Fault Tolerance in Robotics

David Powell, Raja Chatila,
Matthieu Gallien, Jérémie Guiochet,
Félix Ingrand, Marc-Olivier Killijian,
Benjamin Lussier

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Introduction

Context

- Prospective internal research project at LAAS
  - Robotics and Artificial Intelligence group
  - Dependable Computing and Fault Tolerance group

➔ *Dependability of autonomous robots in critical applications*

- Space exploration
- Medical assistance
- Service

Introduction

Dependability basics (cf. IEEE TDSC 1(1)11-33, 2004)

- Four complementary means to achieve dependability:
  - fault prevention
  - fault removal

  fault avoidance: how to *aim for* fault-free systems

  - fault forecasting
  - fault tolerance

  fault acceptance: how to *live with* systems that are subject to faults

- Fault classes
  - physical faults (natural hardware faults, environmental effects…)
  - interaction faults (humans, environmental adversities…)
  - development faults (hardware & software bugs)

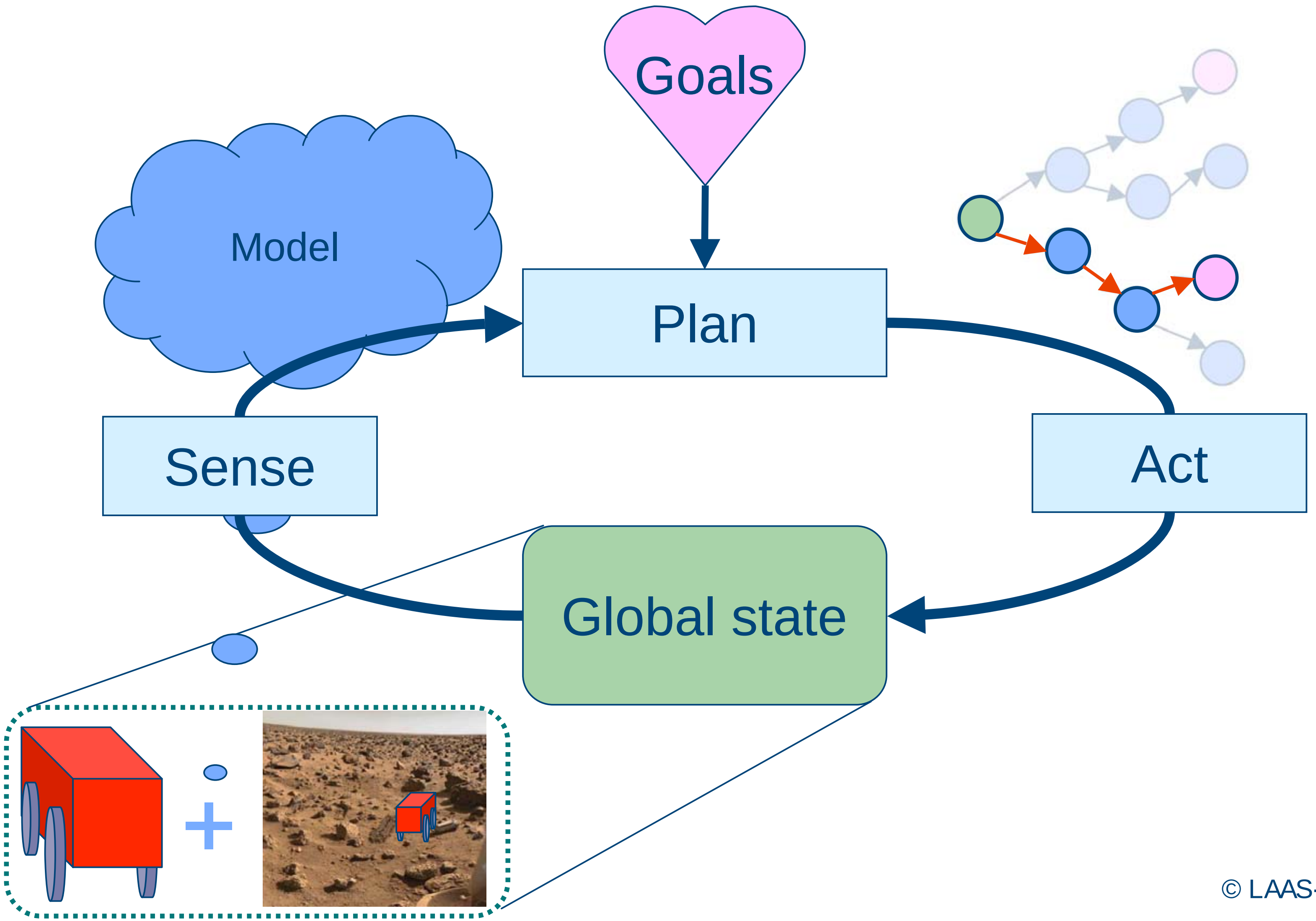
Introduction

Roadmap

- Introduction
- Sense-plan-act paradigm
- Target architecture
- The IxTeT temporal planner
- Tolerating planner faults
- Experimentation environment
- Conclusions

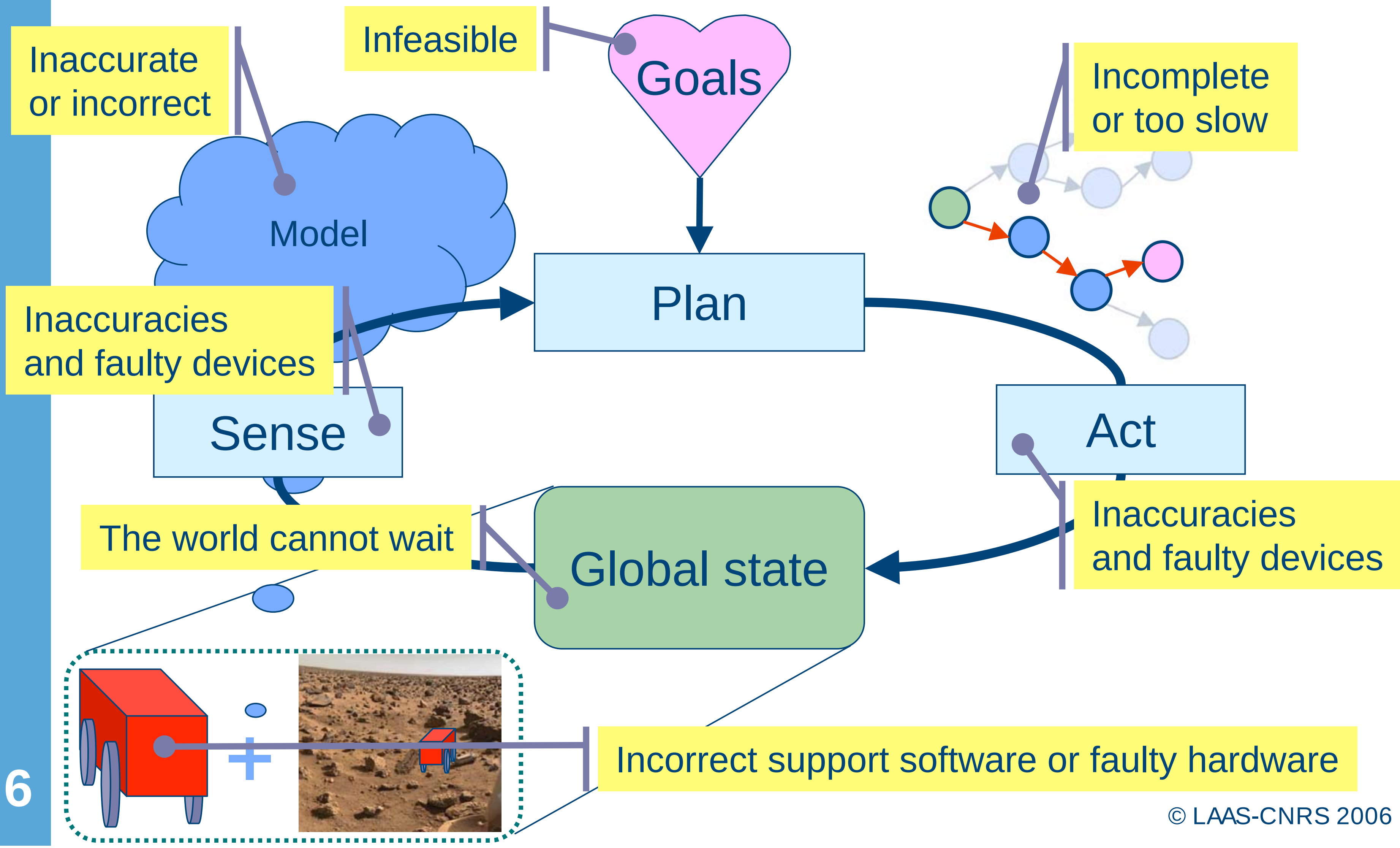
The Sense-Plan-Act Paradigm

Basics



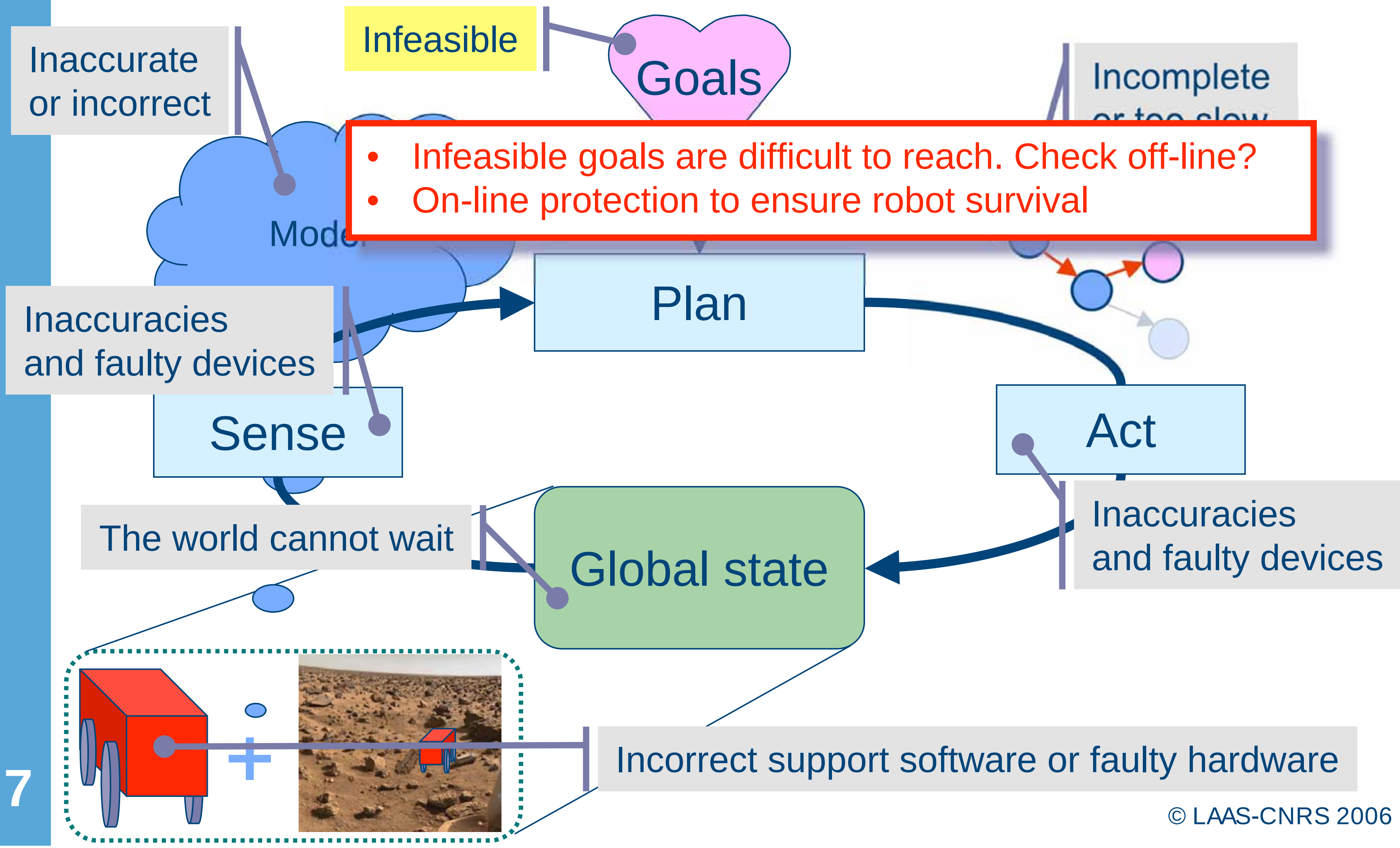
The Sense-Plan-Act Paradigm

What can go wrong ?



The Sense-Plan-Act Paradigm

What can go wrong and what can be done about it ?



- Infeasible goals are difficult to reach. Check off-line?
- On-line protection to ensure robot survival

The Sense-Plan-Act Paradigm

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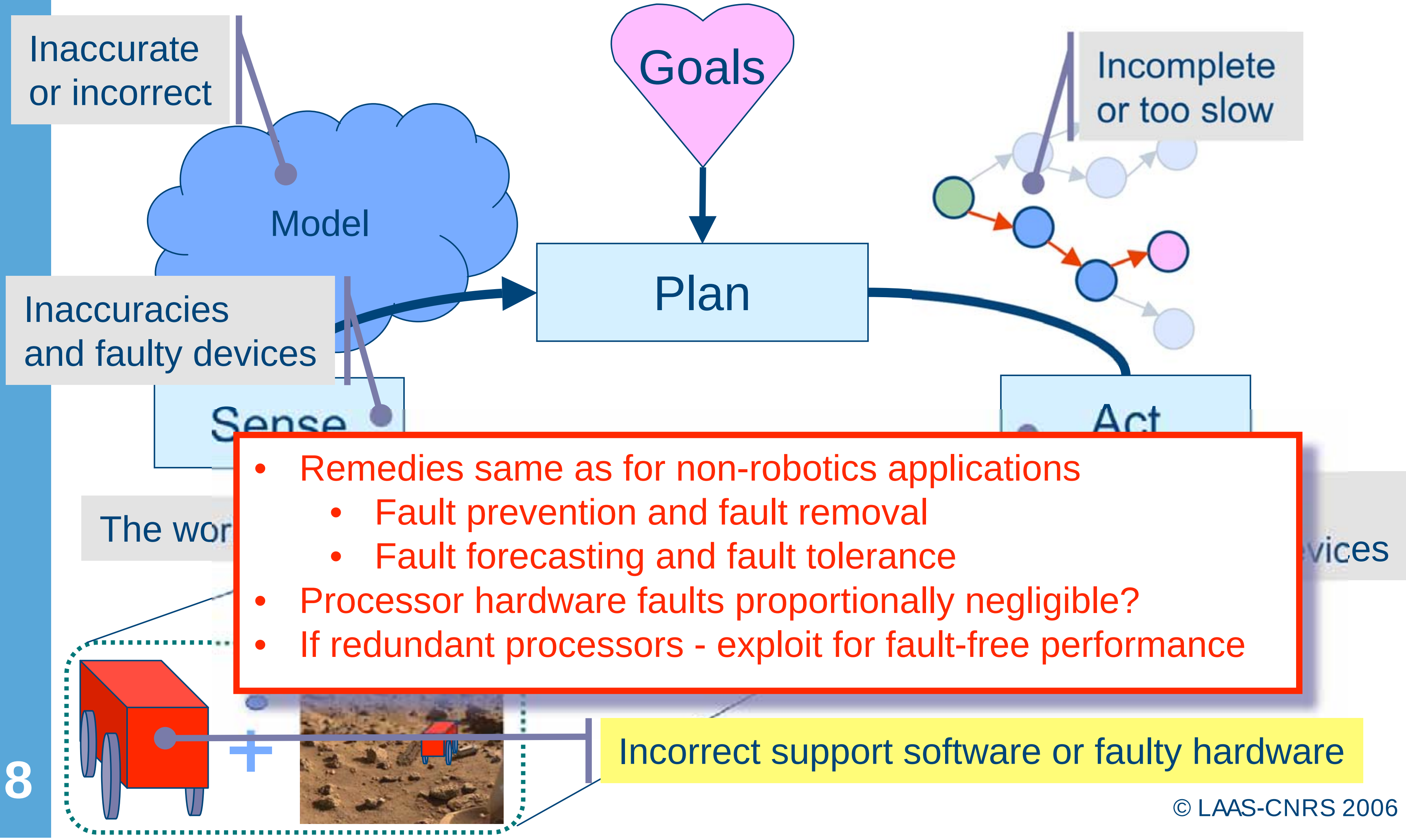
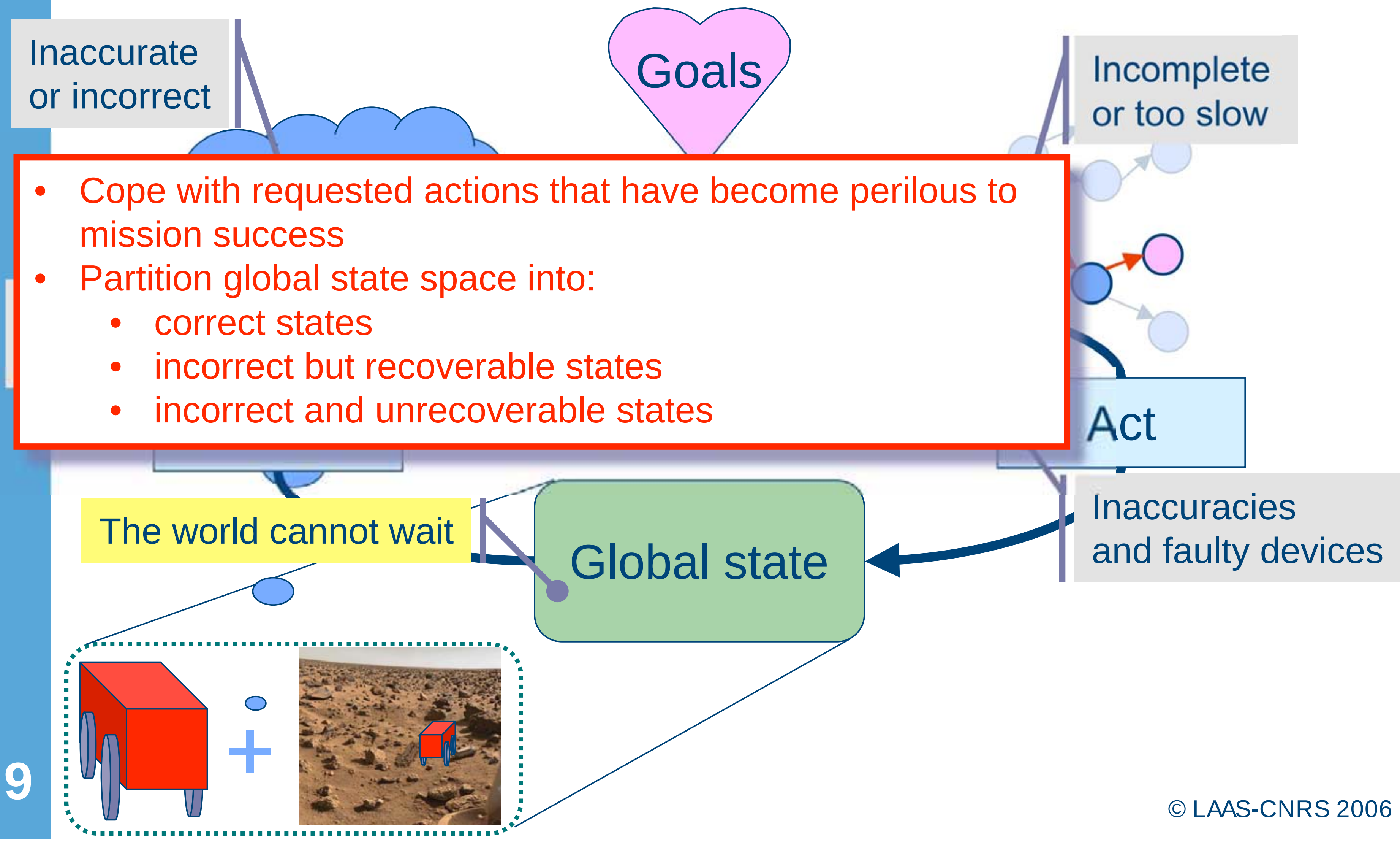


- Remedies same as for non-robotics applications
  - Fault prevention and fault removal
  - Fault forecasting and fault tolerance
- Processor hardware faults proportionally negligible?
- If redundant processors - exploit for fault-free performance

The Sense-Plan-Act Paradigm

What can go wrong and what can be done about it ?



- Cope with requested actions that have become perilous to mission success
- Partition global state space into:
  - correct states
  - incorrect but recoverable states
  - incorrect and unrecoverable states

The Sense-Plan-Act Paradigm

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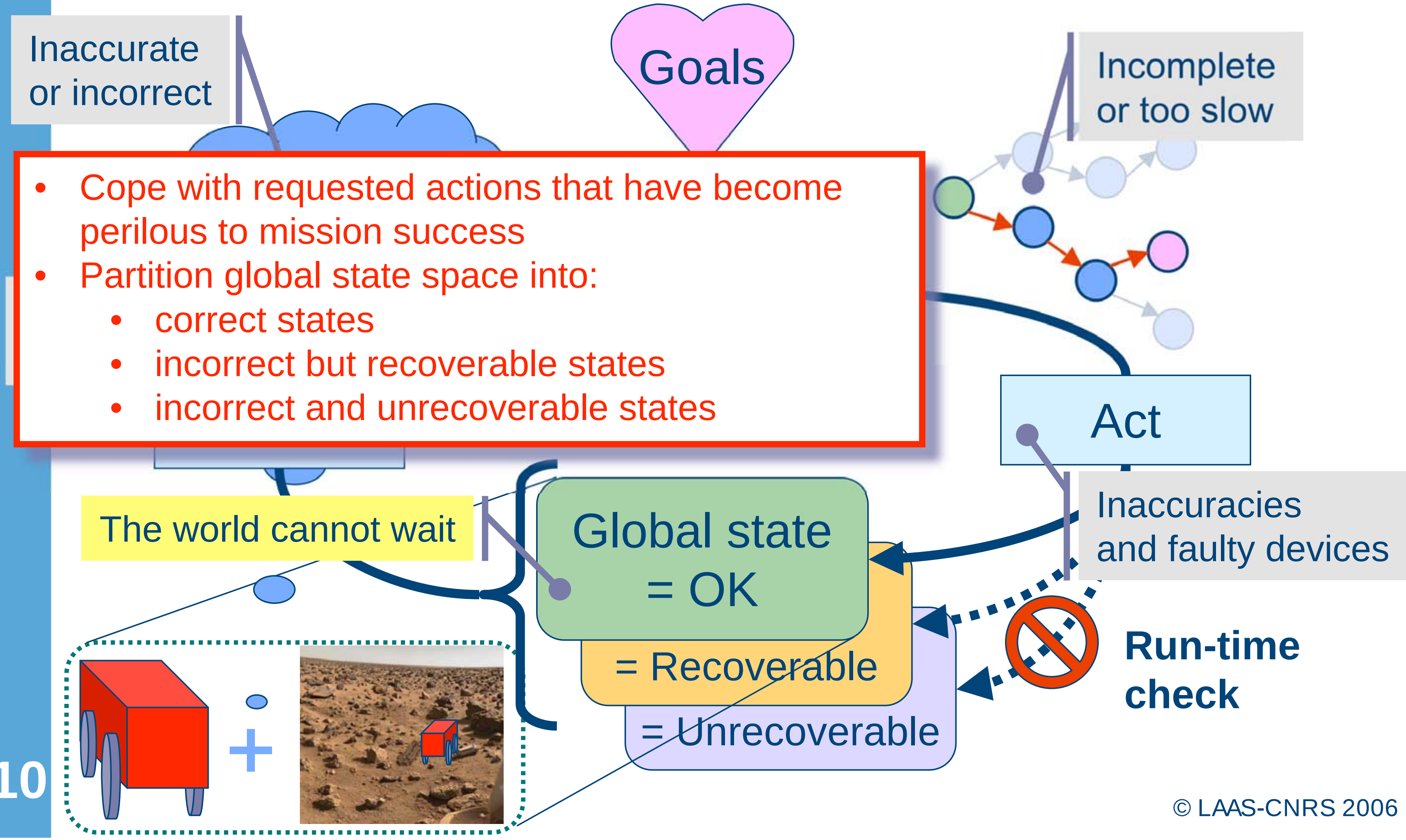
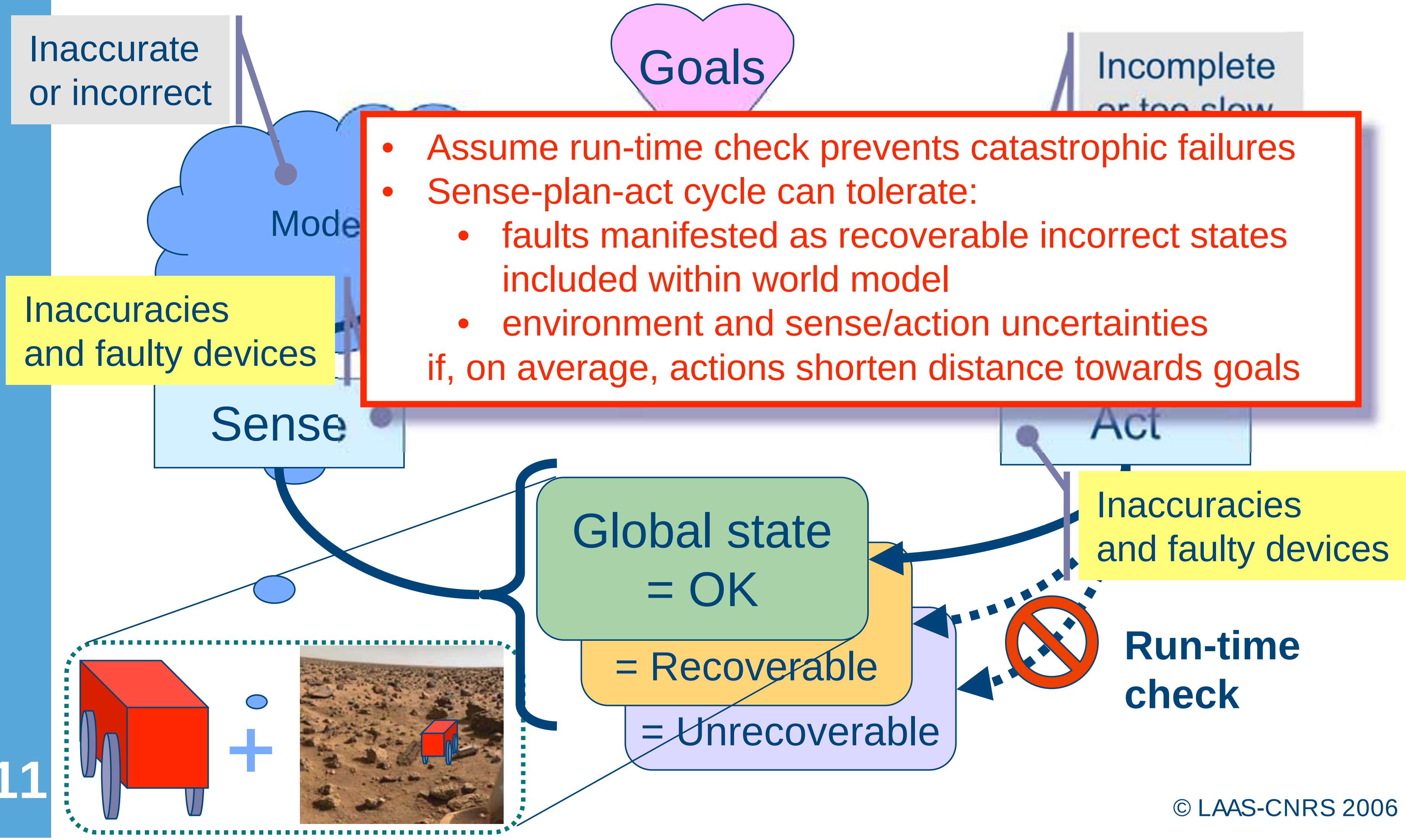


The Sense-Plan-Act Paradigm

What can go wrong and what can be done about it ?

- Assume run-time check prevents catastrophic failures
- Sense-plan-act cycle can tolerate:
  - faults manifested as recoverable incorrect states included within world model
  - environment and sense/action uncertainties

  if, on average, actions shorten distance towards goals



The Sense-Plan-Act Paradigm

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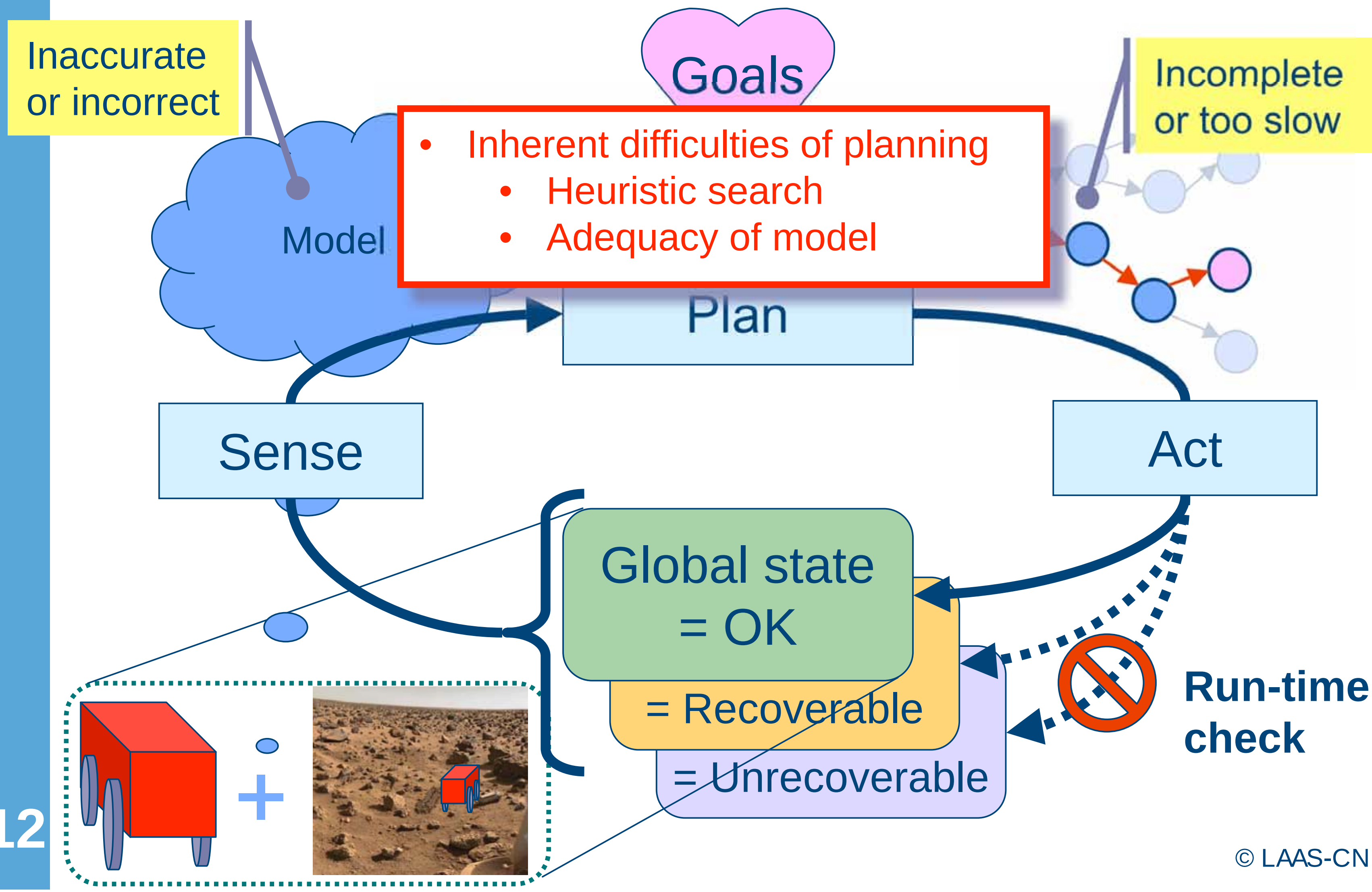
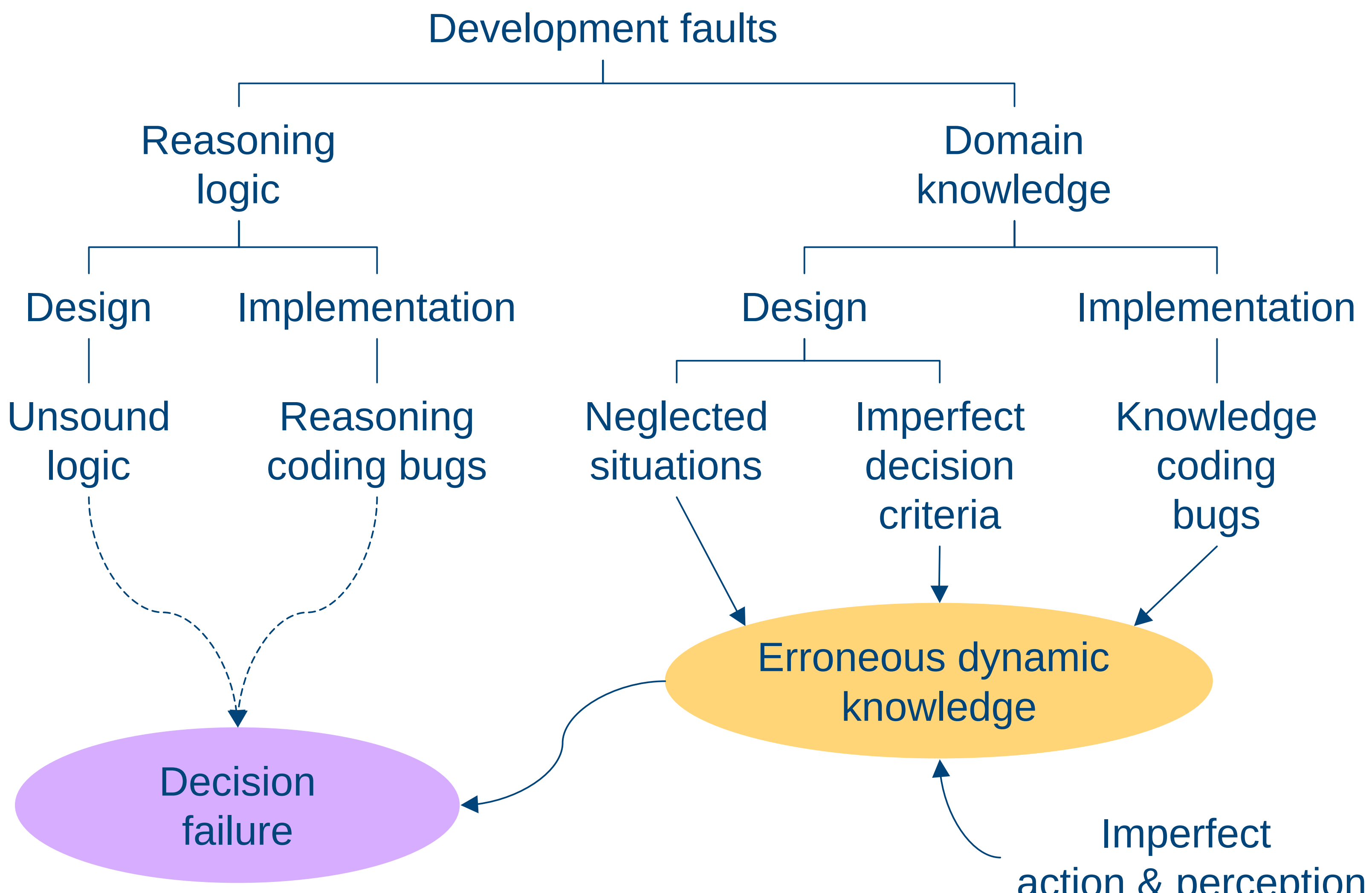


The Sense-Plan-Act Paradigm

Fault and errors affecting decisional mechanisms



Target Architecture

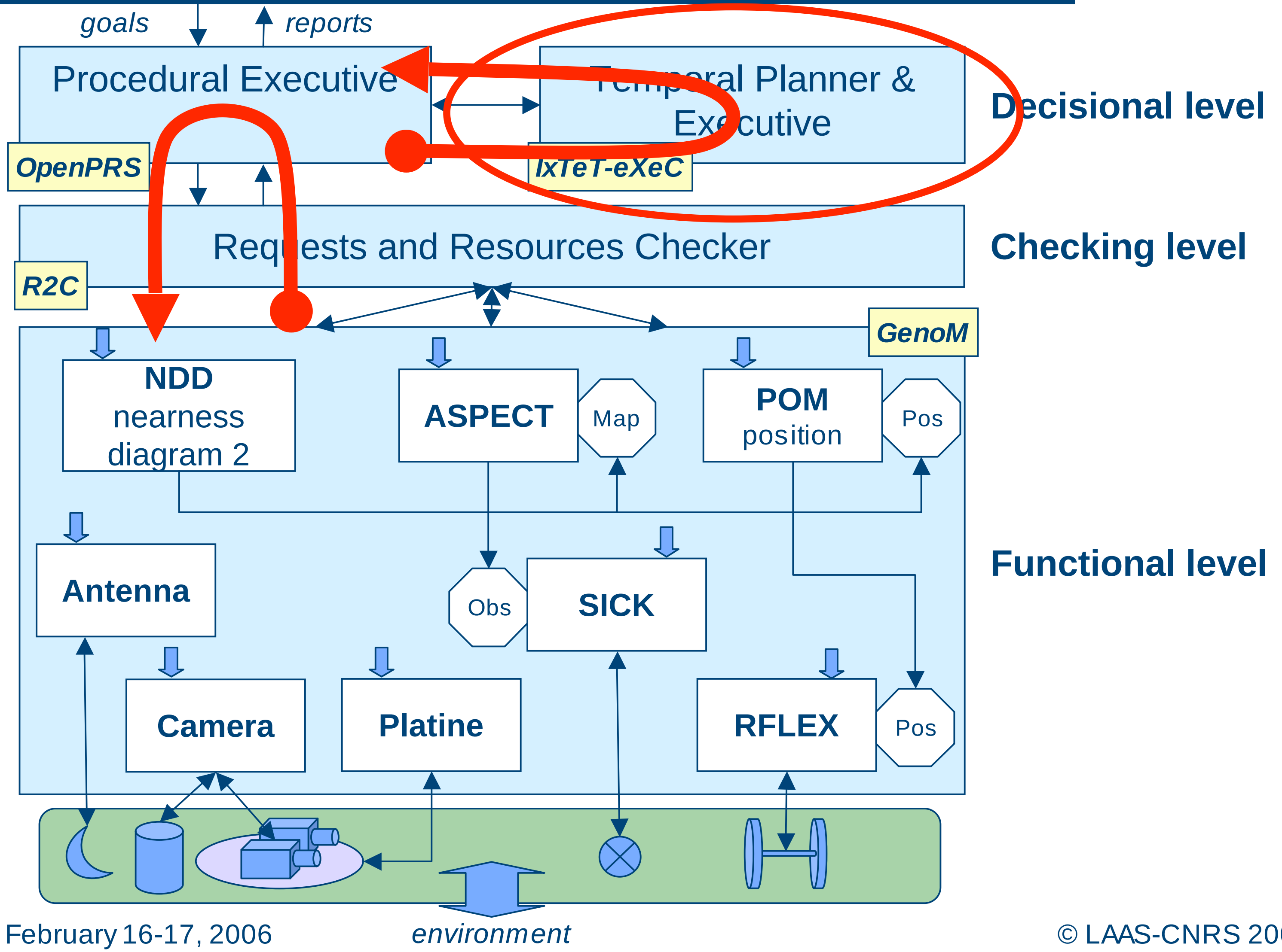
Example: the "Dala" planetary exploration rover

- Commercial ATRV robot platform
- Sensors
  - odometer
  - stereo cameras
  - laser range-finder
- Actuators
  - wheels (differential drive)
  - camera bench Pan & Tilt Unit (PTU)

+ simulated communication facility

Target Architecture

LAAS architecture for autonomous systems (LAAS)

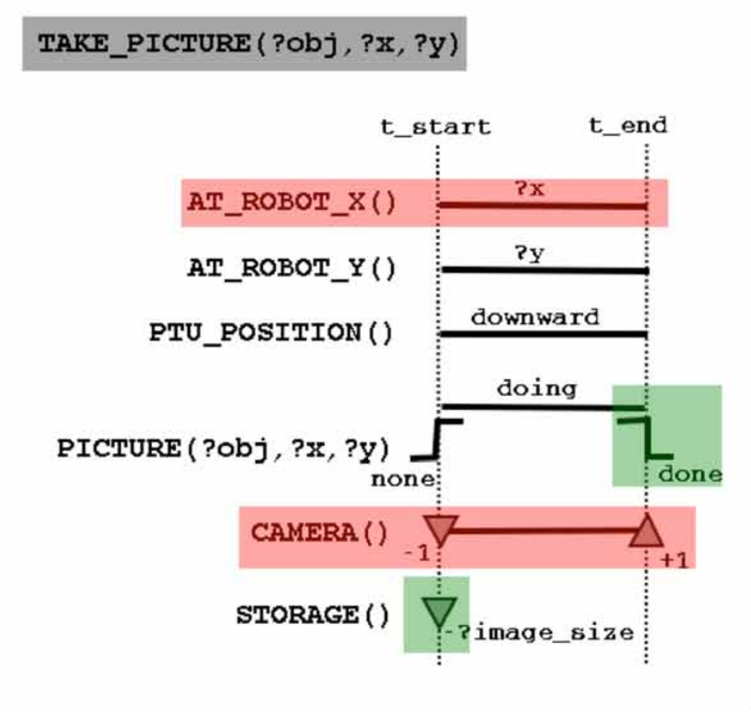


The IxTeT Temporal Planner

Model based on temporal statements about attributes

- **Logical attributes** (hold/event)
  Resource attributes (use/consume/produce)
- **Actions** (specification of the evolution of attributes of interest)

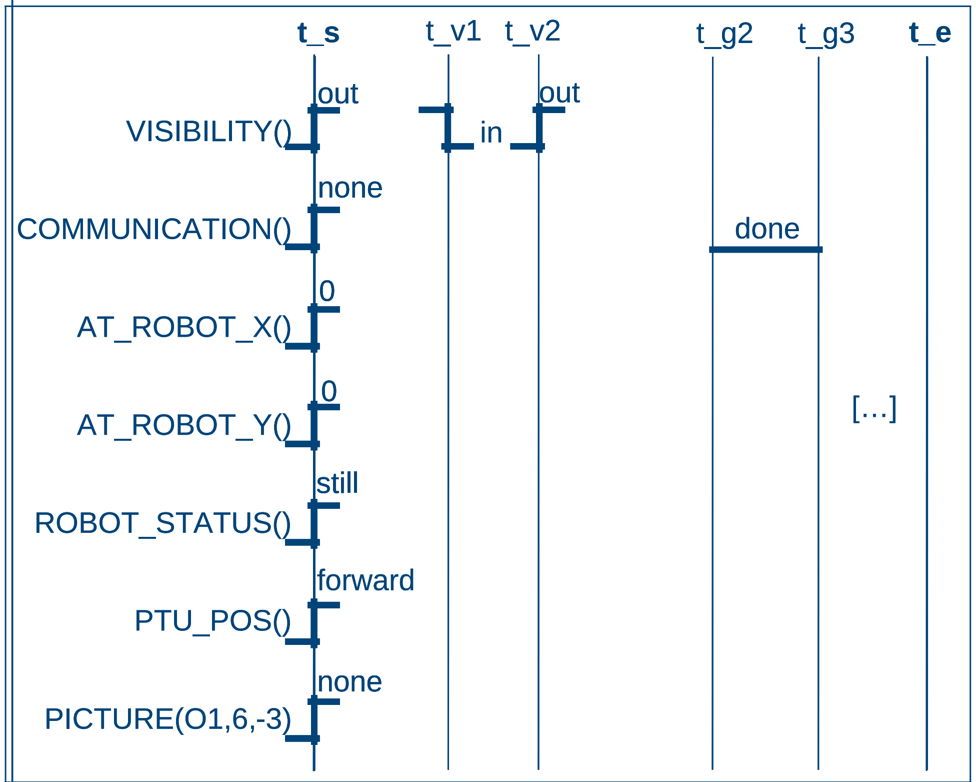
```
task TAKE_PICTURE(?obj,?x,?y)(t_start,t_end){
   ?obj in OBJECTS;
   ?x in ]-oo,+oo[; ?y in ]-oo,+oo[;

  hold(AT_ROBOT_X():?x,(t_start,t_end));
  hold(AT_ROBOT_Y():?y,(t_start,t_end));
  hold(PTU_POSITION():downward,(t_start,t_end));

  event(PICTURE(?obj,?x,?y):(none,doing),t_start);
  hold(PICTURE(?obj,?x,?y):doing,(t_start,t_end));
  event(PICTURE(?obj,?x,?y):(doing,done),t_end);

  use(CAMERA():1,(t_start,t_end));
  variable ?image_size;
  variable ?cr;
  compression_rate(?cr);
  ?image_size = 175610 * ?cr;
  consume(STORAGE():?image_size,t_start);

   (t_end - t_start) in ]0,60];
}nonPreemptive
```



The IxTeT Temporal Planner

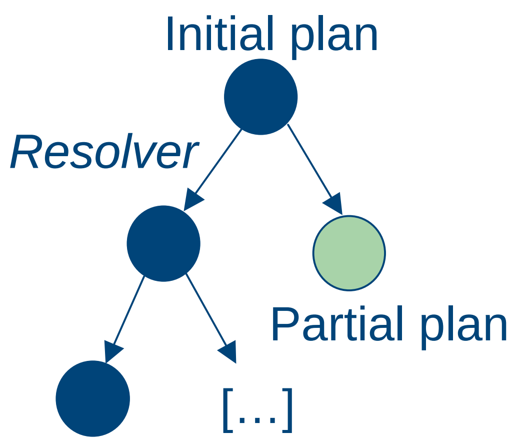
POCL (Partial Order Causal Link) planning

```
task Init() (t_s,t_e){
  timepoint t_v1, t_v2,t_g1,…;
  // Initial State
  explained event(AT_ROBOT_X():(?,0),t_s);
  explained event(AT_ROBOT_Y():(?,0),t_s);
  explained event(ROBOT_STATUS():(?,still),t_s);
  explained event(PTU_POS():(?,forward),t_s);
  explained event(COMMUNICATION():(?,none),t_s);
  variable ?x1,?y1;
  ?x1 in ]-oo,+oo[; ?y1 in ]-oo,+oo[;
  explained event(PICTURE(O1,?x1,?y1):(?,none),t_s);
  // Visibility window
  contingent event(VISIBILITY():(?,out),t_s);
  contingent event(VISIBILITY():(out,in),t_v1);
  contingent event(VISIBILITY():(in,out),t_v2);
  (t_v2-t_v1) in [120,120];
  (t_v1-t_s) in [300,300];
  // Goals
  hold(AT_ROBOT_X():0,(t_g1,t_e)) goal(3,0);
  hold(AT_ROBOT_Y():0,(t_g1,t_e)) goal(3,0);
  hold(COMMUNICATION():done,(t_g2,t_g3)) goal(2,0);
  hold(PICTURE(O1,6,-3):done,(t_g4,t_g5)) goal(1,0);
  // Horizon
  (t_e – t_s) in [1000,1000];
} latePreemptive
```



The IxTeT Temporal Planner

POCL (Partial Order Causal Link) planning



Def. [partial plan] **P = (A,C,L,F)**

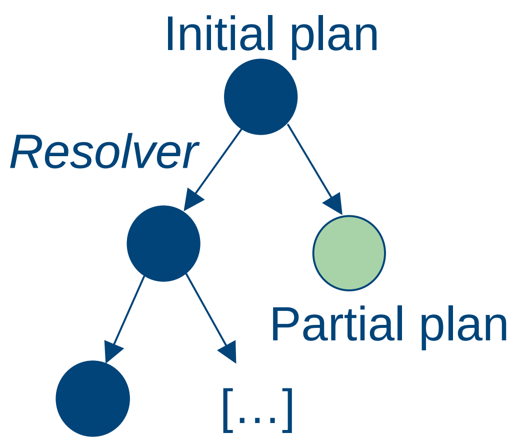
A : *actions*
C : *constraints*
L : *causal links*
F : *flaws*

- open conditions
- threats
- resource conflicts

A partial plan is a solution plan if F = Ø

The IxTeT Temporal Planner

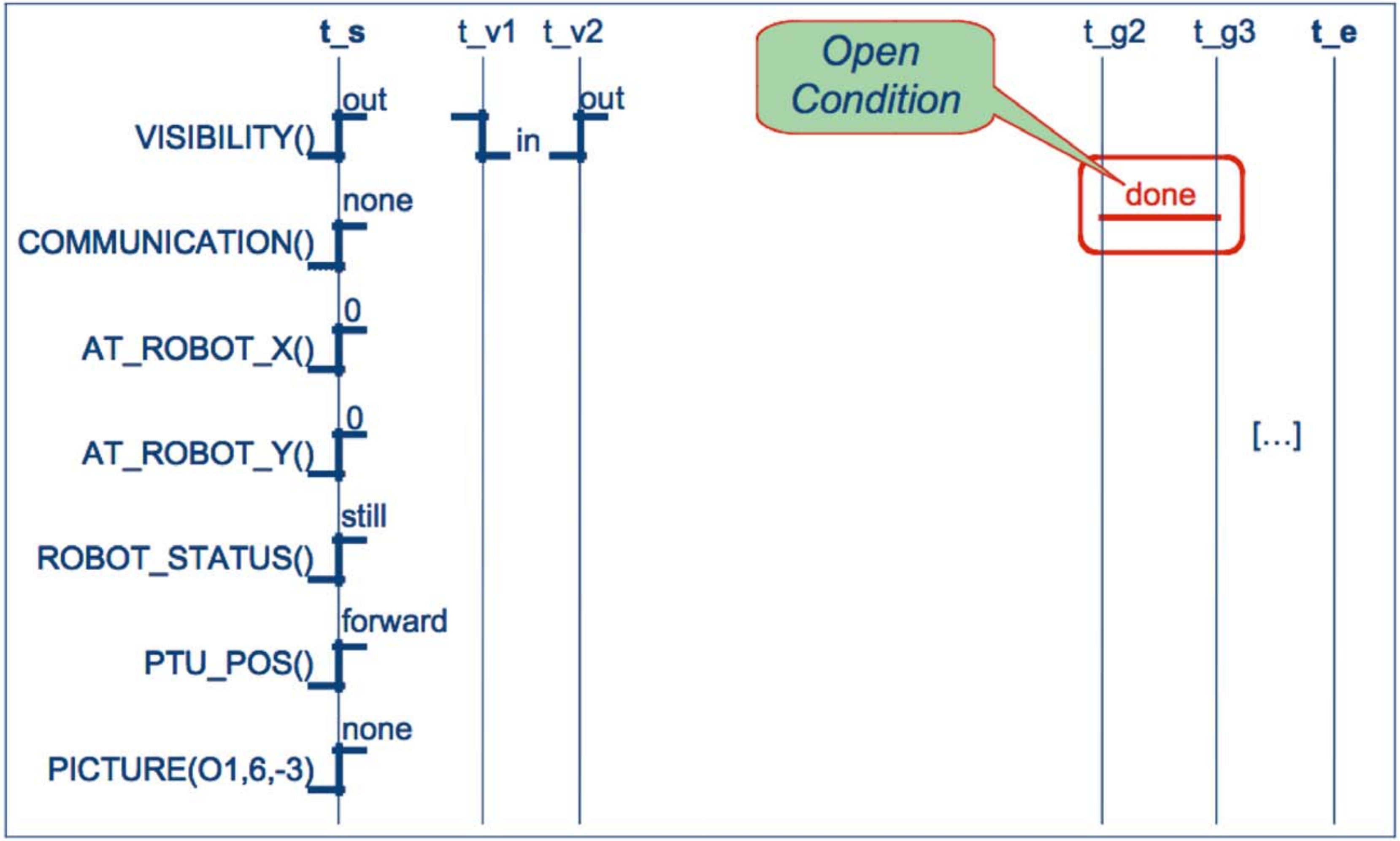
POCL (Partial Order Causal Link) planning



- **A planning step**
  - **Analyze** ⇒ flaws + resolvers
    - Open Conditions
      - Establishing event + causal link
    - Threats
      - Precedence constraint or variable binding
    - Resource Conflicts
      - Precedence constraint or action insertion
  - **Flaw selection**
    - Abstraction hierarchy
    - Least commitment
  - **Resolver selection**
    - A_ε algorithm or Ordered Depth-first search
  - **Resolver insertion**

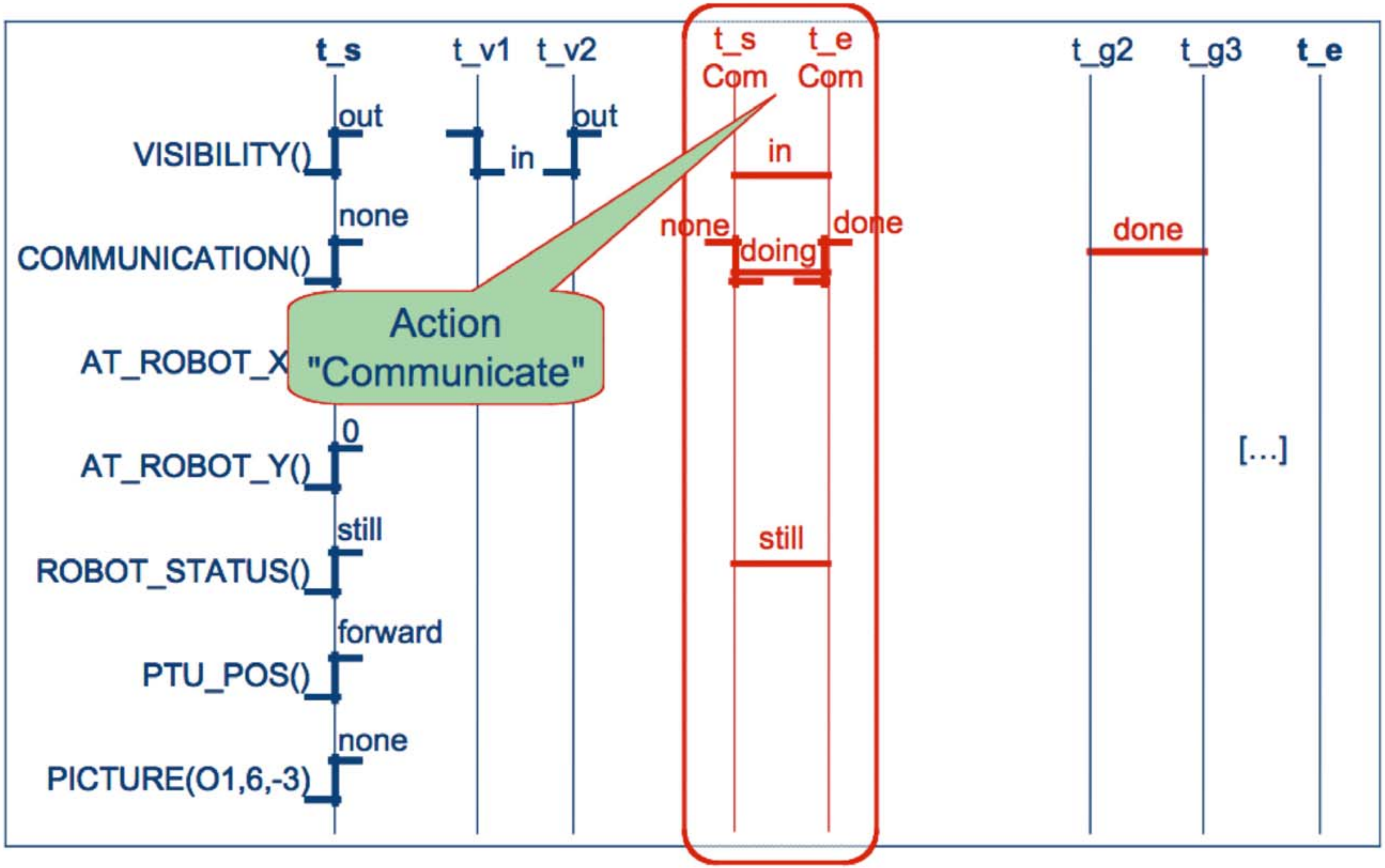
The IxTeT Temporal Planner

POCL (Partial Order Causal Link) planning



The IxTeT Temporal Planner

POCL (Partial Order Causal Link) planning



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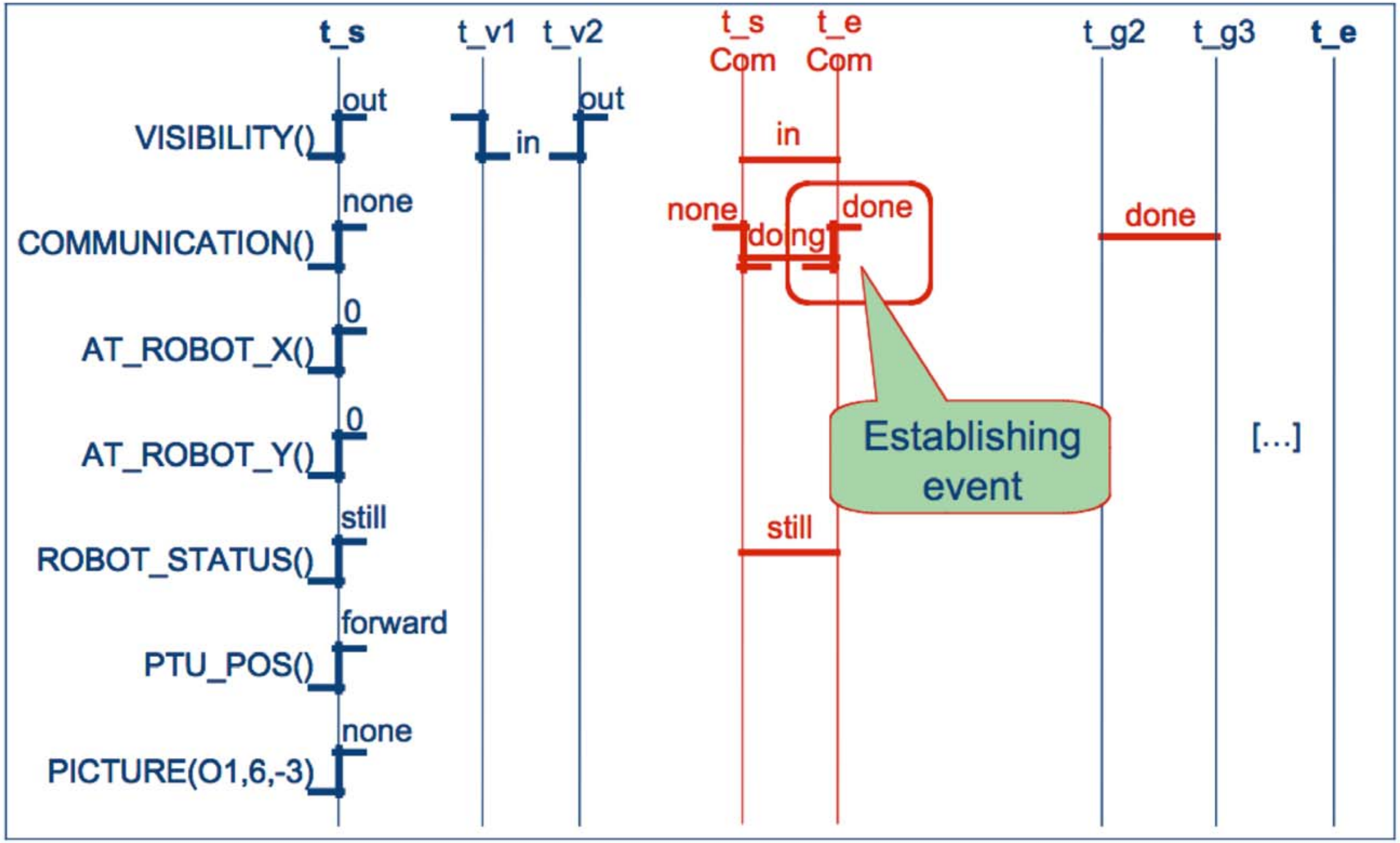

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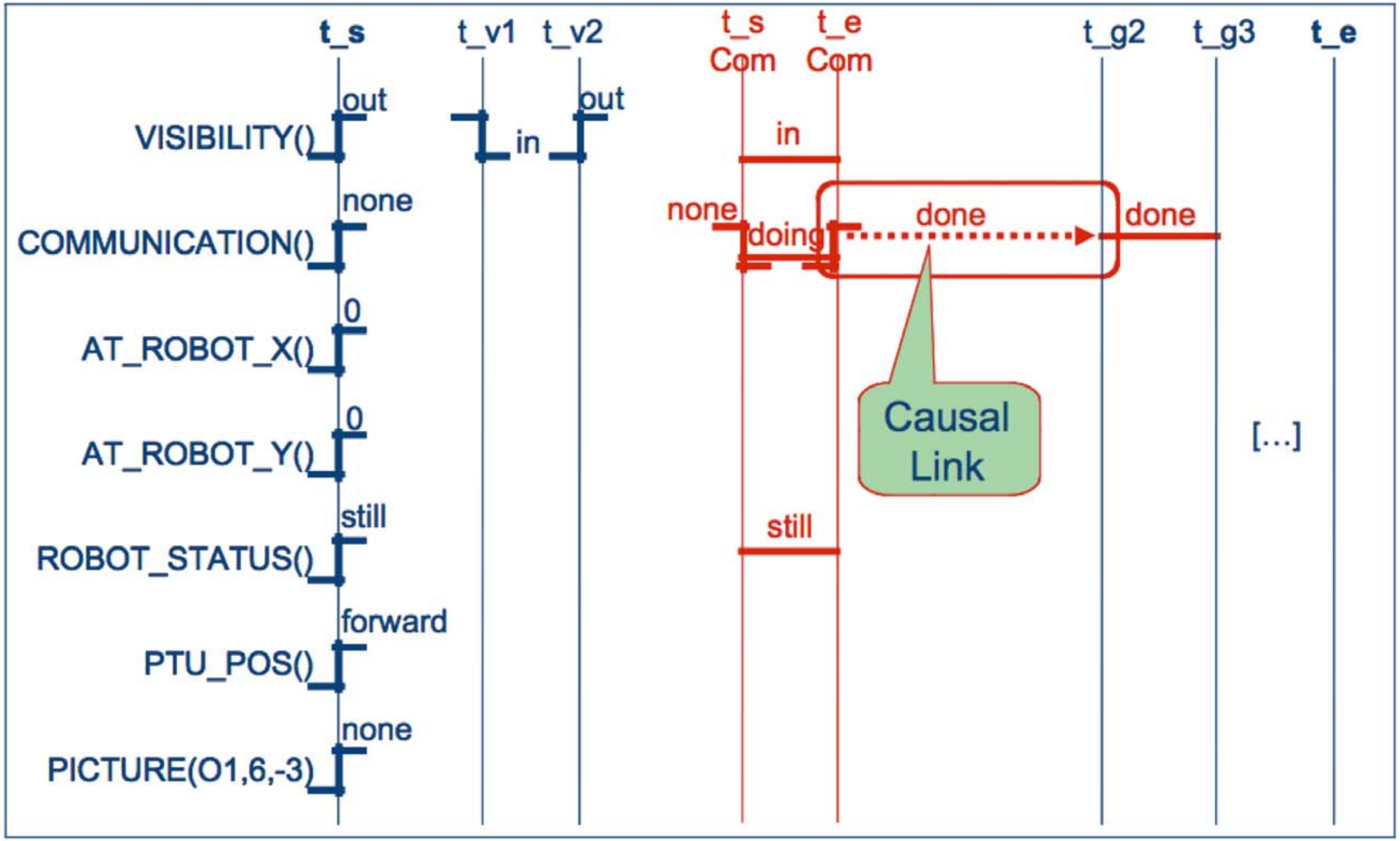

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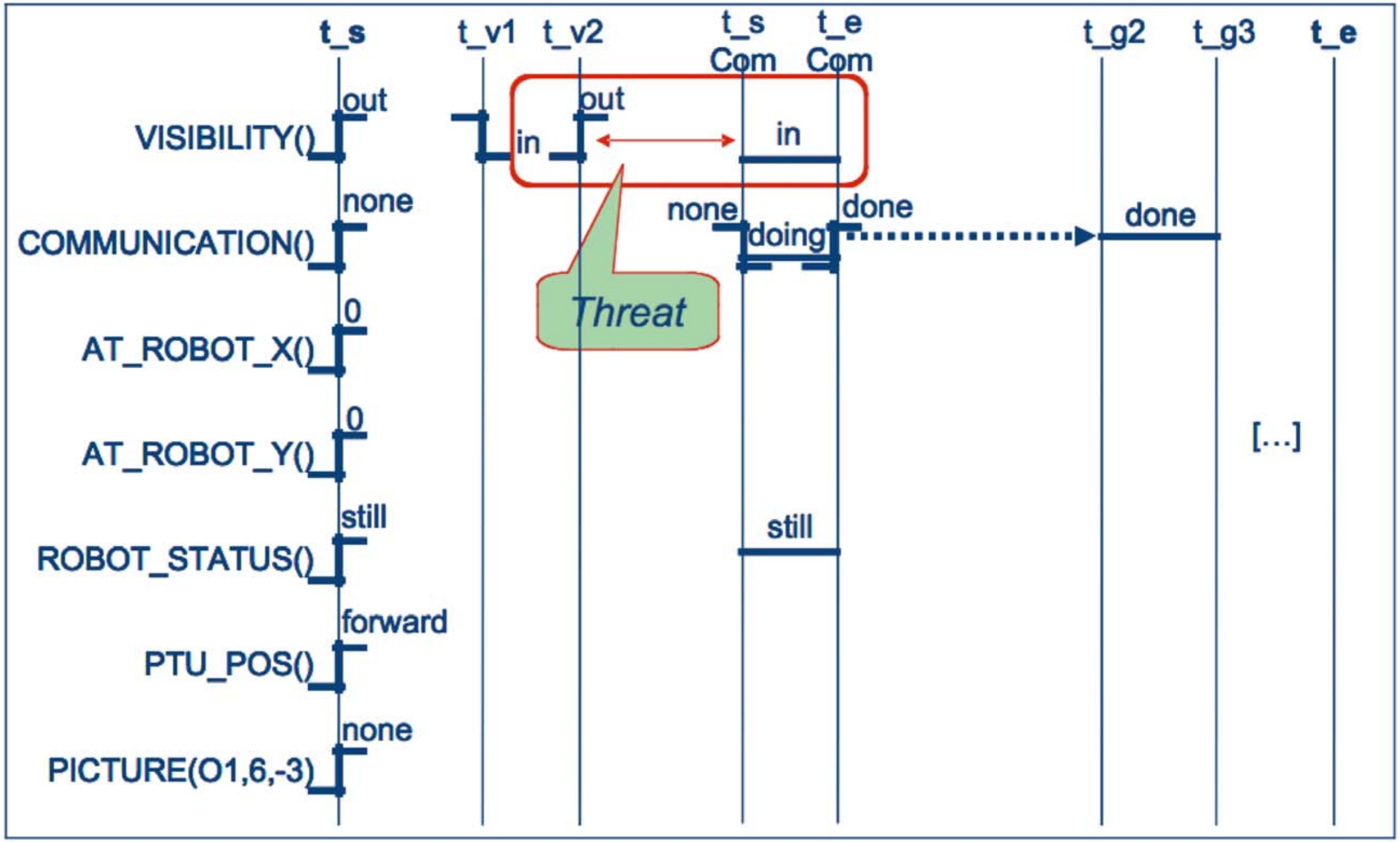

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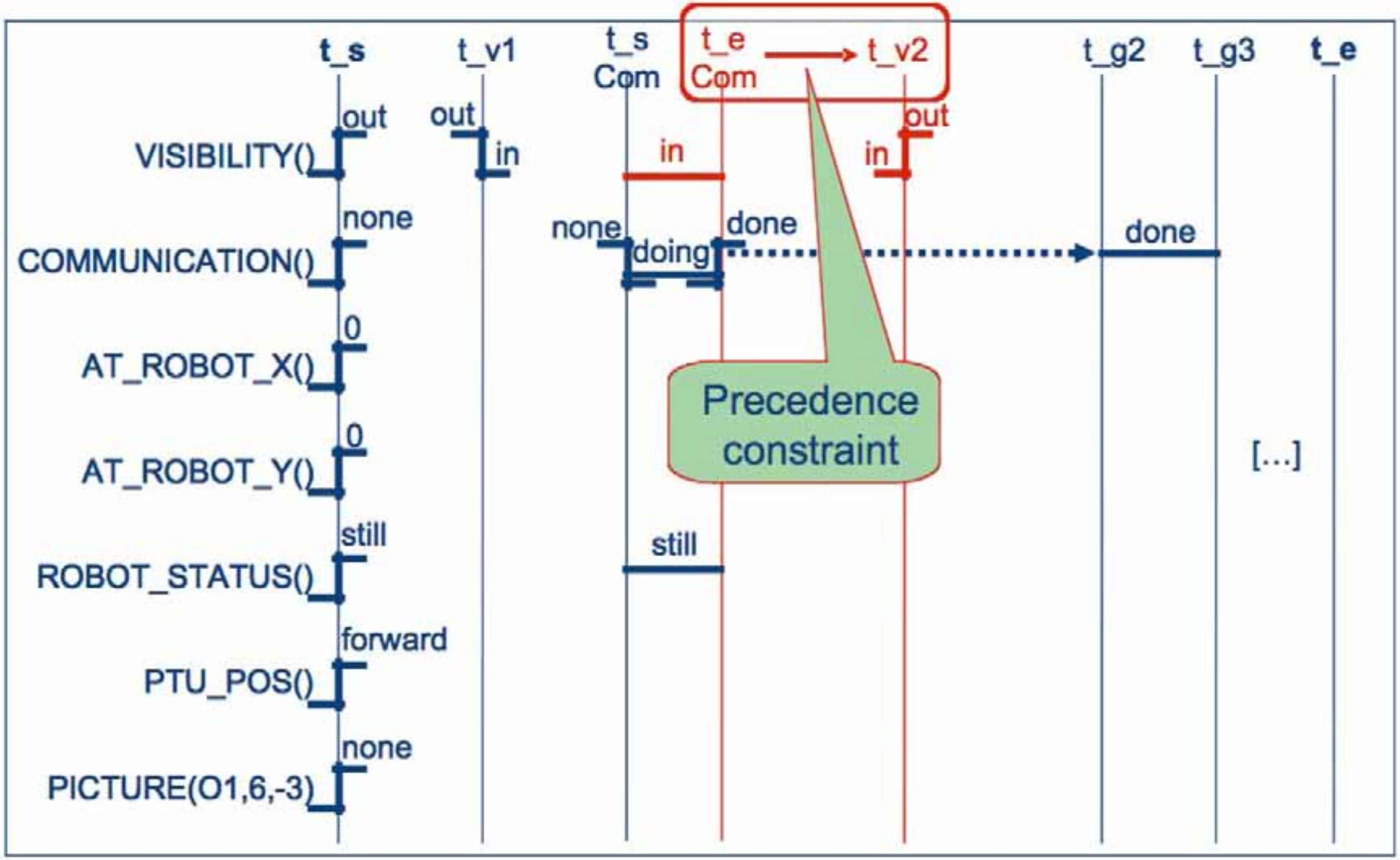
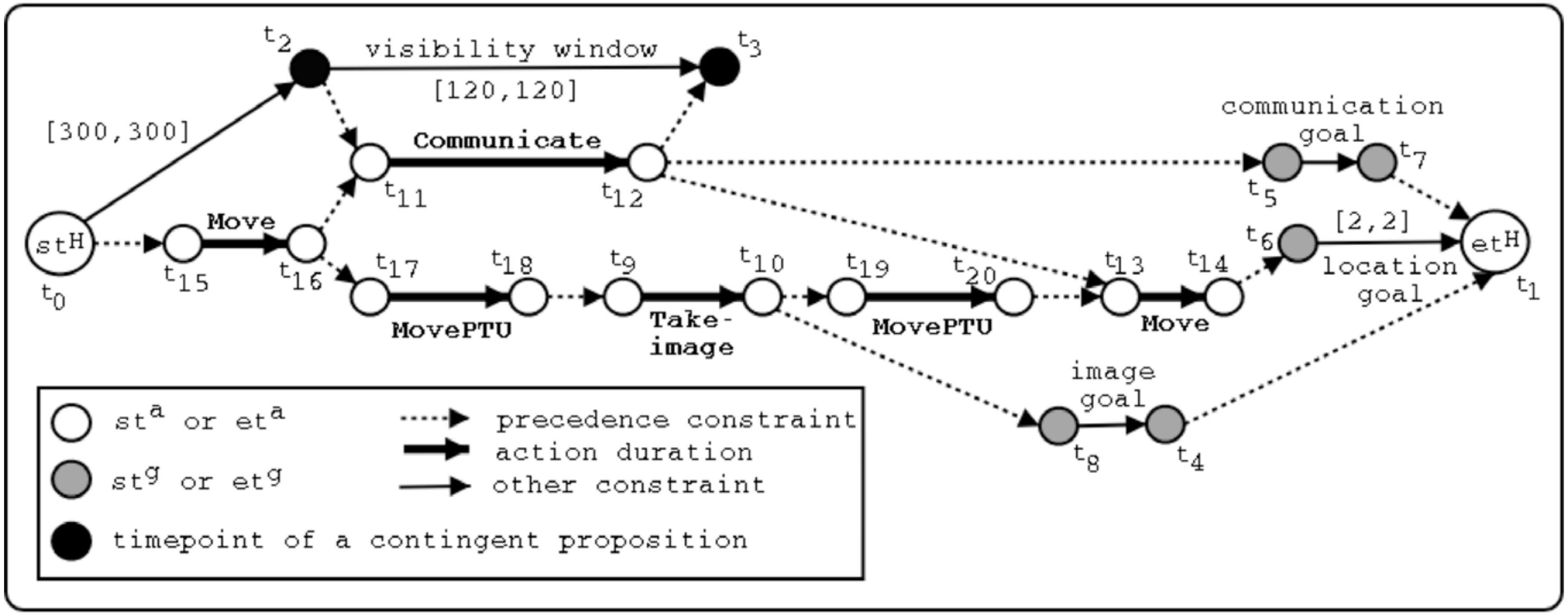


The IxTeT Temporal Planner

Plan database: temporal constraint network



- Execution interval of timepoint T: (T-st^H) in [T_{lb},T_{ub}]
- Start / stop / monitor action execution according to type
- Actual occurrence times propagated to update network

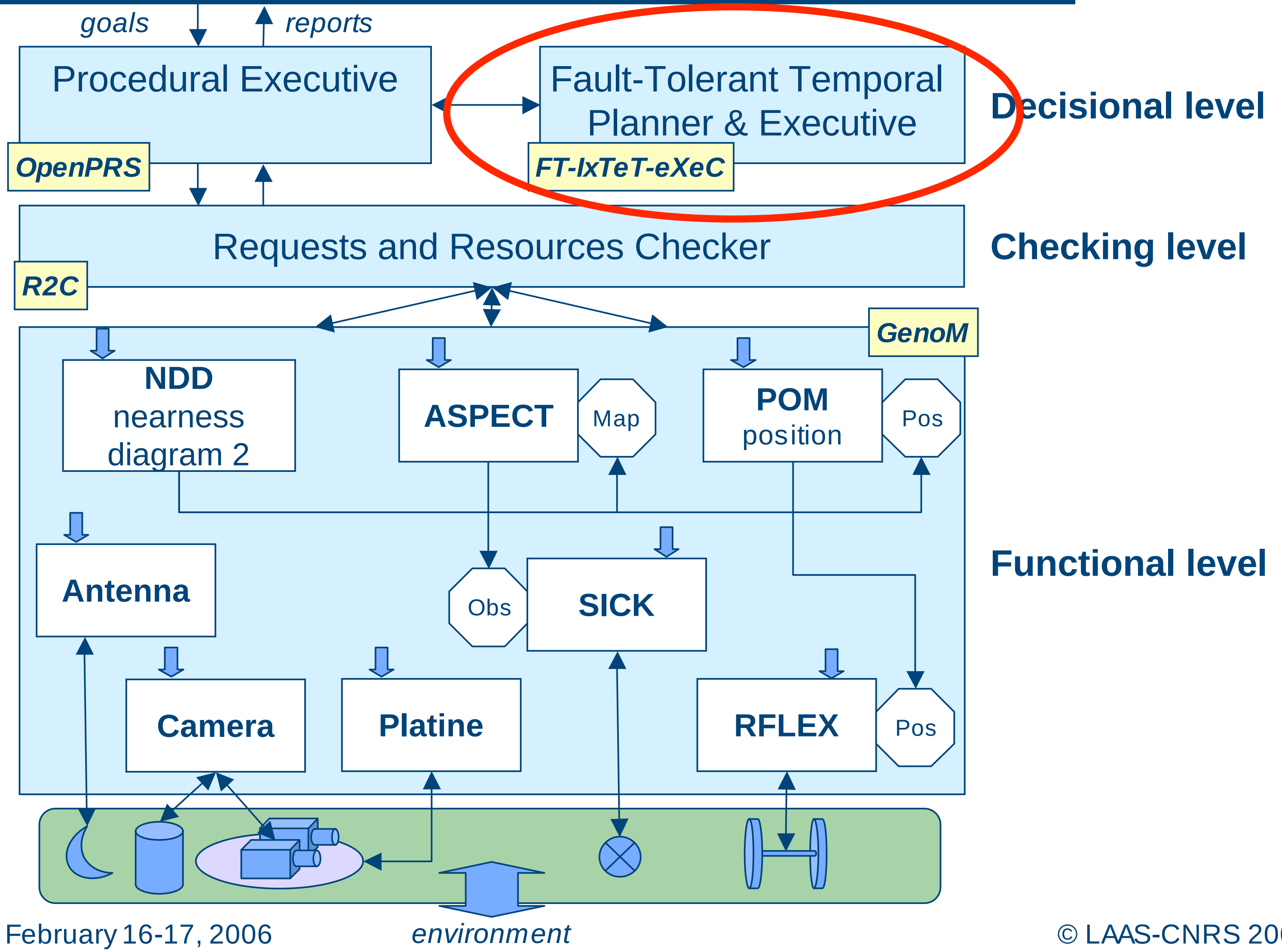
The IxTeT Temporal Planner

Non-nominal situations and new goals

- Adaptation of current plan is required in the following cases:
  - Early or late timing failure of a timepoint occurrence
  - Resource conflict occurs (under/over consumption/production, or detected device failure)
  - Action failure is reported from controlled system
  - New goal is requested
- Adaptation can be of two types:
  - **Plan repair**: planner applies flaw analysis / resolver insertion process to partially invalidated plan, while execution of valid part of plan continues in parallel
  - **Replanning**: start all over from current system state and remaining goals

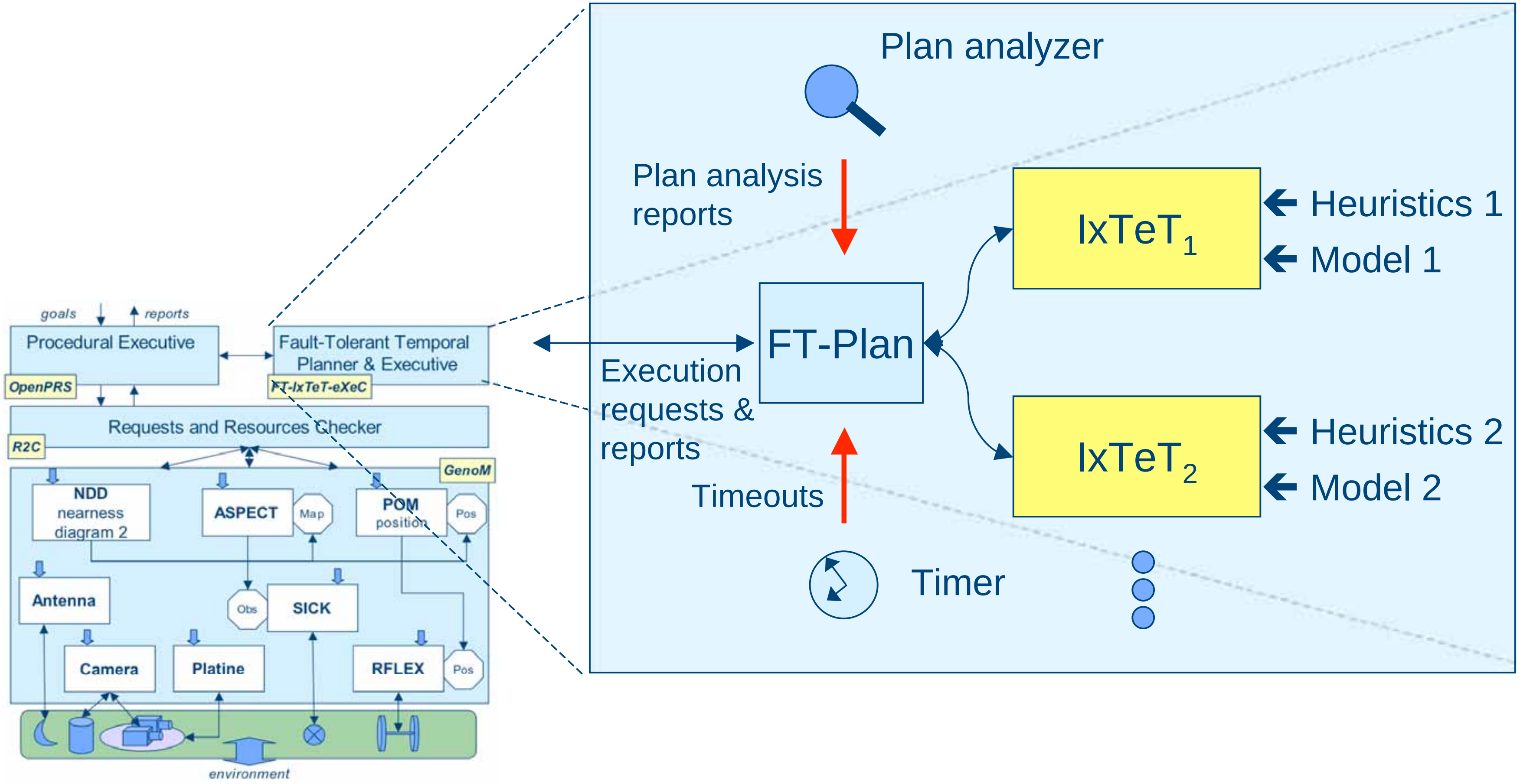
Tolerating Planner Faults

A fault-tolerant IxTeT temporal planner?



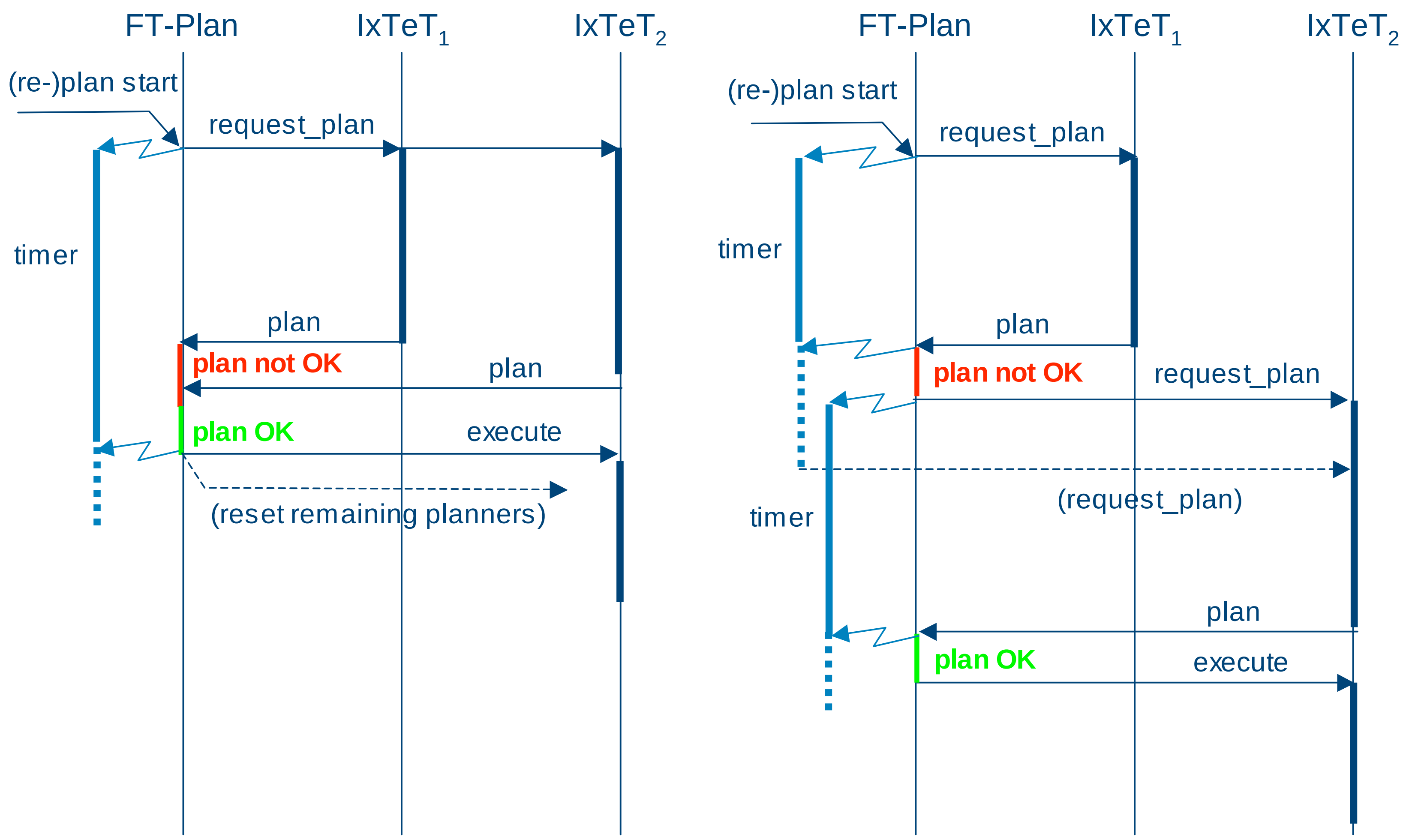
Tolerating Planner Faults

A fault-tolerant IxTeT temporal planner ➔ diversity



Tolerating Planner Faults

Parallel or sequential redundant planners



Tolerating Planner Faults

Parallel redundant planner coordination

```
begin mission
    while(goals≠∅)
        candidates ← planners ;
        send(request_plan) to candidates ; set_timer(max_planning_time) ;
        while(candidates ≠∅)
            wait
             □ plan from any k ∈ candidates
                candidates ← candidates \ k ;
                if analysis(plan)=OK then do
                    send(reset) to candidates ; candidates ← ∅ ;
                    reset_timer(max_planning_time) ;
                    send(execute(plan)) to k ; enddo ;
                    % abnormal termination implies goals≠∅ %
                else do report(k,"invalid plan") ;
                    if candidates = ∅ exception("failure: no valid plan found") ; enddo
             □ timeout(max_planning_time)
                exception("failure: timeout")
        endwhile
    endwhile
end mission
```

Tolerating Planner Faults

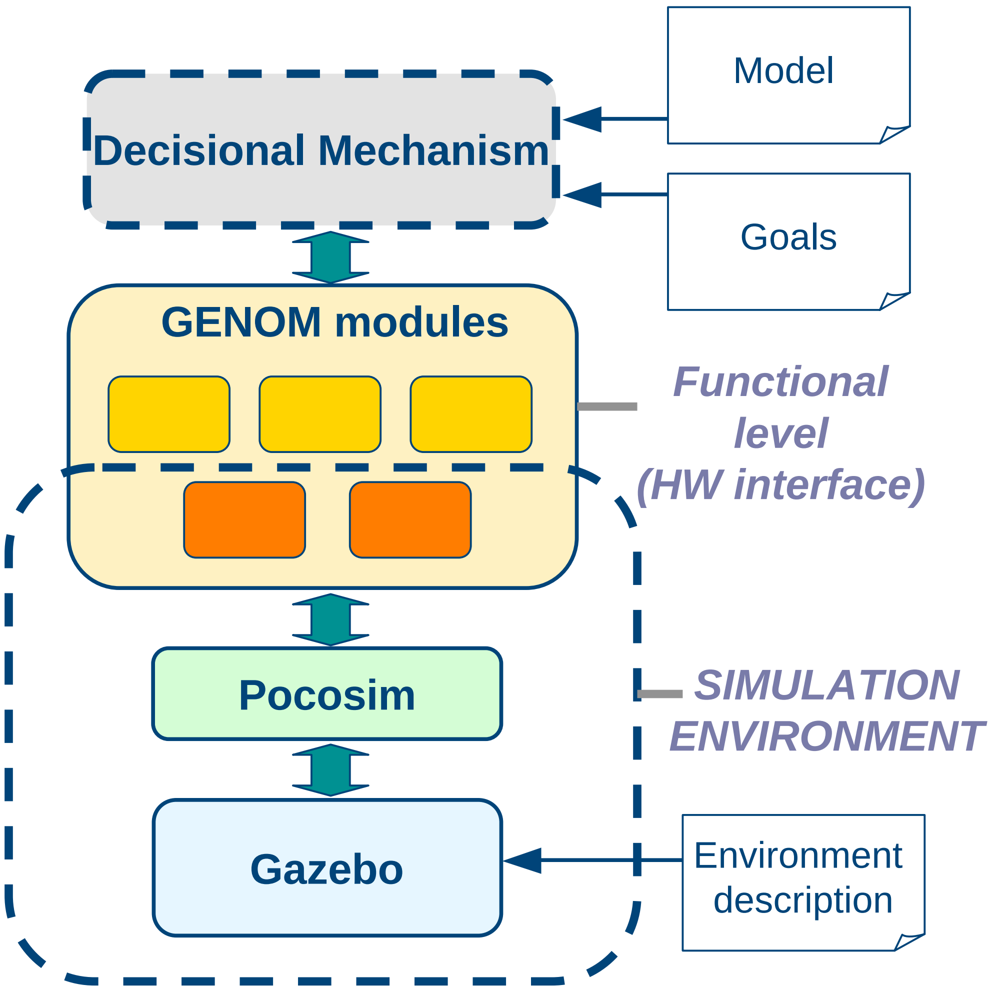
Sequential redundant planner coordination

```
begin mission
    while(goals≠∅)
        candidates ← planners ;
        while(candidates ≠∅)
            choose k ∈ candidates ; % optionally take account of recent failure history %
            candidates ← candidates \ k ;
            send(request_plan) to k ; set_timer(max_planning_time) ;
            wait
            ☐ plan from k
                reset_timer(max_planning_time) ;
                if analysis(plan)=OK then do send(execute(plan)) to k ; enddo
                    % abnormal termination implies goals≠∅ %
                else do report(k,"invalid plan") ;
                    if candidates = ∅ exception("failure: no valid plan found") ;
                    enddo
            ☐ timeout(max_planning_time)
                report(k,"timeout") ;
                if candidates = ∅ exception("failure: no valid plan found") ;
        endwhile
    endwhile
end mission
```

Experimentation Framework

Fault injection and simulation environment

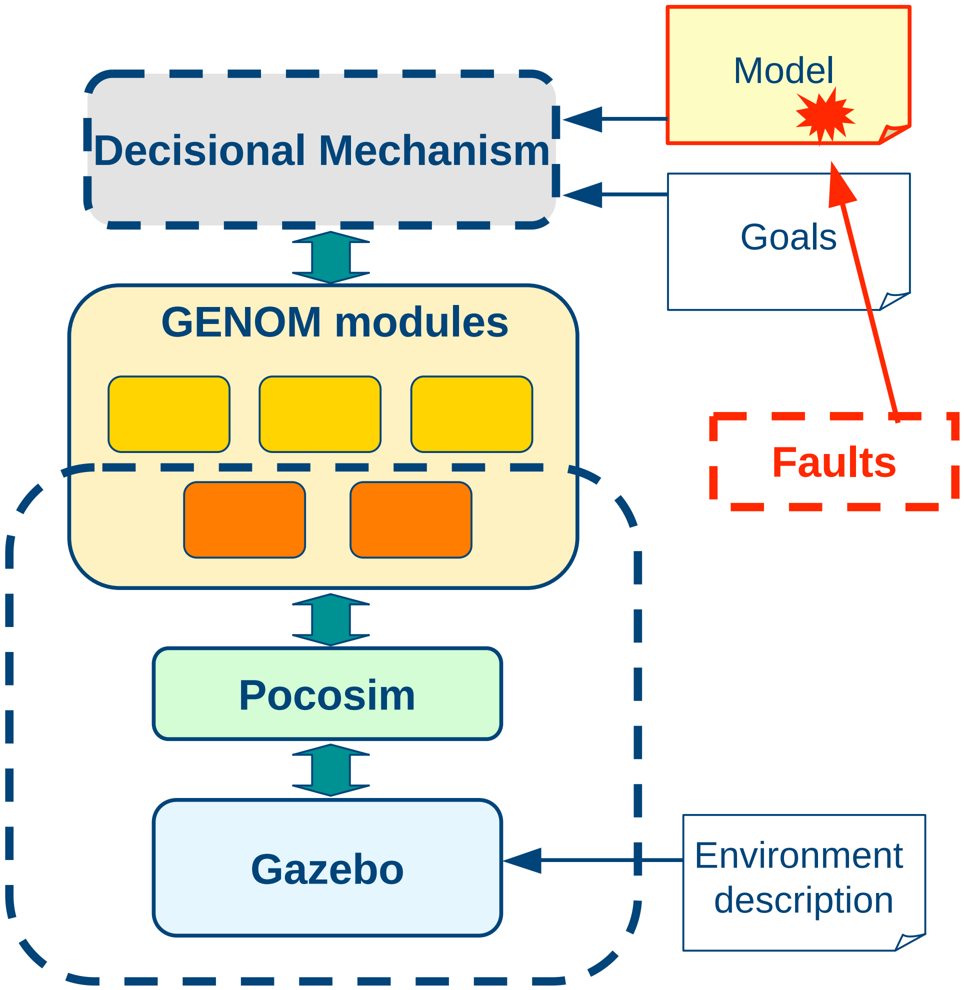
- Why fault injection?
  - To evaluate fault tolerance, we need faults
  - Fault injection simulates efficiently real software faults
- Why simulation?
  - Large number of experiments required for significant evaluation
  - Hazardous behavior of the system during experiments



Experimentation Framework

FARM attributes of fault injection campaign

- Faultload
  - **The faults to be injected**
  - **In our case:** *development faults affecting IxTeT models*
- Activity
- Readouts
- Measures



Experimentation Framework

FARM attributes of fault injection campaign

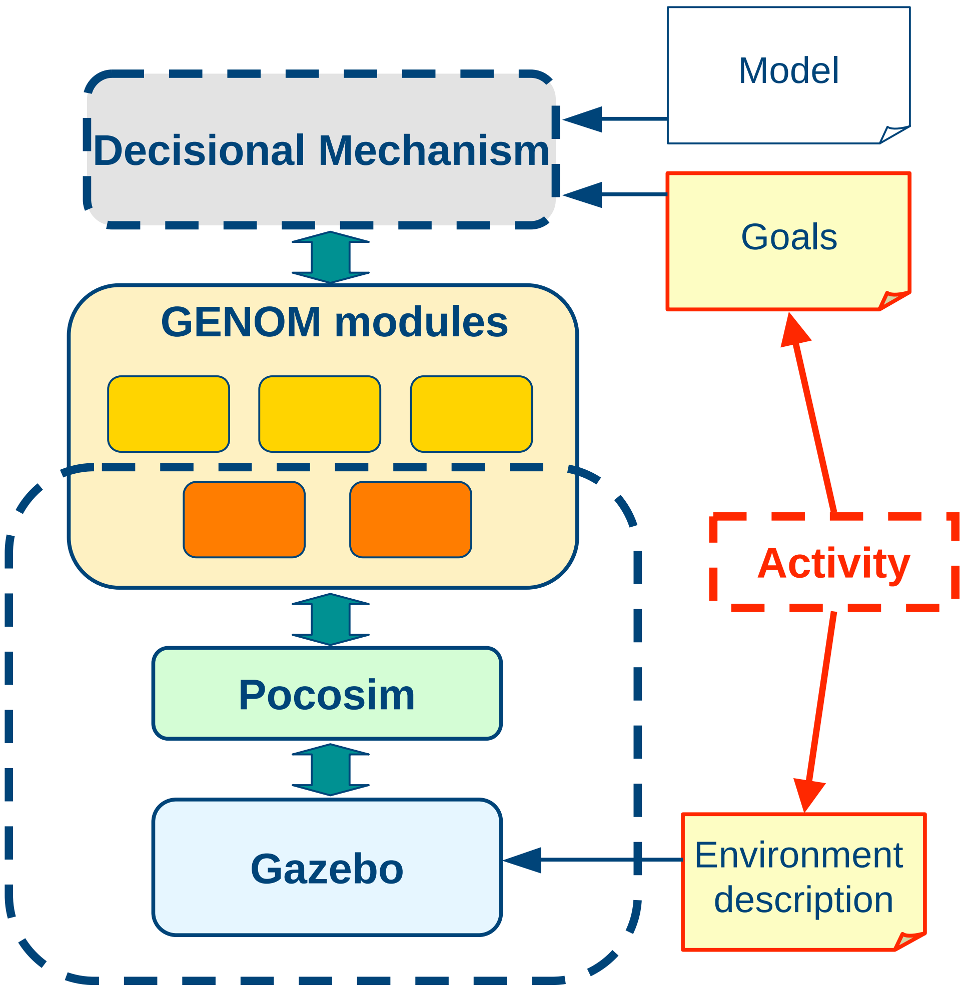
- Syntactic mutations using SESAME tool
  - constant and range substitutions, e.g.
    - {"-oo", "+oo", "0.0", "0.5", "1", "1.4", "1.5", "2", "4", "6", "10", "15", "18", "25", "35", "40", "100", "1000", "0.0-10.0", "0.0-4.0", "9", "100"}
    - {"PICTURE_IDLE", "NONE", "DONE", "COMMUNICATION_IDLE"}
  - variable substitutions, e.g.
    - {"?initpos", "?finpos}"
    - {"?x," "?y", "?obj"}
  - operator substitutions, e.g.
    - {"explained", "contingent")
    - ("nonPreemptive", "latePreemptive", "earlyPreemptive"}
- Addition / removal of a model statement, i.e., a constraint

➔ Database of compilable mutations

Experimentation Framework

FARM attributes of fault injection campaign

- Faultload
- Activity
  - The workload executed by the robot during an experiment
    - Goals
    - Environment
- Readouts
- Measures



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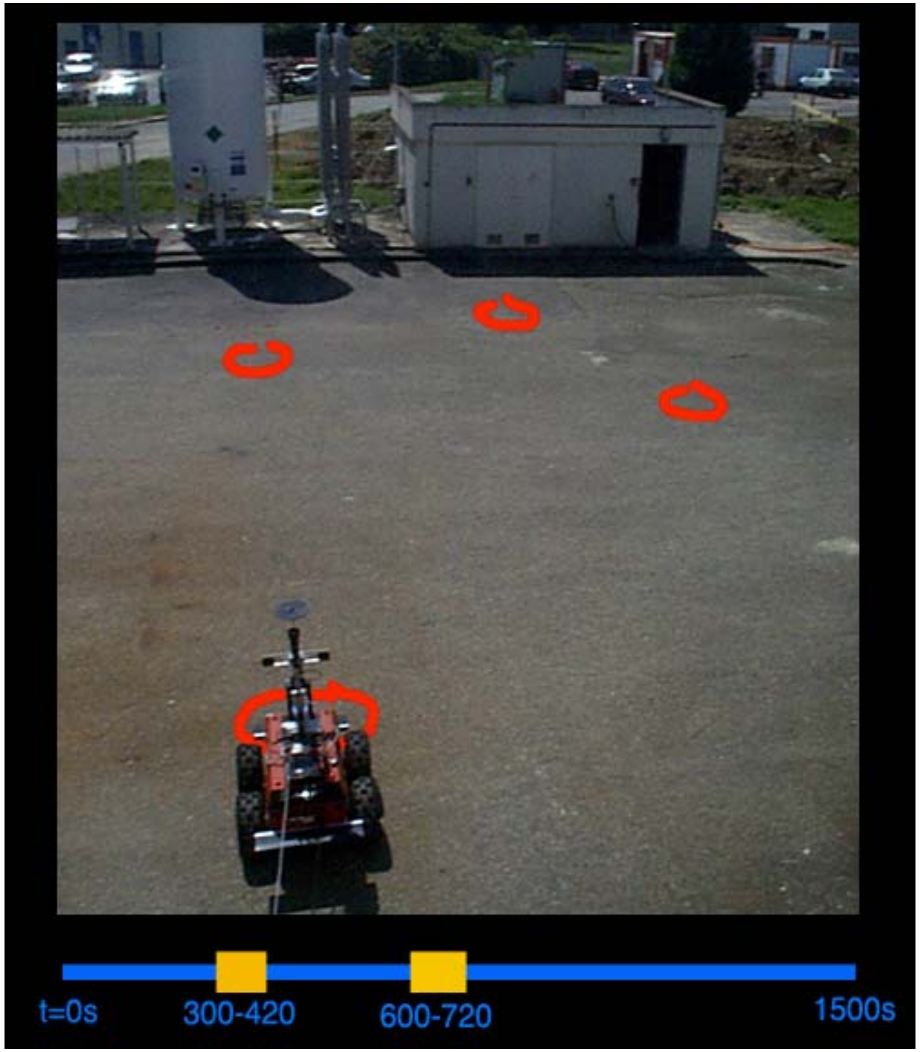
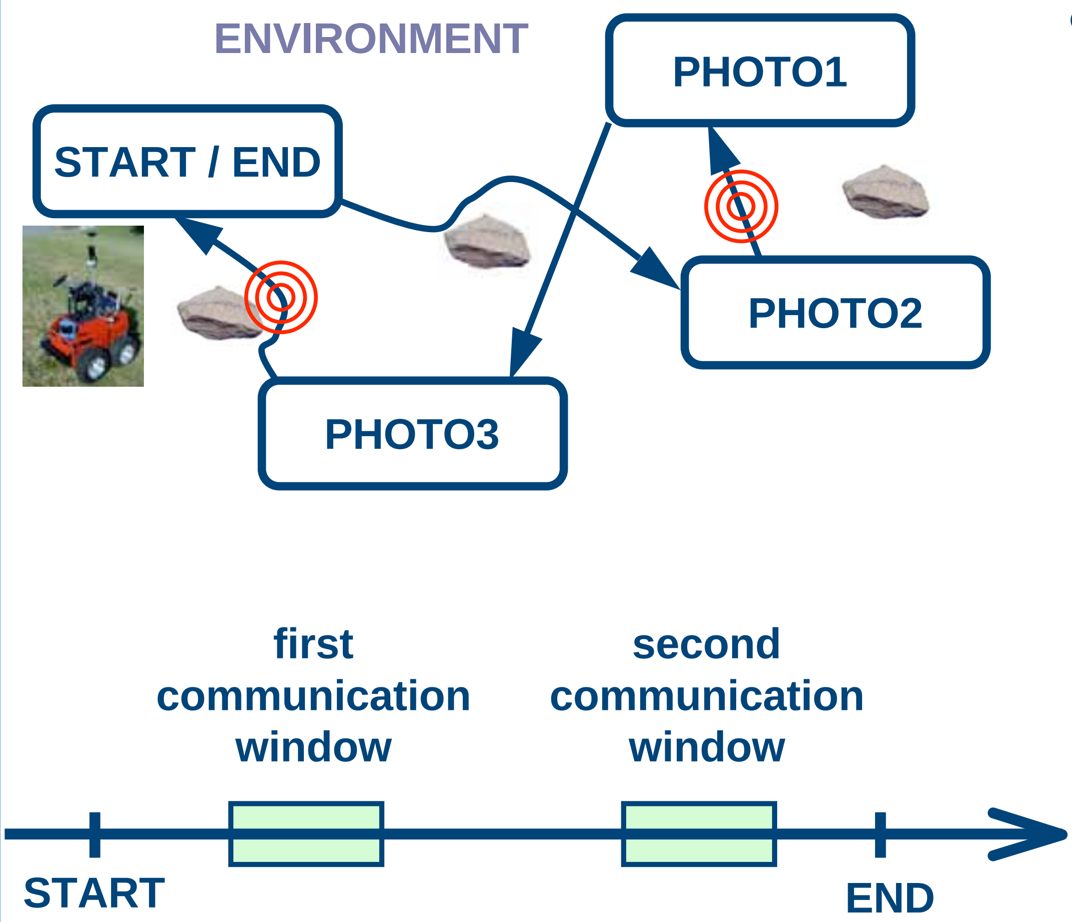


Experimentation Framework

FARM attributes of fault injection campaign

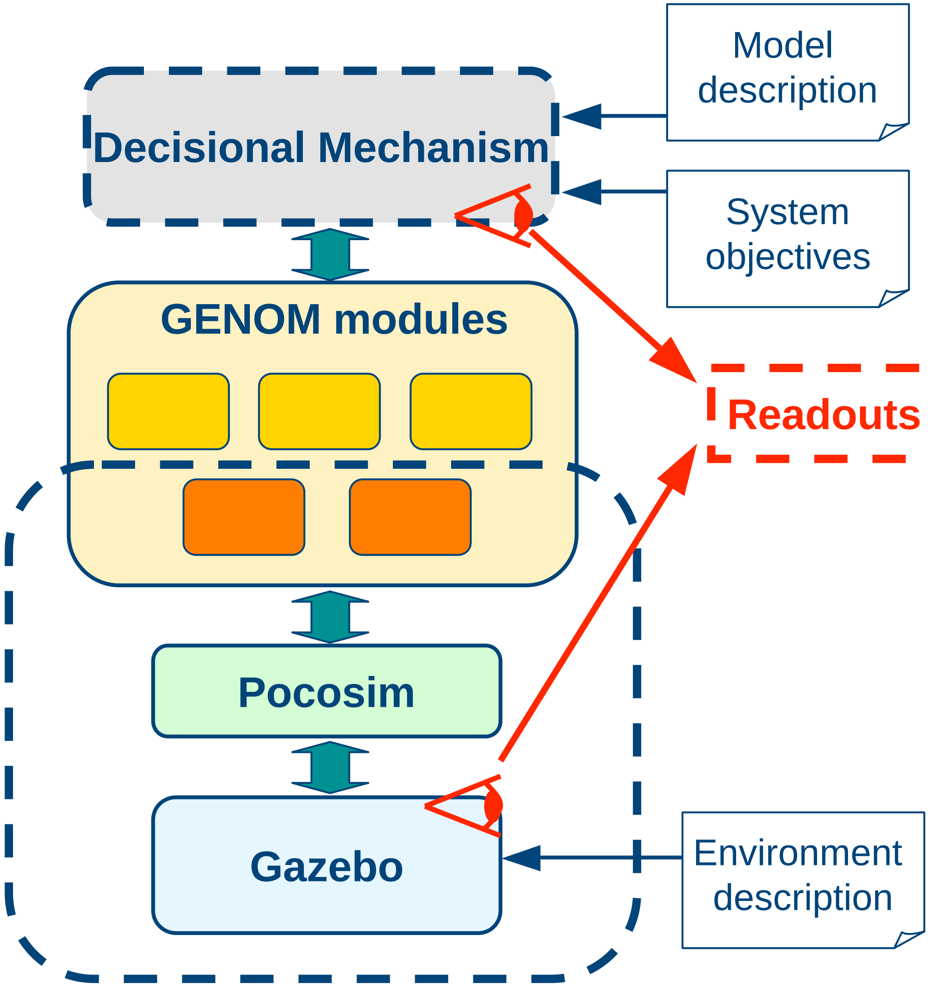


- Activity definition variables
  - Physical dimension
    - Number and location of photos to be taken
    - Topology of the environment
  - Temporal dimension
    - Number and occurrence times of communication windows

Experimentation Framework

FARM attributes of fault injection campaign

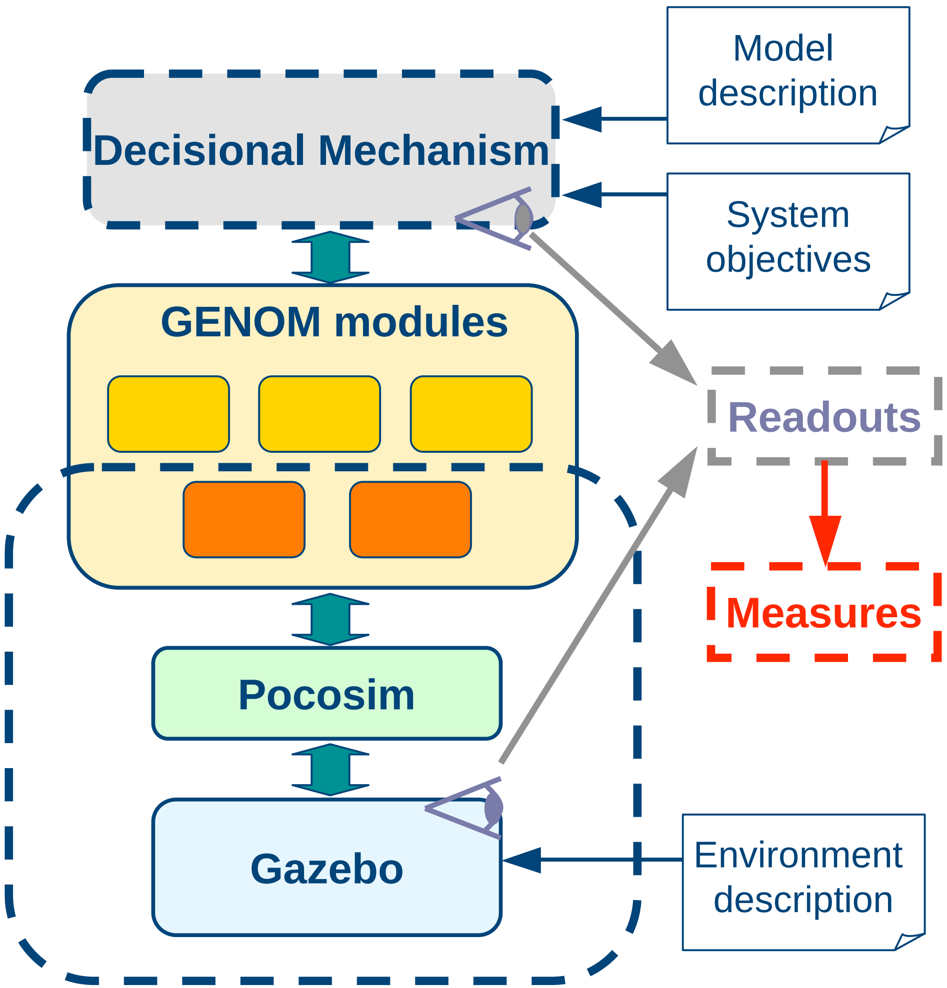
- Faultload
- Activity
- Readouts
  - Observations during one experiment
  - Fault outcome
    - Activated?
    - Error detected?
  - System behavior
    - Goals achieved?
    - Performance?
- Measures



Experimentation Framework

FARM attributes of fault injection campaign

- Faultload
- Activity
- Readouts
- Measures
  - Statistics on set of readouts
  - Dependability-specific
    - Coverage
    - Detection latency
  - Performance
    - Goals achieved
    - Distance and time required



Preliminary results

Baseline configuration: no redundancy

ID	mutation		readouts	possible explanation
	before	after		
3-041	?x in]**-oo**,+oo[;	?x in]**9**,+oo[;	ixtet crash	conflicting constraints for ?x
3-416	?dist =. ?di *. **?du**;	?dist =. ?di *. **?y2**;	ixtet crash	conflicting constraints for ?dist
3-472	**?duration** in]1.5, +oo[;	**?y2** in]1.5, +oo[;	ixtet crash	conflicting constraints for ?y2
1-296	**?Xc** =. _xi -. _xf;\	**_d** =. _xi -. _xf;\	ixtet crash	conflicting constraints for _d
3-525	event(COMMUNICATION(?w):(COMMUNICATION_IDLE,**DONE**),t_end);	event(COMMUNICATION(?w):(COMMUNICATION_IDLE,**COMMUNICATION_IDLE**),t_end);	ixtet hang timeout	ixtet compilation bug
2-162	explained event(AT_ROBOT_X() : (1.0, **0.0**), t_start);	explained event(AT_ROBOT_X() : (1.0, **10.0**), t_start);	ixtet hang timeout	ixtet execution bug
3-110	?mindist =. **0.5**;	?mindist =. **6**;	ixtet search timeout	model overconstrained, thus no solutions found
3-128	?minduration =. **1.4**;	?minduration =. **15**;	ixtet search timeout	model overconstrained, thus no solutions found
3-540	hold(PTU_DRIVER_INITIALIZED():**TRUE**,(t_start,t_end));	hold(PTU_DRIVER_INITIALIZED():**PTU_DRIVER_INITIALIZED_IDLE**,(t_start,t_end));	ixtet search timeout	a necessary condition becomes impossible to achieve as no other action can act as a resolver

Preliminary results

Baseline configuration: no redundancy

ID	mutation		readouts	possible explanation
	before	after		
3-139	?duration in]**1.5**, +oo[;	?duration in]**-oo**, +oo[;	(3, 2, 1, 14.0, 254)	one constraint was relaxed, but no incidence on plan
1-344	_u in [**0.7**,1]	_u in [**0.17**,1]	(3, 2, 1, 14.0, 254)	one constraint was relaxed, but no incidence on plan
3-418	?dist =. ?di *. **?du**;	?dist =. ?di *. **?di**;	(3, 2, 1, 19.0, 320)	wrong distance leads to bad performance, but all goals fulfilled
3-277	**?dist =. ?di *.** ?du;	**?dist =. ?di +.** ?du;	(2, 1, 1, 19.2, 353)	wrong distance leads to missed goals
2-050	explained event (COMMUNICATION(W1) : (COMMUNICATION_IDLE, **NONE**), t_start);	explained event (COMMUNICATION(W1) : (COMMUNICATION_IDLE, **DONE**), t_start);	(3, 1, 1, 14.1, 255)	one communication explained as DONE in the initial situation, thus goal not fulfilled
3-559	}**latePreemptive**	}**nonPreemptive**	(2, 0, 1, 19.1, 155)	action MOVE can no longer be interrupted, thus execution is quicker but some goals are missed

(image, communicate, location, distance, duration)

goals performance

Conclusion

Very preliminary results

- First mutation experiments on declarative models
- Tuning such models is a “black art”
  - easy to get wrong in subtle ways
  - tolerance of subtle faults might indeed be useful
- 15 mutations to date
  - 13% of mutations had no effect (all goals met)
  - 27% of mutations resulted in sub-optimal mission
    - goals missed
    - degraded performance
  - 60% of mutations resulted in crashes/hangs/timeouts
    - easy to detect

Conclusion

Current and future work

- Fault injection process
  - currently being automated
  - random goal selection
  - “difficult” environments
  - multiple parallel simulations (~10 minutes / experiment)
- Implementation of FT-Plan with dual IxTeTs
  - diverse search heuristics
    - parameters of depth-first search cost functions
    - …
  - diverse models
    - cellular model
    - state mapping between models based on different abstractions?
    - …
  - definition of a plan analyzer (on-line test oracle)