Bio-inspired drone control

Safe and robust design with verified neural networks

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Drone Design

[1]

[2]

[3]

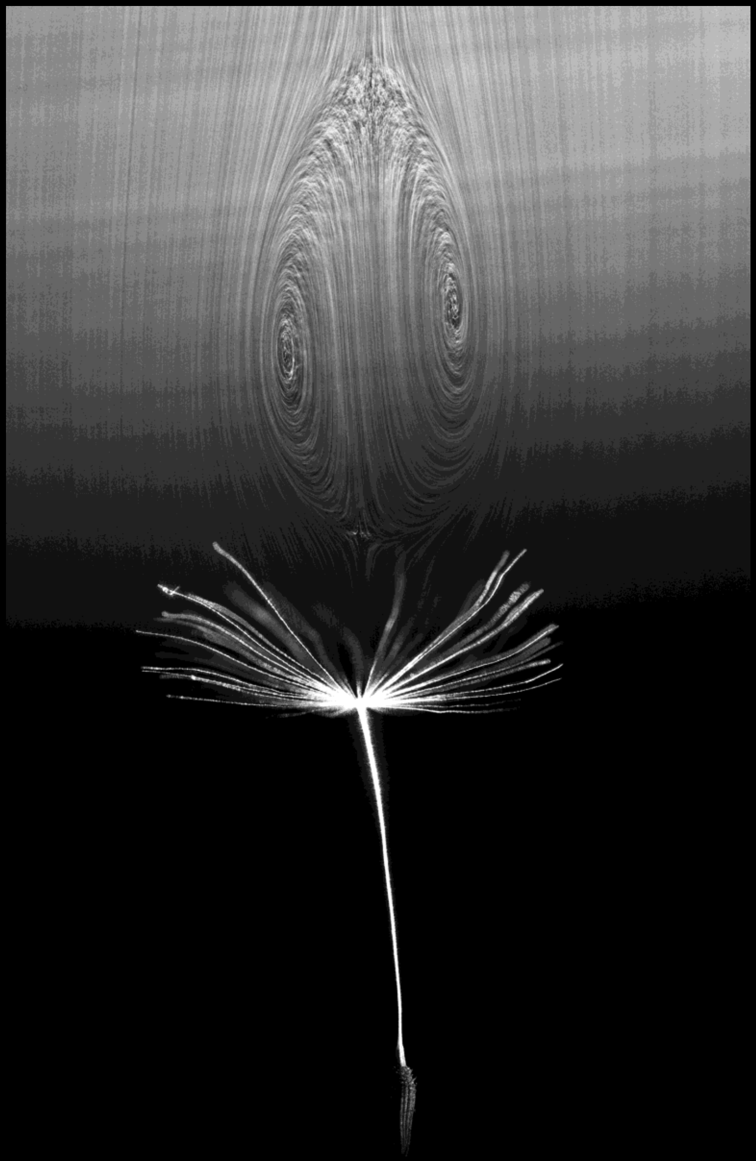
[4]

Dandidrone project

A dandelion-inspired drone for swarm sensing

- Recent research shed light on the fluid mechanics underlying dandelion diaspore flight [5]
- Dandelion drones could remain airborne for days
- VOILAb research includes numerical and experimental investigation of these flyers

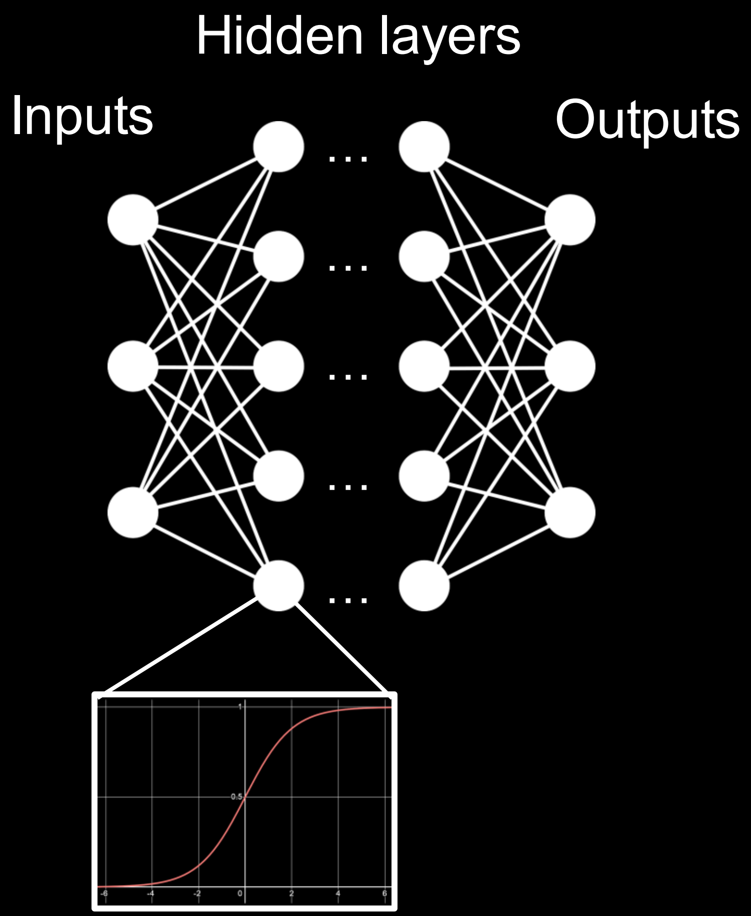
VOILAb Vortex Interaction Laboratory



[5]

Dandidrone project

Neural Networks (NNs)

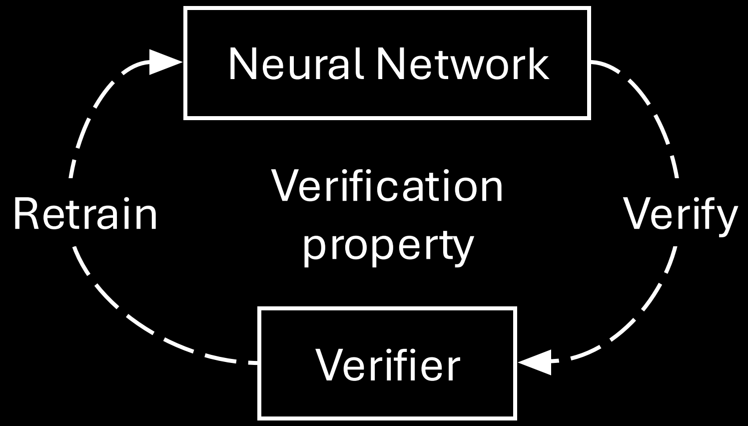


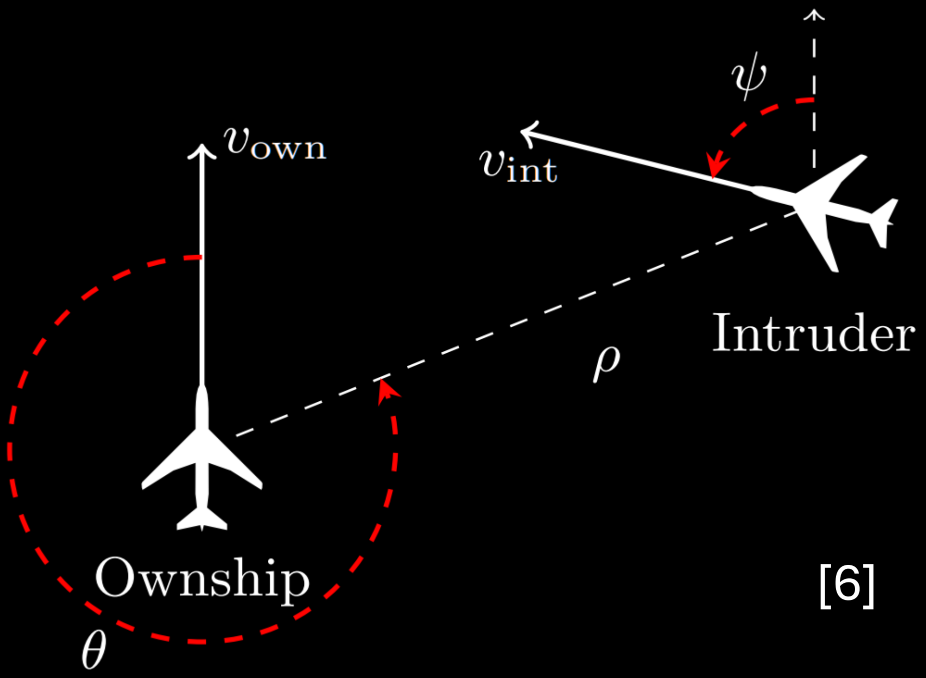
- Layered network of functions, with initially random weights
- NN is trained (weights are calculated) to best reproduce patterns in a dataset
- Can (theoretically) approximate any function or process …

NN Verification

... but NNs typically perform poorly when presented real-world data.

NN verification is a relatively new field, and toolkits can be used to improve robustness and safety.

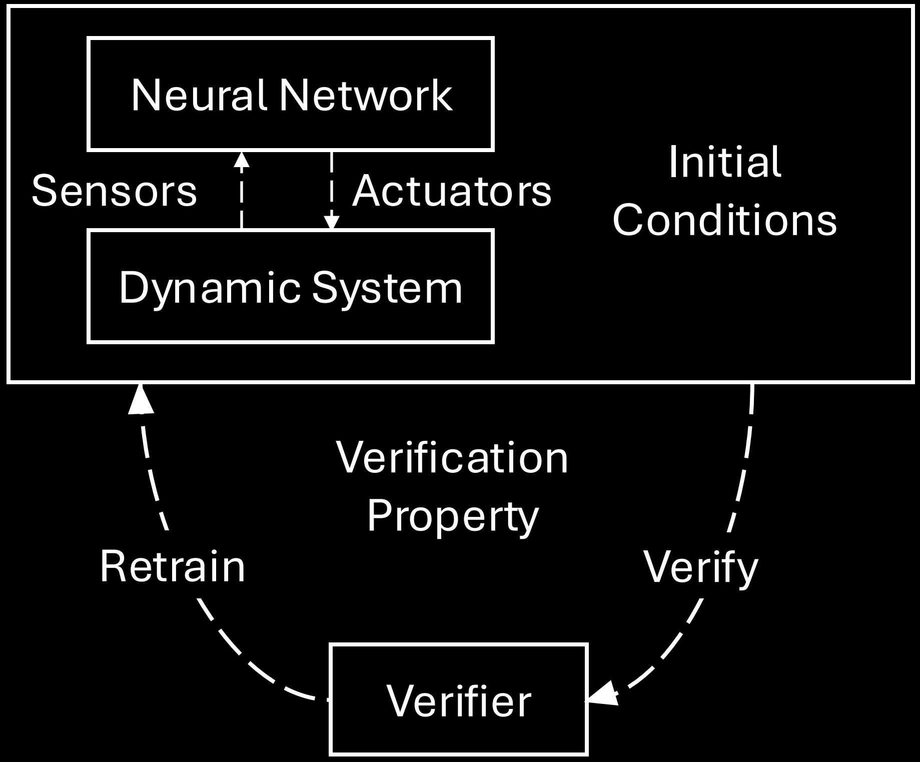


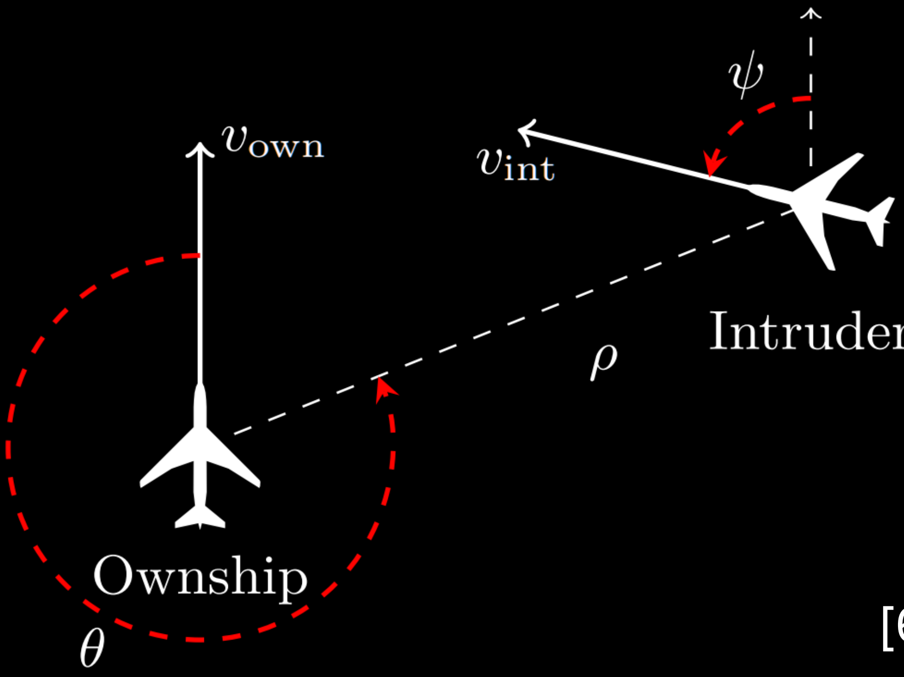


[6]

If the intruder is directly ahead and is moving towards the ownship, the clear-of-conflict instruction will not be given

NN-controlled system verification





[6]

If the intruder is directly ahead and moving towards the ownship, the separation distance will always exceed 3 miles

To Recap…

- Bioinspired flyers could function as airborne sensor networks, but control methods have not been extensively proven

- NNs could be used for controlling such flyers, offering flexibility, data-driven control design, and low computational cost

- NN-controlled flyers behaviour would need formal verification to prove robustness and safety

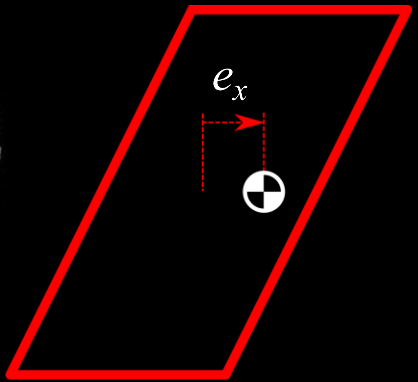
Work to date: *Alsomitra macrocarpa*

[7]

- Gliding diaspores, achieving low terminal velocity with a flat winged shape
- Unique flight characteristics investigated experimentally in recent works [9]
- Modelling experimental trajectories could provide system for NN verification

[8]

Li. et al [10] model



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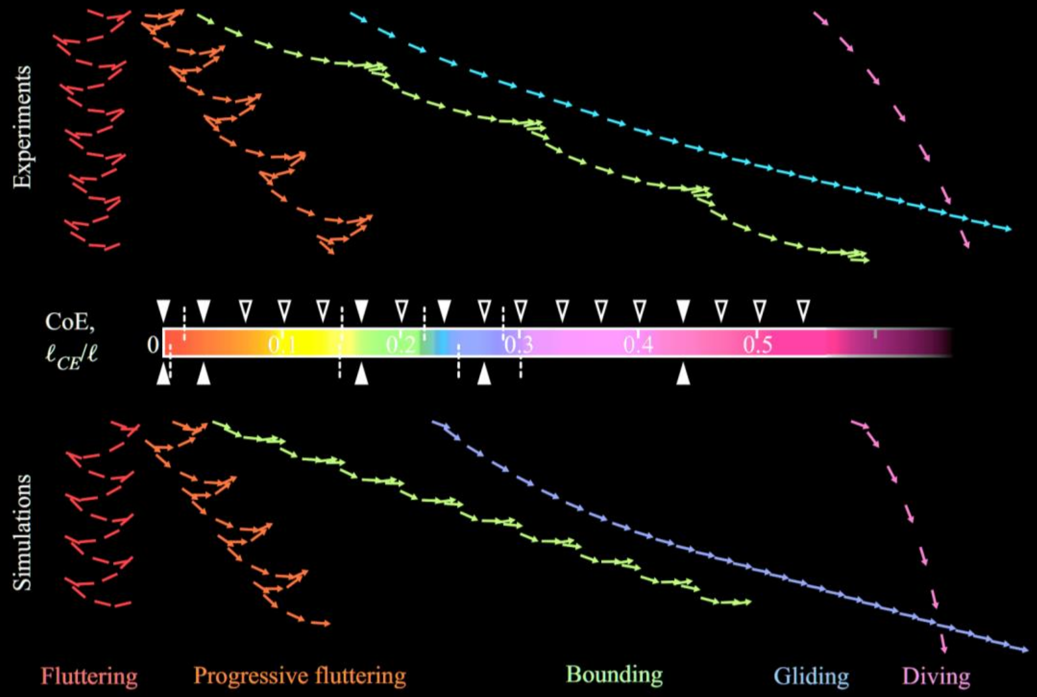

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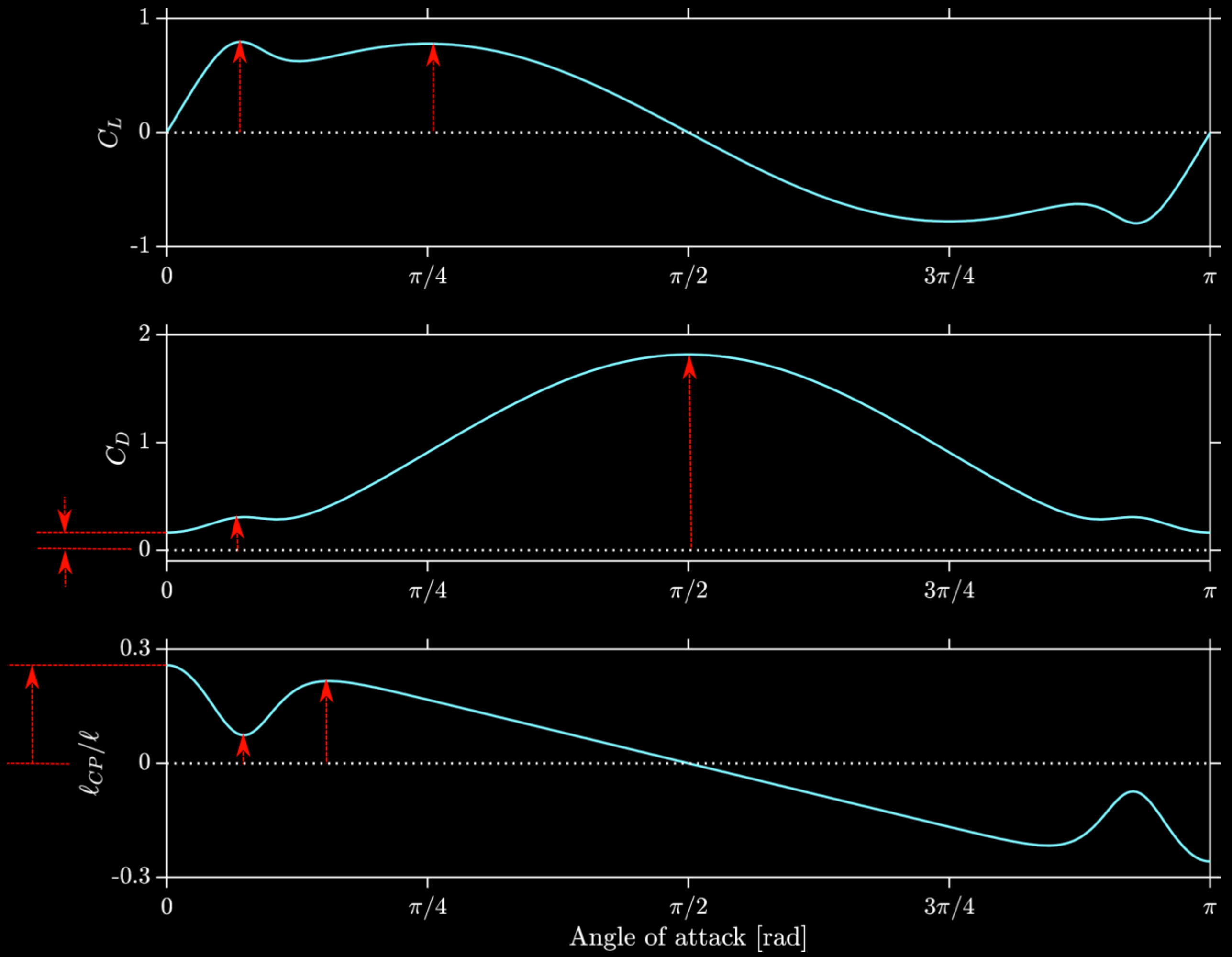
Model Parameters

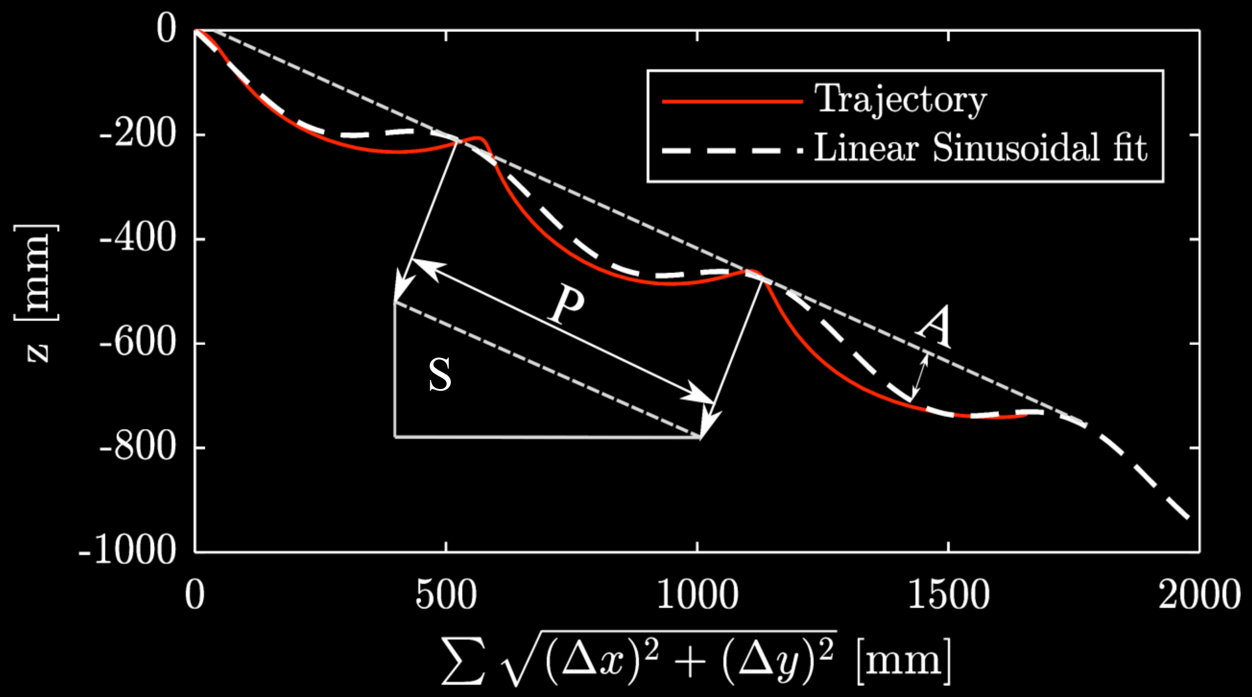


- Lift, drag and center of pressure change with angle of attack
- Reflects complex fluid behaviour
- 9 aerodynamic coefficients dictate dynamic behaviour (and COM position)

Model Optimisation

- Experimental trajectories characterised in terms of slope, period and amplitude (S, P, and A)

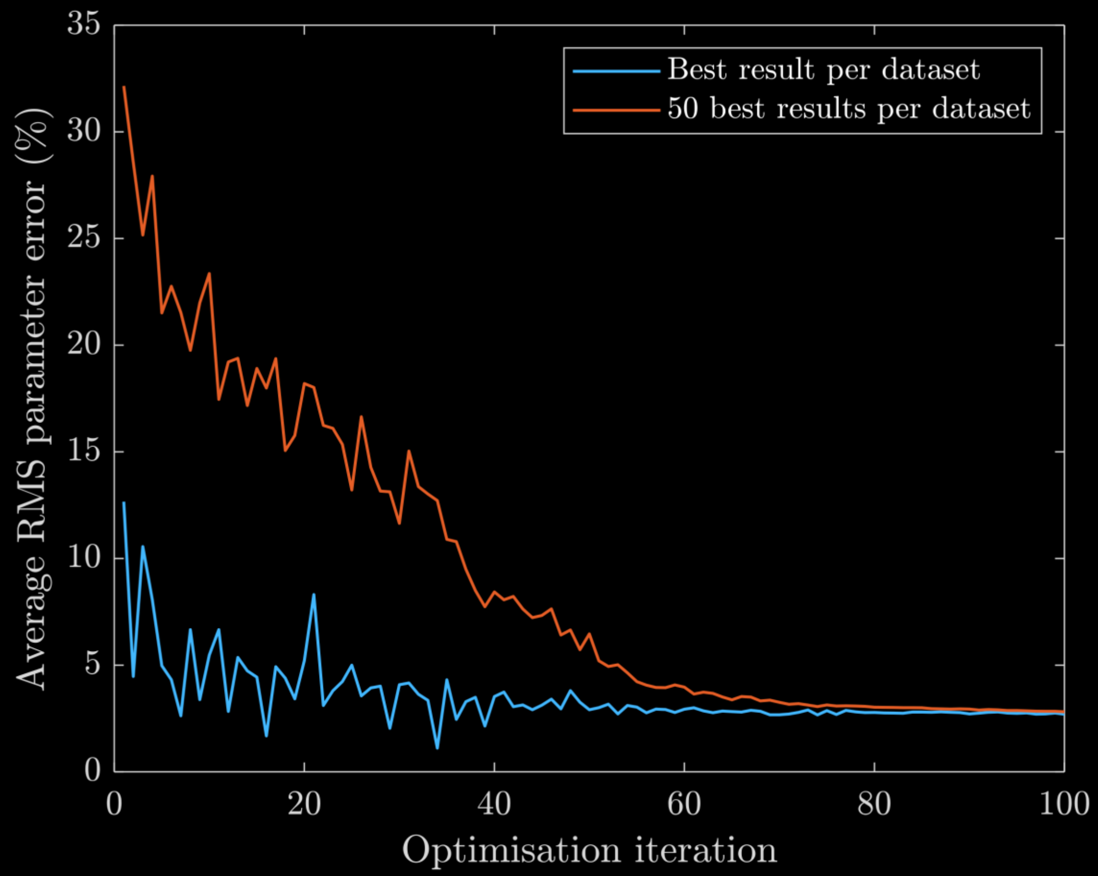
- To fit the model, aim is to minimise the discrepancy in characteristics (f_{Obj})



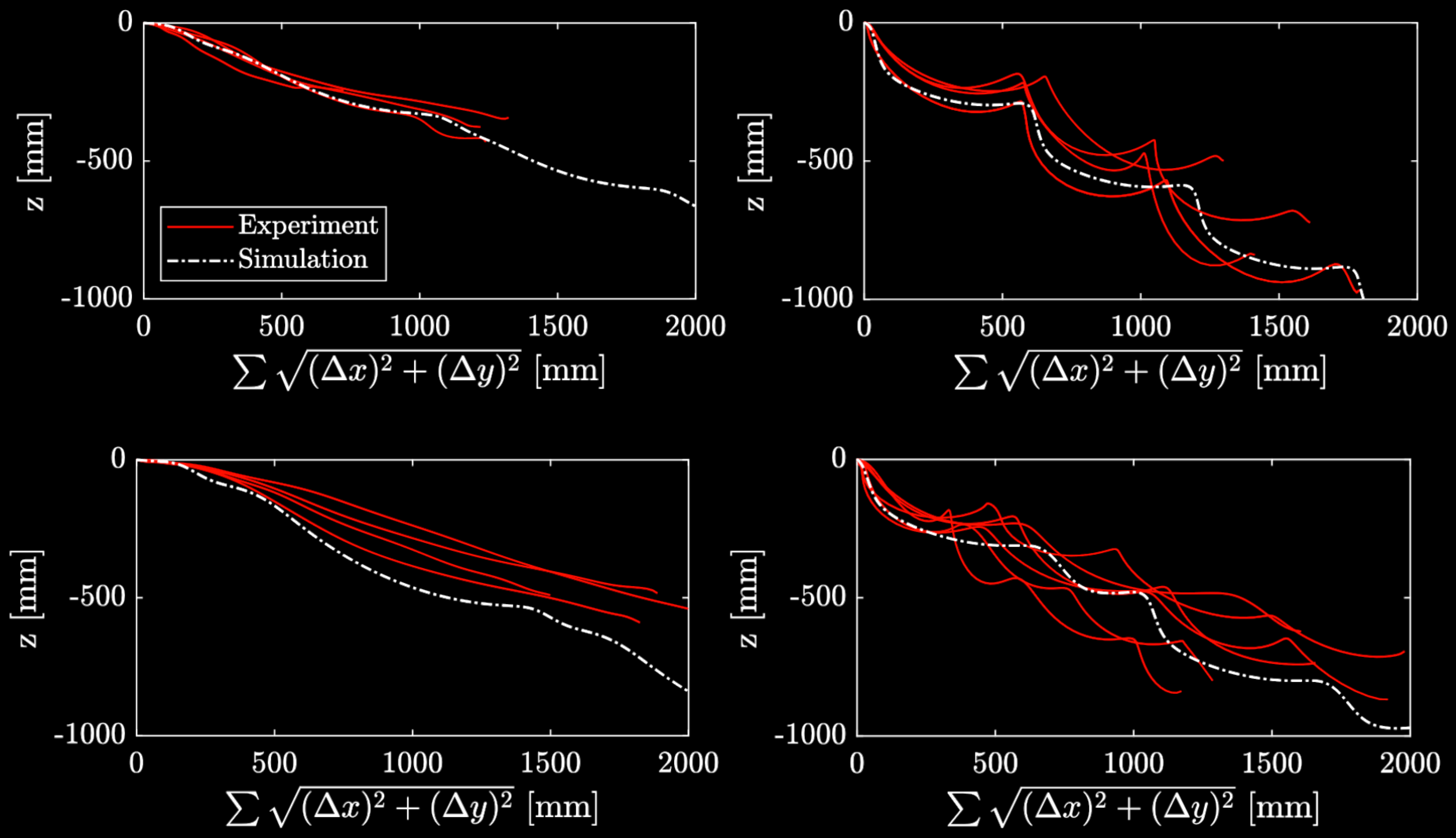
$$f_{\mathrm{Obj}} = \left|\frac{S_{\mathrm{sim}} - S_{\mathrm{exp}}}{S_{\mathrm{sim}}}\right| + \left|\frac{A_{\mathrm{sim}} - A_{\mathrm{exp}}}{A_{\mathrm{sim}}}\right| + \left|\frac{P_{\mathrm{sim}} - P_{\mathrm{exp}}}{P_{\mathrm{sim}}}\right|$$

Optimisation Algorithm (Heuristic Search)

1. Establish bounds on each of the 9 parameters
2. Run 400 simulations with random parameters (between bounds)
3. Establish new bounds based on best 12 results
4. Repeat 100 times



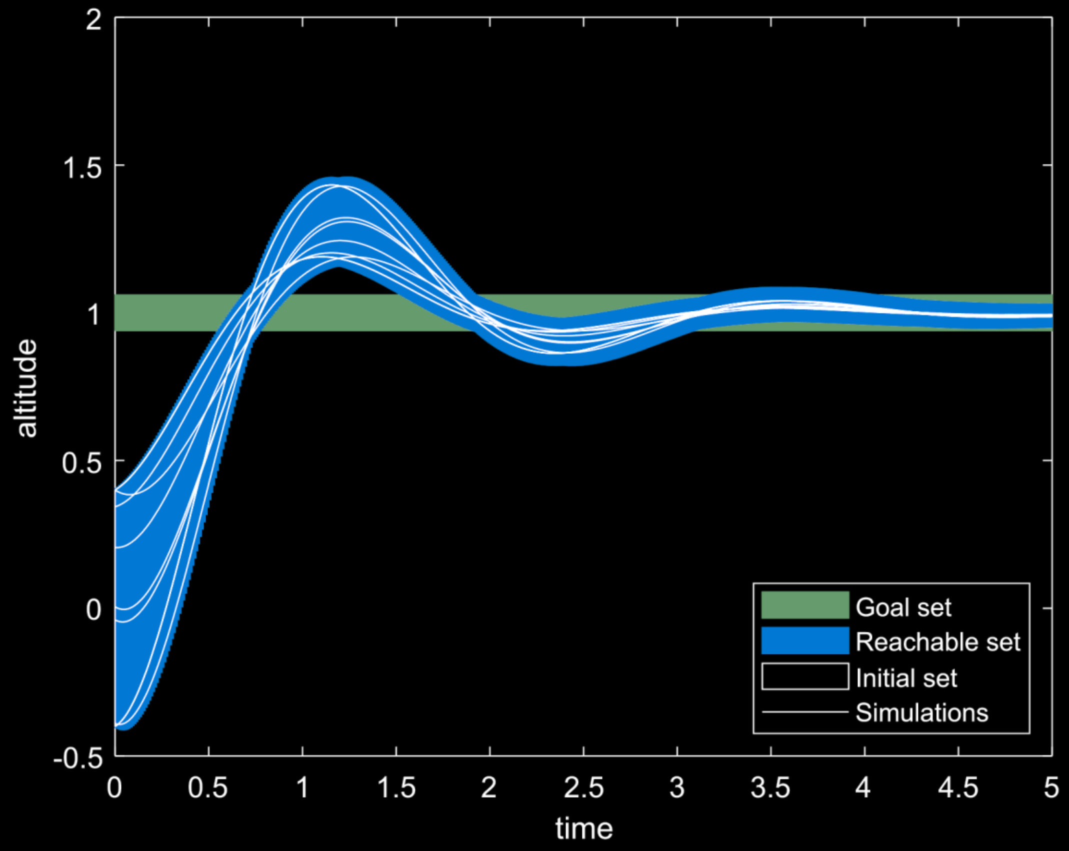
Optimisation results



Summary

- 4 experimental *Alsomitra* trajectories were characterised
- A 2D dynamic model was optimised (using heuristic search) to best fit the 4 trajectories, by only changing the COM position
- The optimised model can now be used to train, test and verify NN control systems for small flyers

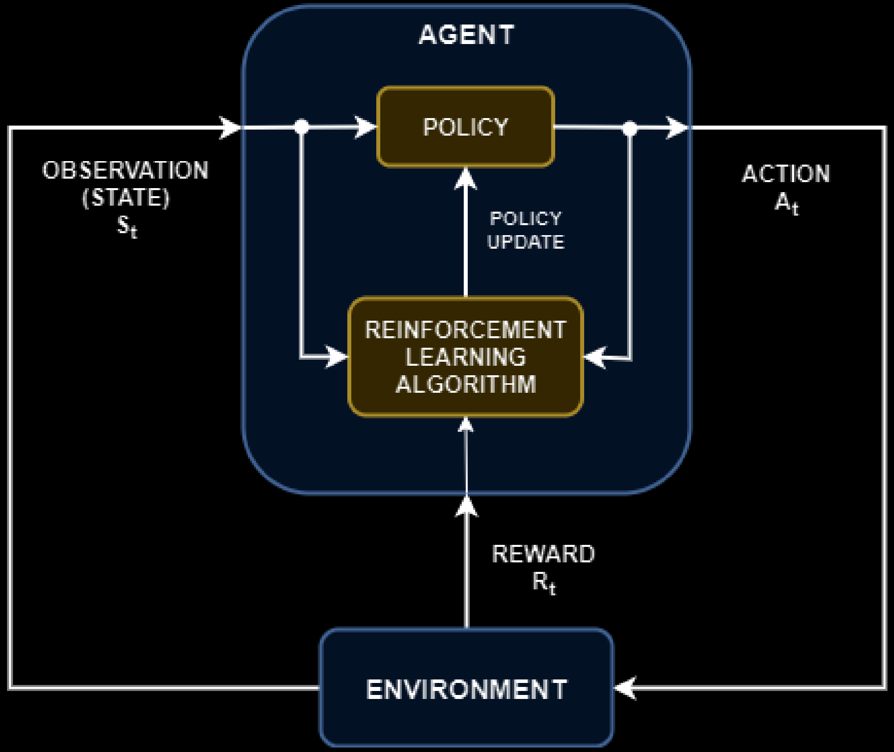
Ongoing work - Reachability of *Alsomitra*



[11]

- Reachability of NN-controlled flying systems has been demonstrated [11]
- QUAD benchmark aims to guarantee stable altitude for a quadcopter [11]
- Implemented in MATLAB using CORA [12]

Controlling *Alsomitra* – Reinforcement Learning



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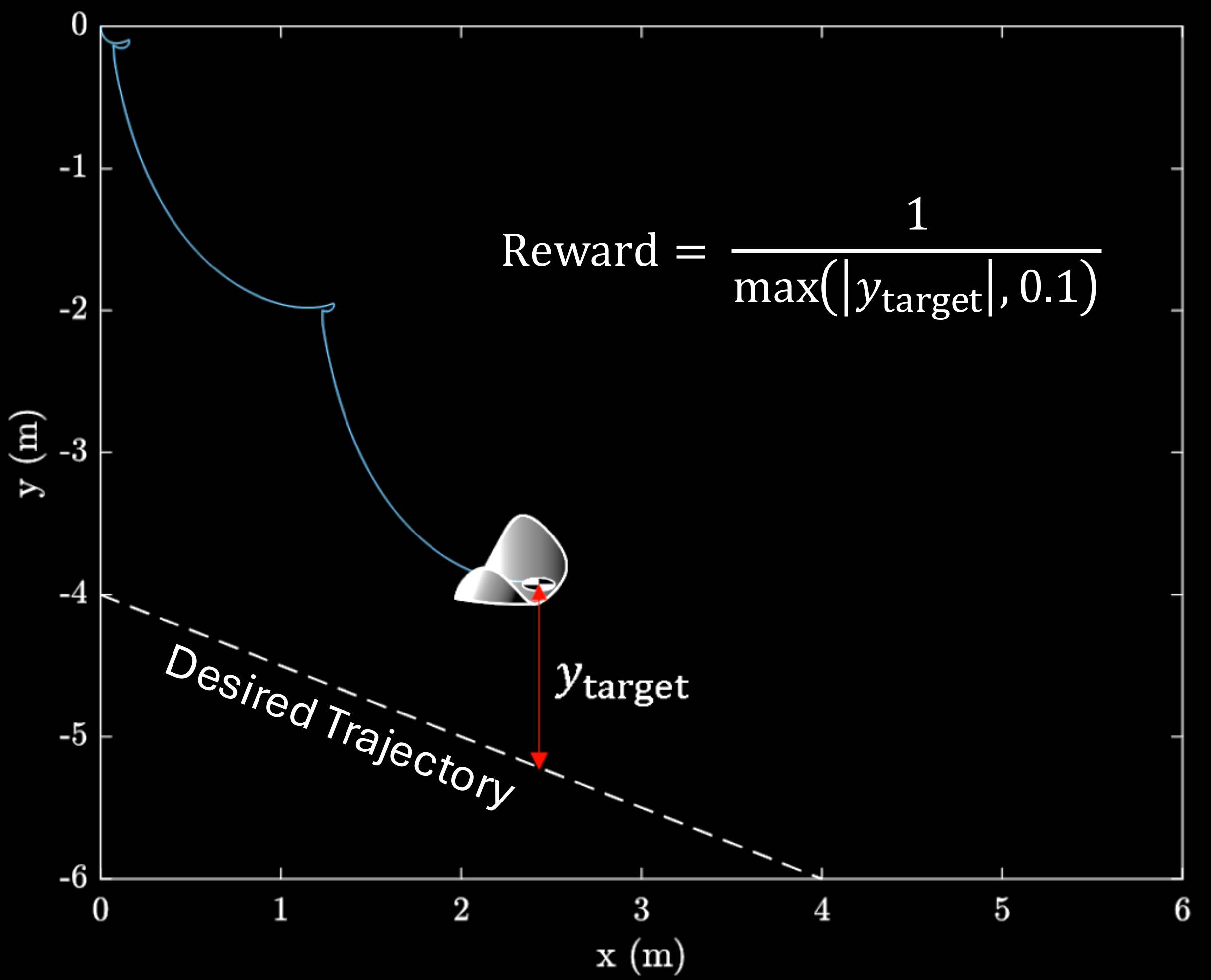
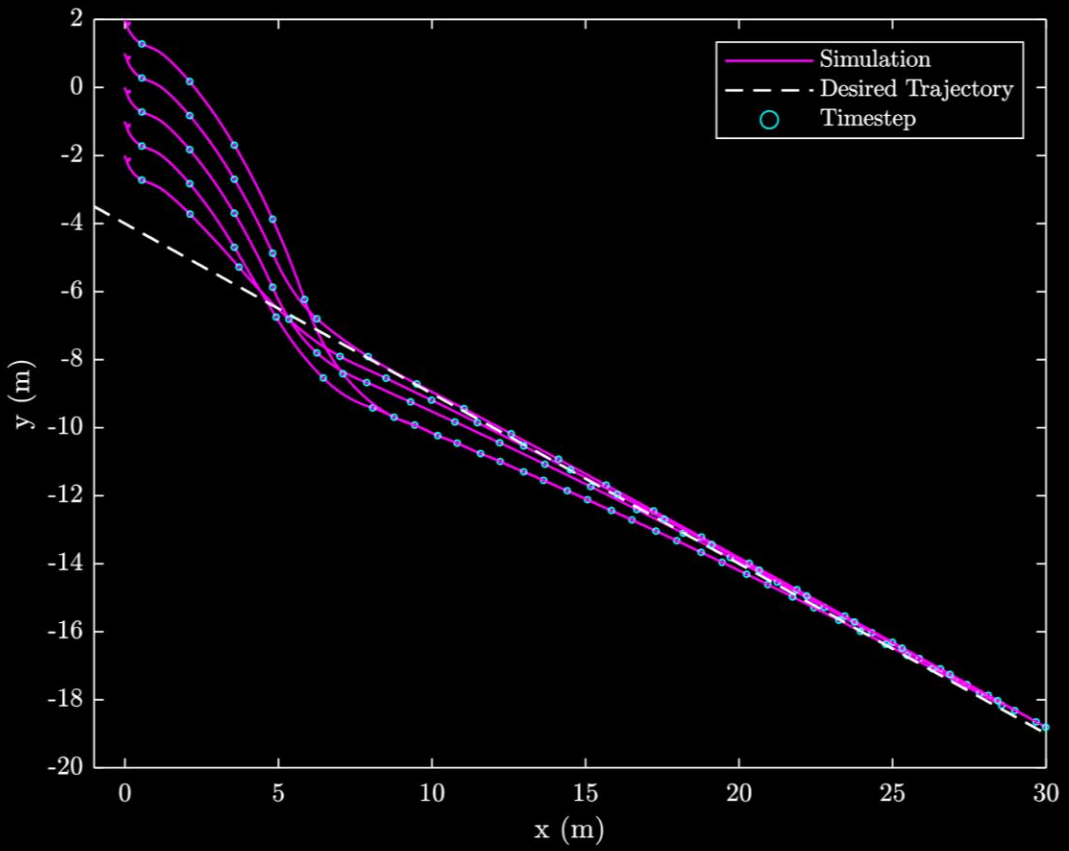
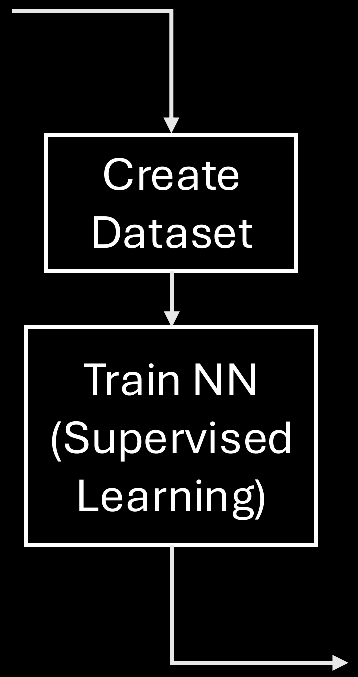
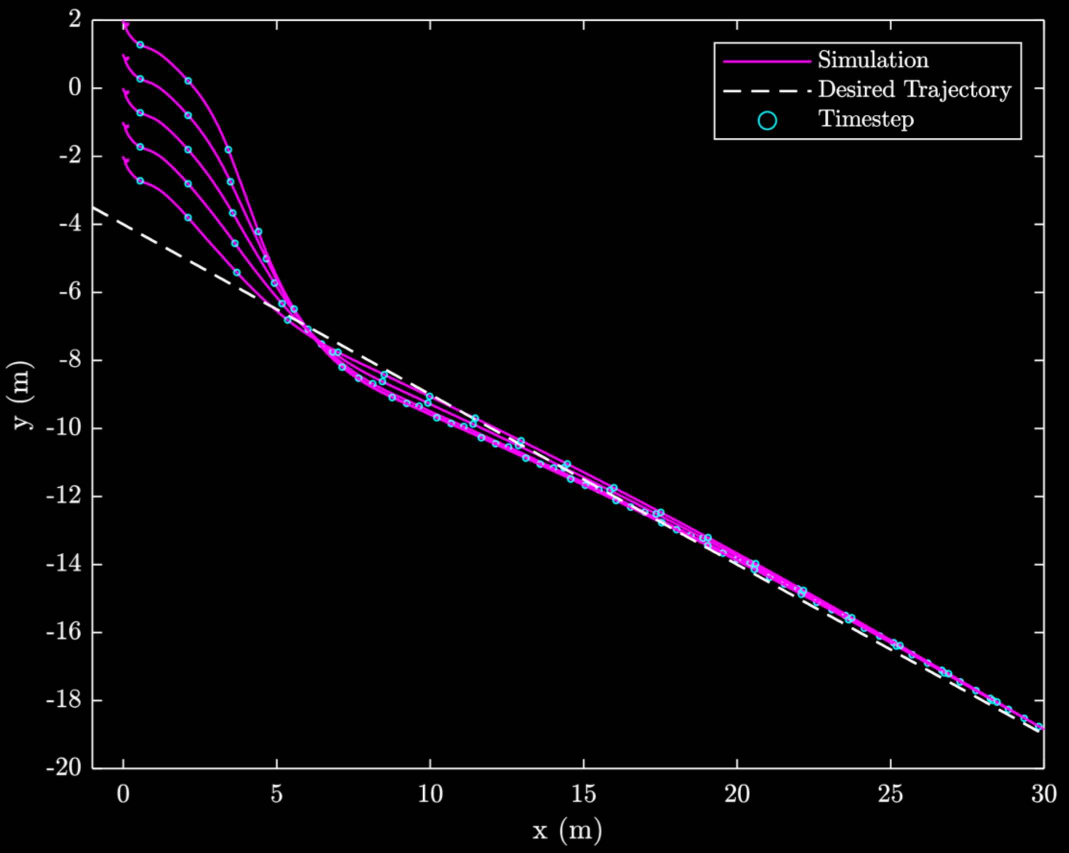


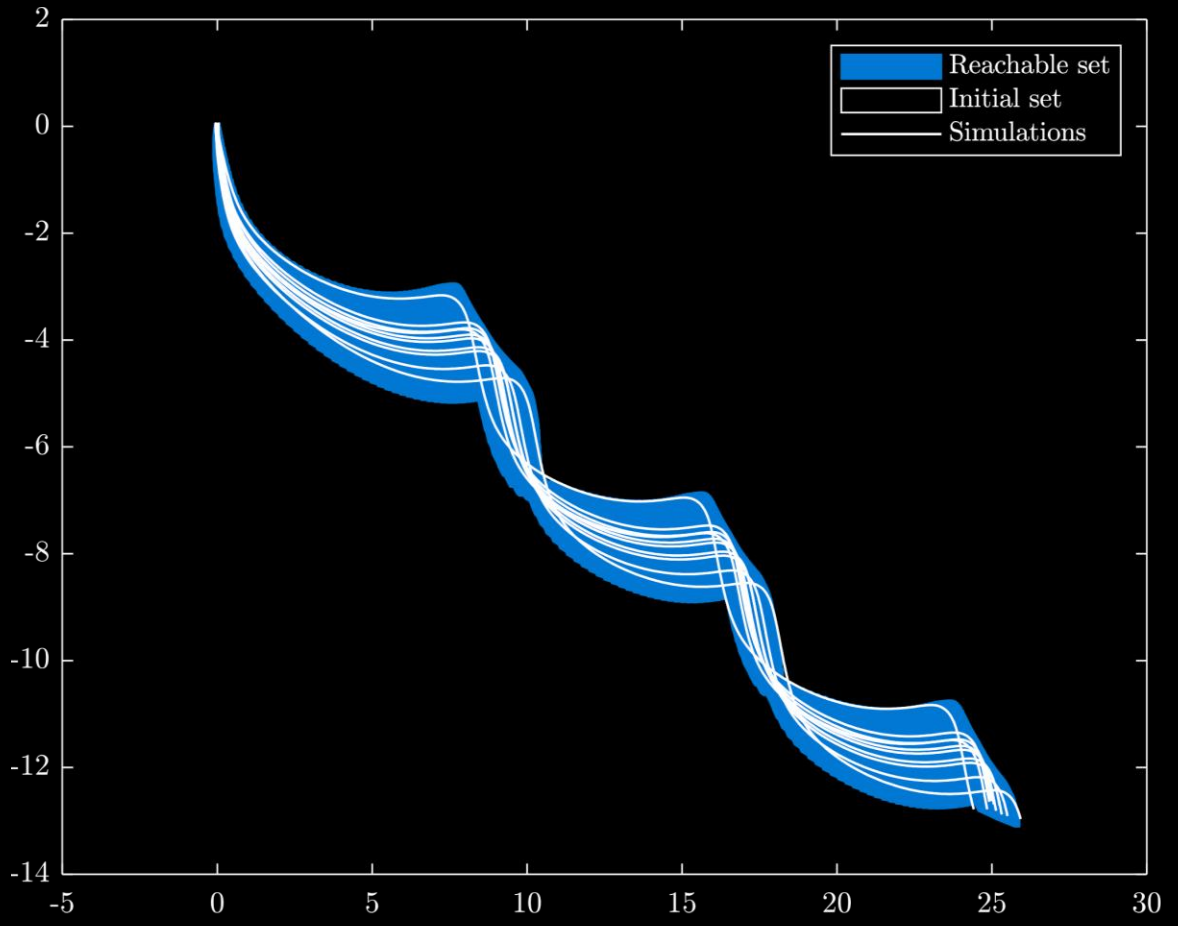
Controlling *Alsomitra* – Behaviour cloning







Reachability of *Alsomitra*



- Reachable set estimation for *Alsomitra* has been implemented in CORA [12]
- Required changes to CORA toolkit, regarding the calculation of derivatives
- Analytical derivatives for Li model [11] are too complex, required approximation method

Future work

- Finish reachability analysis of NN-controlled *Alsomitra* simulation
- Investigate effects of NN training, architecture and control design on reachability

- Fit model to dandelion seed parameters, perform similar analysis
- Demonstrate control on physical system

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