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Decision-Making and Skill-based architectures for Autonomous Mobile Robots

Alexandre Albore

ONERA, DTIS, Université de Toulouse, France

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Context

- Ever-increasing robotic applications **demand**
- Robotic approaches to **autonomy**
- Need of **dependability**
- Need for **tools and methods**

Trust and dependability

Strengthening **trust** in autonomous systems

- Complex robotic systems
- Complex tasks and difficult environments
- Exogenous events (HMI, uncertainty, partial information)

Dependability

- **Specification** made easy
- **Verification and validation** made easy
- **Implementation** made easy

A Robotic 3-layered architecture

The proposed architecture has three layers:

1. The **decision layer**: hosts the mission controller and sets the goals to achieve
2. The **executive layer**: the middleware interface of the system capabilities
3. The **functional layer**: the on-board control procedures

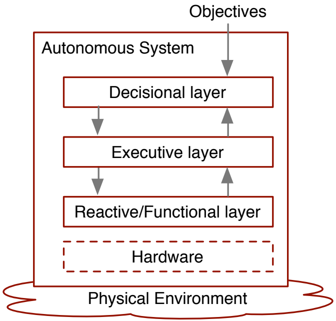
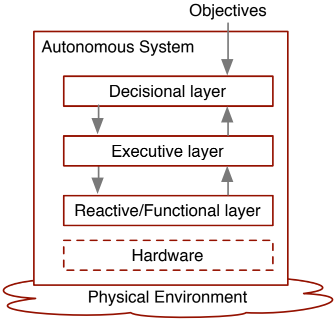


Fig: 3-layers architecture[1]

[1] F. Ingrand and M. Ghallab. "Deliberation for autonomous robots: A survey". In: *Artificial Intelligence* 247 (2017), pp. 10–44

Dependable Skill-based executive layer

- Executive layer:
  - translation of decision *actions* into **executable** commands
  - abstraction of the functional layer
  - “task achieving behaviors”[2], “procedures”[3], “performance profiles”[4], “skills”[5,6,7]
  - **Skills** represent functions/services available in the functional layer



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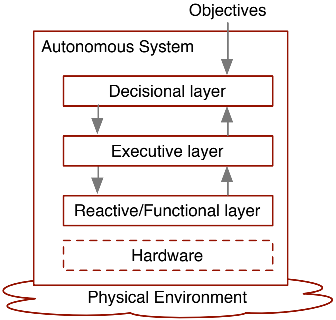
⇝ **Model-based** design of the skill-based executive layer

⇝ Tools/processes to support a **dependability** analysis



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Skill Definitions

- Skills represent functions available in the functional layer
- Skills are modular and participate to the mission design
- Skills that share relations (dependencies, exclusion, . . .) are grouped into a Skillset
- These relations are modeled as Resources
- The correct execution of each skillset is managed by a Skillset Manager

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Skillset formulation

Skillsets are described using a custom *Robot-language*[12].

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Skillset formulation

Skillset is built upon three types of elements:

- data — skillset shared data
- resource — shared resources within the skillset
- event — external means to interact with resources
- skill — robot skill definition

```
skillset name {
    data     { ... } // skillset data definition
    resource { ... } // skillset resources definition
    event    { ... } // skillset events definition
    skill    { ... } // skillset skills definition
}
```

Skill formulation

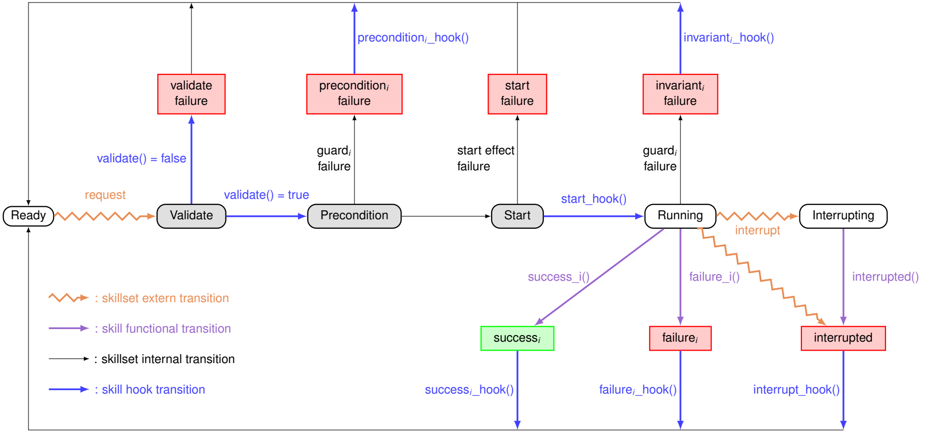
Robot Skill

Input	input data
Output	ouput data
Precond.	preconditions on resources
Start	effects on start
Invariant	resources invariants
Progress	progress of the running skill
Terminate	of the skill: effets & postcondition

Interrupt	interrupting the skill
Success	
Failure	

```
skill skill_name {
    input {...}
    output {...}
    precondition {...}
    start ...
    invariant {...}
    progress {...}
    interrupt ...
    success ...
    failure ...
}
```

Skill Execution Model state-machine



The skillset semantics

Skills Design

Goals

- **"Safe"** robots
  - clear/unambiguous specification
  - specification verification/analyses
  - real execution conforming to specification
- **Abstraction**
  - different robots can share skills
  - don't rewrite code
  - ease deployment and reconfiguration

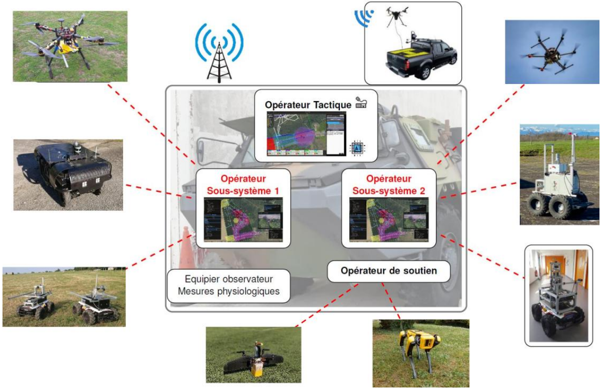
Principe

- "Formal" specification
  - "formal" language: the **Robot-language**
  - **standard interface** for the decision layer
  - various possible **verifications and analyses**
- ROS 2 code generator
  - don't introduce bugs
  - ensure that the real execution conforms to the model

Cohoma Challenge – Robotic platforms

10 platforms

- 2 multi-rotor drones
- 1 captive drone
- 1 convertible drone
- 5 ground robots on wheels
- 1 quadruped robot



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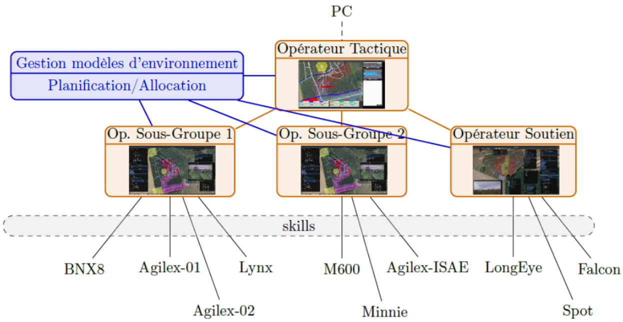

Code Generation

- Generation of a Skillset Manager Template
- . . . as a **ROS 2** node (and messages)
- All the logical behaviour is generated as:
  - resource management (guards, effects, events)
  - skills FSM (inputs/outputs, invariants, states)
- The developer still has to:
  - implement the `validate_hook` if they want to check something before starting
  - implement the **actual skill execution** in relation with the functional layer in between the `start_hook` and the `success` or `failure` terminations

Resolution Techniques

Assisting the design

Verifying the correctness of the skillset models using formal methods.

[13] Leonardo De Moura and Nikolaj Bjørner. "Z3: An efficient SMT solver". In: *International conference on Tools and Algorithms for the Construction and Analysis of Systems*. Springer. 2008, pp. 337–340.

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- Formalism: encoding the formulæ in Satisfaction Modulo Theory (SMT)
  - Resources modeled as state machines
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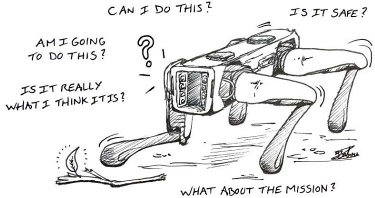
  - Effects (resource transitions)
- Solver used for inconsistencies check: Z3[13]



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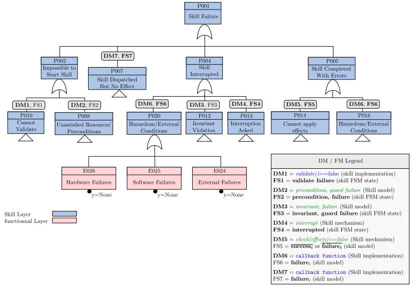

Fault Tree Analysis[14]

- Hazards might be combined using logic symbols
- Qualitative analysis can be performed on the skill fault tree.

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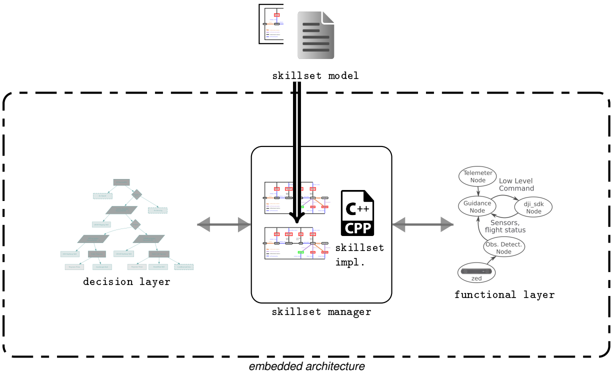

15 Alexandre Albore et al. "Skill-based design of dependable robotic architectures". In: *Robotics and Autonomous Systems* 160.104318 (2023)

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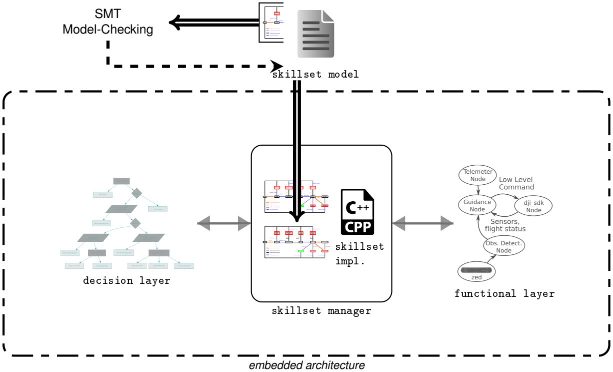

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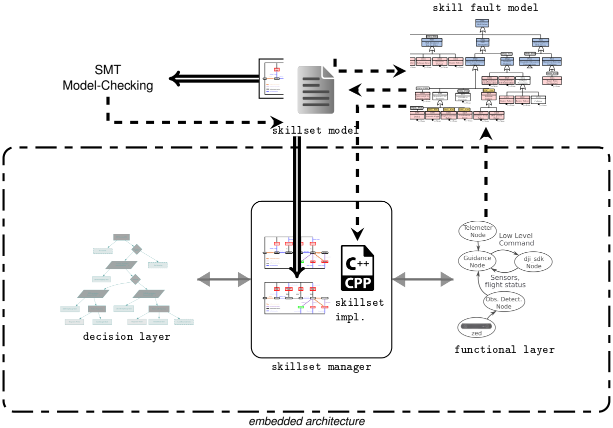

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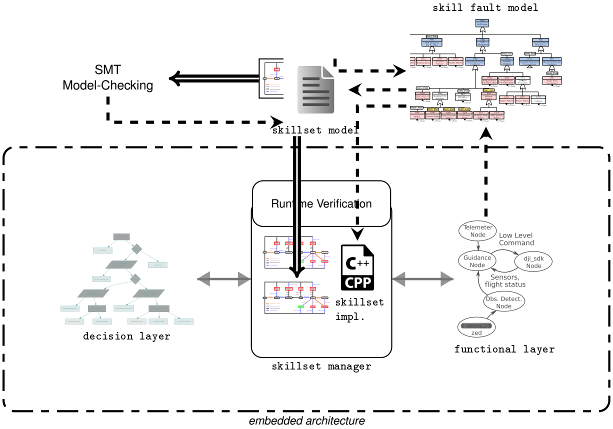

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Decision layer

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Thus it can be implemented in different ways, e.g.

- Behaviour trees
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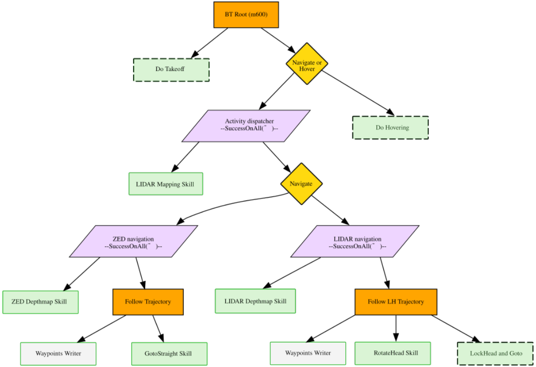
Some examples are coming. . .

Behaviour Trees

- Need to adapt in case of contingency
- E.g. for a UAV mission
  - React to a sensor failure using other on-board sensors and an alternative processing
  - Adapt the mission depending on exogenous events

Behaviour Trees

- Need to adapt in case of contingency
- E.g. for a UAV mission
  - React to a sensor failure using other on-board sensors and an alternative processing
  - Adapt the mission depending on exogenous events
- Behaviour trees allow to specify nominal and degraded plans



UAVs Mission Reconfiguration

- 3D Mapping of a storage building/infrastructure inspection
- BVLOS scenario (Beyond Visual Line of Sight of the teleoperator)[16]

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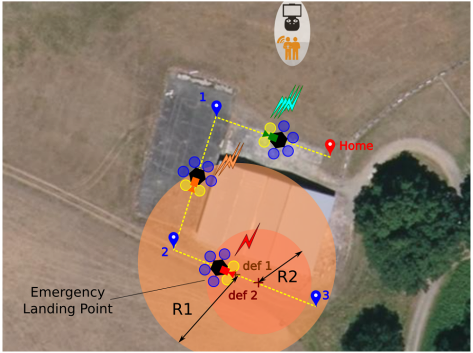
UAVs Mission Reconfiguration

- 3D Mapping of a storage building/infrastructure inspection
- BVLOS scenario (Beyond Visual Line of Sight of the teleoperator)[16]
- **Contingency**: Communication Loss
- **Reconfiguration**:
  - React to a sensor failure using other on-board sensors and an alternative processing
  - Adapt the mission depending on exogenous events
- more concretely:
  1. adapt bandwidth
  2. land if communication lost



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Earth Observation Satellites (EOS)

- An EOS is a spacecraft designed for gathering information about the Earth from orbit
- They point to targets and then take images with a sensor (visible, IR, radio, etc.)
- The orbit determines which areas are visible at a given time

- Observation tasks depend on the environment not known in advance, e.g. cloud cover, etc.
- Platform constraints (Attitude control, energy consumption...)
- New customer's requests

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Need to embed some functions on-board
in order to exploit data only available on-board

A decision layer based on Actors

The decision layer is built upon the OARA framework[17](https://onera-robot-skills.gitlab.io):

- **Architectural framework** to design and manage the **deliberative reasoning** of an autonomous system.
- Based on a **hierarchy of actors** managing planning and acting through **goal decomposition**.

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Derived from:

- Actors [18]: Reasoning components that manage planning and acting of a specific task.
- The concept of goal lifecycle[19]
- The Hierarchical Task Network (HTN) model and the Partial-Order Planning approach.

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[19] Malik Ghallab et al. "The actor's view of automated planning and acting: A position paper". In: *Artificial Intelligence* 288 (2014), pp. 1–17.

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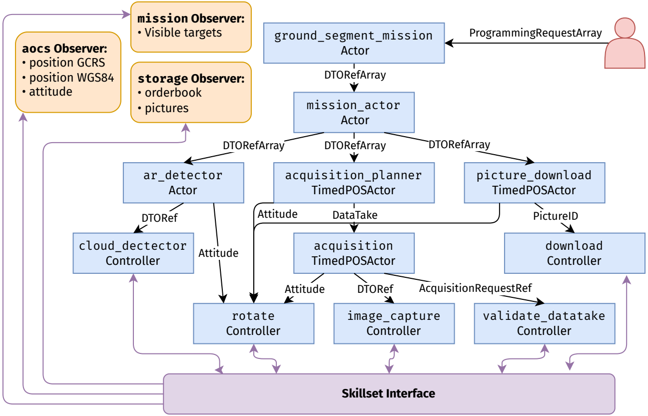
Decision layer architecture for EOS

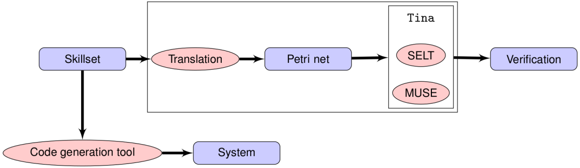


[21] Alexandre Albore and Rafael Bailon-Ruiz. "A Hierarchical Temporal Mission Controller for an Autonomous Earth Observation Satellite". In: *Multi-Agent Systems for Space Applications Workshop (AAMAS)*. Auckland, NZ, 2024.

Conclusions

Skills composition and verification[22]

- Skills can be composed
- and translated to Petri Nets
- and verified with adapted tools (Tina suite[23])



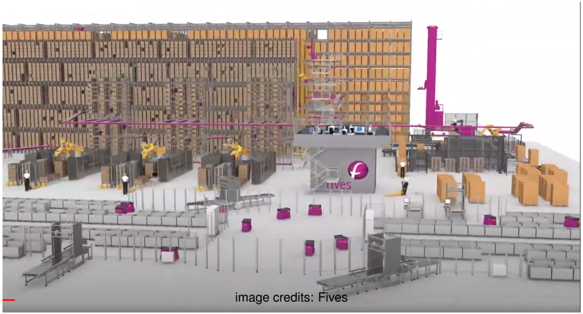
[23] Baptiste Pelletier et al. "SkiNet, A Petri Net Generation Tool for the Verification of Skillset-based Autonomous Systems". In: *International Workshop on Formal Methods for Autonomous Systems.* Berlin, Germany, 2022.

[24] Bernard Berthomieu et al. "The tool TINA – construction of abstract state spaces for Petri nets and time Petri nets". In: *International journal of production research* 42.14 (2004), pp. 2741–2756.

Conclusions

Warehouse robotic management

- Scaling up challenge ($\sim$ ~~800~~ *10k* autonomous UGVs)
- Increasing resilience
- Moving from a centralized architecture to a distributed one
- Advancing on the MAPF front



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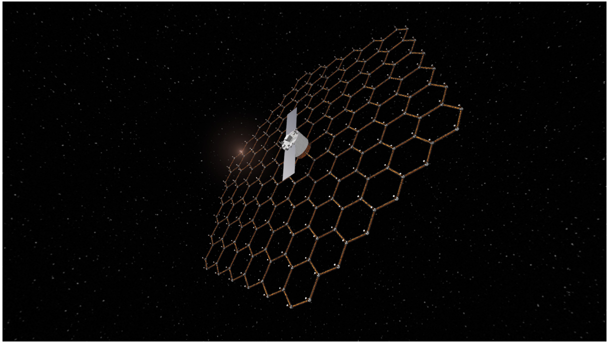

On-orbit satellite assembly

- **Crawling robots** moving on a truss beam lattice structure
- **Automated planning**-based approach[25]
- Advancing on the MAPF front

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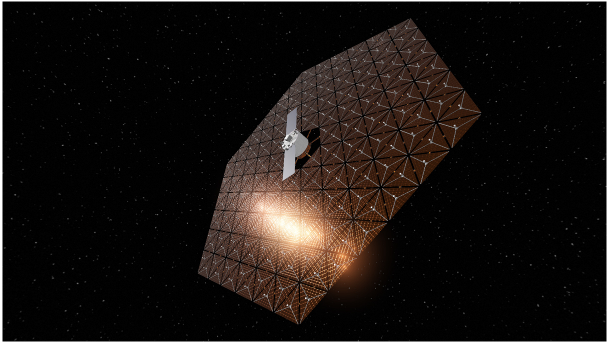

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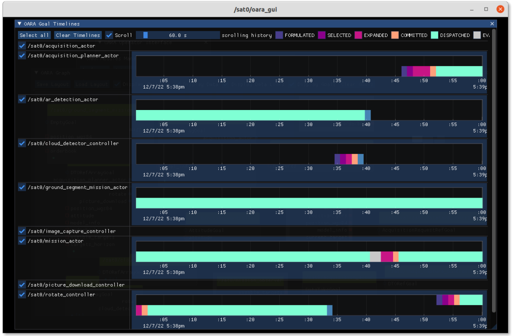
Conclusions

Mission Planning for EOS

- Need to **produce plans for a defined horizon**, steering the satellite towards observation targets
  - Time component of actions is critical
  - Expressiveness of Hierarchical Task Network Planning → **HDDL 2.1** [26]



[26] Damien Pellier et al. “HDDL 2.1: Towards Defining a Formalism and a Semantics for Temporal HTN Planning”. In: *Proceedings of the International Workshop of Hierarchical Planning (ICAPS)*. Prague, 2023.

Thank you!