Outline

- Adaptation
  - Action/Behaviour based on environment
  - Collaboration
  - Structure

- First Paper:

- Analysis of dynamic soaring and a simple mode controller to gain energy from horizontal shear
Dynamic Soaring

- Dynamic Soaring
  - Generally in areas where there are rapid changes in horizontal wind speed

![Horizontal wind shear due to boundary layer](image1.png)

![Wind shear due to geographic conditions such as an obstacle](image2.png)

Gliding Aircraft

- Basic forces on a gliding aircraft in flight

![Forces acting on a gliding aircraft in still air](image3.png)

\[ P = \dot{E} = \frac{1}{2} m g h = m g \dot{h} \]

\[ = \frac{1}{2} m V_a^2 = m \dot{V}_a V_a = -D V_a \]

- Energy is lost due to drag in the form of altitude (sinking flight) or airspeed
Mechanisms of Energy Gain

- Energy is expressed relative to the surrounding air
- This is not a closed system; energy is transferred between the environment and the aircraft

\[ E = mg_y + \frac{1}{2} m V_a^2 \]

- In our case, we wish to maximise the energy gained from a limited height linear wind profile

\[ \frac{dE}{dy} = m \left( g + \frac{\frac{dV_a}{dt}}{\sin \gamma_a} \right) \]

Mechanisms of Energy Gain

\[ \frac{dV_a}{dt} = -\frac{D}{m} - g \sin \gamma_a - V_a \sin \gamma_a \cos \gamma_a \frac{dW_x}{dy} \]

- Implications:
  - Energy is always lost to drag
  - Energy from wind gradients appears in airspeed (due to the necessity of changing altitude to appreciate a horizontal wind gradient)
Mechanisms of Energy Gain

- Maximising energy gain from a linear wind gradient

![Graphs showing energy gain in steady climb](image)

Figure 5: Energy gain for a steady climb through a linear wind profile ($dW_x/dy = -1.0 \text{ s}^{-1}$).

- Optimum climb angle is a function of aircraft parameters and wind conditions

![Graph showing optimum climb angle](image)

Figure 6: Optimum climb angle as a function of airspeed and wind gradient

- Using a two dimensional planar fit with our aircraft parameters, the climb angle can be reduced to a linear function of airspeed and wind gradient

$$\gamma_{\text{optimum}} = 0.230V_x + 7.43 \frac{dW_x}{dy} + 20.1$$
Rayleigh Dynamic Soaring Cycle

- Rayleigh cycle is the most basic dynamic soaring cycle

  ![Rayleigh dynamic soaring cycle](image)

- Upwind climb into wind gradient increases effective air speed
- High Altitude flat turn to face downwind
- Downwind dive with effectively increasing airspeed
- Low altitude flat turn to face upwind

Mode based flight logic

![Mode based flight logic](image)

Figure 7: Rayleigh dynamic soaring cycle in linear horizontal wind gradient

Figure 8: Travel mode logic. Dashed green lines denote the logic if the travel direction is upwind, dash-dot blue for downwind.
Strip method simulation

Figure 9: Strip method simulation. Aerodynamic components are divided into individual strips which can be solved separately, allowing for wind distributions across the aircraft.

Results: Single soaring cycle in linear wind shear

Figure 11: Trajectory and relative energy for a dynamic soaring cycle through a linear wind profile. Flight starts at the green triangle and terminates at the red circle. Profile strength is 1s⁻¹, height is 15m. Vertical lines on the energy plot indicate mode logic changes.
Results: Single soaring cycle in linear wind shear

One cycle of travelling dynamic soaring in a linear wind gradient

- Gradient strength: $dW/dy = -1 \text{ m/s}^2$
- Gradient height: $zh = 15 \text{ m}$
- Wind bearing: $\theta_w = 180^\circ$

Figure 11: Trajectory and relative energy for downwind travelling dynamic soaring through a linear wind profile. Flight starts at the green triangle and terminates at the red circle. Profile strength is $1 \text{ m/s}^2$, height is $15 \text{ m}$. Vertical lines on the energy plot indicate mode change times.
Results: Upwind travelling soaring in linear wind shear

Figure 11: Trajectory and relative energy for upwind travelling dynamic soaring through a linear wind profile. Flight starts at the green triangle and terminates at the red circle. Profile strength is $3 \text{m}^{-1}$, height is 15m. Vertical lines on the energy plot indicate mode change times.

Wind estimation

- Wind is estimated on-line using simulated data from an air data system (airspeed, angles of attack and sideslip)
- Gaussian Process to fit the wind profile and identify soaring altitude limits

Figure 10: Gaussian Process estimation of soaring altitude limits for a Pohlhausen’s quartic profile with zero pressure gradient. Free-stream speed is 12m/s, layer thickness is 15m.
Of interest to this group:

- In this case, we are trying to operate in an unknown and dynamic environment, with only direct observations.

- Importance lies in efficient utilisation of the information we do have:
  - Initial field estimate
  - Knowledge of the types of structures common to wind fields in the area
  - Physical laws governing dynamics of the wind field.
We have a very easy to visualise exploration/exploitation problem.

We want to explore the wind field, but exploration costs energy which is only available by exploiting what has already been explored.

More knowledge allows better/more efficient exploitation.

**Exploration**

- Use out current resources as efficiently as possible to maximise the information gained.

**Exploitation**

- Given current information, what actions will maximise (energy) gain.
\[ \vec{V}_a = \vec{R} - \vec{W} \]

\[ \ddot{\vec{R}} = \frac{1}{m} \left( \vec{L} + \vec{D} + mg \right) = \frac{d}{dt} \left( \dot{\vec{V}}_a + \vec{W} \right) \]
Energy-Based Path Planning

- Energy based reward function

1. First option – greedy reward for total energy gained in each section

\[ R_{\Delta E} = -mg (z_{i,\text{final}} - z_{i,\text{initial}}) + \frac{1}{2} m (V_{a,\text{final}}^2 - V_{a,\text{initial}}^2) \]

2. Second option – account for power available at the end of each segment

\[ R_{\Delta E,E} = -mg (z_{i,\text{final}} - z_{i,\text{initial}}) + \frac{1}{2} m (V_{a,\text{final}}^2 - V_{a,\text{initial}}^2) + K_E \dot{E}_{\text{final}} \Delta t \]
Results – Static Soaring

Climb into thermal with power reward function $R_{\Delta E}$.

Path planning through a toroidal thermal with full wind field knowledge. The thermal is centred at $(100, 20, -200)$. The solid red line indicates the path generated using the greedy $R_{\Delta E}$ reward function. The blue solid line is the path generated using the $R_{\Delta E; E}$ reward function. Light coloured paths indicate alternative branches generated during planning and the wind field is shown by blue arrows.
Wind model – Shear layer

- Horizontal wind shear – Pohlhausen’s quartic boundary layer

Results – Dynamic Soaring

Energy gain in shear with power reward function $R_{M,E}$
Results – Dynamic Soaring

Path planning through horizontal wind shear with full wind field knowledge. The shear layer base is at 100m altitude and is 15m thick. The solid red line indicates the path generated using the greedy $R_{\Delta E}$ reward function. The blue solid line is the path generated using the $R_{\Delta E,E}$ reward function. Light coloured paths indicate alternative branches generated during planning and the wind field is shown by blue arrows.

Energy-Based Path Planning

- Simple mission; travel to a higher-energy level goal point
- Need to integrate the distance to goal into the reward function (i.e., convert distance to energy)
- Use the glide ratio estimate
Energy-Based Path Planning

- Add distance to goal reward

\[ R_{\text{nav}} = mg \frac{\vec{a} \cdot \vec{b}}{(L/D)_{\text{est}}} \]

- Switch mechanism; if you have enough energy to make it to the goal, then focus on travelling to goal. Otherwise, focus on energy capture

\[ R = \begin{cases} 
(1 - K_{\text{nav}}) R_{E,E} + K_{\text{nav}} R_{\text{nav}} & \text{if } E_{\text{current}} > E_{\text{goal}} + mg \frac{\vec{b}}{(L/D)_{\text{est}}} \\
K_{\text{nav}} R_{E,E} + (1 - K_{\text{nav}}) R_{\text{nav}} & \text{if } E_{\text{current}} \leq E_{\text{goal}} + mg \frac{\vec{b}}{(L/D)_{\text{est}}} 
\end{cases} \]

Results - Travel to goal through thermal

Travel to a goal through a thermal. Goal is at 100m higher altitude than the start position.
Results

Path planning to a goal through a thermal with full wind field knowledge. There is one thermal centred at (0, 250, -150). Aircraft starts at (0, 0, -100) indicated by the green triangle. The red path shows the planned path for a goal at (0, 500, -100). The blue path shows the planned path for a goal at (0, 500, -200). The aircraft start heading is reversed in the second case for path clarity.

Energy-Based Path Planning

- Simple scenario; the aircraft is given a goal point above the estimated position of a thermal
Wind mapping

- Suggested solution: Gaussian Process Regression

- Useful for a number of reasons
  - Gracefully handles the continuous nature of a wind field
  - Avoids the problems of defining boundaries or storing a grid-based representation (too big for any on-board computer)
  - Ability to handle multiple dimensions in input and output
  - Provides uncertainty estimation (potentially useful for path planning, control etc.)
Wind mapping

- Simplest, naive approach:
  - Cartesian coordinates, 3xMISO GP trained with same (RBF) kernel functions and shared hyperparameters
  - Computationally efficient due to single inversion operation for all axes:

\[
f(x^*) = K(x^*, x)^T \left( K(x, x) + \sigma^2 I \right)^{-1} \ y
\]

\[
\begin{bmatrix}
[m \times d] \\
[m \times n] \\
[n \times n] \\
[n \times d]
\end{bmatrix}
\]}
20

Autonomous Soaring – CDM Group

Nicholas Lawrance

Original data
Separate hyperparameter solution
Common hyperparameter solution
Original wind vector field

Separate HP estimated wind vector field

Common HP estimated wind vector field
Relatively simple path planning and relatively simple mapping

Combined with a basic task allocation ("get energy" or "explore")
• Results for a static case with one (major) structure

• Wind fields are:
  • Dynamic
  • Usually contain a superposition of many components
  • Each structure can move, change and disappear

• GP framework can include temporal component
• Multiple covariance functions
Adaptation

- Need to work on the root problem of simultaneous exploration/exploitation

- Simple target assignment is possible but not particularly novel

- Would be better to look at more direct links; as we evaluate path segment energy could also integrate to obtain covariance improvement

- Utilisation of natural laws (aerodynamic potential field analysis, Navier-Stokes –type CFD solution, etc.)

- Still have the difficulty of dealing with non-holonomic vehicle and working from path generation to actual control signals.

Thank you for your time
Wind Model - Thermal

- Toroidal thermal updraft model including inflow/outflow

Thermal bubble model – Core vertical wind speed 3 m/s, updraft diameter 200 m, total diameter 400 m, elliptical axis ratio 3:1.
Future work

- Wind mapping and characterisation