University of L'Aquila
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iFLY Mid-Term Review

WP4
Multi-Agent Situation Awareness Consistency Analysis

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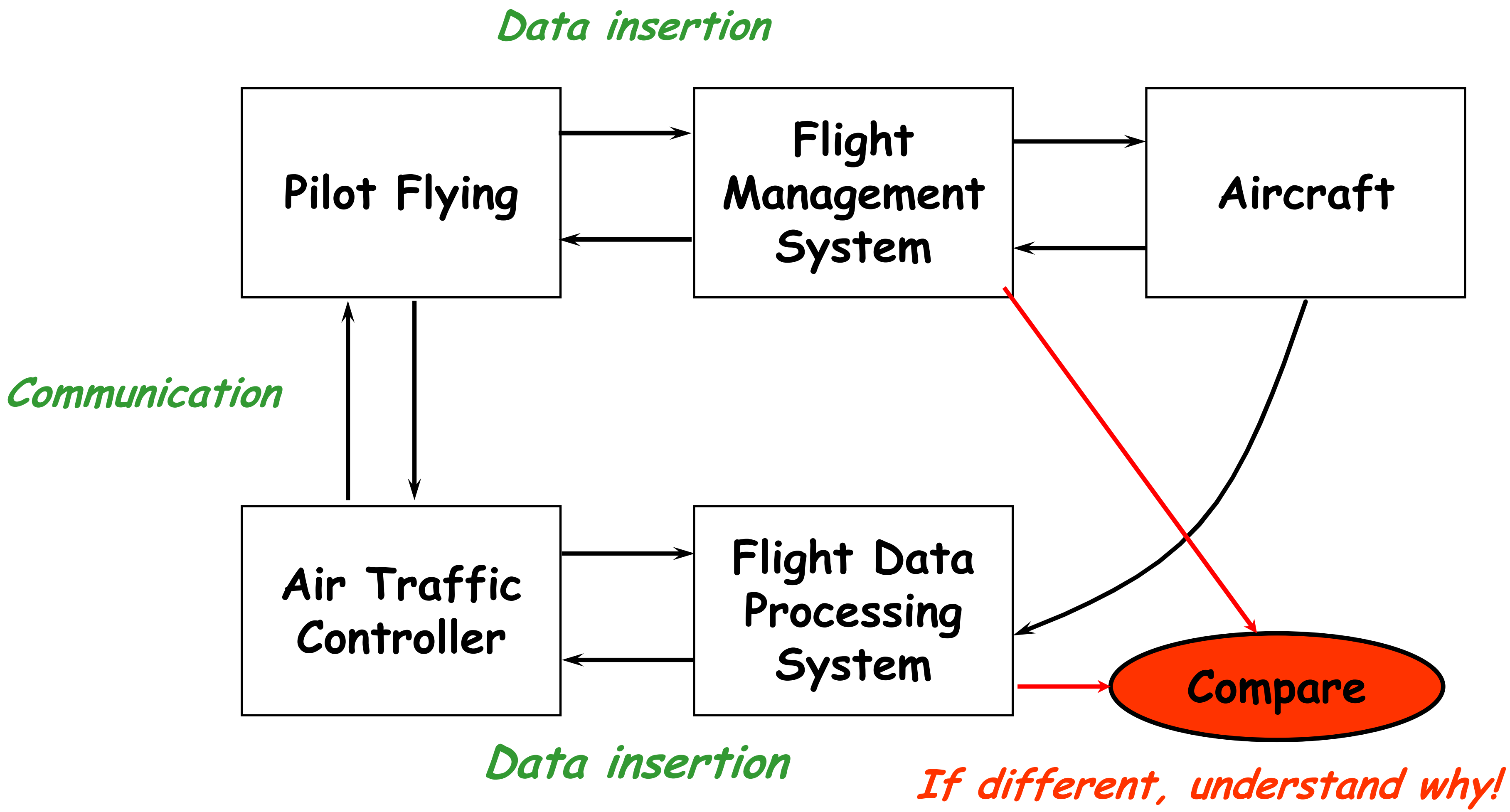
WP4: Multi-agent Situation Awareness consistency analysis

- Task 4.1: *Foundation of MA-SA analysis.* Study techniques that can automatically detect problems with situation awareness, which may lead to a catastrophic situation.
- Task 4.2: *Multi-agent case.* Even though situation awareness errors may cause no significant problem when considered in isolation, in a multi-agent environment they may yield a catastrophic outcome.

Deliverables

- **D4.1:** Report on hybrid models and critical observer synthesis for multi-agent situation awareness (T0+9: Feb.2008) - Final
- **D4.2.i**: Intermediate report on compositionality properties of critical observability (T0+21: Feb. 2009) - Final
- **D4.2**: Final report on compositionality properties of critical observability (T0+32: Jan. 2010)

Case Study
Clearance Changing the Flight-Plan

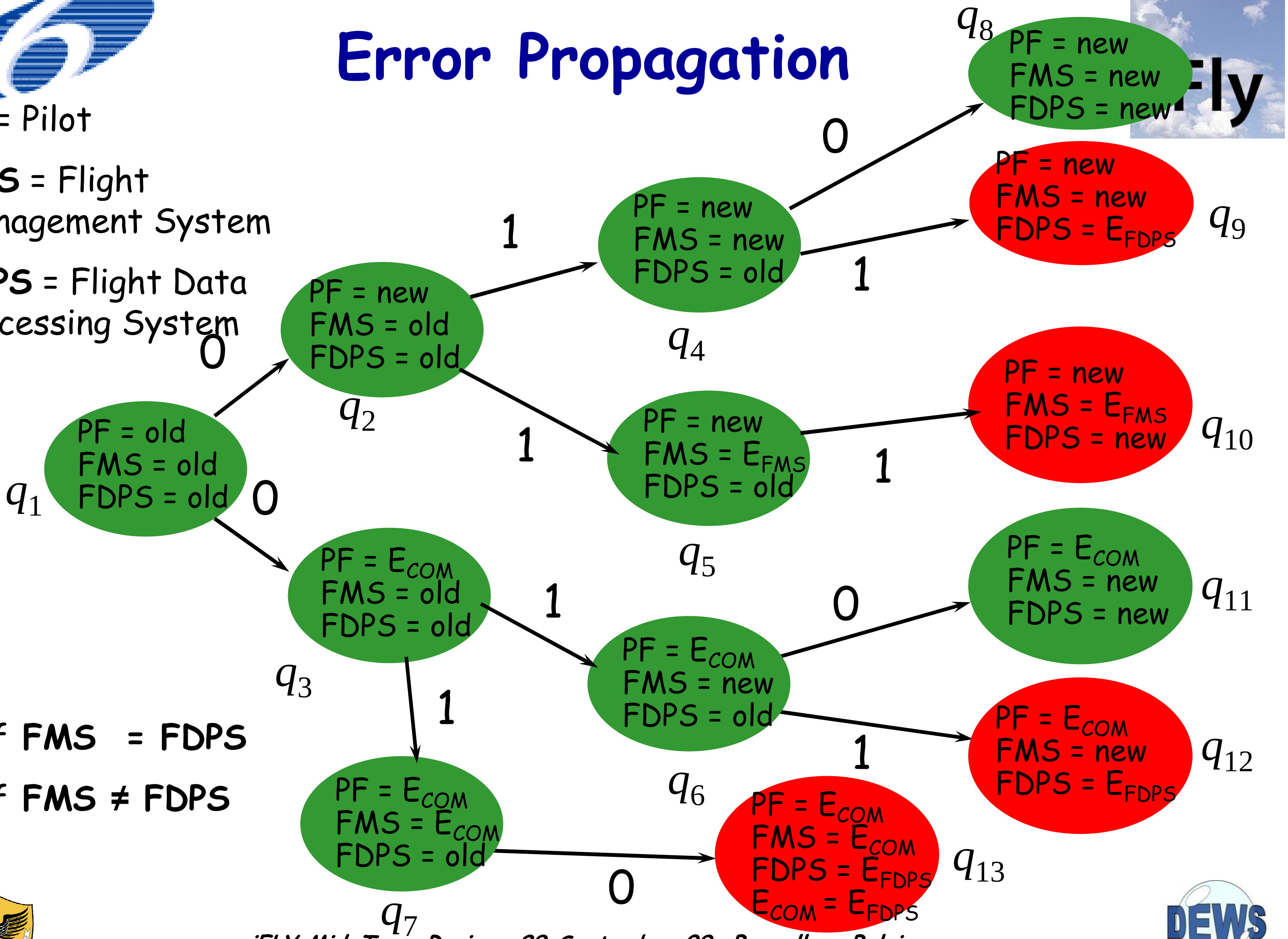


Error Propagation

PF = Pilot

FMS = Flight Management System

FDPS = Flight Data Processing System



0 if **FMS = FDPS**

1 if **FMS ≠ FDPS**

Task 4.1
Foundation of MA-SA analysis

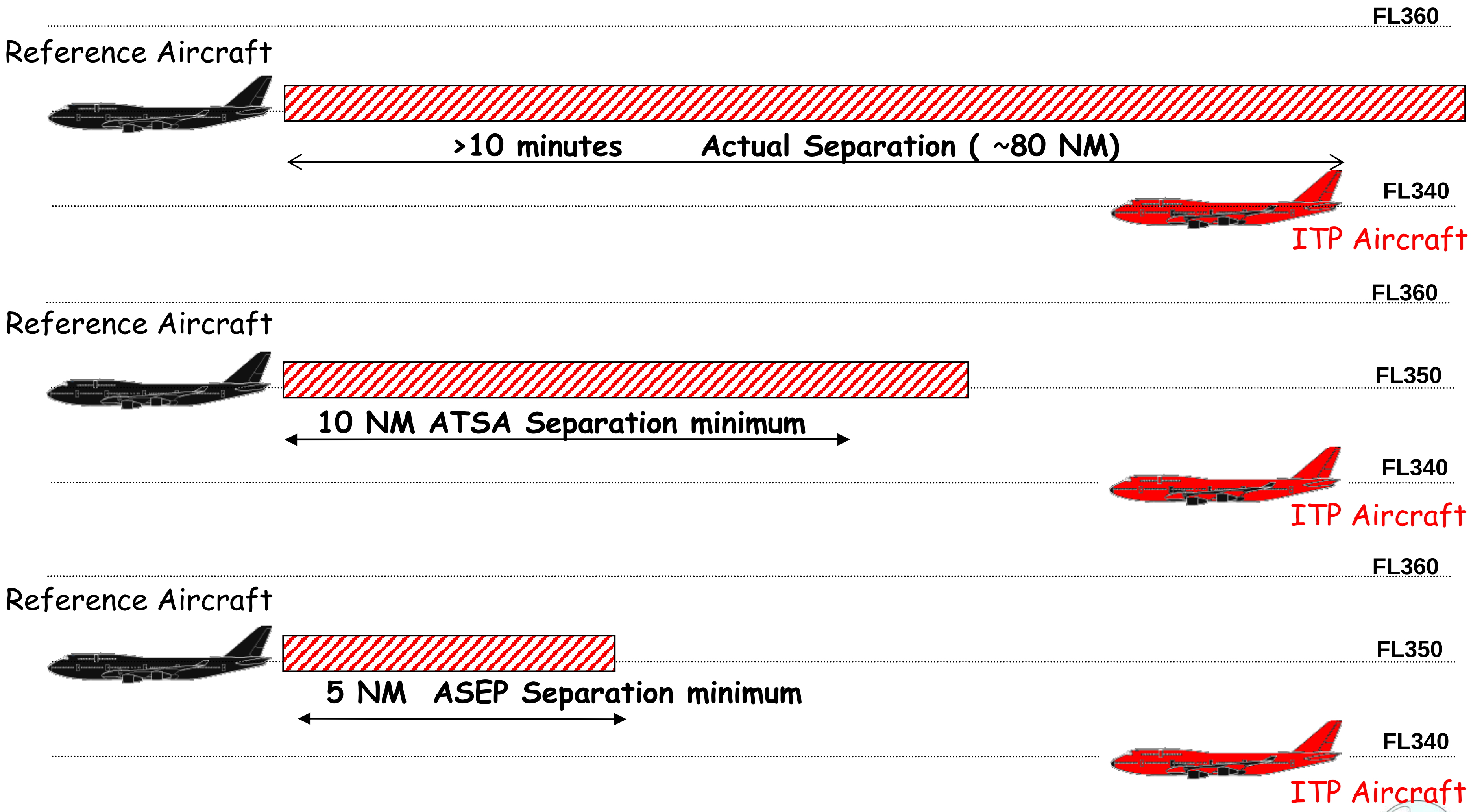
- Case study: ATSA-ITP procedure
- Identification of main components (continuous dynamics, automata) of a hybrid model
- Critical states in the model
- Critical observability properties
- D4.1: Report on hybrid models and critical observer synthesis for multi-agent situation awareness (Final – 12 Sept 2008)

In-Trail Procedures

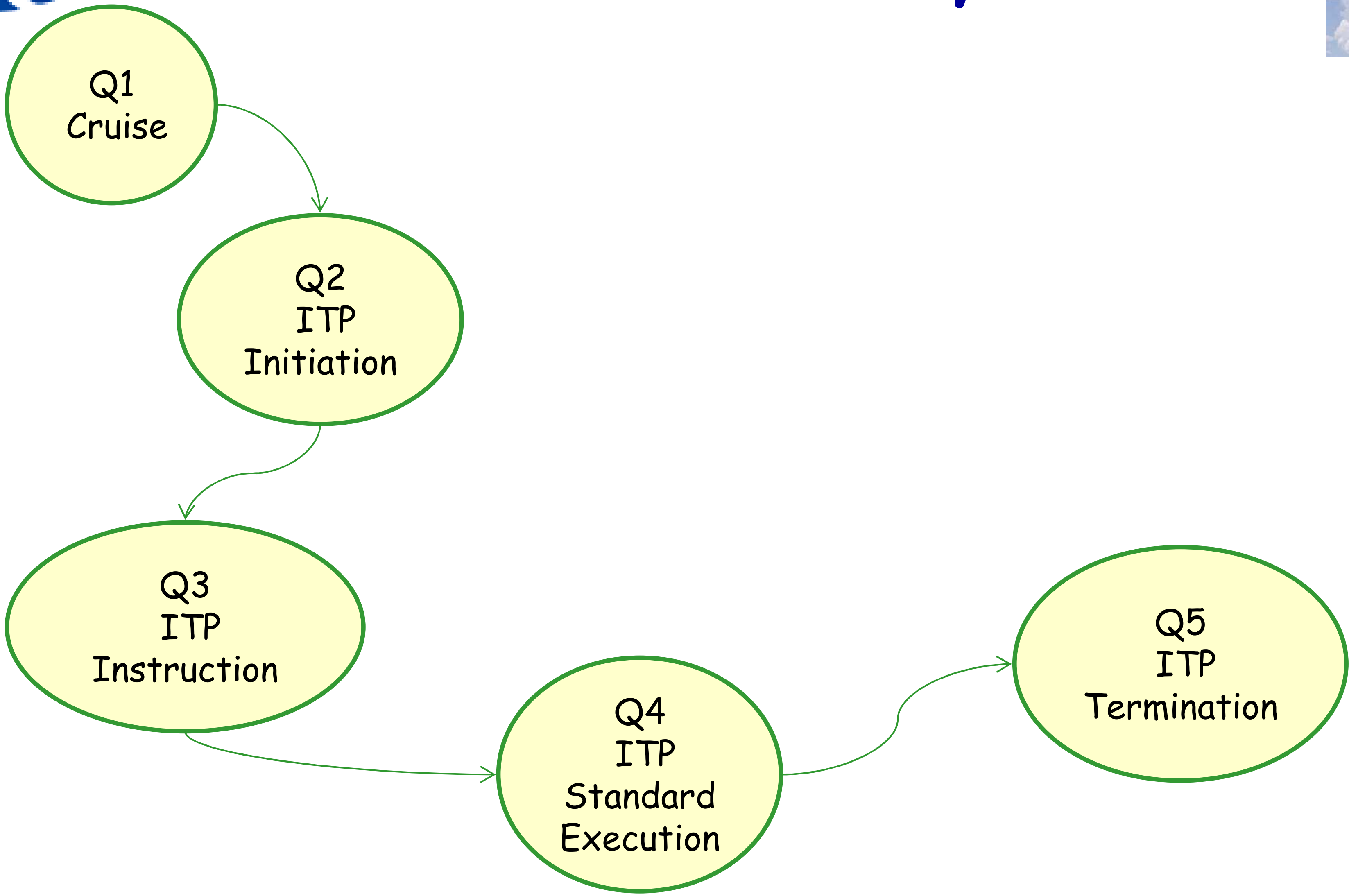
(i.e. No climb allowed if other aircraft in the red hatched areas)

Purpose of ITP: enable aircraft to perform a climb (or possibly a descent) towards a Requested Flight Level, **with less stringent applicability conditions than today's operations** *(using ADS-B, CDTI)*

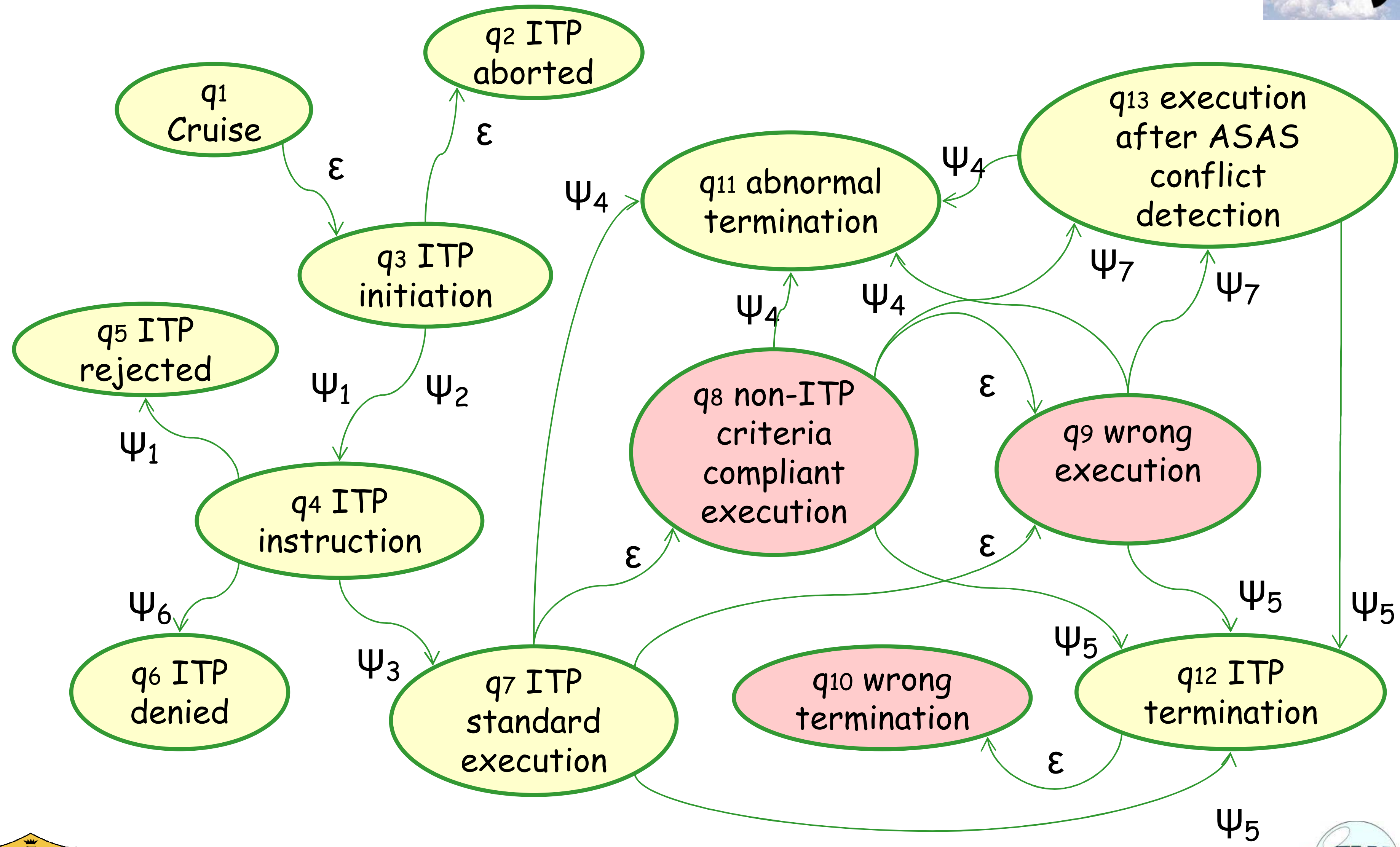
ATSA- and ASEP-ITP



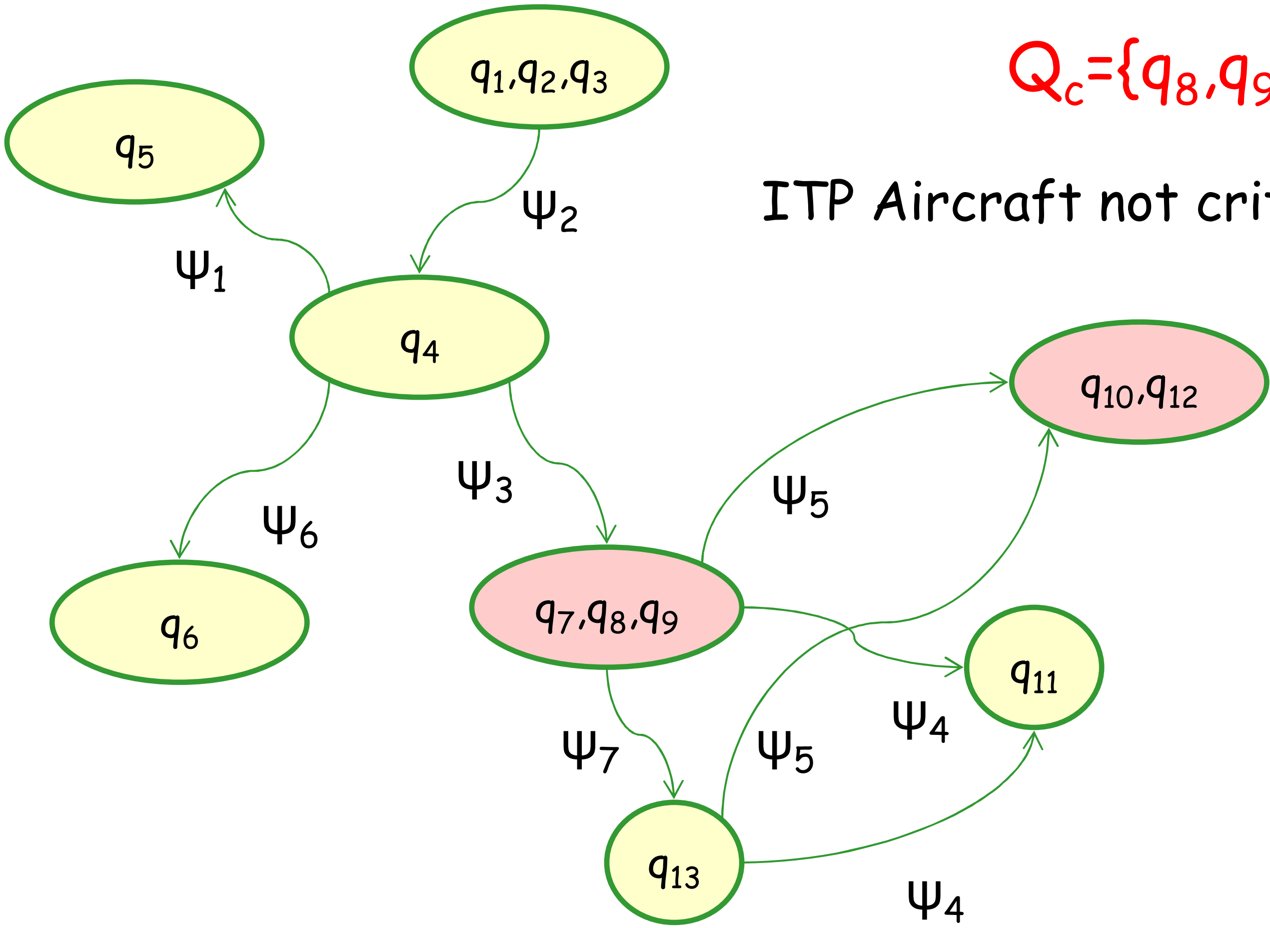
ASEP-ITP aircraft hybrid model



ITP Aircraft Hybrid Model



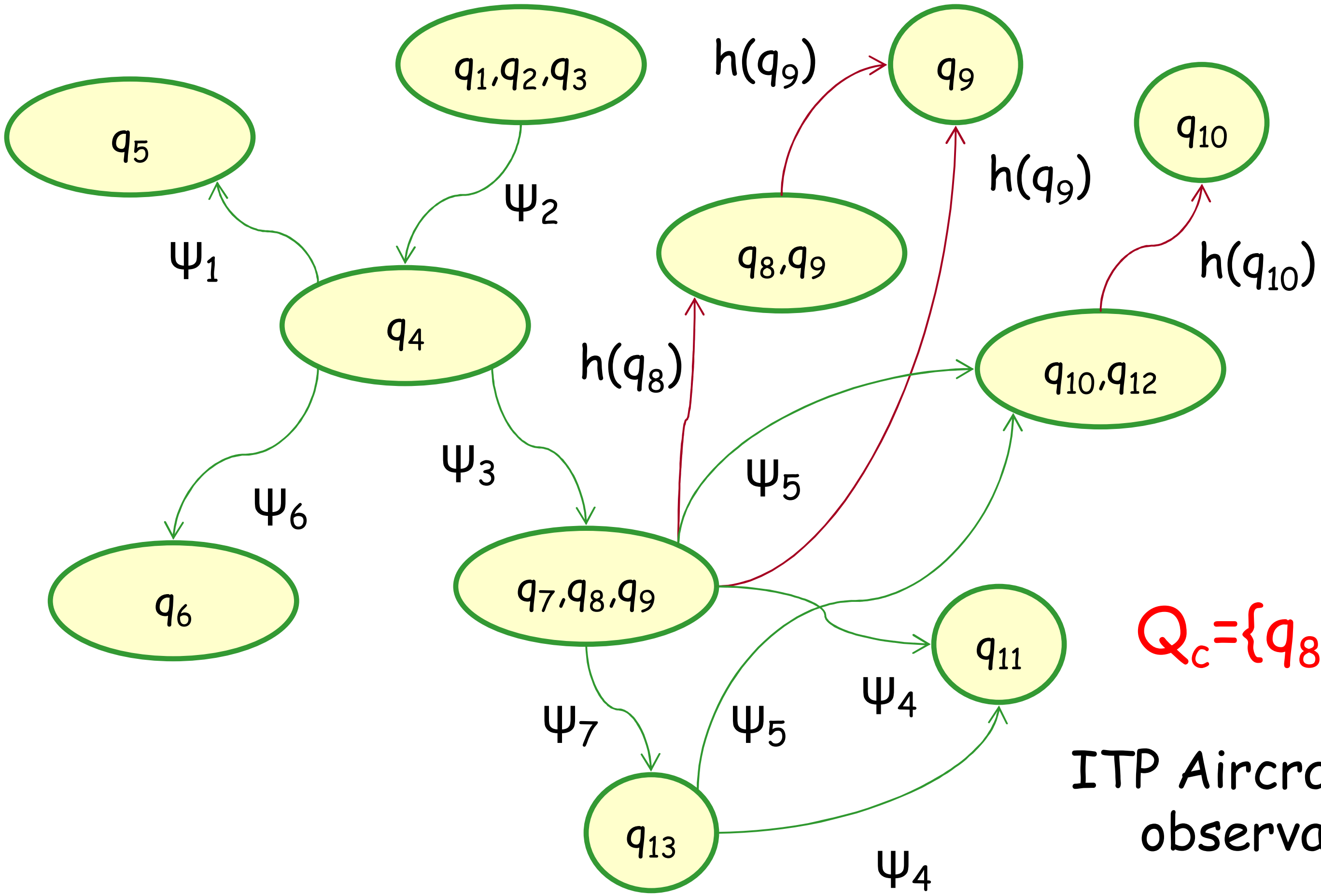
ITP Aircraft Observer



$Q_c=\{q_8,q_9,q_{10}\}$

ITP Aircraft not critically observable

ITP Aircraft Observer with Delay



$Q_c = \{q_8, q_9, q_{10}\}$

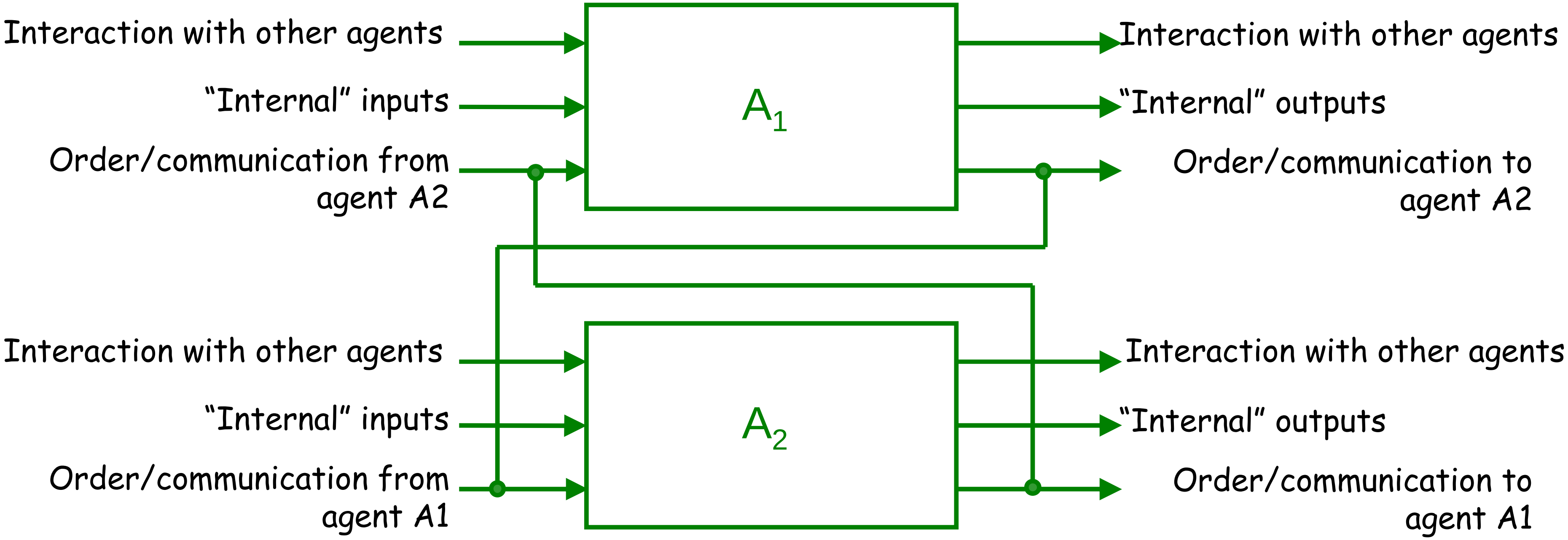
ITP Aircraft critically observable with delay

Task 4.2
Multi-Agent Case

- Hybrid models for the agents involved in the procedures
- Critical states and critical relation to model operational hazards due to the composition of agents
- Critical observability and observers for composed system
- Complexity reduction in checking critical observability of multi-agent systems
- Case study: ASEP-ITP
- D4.2i: Intermediate Report on Compositionality Properties of Critical Observability (Final – 11 May 2009)
- Case studies: Lateral Crossing Procedure, Crossing air traffic in A3 ConOps

Composition of agents

Agents A_1 and A_2



Critical states for Composed Systems

Non-critical states of isolated agents H_1,H_2 can turn into critical states in the composed system $H_1||H_2$:

1. Two aircraft following a path have no critical states considered individually: in the composition, a critical state arises in the intersection of the paths
2. Two aircraft are following correct steps of ATM procedure, which are not allowed simultaneously (e.g. manoeuvre initiation)

Critical observability for multi-agent systems

- Define Hybrid model H_i of each agent
- Define critical relation $R \subset Q_1 \times Q_2 \times \ldots \times Q_N$ capturing critical states of the overall system H
- Define sub-relations
  - $R_{i1} \subset Q_{i1}$ critical states of Agent A_{i1} in isolation
  - $R_{i1,i2} \subset Q_{i1} \times Q_{i2}$ critical states arising from the interaction of agents A_{i1} and A_{i2}

....

  - $R_{i1,i2,\ldots,iN} \subset Q_{i1} \times Q_{i2} \times \ldots \times Q_{iN}$ critical states arising from the interaction of agents $A_{i1}, A_{i2}, \ldots, A_{iN}$

Decomposition of the critical relation

Theorem: The composed system $H_1||H_2||\ldots||H_N$ is R-critically observable if and only if

- H_{i1} is R_{i1}-critically observable

- $H_{i1}||H_{i2}$ is $R_{i1,i2}$-critically observable

....

- $H_1||H_2||\ldots||H_N$ is $R_{i1,i2,\ldots,iN}$-critically observable

Proposition: The composed system $H_1||H_2$ is $R_1 \times R_2$-critically observable if H_1 is R_1-critically observable and H_2 is R_2-critically observable

Application to ASEP-ITP

Space Complexity Reduction

1) $[\ H_1||H_2||H_3,R]$

# of states required: $2^{14x14x5} = 2^{980}$

2) $[\ H_1,R_1\ ] \wedge [\ H_2,R_2\ ] \wedge [\ H_1||H_2,R_{12}\ ] \wedge [\ H_1||H_3,R_{13}\ ] \wedge$
$[\ H_2||H_3,\ R_{23}\ ]$

# of states required: $2^{14} + 2^{14} + 2^{196} + 2^{70} + 2^{70}$

3) $[\ H_1,R_1\ ] \wedge [\ H_2,R_2\ ] \wedge [\ H_1,P_{1,12}\ ] \wedge [\ H_2,P_{2,12}\ ] \wedge [\ H_1,P_{1,13}\ ]$
$\wedge [\ H_3,R_{2,13}\ ] \wedge [\ H_2,P_{1,23}\ ] \wedge [\ H_3,P_{2,23}\ ]$

# of states required: $2^{14} + 2^{14} + 2^{14} + 2^{14} + 2^{14} + 2^{5} + 2^{14} + 2^{5}$

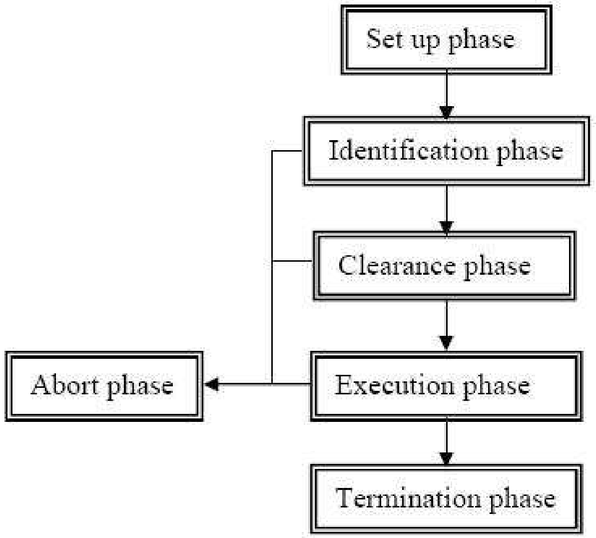
4) $[\ H_1,R_1\ ] \wedge [\ H_1,P_{1,12}\ ] \wedge [\ H_1,P_{1,13}\ ] \wedge [\ H_3,R_{2,13}\ ]$

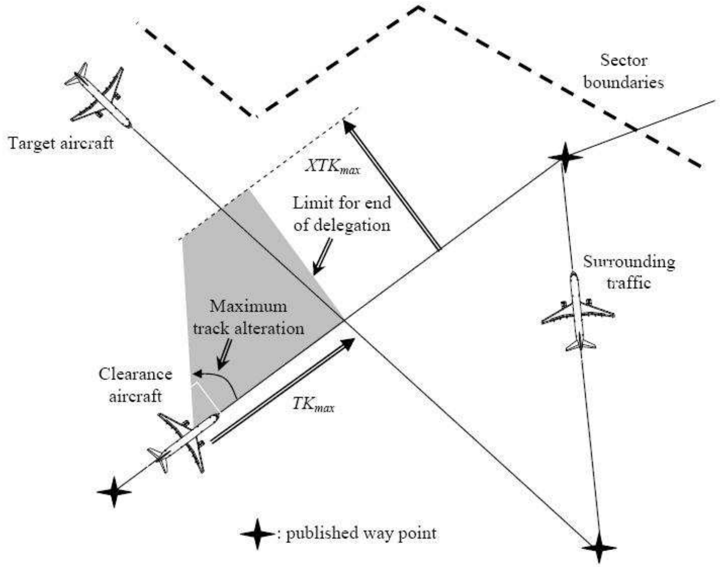
# of states required: $2^{14} + 2^{14} + 2^{14} + 2^{5}$

5) $[\ H_1,\{R_1,P_{1,12},P_{1,13}\}\ ] \wedge [\ H_3,R_{2,13}\ ]$

# of states required: $2^{14} + 2^{5} = 16416$

2nd Case Study: Lateral Crossing Procedure



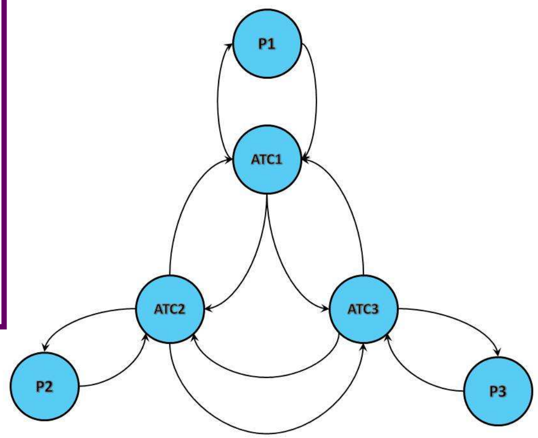


The purpose of the ASAS Lateral Crossing procedure is to provide a new set of air traffic control clearances, allowing **N** aircraft to cross or pass a target aircraft through the use of ASAS.

2^{nd} Case Study: Lateral Crossing Procedure

$H_1||H_2||\ldots||H_N$ is R-critically observable if:

- H_1 is $\{q_8,q_{10},q_{12},q_{13},q_{14},q_{15}\}$-critically observable
- H_1 is $\{q_4\}$-critically observable
- H_N is $\{q_5\}$-critically observable

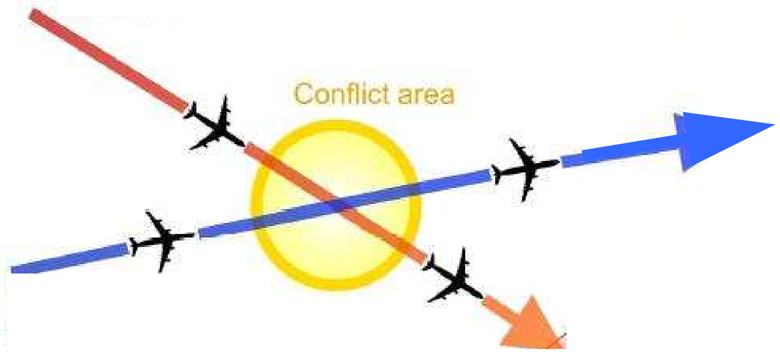


From the analysis of critical observability of an arbitrary large number of N agents taking place in the ASAS Lateral Crossing Procedure to the check of only 3 critical relations involving 1 agent each.

E De Santis, M D Di Benedetto, A Petriccone, G Pola, A Compositional Hybrid System Approach to the Analysis of Air Traffic Management Systems, submitted to INO Workshop, 28 Sept. 09

Plan

Choose A3ConOps scenario



Main intent related (non-nominal) conditions

- ***Main intent related (non-nominal) conditions***

Rank	Class	Description
3	$(A1 \cap P1 \cap Q2)$	Own a/c intent is not conflict free and nobody is aware
4	$(B1 \cap P2 \cap Q2 \cap R1)$	Another a/c intent is not conflict free and nobody is aware
7	$(B1 \cap P2 \cap Q2)$	Another a/c intent intentionally not conflict free; others are not aware
8	$(A1 \cap Q2)$	Own a/c intent intentionally is not conflict free; others are not aware
17	A4	Intent of ownship aircraft not broadcasted
18	B4	Intent of one other aircraft not received
19	$(B4' \cap P4 \cap Q4)$	New intents of multiple a/c not received and crew does not know
29	P2	Own crew has SA difference for another a/c
30	R2	Ownship state/intent is not properly perceived by encountering crew.
42	$(A4 \cap B4' \cap P4 \cap Q4)$	Intent exchange does not work well and nobody is aware

From D7.1b, H. Blom et al.

Publications

Dissemination

- Invited session at the IEEE Conference on Decision and Control (CDC07), New Orleans, USA, December 12-15th, 2007, on "Observability and Observer-Based Control of Hybrid Systems", organized by Elena De Santis and Maria D. Di Benedetto.
- Elena De Santis and Maria D. Di Benedetto are Guest Editors of a *Special Issue of the International Journal of Robust and Nonlinear Control* on "Observability and Observer Design for Hybrid Systems". 8 papers accepted.
- Invited session at the IEEE Conference on Decision and Control CDC08, Cancun, Mexico, 9-11 December 2008, on "Abstraction techniques for dynamical systems: theory and computation". Organized by Alessandro D'Innocenzo and Alessandro Abate.
- M. Colageo, A. Di Francesco, Hybrid System Framework for the Safety Modelling of the In Trail Procedure. *International Conference on Research in Air Transportation 2008, (ICRAT 08)*
- Elena De Santis, Maria D. Di Benedetto, Alessandro Petriccone, Giordano Pola, A Compositional Hybrid System Approach to the Analysis of Air Traffic Management Systems, submitted to EUROCONTROL Innovative ATM Research Workshop & Exhibition, December 2009.

Publications

- Alessandro D'Innocenzo presented the paper "Automatic Verification of Temporal Properties of Air Traffic Management Procedures Using Hybrid Systems" in the EUROCONTROL Innovative ATM Research Workshop & Exhibition, December 2008, Paris, France.

Journal papers

- A.A. Julius, A. D'Innocenzo, G.J. Pappas, M.D. Di Benedetto, Approximate equivalence and synchronization of metric transition systems, *Systems & Control Letters*, 2008.
- E. De Santis, Invariant dual cones for hybrid systems, *Systems & Control Letters*, 2008.
- De Santis E., Di Benedetto M.D., Pola G., A structural approach to detectability for a class of hybrid systems, *Automatica*, 45(5):1202-1206, 2009.
- P. Caravani, E. De Santis, Observer based stabilization of linear switching systems, *International Journal of Robust and Nonlinear Control*, to appear, 2009.
- M.D. Di Benedetto, S. Di Gennaro, A. D'Innocenzo, Discrete State Observability of Hybrid Systems, *International Journal on Robust and Non-Linear Control*, Special Issue on "Observability and Observer Design for Hybrid Systems", to appear, 2009.
- M.D. Di Benedetto, S. Di Gennaro, A. D'Innocenzo, Verification of Hybrid Automata Diagnosability, *IEEE Transactions on Automatic Control*, to appear, 2009.

Publications

Conferences

- A. Abate, A. D'Innocenzo, M.D. Di Benedetto, S. Sastry, Understanding Deadlock and Livelock Behaviors in Hybrid Control Systems, *Nonlinear Analysis: Hybrid Systems*, 2008.
- E. De Santis, M.D. Di Benedetto, Observer design for discrete-time linear switching systems. 3rd IFAC Symposium on System, Structure and Control (SSSC07). Foz de Iguassu, Brazil. October 17-19, 2007
- A. Abate, A. D'Innocenzo, M.D. Di Benedetto, S. Sastry. Markov Set-Chains as abstractions of Stochastic Hybrid Systems. *Hybrid Systems: Computation and Control 2008 (HSCC 2008)*
- E. De Santis, M.D. Di Benedetto, Theory and computation of discrete state space decompositions for hybrid systems, submitted, 2009
- A. D'Innocenzo, A. Abate. PCTL model checking of discrete time Markov chains by approximate stochastic bisimulation, submitted, 2009
- M.D. Di Benedetto, S. Di Gennaro, A. D'Innocenzo, Diagnosability of hybrid automata with measurement uncertainty, *IEEE CDC 08*, Dec. 2008.

Master Theses

- M. Colageo, Hybrid Modelling and Observability Analysis of the ATSA-In Trail Procedure. *Master Thesis*, Advisor: M.D. Di Benedetto, Co-Tutor: A. D'Innocenzo
- A. Di Francesco, Application of the Hybrid Systems Theory to the ASEP In-Trail procedure. *Master Thesis*, Advisor: M.D. Di Benedetto, Co-Tutor: A. D'Innocenzo
- A. Petriccone, Modelli ibridi per la rappresentazione di procedure di controllo del traffico aereo (Hybrid Models for Air Traffic Management Systems Procedure), *Master Thesis*, Advisor: M.D. Di Benedetto, Co-Tutor: A. D'Innocenzo
- Pasquale Visconti, Critical Observability of Interconnected Systems with application to Air Traffic Management Systems, *Master Thesis*, University of L'Aquila, 29 Sept. 2008.
- Valentina D'Alessandro, Hybrid modeling and observability analysis in ATM systems: application to the Lateral Crossing procedure, *Master Thesis*, University of L'Aquila, 11 May 2009.
- Giulia Di Matteo, Analysis of ATM Procedures by Stochastic Model Checking. Master Thesis, Under work.

Conclusions

- Hybrid Systems modeling: a promising tool for a formal analysis of multi-agent SA consistency
- Compositional Hybrid System approach to the analysis of multi-agent ATM scenarios for complexity reduction
- Detection of critical situations which are otherwise unobservable
- Choose a scenario in A3 ConOps
- Address one of the main intent related non-nominal conditions of D7.1b in an A3ConOps scenario