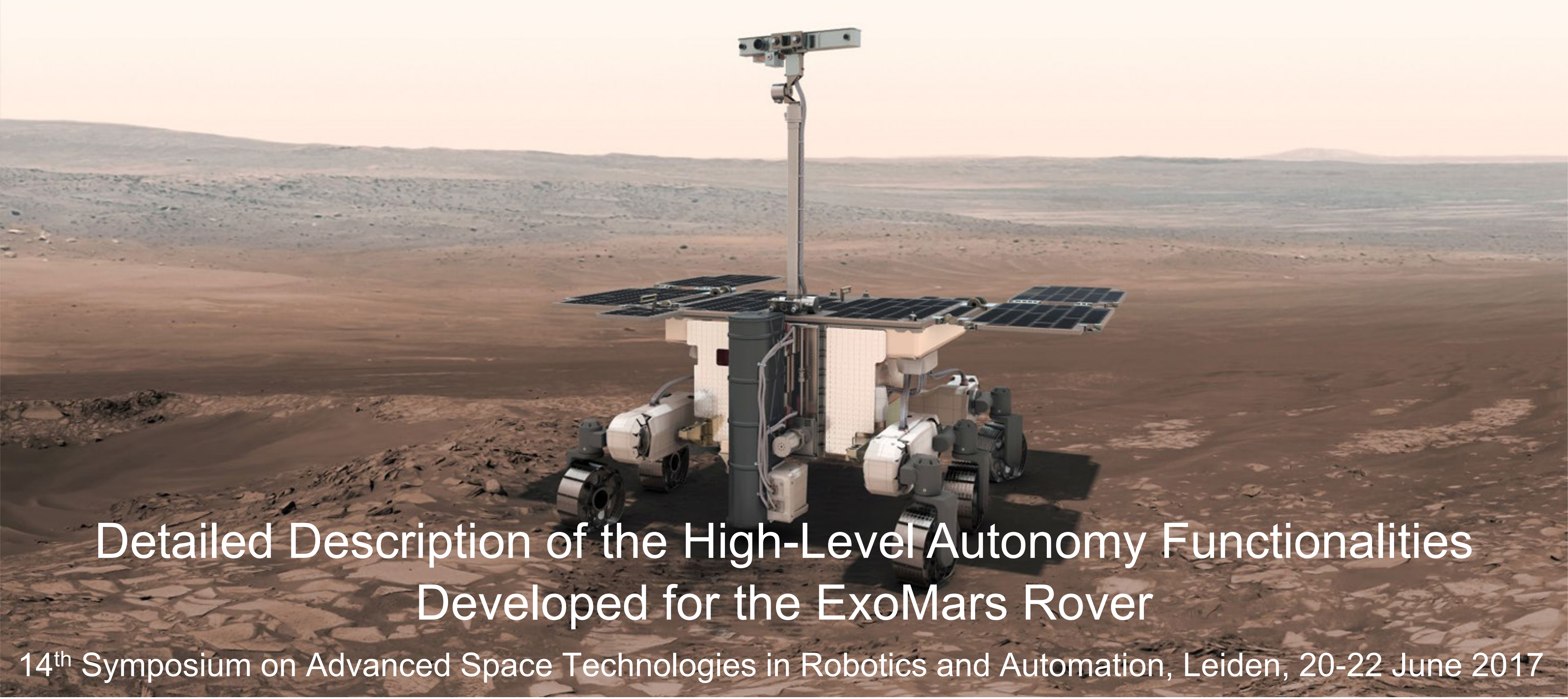

Detailed Description of the High-Level Autonomy Functionalities Developed for the ExoMars Rover

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DEFENCE AND SPACE

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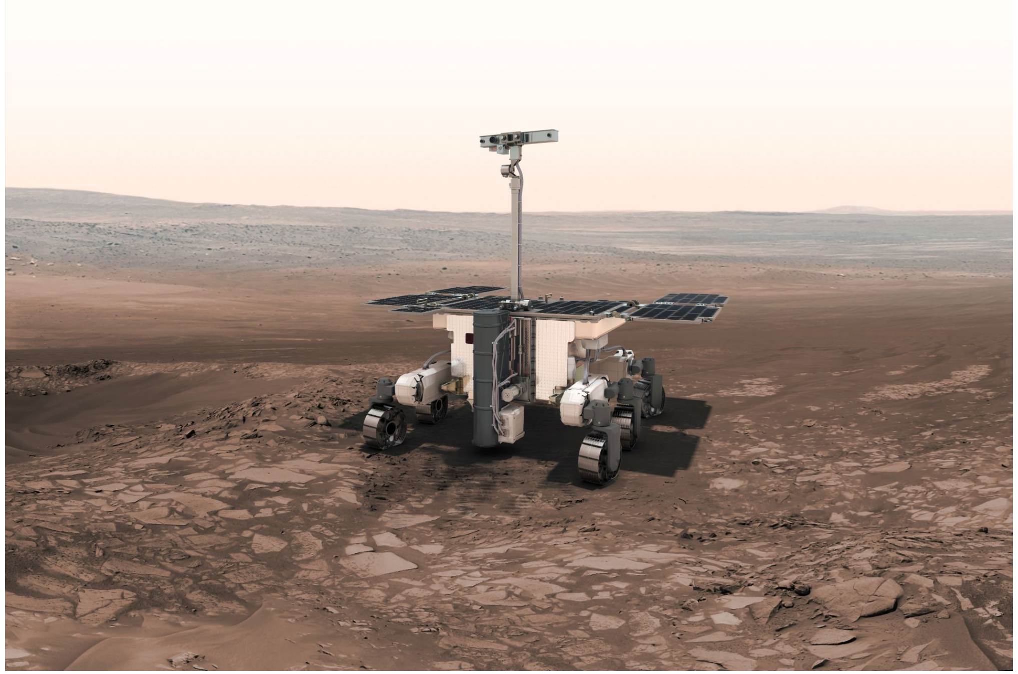
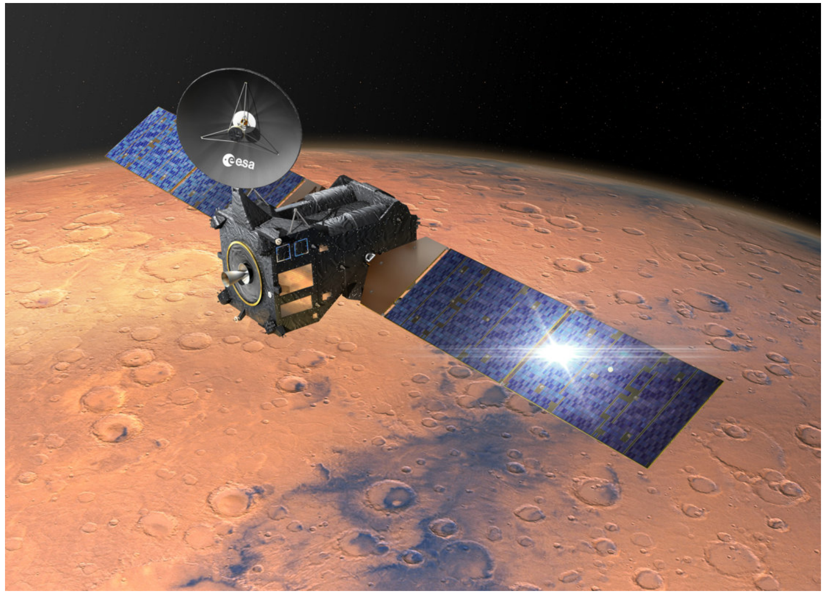
21 June 2017

Content

ExoMars Rover



- To be launched in 2020
- Landing planned for early 2021
- ExoMars Objectives:
  – Search for signs of past and present life on Mars
  – Investigate how the water and geochemical environment varies
  – Investigate Martian atmospheric trace gases and their sources
  – Validation of technology for planetary exploration
- Instruments include a subsurface drill and a ground penetrating radar
- To meet its science objectives, the ExoMars Rover has to traverse several kilometres through previously unknown hazardous Martian terrain with very limited communication opportunities (two short communication windows a day).



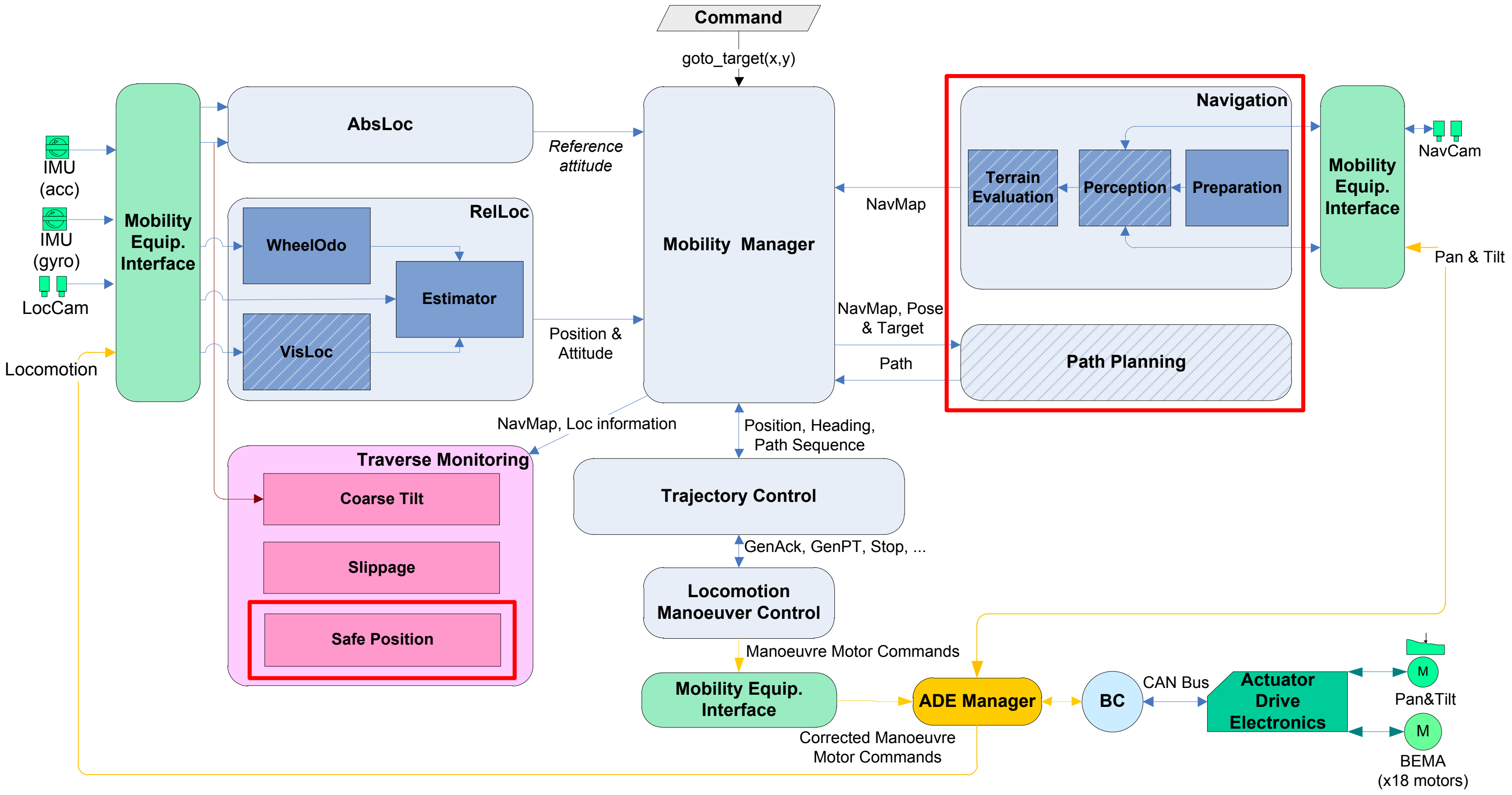
GNC Architecture Overview

Three levels of Autonomy:

1. Full autonomy: Command the rover to reach a target position (no distance limitation).
2. Command the rover to follow a path specified by ground (if full autonomy is implemented, this path can be checked for safety by the rover).
3. Directly drive the rover.

Blocks implementing the functionalities needed for approach 2 and 3 are described in separat presentation (“ExoMars Rover Control, Localisation and Path Planning in a Hazardous and High Disturbance Environment”)

Note that full autonomy (marked in red) is currently not part of the ExoMars Rover baseline.

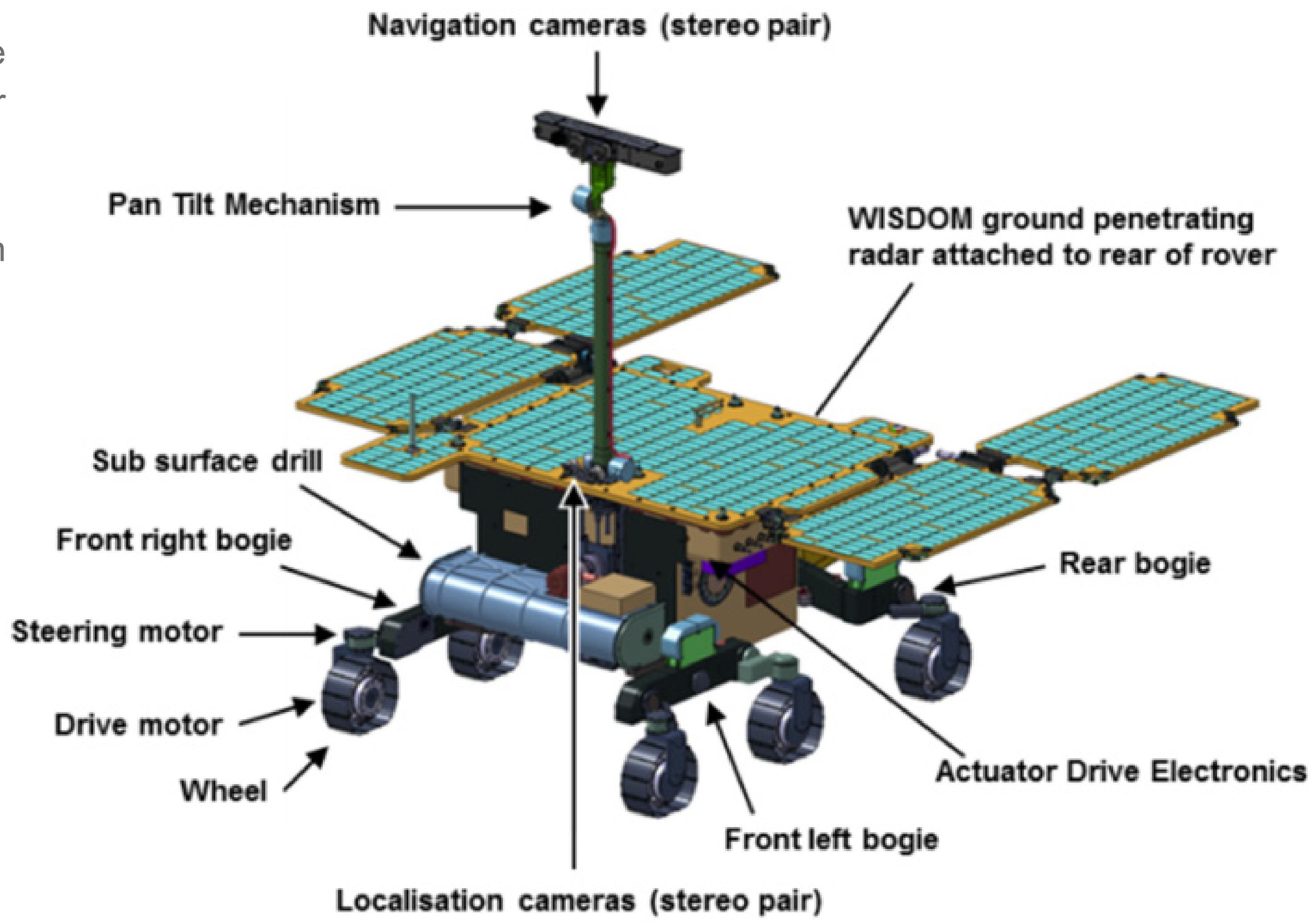


Hardware

Dedicated hardware needed for approach 1 (Note that this hardware is part of the ExoMars Rover baseline):

- Navigation Camera (stereo pair)
- Deployable Mast Assembly (DMA) including Pan and Tilt Mechanism

Camera Parameter	Value
Field of View	65 deg
Stereo Baseline	150 mm
Image Resolution	1024 x 1024
Exposure Time	1 ms to 1000 ms
F-Number	f/8
Focal Length	4.0 mm



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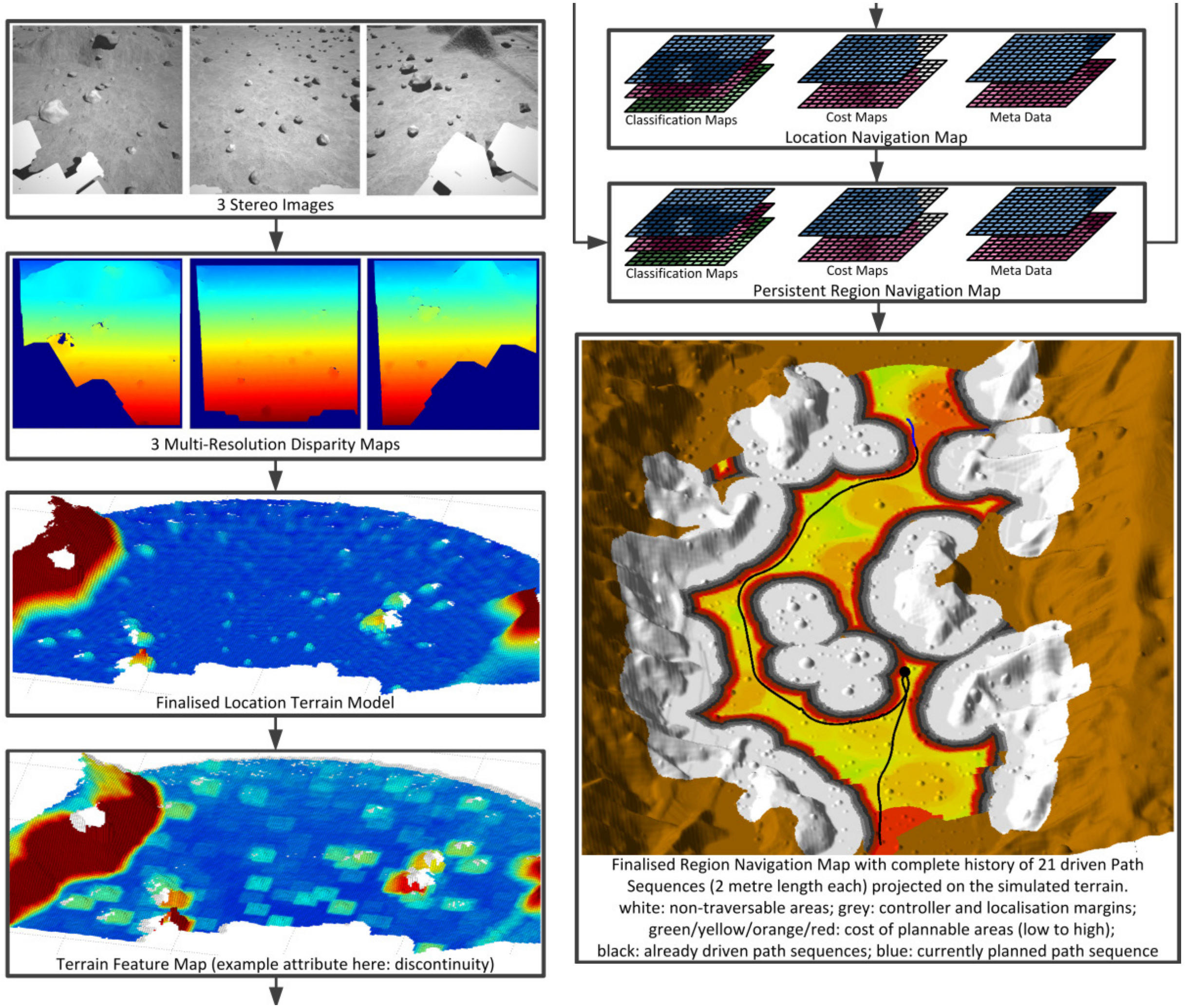
Full Autonomy Overview

Stop & Go approach:

- Every 2.3 metres the rover stops ("navigation stop") to perform the following steps
  1. Take three stereo images of the surrounding terrain.
  2. Model the surrounding terrain.
  3. Create a local map of the surrounding terrain specifying safe and unsafe areas as well as the terrain difficulty.
  4. Merge the data of the local map into a persistent global map which contains the data gathered at previous navigation stops.
  5. Plan a 2.3 metres long safe path towards the target.
  6. Output a traverse monitoring map to the Traverse Monitoring module.
- Closed-loop execution of planned path

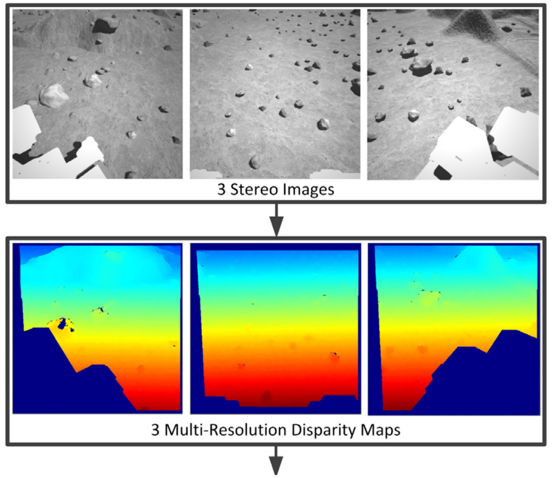
Parameter	Value
Distance driven per day	70 m (full autonomy)
Range accuracy (from target)	7 m (after 70 m traverse)
Heading accuracy	15° (after 70 m traverse)
Heading knowledge	5° (after 70 m traverse)



Key Design Drivers

- **Safety:** The high-level autonomy algorithms have to keep the rover safe at all times. Particularly for collision avoidance (e.g. bottoming out of the rover body on a rock or hitting the solar panels against a rock), the ExoMars Rover FDIR is not able to predict the problem before it has occurred. These can be mission ending events. Therefore, the autonomy algorithms have to be designed to always work conservatively so that they prevent these events from ever happening.
- **Maximise traversable Terrain:** Martian terrain can be very challenging. To allow the rover to traverse smoothly towards its target, a sufficiently large proportion of the terrain has to be classified as safe. Therefore, the system is not allowed to be too conservative in its approach. This (together with the need for safety) leads to a need for accurate uncertainty estimation and propagation instead of applying global margins.
- **Repeatability:** If the same Martian terrain is seen from different distances or perspectives, its evaluation has to be sufficiently similar. Particularly the binary decision if something is an obstacle or not has to be repeatable. Otherwise terrain might act as a one-way valve. This is particularly challenging for borderline traversable terrain.
- **Execution Time:** The algorithms have to execute on the ExoMars Rover 96 MHz LEON2 co-processor. The execution time goal is two minutes (Note that this requires further optimisation of the terrain analysis algorithms). This is particularly challenging taking into account the amount of data processed (> 1.5 million pixels) and the need for accurate uncertainty estimation and propagation.

Perception



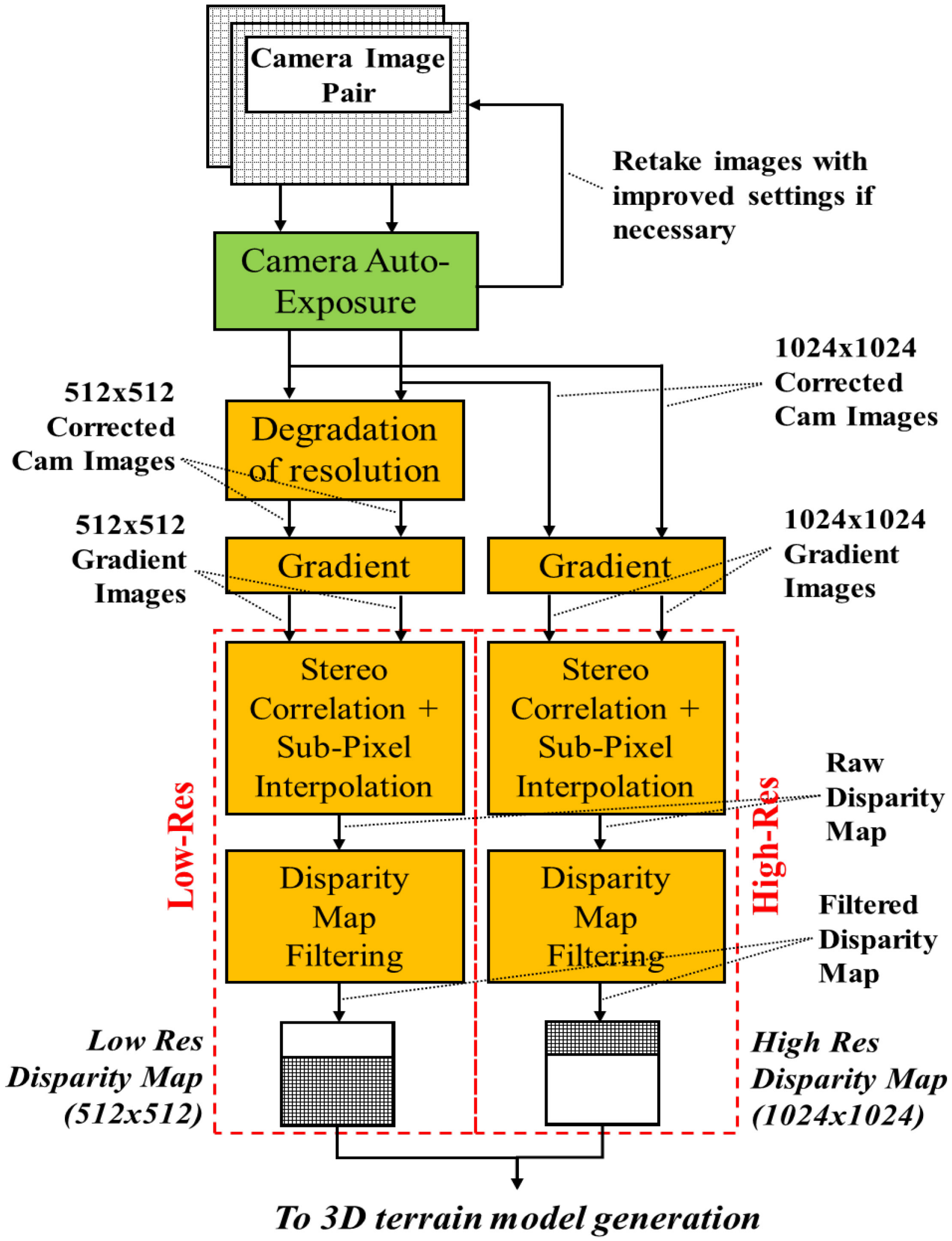
- Stereo Correlation
- Multi-resolution approach

Key Challenges

- Accuracy: The disparity map has to be accurate enough to adequately represent Martian terrain such that the terrain analysis algorithms can determine its safety and traversability.
- Execution Speed: Each call of the perception system has to take less than 20 seconds to run on the ExoMars Rover 96 MHz LEON2 co-processor.

Algorithms have been tested in the following setups:

- ExoMars Rover GNC simulator
- Airbus Mars Yard
- Pictures from NASA rovers
- Leon2 processor



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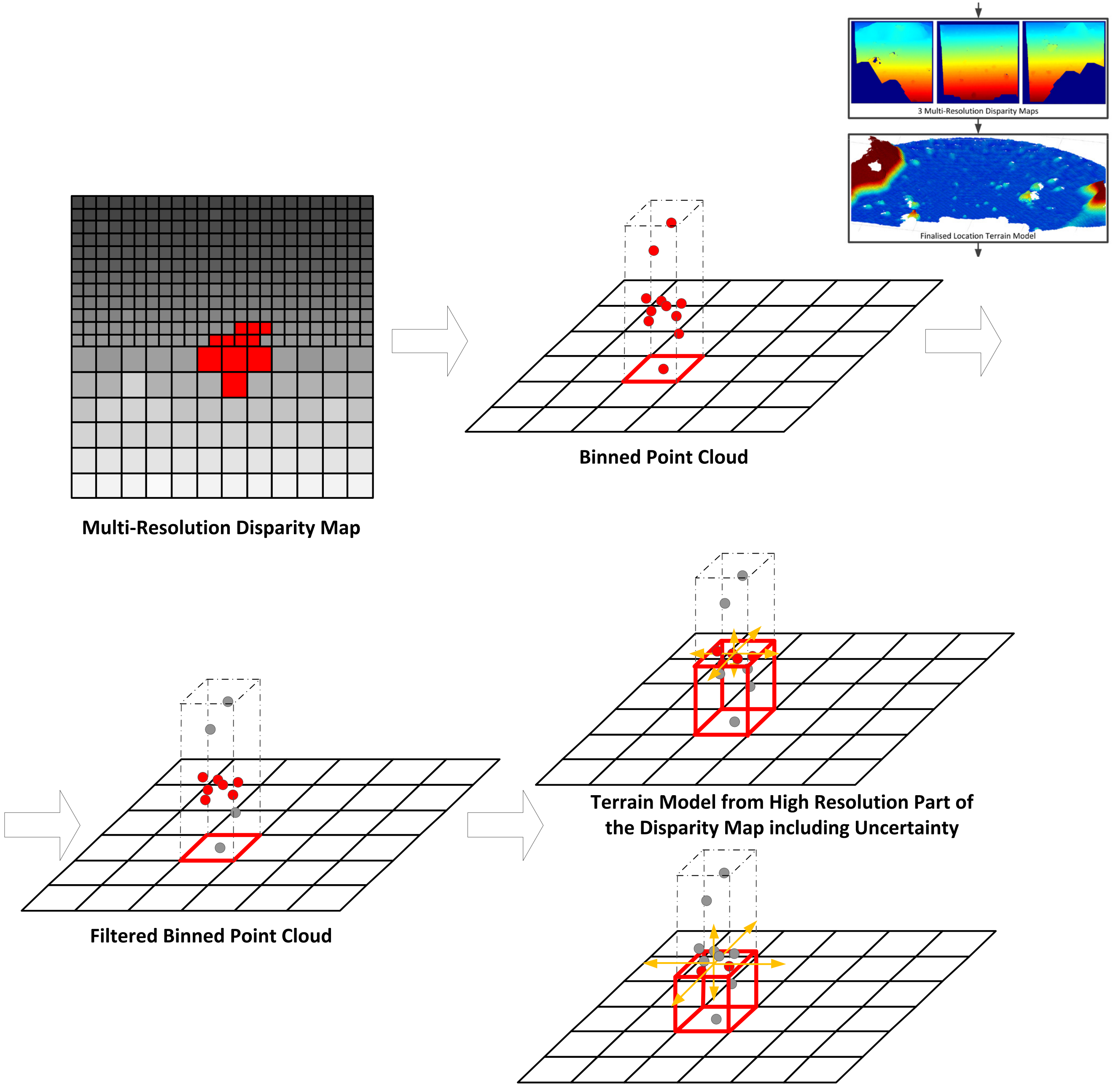
Terrain Modelling (1)

Processing steps:

1. Create one point cloud from each multi-resolution disparity map.
2. Bin points into 2D Cartesian grid.
3. Filter to remove unreliable data.
4. Uncertainty analysis.
5. Create two terrain models from each point cloud (one for low-resolution part of disparity map, one for high-resolution part).
6. Merge two terrain models into single perception terrain model
7. Merge three perception terrain models into single location terrain model.
8. Finalise uncertainty analysis to create three DEMs (max, mean, min).



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Terrain Modelling (2)

Extended Terrain Model for solar panel clearance check:

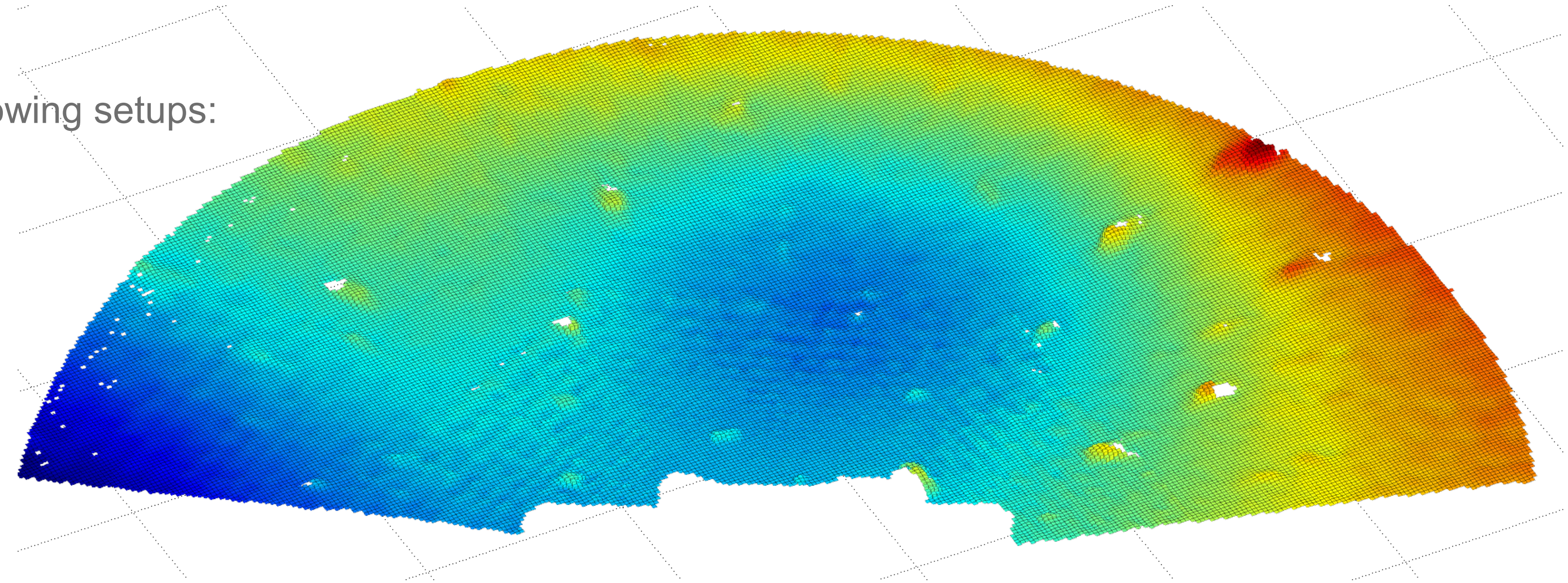
- Needed because of the large size of the solar panels (reaching out 2.1 metres from the rover centre)
- Defined worst-case: highest possible elevation

Key Challenges

- Accuracy: The resulting terrain models have to be always conservative but at the same time they are not allowed to be overly conservative because that would reduce the amount of terrain which is evaluated to be traversable.
- Execution Speed: The terrain modelling algorithms should take less than 35 seconds per navigation stop to execute on the ExoMars Rover 96 MHz LEON2 co-processor. This is particularly challenging because of the large amount of data (point clouds with more than 1.5 million points).

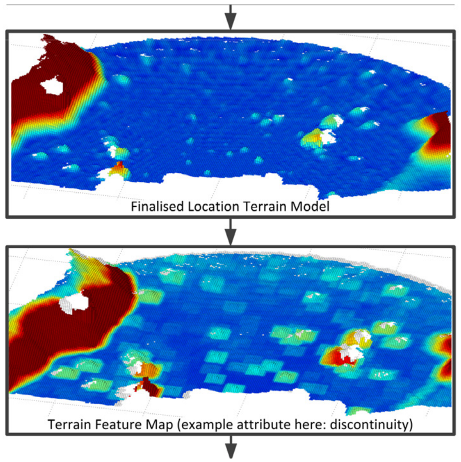
Algorithms have been tested in the following setups:

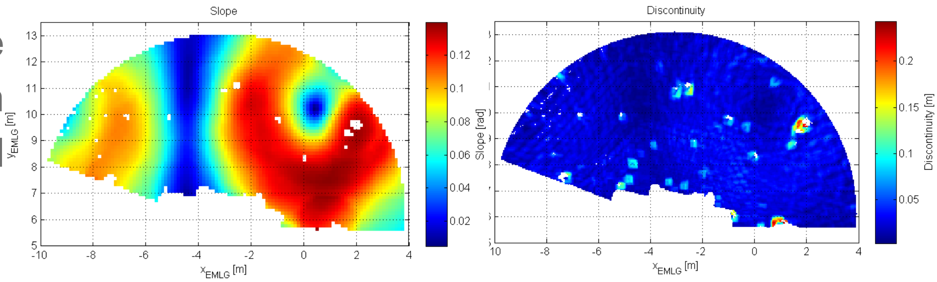
- ExoMars Rover GNC simulator
- Airbus Mars Yard
- Pictures from NASA rovers
- Leon2 processor



Terrain Analysis

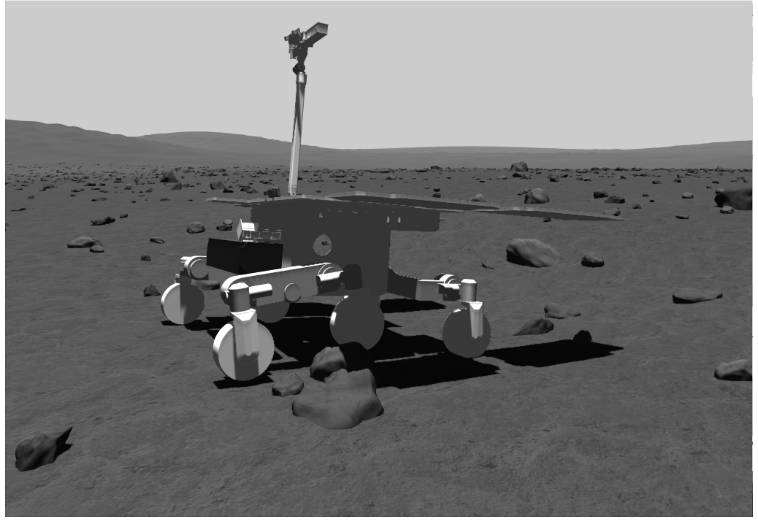
- Analyses terrain model with respect to the capability of the rover to safely traverse it.
- Some terrain attributes fully defined by the terrain (e.g. terrain discontinuity and slope).
- Other terrain attributes take into account the rover's locomotion system (e.g. rover clearance, solar panel clearance, rover tilt angle, bogie angles)
- Particularly important is how the rover would be positioned on the terrain because bottoming out of the rover body on a rock or hitting the solar panels against terrain could potentially be mission ending events. This is evaluated by placing a virtual rover model on the terrain model.





Key challenges:

- Propagation of Uncertainties: The terrain model uncertainties have to be propagated efficiently through the estimation process of the terrain attributes.
- Processing Resources: The algorithms have to run on limited processing resources (SPARC LEON2 96 MHz processor) and limited memory (< 512 MB). This is particularly challenging because of the large number of rover placements (i.e. on each terrain model cell with each heading).



Algorithms have been tested in the following setups:

- ExoMars Rover GNC simulator
- Airbus Mars Yard
- Leon2 processor

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Mapping

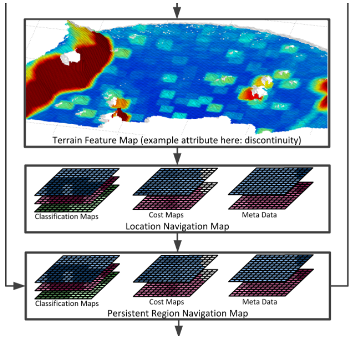
- Creates location navigation map, which specifies traversable, non-traversable and unknown areas. Cost values are defined for traversable areas.
- Merges local map containing the information gathered at the current navigation stop into the persistent region navigation map, which contains the data gathered at previous navigation stops.
- Creates following outputs:
  – Finalised region navigation map
  – Escape boundary
  – Traverse monitoring map

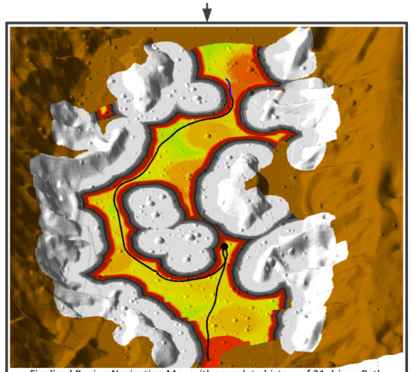
Key challenges:

- Limit dynamic of maps: Changing map caused by addition of new data, data perceived at previous navigation stops becoming increasingly uncertain and areas in some cases getting re-classified when re-mapped from a different perspective and/or distance.
- Execution Speed: < 20 seconds on ExoMars Rover 96 MHz LEON2 co-processor. Algorithms contain a considerable number of steps which use computationally expensive image processing functionalities.

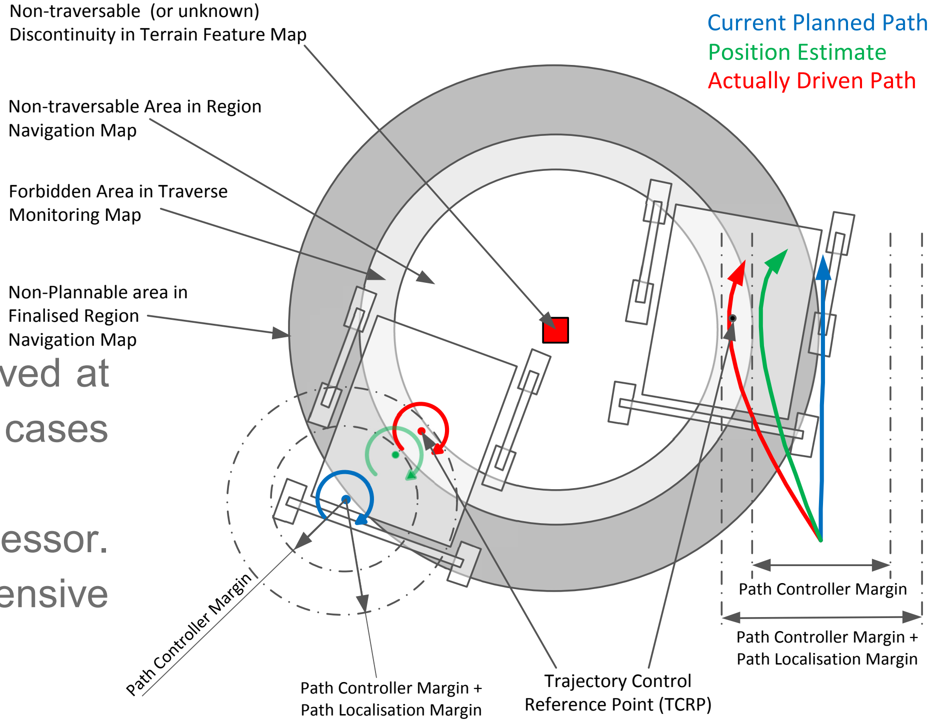
Algorithms have been tested in the following setups:

- ExoMars Rover GNC simulator
- Airbus Mars Yard
- Leon2 processor





Finalised Region Navigation Map with complete history of 21 driven Path Sequences (2 metre length each) projected on the simulated terrain. white: non-traversable areas; grey: controller and localisation margins; green/yellow/orange/red: cost of plannable areas (low to high); black: already driven path sequences; blue: currently planned path sequence



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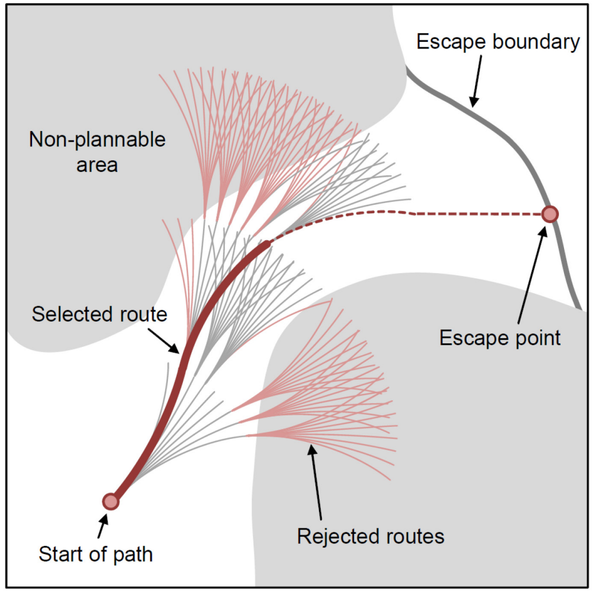
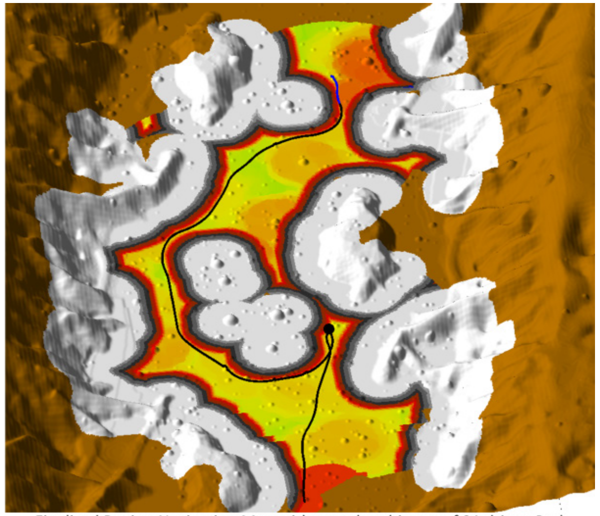
Path Planning

- Plans the next 2.3 metre path to be executed and the long-term path towards the target.
- Unless rover is close to target, the majority of the terrain between rover and target are unknown. Therefore, the long-term path is planned toward escape boundary. The route is planned such that:
  – Unknown and non-plannable areas in the finalised region navigation map are avoided.
  – Costs in the finalised region navigation map cells that the route crosses are minimised.
  – Future cost in yet unknown cells which will have to be traversed to reach the target are minimised.
  – The path is compatible with the dynamics and manoeuvrability of the rover.
- A* search over a hybrid search path containing lattice edges (for the short-term path) and rectilinear grid edges (for the long-term path).

Key challenges:
- Tuning: Trade-off by the algorithm between expected full path length to target and the difficulty of the terrain traversed.
- Path Compatibility: Compatibility of path with the dynamics and manoeuvrability of the rover.
- Execution Speed: < 10 seconds on ExoMars Rover 96 MHz LEON2 co-processor.

Algorithms have been tested in the following setups:
- ExoMars Rover GNC simulator
- Airbus Mars Yard
- Leon2 processor



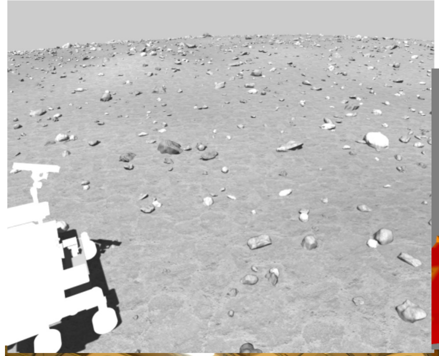
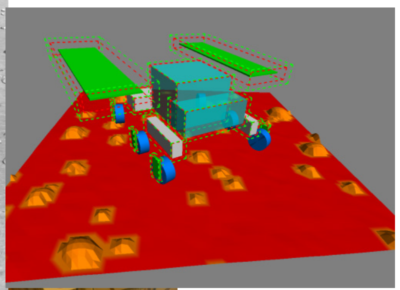


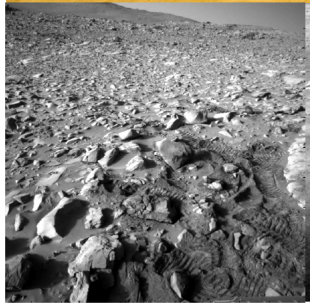
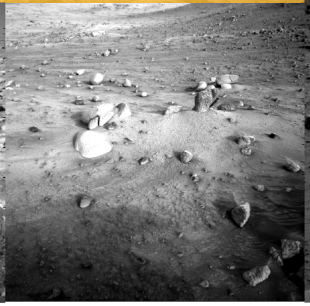
Finalised Region Navigation Map with complete history of 21 driven Path Sequences (2 metre length each) projected on the simulated terrain.
white: non-traversable areas; grey: controller and localisation margins;
green/yellow/orange/red: cost of plannable areas (low to high);
black: already driven path sequences; blue: currently planned path sequence

System Level Testing

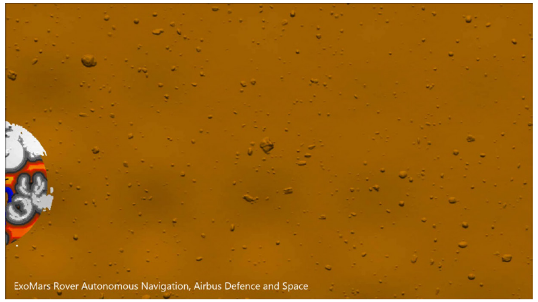
The high-level autonomy functionalities have been successfully tested together with the GNC algorithms which execute the path (where feasible) in the following test environments:

- **ExoMars Rover GNC Simulator:** Simulator with high-fidelity environment and equipment models developed for the formal functional verification of the ExoMars Rover Vehicle Mobility Software.
- **Airbus Mars Yard in Stevenage**: Indoor test facility with more than 500 square metres of representative Martian terrain. The breadboard rover (MDM) utilises breadboard models of the locomotion subsystem and the navigation camera designed for the ExoMars Rover.
- **Data from existing NASA Rovers:** Pictures taken by the MER rovers.
- **LEON2 processor (SPARC):** Pender Electronic Design GR-CPCI-XC4V board with an implementation of a LEON2 processor on it. This environment is used to evaluate the execution speed of the algorithms on a representative processor.


Simulation Result	Value
Rover Kept Safe	100 percent
Reached Final Target	90 percent
Cannot find a Way to the Final Target	10 percent



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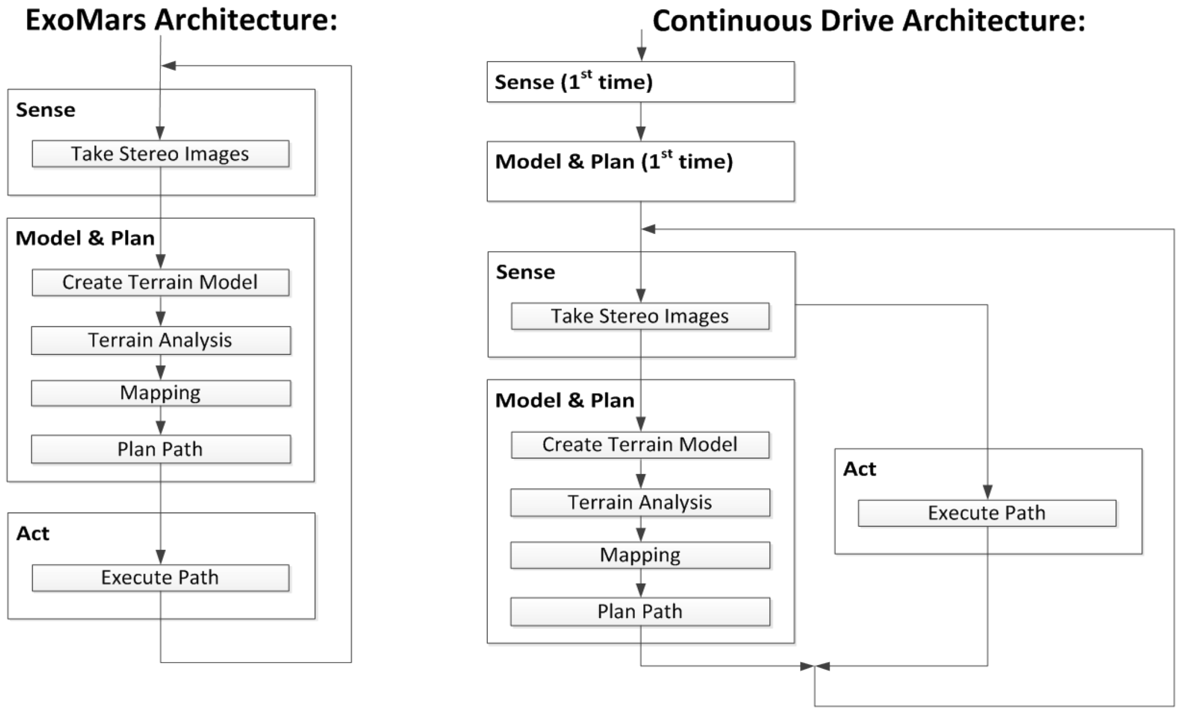
Beyond ExoMars: Continuous Drive

- Airbus has invested into enhancing the mature ExoMars design for the needs of future missions such as Mars Sample Return (MSR) and future missions to Moon and Mars.
- Though the stop & go approach is the right solution for the ExoMars rover (considering constraints on processing resources, thermal and power), the ExoMars Rover would not be able to travel sufficient distance for many MSR mission concepts.
- Architecture update has been design to move towards a continuous drive approach:
  - Instead of repeating the traditional Sense, Model, Plan & Act (SMPA) phases sequentially, the modelling and planning for a future path is performed while executing the previous path.
  - Stopping time reduces to the time needed to take three stereo images (< 10 seconds). A sensor configuration achieving a more rapid measurement (e.g. one or several wide FOV cameras, Flash LIDAR or solid state LIDAR) could reduce this to < 1 second.



Status:

- Continuous drive architecture has been implemented and successfully tested in the ExoMars Rover GNC simulator.
- Currently being migrated from the simulator to a breadboard rover to be tested in the Airbus Mars Yard.

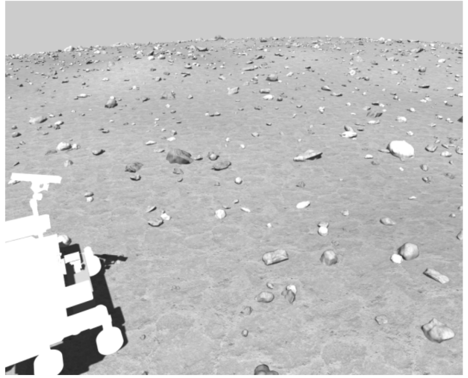
Conclusion: Autonomy Algorithms Status and Rover Operation Baseline

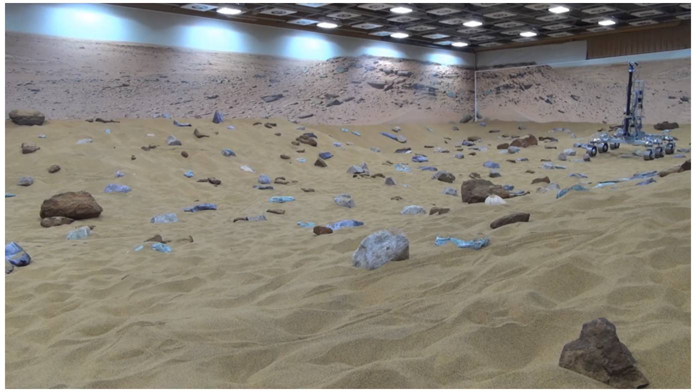
Status of the high-level autonomy functionalities designed for the ExoMars Rover:

- The development of these algorithms has now been completed.
- Algorithms successfully tested in high-fidelity ExoMars Rover GNC simulator, Airbus Mars Yard and with data from NASA rovers.
- Performance of algorithm implementation tested on representative hardware (LEON2 CPU).
- Algorithms now ready to move to the flight software production stage enabling the final end-to-end validation at system level with HITL (hardware in the loop).

Unfortunately these algorithms are currently **not** part of the ExoMars Rover baseline. The current baseline assumes that the ground operator will define the whole path to be driven during one sol in advance. The following challenges will be faced by the ground team:

- Estimate rock heights and slope angles from up to 30 metres away to evaluate if the rover can safely traverse them without bottoming out or hitting the solar panels (Mars Yard images below show rocks up to 20 metres away).
- Estimate the danger of terrain hidden behind rocks and sand dunes.
- Take into account the increasing error in the position and attitude estimate of the rover during a whole day.
- Make sure that the rover safely traverses a sufficient distance per sol whilst meeting the ExoMars science objectives.





Conclusion: Strongly improved Rover Capability if Full Autonomy is implemented

- **Increased Science Return:**
  - Algorithms designed to enable the rover to safely traverse long distances (average speed > 10 m/hr) in complex terrain. Planning paths of 30 metres length in advance by the ground team is only possible in extremely easy (and therefore often scientifically not very interesting) terrain.
  - Full-autonomous system can traverse through more complex terrain because it evaluates its traversability when only a few meters away, enabling it to accurately estimate rock heights and slope angles and look behind all traversable rocks. Also the pose uncertainty of the the rover is considerably smaller if only accumulated for a few metres of driving. Note that scientifically interesting terrain is often particularly challenging terrain.
- **Reduced Risk of Mission Loss:**
  - The autonomy system will have gone through a formal V&V campaign with hundreds of simulations and hardware in the loop testing. Paths planned by a ground operator will inherently be much less pre-determined and based on much less data (images only from one single position per day). On top comes the human factor, as recently demonstrated when a breadboard rover operated by an astronaut on the ISS got stuck on a rock in the Airbus Mars Yard.
  - It is important to note that there is no FDIR protection against bottoming out the rover body or hitting the solar panels against a rock. Both are plausible mission ending scenarios, which will have to be addressed one way or another.

ExoMars Rover Autonomous Navigation, Airbus Defence and Space

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Thank you

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