# EXOMARS ROVER CONTROL, LOCALISATION AND PATH PLANNING IN A HAZARDOUS AND HIGH DISTURBANCE ENVIRONMENT

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ABSTRACT

The 2020 ESA ExoMars mission will land a rover on the Martian surface with the aim of establishing if life ever existed on Mars. To maximise the number and variety of sites visited by the mission, the rover will be fitted with a Mobility subsystem designed to allow it to traverse terrain without real-time assistance from Earth. ExoMars is an international cooperation between ESA and Roscosmos with contribution from NASA. Airbus Defence & Space Ltd. is responsible for the development of the ExoMars Rover Vehicle and its Mobility subsystem. Thales Alenia Space – Italia is the industrial prime.

This paper describes the design and capabilities of the rover that allow it to follow a planned path across the hazardous and high disturbance environment of the Martian terrain. It presents results from a path following test in a representative scenario and it discusses the challenges that are present when trying to plan a safe path for the rover to follow, and the options that are available to do so: (i) pure ground operator planning (ii) path safety checking via on-board terrain analysis (iii) fully autonomous on-board navigation.

## 1. MISSION AND ROVER OVERVIEW

The ExoMars (Exobiology on Mars) mission is an ESA mission to Mars in collaboration with Roscosmos and is divided in two parts. The first part (ExoMars 2016) has been launched to Mars in 2016 and consists of a Trace Gas Orbiter (TGO) currently orbiting around the planet and of an Entry, Descent and Landing (EDM) lander demonstrator. The second part of the mission (ExoMars 2020) will land a rover on the Martian surface, whose main objective is to find evidences of present or past life on Mars.

The ExoMars Rover, shown in Figure 1, features a locomotion system with six flexible wheels hosted on three bogies (Bogie Electro-Mechanical Assembly, BEMA). Each wheel has their own independent drive, steer and deploy motors, which enables each wheel axis to be independently actuated. The mass of the rover is approximately 300 kg and its dimensions when fully deployed are comparable with the ones of a small car. It is solar powered and designed to carry out operations on Mars travelling for several kilometres during its mission. It features a drill capable of sampling down to a depth of 2 m. The front mast hosts the Localisation Cameras (LocCam), which are fixed, and the Navigation Cameras (NavCam), which can rotate thanks to a Pan & Tilt Mechanism. The rover is designed to primarily use the TGO as a relay satellite and can nominally communicate with ground twice per sol.

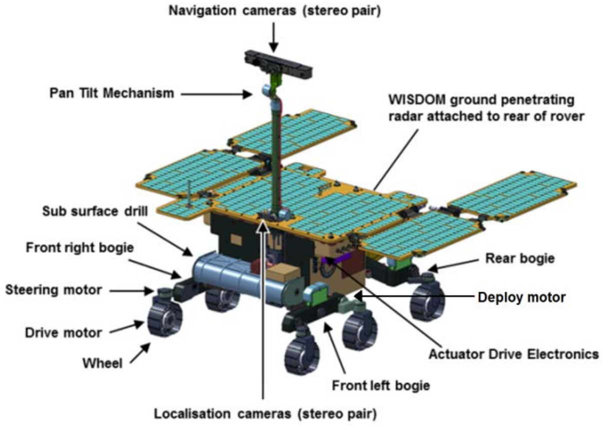


Figure 1, The ExoMars Rover

## 2. MOBILITY SYSTEM DESIGN

In order to meet its science objectives, considering the amount of distance to cover per day, the challenging terrain in which it shall drive and the communication constraints, the rover has been designed to support a highly autonomous mobility system. The mobility system has been designed to have different levels of autonomy. In brief, with the full mobility system, the ground operator can:

1. Command the rover to reach a target: the mobility system would then autonomously analyse terrain and decide which path to follow to reach the target.
2. Command the rover to follow closed loop a path specified by ground: the mobility system would drive the rover following the commanded path while compensating for external disturbances that could push the rover away from the path. Optionally the rover can check the safety of the path as it drives it.
3. Directly drive the rover open loop, for example commanding it to drive straight, to turn on the spot or to stop.

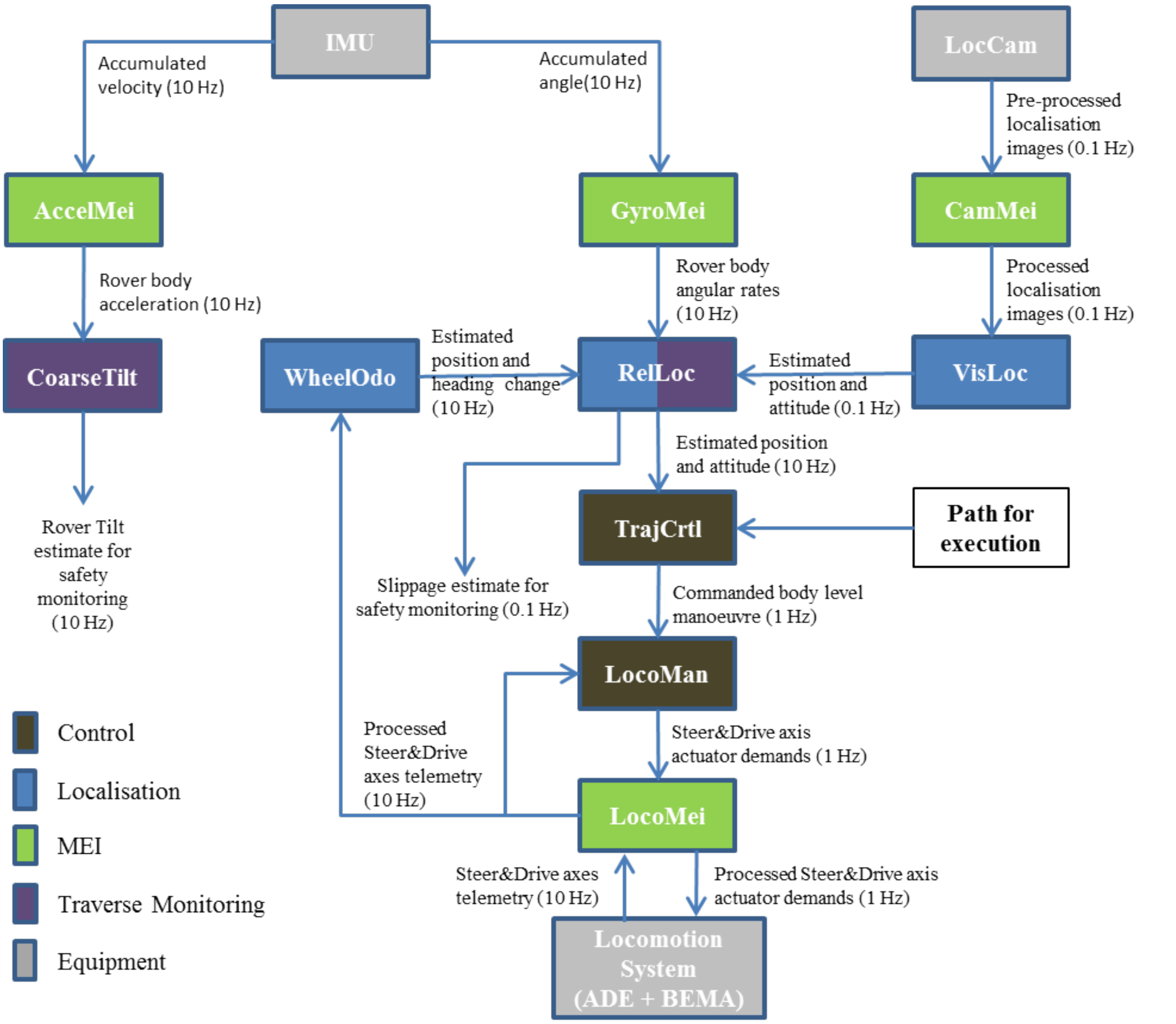


Figure 2, ExoMars Rover Mobility architecture used when following a path closed loop

This paper focuses on the components of the mobility subsystem that allows the rover to traverse the terrain following a specified path.

Figure 2 shows the architecture of the mobility system's GNC SW modules and equipment that take part during the execution of a path. Figure **3** shows how the mobility system updates its attitude knowledge before the path is followed.

The GNC SW modules in Figure 2 can be classified in:

- Control algorithms, responsible for keeping the rover as close as possible to the commanded path;
- Localisation algorithms, responsible for estimating the rover's position and attitude;
- Mobility Equipment Interfaces (MEI), responsible for converting data to/from the equipment into the right format and frame.
- Traverse monitoring, i.e. algorithms responsible for providing outputs useful to assess the safety of the rover while it is driving, e.g. slippage or tilt.

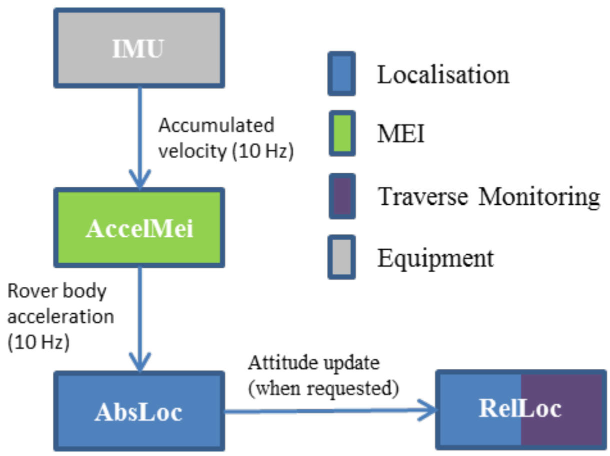


Figure 3, ExoMars Rover Mobility architecture used to perform an attitude update

## 3. CONTROL

### 3.1. Manouevre Definition and Limitations

The ExoMars Rover, thanks to its 6 wheels with 6 independent drive and 6 independent steer axes has a lot more manoeuvrability than a conventional car.
The ExoMars Rover is able to perform:

- Conventional Ackermann manoeuvres (Figure 4A):
  These are manoeuvres that allow the rover to follow an arc of a circle where the centre of this circle, the Centre of Rotation (CoR), lies along the line connecting the middle wheels, outside of the wheel base.
  The wheels are independently steered such that the perpendicular to the drive direction of the wheel intersects the CoR. The drive rates for each wheel are then independently set directly proportional to the commanded rover body speed and inversely proportional to the distance of the wheel to the CoR.
  These manoeuvres are specified through a curvature value and a rover speed, where the curvature is the inverse of the radius of curvature and expresses the amount of heading change per distance travelled.
  It shall be noted that a straight manoeuvre falls under this category, with the CoR being placed infinitely far away from the rover centre.
- Crabbing manoeuvres (Figure 4B):
  These are manoeuvres that allow the rover to drive following straight lines while keeping a fixed heading.
  Crabbing manoeuvres are specified through a crab angle and a rover speed, where the crab angle is the angle shown in Figure 4B.
- Generic Ackermann manoeuvres:
  A combination of conventional Ackermann and crabbing manoeuvres. This manoeuvre is specified by a curvature, a crab angle and a rover speed value.
- Conventional Point Turn (PT) manoeuvre (Figure 4C):
  This manoeuvre allows the rover to rotate around the rover centre, indicated as Traction Geometric Centre (TGC) in Figure 4C.
  While executing this manoeuvre the wheels steering position and driving rate is set in a similar manner as for an Ackermann, with the difference that left and right wheels have opposite drive rate directions.
- Generic Point Turn Manoeuvre:
  This manoeuvre allows the rover to rotate around a point which can be placed conceptually anywhere in the area between the left and right wheels.
  This manoeuvre is specified by the CoR coordinates and the rover angular rate.

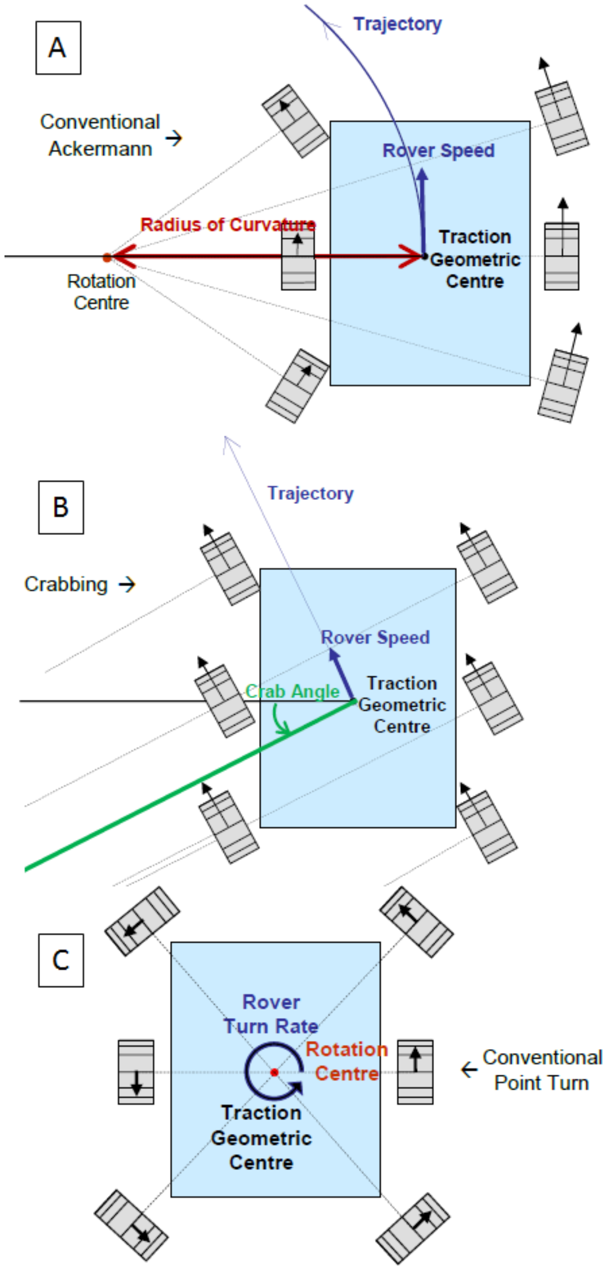


Figure 4, Ackermann, Crabbing and Point Turn manoeuvres

It shall be noted that the limits in the steering range and the maximum rate of the wheels set constraints to the position of the CoR, limiting the feasible domain of parameters characterising the manoeuvres.
The minimum drive rate a wheel can be driven does not represent a limitation in terms of feasible domain, but impacts the performance of the manoeuvre. This happens for example when the CoR is very close to a wheel and the drive rate that should be executed is below the minimum drive rate; this means the wheel will drive faster than it should and this might induce some slippage.

**3.2.** Commanding of steering and driving axes

Locomotion Manoeuvre Control (LocoMan, see Figure 2) is the GNC SW module responsible for converting manoeuvres described in 3.1 into commands to the steering and driving actuators of each wheel.
LocoMan also allows to command preset manoeuvres, i.e. commanding the steering axis to the right geometry for the requested manoeuvre (generic Ackermann or PT), without commanding the drive actuators to move. This is very useful when starting to follow a commanded path because it prevents the rover to start moving with a wrong wheel geometry which would cause an initial deviation from the path.
LocoMan outputs are then processed by LocoMei which converts them into the necessary formats and frames and are then sent to the locomotion subsystem. In the meantime, telemetry from the wheels is sent back to LocoMan to enable it to assess for example if a preset manoeuvre is completed or still ongoing.

**3.3.** Trajectory Control

The objective of the Trajectory Control (TrajCtrl) module is to drive the rover along a path sequence that has been provided directly from ground or by the autonomous path planning functionality. A path sequence consists of a series of path and point turn segments. The TrajCtrl execution calculates the locomotion manoeuvre commands (e.g. generic Ackermann crab and curvature demands) required to follow a path sequence closely, closing the loop online while the rover moves, using the estimated rover position and attitude from localisation as inputs.
When driving along a path, TrajCtrl issues crab demands to correct lateral error with respect to the path, and curvature demands to correct heading error.

## 4. LOCALISATION

The ExoMars rover needs to be able to accurately estimate its position and attitude in order to assess if it is following the path or if it is deviating from it. The localisation on board of the ExoMars rover is mainly the responsibility of the Absolute Localisation (AbsLoc) and Relative Localisation (RelLoc) modules.

**4.1.** Localisation whilst stationary

The Absolute Localisation (AbsLoc) module updates the on-board attitude estimate when the rover is stationary, e.g. before starting to follow a commanded path. The module is capable of performing a gravity (roll and pitch) update of the estimated attitude using the accelerometer measured average acceleration as an estimate of the gravity vector. AbsLoc does not have the capability to estimate the heading autonomously, but it can perform a heading update with a heading value provided from ground.

**4.2.** Localisation whilst driving

The rover defines a Mars Local Geodetic (MLG) frame, with its origin at the rover's initial location, z axis pointing up, the x-y axes in the local horizontal plane, the x axis pointing east. Motion of the rover is tracked in this frame.
The Relative Localisation module is responsible to update the estimates of the position and attitude of the rover relative to the MLG frame while it is driving. When following a commanded path this information is then passed down to TrajCtrl module (see Figure 2).
The most accurate source of position and attitude estimate on board of the Rover comes from the Visual Localisation software, procured from SciSys Ltd. and based on a Visual Odometry algorithm from Oxford University. VisLoc is able to estimate the change of position and attitude between two consecutive LocCam stereopair images by tracking the movement of features between the two. Due to processing power limitations on board of the Rover the updates from VisLoc are only available every 10 s. Since the rover is driving at 1 cm/s while following a path, the mobility system cannot afford to wait 10 s between position and attitude updates because this would result in poor control performance. Therefore RelLoc needs to use other sources of data at higher frequency in order to propagate the position and attitude estimates between the acquisitions of VisLoc updates. In order to propagate between VisLoc samples outputs at 10 Hz from the following modules are used:

- GyroMei module provides RelLoc with rover body angular rates.
- Wheel Odometry (WheelOdo) module provides RelLoc with estimated rover's position increments computed from steering position and drive axes rate telemetry from the locomotion equipment (processed by LocoMei).

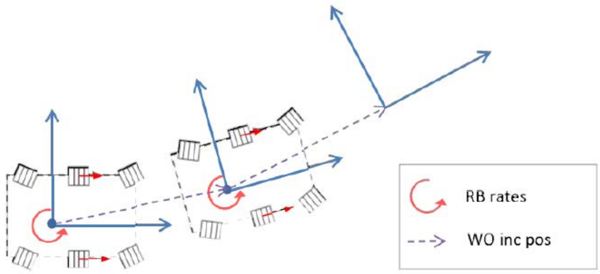


Figure 5, Gyro and WheelOdo propagation

RelLoc employs the angular rates from the GyroMei to propagate the attitude estimate and, together with the incremental positions from WheelOdo propagates the position estimate (see Figure 5).
It shall be noted that VisLoc estimates are considered truth within RelLoc. RelLoc therefore synchronises the various inputs, adding the propagated GyroMei and WheelOdo data to the VisLoc samples.
Since these VisLoc samples are received every 10 s, and

considering that they are referred to the instant 11 s in the past in which the corresponding stereo pair image was captured by the LocCam, the RelLoc position and attitude output will always contain at least 11 s of propagation, and up to a maximum of 21 s of propagation.

### **4.3.** Slippage estimation

The use of the displacement computed by WheelOdo does not allow RelLoc to track certain perturbations, such as those caused by slippage. In the case of the rover traversing laterally across a steep slope it is easy to imagine the whole rover slipping sideways down the slope while travelling forward. However this phenomenon, being purely translational, is not observable by the gyroscope or the wheel sensors. While this could be observable by the accelerometers, the harsh vibration environment the over experiences makes this very challenging. Therefore, when only these two sensors are used to propagate the rover position, the RelLoc module will estimate that the rover is traveling straight forward when in fact it will be also going down the slope as shown in Figure 6.

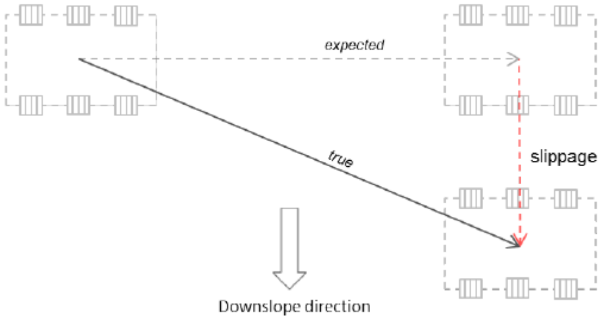


Figure 6, Slippage

This phenomenon can occur with whichever manoeuvre the rover is executing and in order to minimise its impact on the propagated position and attitude RelLoc implements algorithms to estimate longitudinal and lateral slippage (during Ackermann manoeuvres) and angular slippage (during PT manoeuvres). These estimates can then be used to correct the gyro and wheel odometry propagation and are also output by RelLoc to support safety monitoring enabling the detection of dangerous driving conditions before it is too late.
With reference to Figure 6 the slippage is calculated as the difference between the true and expected displacement (heading change if the manoeuvre is a PT). The last two received VisLoc samples are used to estimate the truth, while the WheelOdo displacement (heading change for PT) propagated outputs referred to the time interval between those two VisLoc samples is considered the expected motion. This difference is then divided by the magnitude of the expected motion (displacement or heading change) in order to obtain a slippage ratio, i.e.

$$slippage\ ratio = \frac{true\ motion - expected\ motion}{expected\ motion\ magnitude}$$

For forward motion of the rover, if the true motion is larger than the expected (commanded) one, than the slippage ratio will be positive; otherwise the slippage ratio will be negative. For example if commanded to drive straight but not making any progress at all, the longitudinal slippage ratio will be -1.0 and the lateral slippage ratio will be 0.0.

## **5.** RESULTS FROM TRAVERSE ON EXTRIMELY CHALLENGING TERRAIN IN MARS YARD

This section will present control, localisation and slippage results obtained during the execution of a test in the Airbus Defence and Space Mars Yard facility in Stevenage, using the MDM breadboard rover.
The MDM breadboard rover (shown in Figure 7) is a rover used for development and testing of the mobility algorithms. It is made using a mixture of off-the-shelf components and some prototype models of the ExoMars rover mobility equipment. Although the rover looks quite different from the flight rover shown in Figure 1, its dynamical properties and the locomotion system are representative of the flight rover, because it is 1/3 the mass and hence the correct weight in Earth gravity, which makes it a very good breadboard on which to test the mobility system’s algorithms.
The Mars Yard is a test facility about 30 m x 10 m large with sand, slopes and rocks to mimic the Martian surface.

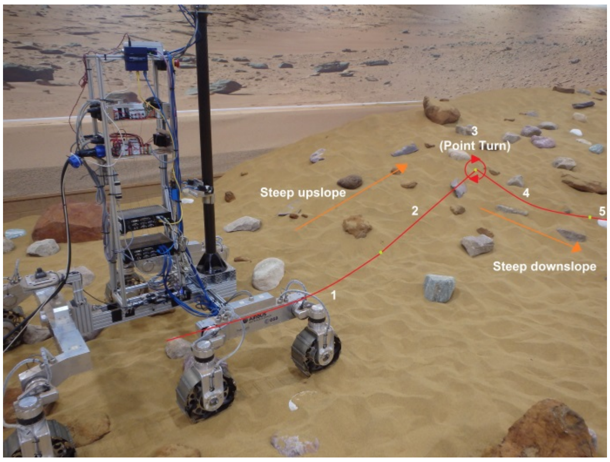


Figure 7, Path sequences illustration

Figure 7 shows the MDM at the beginning of the path which it has been commanded to follow closed loop, exercising the mobility algorithm closed loop chain shown in Figure 2. As it can be seen, this path is made of 5 segments: 4 path segments 2.3 m long with a -90 deg point turn segment in the middle.

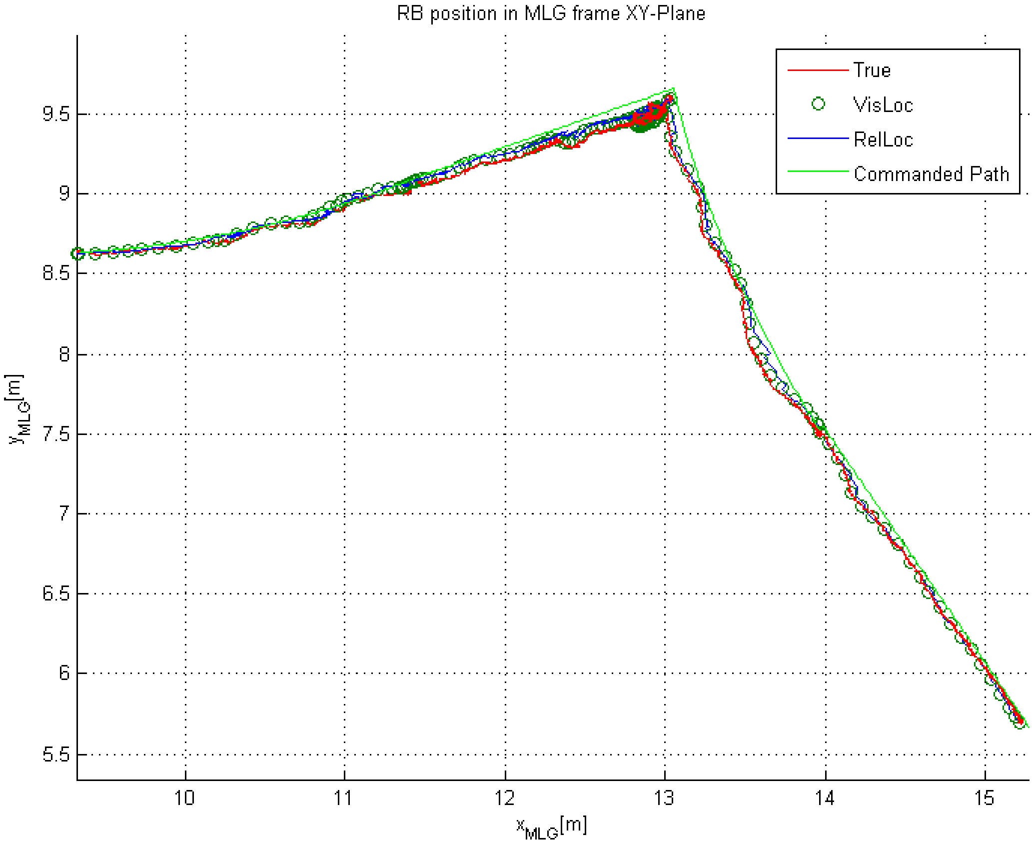


Figure 8, Estimated position in MLG x-y plane output from localisation and the truth tracking system during the traverse. The commanded path is also plotted.

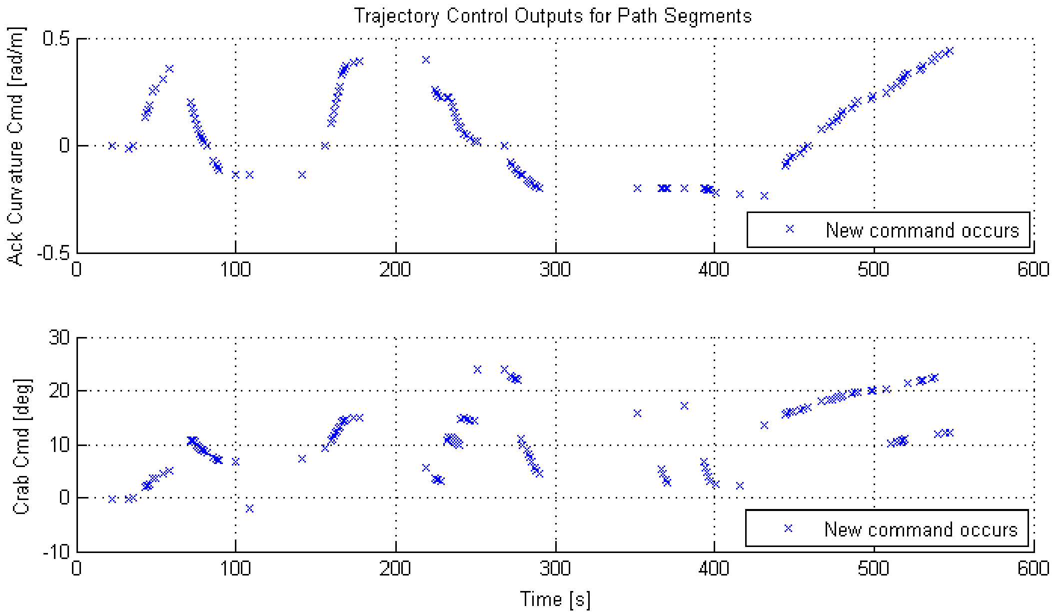


Figure 9, Generic Ackermann commands from trajectory control during execution of Path 2

The commanded path makes the rover traverse a steep slope with multiple rocks of various sizes and slipperiness therefore presenting a challenging scenario, beyond the limit of navigability for nominal operations of the rover. It should therefore experience a lot of slippage and possibly end up being in a risky or problematic situation. As expected, during execution of the second path the slippage increased up to a point that the rover was not making any significant progress along the commanded path and hence the path execution was aborted. The third path (the PT) was then executed starting from the abort location to complete the test.

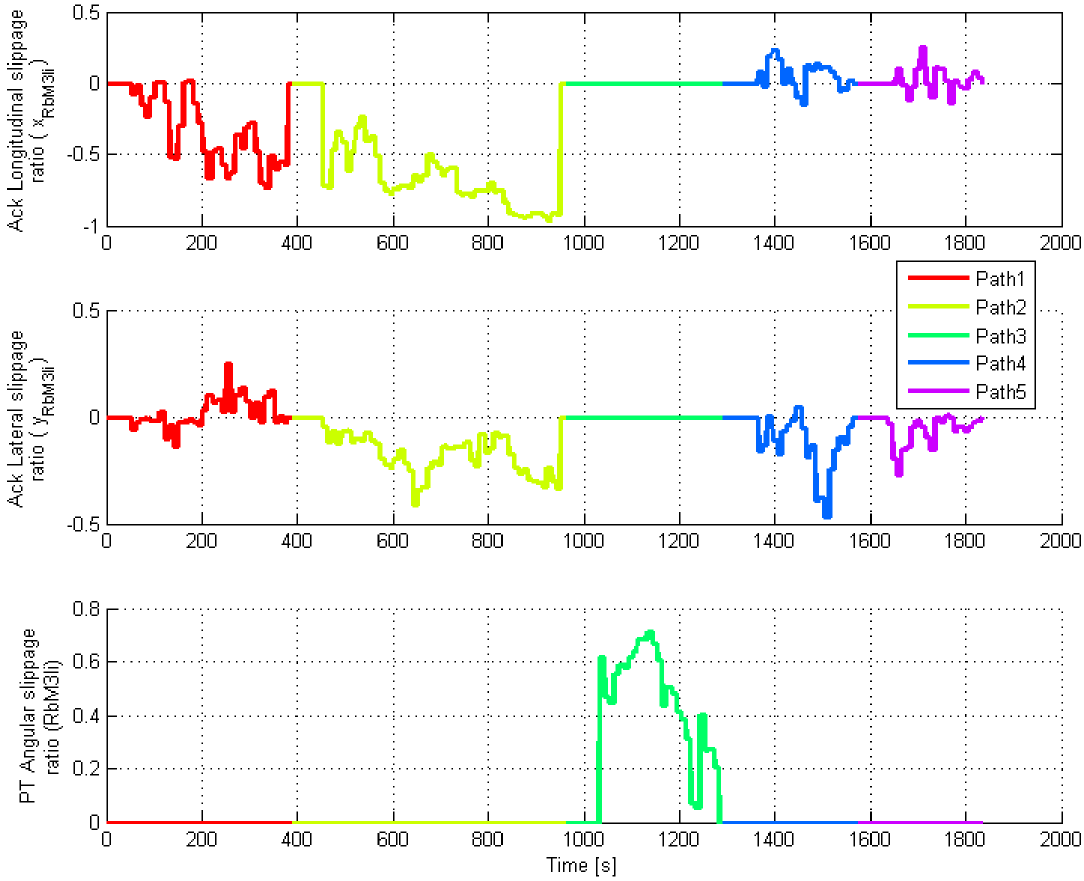


Figure 10, Slippage ratio outputs for the commanded paths

Figure 8 shows that the mobility system's trajectory control successfully kept the rover within few centimetres from the commanded path. It then shows that localisation successfully estimated the position of the rover while following the path. The truth is provided by an off-the-shelf visual tracking system mounted on the MDM.

Figure 9 shows the significant trajectory control crab angle and curvature demands issued to the LocoMan module during the execution of path 2 due to the large disturbance encountered. It can be noted that positive crabbing manoeuvres are requested in order to make the rover steer to the left in order to counteract the lateral error with respect to the planned path caused by the rover slipping laterally down the slope (i.e. towards the right of the rover).

Figure 10 shows the longitudinal, lateral and angular slippage ratio output by RelLoc during the execution of the commanded path sequence, which are expressed in the rover body frame (x points out of the front of the rover, y to the left and z up out of the top) at the instant when the first image of the 2 VisLoc samples was taken (RbM3li frame). It is possible to note a lot of slippage being detected, as expected. In particular, the rover experienced large longitudinal slippage during Path 2 and quite large angular slippage during the Point Turn (Path 3).

It is possible to appreciate from Figure 11 the extent to which the rover was digging itself in the sand during the final part of path 2, i.e. when the rover was barely making progress (values of longitudinal slippage close to -1.0, see Figure 10). Although the rocks were not too large and taken individually should not represent an issue to the rover, the combination of multiple slippery rocks and the relatively steep slope can represent an issue to the safety of the rover and it is paramount that the rover software could detect such situations in complete autonomy before it becomes too late.

This test therefore shows that by monitoring the slippage ratios output by RelLoc these kinds of situations can be effectively prevented.

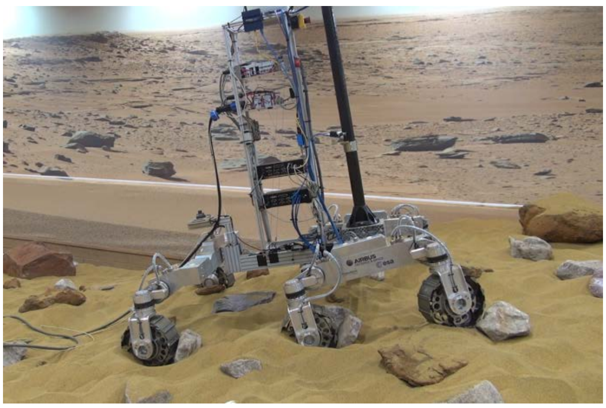

Figure 11, MDM after execution of Path 2

## 6. SAFE PLANNING OF PATHS, AUTONOMY AND HAZARD DETECTION

This paper has shown that the ExoMars rover is capable of effectively following closed loop a commanded path, counteracting navigable external disturbances like rocks and slopes. It shows that the mobility system is capable of detecting slippage and preventing it from becoming a serious issue to the safety of the mission.

However by looking at the pictures taken in the Mars Yard (Figure 7 and Figure 11), especially the real Martian images in the background, it is possible to get a feeling of the challenges for a ground operator planning a sol’s path of 30 m or more. The ground operator would have to consider slope and rock limitations, such as whether the rover will ground out on rocks or mounds of sand. Such considerations are difficult to analyse using camera imagery from the start of such a long drive. The operator would also need to account for localisation errors necessarily accumulating while driving long distances, and therefore would need to properly add larger margins around obstacles that are present in terrain that is further away. This means that, especially in difficult terrains, which are usually the science rich and therefore interesting ones, the area in which ground could be able to plan a long path for the sol and feel comfortable about it being safe might be very limited, and sometimes it might result in limited travelling distances per sol due to the limited communications opportunities with the rover.

The mobility system of the rover has therefore been designed to support on-board autonomous navigation and path planning that can analyse the terrain directly in front of the rover, asses its safety and plan a short 2.3 m path, at the end of which it stops and keeps repeating this sequence of operations until a commanded target is reached (see Figure 12). This has the advantage of being able to accurately analyse the terrain from close range. This also offers the functionality to check the safety of paths uploaded from ground while the rover drives along them. Both of these capabilities allow the rover to make more progress safely, across difficult terrain, than is possible if the ground operator is wholly responsible for the planning and safety analysis for the whole sol; hence increasing the science return of the mission.

## 7. CONCLUSION

This paper has presented the type of manoeuvres that the rover can execute, and the sensors which are exploited while following a path. It has shown how the GNC algorithms involved in the execution of a path, control and keep the rover close to the planned path, while reacting to large external disturbances coming from the terrain (e.g. wheel-rock interactions, slopes, slippage). It has shown how the rover’s GNC algorithms deal with slippage and how the monitoring of the slippage can be effectively used to prevent the rover from becoming stuck in the Martian sand. It has then discussed the challenges inherent in planning a safe path, such as the analysis of rocks and slopes from a distance, and the slow increase in the rover’s position knowledge error as it drives. It has finally presented the planning options such as path safety checking via on-board terrain analysis and autonomous on-board navigation that can be used to mitigate these challenges.

## 8. REFERENCES


1. Winter, M., Barclay, C. et al. (2015). ExoMars Rover Vehicle: Detailed Description of the GNC System. *ASTRA Conference 2015*.
2. Silva, N., Lancaster R., Clemmet, J., (2013). ExoMars Rover Vehicle Mobility Functional Architecture and Key Design Drivers. *ASTRA Conference 2013*.


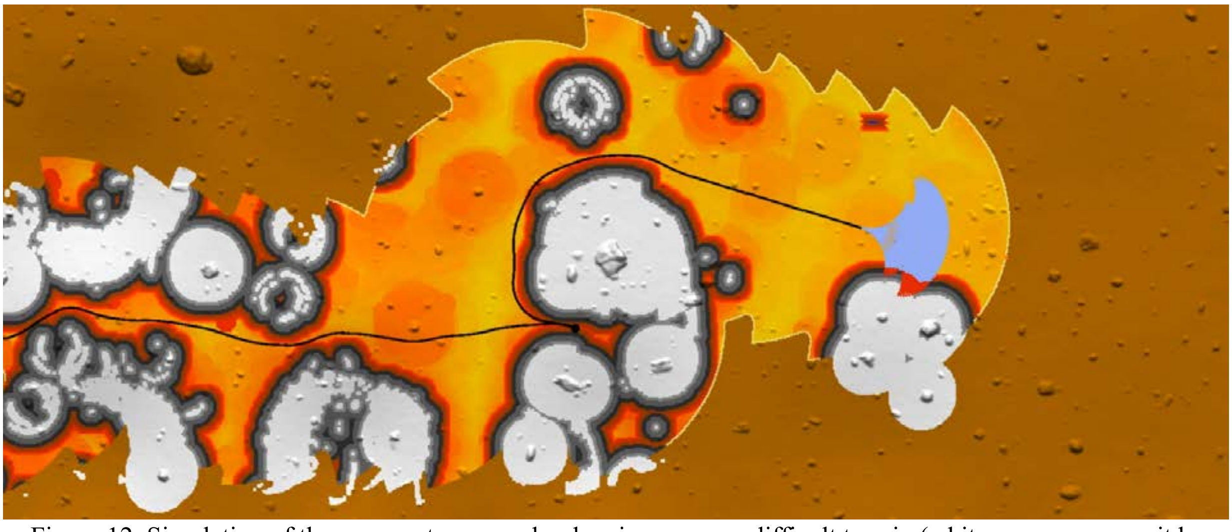

Figure 12, Simulation of the rover autonomously planning across a difficult terrain (white areas are areas it has classified as hazardous)