# Timeline-based planning: Theory and Practice

## Dottorato in Informatica e Scienze Matematiche e Fisiche

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# CNR-ISTC description

**Institute for Cognitive Science and Technology @ CNR - National Research Council of Italy**

ISTITUTO DI SCIENZE E TECNOLOGIE DELLA COGNIZIONE

**Our Location:**
Via S. Martino della Battaglia, 44
I-00185 Rome, Italy
http://www.istc.cnr.it/

# CNR-ISTC description (2)

The CNR Institute for Cognitive Science and Technology

- covers research fields related to **human cognition** and **cognitive technologies**
- is the reference institution for **Cognitive Science** in Italy
- is a leading institution for **Artificial Intelligence** research

**Research Areas**

- Psychology and Cognitive Science
- Neuroscience
- **A.I., Robotics, and ICT**

**Excellence in AI Research**

- The institute has three Fellows of EurAI (the European AI Association) on key AI fields (Theory of Multi-Agent Systems, Ontology Foundations, AI Planning)
- A recent ERC winner (the neuroscience basis of human planning)
- … and more …

# PST Research Statement

The Planning and Scheduling Technology Laboratory (PST, http://www.istc.cnr.it/group/pst) is a research group focused on AI research

The group has lines of research for

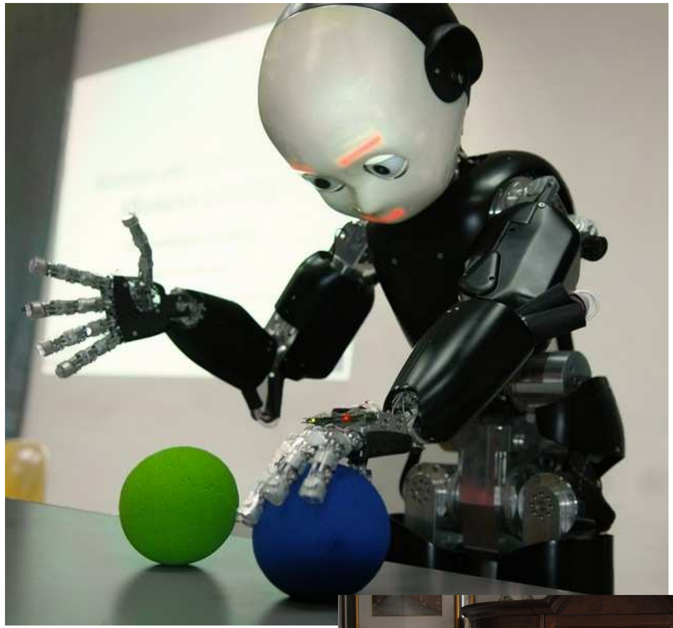
- **Problem solving techniques for complex scheduling problems**
- **Planning, Execution, Validation and Verification techniques**
- **Interactive and User Adaptive Artificial Intelligence**

Constant attention to deploy Intelligent Systems in real environments with human interaction

Main application areas

- Decision support for space (e.g., collaboration with the ESA for more than a decade)
- Ambient Assisted Living – Intelligent software & robots for **supporting elderly people** at home
- **Manufacturing & Robotics** –Factory of the Future

# Robotics @ CNR-ISTC

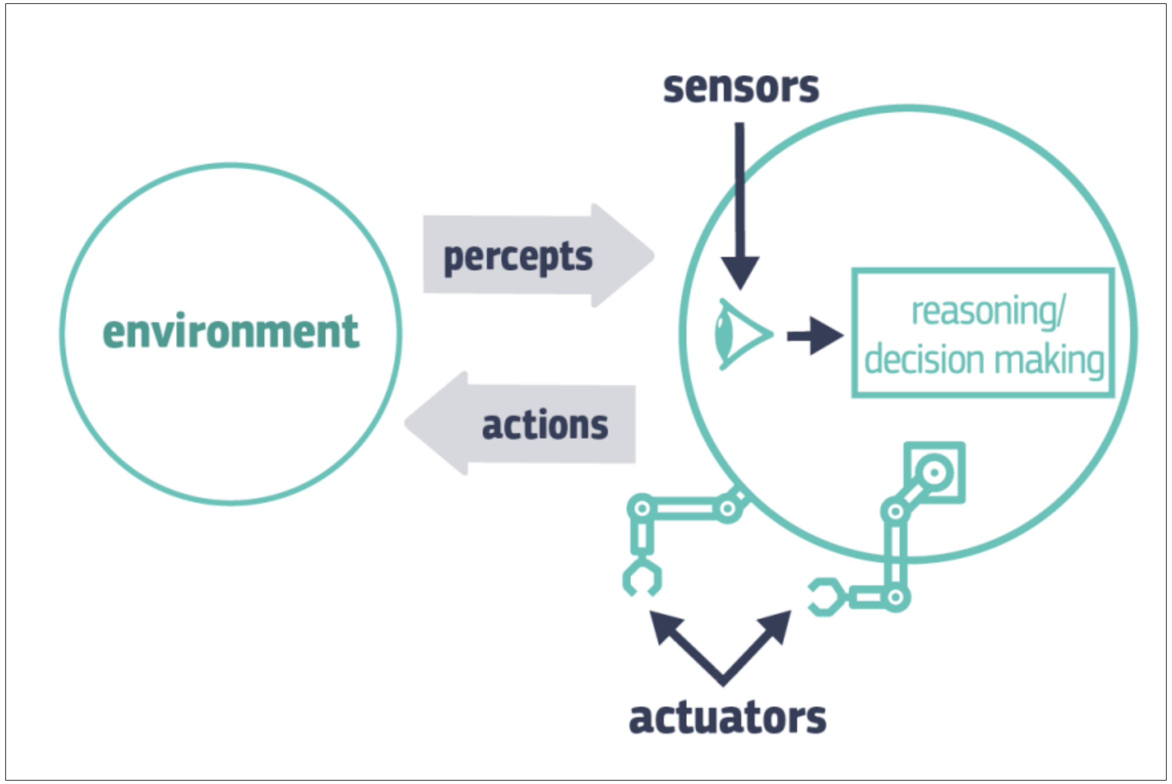


# Artificial Intelligence (AI)

(*) **Artificial intelligence (AI)** refers to systems designed by humans that, given a complex **goal**, act in the **physical or digital world** by **perceiving** their environment, interpreting the collected structured or unstructured data, **reasoning** on the knowledge derived from this data and deciding the best **action(s)** to take (according to pre-defined parameters) to achieve the given goal. **AI systems** can also be designed to **learn** to adapt their behaviour by analysing how the environment is affected by their previous actions…

* High-Level Expert Group on Artificial Intelligence, A definition of AI: Main capabilities and scientific disciplines. European Commission, Directorate-General for Communication, 18 December 2018. https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=56341

# An AI system

*


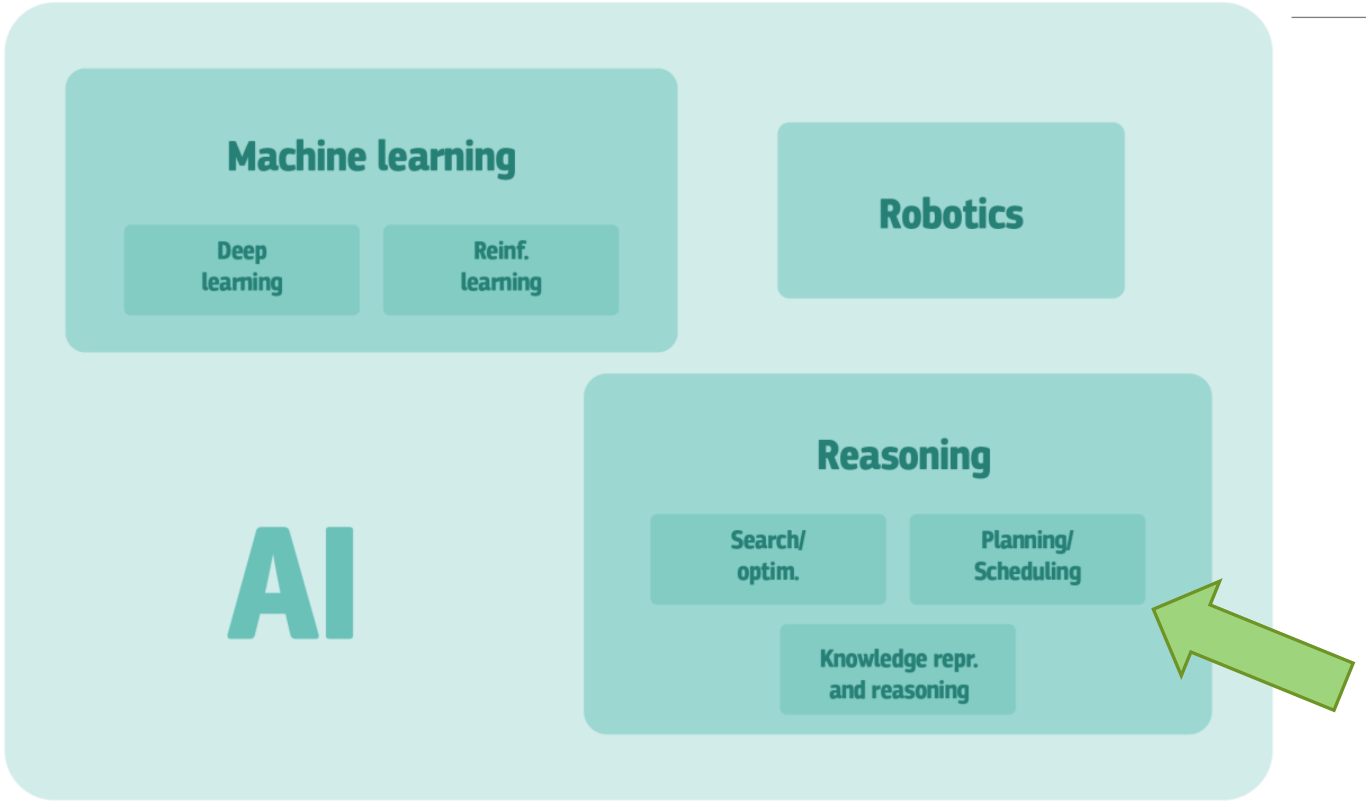

* High-Level Expert Group on Artificial Intelligence, A definition of AI: Main capabilities and scientific disciplines. European Commission, Directorate-General for Communication, 18 December 2018. https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=56341

# AI’s sub-fields (1)

(*) … As a scientific discipline, AI includes several approaches and techniques, such as **machine learning** (of which deep learning and reinforcement learning are specific examples), **machine reasoning** (which includes **planning, scheduling**, knowledge representation and reasoning, search, and optimization), and **robotics** (which includes control, perception, sensors and actuators, as well as the integration of all other techniques into cyber-physical systems).”

* High-Level Expert Group on Artificial Intelligence, A definition of AI: Main capabilities and scientific disciplines. European Commission, Directorate-General for Communication, 18 December 2018. https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=56341

# AI’s sub-fields (2)

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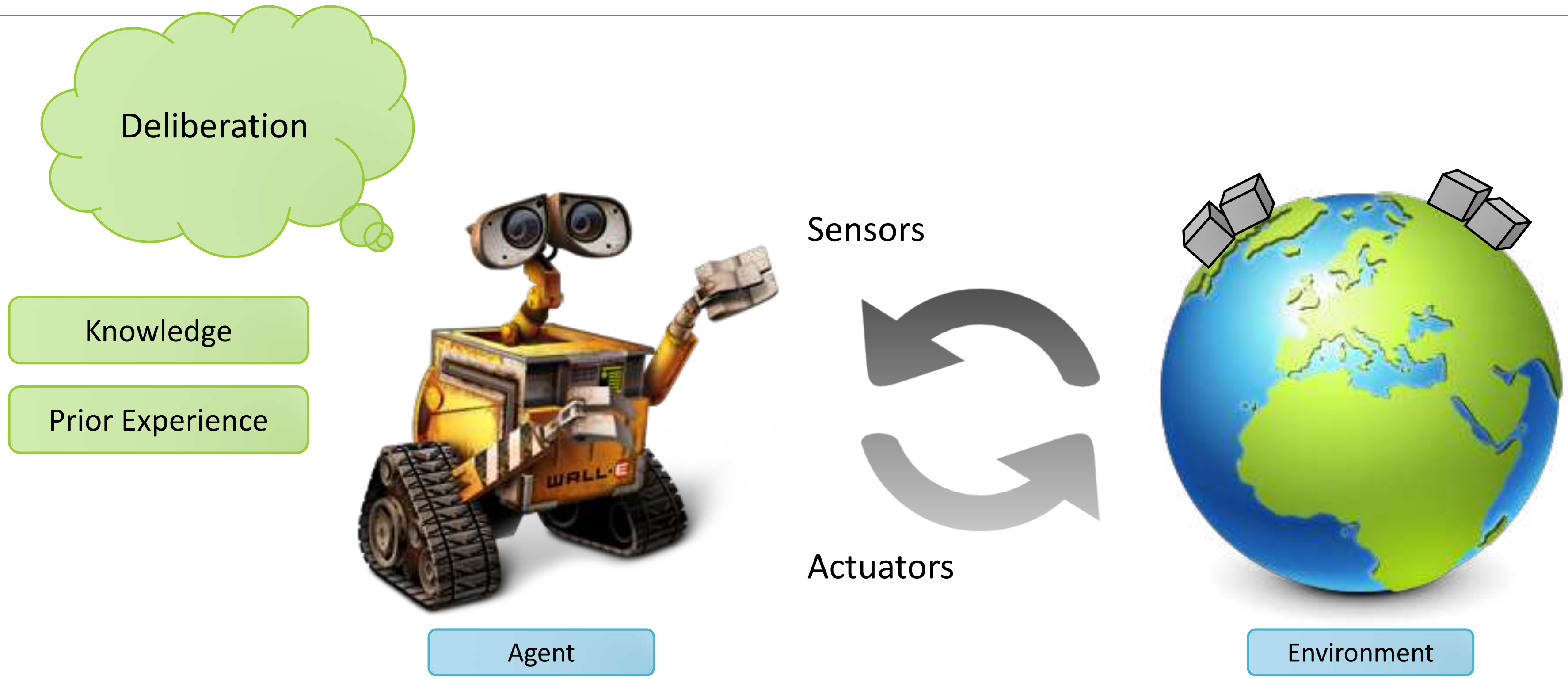
# Planning as a deliberation process

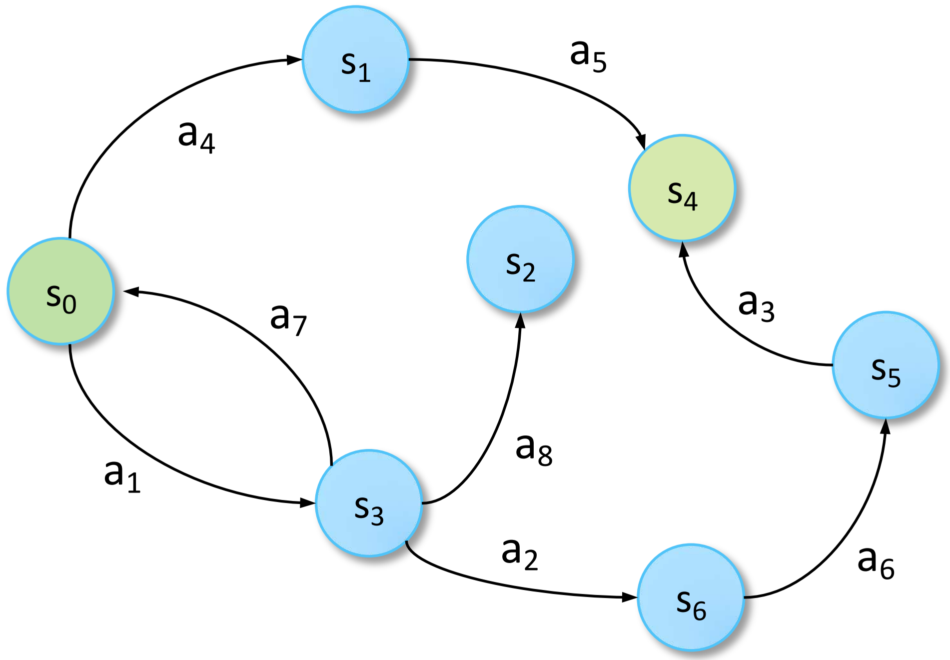



**Planning** consists in deciding which *actions* to undertake and how to perform them to achieve an *objective*
[Automated Planning and Acting, Malik Ghallab, Dana Nau, Paolo Traverso, 2016]

# State model for classical planning

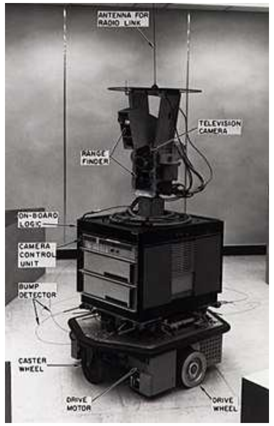
- In order to choose (and, eventually, perform) proper actions motivated by some **objective,** agents need **predictive state models**
  - finite and discrete state space S
  - a known initial state $s_0 \in S$
  - a set $S_G \subseteq S$ of goal states
  - actions $A(s) \subseteq A$ applicable in each $s \in S$
  - a deterministic transition function $s' = f(a, s)$ for $a \in A(s)$
  - positive action costs $c(a, s)$
- A **solution** is a sequence of applicable actions that maps $s_0$ into $S_G$, and it is **optimal** if it minimizes sum of action costs (e.g., # of steps)

Initial state $s_1$, $S_G = \{s_5\}$



# Different approaches to planning

- Domain **dependent** vs domain **independent** approaches
- **States** can be represented in different ways:
  - A combination of propositional symbols (e.g. STRIPS), multi-valued state variables (e.g. SAS+), temporal evolutions of features (e.g. timelines), etc.
- **Objectives** can be represented in different ways:
  - States to be reached, states to go through (e.g. trajectories), states to avoid, tasks to perform (e.g. HTN), etc.
- Implicit Vs. explicit **time**, sequential Vs. concurrent plans
- **Deterministic** vs **nondeterministic** plans
  - actions might fail, unexpected outcomes

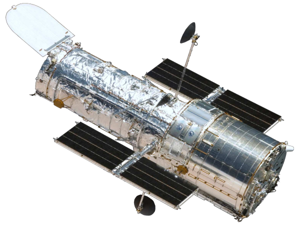



**Classical Planning**

The oldest and most studied approach

Richard E.Fikes, Nils J.Nilsson. **Strips: A new approach to the application of theorem proving to problem solving**. Presented at the 2nd IJCAI, Imperial College, London, England, September 1–3, 1971.

# Different approaches to planning



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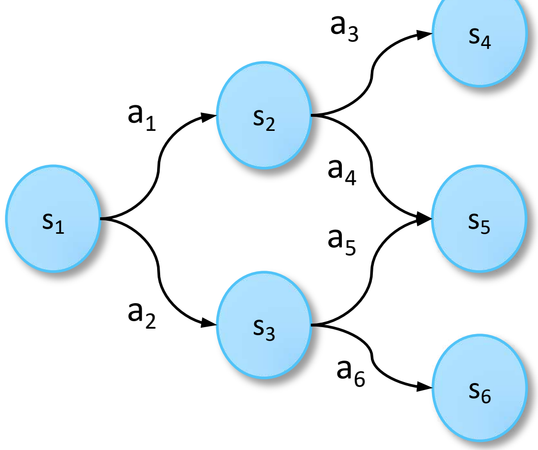
**Timeline-based Planning**

More recent approach


- N Muscettola, SF Smith, A Cesta, D D'Aloisi . **Coordinating space telescope operations in an integrated planning and scheduling architecture**. IEEE Control Systems, 1992.
- Muscettola, N. **HSTS: integrating planning and scheduling**. In Intelligent Scheduling, M Zweben and M Fox, eds., Morgan Kaufmann, 1994.

# A classical approach to planning

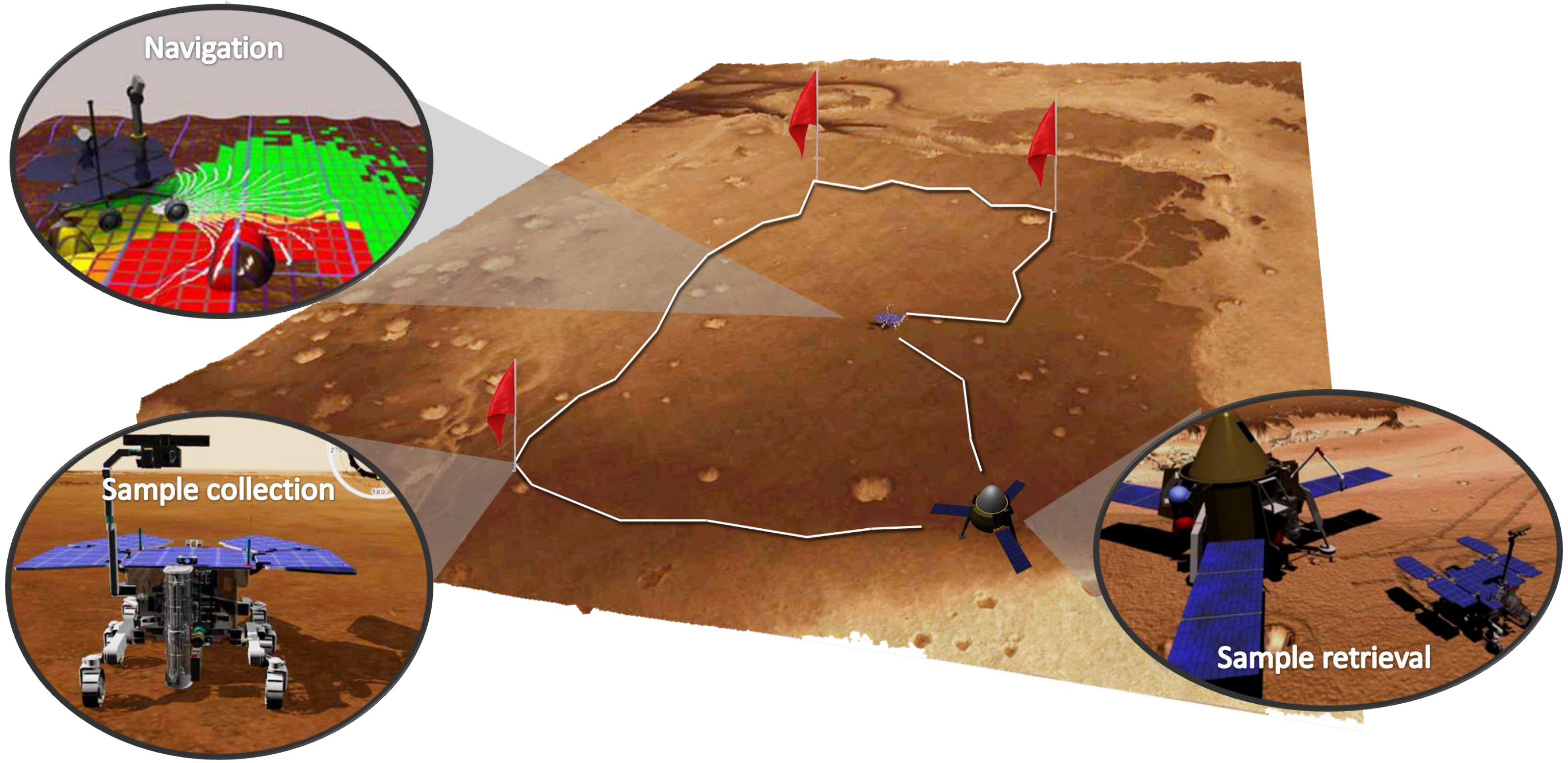
- Starting from a description of the **initial state** of the world, a description of the desired **goals**, and a description of a set of possible **actions**, synthesize a **plan**, i.e. a sequence of actions, that is guaranteed, when applied to the initial state, to generate a state, called a **goal state**, which contains the desired goals




- **States** are represented through proposition symbols, e.g. `on_a_b`, `at_truck0_loc2`.
- **Goals** are represented through a set of proposition symbols, e.g. `at_truck0_loc5`.

- **Actions** are described in terms of:
- A set of proposition symbols, which must hold in a state for the action to be **applicable**, called the **preconditions**
- A set of proposition symbols which are added (removed) to the state whenever the action is applied, called the **positive** (**negative**) **effects**

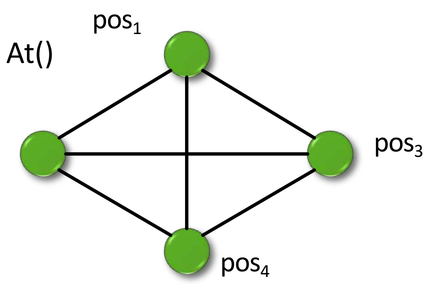
# Planetary rover domain




Courtesy of A. Oddi & R. Rasconi

# An introductory example (1)

**Navigation module:**



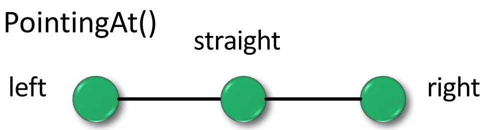

**Operators:**

LookAt(*?from*, *?to*)
 pre: {PointingAt(*?from*)}
 $eff^+$: {PointingAt(*?to*)}
 $eff^-$: {PointingAt(*?from*)}

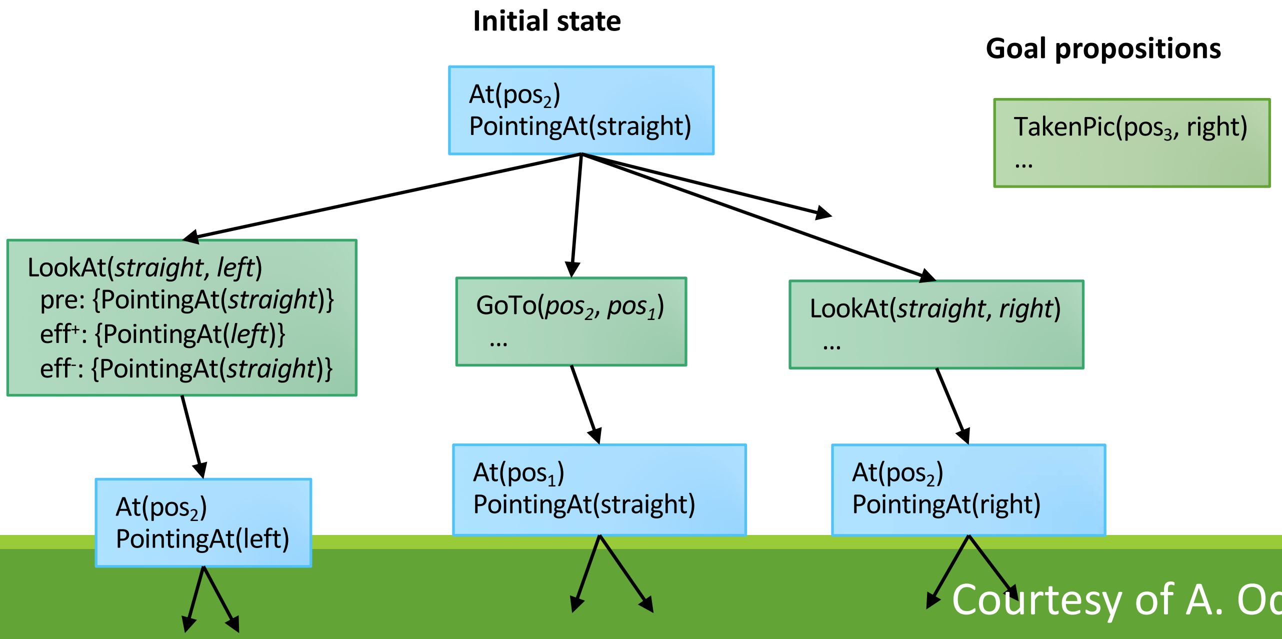
TakePicture(*?at*, *?pointing*)
 pre: {At(*?at*), PointingAt(*?pointing*)}
 $eff^+$: {TakenPic(*?at*, *?pointing*)}
 $eff^-$: {}

GoTo(*?from*, *?to*)
 pre: {At(*?from*)}
 $eff^+$: {At(*?to*)}
 $eff^-$: {At(*?from*)}

**Pan-tilt unit:**




TakePicture( , )



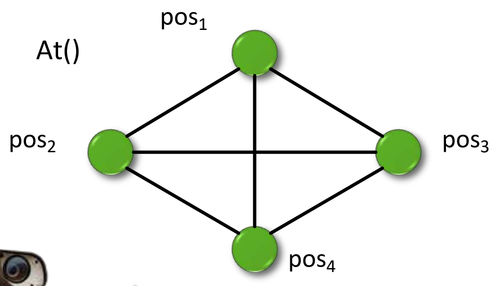

Courtesy of A. Oddi & R. Rasconi

# An introductory example (2)

**Operators:**

**Navigation module:**

At()



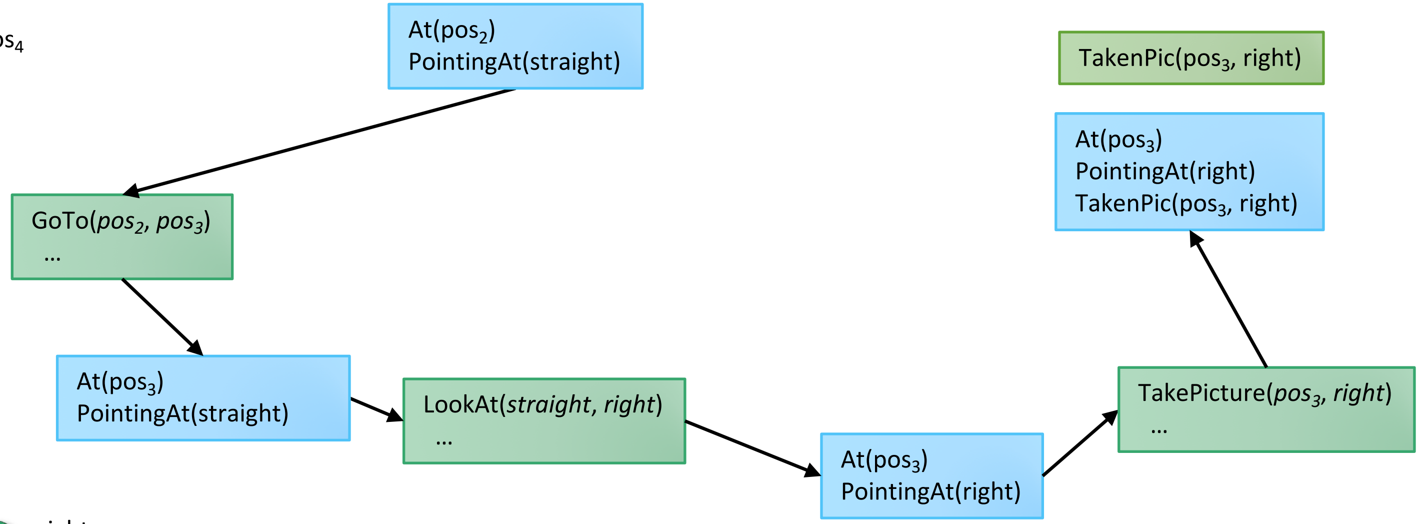

LookAt(*?from*, *?to*)
pre: {PointingAt(*?from*)}
eff$^+$: {PointingAt(*?to*)}
eff$^-$: {PointingAt(*?from*)}

TakePicture(*?at*, *?pointing*)
pre: {At(*?at*), PointingAt(*?pntng*)}
eff$^+$: {TakenPic(*?at*, *?pointing*)}
eff$^-$: {}

GoTo(*?from*, *?to*)
pre: {At(*?from*)}
eff$^+$: {At(*?to*)}
eff$^-$: {At(*?from*)}

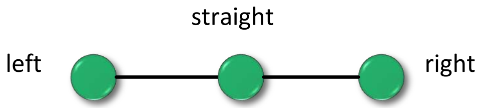
**Initial state**

**Goal propositions**




**Pan-tilt unit:**

PointingAt()



# PDDL [McDermott et al, 1998]

Planning Domain Definition Language (PDDL)

- Inspired by the STRIPS and ADL languages
- Most widespread
- Official language of International Planning Competitions (IPCs)

# Versions of PDDL

- PDDL 1.2
  - Predicate centric (i.e., classical representation)
  - Object types
  - ADL features (e.g., conditional effects, equality)
- **PDDL 2.1**
  - **Numeric Fluents**
  - **Durative Actions**
- PDDL 2.2
  - Timed-initial literals
  - Derived Predicates
- PDDL 3.0
  - State-trajectory constraints (hard constraints for the planning process)
  - Preferences (soft constraints for the planning process)
- PDDL 3.1
  - Object Fluents

```
(define (domain blocksworld)
  (:requirements :strips :typing)
  (:types block)
  (:predicates (on ?x - block ?y - block)
        (ontable ?x - block)
        (clear ?x - block)
        (handempty)
        (holding ?x - block)
        )
  (:action pick-up
     :parameters (?x - block)
     :precondition (and (clear ?x)
                        (ontable ?x)
(handempty))
     :effect (and (not (ontable ?x))
                        (not (clear ?x))
                        (not (handempty))
                        (holding ?x))
)
…
```

# PDDL 2.1 Standard: Summary

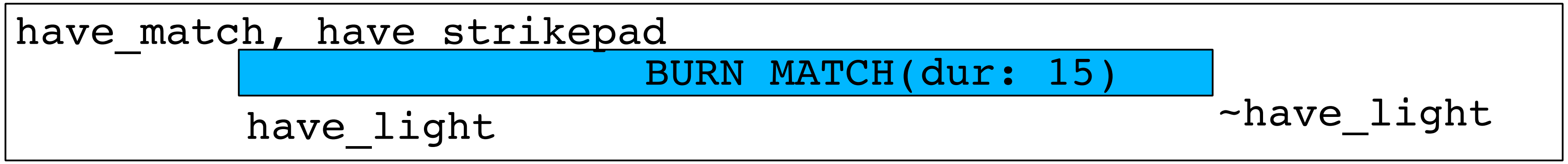
Durations
- Static and dynamic durations allowed
- Also allows duration inequalities

Preconditions
- Can be “at start” or “over all” (throughout the duration)
  - Doesn’t model preconditions being needed for arbitrary durations in the middle

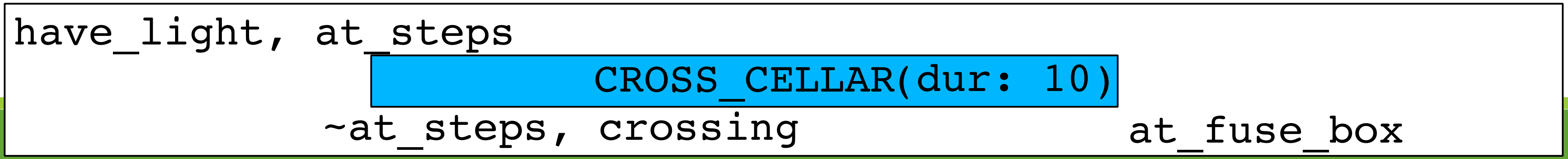
Effects
- Can be “at start” or “at end”
  - This makes effects “discrete”

Numeric quantities
- Can be present in the preconditions or effects
- Presence in the effects can be “discrete” (“at start”/”at end”) or continuous
  - Continuous change specified  by giving a “rate” at which the quantity changes
    - Non-linear rate harder

```
(:durative-action  burn_match
:parameters ()
:duration (= ?duration 15)
:condition: (and (at start have_match)
                 (at start have_strikepad))
:effect (and (at start have_light)
             (at end (not have_light))
          )
)
```




```
(:durative-action cross_cellar
:parameters ()
:duration (= ?duration 10)
:condition (and (at start have_light)
                       (over all have_light)
                       (at start at_steps))
:effect (and (at start (not at_steps))
             (at start crossing)(at end
at_fuse_box))
```



# Hierarchy of Planning Problems

POMDP (undecidable [MHC03])

↑

Partially observable (2-EXPTIME [Rin04a])

↑

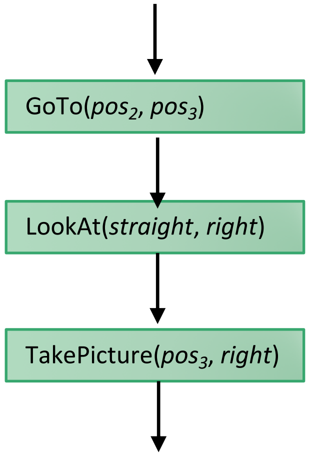
Conditional/MDP (EXP [Lit97])

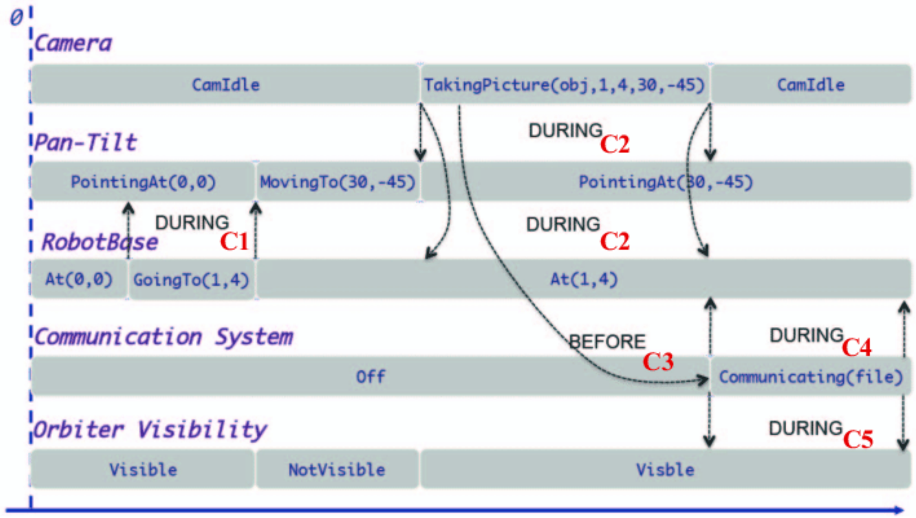
Temporal (EXPSPACE [Rin07])

Classical (PSPACE [GW83, Loz88, LB90, Byl94])

# Why a Timeline-based approach

- Classical restrictions *might be* too severe
  - We want to manage **concurrency** (e.g., turn the key *while* the lever is pressed down)
  - We want to explicitly represent **time** (e.g., communicate during [17:00, 23:00])
  - We want to reason on **extended goals** (e.g., plan trajectories or tasks to be performed)
  - We want to use **quantitative** states, e.g., resources and/or start-times of operations (**scheduling)**

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(*) Andrea Orlandini, Marco Suriano, Amedeo Cesta, Alberto Finzi. Controller Synthesis for Safety Critical Planning. Proceedings of the 2013 IEEE 25th International Conference on Tools with Artificial Intelligence

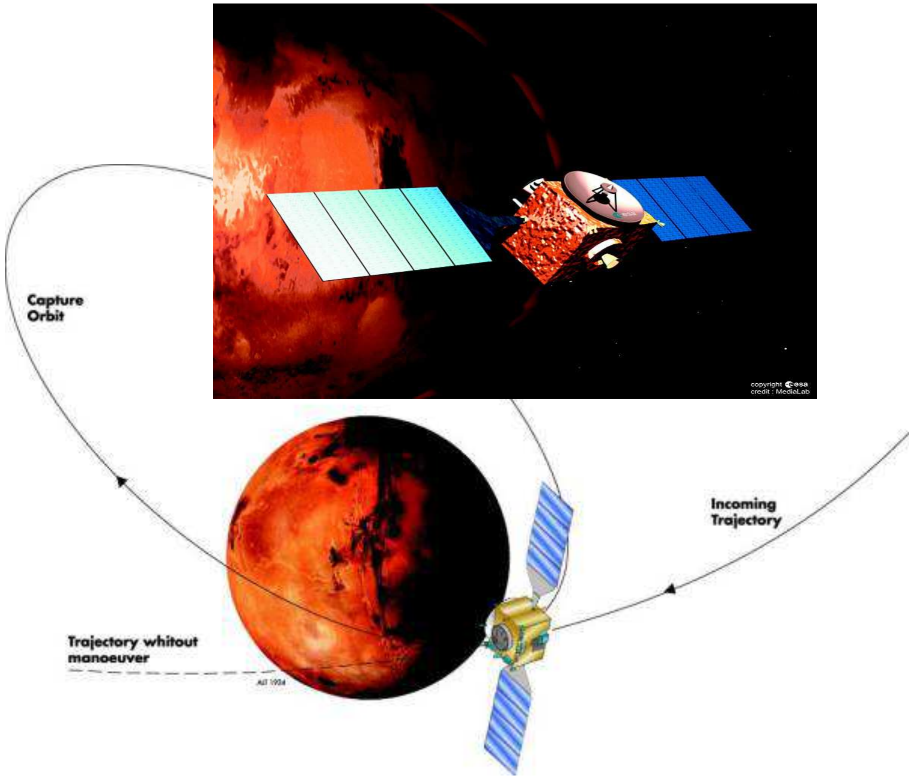
# The Mars-Express (MEX) mission

- Launched on June 2003

- The space probe is orbiting around Mars since January 2004 (very successful mission)

- Seven scientific payloads which collect data to study the Martian atmosphere and the planet's structure and geology

- 2-3 Gb of data generated on a daily basis



# Timeline-based planning (1/2)

Timeline-based planning is a different approach to AI planning originally introduced in the context of planning and scheduling of space operations.

# Timeline-based planning (2/2)

Timeline-based planning is mostly focused on temporal reasoning:

- no clear separation between actions, states, and goals
- planning problems are modeled as systems made of a number of independent, but interacting, components
- components are described by **state variables**
- the **timelines** describe their evolution over time
- the evolution of the system is governed by a set of temporal constraints called **synchronization rules**

# Why timelines?

Timeline-based planning systems shine when:

- modeling and reasoning about systems made of *many components*, rather than the behavior of a single agent
- approaching problems where both **temporal** and resource reasoning are predominant
- A tight **integration between planning and scheduling** is a key feature to deploy effective applications in real-world contexts
- the planning process needs to be integrated with plan **execution**

# Recent developments (1/2)

Timeline-based planning has been successfully deployed over the last decades in a large number of complex real-world scenarios.

- However, only recently the paradigm has been studied from a foundational perspective
- Recent developments provided a uniform **formalization** of the approach and a first understanding of the theoretical properties of the paradigm
  - comprehensive formalization of timelines and *flexible timelines*, including **controllability** issues
  - **expressiveness** issues, both in terms of comparison with action-based formalisms, and from a logical standpoint
  - computational **complexity** of the involved problems

# Recent developments (2/2)

Cialdea Mayer, Marta, Andrea Orlandini, and Alessandro Umbrico (2016). *Planning and Execution with Flexible Timelines: a Formal Account*. In: Acta Informatica 53.6-8, pp. 649–680.

Gigante, Nicola, Angelo Montanari, Marta Cialdea Mayer, and Andrea Orlandini (2016). *Timelines are Expressive Enough to Capture Action-Based Temporal Planning*. In: Proc. of the 23rd International Symposium on Temporal Representation and Reasoning, pp. 100–109.

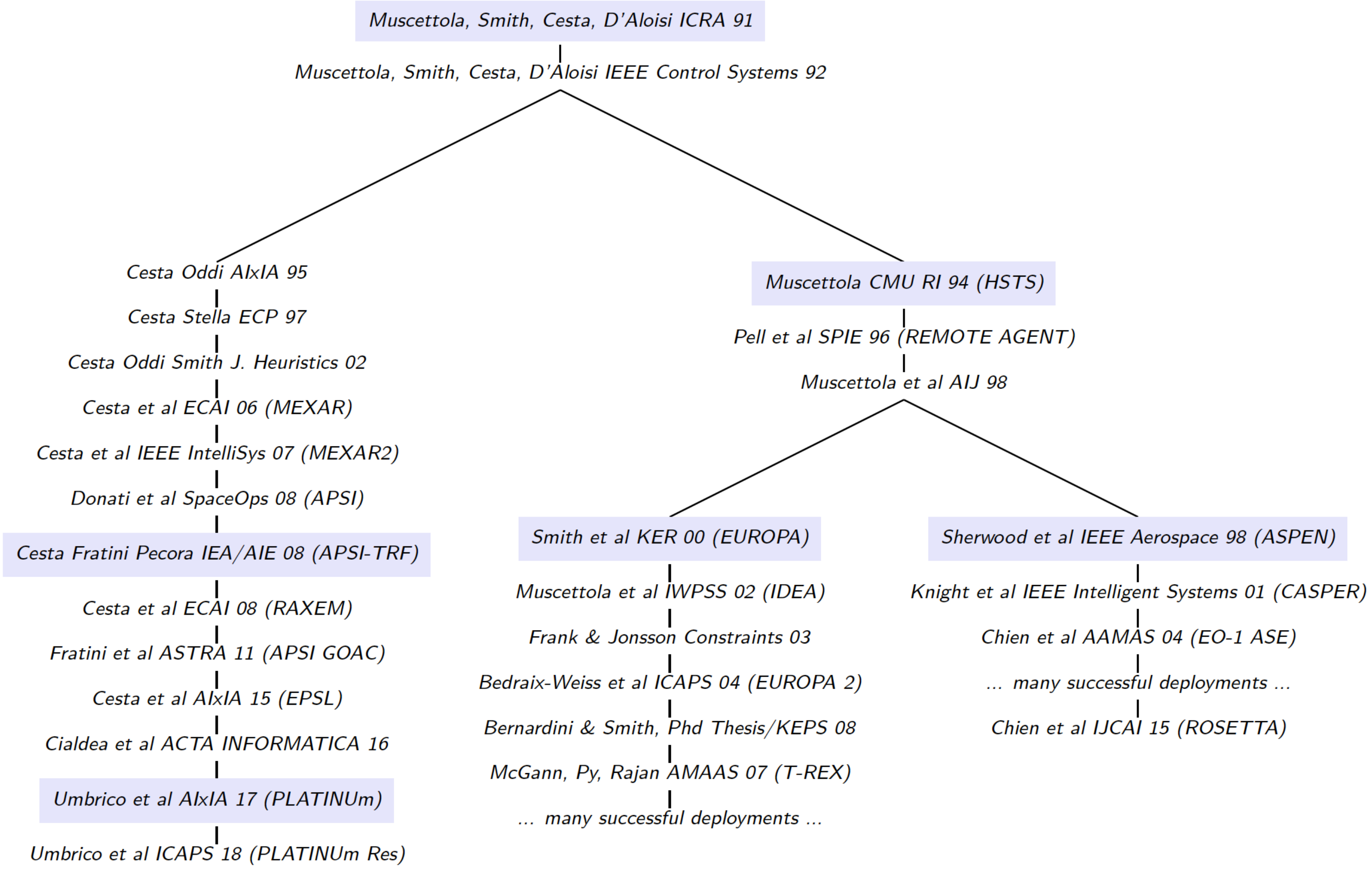
Nicola Gigante, Angelo Montanari, Marta Cialdea Mayer, Andrea Orlandini: *Complexity of Timeline-Based Planning*. ICAPS 2017: 116-124.

Nicola Gigante. *On the Complexity and Expressiveness of Automated Planning Languages Supporting Temporal Reasoning*. IJCAI 2017: 5181-5182.

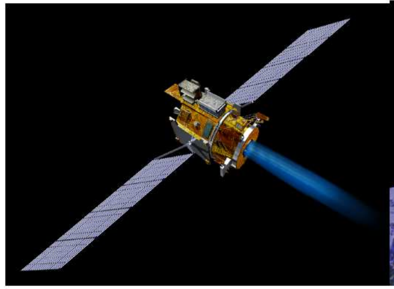
Nicola Gigante, Angelo Montanari, Marta Cialdea Mayer, Andrea Orlandini, Mark Reynolds. *A Game-Theoretic Approach to Timeline-Based Planning with Uncertainty*. TIME 2018: 13:1-13:17.

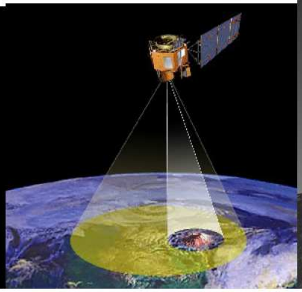
Alessandro Umbrico, Amedeo Cesta, Marta Cialdea Mayer, Andrea Orlandini: *Integrating Resource Management and Timeline-Based Planning*. ICAPS 2018: 264-272.

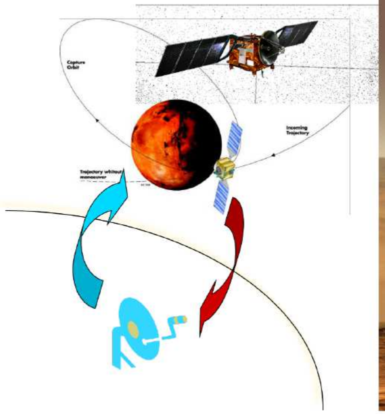
# Almost 30 years of timelines

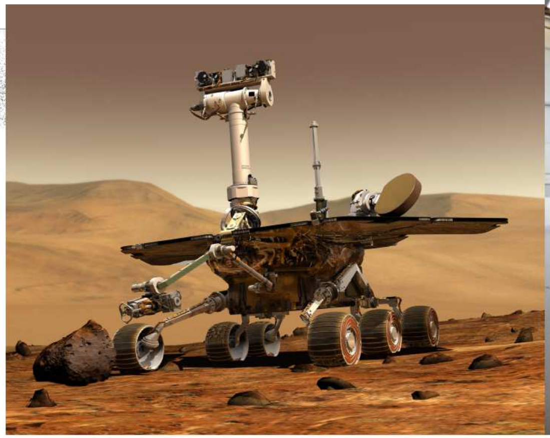


# Successful space missions









# Closed-loop Execution of Timeline-based Plans

A PLATINUm executive consists of a **closed-loop control process** which iteratively fix flexible timelines over time

A **Dispatcher** actually executes the timelines of a plan by sending commands to a physical system

- It is responsible for deciding the start of the execution of the tokens that compose the timelines of a plan

A **Monitor** handles execution feedbacks to verify whether the plan complies with the observed status of the environment or not

- It is responsible for propagating information about the actual duration of uncontrollable tokens

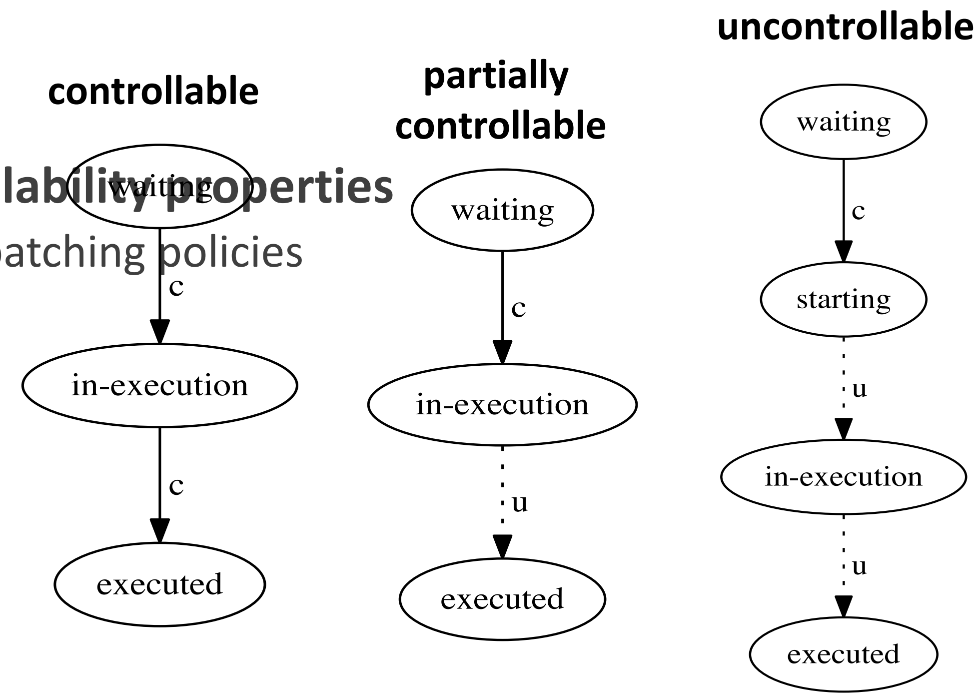
# Executing Timelines under Temporal Uncertainty

Extract **start/end execution dependencies** by analyzing temporal relations of a plan

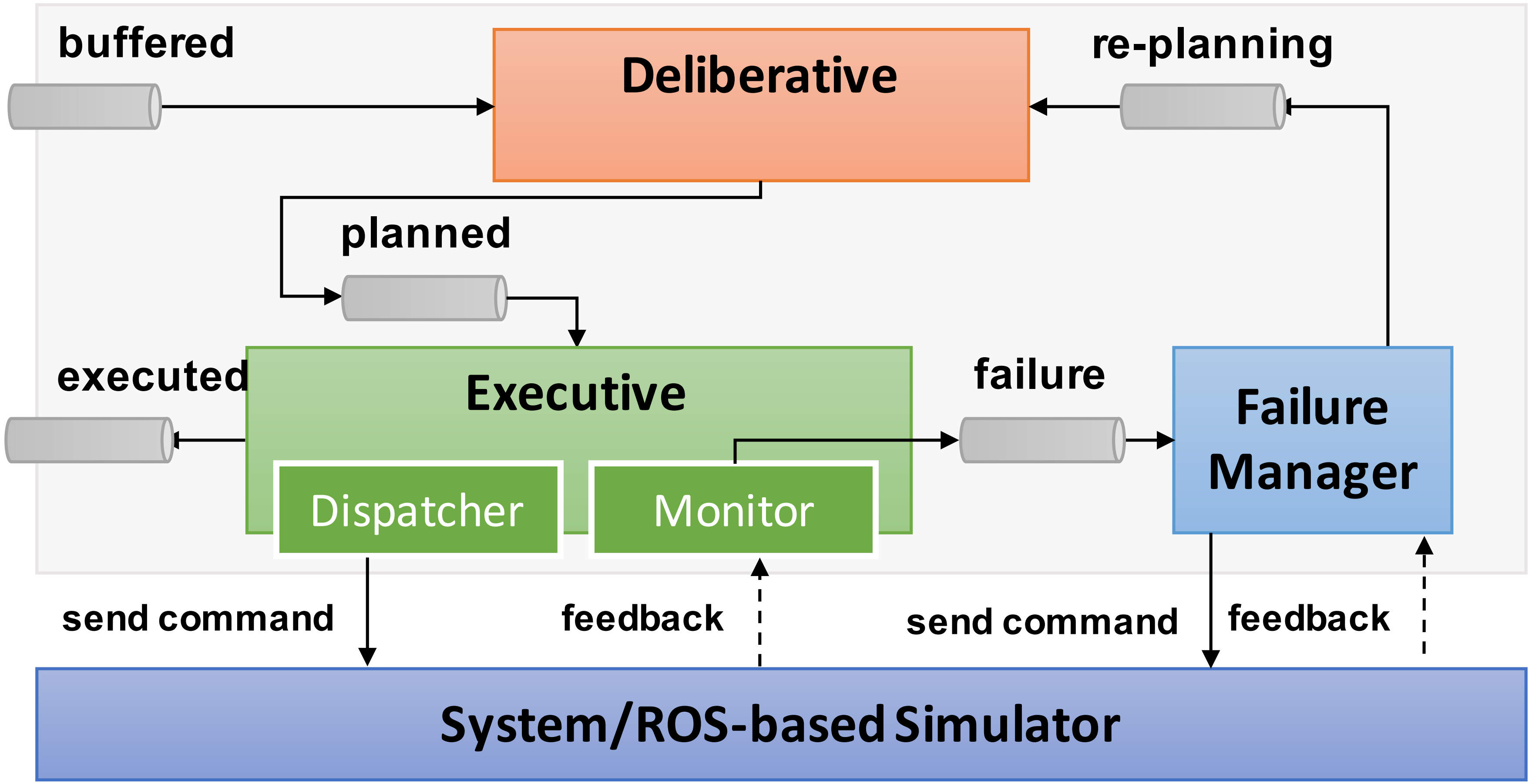
- Dynamically generate a **execution dependency graph**

Manage token transitions according to their **controllability properties**

- Different controllability properties entail different dispatching policies



# Closed-loop Control Architecture



# Human-robot collaboration case study

# The FourByThree Research Project

Horizon 2020 research project

- Call FoF-06-2014 “Symbiotic Human-Robot Collaboration for safe and dynamic multimodal manufacturing systems”
- Coordinated by FUNDACION TEKNIKER (Spain)
- http://fourbythree.eu/

# ABOUT SHAREWORK

Safe and effective human-robot cooperation towards a better competiveness on current automation lack manufacturing processes

- **4 years** duration, from 1/10/2018 to 31/10/2022
- **Budget**: 7,4 M€, 100% funded by the EC
- **15 participants** from **6** different **countries**
- **Coordinated by Eurecat**, RTO, ES
- **Grant agreement ID**: 820807

eurecat

AUTOMOTIVE – RAILWAY – GOODS – METAL

# CONSORTIUM

15 partners from 6 European countries

| 3 | 3 | 4 | 4 | 1 |
|---|---|---|---|---|
| RTOs | Universities | SMEs | Large industries | Standardisation body |

# Objectives of the Project

Develop a new generation of **modular** industrial robotic solutions that are suitable for **efficient** task execution in collaboration with humans in a **safe** way and are **easy** to use and program

- **Vision**: A system integrator (or end-user) can create its own custom robot according to their application needs ("kit" of hardware and software components)

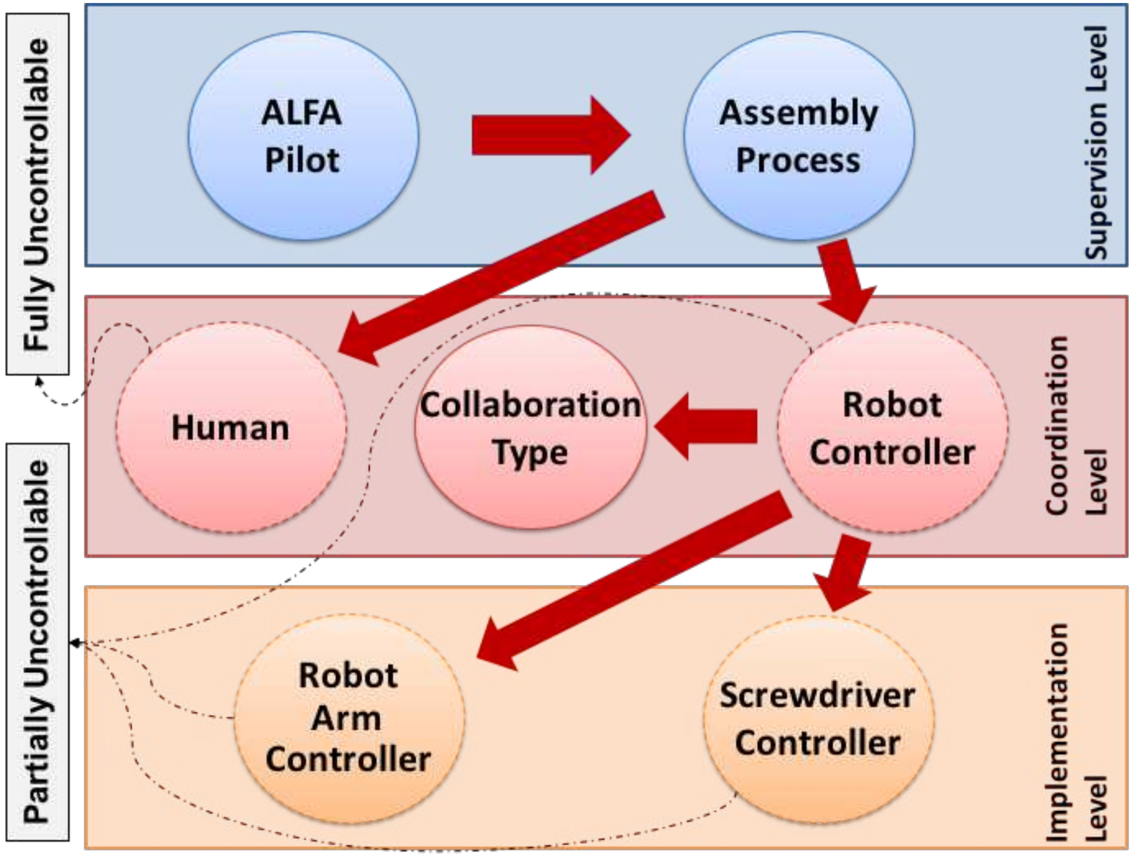
Real-world Pilot case studies to test Human-Robot Collaboration

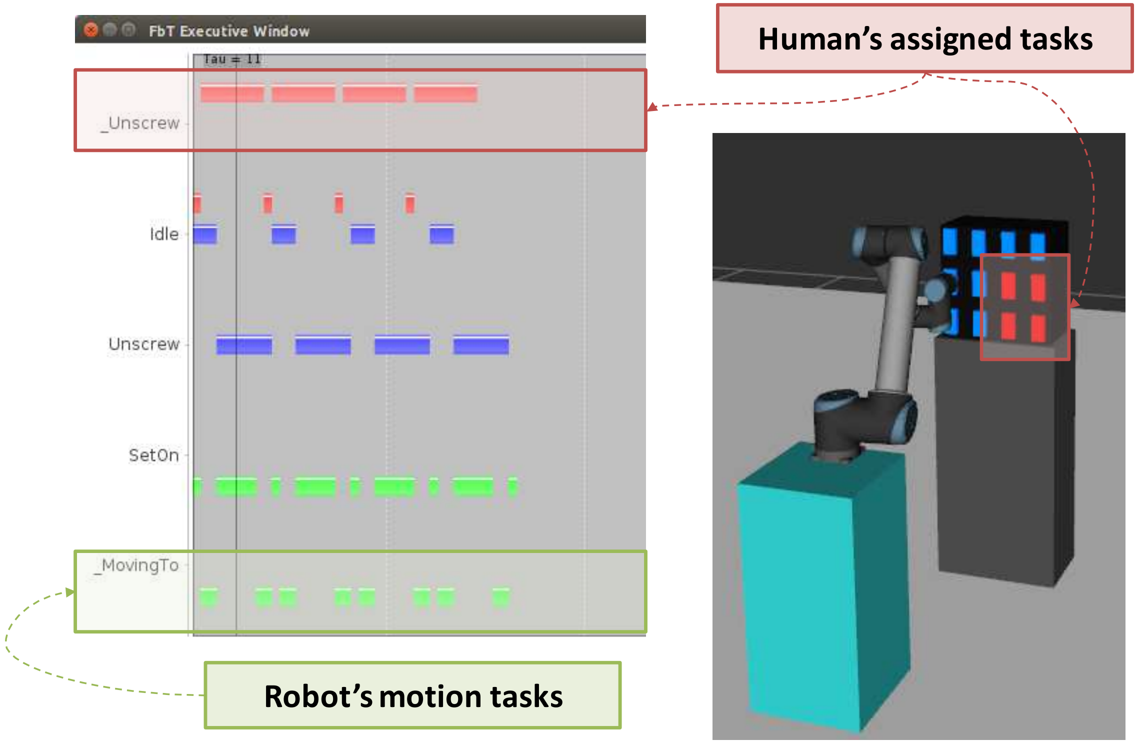
- **ALFA**, WOLL, STODT, PREMIUM

# ALFA: A Collaborative Assembly Case Study

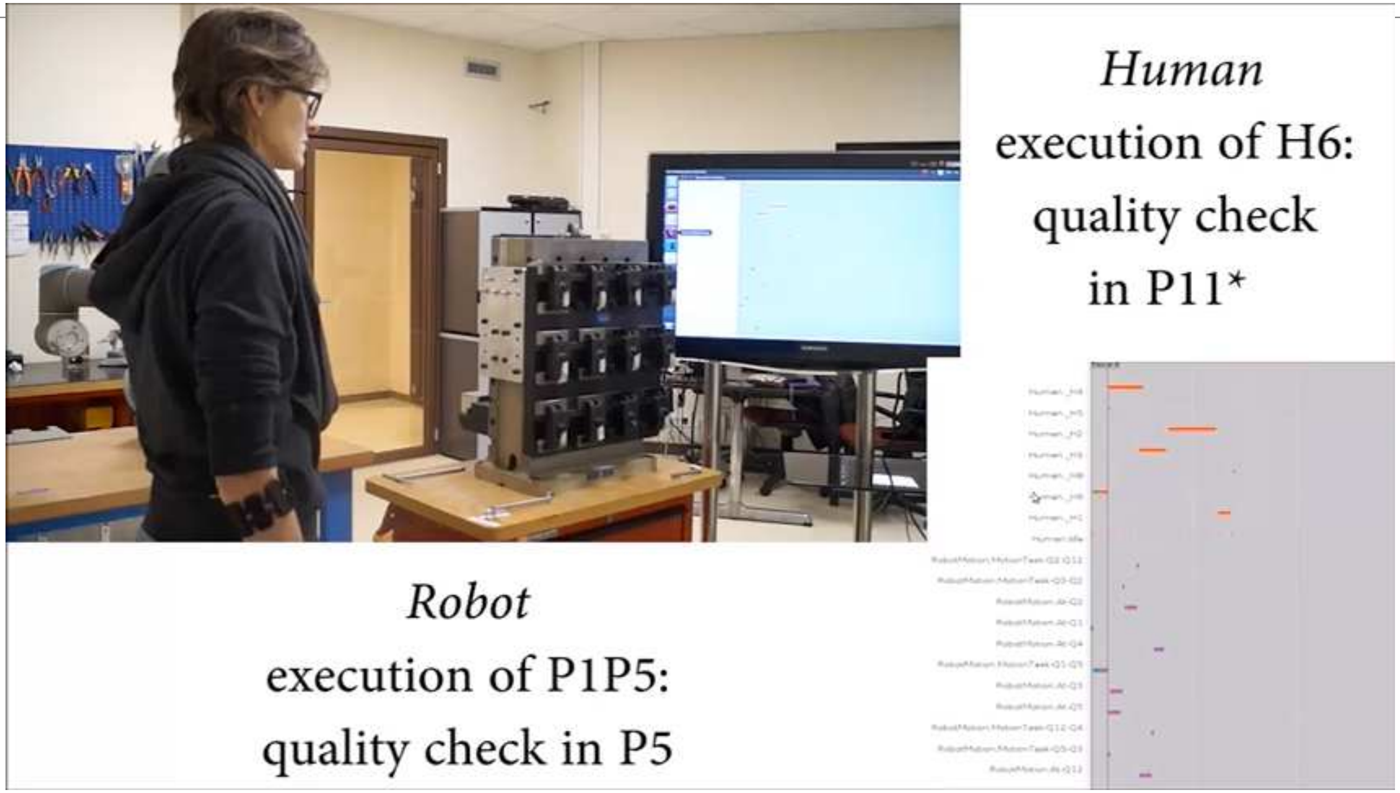

- Investment Casting process
  - Dies are assembled and disassembled manually
  - Some operations need human dexterity
  - Others can be done by a robot
- Re-design the process by taking into account an HRC perspective
  - **Hierarchical process description**
  - Three levels: **Supervision**, **Coordination**, **Implementation**

# A Hierarchical Planning Model for Collaborative Assembly Scenarios



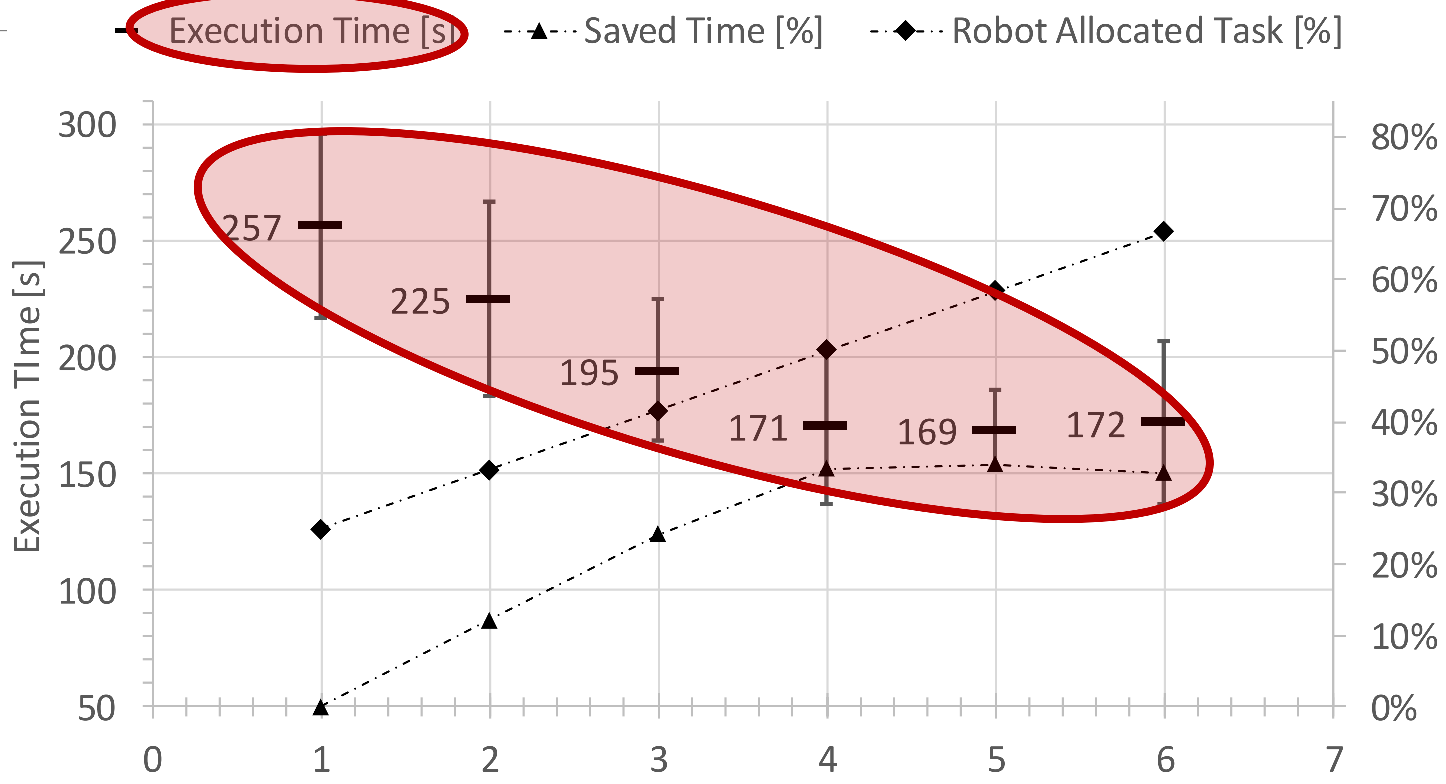



# Flexible Collaboration with Dynamic Trajectory Selection




**Verify the capabilities of an integrated task and motion planning control to improve the efficiency of HRC assembly processes**

# Experimental Results




**Planning *can reduce* the duration HRC processes and realize effective and safe collaborations between human operators and robots [Pellegrinelli et al. CIRP Annals 2017]**

# Final Remarks

- **HRC** is particularly suited to show the capabilities of PLATINUm
  - **Temporal uncertainty** and **hierarchical problem modeling and solving**

The FourByThree research project has shown the capability of PLATINUm to **synthesize flexible and adaptable behaviors of a robot acting in the real-world**

- **Flexible architecture** for robot task planning and execution
- Successfully **coordinate robot and human behaviors in a reliable and safe way**
- **Adapt task assignment and execution** according to **human preferences** through dedicated human-robot interaction mechanisms

# Correlated PROJECTS and future developments

# KEEN– The Knowledge Engineering Environment for Timeline-based Planning

A knowledge engineering environment aimed at supporting the design and development of timeline-based applications

- **Round-trip-engineering** to support both graphical and programming user interface to model timeline-based domains
- Available as plugin for the Eclipse IDE
- https://ugilio.github.io/keen/

**Integrated with PLATINUm**

- Launch platinum-based planners on designed timeline-based domains
- Launch platinum-based executive to simulate execution of synthesized plans

# Conclusions and Future Works

PLATINUm is an open framework which can be “easily” extended to introduce new representation features and solving capabilities

- Discrete and Reservoir Resource management has been recently introduced **[Umbrico et al. ICAPS 2018]**
  - **Don’t miss paper presentation at the main track on Wednesday!**

Future works

- Investigate new heuristics and new search strategies
- Integrate dynamic controllability checking algorithms
- Comparison with other state of the art timeline-based and hybrid planners
  - EUROPA [Barreiro et al., 2012], CHIMP [Stock et al., 2015], FAPE [Dvorak et al., 2014]

# Thanks for your Attention!

**PLATINUm** – **PL**anning and **A**cting with **TI**meli**N**es under **U**ncertainty

Consiglio Nazionale delle Ricerche

ISTC - CNR

Available on GitHub
**https://github.com/pstlab/PLATINUm**

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