MODEL-BASED SYSTEMS ENGINEERING IN SPACE ROBOTICS: THE ADE EXPERIENCE

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OUTLINE

- The ADE Project
- ADE Capabilities
- Design and Validation Approach
- Conclusion

THE ADE PROJECT

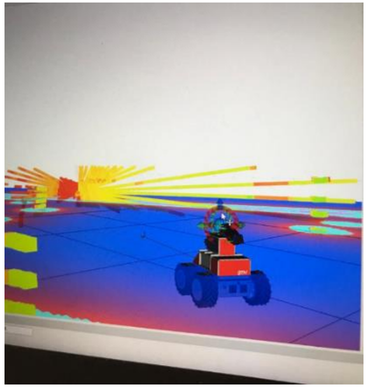
INTRODUCTION

- **ADE**: **Autonomous Decision Making in very long traverses** (https://www.h2020-ade.eu/, 2019-2021)
  - 10th operational grant (OG10) of the PERASPERA Programme (https://www.h2020-peraspera.eu/) dedicated to space robotics technologies
  - Focus on the development of key technologies for future autonomous space robotics exploration
  - Showcase of the system capabilities in a terrestrial demonstrator inspired from the Mars Sample Fetching Rover (MSR-SFR) mission
  - Spin-off to nuclear plant decommissioning activities
  - Development done by a Consortium of 14 partners from 7 countries, coordinated by GMV

SherpaTT (DFKI) in the Moroccan desert

Fuerteventura: analogue Mars representative environment

Foxizirc (GMV) in a nuclear plant representative environment



Nuclear plant map reconstruction

ON-BOARD AUTONOMY

- **The capability of a system to work without human interaction**
- There are multiple capabilities for a robot associated to autonomy such as:
  - **Autonomous mission planning**:
    - The robot is commanded via high-level goals
    - Examples: go to point (x,y) and take image, pick sample at (u,v) and take it to (z,t)
  - **Autonomous science detection**:
    - The robot detects serendipitous events and changes the current mission plan in order to gather science without abandoning the other activities
    - Example: detect a rock with specific characteristics and take pictures of it at a closer position
  - **Autonomous locomotion**:
    - The robot navigates a terrain in a safe way, reaching different objectives
  - **Autonomous device mobility**:
    - The robot performs complex operations in a safe manner with the devices that are available/connected to it
    - Example: use a robotic arm to pick a sample while avoiding collisions with the robot or the environment
  - **Autonomous safe operation in adverse conditions**:
    - The robot detects the presence of a harmful situation and reacts correspondingly
    - Example: detect that an on-board system is non-responsive and restart/reconfigure it to use a back-up system

ADE CHALLENGES

- Simulation of a **fully autonomous** MSR-SFR mission
- What is **expected**:
  - Autonomous long range navigation with high reliability (kms/sol)
  - Consistent data detection while avoiding un-detection of interesting data along mission path
  - Autonomous decision making capabilities in presence of conflicts (new goals to achieve, unexpected events, etc.)
  - Safety first in presence of failures or any unexpected events
  - Higher technology readiness level to prepare its reuse in future missions
  - Flexible-purpose robotic system design that could be used in terrestrial applications

ADE CAPABILTIES

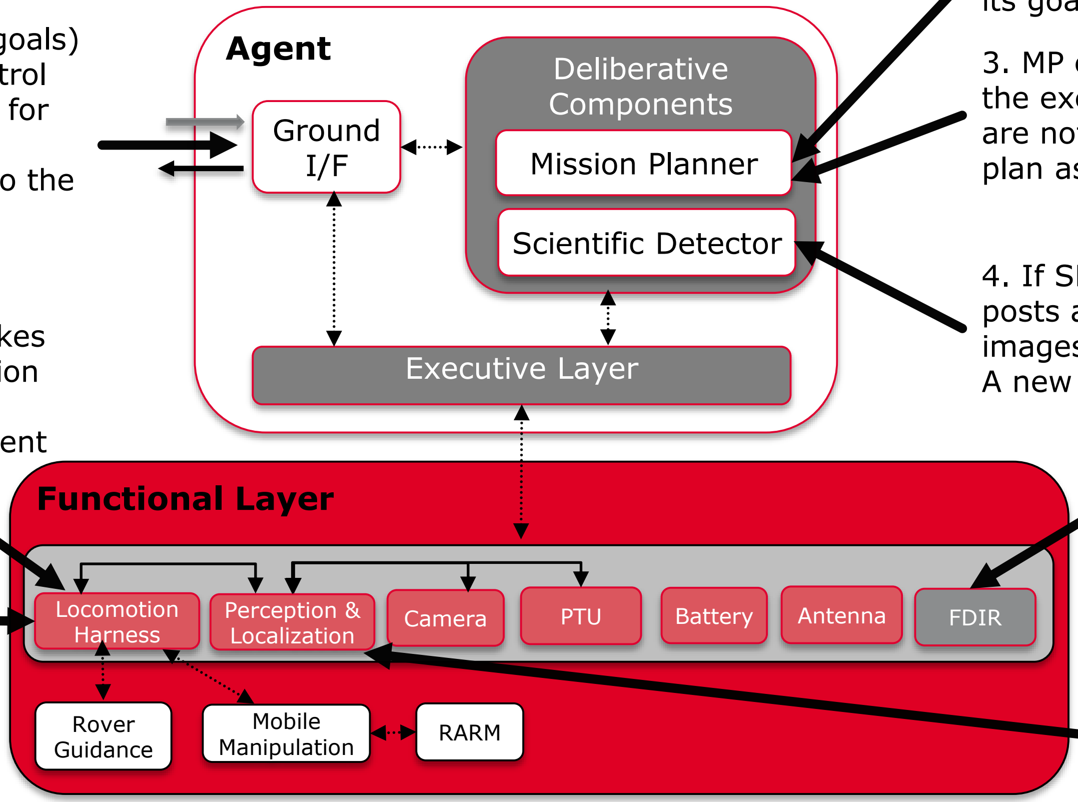
ON-BOARD AUTONOMY FOR PLANETARY EXPLORATION

1. High level commands (goals) are sent from Ground Control Station through I/F. Goals for detection are sent to SD, remaining goals are sent to the MP.

2. MP produces a plan to fulfil all its goals.

3. MP executes the plan and monitors the execution. If the plan constraints are not satisfied, it generates a new plan as appropriate.

4. If SD detects an event of interest, posts a goal to the MP to take images/analyze the detected object. A new plan is generated by MP.



5. Locomotion Harness takes us to the desired destination point (RG), with coupled rover-robotic arm movement (MM)

6. And performs with the robotic arm (MM) complex (pick/drop) operations

7. Visual perception and localization supports LH (rover, robotic arm) and SD capabilities

8. FDIR ensures continuous safe execution in adverse conditions.

AI MODELS

- **Planning Domain Definition Language (PDDL) model**:
  - Provides an abstract representation of the world to reason on
  - Used by the **Mission Planner** to transform high-level goals (e.g., move sample from one location to another) to low-level operations (e.g., move, pick, move, drop)
    - Provides the **autonomous mission planning capabilities**
    - Component agnostic to the PDDL model using computational logic (LTL, SAS+) as internal representation
    - Model reusable for other missions working on the same representation
- **Neural Network models**:
  - Provides simplified reasoning functionalities with respect to well specified tasks
    - Many models (classes) are obtained via training, one per each task
    - Models reusable for other missions that require the classification of the same events of interest
    - Subject to false positives, intensive training and parametrization needed
  - Used by **Scientific Detector** to detect novelty and classify the detected events
    - Provides the **autonomous opportunistic science capabilities**
  - Used by **Soil Traversability** (offline component) to provide an estimate of the soil traficability (e.g., no sand) and the impact on the rover

EXECUTION MODELS

- **Discrete time/discretized control models**
  - Describes the execution of components in terms of ticks/periods
  - Used by the **Agent** to control the consistent execution of the entire on-board software
    - Main controller embedding a hierarchy of control loops based on the Sense-Plan-Act paradigm
    - Configurable component with automated code generation applicable to any mission
  - Used by **Rover Guidance** to move the rover in a safe manner from one location to another
    - Provides the **autonomous locomotion capabilities**
    - Reusable control model/design principles, but tailored to the rover configuration (e.g., 4 wheel vs 6 wheel rover)
  - Used by **Mobile Manipulation** to reach samples with a coordinated approach of rover and robotic arm movements
    - Provides the **autonomous device mobility capabilities**
    - Reusable control model/design principles, but tailored to the rover model
- **Timed model**
  - Describes the execution of components in continuous real-time
  - Used by **FDIR** to detect hazardous situations and reconfigure the system
    - Enables the **autonomous safe operation in harmful conditions**
    - Dependent on the mission scenario
    - Obtained from a **formal specification** in **BIP** of the **system** and the **properties** to satisfy

ROBOTICS MODELS

- **Geometrical model**
  - Provides the static configuration of the rover
  - Consists of **Computer-Aided Design** (CAD) **model** and **kinematics model**
  - Used by **Mobile Manipulation** for collision avoidance
  - Used by **Visual Perception and Localization** to build the relevant environment for the mission goals
    - Supports the Scientific Detector, Rover Guidance and Mobile Manipulation
    - Provides an environment model and the rover position in the environment
  - Used by **Ground Control Station** to illustrate the rover and its operations in the environment for assessment purposes
    - Commands and monitors the system and assesses the results
  - Used by **Rover Simulator** to illustrate the rover and its operations in the environment for virtual execution and debugging purposes of the entire system

- **Dynamics model**
  - Provides the actuator behavior (based on physical laws)
  - Used by **Rover Simulator** to compute the rover reaction to the commands from the control system
    - A dynamics model of the physical environment interacting with the rover is also embedded

ENVIRONMENT MODELS

- **Orbital Map**
  - Representation of the global environment in which the rover performs its mission
  - Used by Rover Guidance to classify the difficulty of the terrain for traverses
- **Digital Elevation Map**
  - Representation of the local environment (e.g. 8m around the rover)
  - Used by Rover Guidance and Mobile Manipulation for their capabilities
- **3D environment model**
  - Global graphical reconstructed representation of the environment
  - Used by **Ground Truth** for the rover position validation

JOANNEUM RESEARCH

DESIGN AND VALIDATION APPROACH

DESIGN CHALLENGES

- A **complete framework** providing all the desired capabilities for on-board autonomy
  - Using at least one model for each component
  - Integrates on a **plethora of different technologies and formalisms**
- **Developing** a system that uses the different features is a complex task:
  - Correct interfaces between the different components
  - Mix of paradigms and computational models
  - Non-deterministic and deterministic behaviors (e.g., deliberative vs control)
  - Real-time safe behavior
  - Avoid deadlocks (can be costly to correct from ground)
  - Deployment on different HW components
- To tame the complexity of such development one **needs**:
  - A system design process, e.g., the waterfall model
  - Models which describe the system architecture (SW and HW) and interactions, possibly refined towards implementations
  - A model-driven engineering tool encompassing the features above, while automating some static checks, code generation, etc.

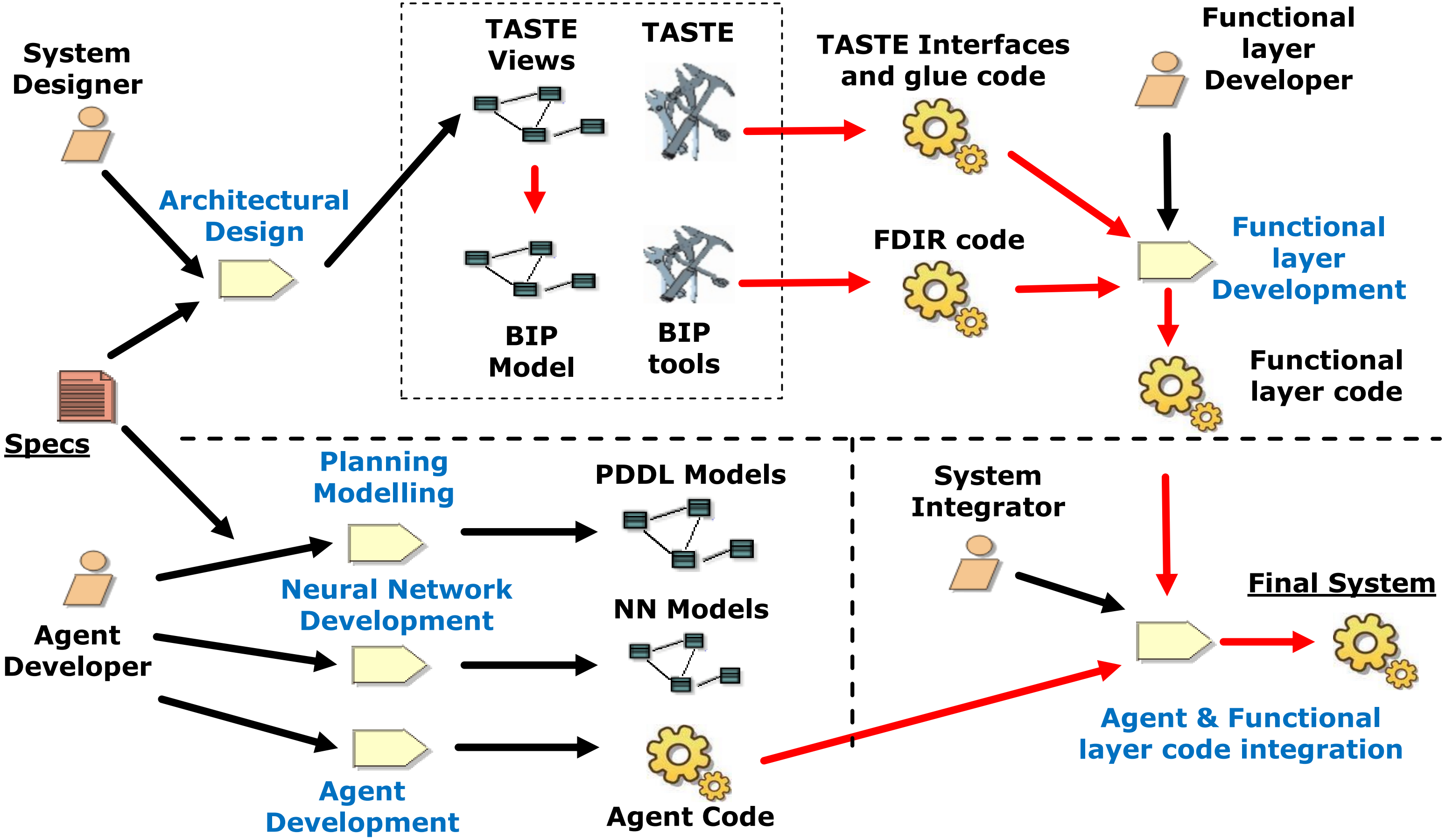
DESIGN AND VALIDATION CHOICES

- Use the **V development model**
- Perform a complete but **high-level system design with UML**
  - Identify the dependencies and interfaces between the components
  - Readable by most of the partners
- **Design** the **integrated system with TASTE toolset**
  - Define and type the interfaces
  - Update the components design according to the computational model
  - Group components based on common functionalities to have a smooth integrated design
- Design, implement and validate the **components independently**
- **Generate** the **executable(s)**
- **Validate** the system with **extensive testing**
  - Several testing levels, from unit testing to field trials
  - No formal V&V, the system too complex

THE TASTE TOOLSET

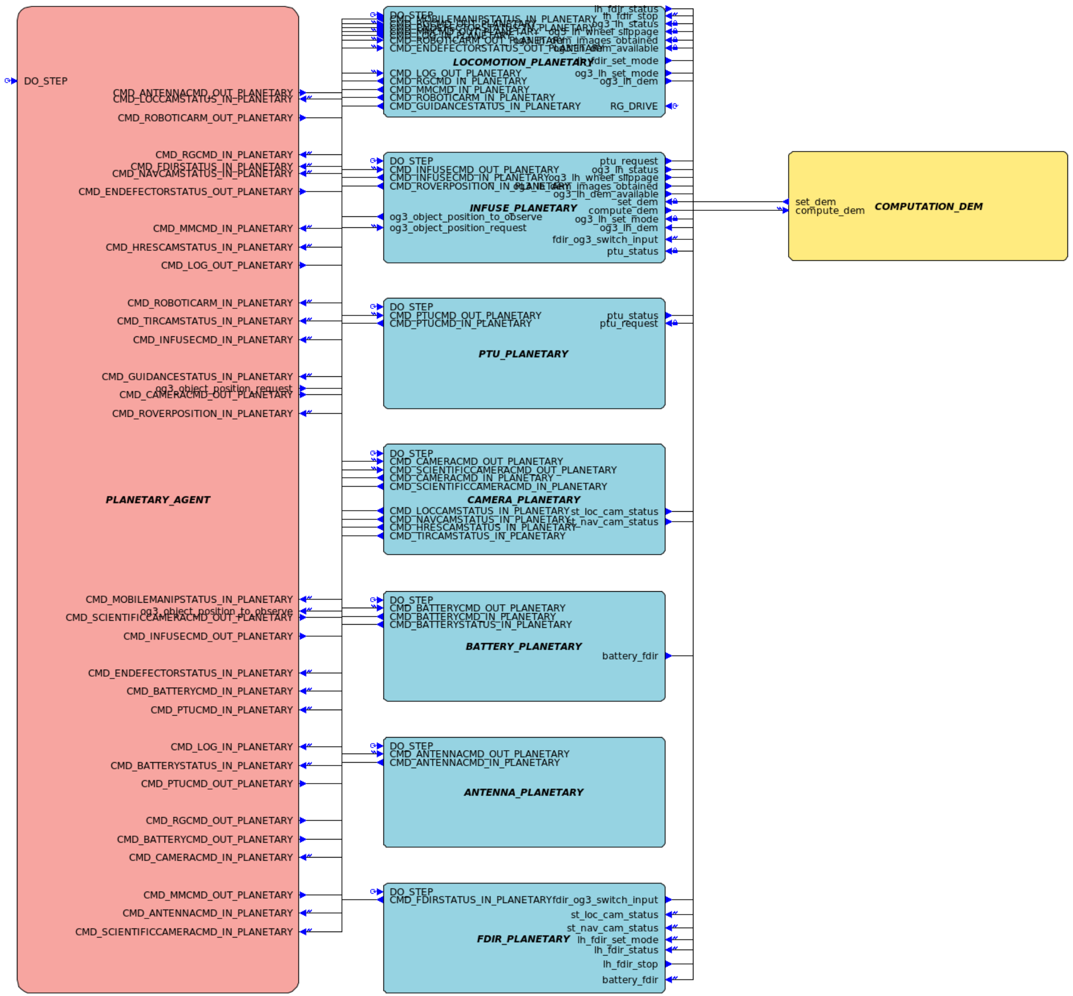
- Targets the **model-based development of heterogeneous, reactive, discrete embedded systems**
- A **TASTE design** consists of datatypes, architecture and behaviour modelling, deployment and tasks scheduling
- Some **features**:
  - Well-formedness and typing analysis of a design wrt the used modelling formalisms
  - Real-time scheduling analysis (e.g., Cheddar)
  - Code generation and deployment (in C/C++,Ada) wrt an execution platform
  - Simulation, debugging and testing
- Some **inconveniences**:
  - **Lack of a formal specification** of the modelling, programming and computational models used (opaque to the system designer)
    - Leads to interpretation errors that are detected and handled during simulation/testing
  - **Tied to the Ravenscar profile**
    - Important for space systems, but
    - cumbersome for the design of robotics systems since tasks cannot be dynamically generated
  - **Inefficient memory assignment** (for sporadic interfaces the maximum heap is assigned)
  - **Limited usability** for complex systems (e.g., for the graphical editors)

ADE DESIGN METHODOLOGY (PARTIAL)



TASTE DESIGN

- 9 TASTE functions
- 58 interfaces:
  - 9 cyclic
  - 8 protected
  - 41 sporadic
- Deployment on an Intel i7 and Arm A53



CONCLUSION

SUMMARY

- The **ADE framework for on-board autonomy**
  - Commanding a robot from ground via high-level goals transformed on-board into operations
  - Plan the daily operations from the goals requested by ground
  - Opportunistic science while performing other activities
  - Complex Mars-representative rover operations (traverse, coupled traverse-robotic arm movement, pick/drop) in safe conditions
- The **ADE approach**
  - Model-based development approach, however code-centric
  - Validation by extensive testing, no formal V&V
- **Validation** in two scenarios
  - Planetary scenario inspired from the MSR-SFR mission
  - Nuclear scenario inspired from nuclear plant decommissioning
- Both the framework and approach are **generic** enough to be tailored to different types of robotic missions (orbital, deep space probe, etc.), but also to robotics terrestrial applications

CONCLUSION (1/2)

- **Very complex design process**
  - No known means to simplify it
  - Adding new components to the system (on-board, on-ground) increases the complexity
- **Requires knowledge in multiple technologies**
  - E.g., domain and theory, computational model, programming language
  - Very difficult to find system designers/integrators with such capabilities
- Preferable **automation** of as many steps as possible by e.g., code generation
  - These steps should be correct in the formal sense
- The **tool/technology used** for system design **drives the implementation of the system and of different components**
  - Transformations at semantic level or artificial constructions are sometimes required to be able to integrate components

CONCLUSION (2/2)

- (Space) Robotics is an **inter-disciplinary field**: robotics engineer, software engineer, systems engineer, …
  - **A model has different meanings** for different communities, e.g., physical/kinematics model, software architecture
  - The **lack of unified language** is challenging in such domains
- Current system design practices are not tailored for robotics system development
  - **Model-based design** is **a viable solution**, but …
  - … the systems are complex, so to well-define an integrated model and its interfaces is a difficult task
  - … the system designer has to deal with many legacy models and code
  - … there is not one model, each component has one in a possibly different computational model
    - Multi-view modelling and views consistency could be considered for heterogeneous systems
  - … new technologies emerge, e.g., neural networks, that are not incorporated in a modelling process or have a different design process
- **Tools** are needed **for consistent system design** process taming the growing complexity and the heterogeneity of technologies used
- Yet, different communities embrace the use of model-based design and apply it at different levels
- It is **possible to build valid complex systems** even without end-to-end off-the-shelf solutions

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THANK YOU