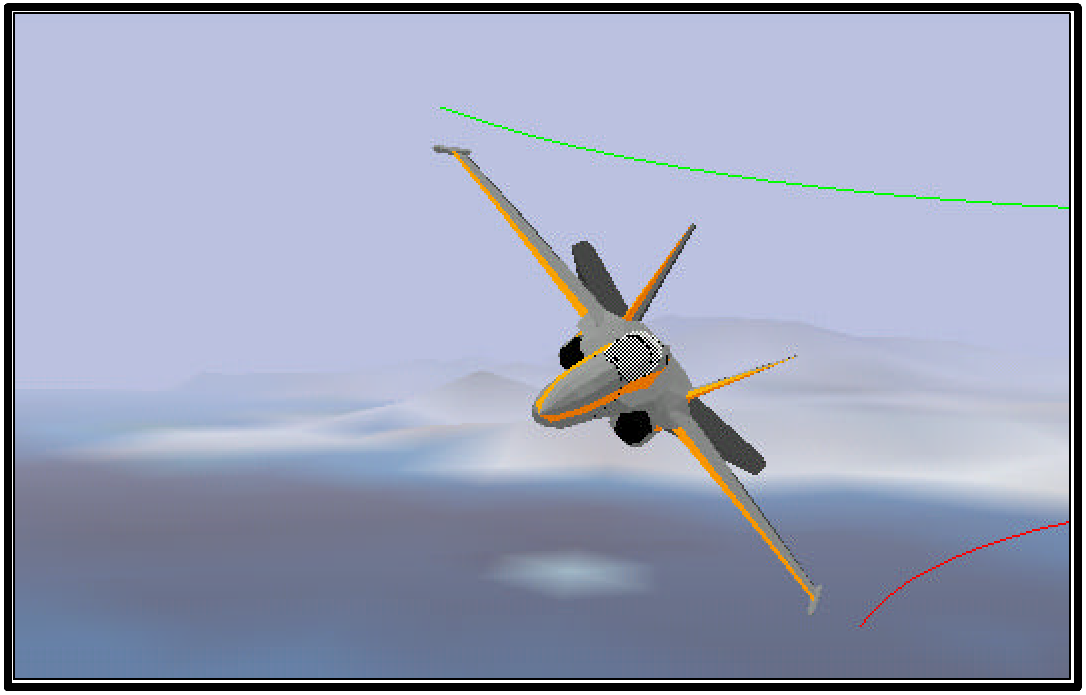
Coordinated Flight of Uninhabited Air Vehicles



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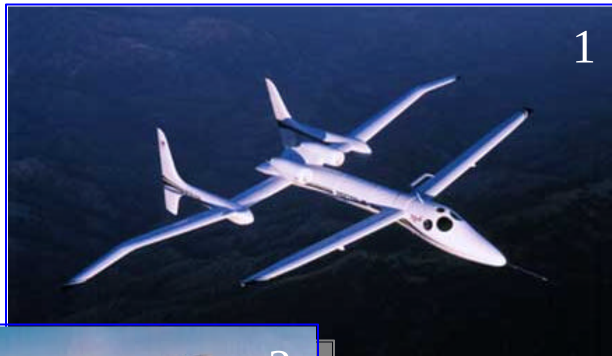
Quarterly Review - April, 2001

Outline

- **Introduction**
- **Regrouping during straight & level flight**
  - Simulation architecture
  - Rule-based scheduler presentation
  - An example of rule base
- **Trajectory tracking nonlinear UAV**
  - Aircraft model
  - Nonlinear Inverse Dynamics control
  - Barrel roll test
- **Concluding remarks**

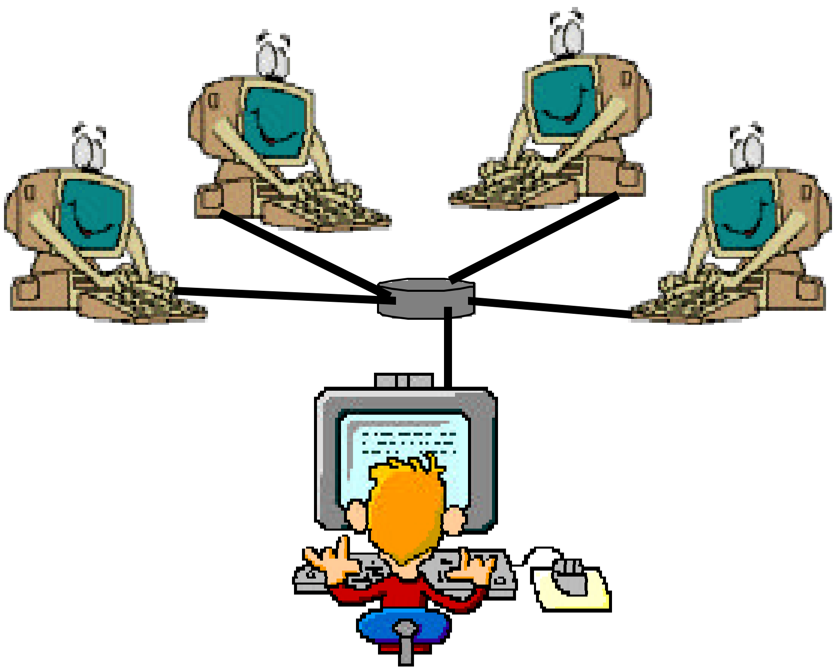
New UAV* requirements



- **Foreseen UAV applications**
  - **Unmanned Combat Air Vehicles[1]**
    - (Boeing / Lockheed Martin)
  - **Wireless communications relay[2]**
    - (Proteus - Scaled Composites)
  - **Meteorological probing[3]**
    - (Aerosonde)
- **Requirements**
  - **Long and/or dangerous missions**
  - **Team approach for increased reliability**
    - Aircraft failure accommodation
    - Concerted action

*Unmanned Air Vehicles

Multi-Aircraft Simulation

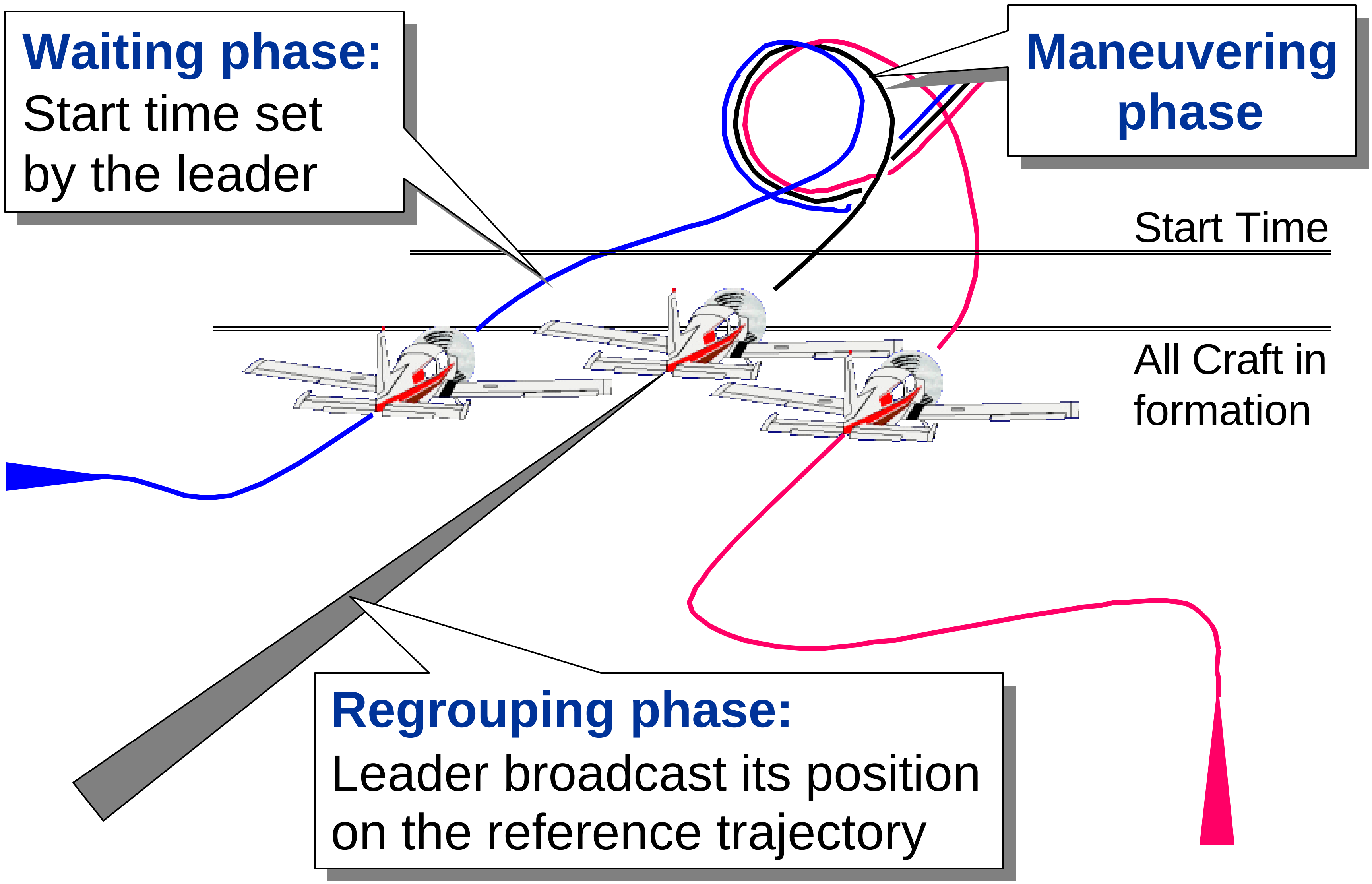


- **Preliminary Objective**
  - Coordinate aerobatics maneuver execution by a team of UAV

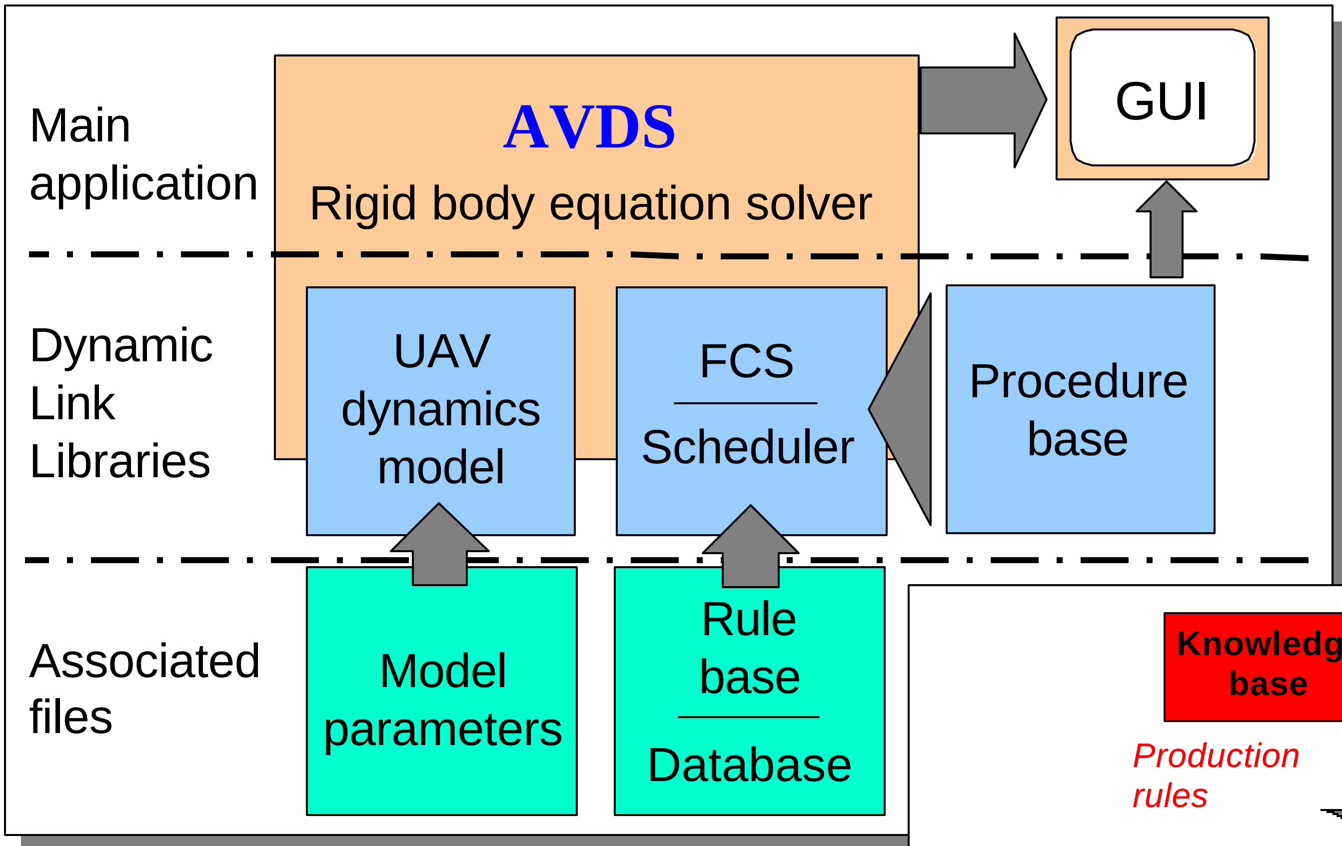
- **Environment**
  - Four computers (one per UAV)
  - Communications through the local area network

- **Method**
  - Broadcast position on trajectory
  - Logic to choose an aircraft as reference (rule-based controller)
  - Timing taking advantage of the fixed throttle control law

Regrouping on a line

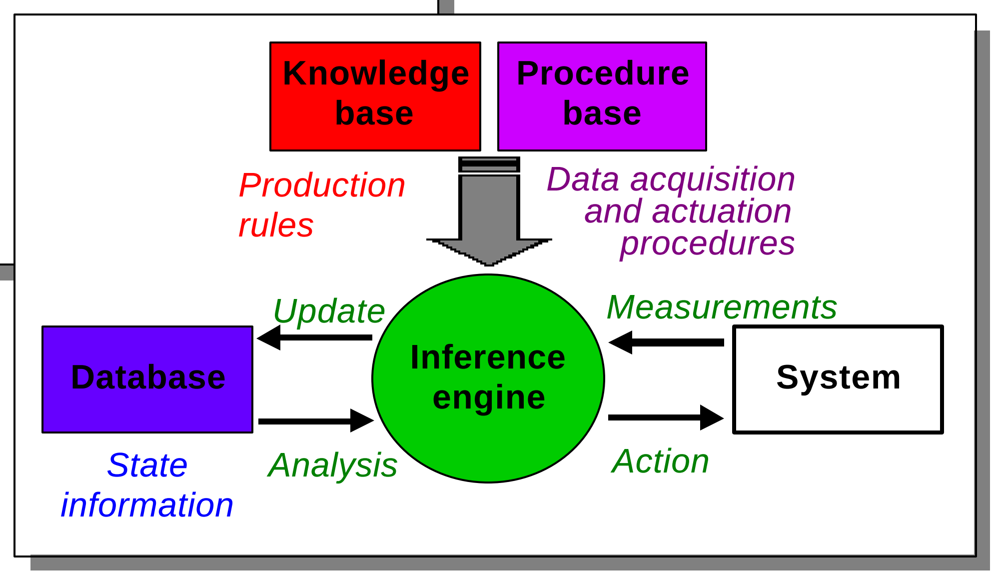


Simulation Architecture



- **Code architecture**

  Highly modular for maintainability

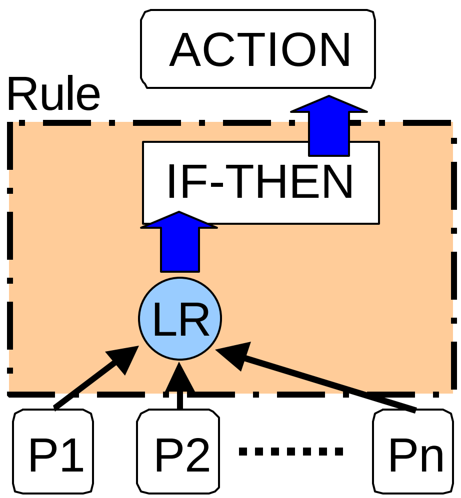


- **Rule-based scheduler structure**

Rule-based Scheduler Presentation

- **Rule base paradigm**

  ⇒ Production rules applied to a database storing the parameters by matching premises

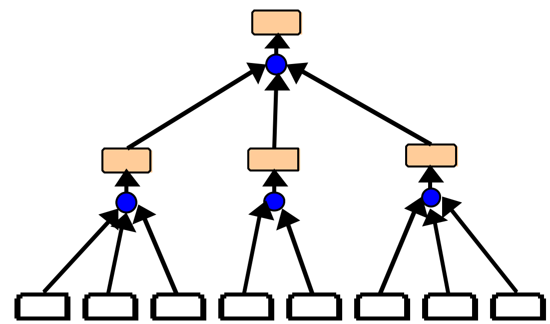


LR: Logical Relation (AND,OR)

P1,…,Pn: Premises 1 to n

Action and Premises are either parameters or procedures returning a value.

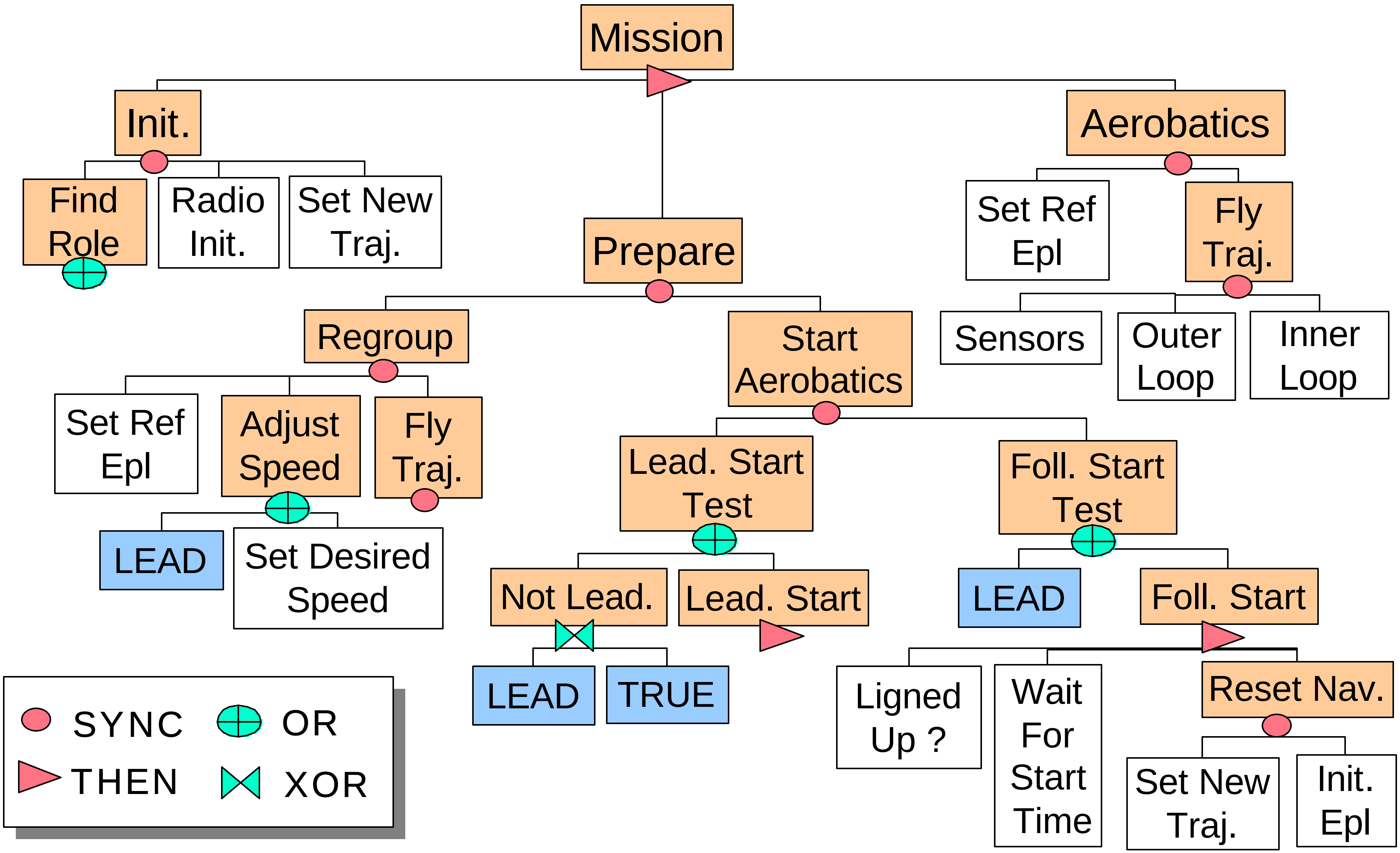
- **Rule-based scheduler**
  - 1 to 1 relation between actions and rules
  - Hierarchical structure of rules



  - Uses THEN or SYNC as logical relations between tasks
  - Leaves of the tree are procedures representing subtasks while the root is the main task.
  - Parameters take values:

    “Done”, “Not Done”

Rule Base Used for Regrouping



UAV Nonlinear Model

- **Assumptions**
  - Three time differentiable trajectory specified in earth coordinates, $x_e(t)$
  - No sideslip

- **Notations**

  d - desired value

  e - earth frame

  b - body frame

  w - wind frame

  $\mathbf{H}_1^2$ - transformation from frame 1 to frame 2

  I - inertia matrix

- **Dynamics equations**
  - Split into fast mode

$$\begin{cases} \dot{\grave{\mathbf{u}}}_{\mathbf{b}} = \mathbf{I}^{-1}\left[\mathbf{M}_{\mathbf{b}} - \grave{\mathbf{u}}_{\mathbf{b}} \times \mathbf{I}\grave{\mathbf{u}}_{\mathbf{b}}\right] \\ \grave{\mathbf{u}}_{\mathbf{w}} = \mathbf{H}_{\mathbf{b}}^{\mathbf{w}} \grave{\mathbf{u}}_{\mathbf{b}} \\ \mathbf{a}_{\mathbf{w}} = \mathbf{a}_{\mathbf{w}}(a, b, T) \end{cases}$$

  - and slow mode

$$\begin{cases} \ddot{\mathbf{x}}_{\mathbf{e}} = \mathbf{g} + \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \mathbf{a}_{\mathbf{w}} \\ \dot{\mathbf{H}}_{\mathbf{w}}^{\mathbf{e}} = \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \hat{\grave{\mathbf{u}}}_{\mathbf{w}} \end{cases}$$

See J. Hauser et al.,

"Aggressive Flight Maneuvers"

Trajectory Tracking
Outer Loop

- **State feedback linearization**
  - **Desired trajectory third derivative:**

$$\dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} = \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \begin{bmatrix} \omega_{w2} a_{w3} \\ \omega_{w3} a_{w1} \\ -\omega_{w2} a_{w1} \end{bmatrix} + \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \begin{bmatrix} \dot{a}_{w1} \\ -a_{w3}\omega_{w1} \\ \dot{a}_{w3} \end{bmatrix}$$

  - **Linearizing control law:**

$$\begin{bmatrix} \dot{a}_{w1}^{d} \\ -a_{w3}\omega_{w1}^{d} \\ \dot{a}_{w3}^{d} \end{bmatrix} = \begin{bmatrix} -\omega_{w2} a_{w3} \\ \omega_{w3} a_{w1} / a_{w3} \\ \omega_{w2} a_{w1} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1/a_{w3} & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{H}_{\mathbf{w}}^{\mathbf{e}\,T} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

$$\mathbf{u} = \dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} + k_2(\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \ddot{\mathbf{x}}_{\mathbf{e}}) + k_1(\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \dot{\mathbf{x}}_{\mathbf{e}}) + k_0(\mathbf{x}_{\mathbf{e}}^{\mathbf{d}} - \mathbf{x}_{\mathbf{e}})$$

Can be solved for w_{w1}^{d} if $a_{w3} \neq 0$

Trajectory tracking
Inner Loop

- **Nonlinear dynamic inversion**

$$\dot{a}^{d} = -2m\dot{a}^{d}_{w3} \big/ (r\,SV^{2}C_{La})$$

$$\dot{b}^{d} = 2m\dot{a}^{d}_{w2} \big/ (r\,SV^{2}C_{Yb})$$

$$\dot{a}^{d}_{w2} = -k_{b}a_{w2}$$

$$\mathbf{\grave{u}}^{\mathbf{d}}_{\mathbf{b}} = \begin{bmatrix} 0 \\ \dot{a}^{d} \\ 0 \end{bmatrix} + \mathbf{H}^{\mathbf{b}}_{\mathbf{w}} \begin{bmatrix} w^{d}_{w1} \\ -(a_{w3} + g_{w3})/V \\ g_{w2}/V - \dot{b}^{d} \end{bmatrix}$$

- **Body torque computation**

$$\mathbf{M}^{d} = K\,\mathbf{I}(\mathbf{\grave{u}}^{\mathbf{d}}_{\mathbf{b}} - \mathbf{\grave{u}}_{\mathbf{b}}) + \mathbf{\grave{u}}_{\mathbf{b}} \times \mathbf{I}\mathbf{\grave{u}}_{\mathbf{b}}$$

- **Actuator deflection computation**

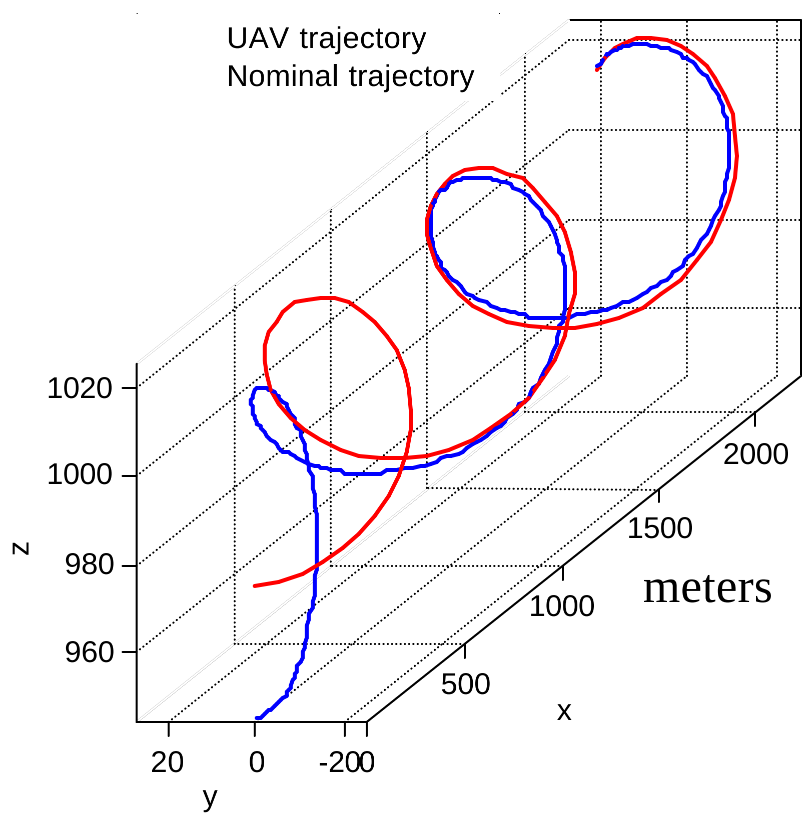
$$\begin{bmatrix} \text{aileron} \\ \text{rudder} \end{bmatrix} = \begin{bmatrix} C_{lda} & C_{ldr} \\ C_{nda} & C_{ndr} \end{bmatrix}^{-1} \begin{bmatrix} L/\tfrac{1}{2}\,rSbV^{2} - C_{lb}b - \tfrac{2b}{V}C_{lp}w_{b1} - \tfrac{2b}{V}C_{lr}w_{b3} \\ N/\tfrac{1}{2}\,rSbV^{2} - C_{nb}b - \tfrac{2b}{V}C_{np}w_{b1} - \tfrac{2b}{V}C_{nr}w_{b3} \end{bmatrix}$$

$$\text{elevator} = \frac{1}{C_{mde}}\left[M/\tfrac{1}{2}\,rS\bar{c}V^{2} - C_{m0} - C_{ma}a - \tfrac{2\bar{c}}{V}C_{mq}w_{b2}\right]$$

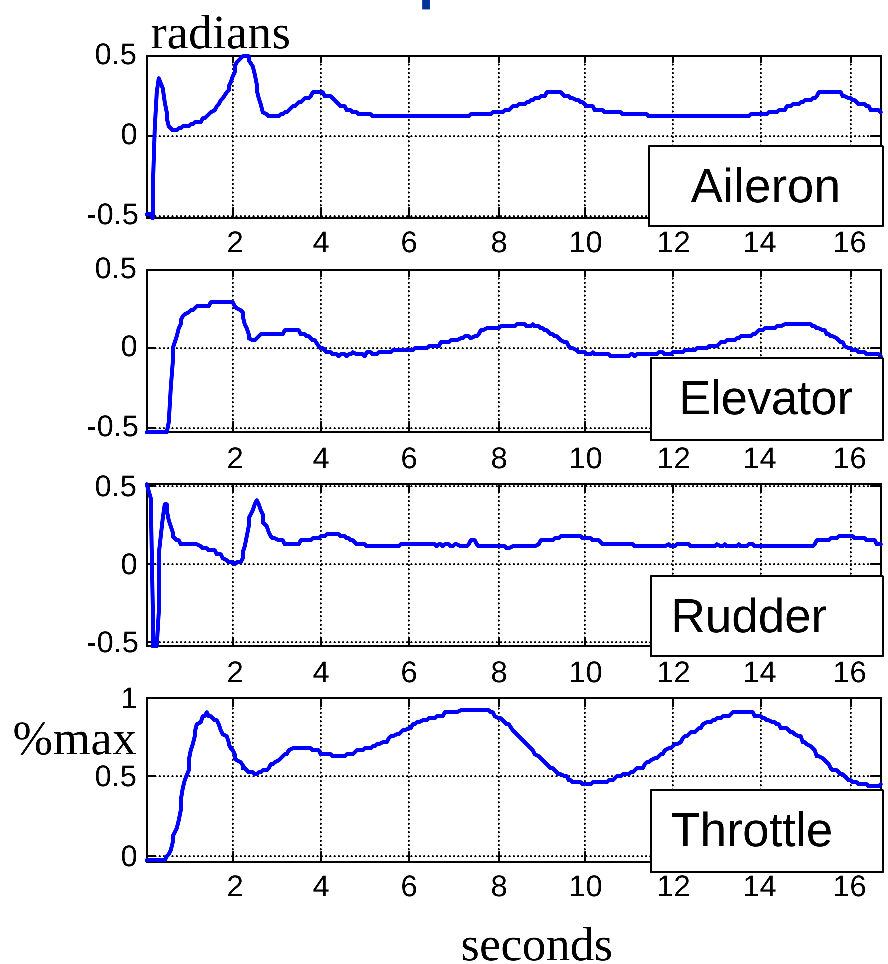
$$\dot{T} = \dot{T}(\dot{a}^{d}_{w1}, a, \dot{a}^{d})$$

Barrel roll test

- **3D view of the UAV trajectory**



- **Control inputs used**



Concluding Remarks

- **Current regrouping method**
  - **Successfully performed regrouping of four aircraft and subsequent flight of a formation barrel roll.**
  - **Need to control where and when the maneuver starts.**
- **Solution: regrouping while orbiting**
  - **Use a circle as a reference trajectory**
  - **Issues: computation of the converging trajectory**
- **Future work:**
  - **Role assignment**
  - **Maneuver assignment**