

# Experimental Cooperative Control of Fixed-Wing Unmanned Aerial Vehicles



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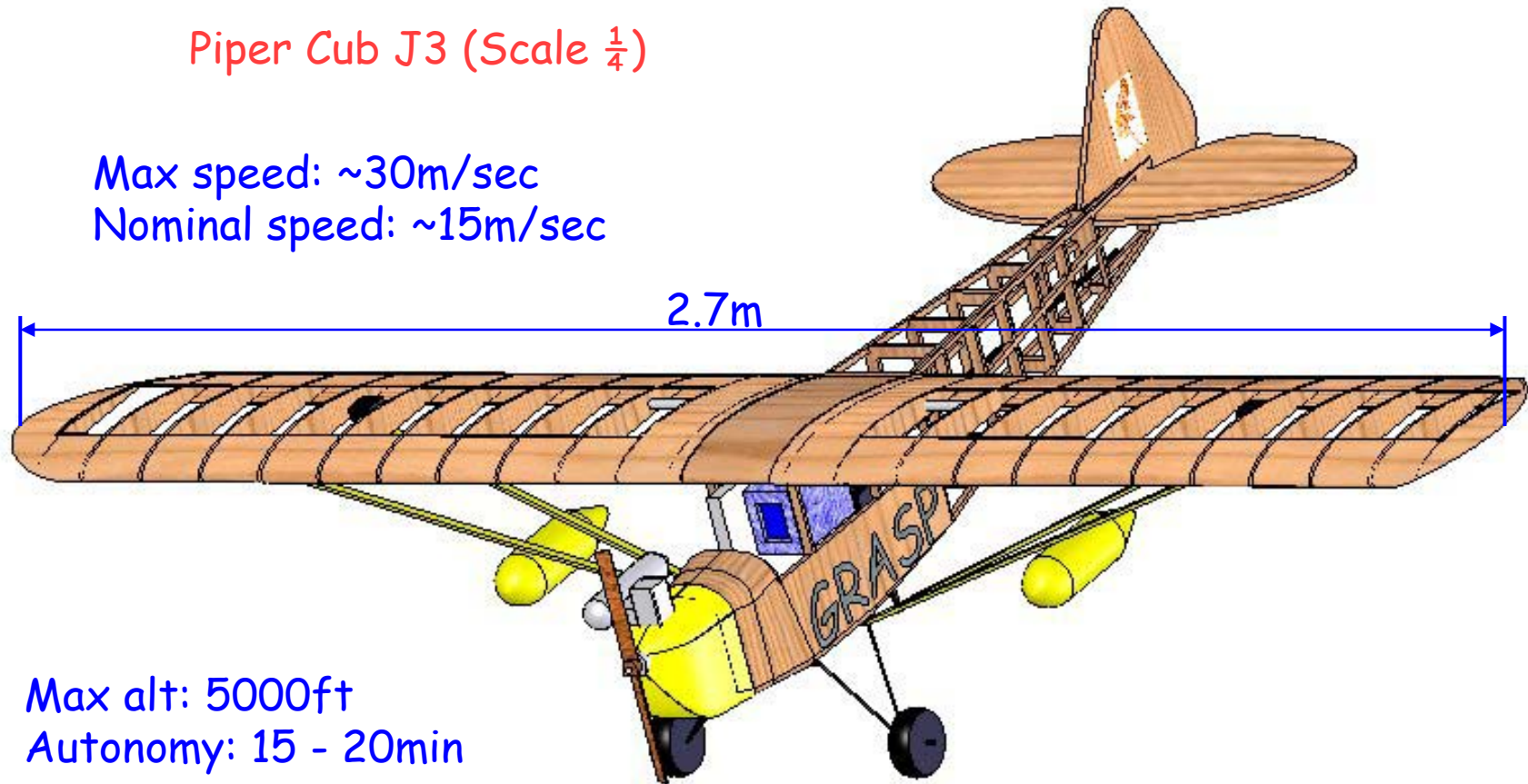
# UAV Initiative at Penn

- Outline
  - Design philosophy
  - Test-bed
    - ◆ Piper J3 Cub Model
    - ◆ System architecture (Cloud cap technologies)
  - Hybrid Modeling (of the Piccolo autopilot)
  - Experiments
    - ◆ Autonomous Flight Formation
    - ◆ Surveillance
    - ◆ UAV-UGV cooperation
  - Future directions
    - ◆ Temporal logic motion planning

# UAVs @ Penn

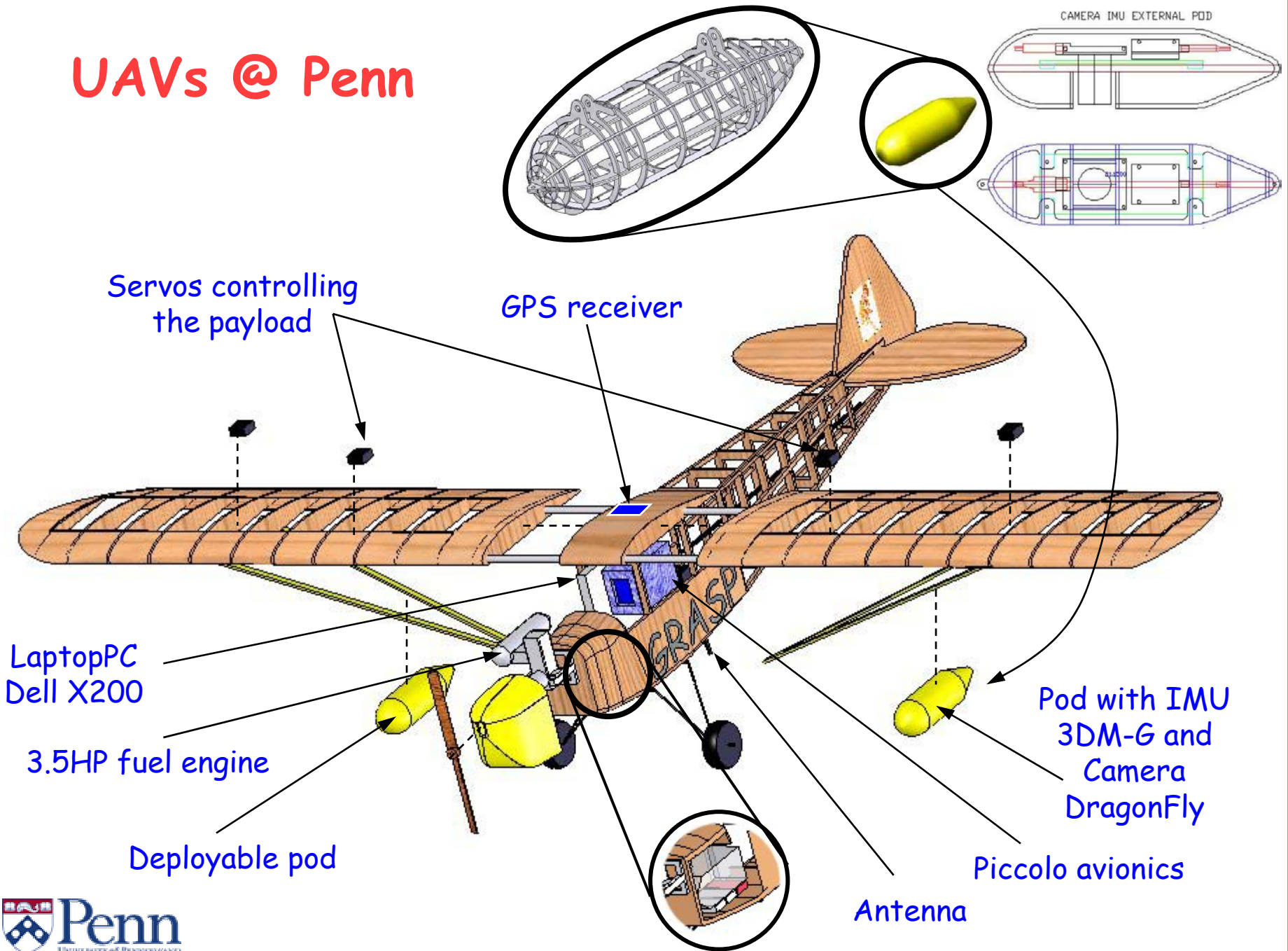
Piper Cub J3 (Scale  $\frac{1}{4}$ )

Max speed:  $\sim 30\text{m/sec}$   
Nominal speed:  $\sim 15\text{m/sec}$



Max alt: 5000ft  
Autonomy: 15 - 20min

# UAVs @ Penn



# UAVs @ Penn



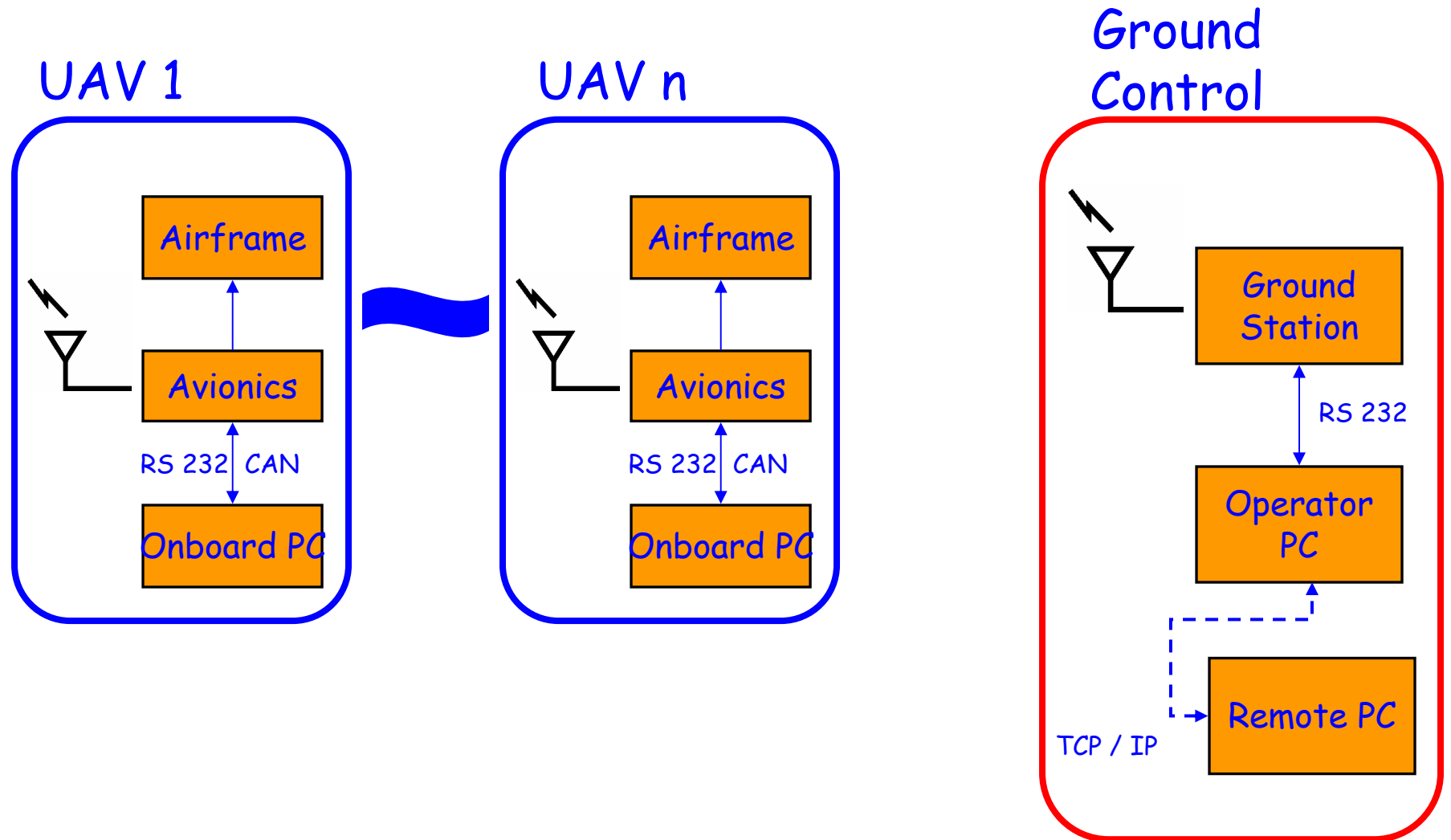
**Avionics Box Enclosure  
CloudCap Piccolo**



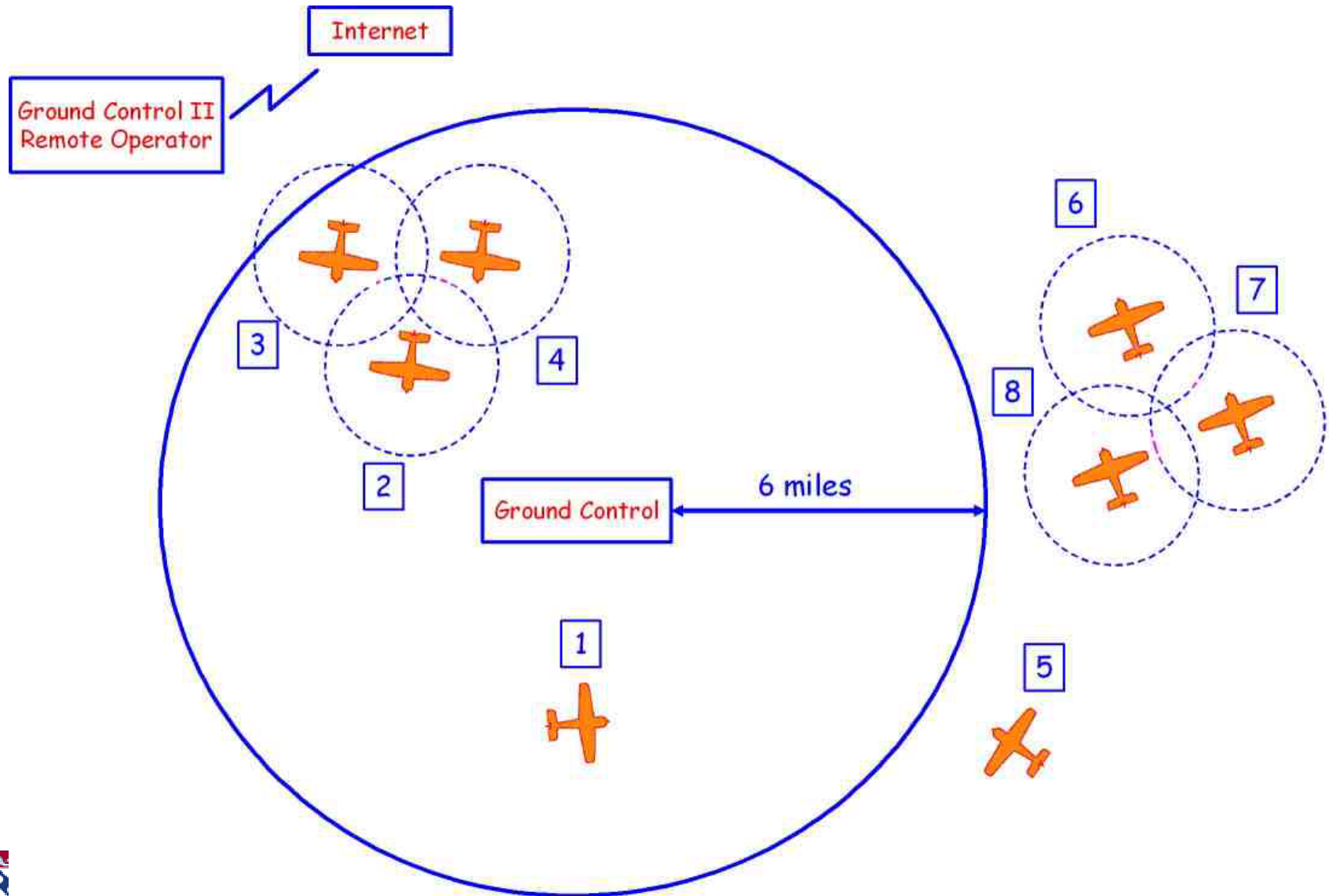
**Deployable POD  
(Sensor , Beacon,  
Landmark, micro-UAV)**

**Hi Res Camera & IMU  
POD Controllable**

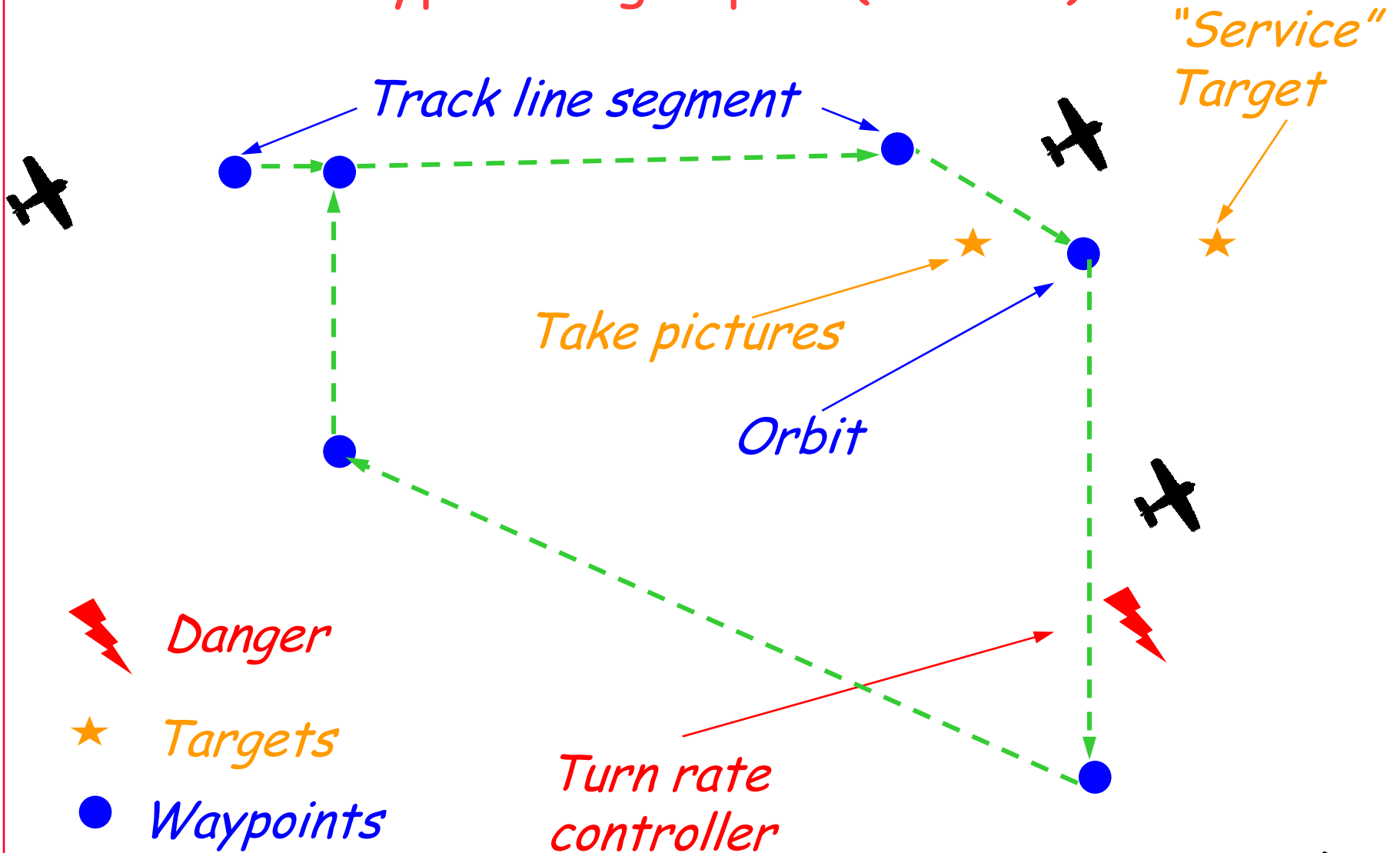
# System architecture



# Possible Configurations

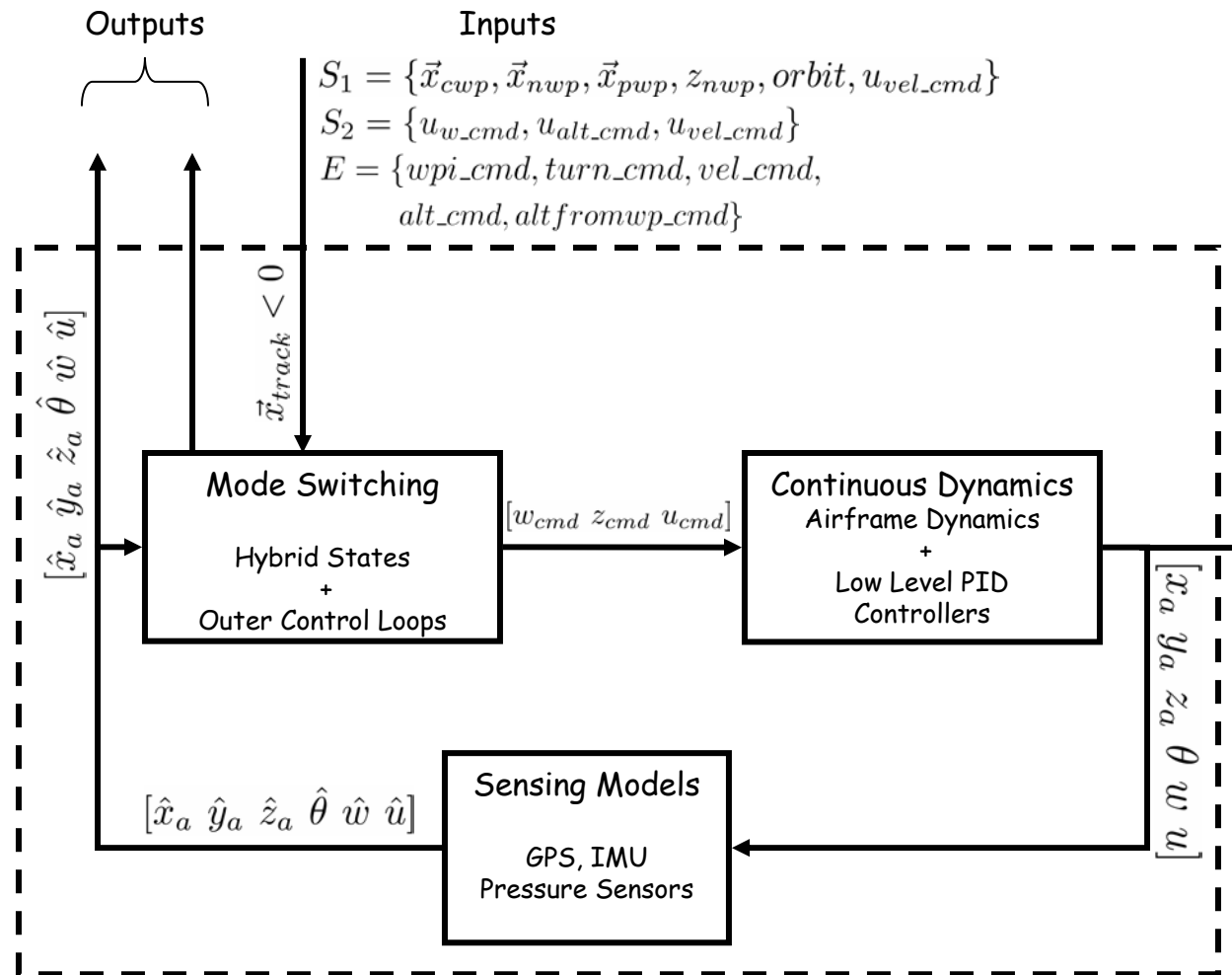


# Typical flight plan (mission)

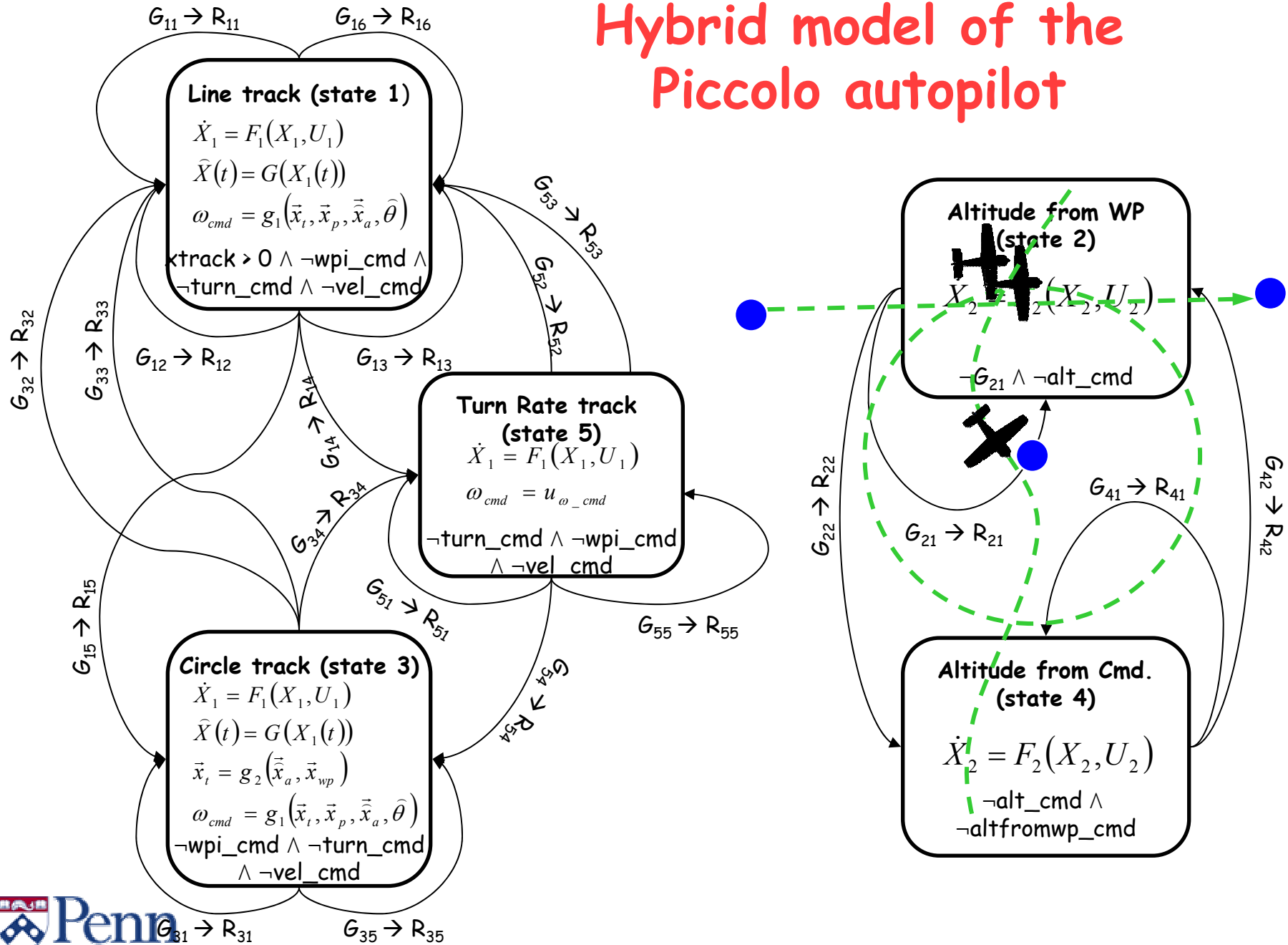


# Hybrid UAV Control Loop

## \* Piccolo autopilot \*



# Hybrid model of the Piccolo autopilot



# Experiments

## Autonomous Formation Flight (AFF)

- Simple leader-follower formation

- Proof of Concept

## Continuous visual tracking of multiple objects

- On the ground or in the air

- Coverage transition from one UAV to another

## Aerial, mobile sensor network

- Collective but complementary visual coverage of an area

- Provide mobile, communication coverage

- Aerial 2D or 3D mosaics

## Air-ground integration (ARO MURI)

- Search in the air, rescue on the ground

- UAV-UGV cooperation

# Autonomous Formation Flight (AFF)

Fort Benning Aug. 2003

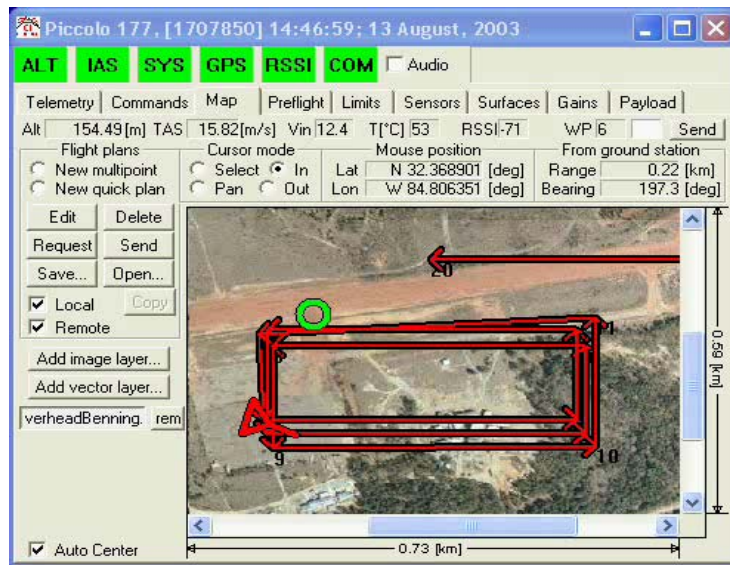


S. Bayraktar, G. E. Fainekos, and G.J. Pappas, "*Hybrid Modeling and Experimental Cooperative Control of Multiple Unmanned Aerial Vehicles*", Technical Report, Department of CIS, University of Pennsylvania, 2004.

# Autonomous Formation Flight (AFF)



# Reconnaissance Mission



# Eye in the sky (150m)



# Eye in the sky (65m)



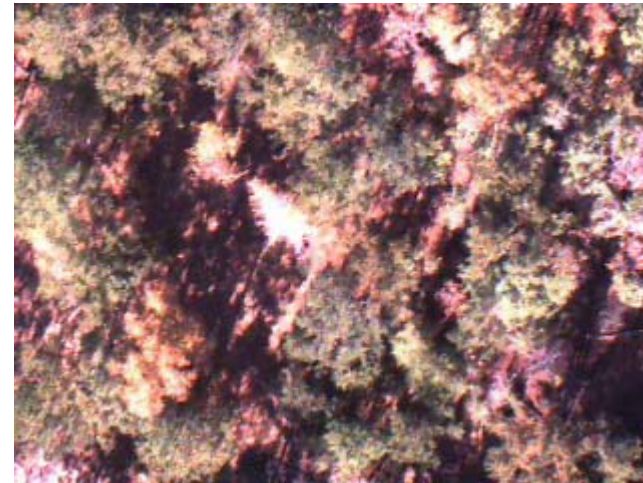
# Aerial mosaic†



† with Rahul Swaminathan

Fort Benning Aug. 2003

# UAV-UGV cooperation



**Fort Benning, Georgia**

**Nov. 2004**

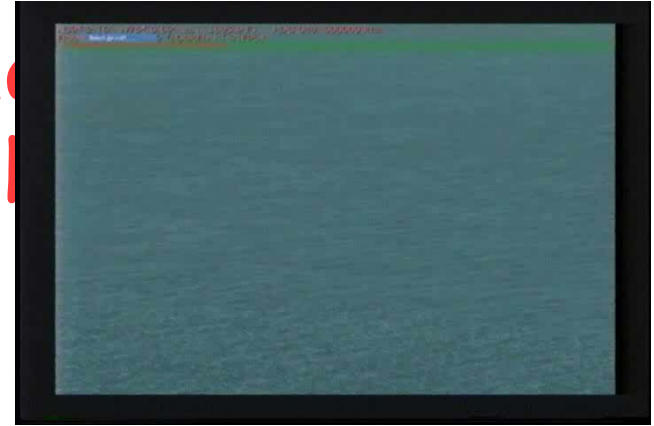
•B. Grocholsky, S. Bayraktar, V. Kumar, C. J. Taylor, and G. J. Pappas, "*Synergies in Feature Localization by Air-Ground Robot Teams*", Proceedings of the 9th International Symposium on Experimental Robotics 2004, Singapore, June 2004.

•B. Grocholsky, S. Bayraktar, V. Kumar and G. Pappas, "*UAV and UGV Collaboration for Active Ground Feature Search and Localization*", AIAA 3rd "Unmanned Unlimited" Technical Conference, Workshop and Exhibit, Chicago, Illinois, Sep. 20-23, 2004.

# Some Technical Challenges

[H. Tanner et. al. 42<sup>nd</sup> CDC 2003]

## \* Future Work



### Synchronous formations

- Fixed relative distance or orientation

- Robust formations critical as UAVs get smaller

### Cooperative control with sensor constraints

### Asynchronous cooperation in dynamic environments

- Include sequencing and concurrency constraints

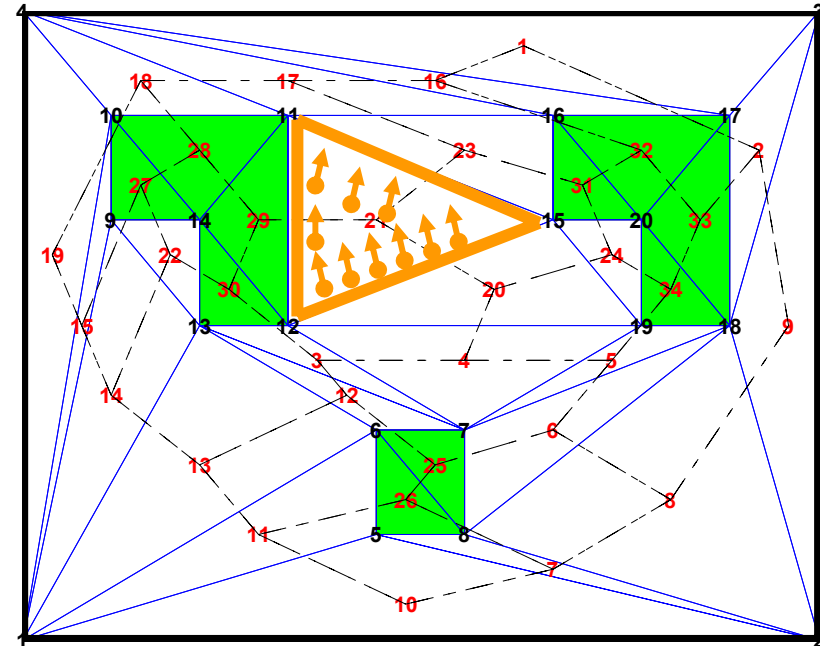
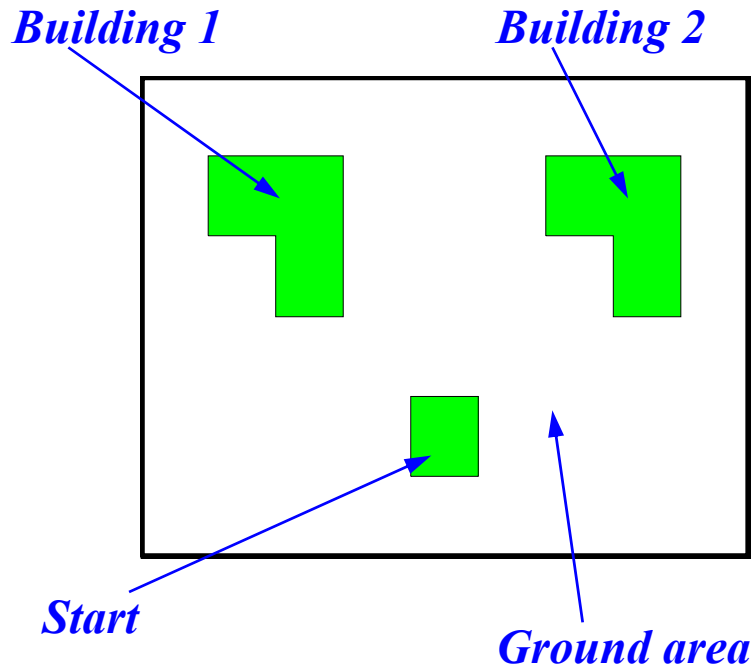
### Formal languages for mission/task descriptions

### Abstractions for controller, sensor primitives

- Decompose missions into controller primitives

### Dynamic verifiable composition of components

# Temporal logic motion planning



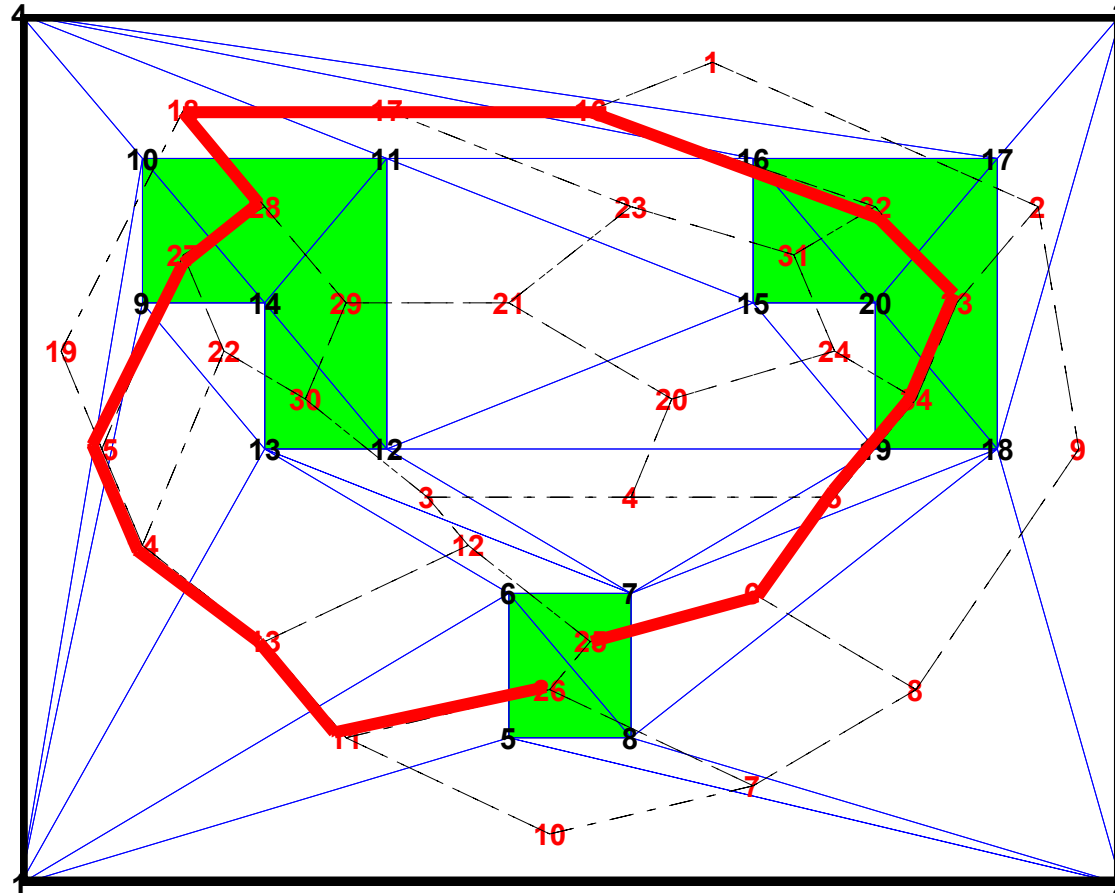
[C. Belta and L. Habetts 43<sup>rd</sup> CDC 2004]

*UAV go to Building 1 and then to Building 2 and then return to Start and UGV cover Ground Area.*

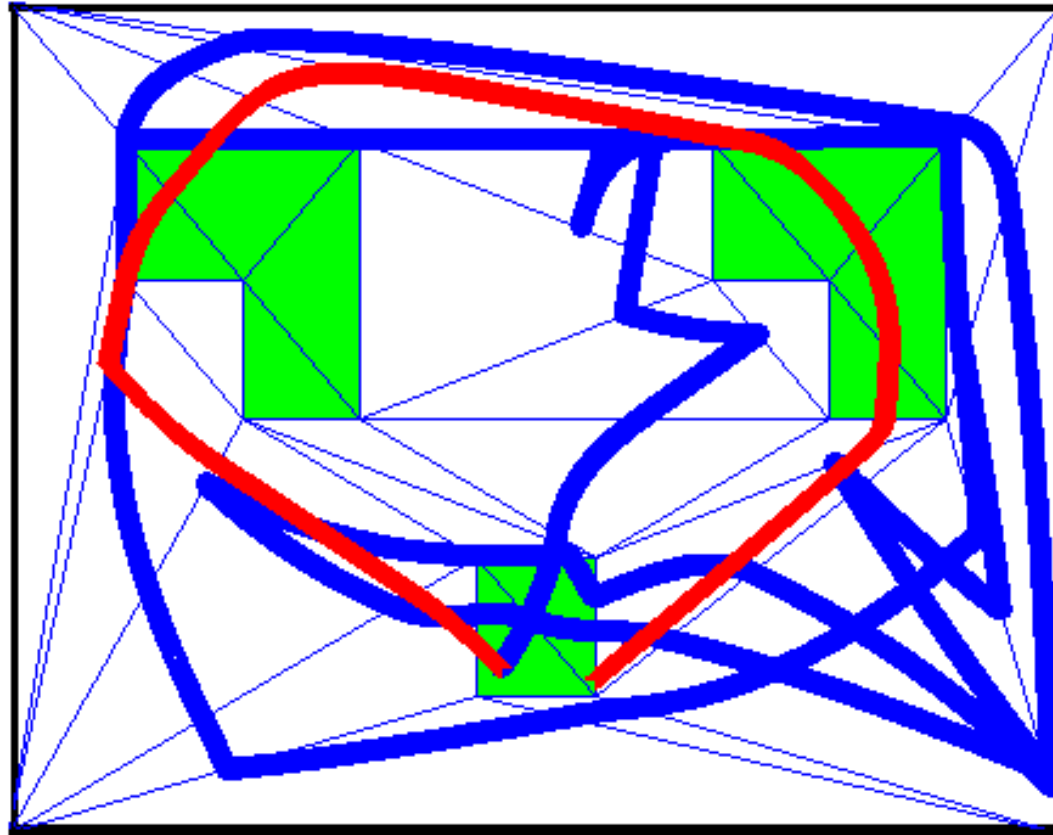


$$\begin{aligned} & \exists (\diamond UAV.Building1 \wedge (\diamond UAV.Building2 \wedge \\ & (\diamond UAV.Starting Area))) \wedge \\ & \exists (UGV.cover(GroundArea) \text{ while } \\ & UGV.avoid(Building1 \wedge Building1)) \end{aligned}$$

# Temporal logic motion planning



# Temporal logic motion planning



# Conclusions

- Development of a fleet of autonomous UAVs
- Various experiments that demonstrate the operational capabilities of the test-bed
- Current work in the development of algorithms for the composition of control primitives that satisfy user specifications

The END  
Thank you!  
Questions?

