ROVER AUTONOMY TEST-BED (RAT)

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INNOVATING SOLUTIONS

SYSTEM DESCRIPTION

PROJECT OBJECTIVES

ARCHITECTURE

USE OF THE SYSTEM

PROJECT OBJECTIVES

The subject activity aims at developing a platform to support the investigation into different levels of autonomy, their related perception, communication, presentation and MMI needs and their effectiveness in attaining mission success.

- Two-in-one approach (real & virtual rover) maximizing commonalities (functional layer, ground-segment)
- Inclusion of advanced perception/navigation sensors and avionics
- End-to-end control under a space operational scenario with E1 autonomy level (teleoperation using MMI devices)
- Designed for GOAC integration (use of GenoM robotics framework)
- Enable assessment of candidate robotic systems:
  - Sufficiency of equipment/data to determine internal status of a rover
  - Sufficiency of equipment/data to determine the situation around a rover
  - Determine optimal share of control between ground & onboard
- Support of field testing activities

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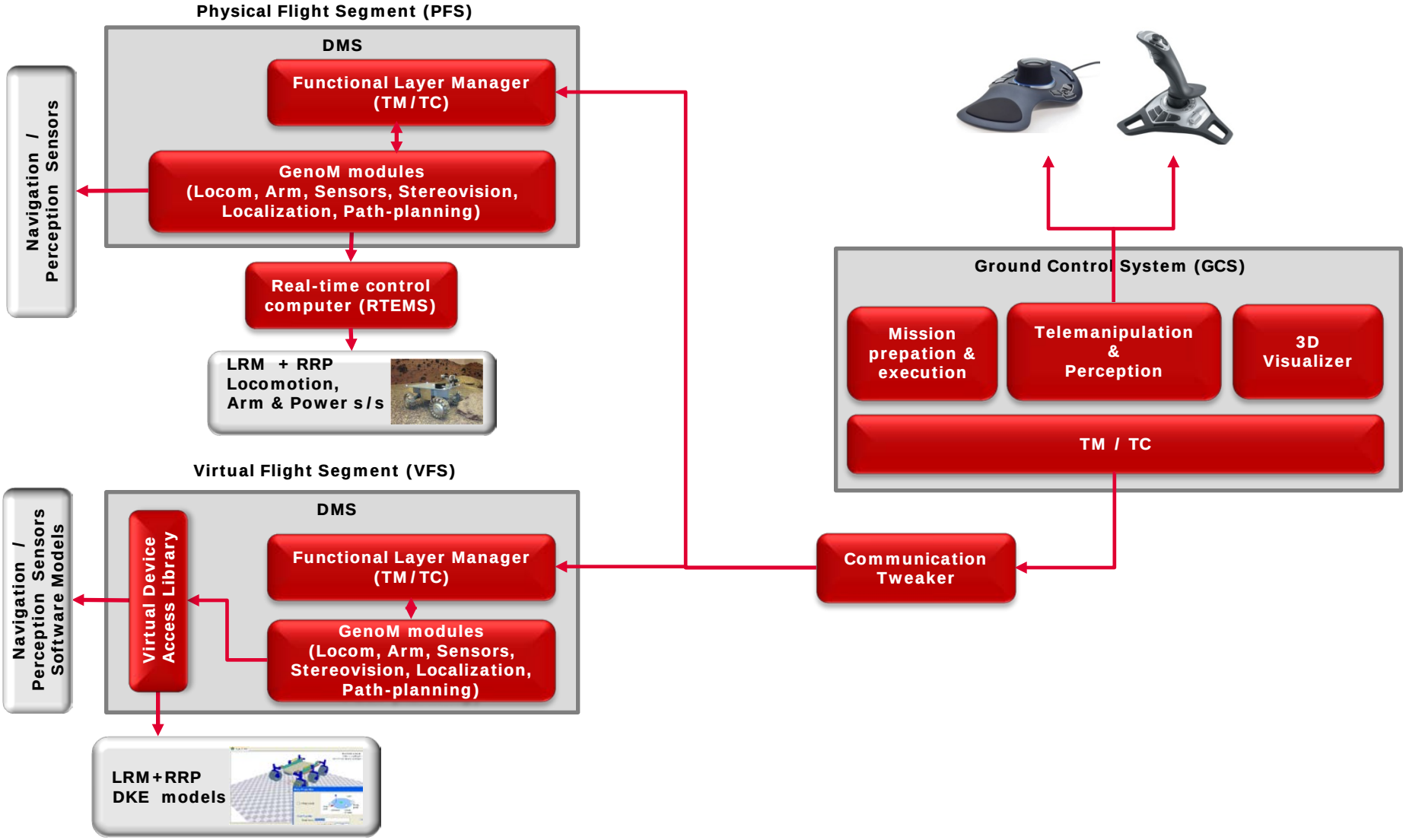
SYSTEM ARCHITECTURE



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WHO WILL USE THE RAT AND WHY?

Who? RAT is intended for Robotics Design Engineers:

- High fidelity investigation, testing and validation environment:
  - At a SW (virtual / simulated) level
  - At a HW (physical) level

Why? For the evaluation of impact of different mission execution options:

- from an autonomy viewpoint
- from operations viewpoint (e.g. perception devices, path planning, navigation approach, ...)
  - ✓ Trade-off those options
  - ✓ Develop and test specific elements/components (either at ground prototype or proto-flight status)
  - ✓ Assess/quantify the impact of each element/component (performances, operations, budgets, inter-system interfaces, on-board/on-ground control sharing ...)
  - ✓ Integrate all elements/components and to verify the design

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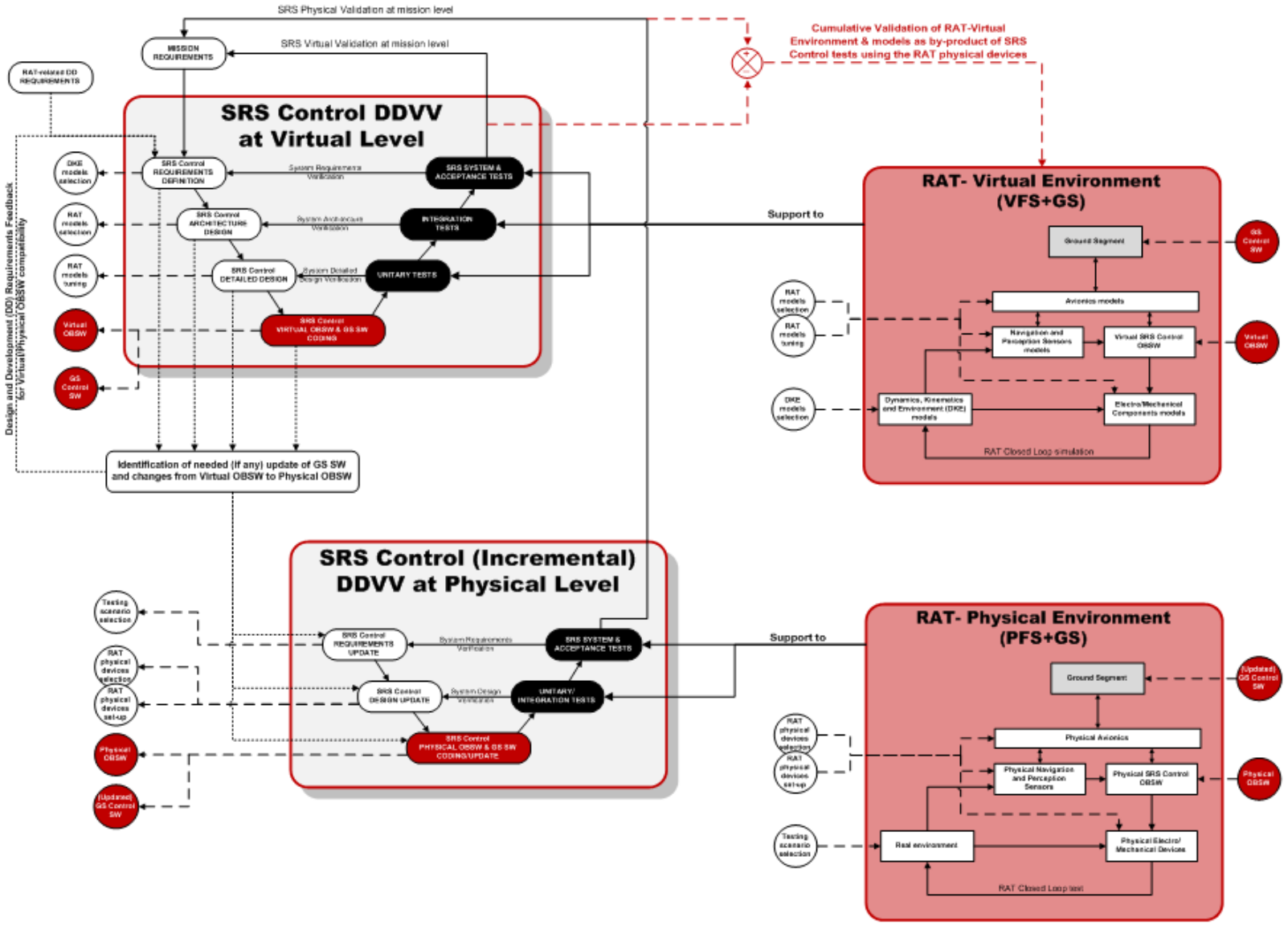
PROPOSED METHODOLOGY TO USE RAT



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PHYSICAL FLIGHT SYSTEM (PFS)

PERCEPTION & NAV. SENSORS
AVIONICS
SENSORS PLACEMENT
SOFTWARE ARCHITECTURE
PERFORMANCES

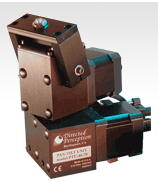
PERCEPTION SENSORS

Panoramic imager
Ladybug 2
Spherical digital video camera

Navigation cameras
Bumblebee XB3 stereovision syst

Time-Of-Flight Camera
MESA SR4000-13
56° x 69° FOV
54 FPS

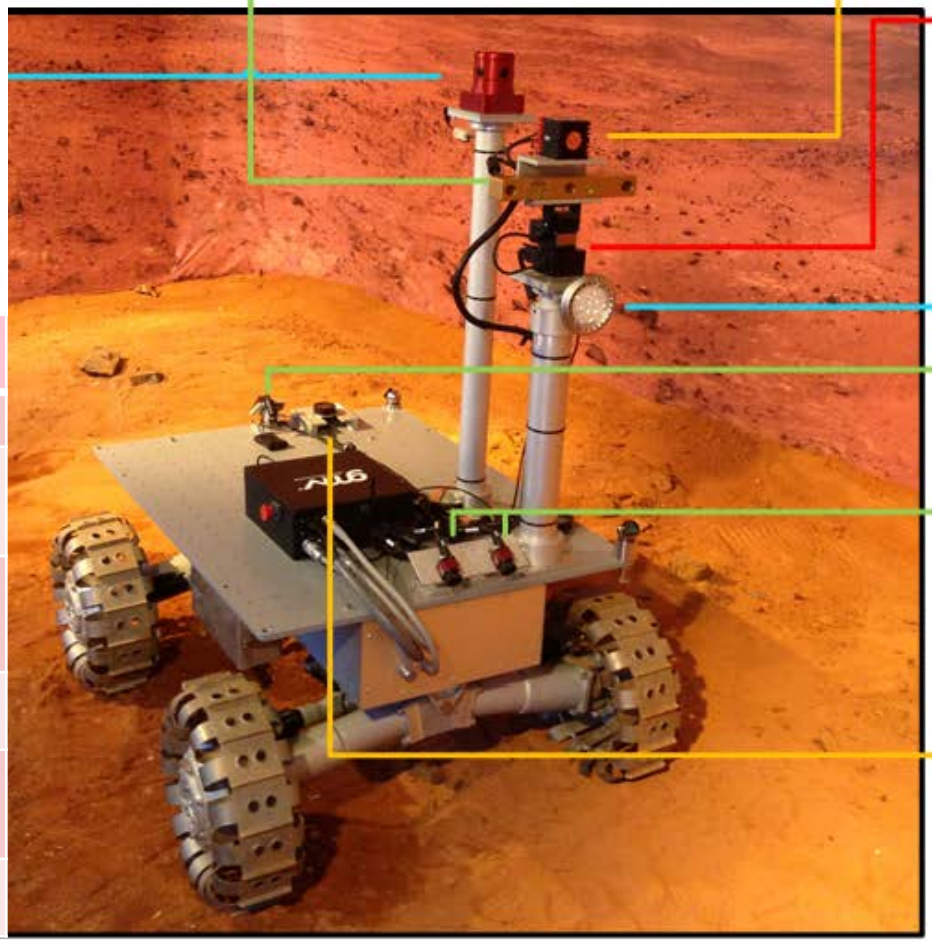
Pan & Tilt Unit
PTU D46-17
360° view



Flash light
LED based white light source
180W ~ 30m range

3x Hazard Cameras
AVT Guppy PRO F-125B
2 Front cameras
1 Rear camera with FishEye optics

Sun Sensor
ISS-D60



Size	1200 x 900 mm
Mass	120 kg
Payload Mass	60 kg
Wheels	4 traction/steering elastic titanium
Motors	8 (2 motors per wheel)
Nominal Speed	440-480 m/h on flat sandy terrain
Payload deck	1000 x 760 mm

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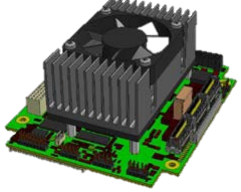
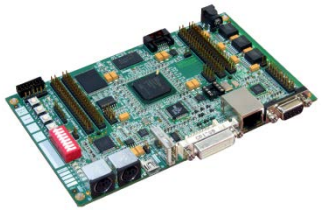
AVIONICS





Motion Control Electronics

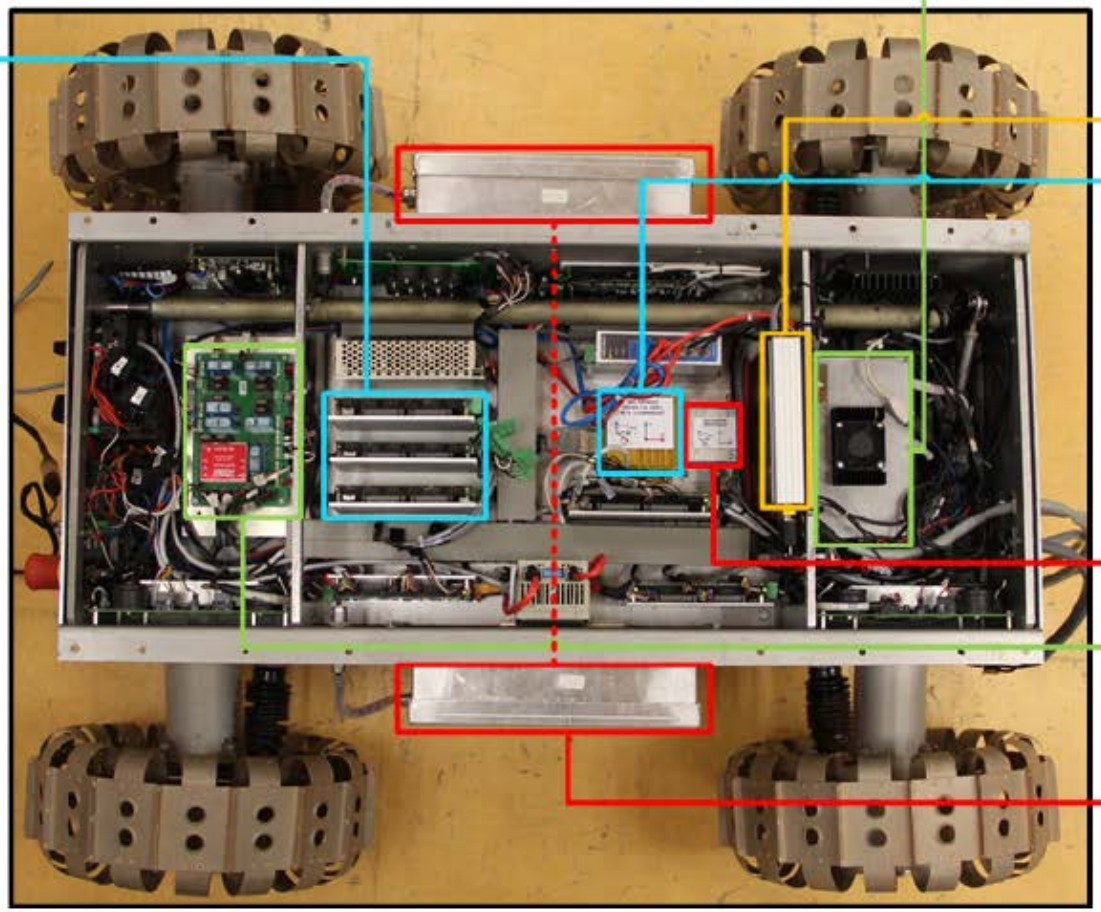
4x Elmo Whistle DUO
CAN-Open based
distributed architecture

Data Management OBC

Cool ExpressRunner-GS45 PCI
HD 32Gb SSD + 500Gb SATA-300
OS: Linux Ubuntu

Real-Time OBC

LEON3 GR-XC6S-LX75
FPGA Xilinx Spartan6
OS: RTEMS



IMU

MEMSIC VG440 – 6DoF

Inclinometer

MEAS NS-45 / P2
Roll & Pitch

Power Distribution Unit

Battery packs

2x Li-Po
25.9V / 31Ah (~800Wh)

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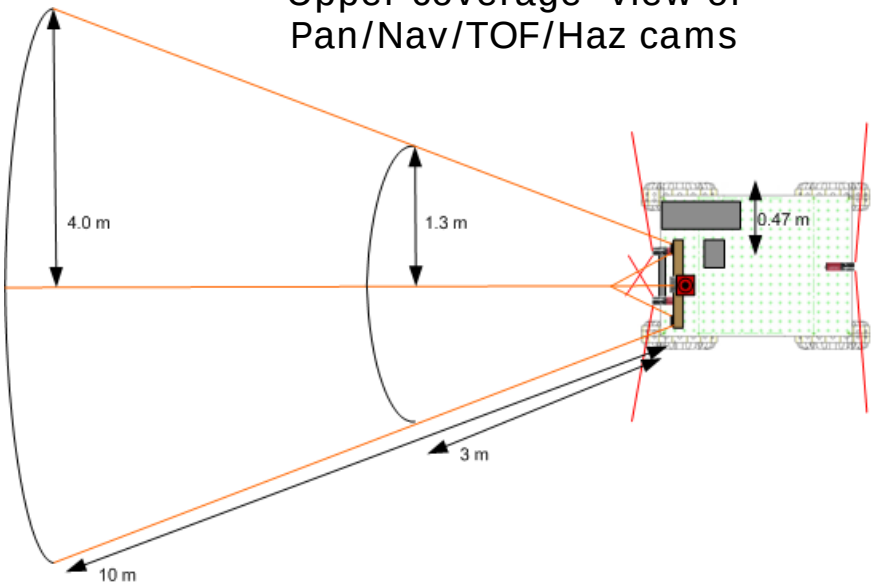
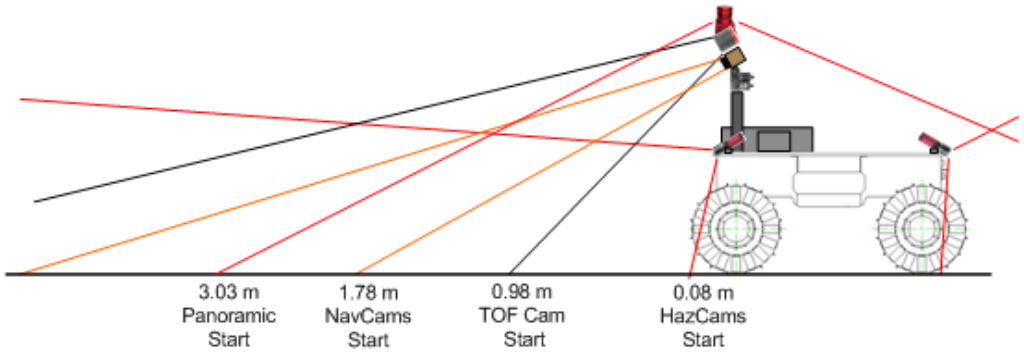
SENSORS PLACEMENT

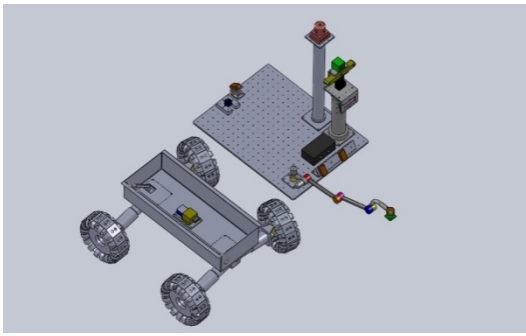
Telescopic mast:
PTU, Stereo bench and TOF

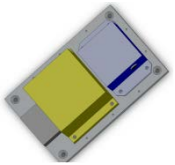
Upper coverage view of Pan/Nav/TOF/Haz cams



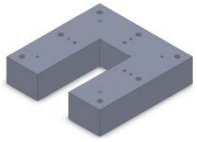


Profile coverage of Pan/Nav/TOF/Haz cams

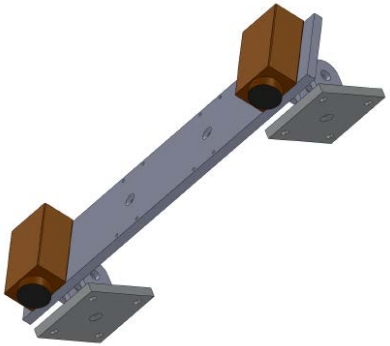




IMU+Inclinometer



Sun-sensor plate



Hazard stereobench

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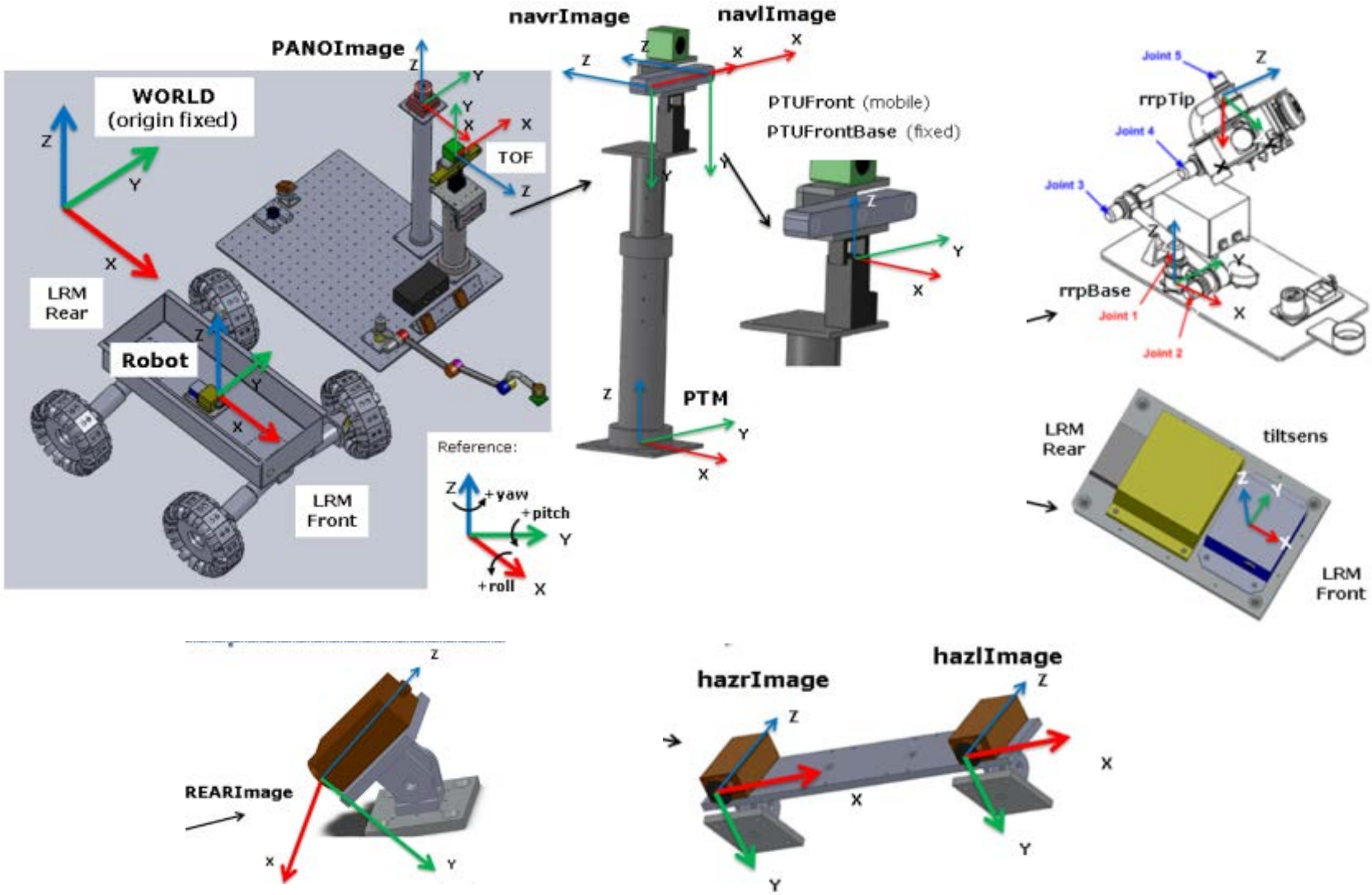
FRAMES DEFINITION



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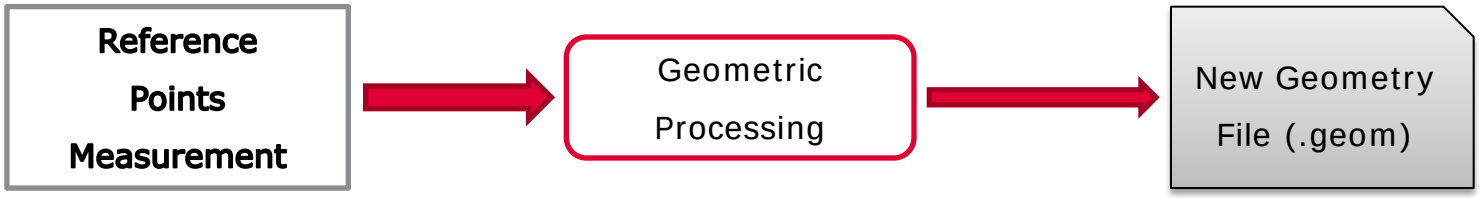
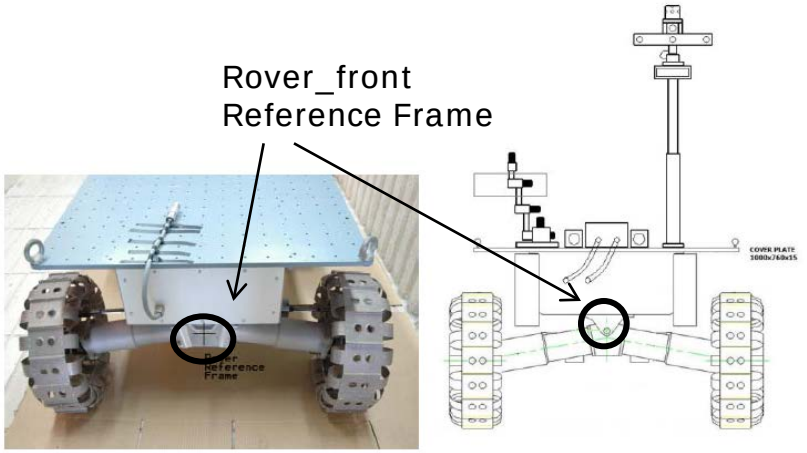
REFERENCE FRAMES CALIBRATION

LRM Reference frame transformations: Calibration procedure & relationship to geom.

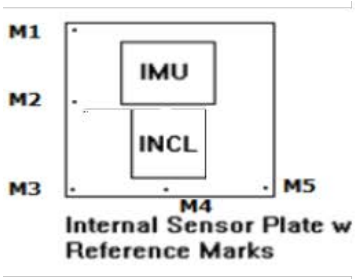


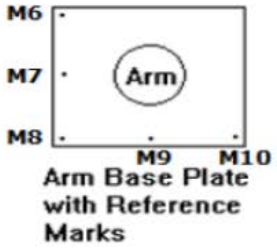
Use of K600 Metris system

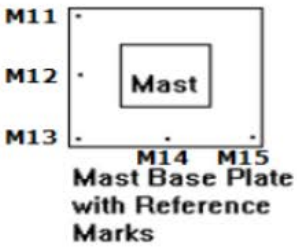
Rover_front
Reference Frame

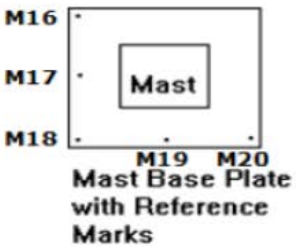


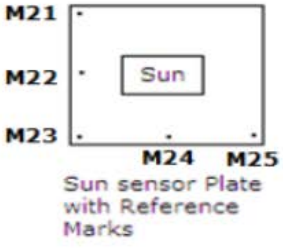
Sensor Plates with reference marks











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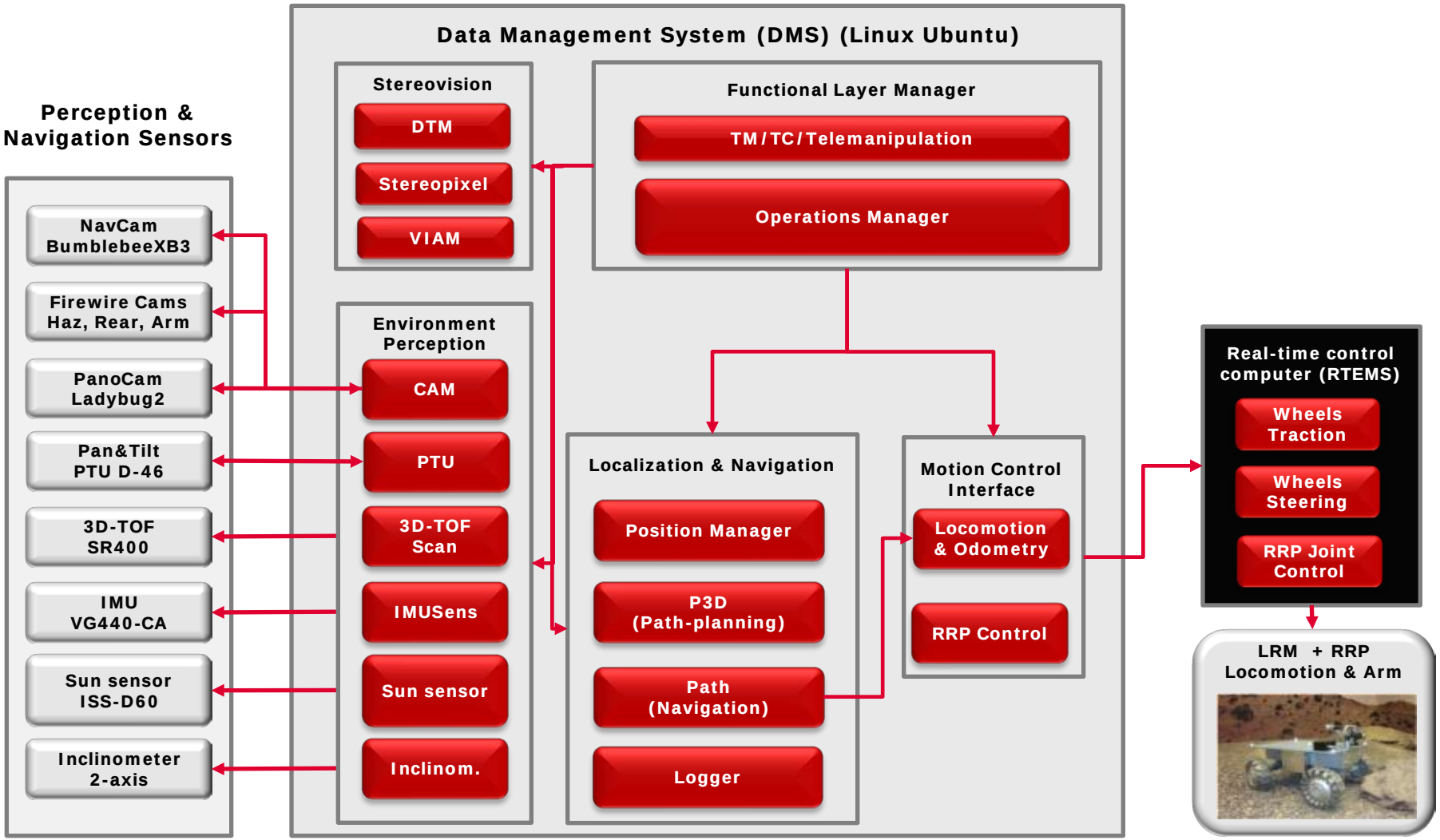
PFS SOFTWARE ARCHITECTURE



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PFS: DMS (CAMERAS)

- Individual and parallel image acquisition:
  - XB3, Ladybug2 and Firewire 1394B cameras
  - Image acquisition:
    - Single-shot images
    - Periodic (start/stop)
  - On-board image compression:
    - **Output image formats**:BMP, JPEG, GIF, PNG or TIFF
    - **Compression types**: None, JPEG, Lossless or Zip.
    - **Compression levels**: 1-100
  - Image details provided within HKTM message

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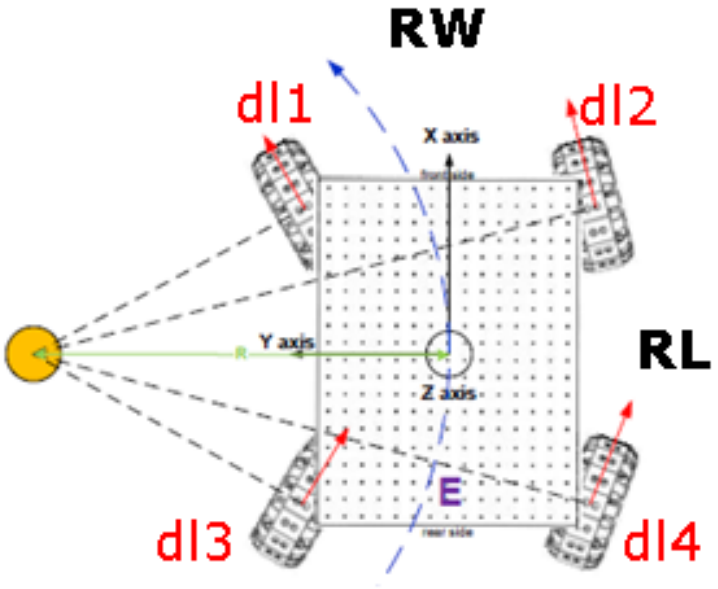
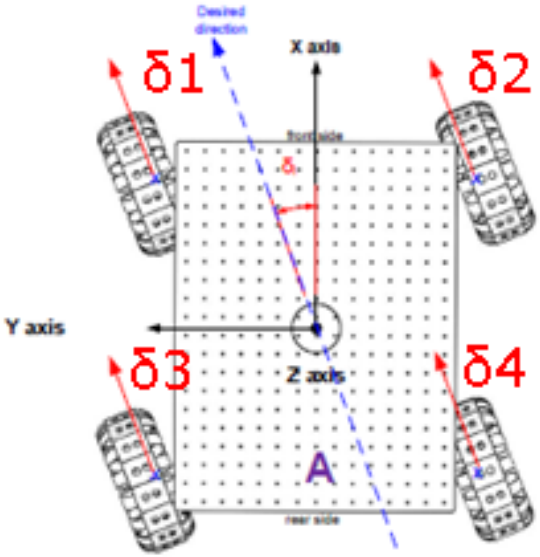
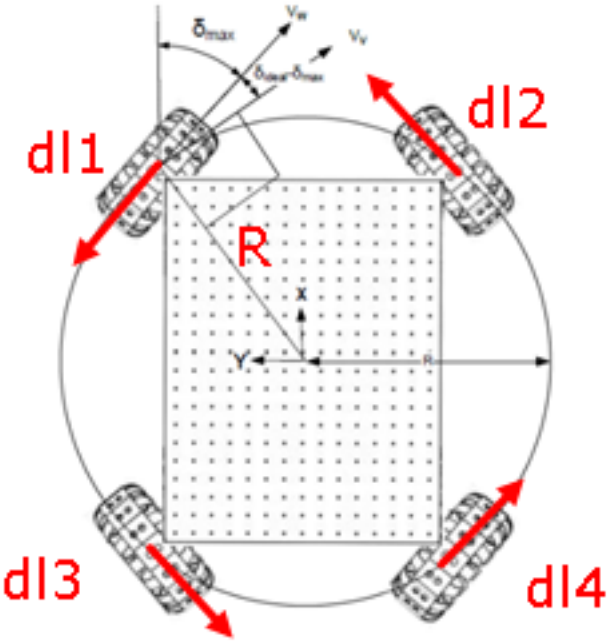
PFS: DMS (LOCOM)

- Operation modes:
  - Individual wheel traction and steering motion
  - Joystick control
  - Crab / Double-Ackerman / Turn-on-spot
- Periodic telemetry
- Blind navigation to target
- Follow waypoints path







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PFS: DMS (POM)

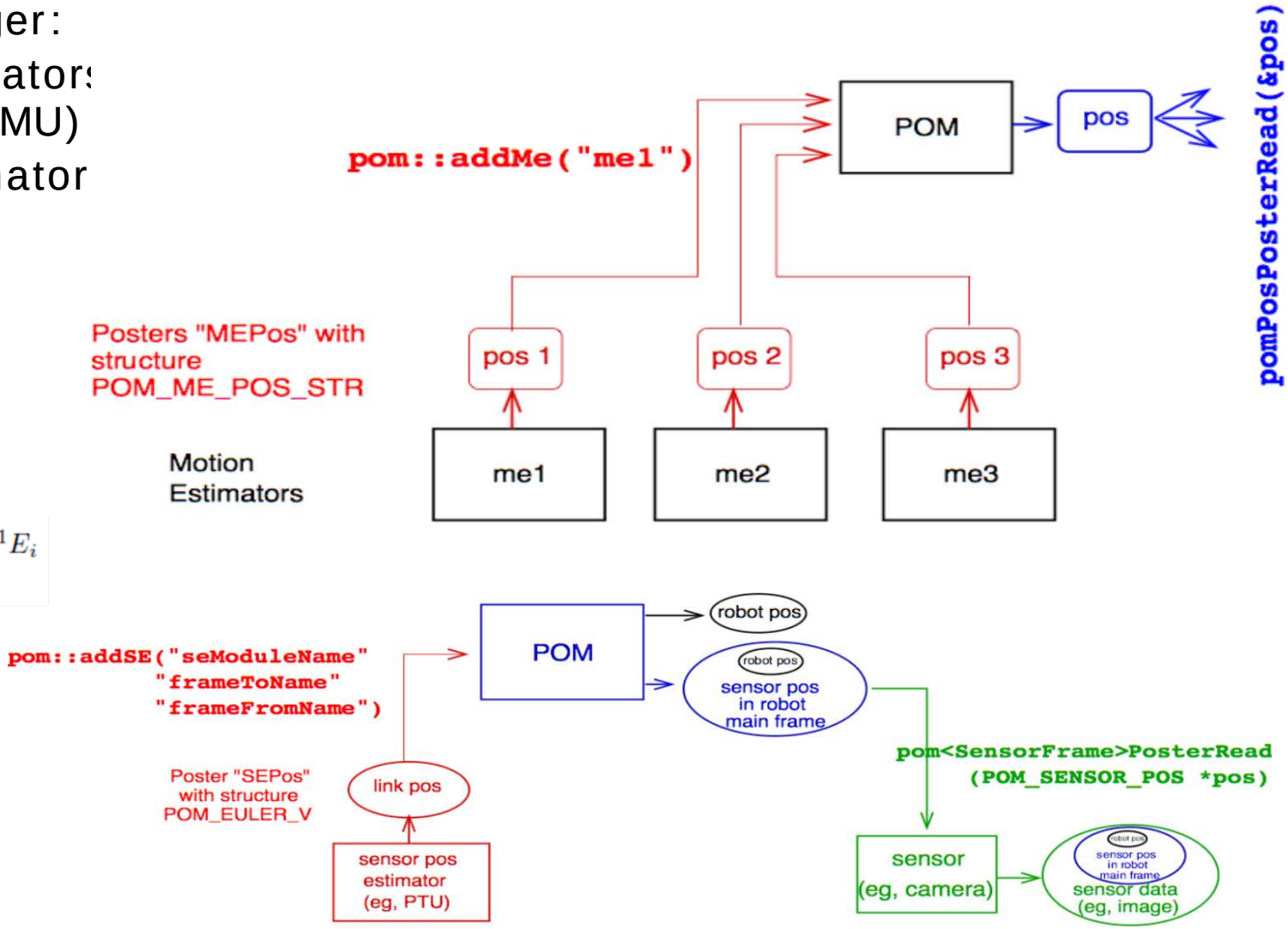
Position Manager:

- Motion estimators (odometry, IMU)
- Sensor estimator (PTU)

Using Robot geometry file

Kalman-like average:

$$\begin{cases} \hat{E} = V^{-1} \sum V(E(i))^{-1} E_i \\ V = \sum V(E_i) \end{cases}$$



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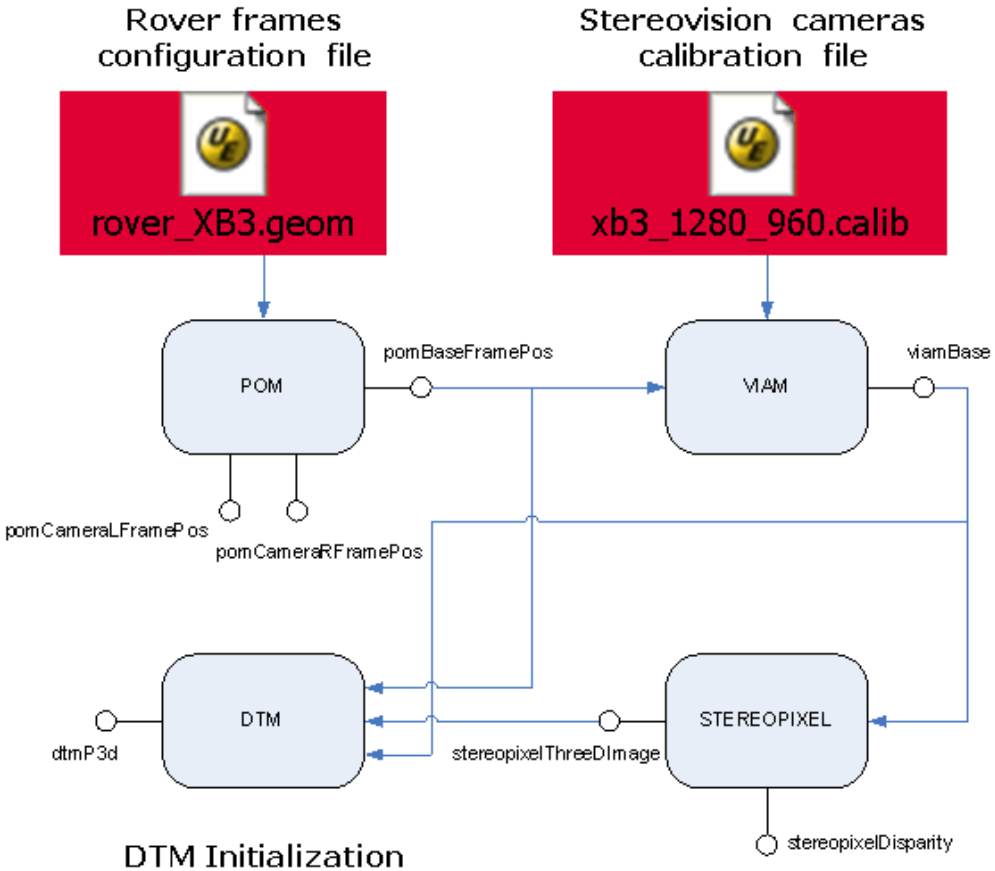
PFS: DMS (STEREOVISION-DEM's-P3D)



DTM Initialization

Number of points
Resolution
Origin coordinates
Max. distance and vertical treshold
Navigation map dimensions and resolution

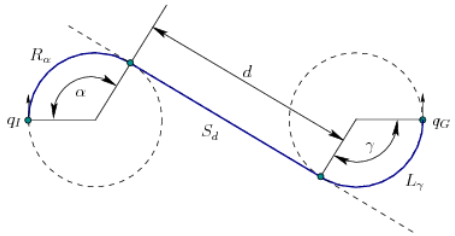
Stereo-correlation parameters

Mask 15x15 pixels

Deviation: 240 pixels

P3D Navigation:

- Potential field based-search
- Terrain cost based in chassis pitch and roll inclinations



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PFS OBJECTIVES AND PERFORMANCES

- RTCC: Real-time performances (100 Hz)
- DMS: Soft-time performances (Navigation 10Hz, Teleoperation 20Hz)
- Cameras:
  - Images acquisition frequency: 1-3Hz
  - Relocatable masts
  - Telescopic stereovision mast
- Locomotion capabilities:
  - Maximum speed: 0.1m/s
  - Positioning accuracy: 0.25m (10m)
  - Heading accuracy: < 5º
- Arm (RRP 5DOF):
  - Direct joints and inverse kinematics XYZ commanding
  - Trajectory planner

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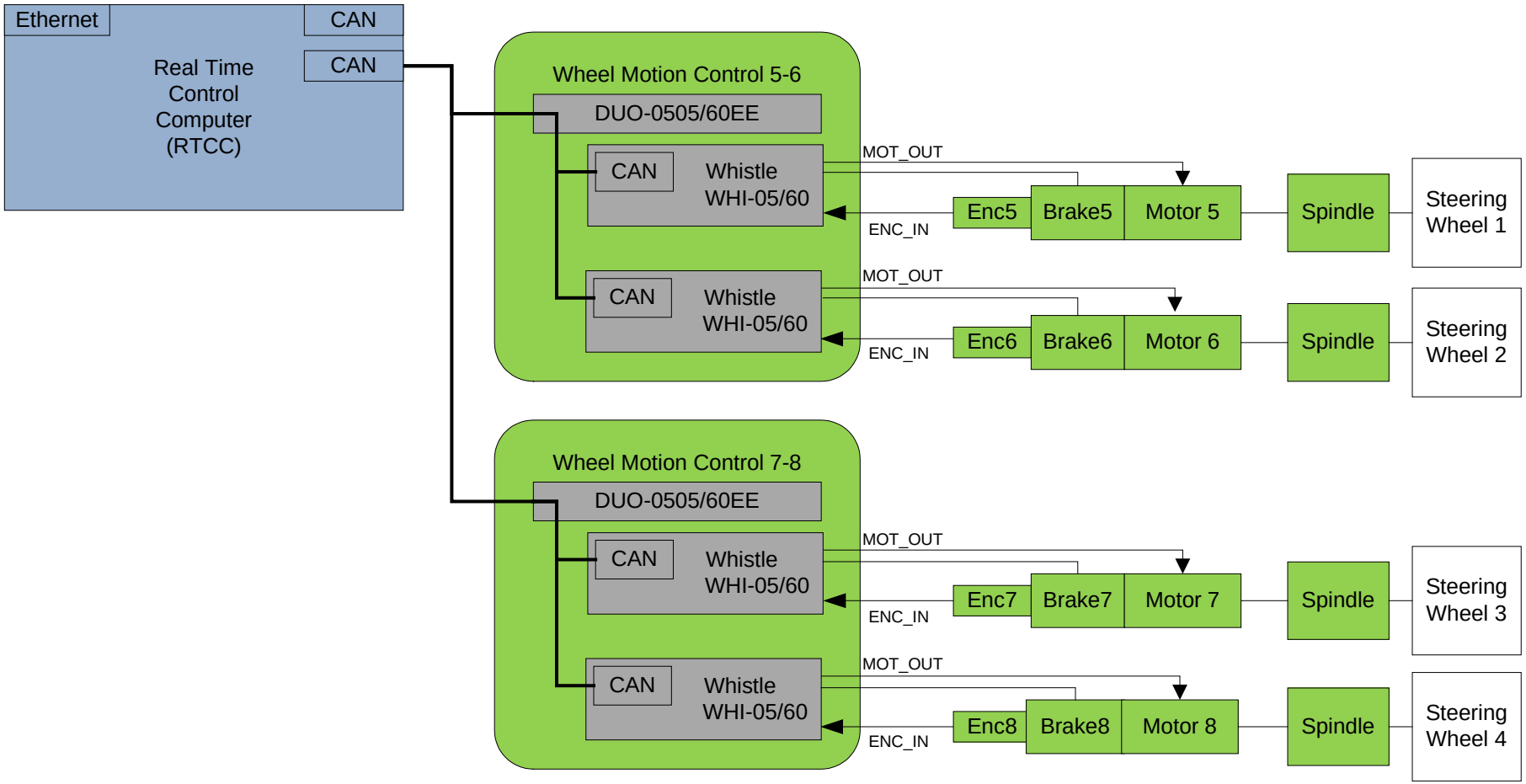
PFS: RTCC HARDWARE ARCHITECTURE



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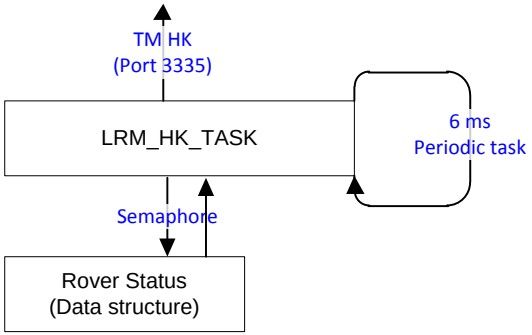
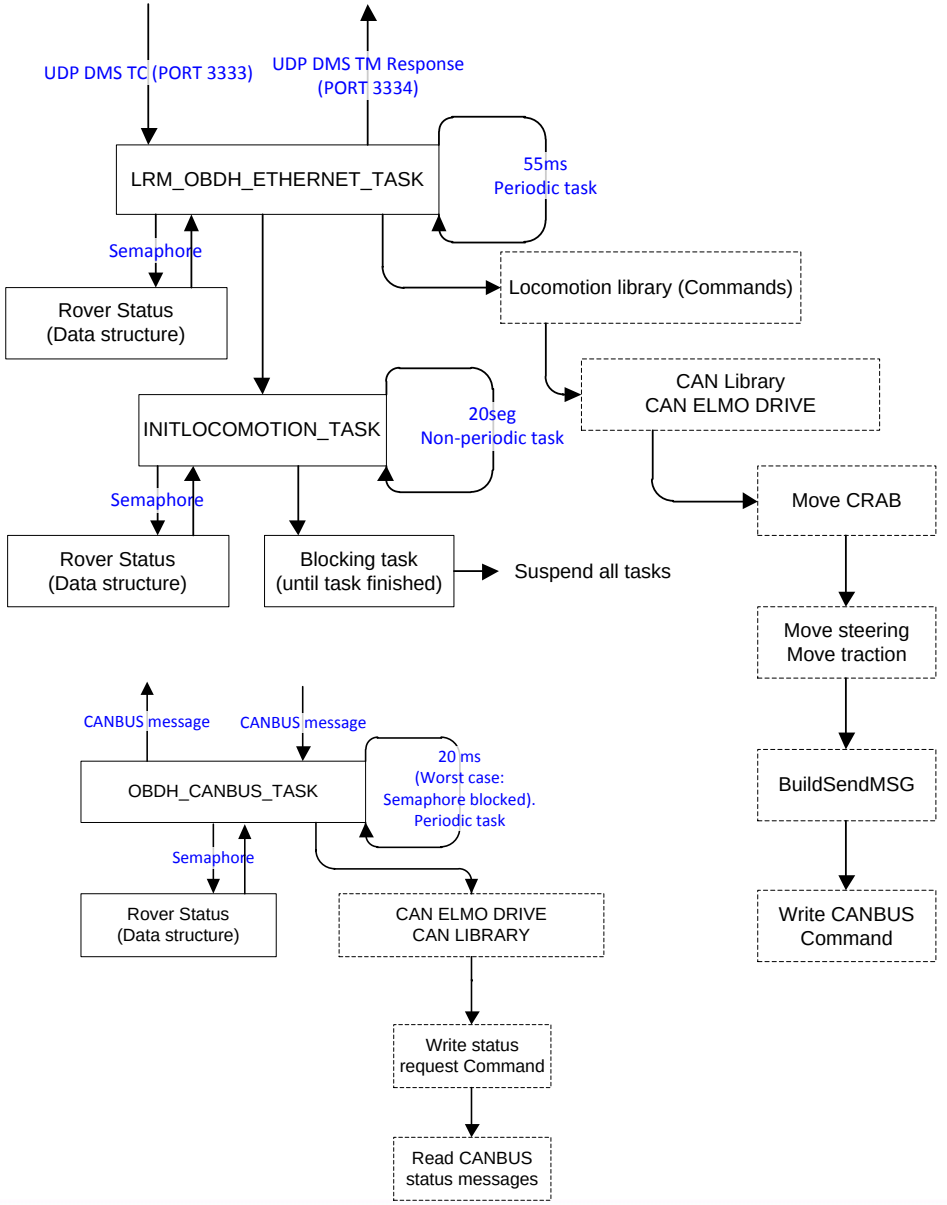
PFS: RTCC SOFTWARE ARCHITECTURE

- **Init Locomotion Task**: Non-periodic task in charge of initializing all internal data structure and communications with the Elmo Whistle controllers (homing of the steering wheels).
- **LRM OBDH Ethernet Task**: Interfacing between the RTCC and the DMS processors.
- **LRM HK Task**: Generation of periodic locom TM message.
- **RRP Task**: Generation of periodic arm message.
- **OBDH CANBUS Task**: Forwarding of CAN Bus messages to the Elmo Whistle controllers.





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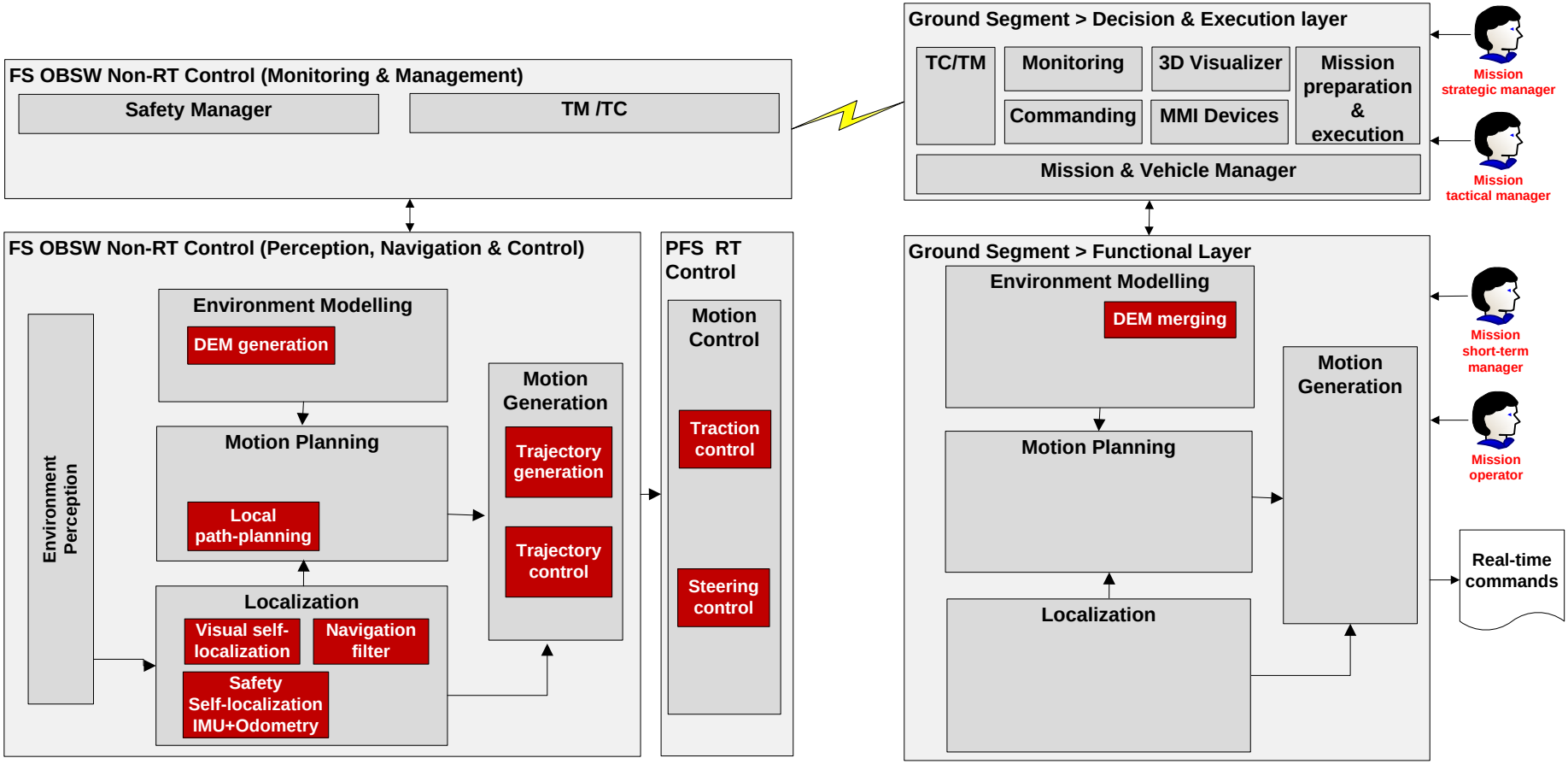
PFS-GS SEAMLESS TRANSITION (1/2)

- Maximum On-Board functionality scenario:
  - On-Board: DEM generation and navigation
  - On-Ground: DEM Refinement and Merging



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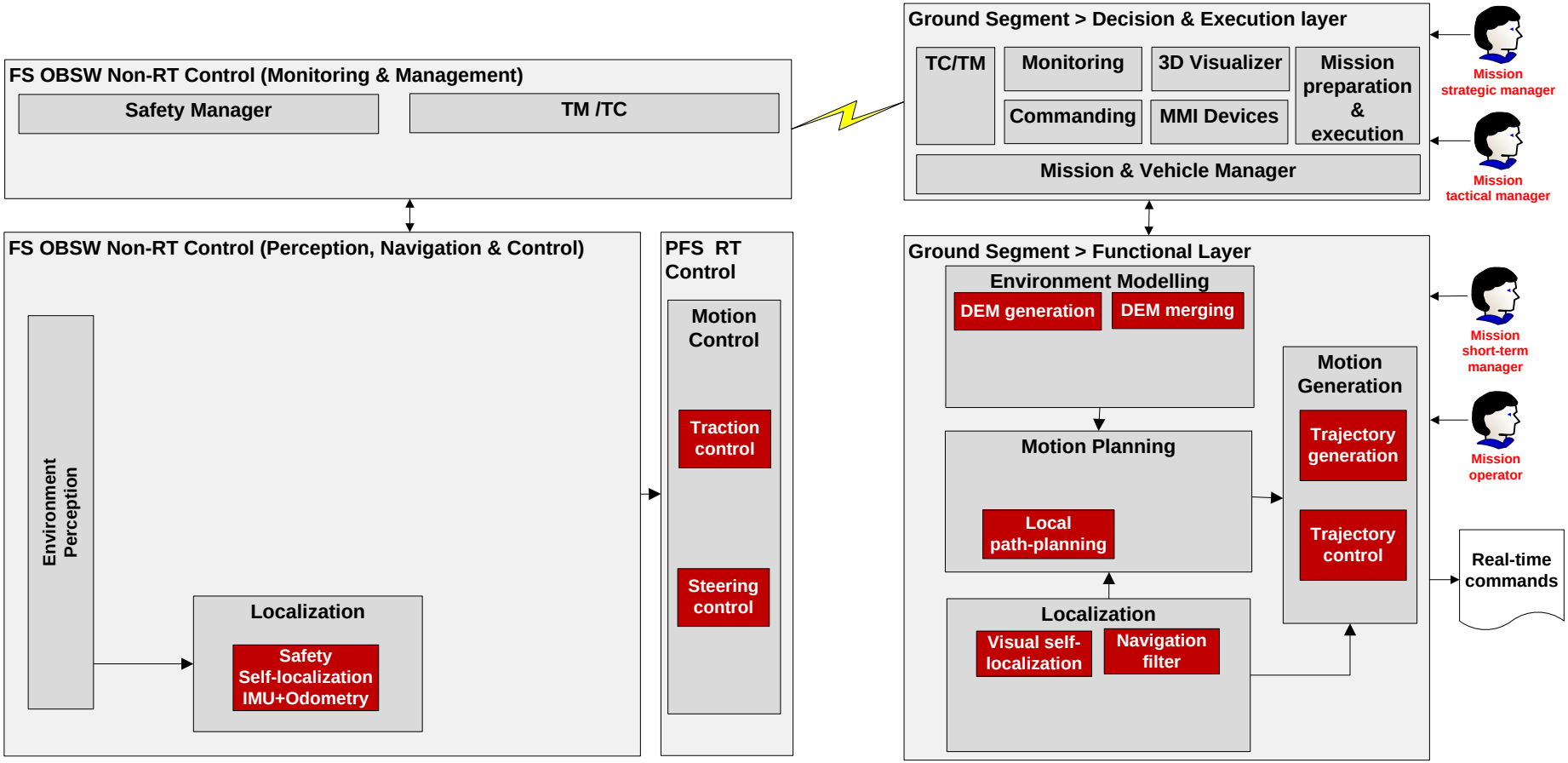
PFS-GS SEAMLESS TRANSITION (2/2)

- Minimal On-Board functionality scenario:
  - On-Board: Only low-level locomotion, perception and safety-localization
  - On-Ground: Localization, DEM Generation and Navigation, Trajectory control



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VIRTUAL FLIGHT SYSTEM (VFS)

OBJECTIVES AND DESIGN
MODELS (LRM, ATMOSPHERE, ENVIRONMENT)
SW ARCHITECTURE

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RAT VIRTUAL FLIGHT SEGMENT

- **Objectives**
  - Simulation environment for the validation of RAT operations
  - Operations Rehearsal
  - Predictive simulation
  - Integration and validation of new control algorithms

- **Background**
  - 3DROV instantiated with the Moon environment models and RAT rover models

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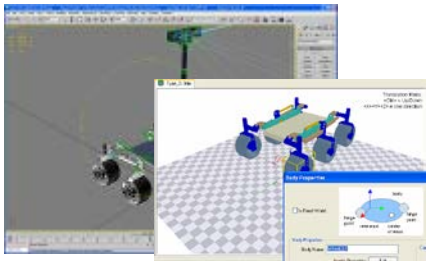
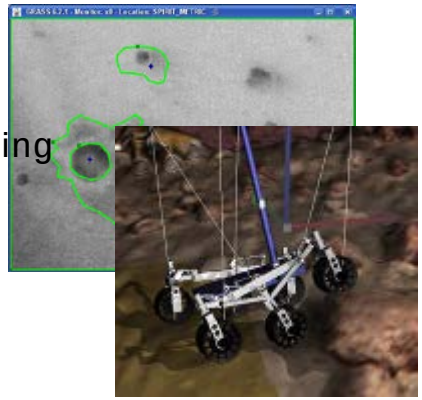
VFS – A 3DROV INSTANTIATION

3DROV Design / Modeling

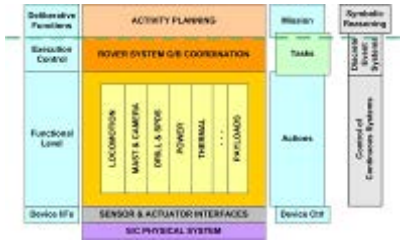
Rover
- Mechanical
- Thermal
- Power



Environment
- Atmosphere
- Orbiter & Timekeeping
- Terrain

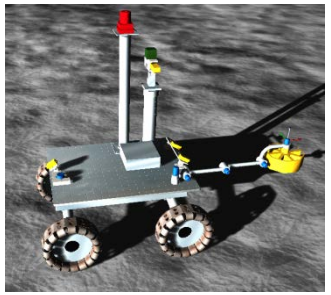


Generic Controller
- Actions
- Tasks
- Real-time impl.

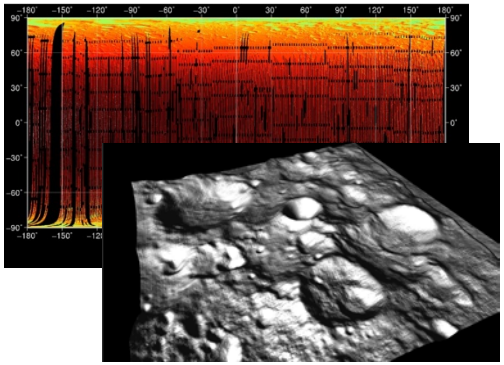


RAT VFS

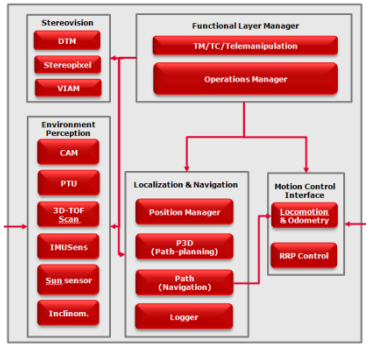
LRM platform, RRP arm, cameras, …



Moon environment



Integration of the DMS Genom modules through VDAL-RPC library



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VFS MODELS

VFS Models
Rover Vehicle
IMU
Sun Sensor
Inclinometer
Robotic Arm
Mast
Visual Stereo System
Panoramic Imager
3D TOF camera
Power
Communications
Data Handling
Controller
Orbital and Timekeeping
Atmosphere

- Uniform representation of the models
  - *ComponentType*
    - Status (ON, STANDBY, OFF, ...)
    - Power line current
    - Power consumption
    - Heat dissipation
    - Temperature
    - Datarate
  - *MechanicalComponentType*
    - Status (ON, STANDBY, OFF, ...)
    - Power line current
    - Power consumption
    - Heat dissipation
    - Temperature
    - Datarate
    - Cartesian position
    - Joints position
  - *MotorsType*
    - Target state
    - Current state
    - Sensor state
- Systematic Models Management API
- Ensures SMP2 compatibility

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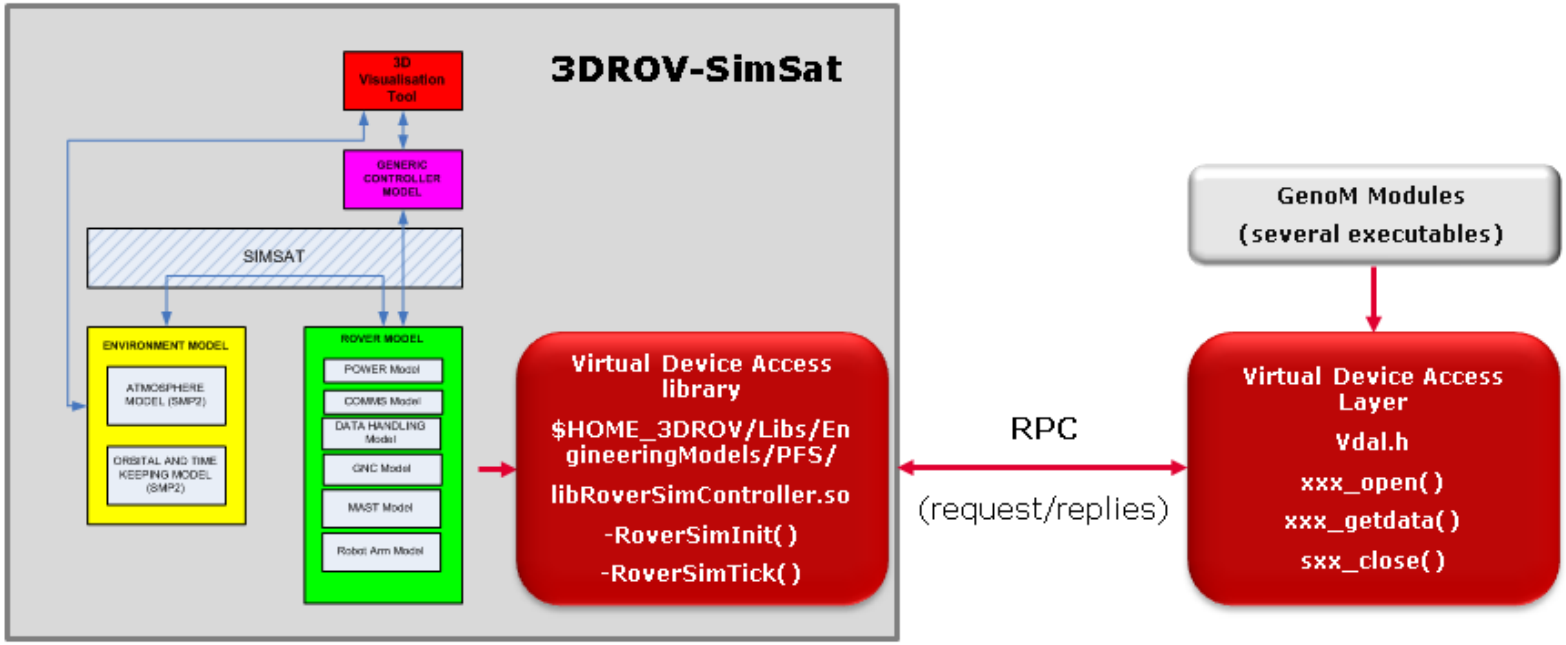
VFS: VDAL LIBRARY

VDAL Interface (client/server approach) between VFS models and GenoM modules :

- **RoverSimController**: This is a shared library linked with the 3DROV system and including the VDAL RPC server-side definitions.
- **Algo3drovRpc.x**: XDR file containing the definitions of the RPC functions.
- **VDAL client layer:** RPC client side within GenoM modules



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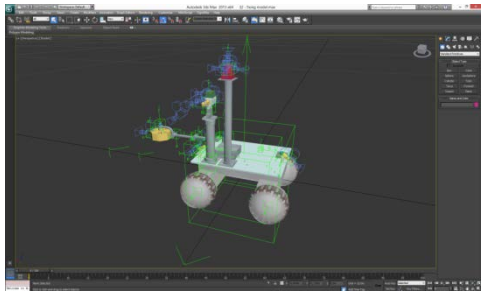
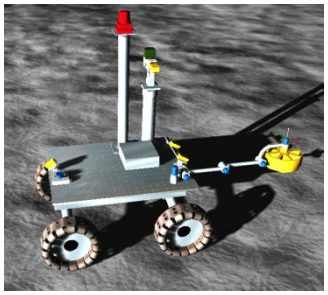
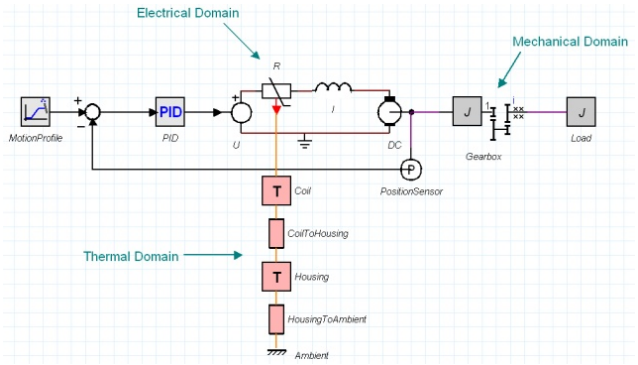
ROVER – LRM MODEL

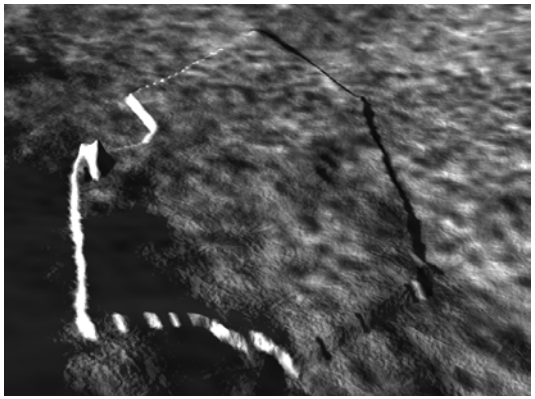
- The LRM platform model includes:
  - LRM mechanical model (use of Bullet)
  - Models of the actuators and their low level control
  - Control inputs issued by the DMS component
  - Wheel/terrain interaction module from the 3D Visualization tool.







- Cameras models:
  - Images and DEMs generation using the synthetic scene



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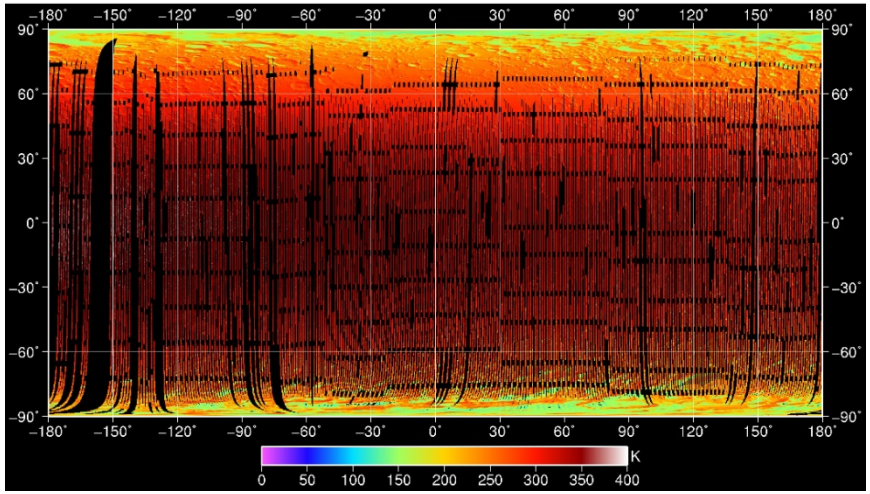
ENVIRONMENT – ATMOSPHERE MODEL

- The Atmosphere model provides data on the Moon surface environment conditions:
  - Solar flux, reflected solar flux: computed based on the Sun position
  - Surface temperature.



- Ground temperature & ground emissivity: use of the DIVINER Lunar Radiometer Experiment data (http://pds-geosciences.wustl.edu/missions/lro/diviner.htm)

- Information used by other models such as the thermal s/s models, and the solar panel models.

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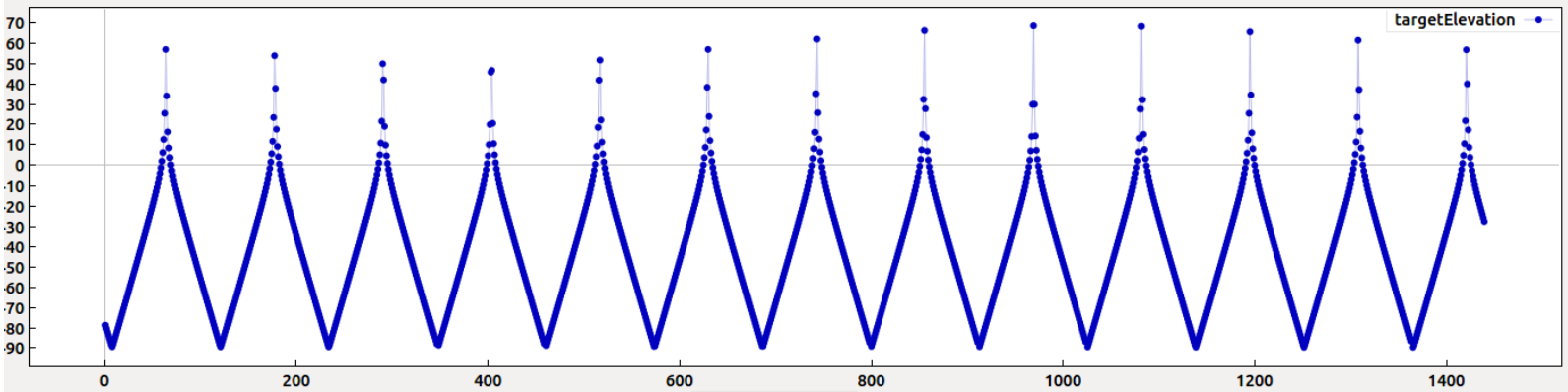
ENVIRONMENT – ORBITAL&TIMEKEEPING

- The Orbital and Timekeeping model computes and publishes ephemeris and line-of-sight condition between:
  - the rover and the sun
    - simulate solar illumination conditions
  - the rover and the lander
  - the rover and an orbiter (e.g. Lunar Reconnaissance Orbiter)
  - the rover and a location on Earth
    - support the simulation of communication activities



- Use of NAIF/Spice

  $HOME_3DROV/configFiles/Cspice.conf

  ... KERNELS_TO_LOAD = ('$LSK/naif0009.tls', '$PCK/pck00008.tpc' '$PLT/de421.bsp')

- Rover–Lander communications is provided by the visualization tool

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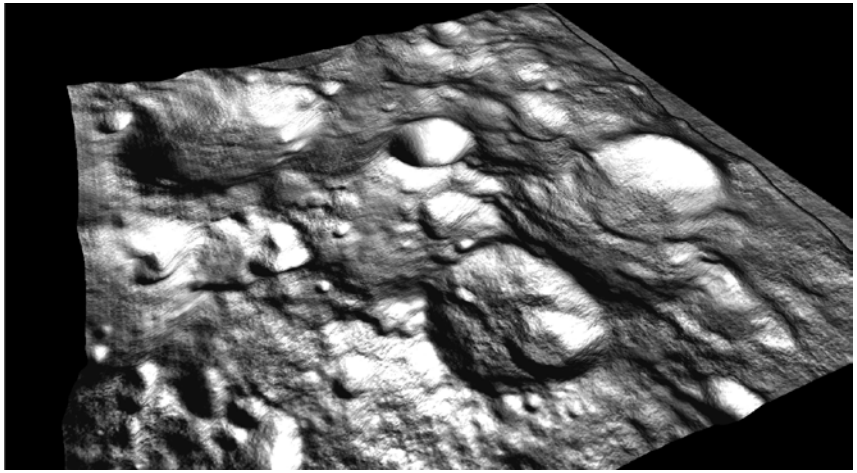
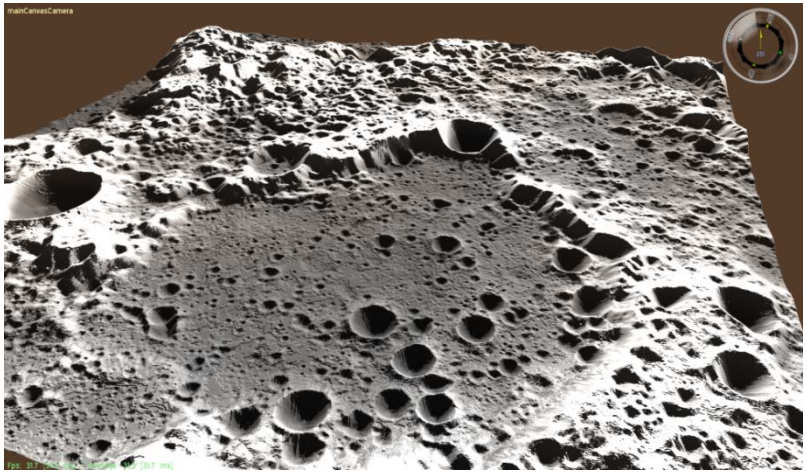
ENVIRONMENT – TERRAIN MODEL

- The Moon South Pole terrain
- Use of the LOLA data
  (http://pds-geosciences.wustl.edu/missions/lro/lola.htm)
- Patches of the terrain are extracted





- ESTEC Laboratory

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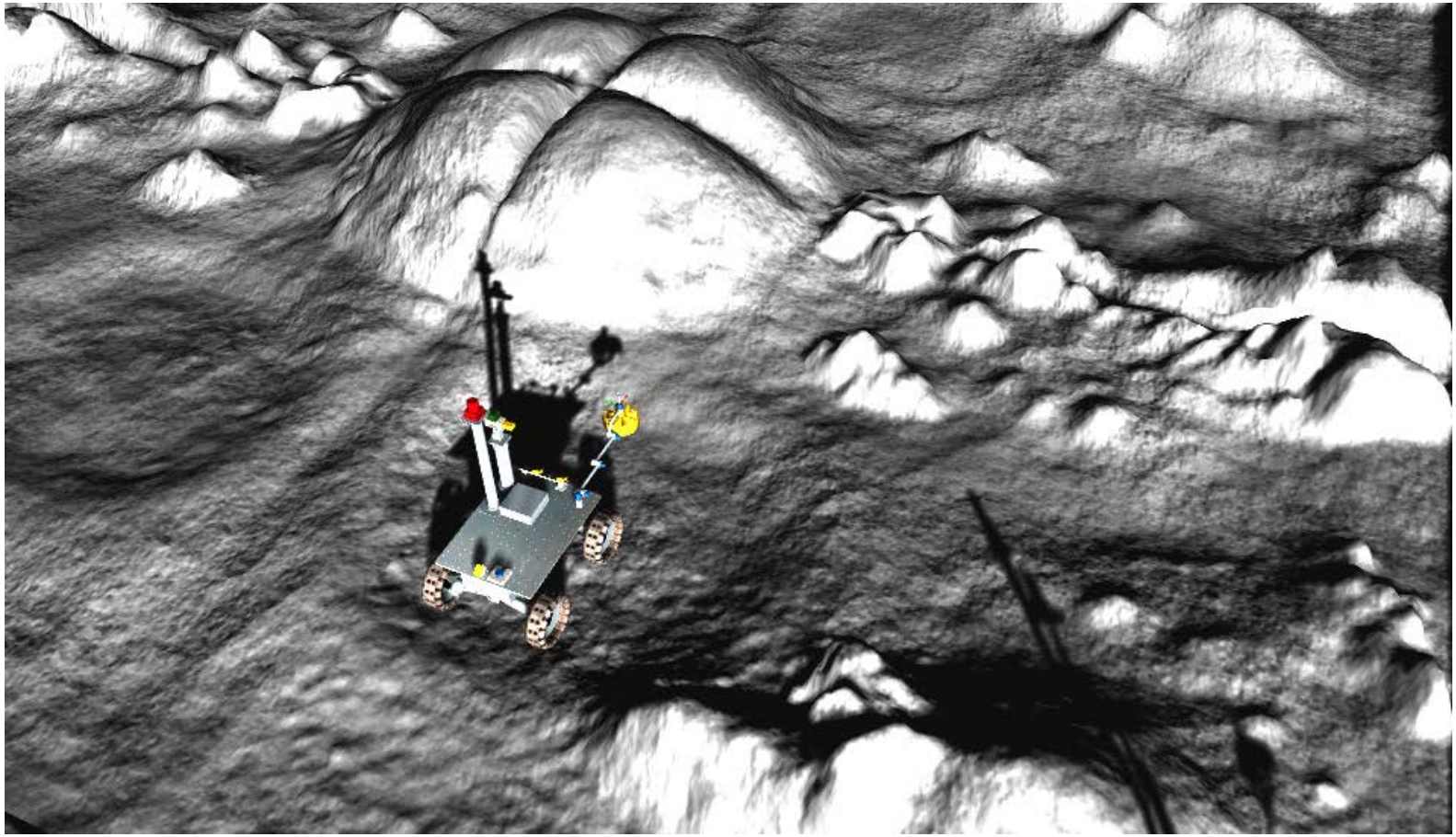
ENVIRONMENT – TERRAIN MODEL

- ESTEC Laboratory



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RAT – FP

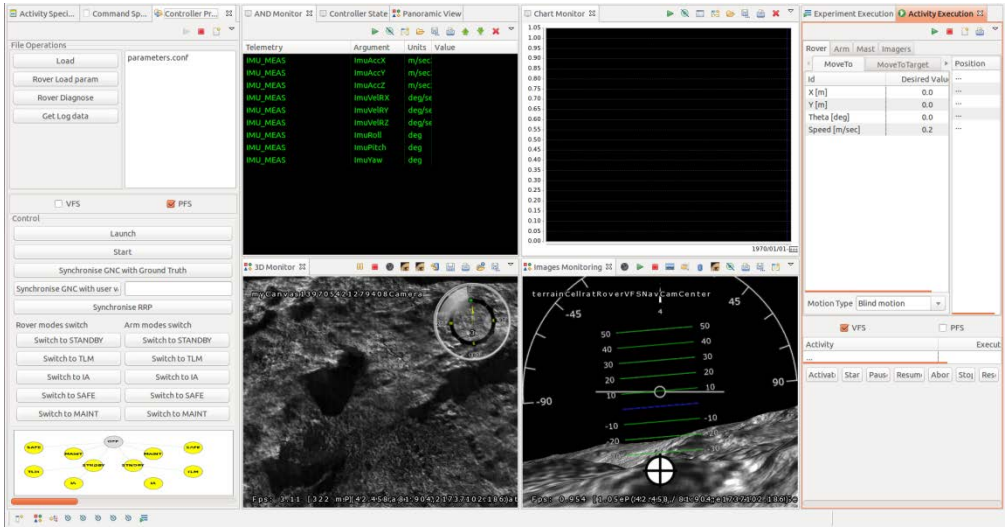
GROUND CONTROL SEGMENT (GCS)

- OBJECTIVES AND MAIN DRIVES
- MAIN COMPONENTS
- IMAGES MONITORING
- TELEMANIPULATION
- COMMUNICATIONS TWEAKER
- HARDWARE ARCHITECTURE

GCS OBJECTIVES

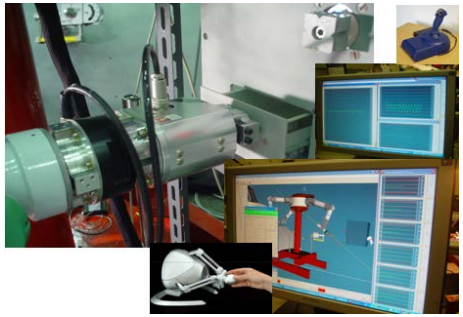
- The RAT Ground Control Station aims to provide an end-to-end system for:
  - specification,
  - validation,
  - monitoring and control

  of RAT operations



- Operational modes
  - Telemanipulation
  - Interactive Autonomy

- Background: DREAMS developments
  - Reengineering the MMIs (use of Eclipse/RCP)
  - Instantiation for rover operations
  - Focus on operators aids



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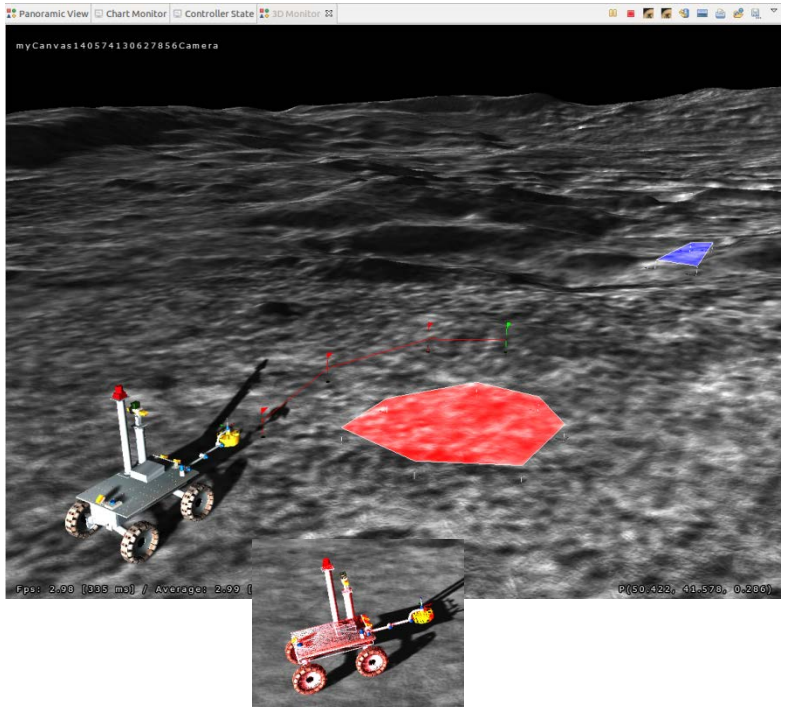
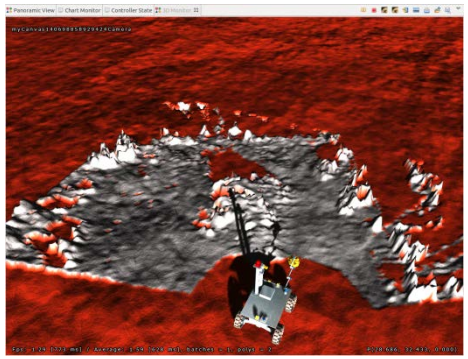
3D MONITORING

- Visualization on 3D canvas
  - The terrain on which the rover operates
  - The real and a phantom (virtual) rover
  - User annotations
    - Targets
    - Paths
    - Areas of interest or forbidden areas



- Terrain enhancement
  - Importing downloaded DEMs



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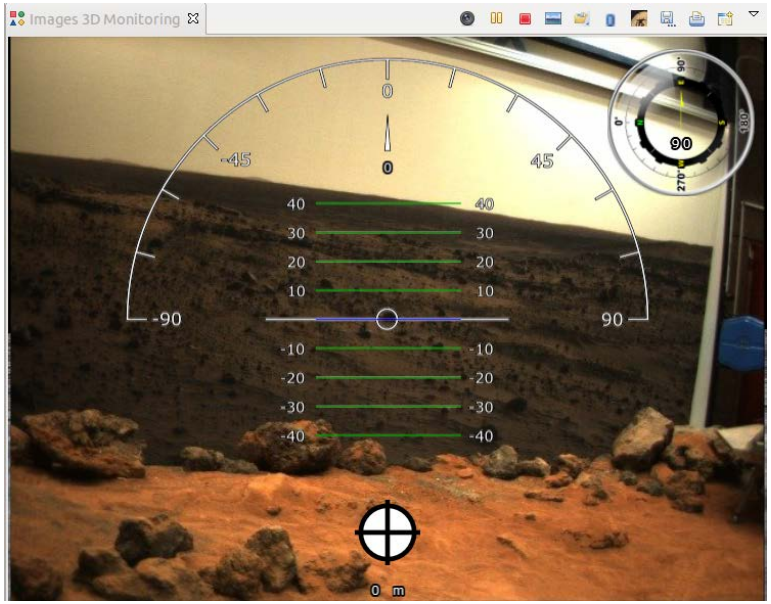
IMAGES MONITORING

- Visualization on 3D canvas
  - Images overlaid on the synthetic terrain
  - Features (target, paths, areas) specified on the terrain can be displayed/hidden
  - Visual cues indicating:
    - Rover Tilt angle
    - Rover Heading
    - Distance from the next target



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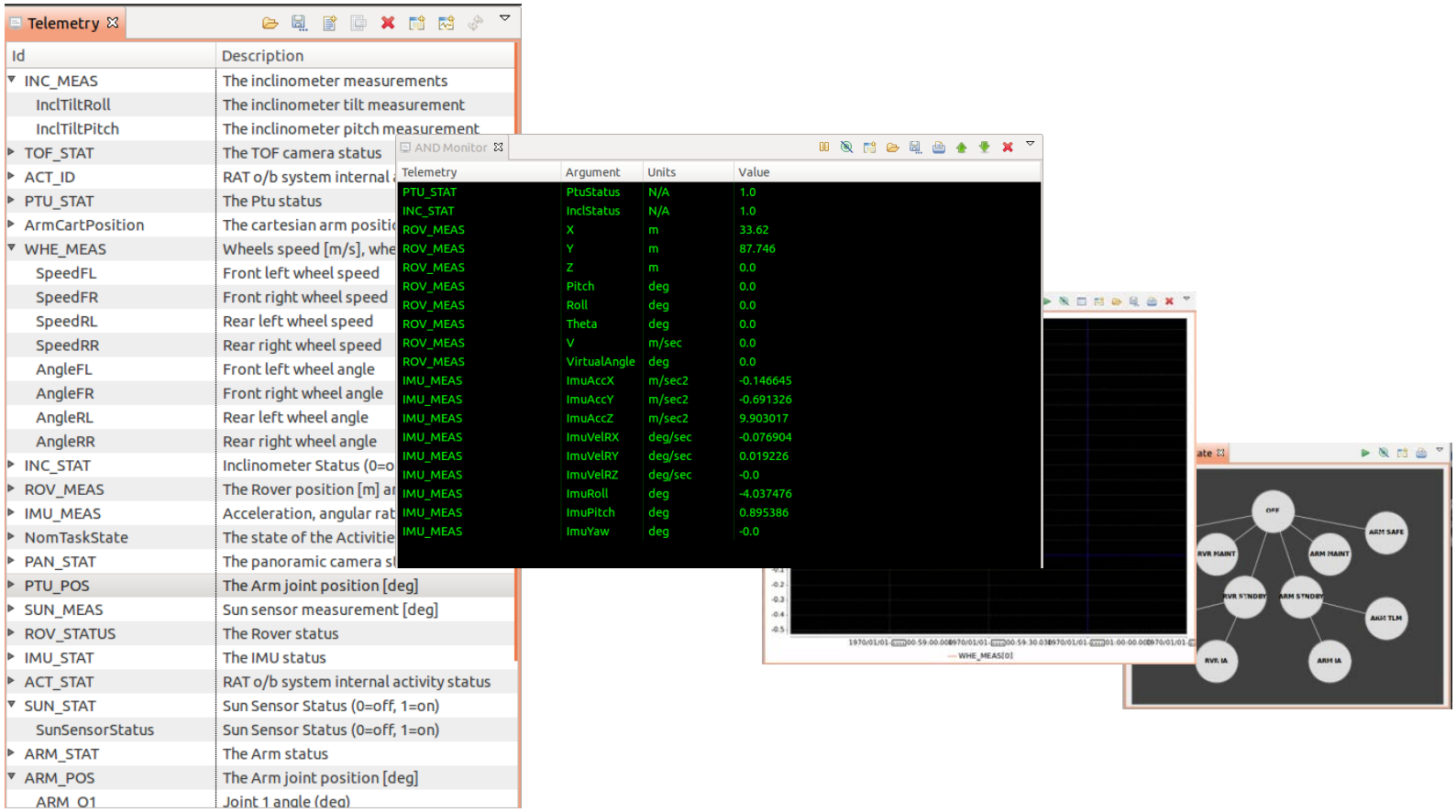
2D MONITORING

- Alphanumeric, Chart and FSM displays



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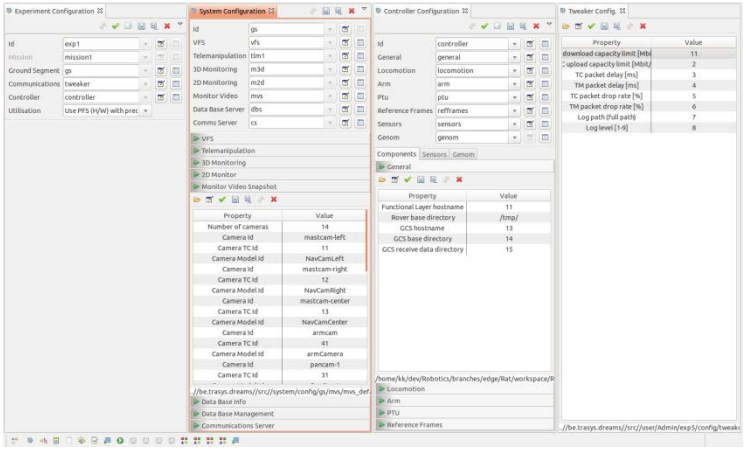
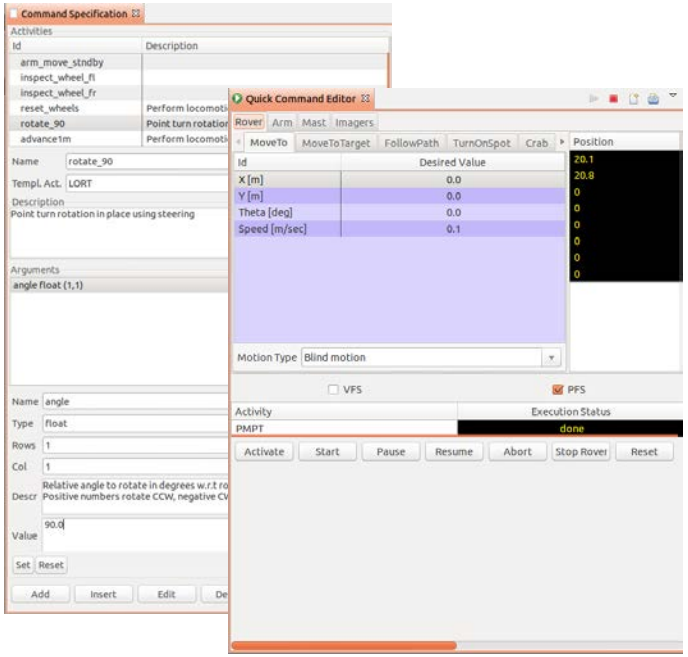
MAIN COMPONENTS

- **Configuration**: allows to configure through dedicated HMIs elements of the different components of the RAT system



- **Activity Preparation**: to prepare Template Activities and Activities to be executed by the VFS/PFS



- **Activity Execution**: execution and control of
  - predefined Template Activities and
  - sequences of Activities

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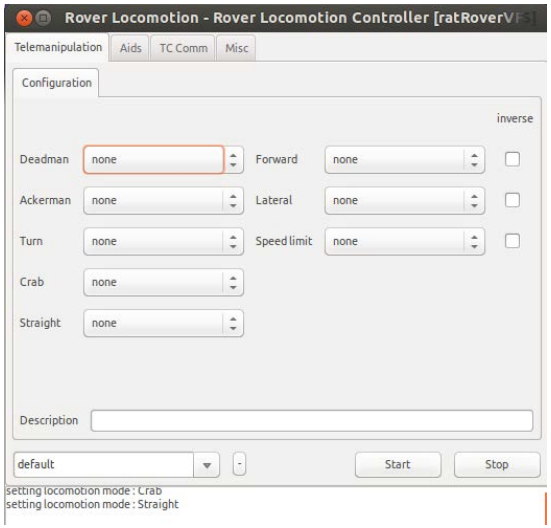
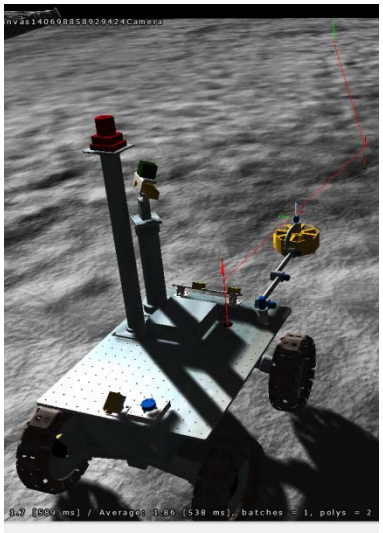
TELEMANIPULATION

- Use of joysticks, game pads, space mouse

- Configuration
  - Association of Actions to axis/buttons
  - Max linear/angular speeds
  - Saved in XML configurations file

- User Aids
  - Move straight
  - Go To Location using crab
  - Follow path using crab





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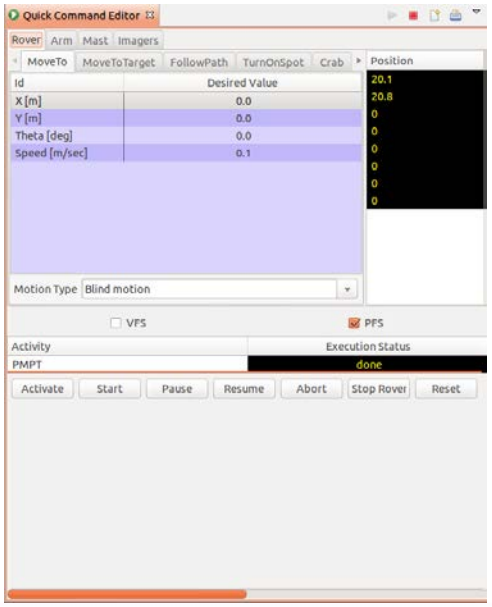
ACTIVITY CONTROL

- **Activity Preparation**: to prepare Template Activities and Activities to be executed by the VFS/PFS

- **Activity Execution**: execution and control of
  - predefined Template Activities and
  - sequences of Activities



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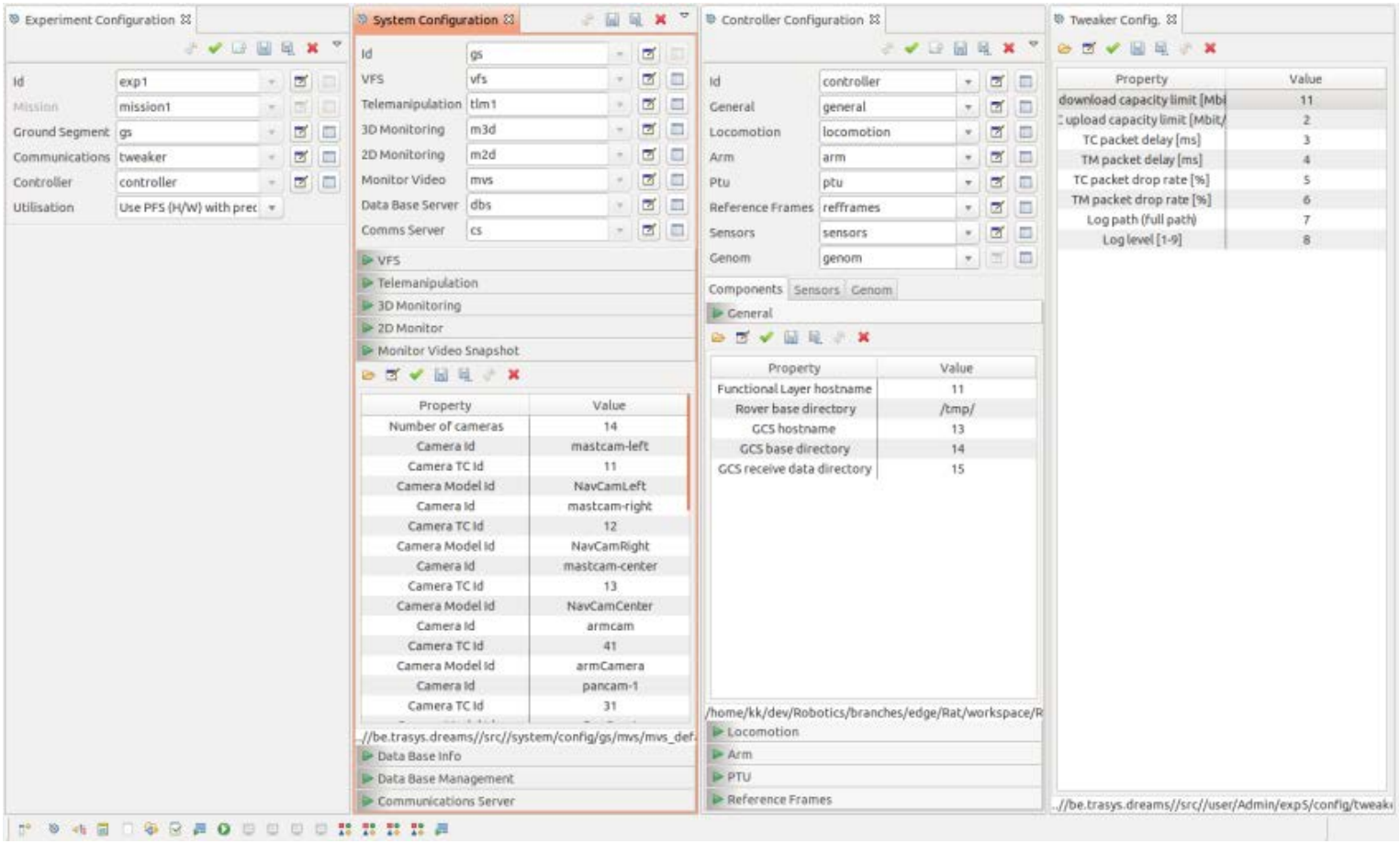
CONFIGURATION

- **Configuration**: allows to configure through dedicated HMIs elements of the different components of the RAT system



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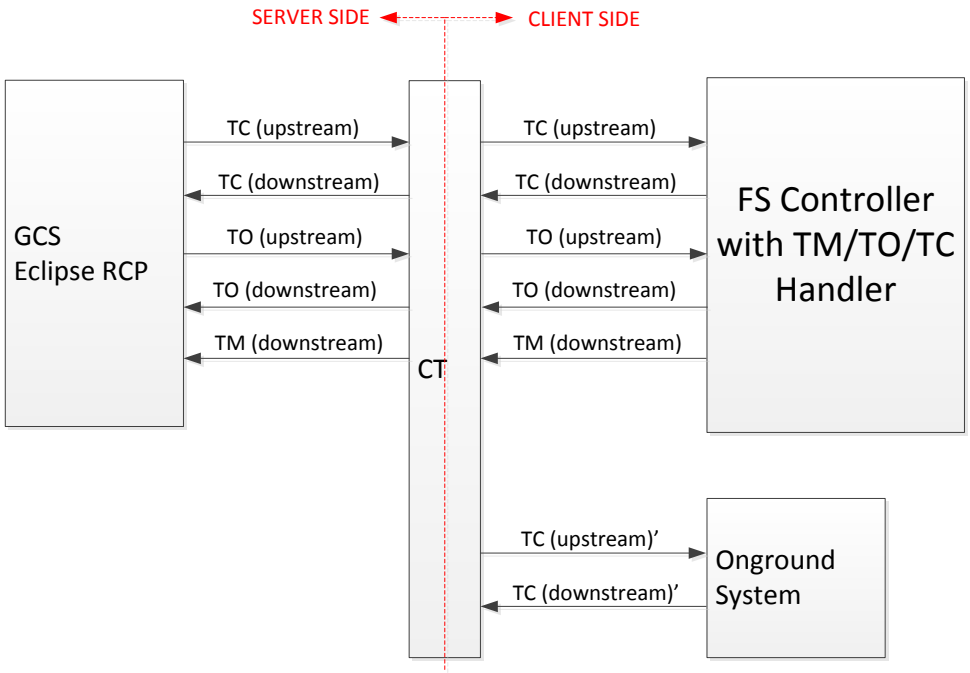
GS: COMMUNICATIONS TWEAKER

- **Transparent messages forwarding** (telecommands, teleoperation and telemetry)
- '**Hot**' configuration trough GCS
- Easy to simulate **Moon** scenarios (2-4s delay, 5% drop, 1Mb)

1. **Bandwidth restrictions:** Ethernet device is set-up (uplink/downlink) at user configured bandwidth (0-100 Mbps) using traffic shapping.

2. **Delays**: Any received TM/TC packet is forwarded after a configurable delay.

3. **Errors**: In a random manner and accounting for a predefined error percentage some of the TC's and TM's are dropped



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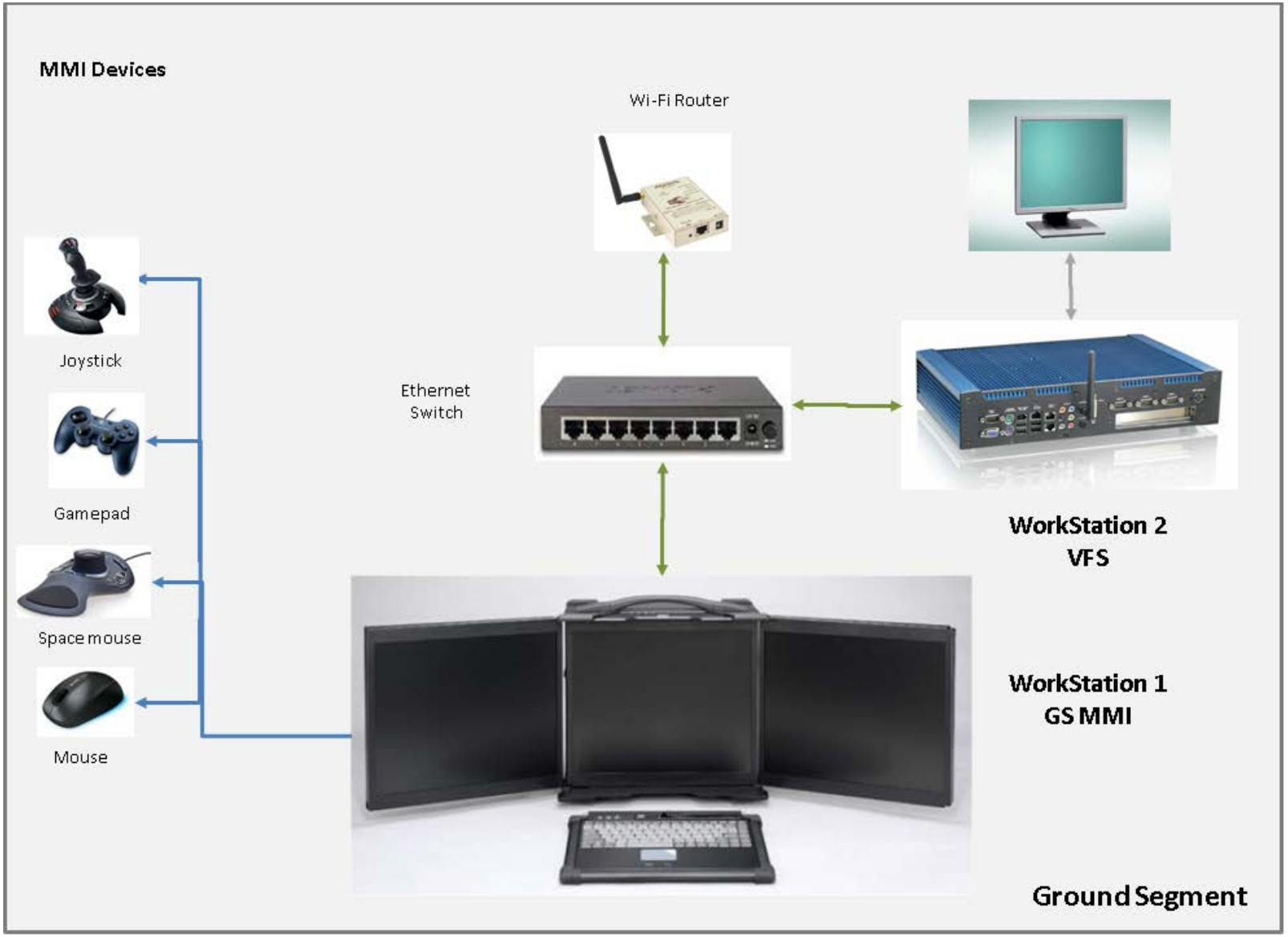
GS: HARDWARE ARCHITECTURE



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AIT

SYSTEM INTEGRATION

OPTIMISATION ACTIVITIES

TESTING AND VALIDATION

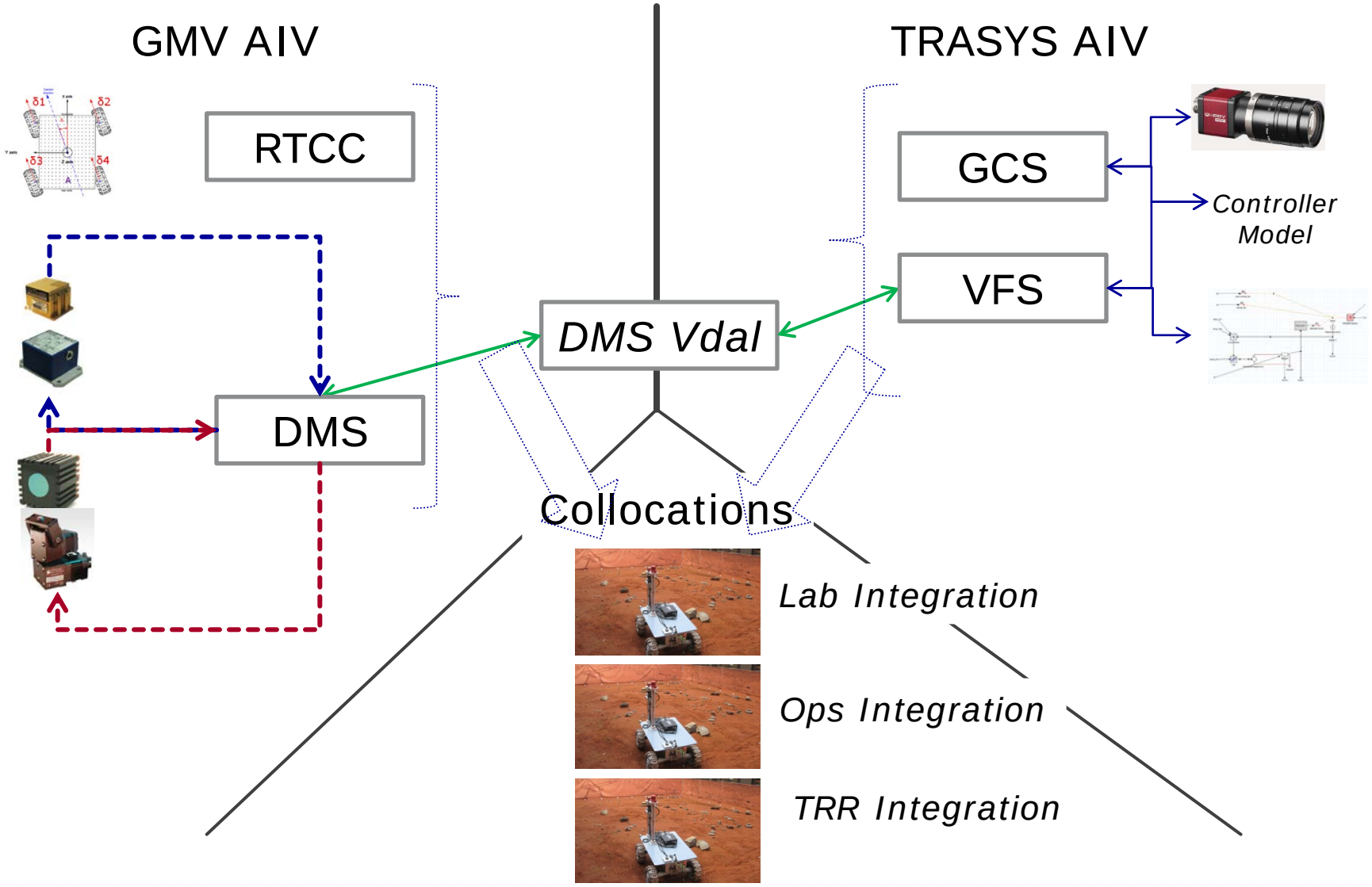
CONCLUSIONS

TRASYS
WE GET IT DONE

gmv®
INNOVATING SOLUTIONS

SYSTEM INTEGRATION

- Iterative and incremental approach:



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TESTING: FAT @ GMV MARSYARD

- **Experiment 1. Moon South Pole Scenario**:
  - LRM navigation
  - RRP telemanipulation

- **Experiment 2**. **Mapping** of Marsyard (DEM generation):
  - Concatenation of several DEM's
  - External correction (FARO laser system) of rover position
  - Importing of DEM into GCS
  - Determination of the LRM navigation accuracy

- **Experiment 3**. **Telemanipulation** under low lightning conditions using different light sources:
  - LRM LED lamp (85W)
  - Spot light (2Kw)
  - Darkness

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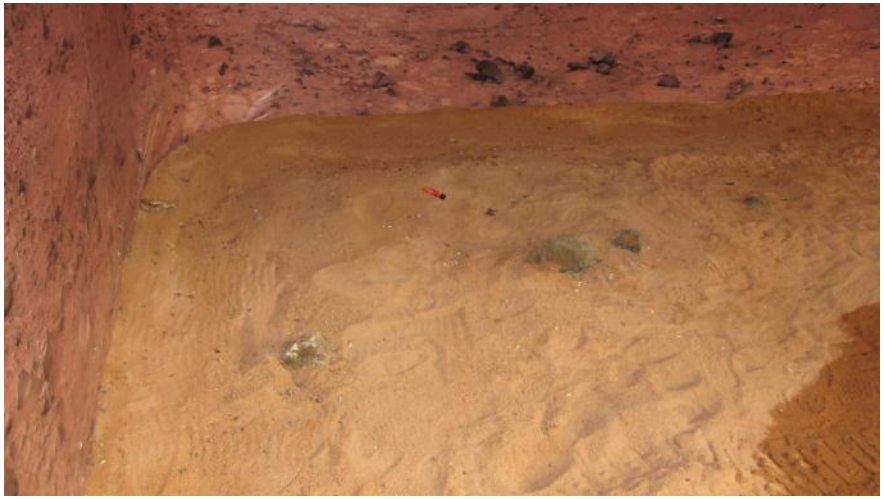
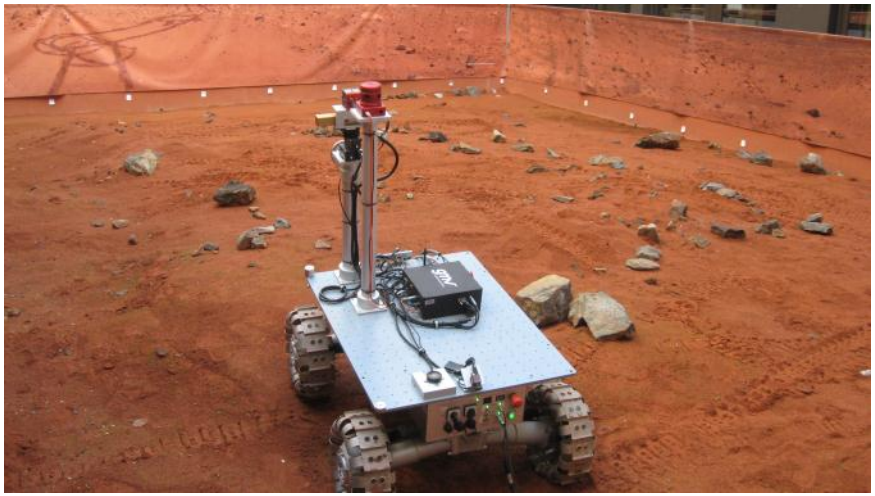
TESTING: FAT @ GMV MARSYARD

- **Experiment 4. Scientific goal discovery** (blind operator)





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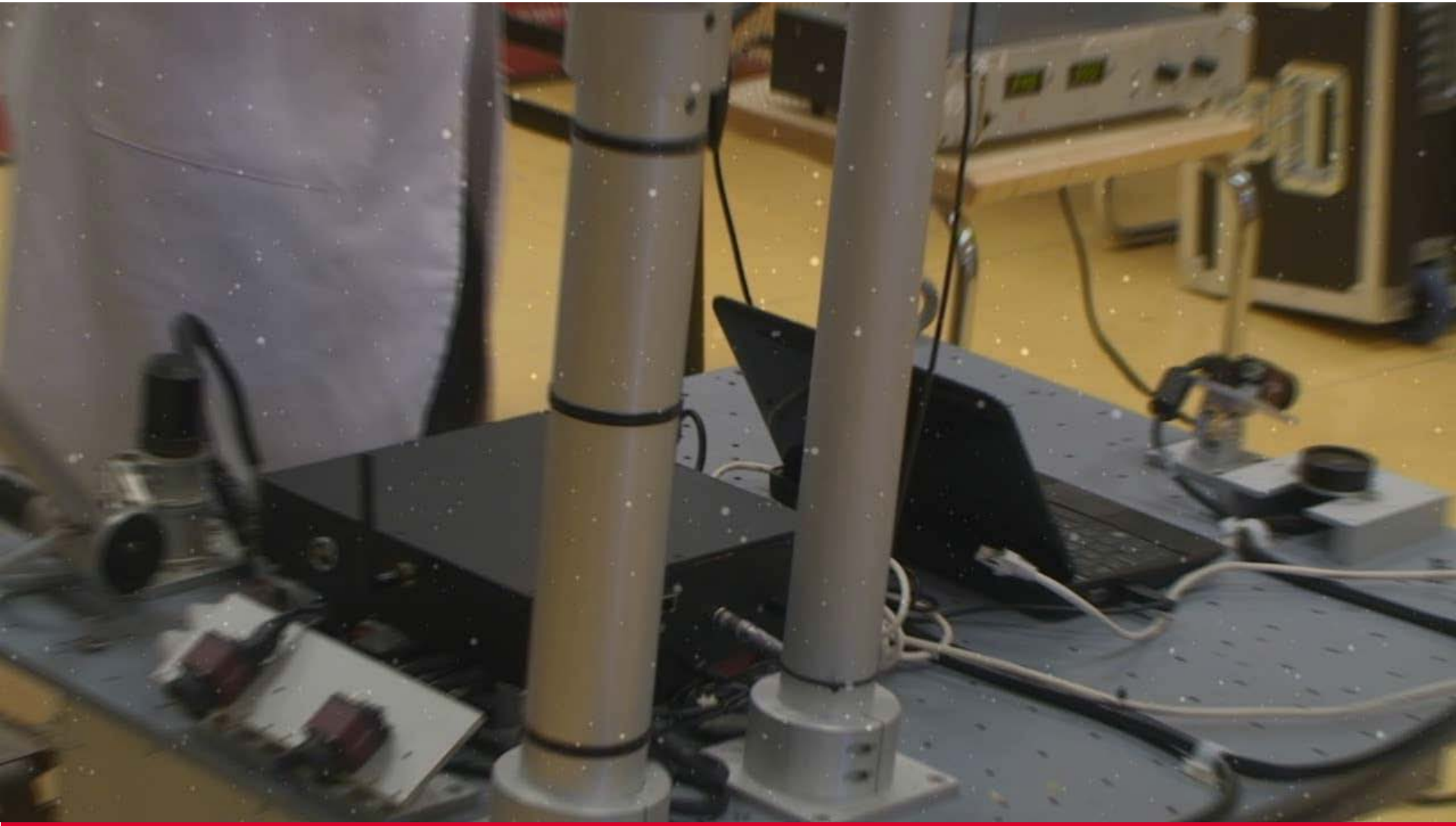
RAT OPERATIONS AT GMV MARSYARD



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MAJOR CHALLENGES

- Broad statement of work
- Use of LRM CFI (Rover + robotic arm)
- Incremental approach over previous ESA activities :
  - DREAMS
  - 3DROV
  - GOAC
- RAT-PFS includes two different software frameworks:
  - RTEMS
  - GenoM
- Embedded avionics, many perception sensors, flexible set-up, reference frames calibration
- Synchronization of a real-time controller with virtual rover simulation environment
- Space planetary rover and Ground Control Station with limited amount of budget

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CONCLUSIONS

- LRM as a complete planetary exploration rover:
  - Oriented to E1 – Telemanipulation capabilities
  - Low-lovel motion controllers implemented under RTEMS
  - Smart combination of Pan/Nav/TOF/Hazard cameras point-of-view
  - Robust and flexible functional layer (locomotion, arm, perception, navigation)
  - Outdoor experiments in GMV Marsyard have validated RAT capabilities
- Complemented with an equivalent virtual rover (VFS):
  - VFS simulates the RAT rover evolving on the lunar south pole
  - Interfaces the DMS to receive and execute the DMS control outputs and provide proprioceptive and exteroceptive sensors outputs
  - Simulates the main rover subsystems: Power, Data Handling, Solar Panels, …
  - Allows to rehearse RAT rover operations in combination with the RAT GCS
- Monitored and Controlled by the RAT GCS:
  - Allows the specification, validation, monitoring and control of rover operations in Interactive Autonomy and Telemanipulation operational modes
  - Focus on situational awareness and telemanipulation aids

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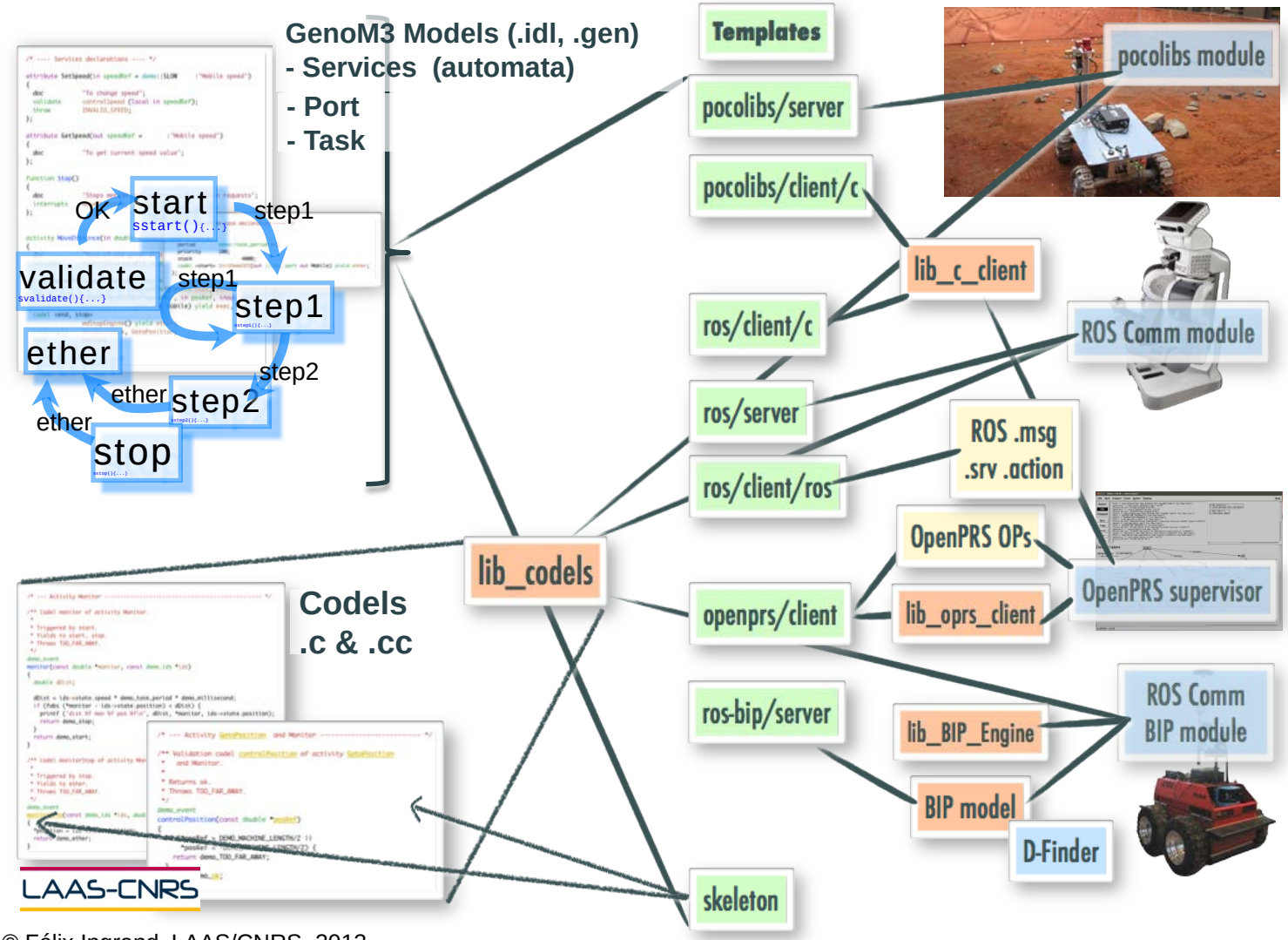
FUTURE DIRECTIONS (1/2)

- Interfacing with other frameworks (ROS/GenoM3/ROCK)



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FUTURE DIRECTIONS (2/2)

- Increase the range of operations of the RAT:
  - Field-test Campaigns (e.g. CNES Serom facilities)
  - Integrate other subsystems and algorithms: navigation sensors, DELIAN arm, payloads, etc.
  - Rehearsal of ExoMars ROCS (GMV/Trasys) operations

- Introduce higher level of autonomy (E3/E4)
  - Autonomous navigation operations
  - Goal-commanding

- Contribute in future missions of ESA (Moon/Mars-based)

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Thank you very much for your attention
The RAT Team
TRASYS
WE GET IT DONE
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INNOVATING SOLUTIONS

RAT OPERATIONS UNDER LOW ILLUMINATION CONDITIONS

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RAT OPERATIONS AT ESTEC

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