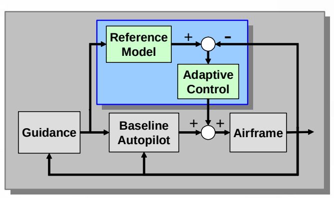


Cooperative Control Challenges for Aerial Vehicles





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Presentation Overview

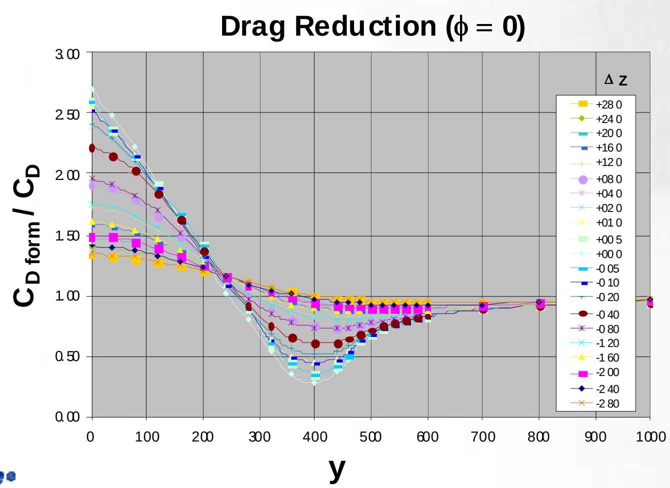
- **Introduction**
  - **Single vehicle → Multiple Vehicles → Waves of multiple vehicles**

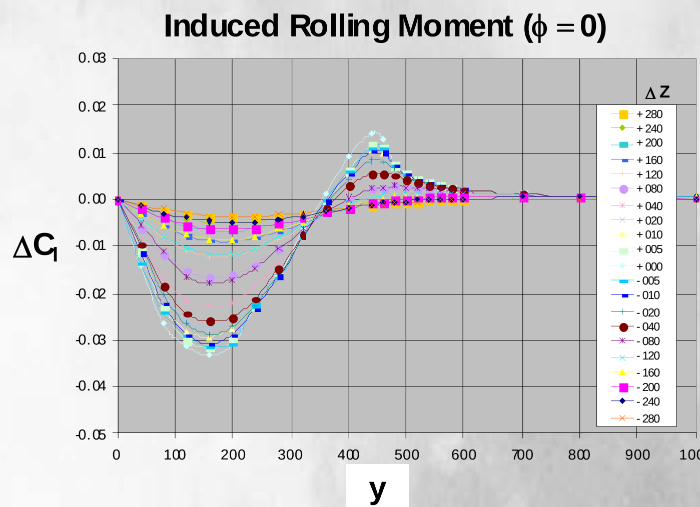
- **Control Challenge Problems**
  - Single Vehicle in Close-Coupled Flight with a Leader
    - Simplified Flight Dynamics
    - Applications
      - Autonomous Aerial Refueling, (AAR)
      - Autonomous Formation Flight, (AFF)
  - Multiple Unmanned Aerial Vehicles, (UAVs)
    - Simplified UAV dynamics
      - Dubins' car
      - Dubins' aircraft
    - Collaborative Control in Hostile / Adversarial Environment
      - Task allocation
      - Path planning
      - Cooperative attack
      - Intelligence Surveillance and Reconnaissance, (ISR)
  - "Ultimate" Challenge
    - Waves of multiple UAVs prosecuting multiple targets in uncertain environment

- **Conclusions**

Close-Coupled Flight Dynamics and Control

- **Aerodynamic Phenomenon**
  - Unknown unsteady flow field behind lead aircraft
  - Lead aircraft wingtip vortices influence trailing aircraft aerodynamic forces and moments
    - **Longitudinal separation**
      - changes are uniform within 5 aircraft body length
    - **Vertical and Lateral Separation**
      - induced aerodynamic drag
      - rolling moment
    - **Relative bank angle**





Close-Coupled Flight: System Dynamics

- **Trailing aircraft in close-coupled formation (relative dynamics)**
  - **2 Control Inputs**
    - Thrust for Airspeed
    - Differential Aileron for Roll
  - **Unknown Constant Parameters**
    - Throttle effectiveness
    - Roll damping
    - Aileron effectiveness
  - **Unknown functions**
    - Vortex induced aerodynamics
      - Drag force $D(y,\varphi)$
      - Rolling moment $\Delta L(y,\varphi)$
  - **Applications**
    - Autonomous Formation Flight
    - Autonomous Aerial Refueling

$$\dot{d} = V$$ (airspeed)

$$\dot{V} = T_{\delta_T}\,\delta_T - D(y,\varphi)$$ (Thrust; induced drag force)

$$\ddot{y} = g\,n_z\,\varphi$$ (bank angle)

$$\dot{\varphi} = p$$ (roll rate)

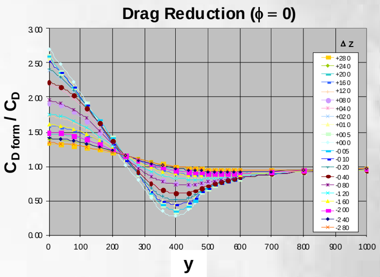
$$\dot{p} = L_p\,p + L_{\delta_a}\,\delta_a + \Delta L(y,\varphi)$$ (Diff Aileron; induced rolling moment)

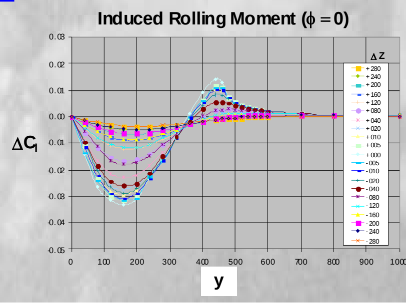
Autonomous Aerial Refueling, (AAR)


Autonomous Formation Flight, (AFF)

$$D(-y,\varphi) = D(y,\varphi)$$

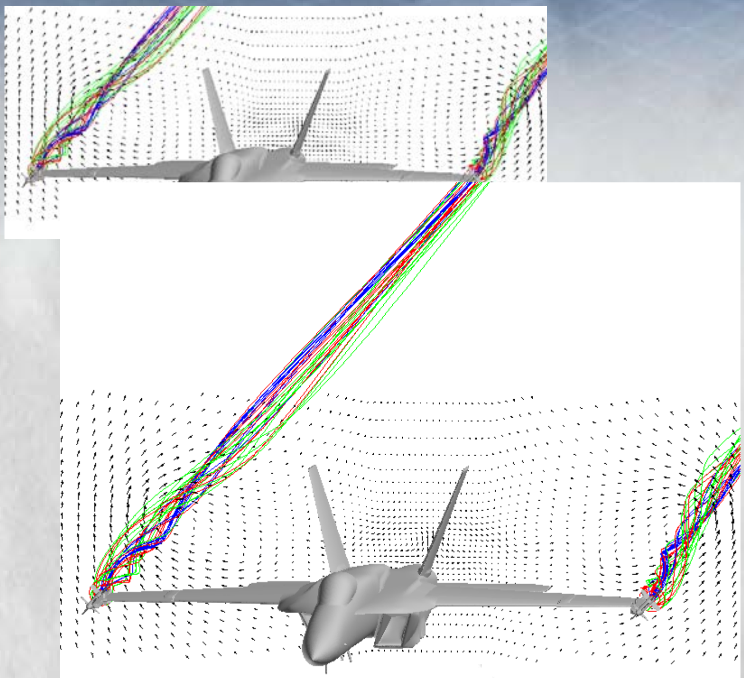
$$\Delta L(-y,\varphi) = -\Delta L(y,\varphi)$$



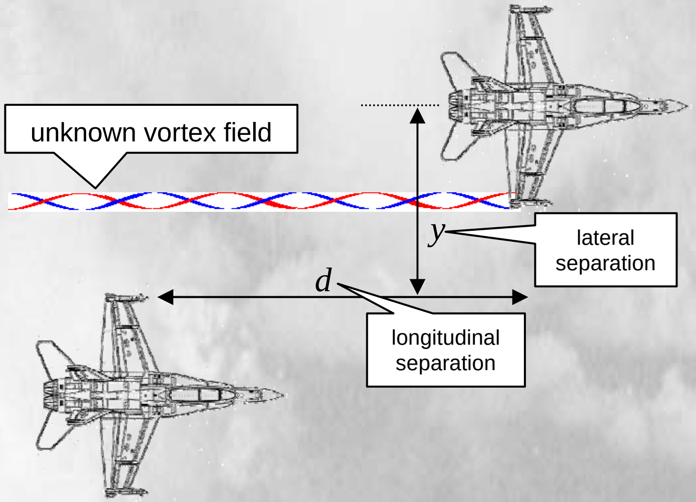


Close-Coupled Flight: AFF Control Challenge

- **Benefit**
  - Flying in the vortex field
    - reduces induced drag by 20 – 25%
      - range extension
      - less fuel
- **Control Challenges**
  - wingtip vortex induced uncertainties
  - unknown / unsteady vortex location
- **Control Goals**
  - Bounded tracking
  - Vortex seeking → drag reduction



F/A-18 Formation Flight Tests @ NASA Dryden, 2000



UAV Dynamics for Control Design

- **Dubins' Car**

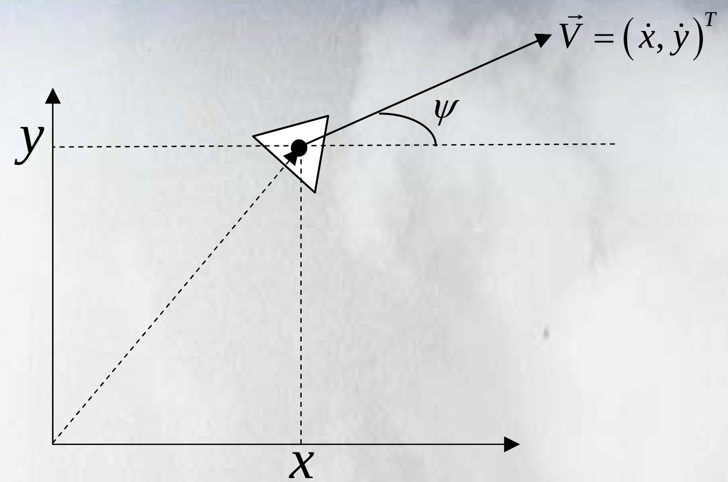
$$\dot{x} = V \cos\psi$$

$$\dot{y} = V \sin\psi$$

$$\dot{\psi} = \dot{\psi}_{\max}\, u_{\psi}$$

$$\dot{V} = \dot{V}_{\max}\, u_{V}$$

turn control (u_{ψ}), max turn rate ($\dot{\psi}_{\max}$), speed control (u_{V}), max thrust ($\dot{V}_{\max}$)



- **2 control inputs**
  - Speed control, (thrust)
    - limited between 0 and 1
  - Heading control, (rate of turning)
    - limited between 0 and 1
- **2 controlled outputs**
  - (x, y) – positions

UAV Dynamics for Control Design (continued)

- **Dubins' Aircraft**

$$\dot{x} = V \cos\gamma \cos\psi$$

$$\dot{y} = V \cos\gamma \sin\psi$$

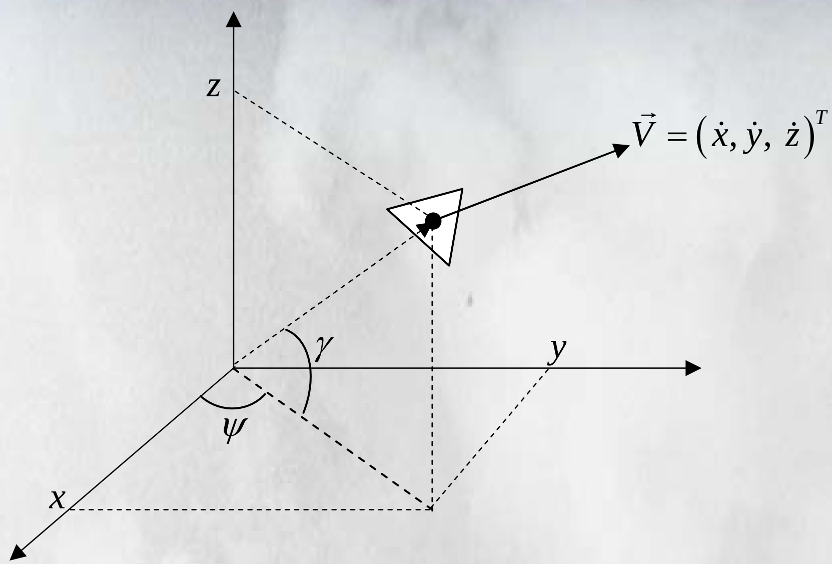
$$\dot{z} = V \sin\gamma$$

$$\dot{\gamma} = \dot{\gamma}_{\max}\, u_{\gamma}$$

$$\dot{\psi} = \dot{\psi}_{\max}\, u_{\psi}$$

$$\dot{V} = \dot{V}_{\max}\, u_{V}$$

climb control
max climb rate
turn control
max turn rate
speed control
max thrust



  - **3 control inputs**
    - Speed control, (thrust)
      - limited between 0 and max thrust available
    - Heading and flight path controls, (turn and climb rates)
      - limited between 0 and 1
  - **3 controlled outputs**
    - (x, y, z) – positions

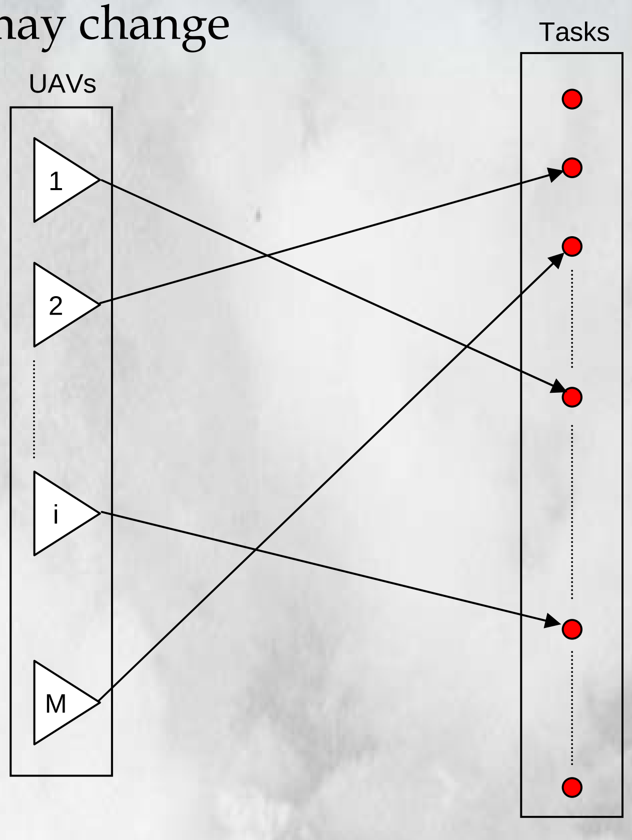
Control Challenge: Single UAV Path Planning

- **Single vehicle operating in uncertain environment**
  - Finding "shortest" path in finite graph
    - System dynamics
      - Simple model: → $x_{k+1} = u_k$
      - Dubins' car / aircraft model → $\dot{x} = V\cos\psi$, $\dot{y} = V\sin\psi$, $\dot{\psi} = \dot{\psi}_{\max} u_{\psi}$, $\dot{V} = \dot{V}_{\max} u_V$ → $\dot{x} = V\cos\gamma\cos\psi$, $\dot{y} = V\cos\gamma\sin\psi$, $\dot{z} = V\sin\gamma$, $\dot{\gamma} = \dot{\gamma}_{\max} u_{\gamma}$, $\dot{\psi} = \dot{\psi}_{\max} u_{\psi}$, $\dot{V} = \dot{V}_{\max} u_V$
      - Other
  - Optimality criterion
    - not a distance-like measure
      - doesn't satisfy the triangular inequality
    - instant connection cost matrix is not-symmetric
  - "Optimal" path / route
      - node precedence constraints
      - obstacles and pop-up threats avoidance
      - collision avoidance with other vehicles

Constrained Shortest Path Problem

Control Challenge: Task Allocation

- **Dynamic Optimization Problem**
  - M vehicles → N Tasks, (M < N)
    - number of assets (M) and tasks (N) may change
  - **Goal**
    - maximize total assignment benefit
    - account for vehicle capabilities
  - Online solution computation



Constrained Optimal Assignment Problem

Control Challenge: Cooperative Attack

- **Multiple UAVs Prosecuting Multiple Targets**
  - **Task allocation**
    - Constraints
      - individual vehicle capability
      - time-critical targets
      - task precedence
      - relative timing
  - **Path / Route planning**
    - Obstacle & Collision Avoidance
  - **Sensing, Estimation and Information Sharing**
    - Uncertain & hostile environment
    - Limited communication data links

Constrained Multi-Vehicle Shortest Path and Travelling Salesman Problems

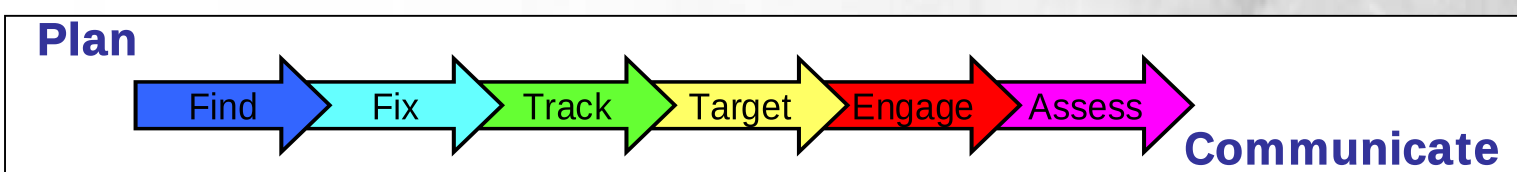
"Ultimate" Challenge

- **Single UAV → Multiple UAVs → Waves of Multiple UAVs**
  - Performing tasks to accomplish higher level objectives
- **Collaborative Control Tasks in Uncertain Environment**
  - Cooperative Strike, Intelligence Surveillance Reconnaissance (ISR)
  - Task allocation, Route planning, and Obstacle Avoidance
  - Task precedence and timing constraints
    - ✓ Prosecution of time critical targets
  - Execution in the presence of uncertainty caused by adversarial actions
    - ✓ threat location, anti-tactics
    - ✓ degraded communications
- **Information Management Between Platforms**
  - Support data fusion / estimation and collaboration
    - ✓ limited available data links
    - ✓ interruptions of service
    - ✓ degraded performance

Conclusions

- **Control Challenge Problems for Aerial Vehicles**
  - single UAV
  - multiple UAVs
  - waves of multiple UAVs

- **Need Close-to-Real-Time Control Solutions**
  - Frequently generate "optimal" task assignment and multi-vehicle routes in the presence of:
    - uncertain and hostile environment
    - battle damage
    - limited communications
  - Assign and prosecute time-critical targets



Shorten the Kill Chain

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