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POLITECNICO DI MILANO

Foresight conference on Technology Breakthroughs for (space) scientific progress

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Outlines

- ✓ Autonomy in space
  - the space mission domain
  - The agents' technology exploitation
- ✓ Final remarks

Autonomy Why?

Autonomy represents a powerful tool to

→**better exploit** robotic systems **performance**
→**enhance** robotic systems **productivity**

Robots need
automation→ to manage and control repeatable low level operations
Intelligent robots exploit
autonomy→to enable low/high level operations in changing/unknown environments

Intelligence entails robots to be provided with reasoning/Decision-Making mechanisms which offer:

- **Flexibility**: unpredictable events, not pre-designed situations become manageable; failed systems still produce
- **Timely response**: idleness is avoidable as the system senses and rapidly reacts
- **Adaptation**: better suited behaviour/control according to the actual sensed environment is achievable; limited resources allocated at best to maximise the robot efficiency

Actors in space: the space mission domain building blocks

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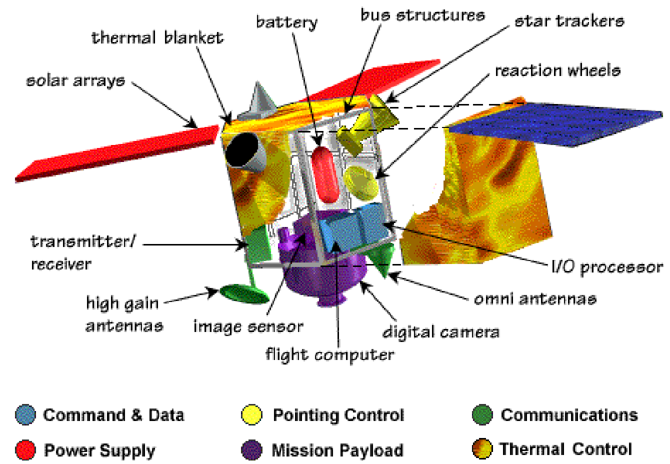
The space system

- Complex
- Multi-disciplinary
- Generally mission dependent
- Highly constrained
- Cost function drivers

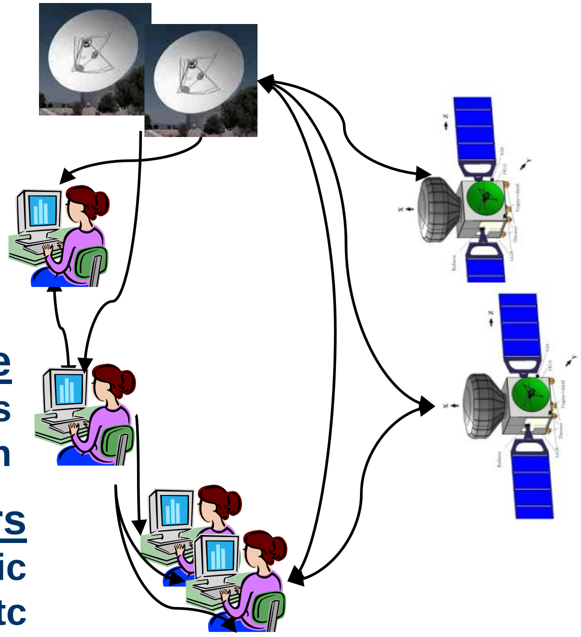


(GS)Ground Stations
Data collection/command sending

Mission Operation Centre
Space segment control timeline definition and setting

Science Operation Centre
On board payload activities planning/analysis/distribution

End users
Data buyers/scientific community/etc



The space mission scenario

- Complex/heterogeneous
- Multi-disciplinary
- Generally mission dependent
- Highly constrained
- Cost function drivers
- (Fast) dynamics involved
- Humans in the loop
- Different time scales

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Reasoning/Decision-Making mechanisms occur during

	features	Decision making on	Goal/needs
Design phase	•Large variables domain: subsystem sizing/device selection •Large net of constraints (temporal/technological/financial,programmatics,etc) •Multiple clashing design drivers •Numerous disciplinary models/tools •Numerous experts involved one System Engineer	•Engineering design •Technological development needs •Modules/mission sequencing •Financing profile	•Feasible system/mission design and lifecycle definition •Team support tool

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Reasoning/Decision-Making mechanisms occur during

	features	Decision making on	Goal/needs
Mission operation phase	• Features segment dependent/mission dependent • Large variables domain: subsystem/system state vector in time • Discrete/continuous domains • Different operational phases differently constrained • Large net of temporal/logical constraints • Different and complex resources/resource availability dynamics • Both hierarchical and peer-to-peer architectures among actors • Uncomplete environmental and behavioural knowledge	▪goal(local/global) ▪Strategies to get the goal ▪Resources/tasks allocation/distribution ▪Action/commands to cope with uncertainties/unpredictable events coping ▪control law ▪Strategies for the basic behaviours coordination	• Robust and consistent allocation of actions/activities and resources in time • Logical/temporal solvers • Supports to operators

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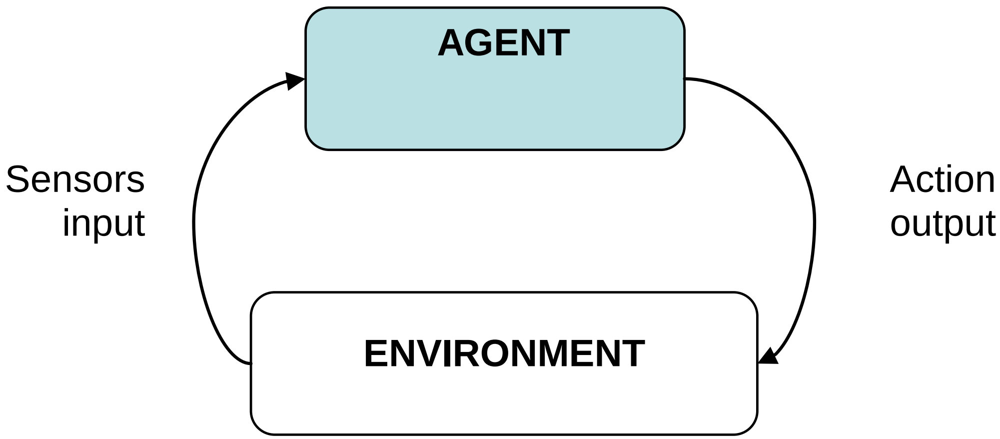
Autonomy in space would support and cope issues for:

- Complex mission scenarios
  Formation flying (Darwin, Lisa, GMES)
  Multimodule missions (ExoMars, Bepicolombo, MSR)
  cooperative heterogeneous entities (Human bases)
- Very far missions → comms delays→ mission return degradations and lack of robustness (Asteroids missions, Laplace, Cassini like)
- Complexity in space operations
  Docking/RV, In space Buildings, human bases-Astronauts supports
- Huge scientific data managements: possible multiple p/l, possible timeliness need in elaboration
  Earth monitoring/protection missions (GMES, Envisat like)
- Mission with harsh and unknown environment
  Exploration missions to NEO, Mars, Moon, Comets
- Limited on-ground resources scenarios
  Mission control centre bottleneck support
- Anomalies & unpredictable events/opportunities management

Autonomy how: the Agent tech answer

“agents are simply computer systems that are capable of autonomous action in order to meet their design objectives” [Wooldridge]

“an agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators” [Russell and Norvig]



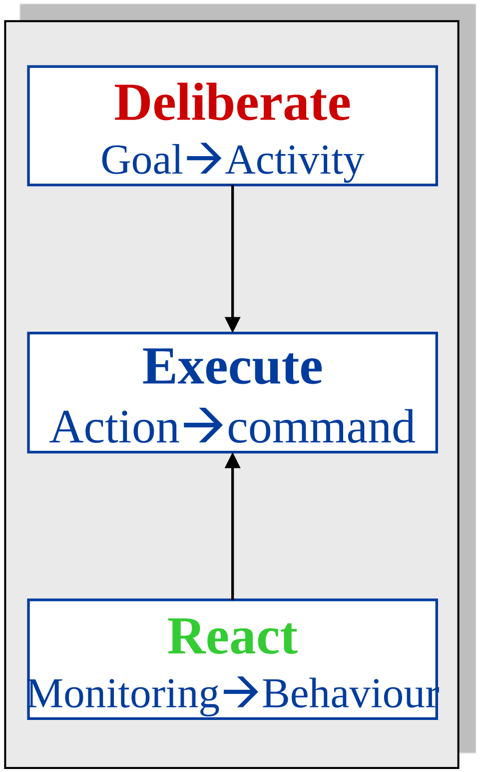
Autonomy how: the Agent tech answer

Solution→ to shift part of the decision-making processes on-board through **Agent paradigms** exploitation

In an Artificial Intelligence framework an **agent** enjoys the properties of:

- **autonomy** → agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state;
- **social ability** →agents interact with other agents (and possibly humans) via some kind of agent-communication language;
- **reactivity** →agents perceive their environment, (which may be the physical world, a user via a graphical user interface, a collection of other agents, etc), and respond in a timely fashion to changes that occur in it;
- **pro-activeness** →agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative

The Agent functionalities



DELIBERATIVE LEVEL

- Produces the high level decisions at system level (goals);
- Deliberates activities exploited to obtain a long-term control strategy to satisfy high level goals according to the system/environment physical constraints
- States for failures occurrence and recovers

INTERMEDIATE LEVEL

- Turns actions into real commands to the hw coping with possible uncertainties rising from unknown and dynamic environment

REACTIVE LEVEL

- Monitors the actual system/environment conditions and identifies – within the short incoming time span –the set of commands consistent with them

The Agent building blocks

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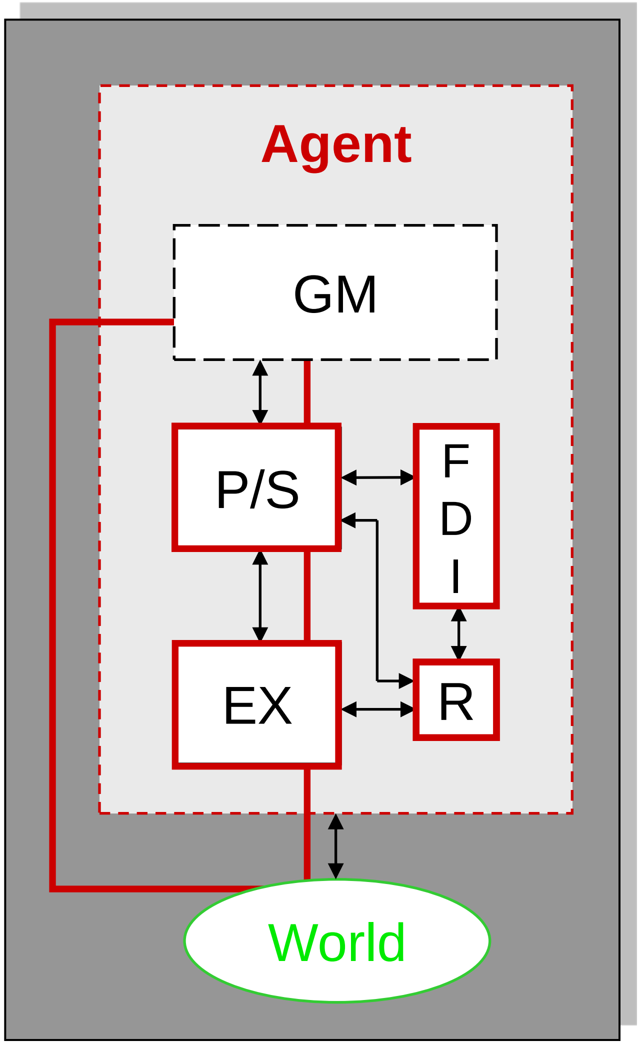
- Goal Management
- Planning/Scheduling
- Execution
- Failure Detection & Identification/Reconfiguration



Partial architectures/paradigms can be selected depending on the applicative scenario

Deliberative: based on the symbolic reasoning needs a world representation

Reactive: no knowledge of the world is needed

Hybrid: focused on merging the benefits of both the deliberative and reactive architectures

The Deliberative Agent

Goal generation

- Aim: to identify the best/most convenient particular state of the world to satisfy given criteria
- Control variables: system state/environment
- Constraints: feasibility

Goal generation is a Decision Making/Opt problem on system states/resources

Planning

- Aim: to reach a particular state of the world, starting from the current one
- Control variables: actions to be sequenced (i.e., a plan) to achieve the objectives
- Constraints: pre, post or during conditions among selected activities in the plan

Planning deals with system states, and their changes & logical dependencies

Scheduling

- Aim: To select the feasible plan that satisfies constraints related with time
- Control variables: Timelines of activities
- Constraints: Resource limitation and temporal constraints

Scheduling deals with allocation in time and resources exploitation

Failure Detection/identification

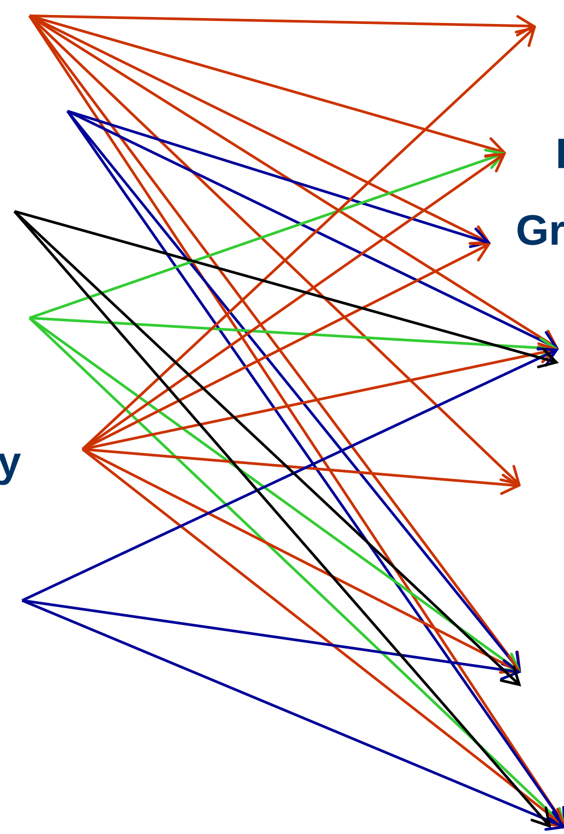
- Aim: To classify deviation as failures/to identify faulty units
- Control variables: Timelines of activities
- Constraints: functional dependencies in the system

FDI deals with modelling robustness and abductive reasoning

AGENT in space for AUTONOMY

Functionalities

- Science (Re)-planning
- Resource management
- Mission management
- Timeline management
- Failure detection & Identification & Recovery
- Opportunity exploitation\reaction



Scenarios

- Deep Space Navigation & Control
- Entry Descent & Landing
- Ground stations automation
- Planetary Exploration
- Rendez-vous & docking maneuvers
- Coordination of multiple segments (humans included)
- Interplanetary probe\ Earth spacecraft

The Deliberative Agent

Pro-activeness → **Deliberative**

Top-down reasoning

→ large problems/largely constrained managed

→ wide time horizon managed

→ large knowledge to be uploaded (e.g.model needed for resource propagation)

The deliberative paradigm is greatly exploited to get rid of ***decision making***

Pro's

- Forecasting skills
- Decision making supported by a global point of view

Cont's

- Problem solving limited to situations included in the domain of experience
- No reactive behaviour to environment exists

Methods

MCDM/MADM
CSP
COP

Soft computing/heuristics
Global optimization/MDO
Graph theory
Logical reasoning

The Reactive Agent

Reactivity → **Reactive**

Bottom-up reasoning → actions focused on perception
→ very short time horizon managed
→ very limited knowledge required

Pro's

- adaptive to the system current status
- robustness+flexibility+time
- learning from experience capabilities

Cont's

- lack of global vision in time→local point of view
- strategies to be defined for complex reasoning

Methods

MCDM/MADM

Soft computing/heuristics
Global optimization/MDO
Behaviour based reasoning

The Agent's architecture comparison

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Architectural aspects\General scenarios	Reactive	Deliberative	Hybrid
Known environment	Useful if no P/S functions are required (or simple tasks/goals have been implemented)	Correct choice in P/S functions are required	Maybe too much complex for this case
Unknown environment	Well suited even it can involve a huge list of behaviours in case of very complex and unknown environment	Not suited because planning is (rather) impossible and not effective	It could be used according to the flexibility and robustness of the agent towards the environmental uncertainties
Timeliness required	Applicable only when the tasks and the actions to be performed, and the goals to be accomplished are extremely simple	Well suited in case of perfect model of the world (extremely high confidence in actions execution by the agent)	Hybrid agent is well suited because guarantees short-term execution and long-term deliberation
Long term vision required	Not applicable	Correct choice	Correct choice if the agent has long-term deliberative faculties
Autonomy level	Low level of autonomy (i.e. directly controlled or semi-controlled robot) or fail-safe functions	High level of autonomy, but with a perfect knowledge of the world (ideal case).	High level of autonomy in a very complex situation and real environment

Autonomy in space: levels definition

From the European ECSS Space Segment Operability Standard : on-board autonomy management addresses all aspects of on-board autonomous functions that provide the space segment with the capability to

continue mission operations and to survive critical situations without relying on ground segment intervention

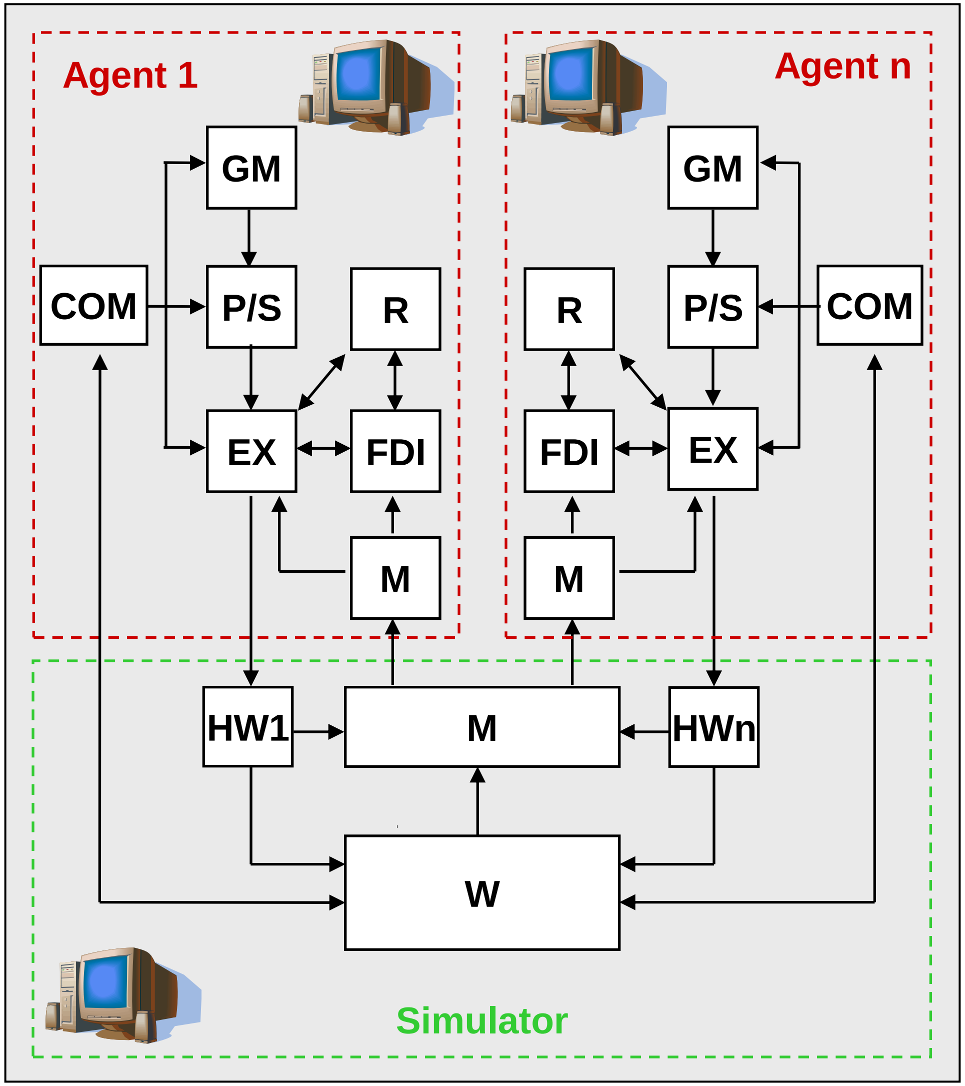
Autonomy levels and criticalities

Level	Description	Functions
E1	Mission execution under ground control; limited onboard capability for safety issues	Real-time control from ground for nominal operations Execution of time-tagged commands for safety issues
E2	Execution of pre-planned, ground-defined, mission operations on-board	Capability to store time-based commands in an on-board scheduler
E3	Execution of adaptive mission operations on-board	Event-based autonomous operations Execution of on-board operations control procedures
E4	Execution of goal-oriented mission operations on-board	Goal-oriented mission re-planning

Agents

Courtesy of ESA-ECSS

Single Agent→Multiple Agents



The Multiple Agents' technology

A multi-agent system is one that consists of a number of agents, which ***interact*** with one-another.

To successfully interact, they will require the ability to:

- Cooperate
- Coordinate
- Negotiate

Key aspects for designing MAS

All those functionalities ask for a **communication paradigm** to be defined to let information be shared among the team units

The Multiple Agents’ distribution

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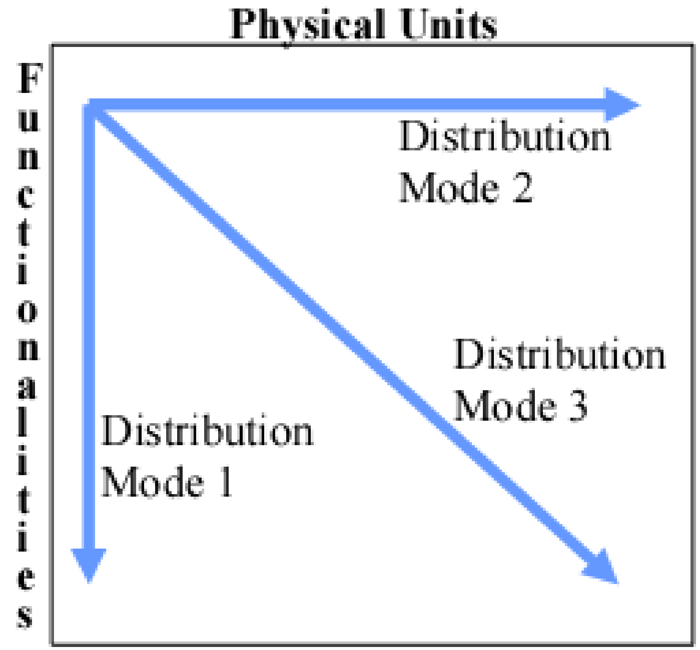
•The **Physical Distribution** implies the deployment of a MAS architecture across multiple physically distinct platforms

•the **Functional Distribution** is such that, a MAS architecture is used to perform the different functions required by a single system, by dedicating an agent to each function or task.

agent technology can be distributed in terms of:

•Intelligence
• capabilities
• communications
• resources



The Multiple Agent's architecture comparison

Architectural aspects\General scenarios	Communication	Auction & Negotiation	Organisation
Physical distribution	Extremely important for reaching coordination. Mean of communications to be carefully evaluated (radio-link, internet/ethernet, …).	Negotiation becomes relevant in case of private resources to be used by other agents or by the agency, or in case of instruments to be physically shared, otherwise distribution is not demanding.	The organization pattern is extremely important and could have an added value in this case. Physical distribution helps in choose the pattern (i.e.: mimicking the real-world structure of the agency)
Logical distribution	Communication protocols must be established (in general they are the interfaces among the logical units of the MAS), but they are not demanding because in general there is a unique physical entity.	Coordination is important because different functions (i.e. agents) could be in conflict among each agents, or they could use the same physical resources.	Organisation in general maps the logical relationships among the functions/agents, thus keeping the hierarchies and the dependencies.

The Multiple Agent's architecture comparison

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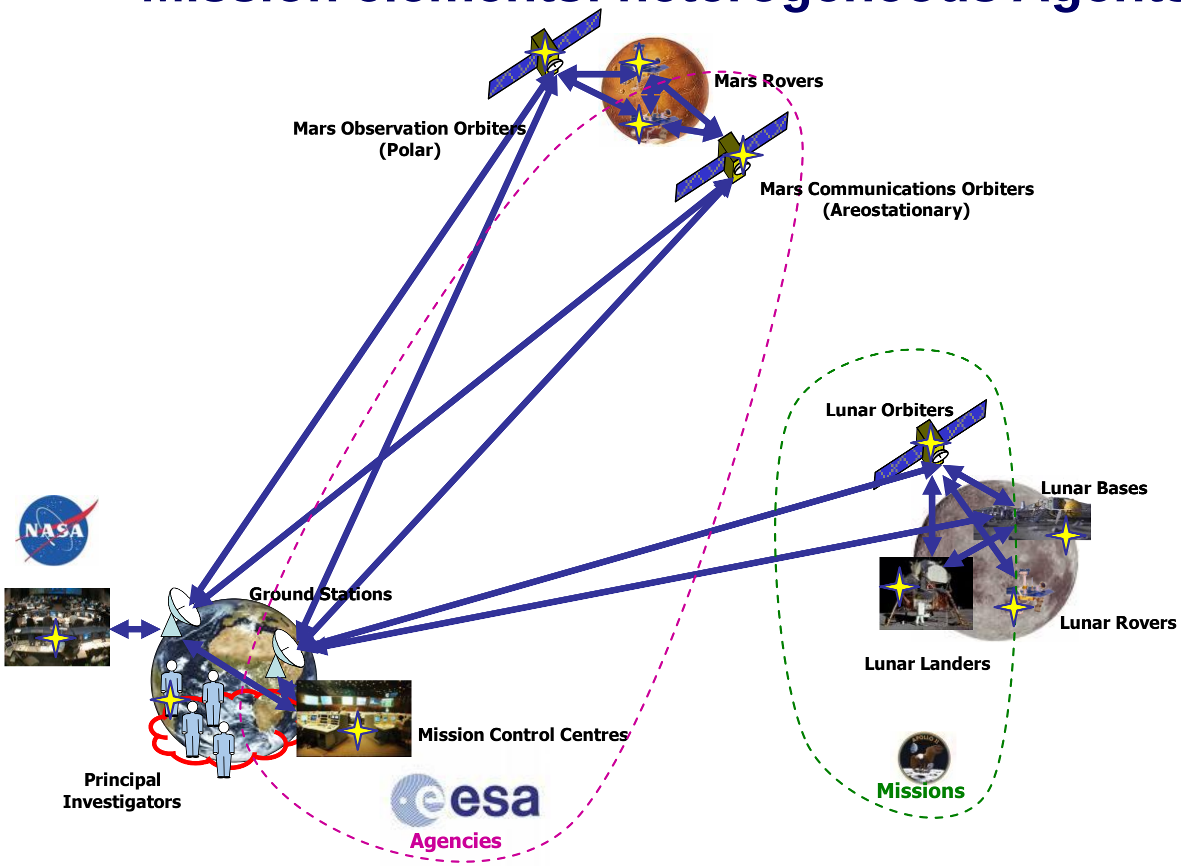
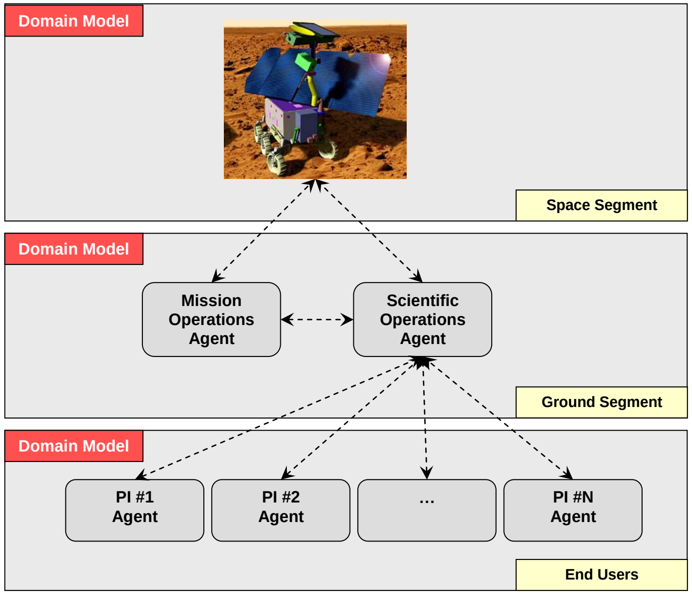
Architectural aspects\General scenarios	Communication	Auction & Negotiation	Organisation
Limited resources	Extremely relevant in case of a limited number of messages or a limited information flow between the agents; otherwise communication protocols and languages are only functional for reaching the agreement on shared resources.	Extremely relevant issue for the optimization of the limited resources.	The choice of the good MAS pattern could help in optimizing the usage of limited resources or in reaching coordination.
Unlimited resources	Not relevant issue	Negotiation and auction may be useless because resources could be freely exploited; coordination is always relevant when two or more agents execute different actions at the same time or when there are other constraints.	Organization could be extremely important with unlimited resources because could give an added value in the reaching of the common goal (e.g.: could be a pathfinder for the limited resources case).

Mission elements: heterogeneous Agents, nested architectures





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Formation Flying/Swarms

of units N=[2;100] thight control on relative dynamics→hard constraint → on-board autonomy needed

In orbit missions: EO-1+Landsat-7; GRACE(DLR); LISA (ESA); SMART2 (ESA); DARWIN(ESA); Proba 3;Terrestrial Planet Finder(NASA);ST5 Nanosat(NASA)

Constraints: hard→Formation geometry/relative dynamics

→available local/shared on board resources

→ real-time

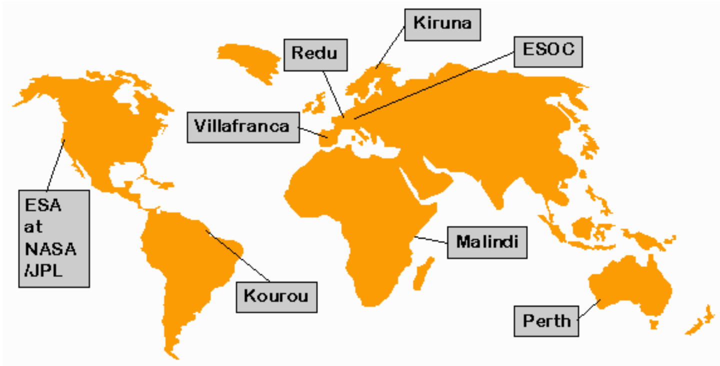
→ common high level goals (scientific data collection, maneuvers, etc)

FF autonomous management: centralized (hub)←→distributed

Requisites: flexibility/robustness

Challenges: local ↔local consistency ⇒negotiation, comms strategies, knowledge bases management and distribution, very limited computational resources

Ground station nets



1 Mission Control Centre → N Ground stations devoted to:

Tracking/Ranging orbiting systems

Telemetry/data Rx

Telecommands Tx

ESTRACK: Darmstadt (MOC), 7 Ground stations (Redu 10 Antennas, Villafranca 8)

Constraints: hard→orbiting systems/antennas relative dynamicss (visibility)

→shared technical/financial resources

→ high dimension problem

→on-board functional constraints

Autonomous/smart management: centralized/disributed (hetero/homo-geneous nets)

Requisites: flexibility/robustness possible human interaction

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Team of Robots

Robots: rover flottillas/UAV from 10 to 100

Scenario: planetary exploration / Location setting for human habitat→autonomy

Elements: heterogeneous/homogeneous

Constraints: →common/coordinated goals/tasks

→ local/shared resources

→ relative dynamics

Autonomous management: centralized←→distributed; hierarchical/peer-to-peer

Requisites: flexibility/robustness/reactivity

Issues: unknown environment; comms management; possible human interaction; learning needed

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Single Vehicle

Scenario: planetary surface vehicle exploration/satellite

Agents: cluster of on-board subsystems/cluster of on board functionalities

Goal: robustness/flexibility increase; system product return increase

Constraints: →system functional model

→ shared/local resources

Interaction strategy: competitivw/collaborative

Issues: comms; interfaces; architecture selection

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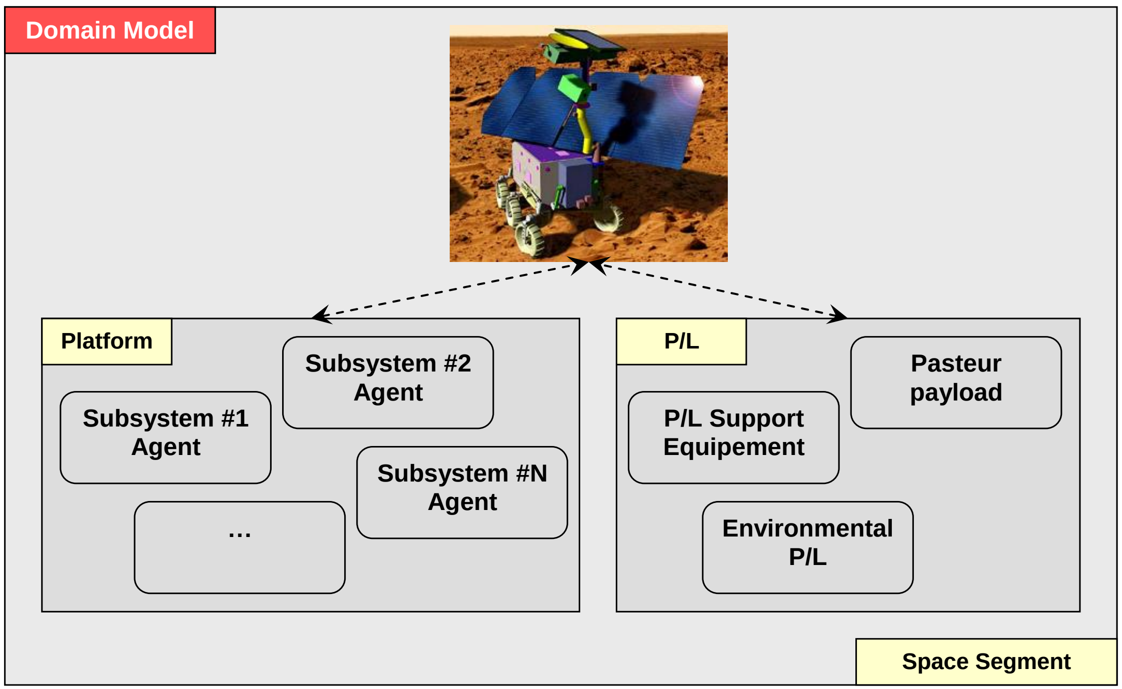
Single Vehicle, Multiple Agents



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Design phase

Space System: orbiter/lander/robot etc

Scenario: Concurrent Engineering Process

Agents: Subsystem discipline

Constraints: →design relationships inter/intra-disciplines

→ temporal/financial/technological resources

Architecture/Interaction:
centralized←→distributed,competitive←→collaborative

Requisites: robustness/reactivity/flexibility

Issues: Strongly coupled design among disciplines; human behaviour in decision making to be possibly modelled

Distribution: where?

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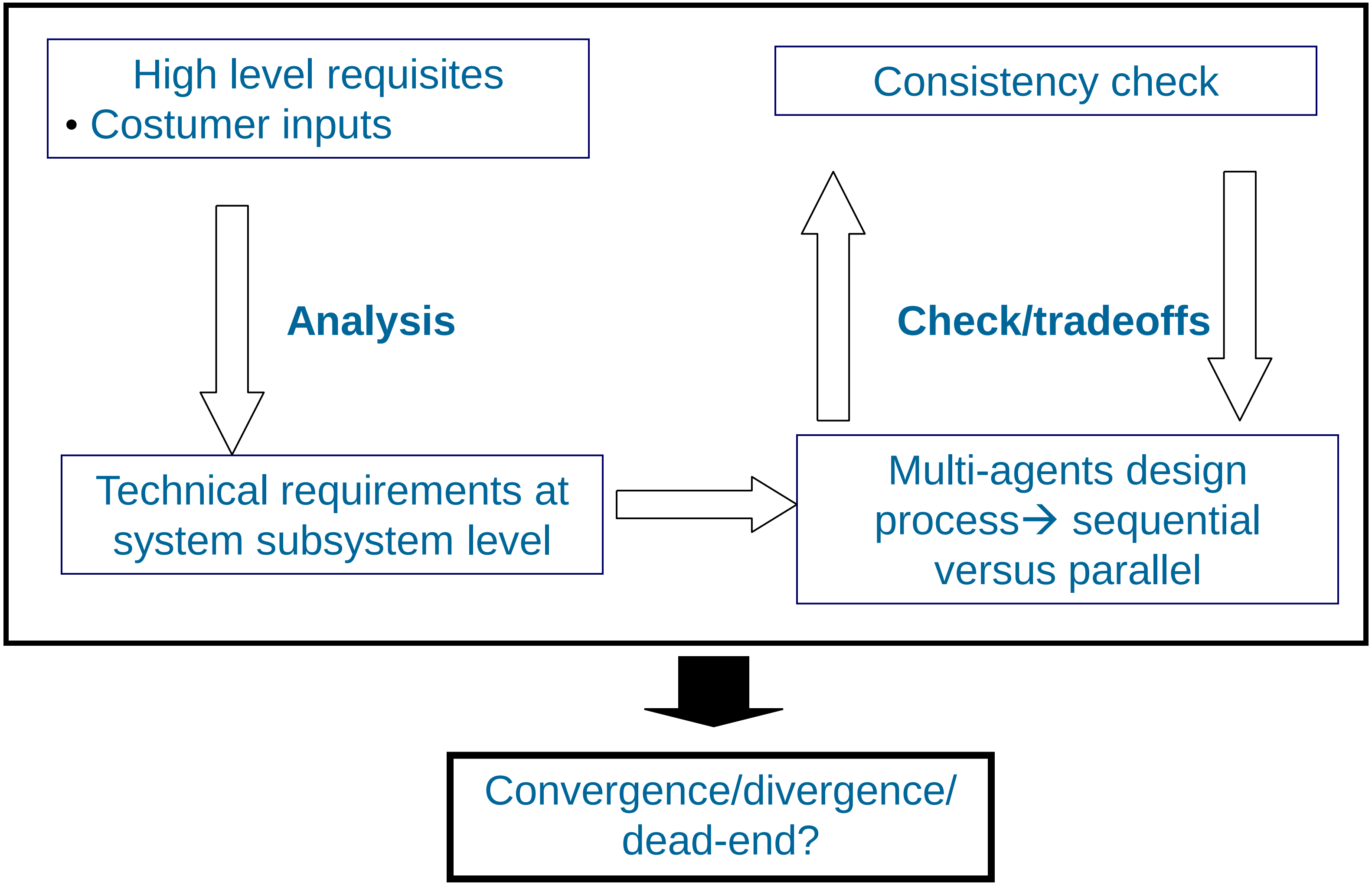

Agents' tech TRL

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	Current status EU	Current status US	notes
Goal Generation	3	7 very limited functionalities in scientific location for Mars rover selection	•Well-known decision making techs on completely new application
Planning	4-5 demonstration limited to p/l activities sequencing	7	Well-proven algorithms Industrial applications
Scheduling	3-4	7	Main challenge represented by the type of resource to be managed
FDI	3-4	7	Main challenge represented by the modelling limitations
Reactive agent	3	4	
Hybrid agent	3-4	7	Challenge: system harmonic representation/interface management/execution module
MAS	3	3	

Development steps

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1. To test and validate each agent's component with a real mission sw simulator
2. To test and validate each agent's component with a real mission hw in the loop
3. To test and validate each agent's component on ground, run as a back-up of the mission management in nominal and off-nominal scenarios
4. To test and validate the whole hybrid architecture with a real mission hw in the loop
5. To test and validate fly as an experiment on board either partial or the whole agent tool

Final remarks

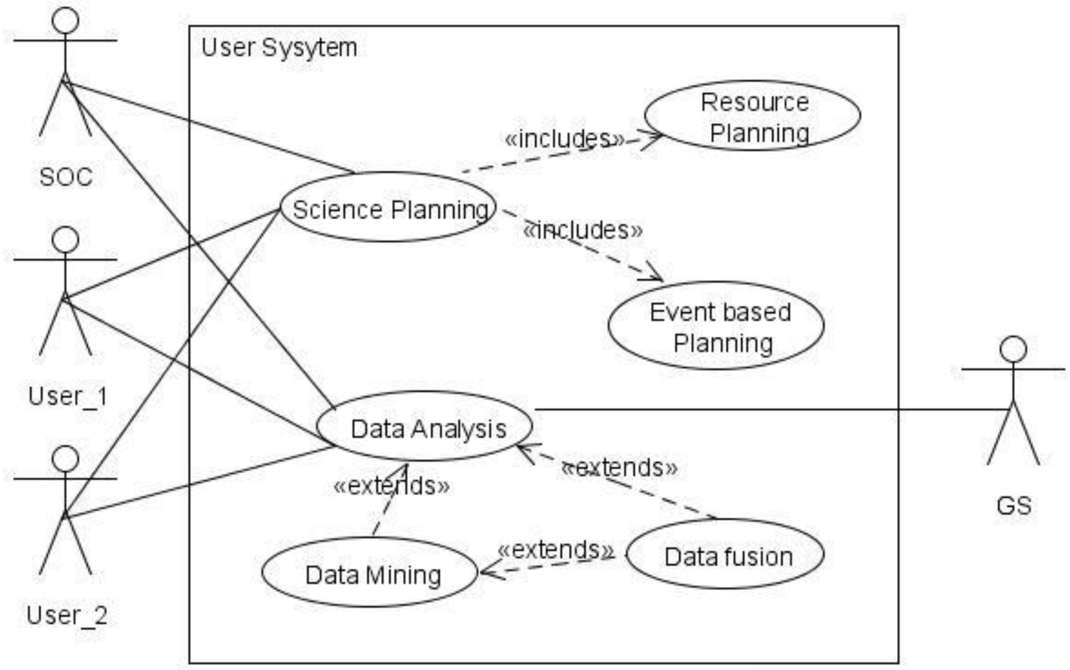
•Within the space domain to study and apply autonomy and distribution is an **obliged step to answer mission goals** tighter and more challenging

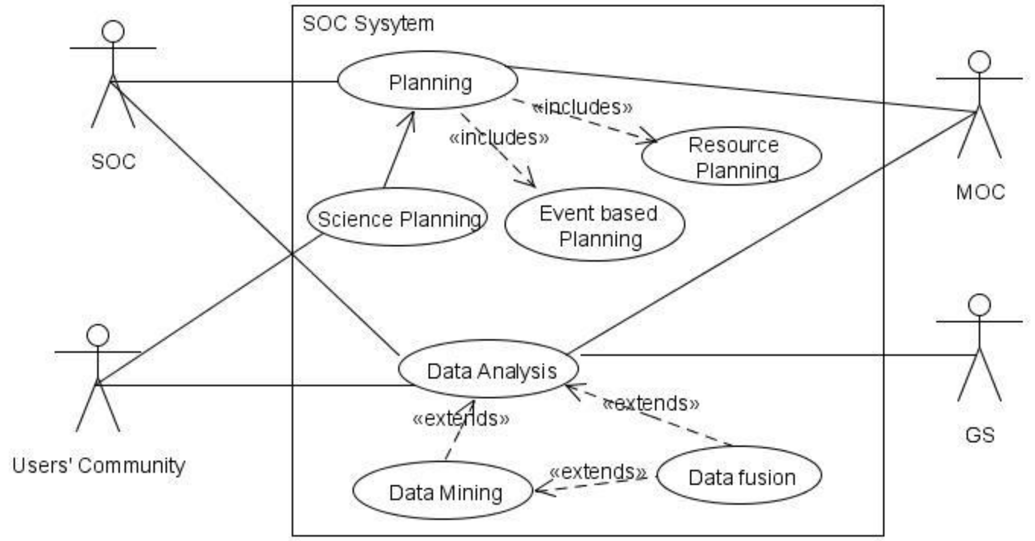
•**Single Agent** architectures seems to be the well-suited tool especially within the operative phases **to answer flexibility, feasibility and robustness** requirements

•**Multiple Agents Systems** may answer **a wide class of issues and bottlenecks** the space engineering community is facing; this technology, however, post further challenges in the communication management, the knowledge sharing and the common constraints resource management and need the single agent technology to be firstly exploited and validated in the space activities framework.

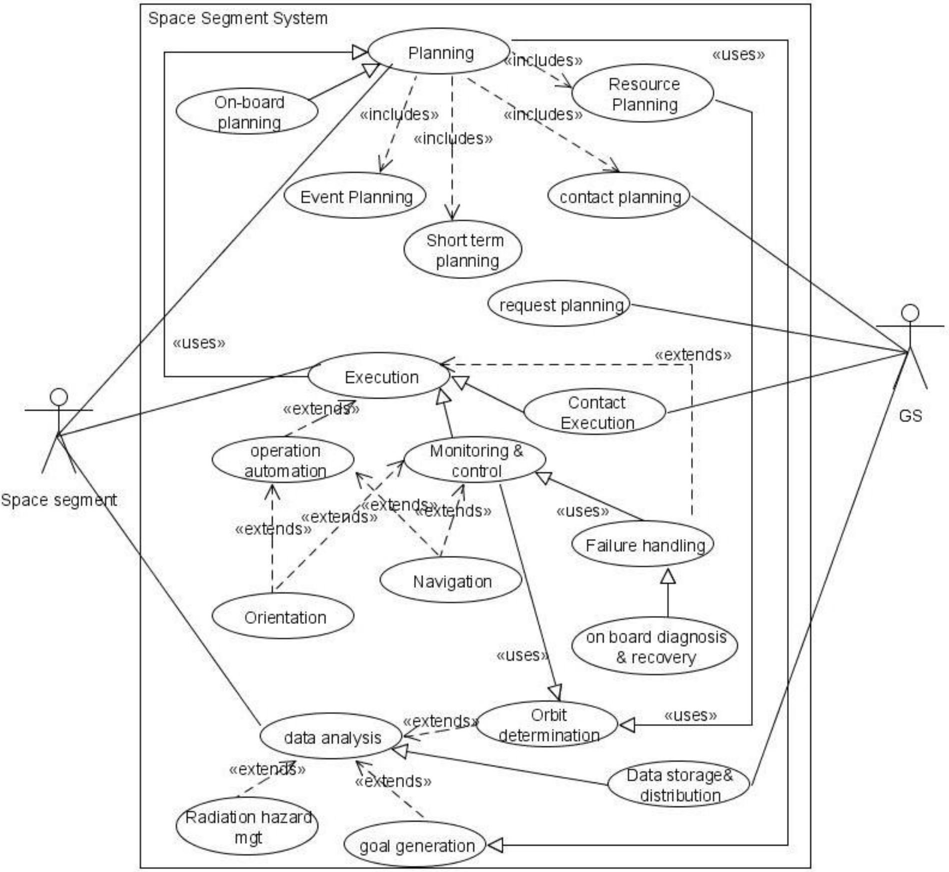
backup

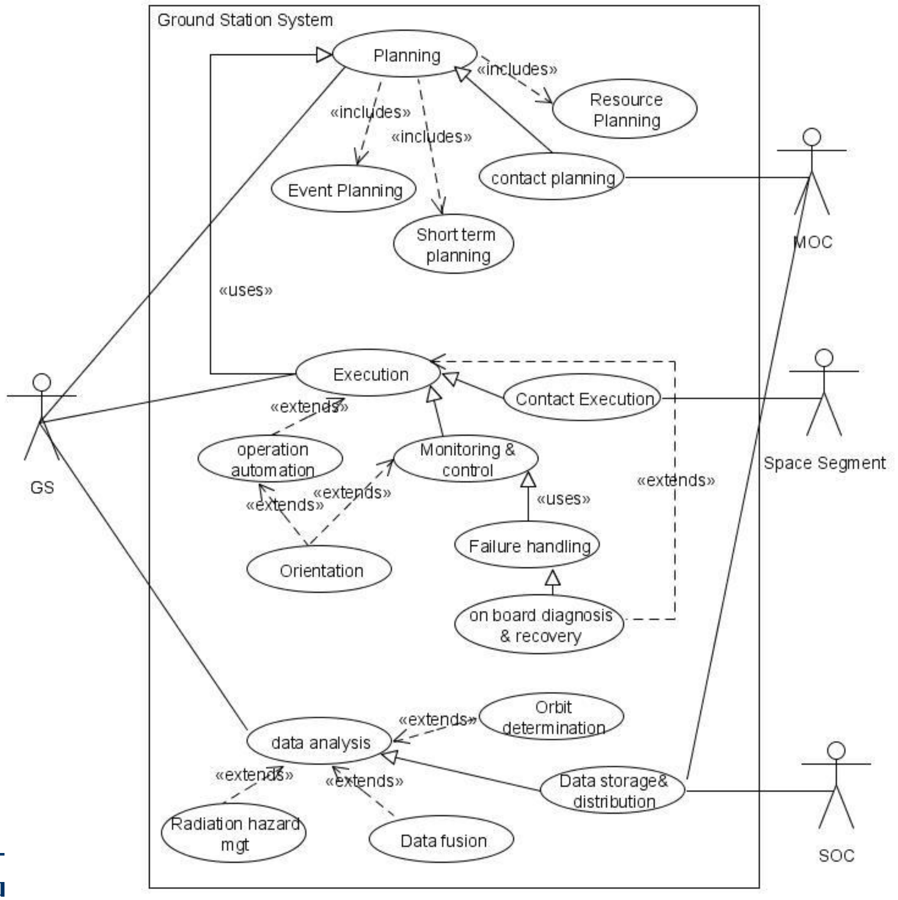
Earth Observation Scenario





Earth Observation Scenario





Formation Flying-multiple in space segments

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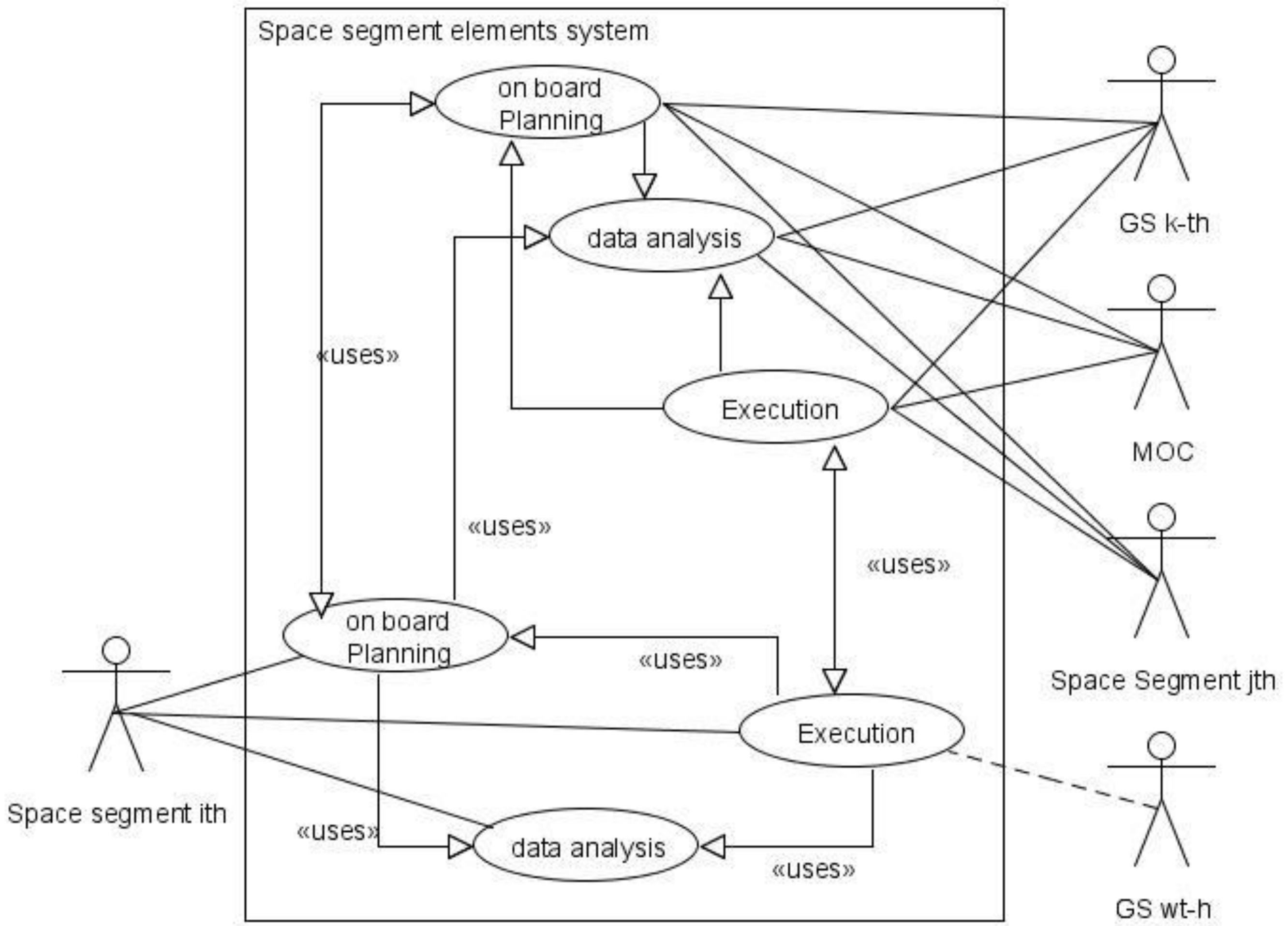

Formation Flying-multiple in space segments

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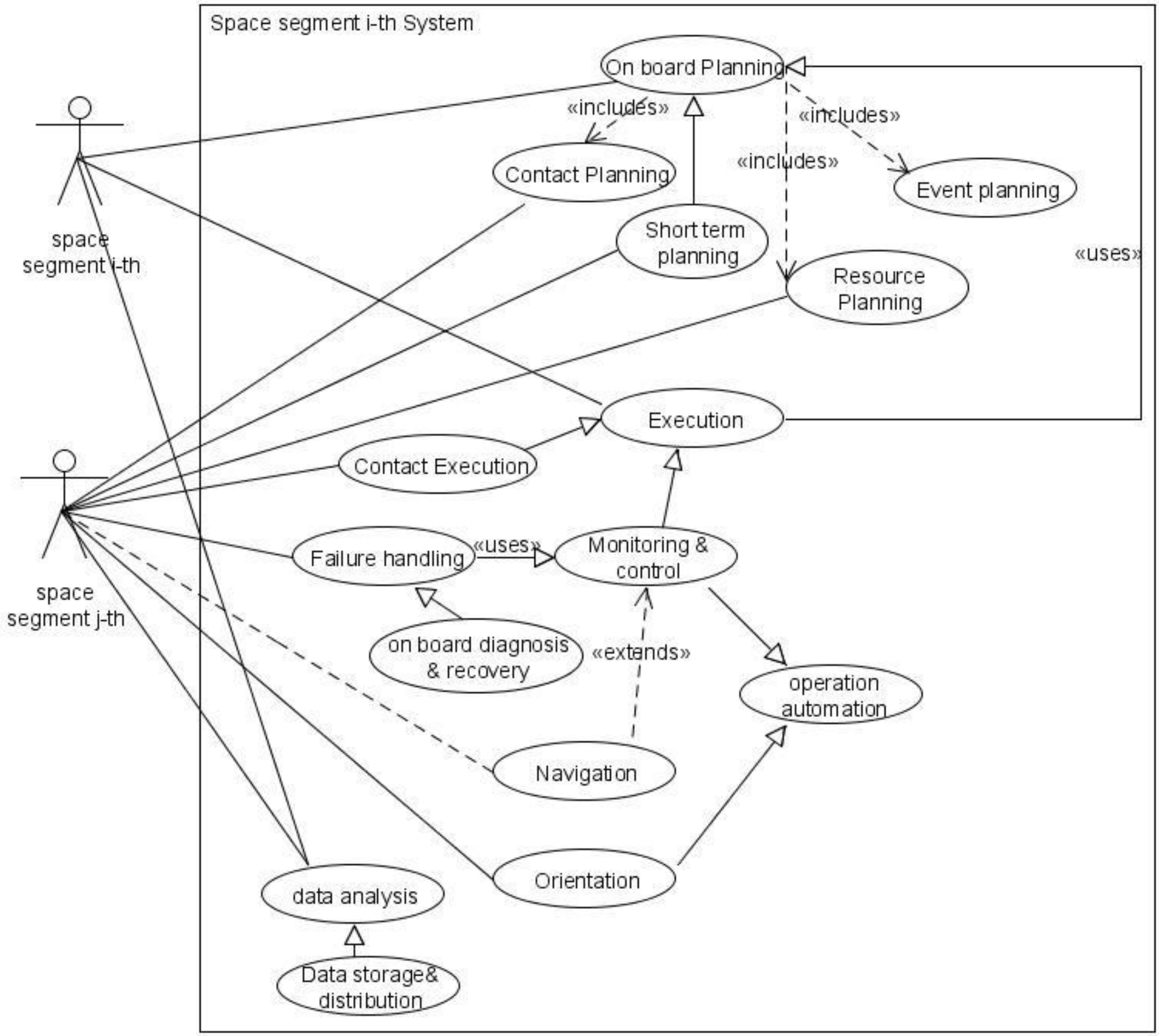

Space Exploration

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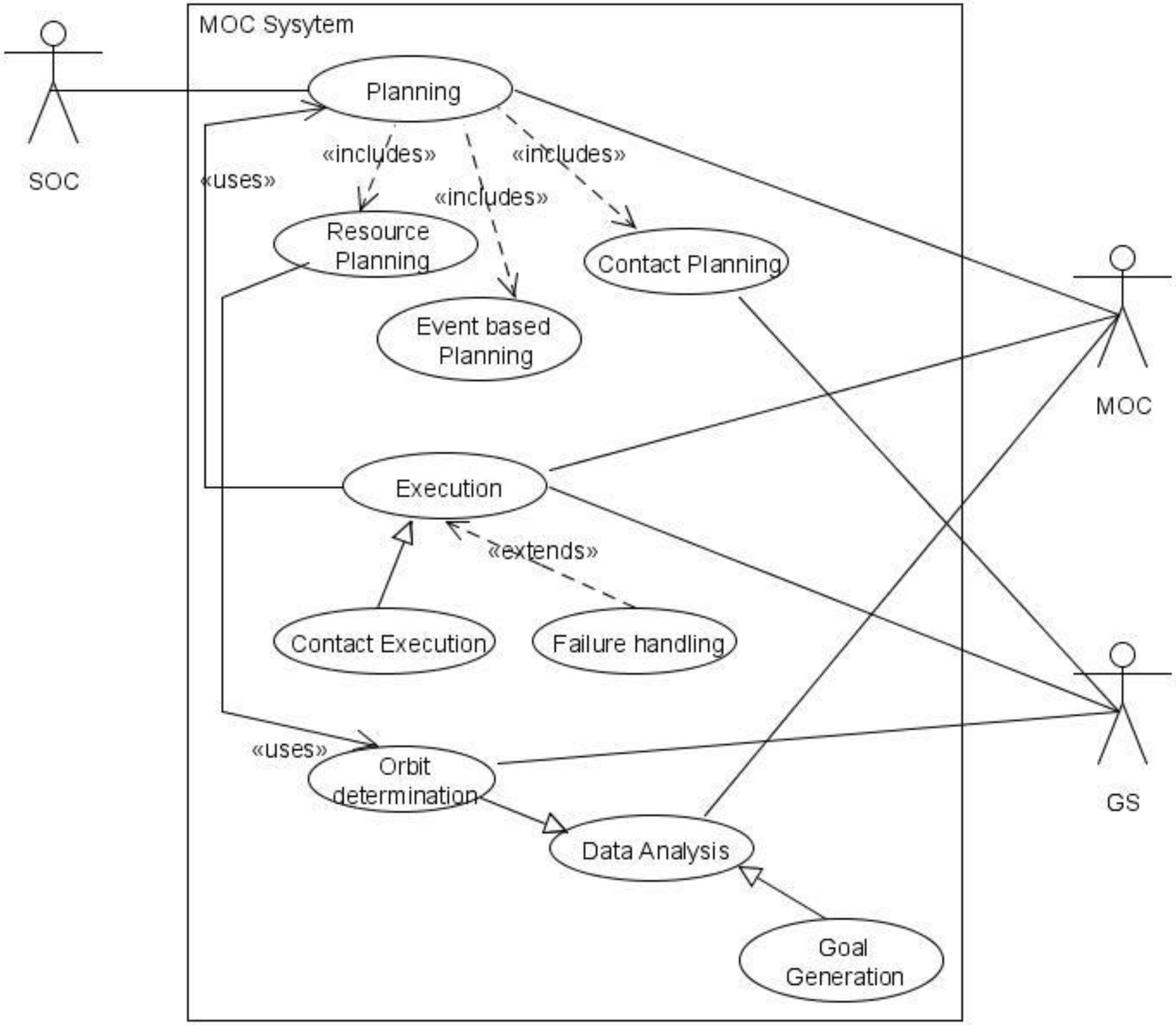
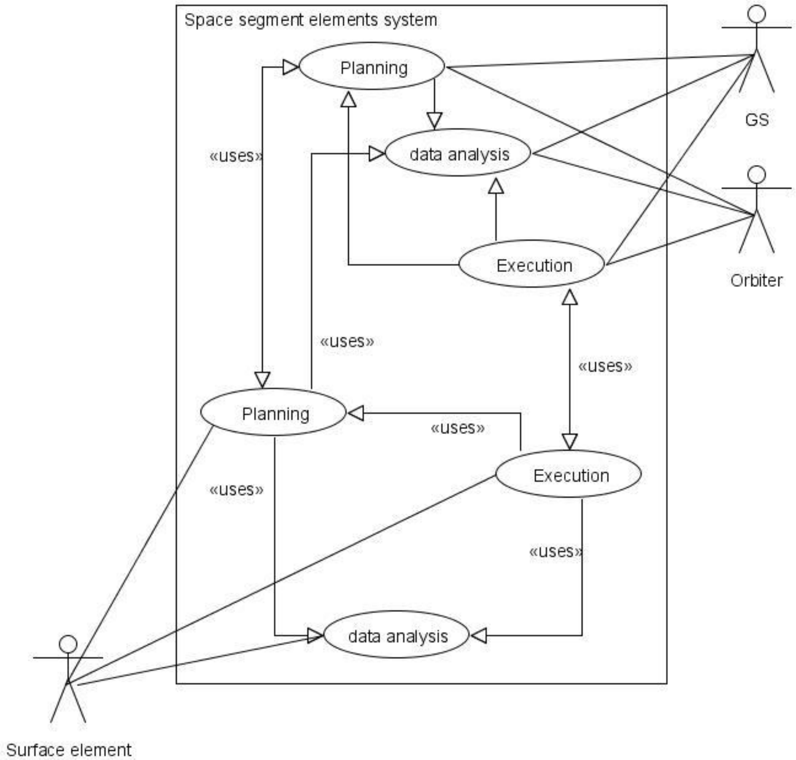
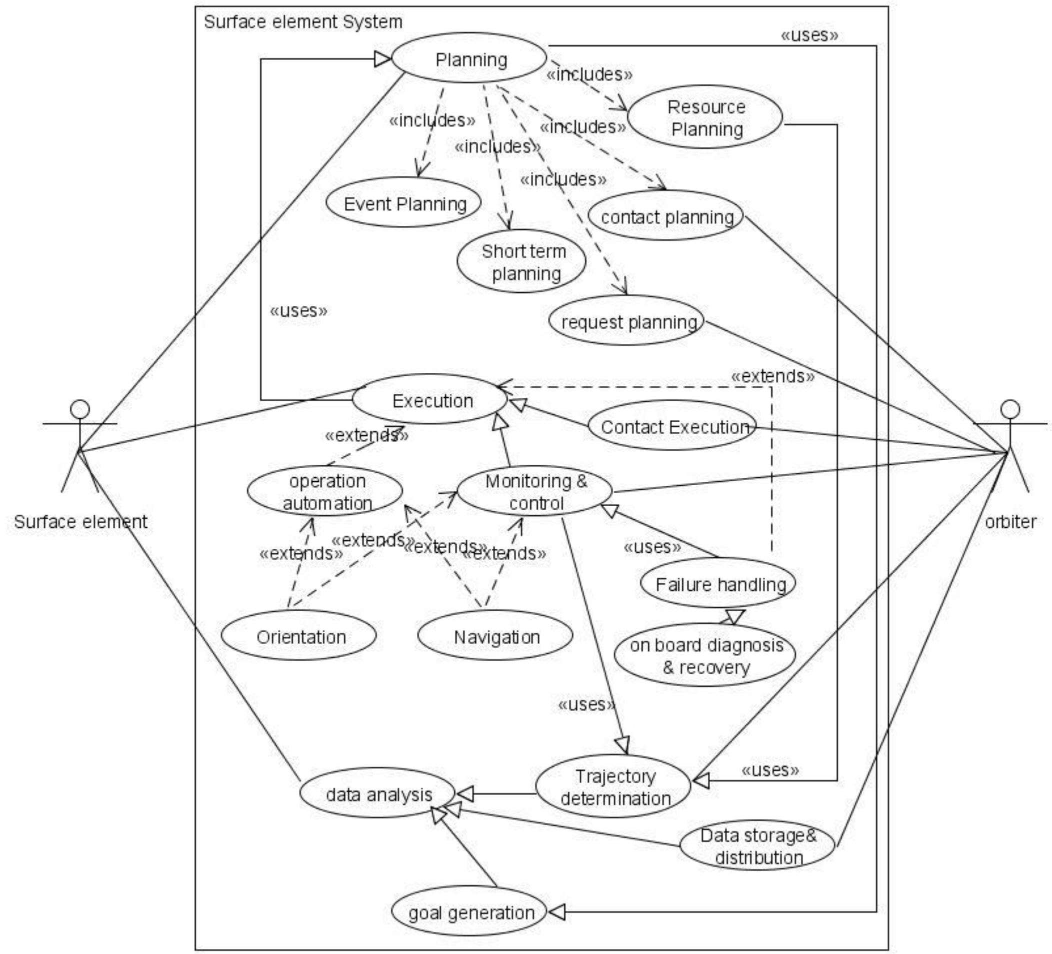
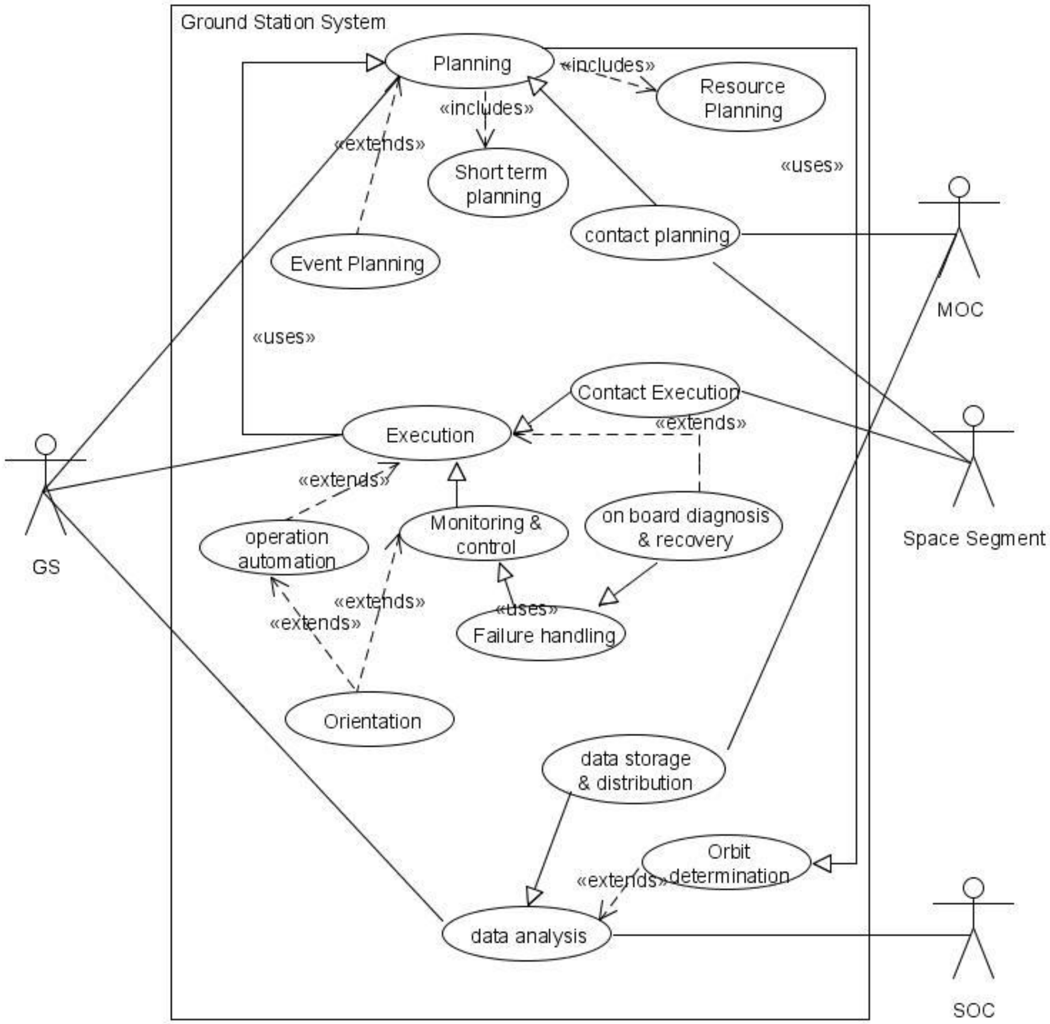


Space Exploration





Space Exploration



Autonomy: virtual simulator

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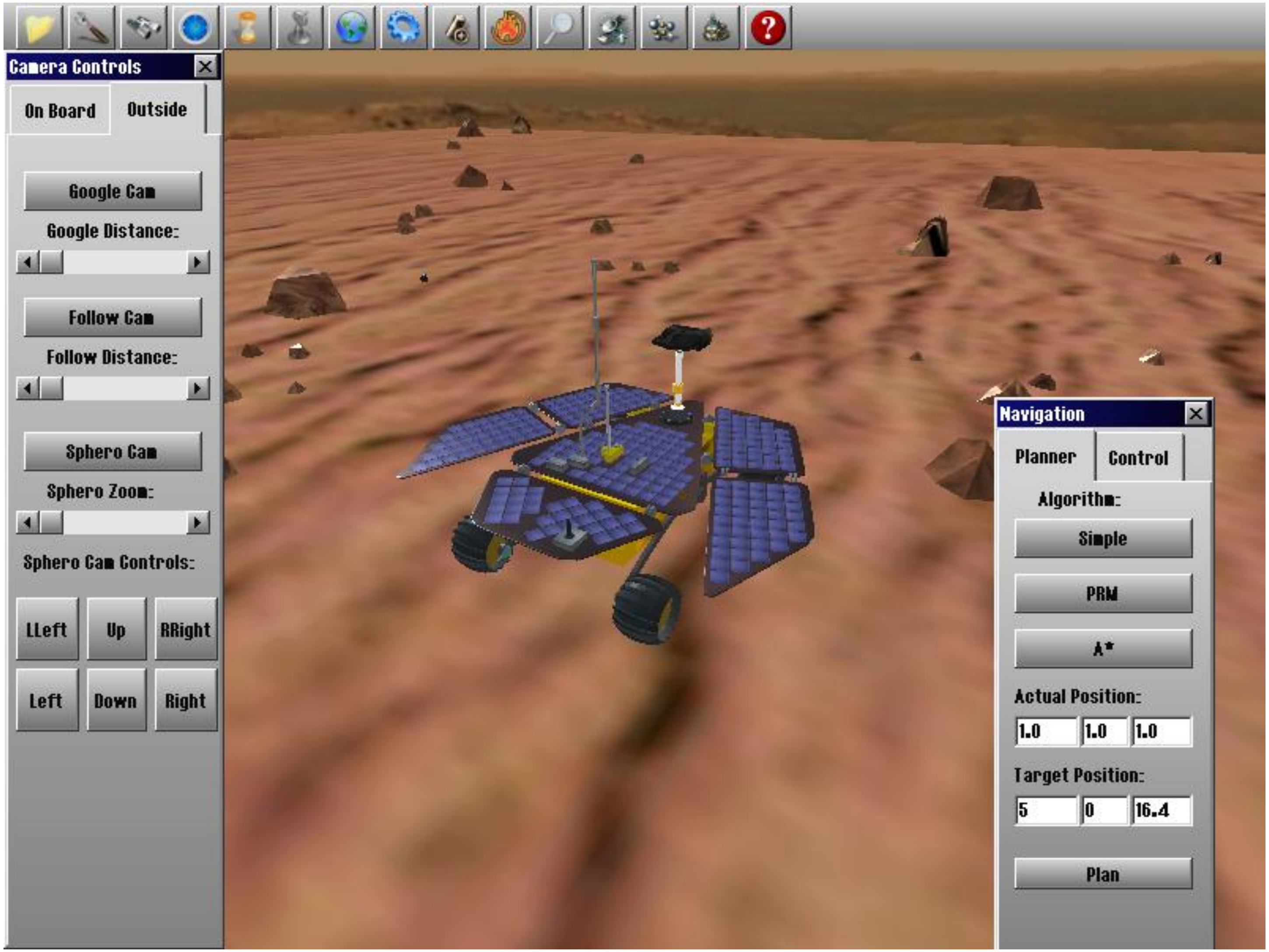

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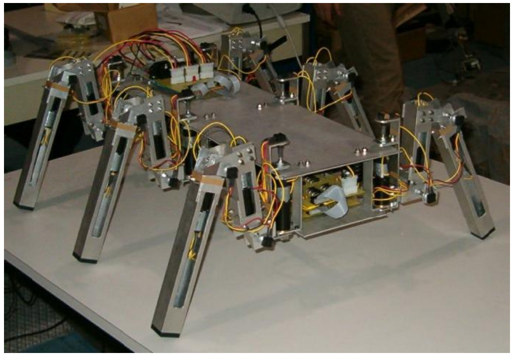
Goal→testbeds for testing and tuning sw and hw technologies

Planetary exploration

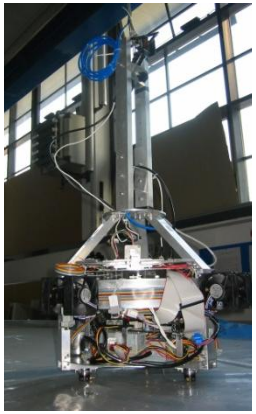
CASIMIRO

- Six independent wheels with Rocker-Boogie Suspension System
- Pentium Class On Board CPU
- 50 W solar Array + Li-Ion Battery
- 2 Stereo Cameras
- 25 Kg and 70 cm (100 cm SA)
- 50 W Peak Power (35 W Avg.)



NEMESYS

- Six legs, 18 DOF
- Pentium IV Class Off-Board CPU
- Off-Board Power Supply
- No contact Sensors
- Both CTRNN Neural Network and PID controller
- 7 kg and 60 cm
- 30 W Peak Power (19 W Avg.)



Orbiting systems

- 3DOF
- Sensors: monocamera; IMU platform
- Actuators: 8 fans
- Requested power: 60 W (Li-Ion Battery)
- Mass: 11 kg
- PCU: PC104+

The Deliberative Agent

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	Algorithms/approaches	Notes
Planning	▪ the state-space planning ▪ the Partially Ordered Planning (POP) where the solution is searched into the plan-space. ▪ The graph theory ▪ Hierarchical Task Network (HTN) ▪ Decision-theoretic planning, using mainly Markov Decision Processes (MDPs); ▪ Case-based or Explanation-based planning.	• Industrial logistics • Path planning •Operative system designs •Well-proven algorithm •Knowledge setting required
Scheduling	• CSP→STN • COP • Constructive search • Repair methods	• Commodities due time • Plants production scheduling • PC kernel activity scheduling • Depending on the resource type algorithms are closed or heuristic based
FDI	•Abductive reasoning •Expert systems •Model based reasoning	Search space limited by the designer
Goal Generation	•MADM/MDO methods •Belief/Desires/Intention •Motivated agents	

High level goal

Foreseen initial state X_{fin}
Desired final state X_{init}

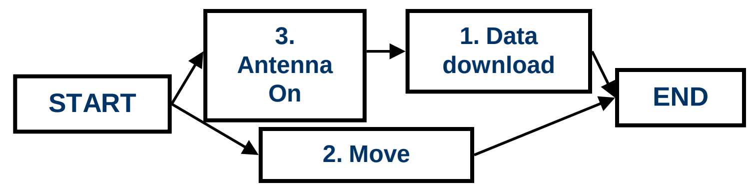
Planner

Database Planner

plan

Start A1 *after* end A3
Start A3 *after* end ST

Pre/post constraint satisfaction
POP algorithm



Scheduler

Database Scheduler

schedule

A1 [est, lst, eet, let, R, CI, CF]
A2 [est, lst, eet, let, R, CI, CF]

An [est, lst, eet, let, R, CI, CF]

Time and resource constraints satisfaction

ASP on STN +Maximum weighted clique algorithms with sequencing