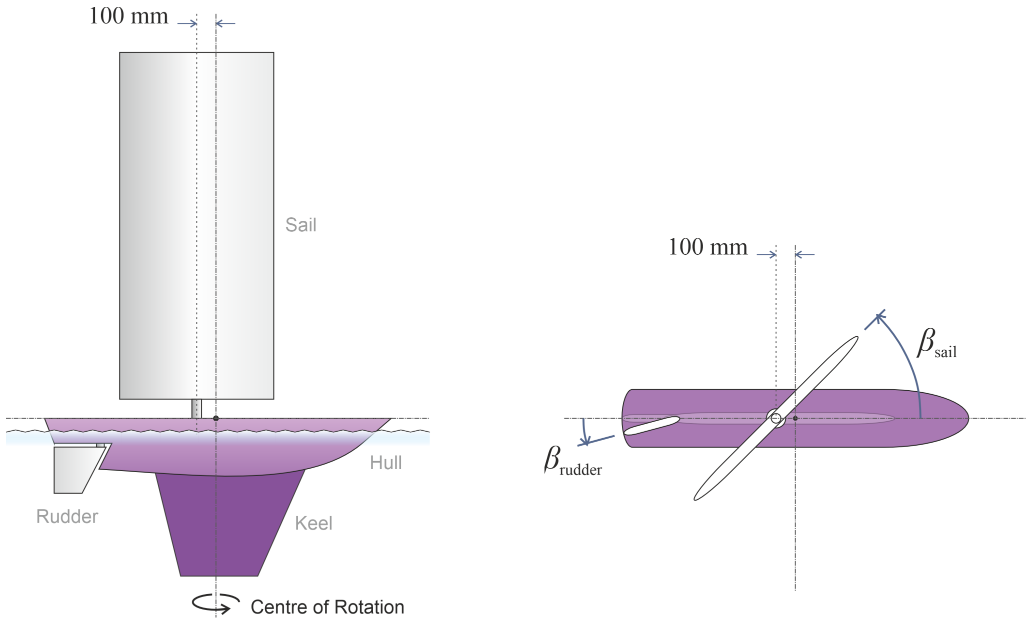
Sailing vessels offer a zero-carbon alternative for sustainable transport and mobility at sea. Small, autonomous sailing vessels can operate persistently, with solar energy supporting on-board instruments and payloads. These platforms unlock new capabilities in oceanographic and environmental monitoring, and enable distributed maritime communication networks. Sometimes referred to as "*satellites of the sea*", they represent a scalable and sustainable approach to persistent ocean observation.

A marine technology company is developing a *sail drone*, and **you are part of the software engineering team.**

The drone has a mass of $M = 2,500$ kg and a rotational inertia of $I = 10,000\ \text{kg} \cdot \text{m}^2$ in the horizontal plane. It is equipped with a symmetrical, rigid sail of area $A = 15\ \text{m}^2$, which can be rotated through angles $\beta_{\text{sail}} \in [-180, 180]$ degrees. The sail is positioned 100 mm behind (*aft*) the centre of rotation, creating a natural tendency for the drone to turn into the wind. The rudder is constrained to operate within a deflection range of $\beta_{\text{rudder}} \in [-30, 30]$ degrees. The design drawings are shown in Figure 2.

[1]Image source: SailDrone website `https://www.saildrone.com/`

[2]Image source: Ocius website `https://https://ocius.com.au/usv/`



(a) (b)

Figure 2: Sail drone design drawings: (a) side view, (b) top view.

The aerodynamics team has characterised the performance of the sail using computational fluid dynamics modelling software. To support further analysis, they have fitted simple analytical models for the coefficients of drag and (horizontal) lift,

$$\begin{aligned} C_{\mathrm{D}} &= 1 - \cos(2\alpha) \\ C_{\mathrm{L}} &= 1.5\,\sin\Big(2\alpha + 0.5\,\sin(2\alpha)\Big), \end{aligned}$$

respectively, where α is the sail's angle of attack relative to the *apparent* wind in radians.

The hydrodynamics team has measured the integrated performance of the hull, keel, and rudder experimentally in a flow tank. Their measurements capture (horizontal) lift generated by the keel, drag induced by the hull, rotational hydrodynamic resistance, and turning moment caused by deflection of the rudder. To access these measurements, they have provided a Python function `get_vals` in the module `saildrone_hydro.py`, which reads from the accompanying data file `saildrone_hydro.dat`. Both the module and data file are available on Moodle.

```
[force,torque] = get_vals(velocity,heading,turn_rate,rudder_angle).
```

The input parameters are the drone's 2-D velocity vector $(\dot{x}, \dot{y})$ in m/s, orientation or *heading* θ in radians, turning rate $\dot{\theta}$ in rad/s, and rudder deflection angle β_{rudder} in radians. All angles follow the convention of positive values in the anti-clockwise direction relative to the positive x axis. The function returns the resultant 2-D force vector in N and torque in N $\cdot$ m.

2 Tasks

Within the software engineering team, it is your responsibility to develop the Python software for modelling the sail drone's navigation system.

To test and demonstrate your software, you must predict the trajectory of the drone in a test scenario involving a transition between two legs of a larger sailing course, labelled **A**-**B**-**C** in Figure 3(a). Consider a 2-D coordinate system with the drone located at the origin at time

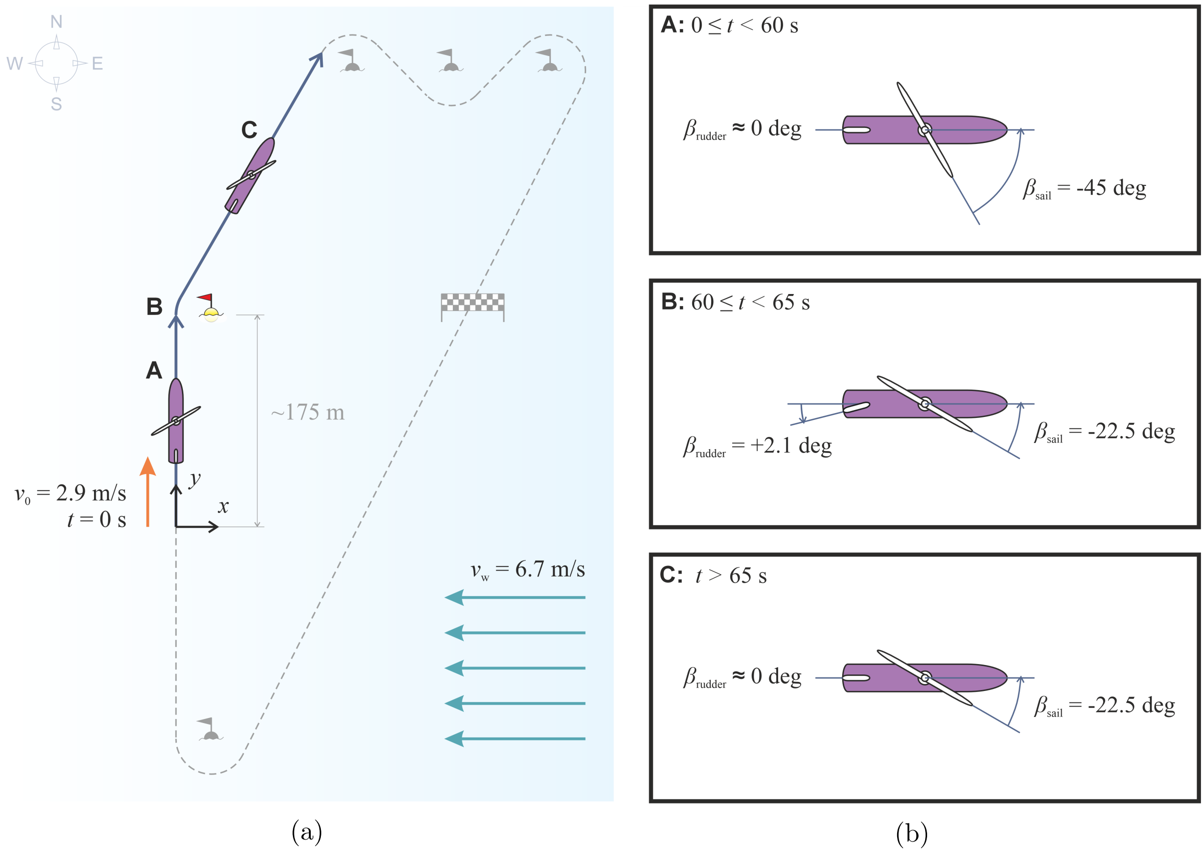


Figure 3: Sail drone testing in an Easterly wind of 6.7 m/s (13 knots). **A:** travelling Northward, across the wind (*beam reach*); **B:** making a clockwise turn (to *starboard*); and **C:** travelling up-wind (*close reach*). The required sail and rudder angles and timings are given in the insets on the right-hand side.

$t = 0$ with an initial velocity of 2.9 m/s aligned with the positive y axis. Consider a wind blowing steadily in the negative x direction at a constant speed of 6.7 m/s. The sail and rudder angles and timings expected to achieve the desired trajectory are provided in Figure 3(b).

You will achieve your goal by following these steps:

1. Draw a free-body diagram (FBD) illustrating the forces and torques acting upon the sail drone.
2. Using the FBD, derive three 2nd-order ordinary differential equations (ODEs) that govern the drone's motion in terms of its 2-D position (x, y) and orientation θ.
3. Define a 6-D state vector that includes both translational and rotational components. Use this to express the system as six coupled first-order ODEs.
4. Reuse the `solve_ivp` function developed in Lab 5 to solve these equations numerically using the Runge-Kutta method. This will require defining a new state-derivative function tailored to the sail drone dynamics.
5. Compute and plot the trajectory of the drone.

Once you have solved the problem – well done! This satisfies the minimum requirements for passing the assignment.

3 Extension Tasks

As with most engineering problems, this one is open-ended. To achieve a higher grade, you must apply your own creativity and initiative to extend the work beyond the minimum requirements. How you choose to do this is entirely up to you, but the following suggestions might provide inspiration:

- Increased realism
  - Introduce environmental variability, such as ocean currents or time-varying wind conditions.
  - Incorporate physical constraints, such as limits on the sail and rudder actuation rates.
  - Extend the model to 3-D and explore the effects of roll and pitch, especially under strong wind conditions or during sharp manoeuvres.
- Alternative drone designs
  - Design a different sail drone, such as one optimised for racing, endurance, or manoeuvrability.
- Full-course navigation
  - Determine the sail and rudder angle profiles required for the drone to complete the entire sailing course, or any arbitrary course.
- Autonomous sensing and control
  - Implement feedback control that adjusts the sail and rudder angles based on real-time position and heading measurements.
  - Apply boundary value or optimisation methods to compute ideal control inputs that minimise travel time or deviation from a desired path.
  - Consider collision avoidance or path planning by introducing obstacles or other vessels into the environment.
- Visualisation and user interaction
  - Visualise the evolution of hydrodynamic and aerodynamic forces over time and their influence on the drone's motion.
  - Develop a graphical user interface to allow interactive control or visualisation.
  - Create a game-like environment for training or experimentation.

4 Deliverables

Report

Summarise your work in a brief report. This must include:

- The FBD and derivation of your ODEs, including assumptions.
- Graph(s) of the sail drone's trajectory, indicating the locations corresponding to the sail and rudder changes.
- Discussion of the results and impact of assumptions
- Descriptions and results for the extension tasks
- Python code in an appendix (not included in the page limit)

The report is strictly limited to 8 pages; this includes title, abstract, and figures, **but excludes references and appendices**.

Do not use an entire page for the title and author list (a short header will suffice). Do not provide a table of contents (this is unnecessary in a brief report). Do not use unreasonably small fonts or margins to satisfy the page limit (this adversely affects readability). Apart from the requested material, any other material provided in the appendices will be considered as supplementary and will not be assessed.

Python Code

Put all of your code into a single Zip file.

5 Submission Deadlines

★ 16:00, Fri 5 Dec – Main Submission (75% Weighting)

As a group, submit your report (PDF) and Python code (Zip) to both the *submission* portal and the *peer review* portal on Moodle.

★ 16:00, Fri 12 Dec – Peer Review (Influences 15% of Main Submission Grade)

As an individual, you will be assigned the work from 3 other groups at random as well as your own (4 total). Review this work, providing grades and feedback via the *peer review* portal on Moodle.

★ 16:00, Fri 12 Dec – Group Performance Review (15% Weighting)

As an individual, provide an assessment of the performance of your group members as well as yourself via the *group performance review* portal on Moodle.

6 Policy on the Use of Generative Artificial Intelligence (AI)

If you *choose* to use generative AI as an aid, then **you must document, justify, and reflect on this** in an appendix, providing the following details:

- A narrative (written by you) *for each task*, including:
  - Description of the task and how you used AI.
  - Explanation of how this supported your understanding and learning, rather than simply completing the work for you.
  - Critical analysis of the AI's outputs.
  - Signposting to where the outputs appear in, or influenced, your submission.
- The AI model and version number used.
- A complete log of *all* prompts and outputs, including time stamps.

This appendix will be excluded from the page limit.

Failure to provide satisfactory justification and/or reflection will result in a lesser grade. **Failure to disclose this information or incomplete disclosure will be considered plagiarism.** For further guidance on academic integrity, plagiarism, and AI, visit: `https://library.bath.ac.uk/referencing/plagiarism`.