EXOMARS ROVER VEHICLE MOBILITY FUNCTIONAL ARCHITECTURE AND KEY DESIGN DRIVERS

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ABSTRACT

The ExoMars programme represents the return of Europe to Mars after Mars Express and Beagle2. It is composed of two missions: the 2016 mission focused on demonstrating European landing capabilities on Mars and proving a communications relay for the 2018 mission; the 2018 mission focuses on surface operations using the most autonomous Rover ever on Mars (Fig.1).
The European Space Agency (ESA) is the customer for the ExoMars programme. Thales Alenia Space – Italia (TAS-I) is the programme industrial prime. Astrium Ltd. (ASU) is responsible for the Rover vehicle, the platform on which the payload will be integrated by TAS-I.
A key aspect of the Rover autonomy is its mobility subsystem, a key technological objective for Europe. This subsystem enables the Rover to traverse large distances on challenging regions of Mars with minimal ground intervention maximising mission science return.
This paper presents the drivers of the subsystem and how this was used by ASU to define the necessary functions, their interactions, and how safety vs autonomy has been traded-off.

1. Autonomous Mobility Key Requirements

The ExoMars Rover will have to achieve a level of autonomy not yet tried on the surface of another planet. The constraints explained below drive the design of the autonomous Mobility Sub-System of the Rover.

1.1. Martian Environment

One of the key requirements is the environment. The Rover will have to drive over an unknown terrain/soil, with a very specific visual environment, with dust, under extreme temperatures and with stringent planetary protection and cleanliness constraints.
ASU has worked with ESA to derive a typical Martian terrain. It consists of two independent statistical distributions, one for slopes and another for rocks. The rock abundance is of 6.9% as in [2] and (adirectional) slopes up to 21.5º exist with a frequency of 99.7% of all slopes. The terrain definition is used at ASU for the development, testing and verification of the Rover Mobility SW. This allows for a faster, easier/practical, more flexible development. Field testing, performed in the ASU Mars yard, is fundamental to complement the simulators.

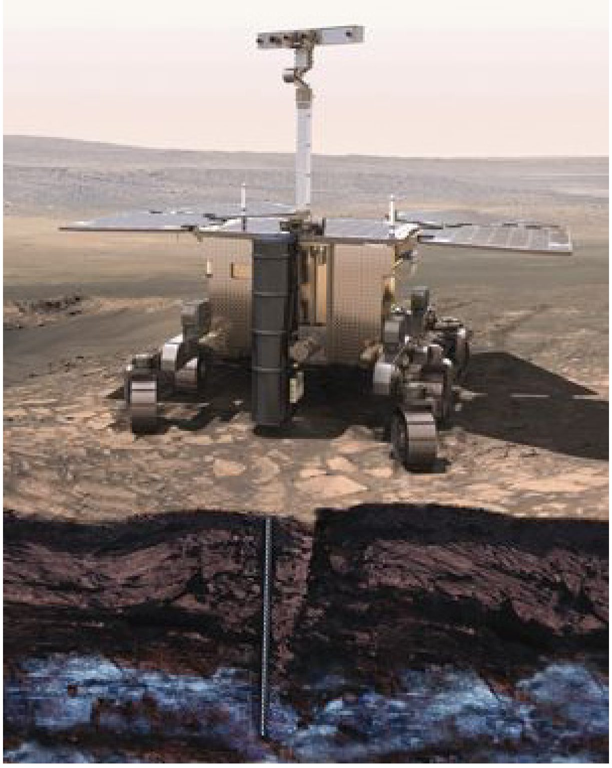

Figure 1. ExoMars Rover with its drill deployed (ESA)

The visual environment considers the Sun light on Mars, the properties of the atmosphere (with particular emphasis on the optical depth), shadows, diffuse light, etc. The University of Dundee has enhanced PANGU (Planet and Asteroid Natural scene Generation Utility) for ASU under the ExoMars program. This is coupled with the Rover Engineering Cameras, since it is also about how the environment is captured by those. All these elements have been considered and integrated in the ASU development simulator. Fig. 2 depicts one example of the Rover on the terrain referred above with the modelled visual environment.
The Rover HW must survive and operate under extreme temperatures and under a dusty environment. Equipment must survive temperatures ranging from -120ºC to +40ºC, and must operate between -50ºC and +40ºC. Such survival temperature presents new and challenging problems for electronics.
Energy/Power is a key constraint on the Rover. There is a limit to how much energy a Solar panel can produce, in particular in the latitude range ExoMars may operate

within. This translates into a maximum duration per sol available for driving, regardless of how autonomous and mobile the Rover is. The on-board autonomy is responsible for the Rover net speed: i.e. distance the Rover can drive in 1h considering all autonomous processes, when the Rover is moving or at a stop (eg. planning) assuming enough energy/power is available. The Rover actual distance travelled is the product of these two drivers.

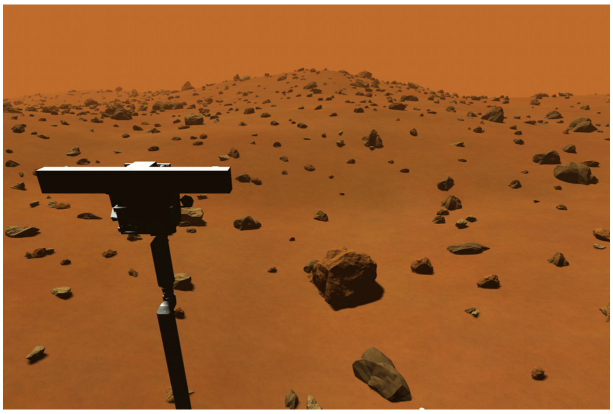

Figure 2. Scene from the ExoMars Rover Simulator

1.2. Autonomy

The Rover will be able to continue performing its mission without ground in the loop for 2 sols (a sol is a Martian day and lasts ~24h37m). For example, this could imply fully autonomous driving during that duration.

Such distance has implications on Rover safety whilst driving. However, this is needed as soon as the Rover needs to move outside what an operator can safely assess – typically up to 20m in easy terrain, but less in terrains as difficult as where ExoMars aims at operating on. Longer drives have a more significant impact on performance since errors build up as the Rover moves.

Due to the long drives, there is also a need to keep driving safety/difficulty knowledge on-board, in case the Rover is blocked at some point for example. With larger drives the knowledge to store and process increases, together with the associated driving errors which degrade the utility of that information.

As mentioned above, since the Rover will drive outside areas analysed by operators, there is a need of autonomously ensuring the Rover safety whilst driving (in the context of this paper this is limited to vehicle safety associated with Rover motion).

1.3. Performance

In addition to the challenging functional capabilities, the Rover will also achieve unprecedented accuracy and autonomous traverse capability on Mars.

The Rover will drive 70m/sol with maximum autonomy active. If the Rover is on an easy terrain, operators may decide to disable the on-board production of the path (only part of the autonomy), allowing for approximately doubling the distance travelled per sol – "fast drive".

Good accuracy allows placing the Rover or its instruments in the science locations with fewer ground interventions. Consequently, more science observations can be made in the same amount of time with a more accurate Rover. This increases the science return of the mission.

There is an additional implication of accuracy. Indeed, the more accurate the Rover is, the fewer margins are needed around real or potential obstacles to the safe motion of the Rover. By decreasing the size of the safety margins, not only more efficient paths can be found, but also new paths become available allowing to find (more) solutions in difficult terrains. This has different implications in short and medium/long ranges.

After autonomously travelling 70m, the Mobility Sub-System will place the Rover within 7m of a target in Martian Local Geodesic (MLG) coordinates, and with a heading within 5º of the command. The Rover will also accurately place its drill from 7m away (distance as the crow flies). Since the drill is off-centred, this implies a coupling between its position and the Rover heading. It will be placed within 0.15m of the drilling target and with heading within 15º of the command.

2. FUNCTIONAL ANALYSIS

The summary of the analysis of the key requirements presented in the previous section implies the need for certain functions in the Rover Mobility.

Terminology used in this paper differs from the traditional GNC (Guidance, Navigation and Control) definition for historical reasons.

2.1. Localisation

The Rover needs to know where the target is in order to be able to reach it. Since the target is given in MLG frame, the Rover needs to know its orientation (attitude) on that same reference. Such function has been designated "Absolute Localisation" and relies on the Sun and gravity directions for its estimation.

As the Rover drives to the target, it needs to know how its position changes as it moves. Additionally, since it also needs to point to a particular direction at the target, it also needs to know how heading changes as it moves. Such functions has been designated "Relative Localisation".

Attitude could be propagated by a gyro. However, considering the level of accuracy required to build terrain models, this would require a class of gyro of unaffordable mass, volume and power for a Rover. Position could be expected to be propagated by double integration of accelerometer measurements. However, the disturbance accelerations imposed by the terrain and the Rover flexible locomotion, plus the placement accuracy required, invalidate this option. Wheel odometry could be used instead but it is inaccurate since the wheels slip. Therefore another technique is needed: 'Visual Localisation'. This solution tracks features in the terrain as the Rover moves. The apparent motion of the features is used to deduce the Rover ego-motion. Because it is processing intensive, when necessary design margins are applied, the design is such that it only runs every 10s. Between captured frames, gyroscope information and wheel odometry are used.

2.2. Locomotion, Trajectory & Manoeuvre Control

The Martian terrain presents several challenges for a Rover to drive over. From visible obstacles such as rocks, craters, steep slopes (up or down), or combinations of these, to invisible enemies such as slippage; the Rover needs to be kept safe from these whilst driving.

This translates into two different needs. One is to plan a safe path to the target; the other is to be able to follow that path. As previously stated, in very easy terrains, operators may decide to use the Rover in a more manual way to save (processing) time and therefore command the path themselves. Nevertheless, the need to follow the path remains since the Rover has to reach its target and within the expected time interval – if the Rover drifts too much away from the path it is likely to take longer. In more complex terrains (nominal case for ExoMars), the path needs to be determined on-board and accurately followed (details in §2.3).

Several strategies exist to follow the path. From fully open-loop strategies, to a full closed-loop one: naturally the level of accuracy radically changes from one approach to another depending on the level of disturbances. Indeed, the obstacles mentioned above are not only a safety threat; they are also disturbances to the Rover motion. When the Rover drives across slopes or tries to drive over rocks, it will deviate from the theoretical path.

Based on the Locomotion Performance Model (in [4]) test results, open-loop control is immediately excluded since it does not even allow meeting the target acquisition requirements. The NASA/JPL Rovers (MER and MSL), mostly drive in open-loop, but also offer the operators a very slow "closed-loop" control drive mode: when the Rover stops to plan its next path, its new planned path takes into account its current location. This effectively implies that the Rover is in open-loop whilst driving along the planned path.

ExoMars will drive over challenging terrains. This means that not far from a safety threat there is another safety threat and in-between there are disturbances pushing the Rover away from its safe path. Therefore, for the ExoMars needs and mission ambitions, more frequent trajectory corrections are required and a closed-loop on-the-move function is needed.

The Rover actuator is its locomotion, formed by 6 wheels on a 3-bogie system controlled by an Actuator Drive Electronics (ADE). Each wheel is equipped with 3 actuators: drive, steer and deployment (or wheel walking). All 6 wheels can drive and steer simultaneously which is a major manoeuvrability (controllability) advantage when compared to MER or MSL (both do not steer the middle wheels and cannot drive and steer simultaneously). Therefore, there is a need to translate vehicle level manoeuvres (eg. Ackermann geometry) to individual motor commands and to synchronise all actuators in a harmonious geometry. This function has been designated "Locomotion Manoeuvre Control" whilst the vehicle level control function is named "Trajectory Control".

2.3. Perception, Navigation & Path Planning

The previous section (§2.2) has hinted at the need to avoid obstacles that could threaten the Rover safety. Indeed, since the ExoMars Rover drives farther than what can be safely assessed by ground operators, an on-board function to identify and avoid those obstacles is needed. Whilst §2.1 is about the need to know where the Rover is, the present section is about the need to know where obstacles are (both safety threatening and disturbances categories) and how to deal with them.

2.3.1. Perception

The first step is to know what is around the Rover. This is designated by "Perception" and is presented in [3]. Again, several options exist to achieve this but ASU has selected stereovision because of its technical maturity and heritage on Mars. The threat of loose sand is not visually detected and is dealt with differently.

Algorithms that implement such function belong to the image processing domain which are known to be processing time consuming and therefore an issue for a real-time system SW. In addition, because this is about detecting obstacles (or, equally important, being sure there aren't any), one aims for the best quality images of the Rover surroundings. This leads to two consequences: the Rover should have a separate processing unit for these algorithms decoupling it from the real-time constraints, and images should be taken at a stop to minimise blur from motion.

2.3.2. Navigation

Once the surroundings of the Rover are known they need to be analysed to detect and characterise obstacles. Not only safety threats need to be identified, as disturbances for driving need to be known. Once these are known, adequate weights and/or flags are associated with the terrain surrounding the Rover. This requires a detailed knowledge of the Rover locomotion performance whilst driving on that terrain. This function has been designated "Navigation".

There are two aspects to the Navigation function in characterising the Rover surroundings. One is over short-range distances, between points where Navigation is performed (waypoints). The other is medium/long range when the Rover has moved several waypoints away but may need using past acquired information.

The short-range case is driven by the fact that the Rover will drive up to the next waypoint without additional information about obstacles being acquired before. It is therefore necessary to ensure that during that drive the Rover does not drive over safety threats, tries to avoid getting close to them or of areas of higher motion disturbances.

The medium/long range case is driven by the need to not throw away past information that would enable the Rover to find solutions to progress towards the target (eg. dead-ends). This leads to the need of being able to store and efficiently use past information.

2.3.3. Path Planning

The previous steps have allowed the Mobility Sub-System to have a detailed knowledge of its surroundings. Another aspect to consider is what is actually drivable without having to stop the Rover (eg. point turns are highly inefficient time wise - no progress towards target - and of limited controllability). This involves not only the locomotion capabilities but also the Trajectory Control (§2.2) ones.

Therefore there is a need to efficiently make use of this information and constraints in order to produce a safe, drivable and efficient path. This function has been designated “Path Planning”.

There are two different applications for this function: normal traverse, and drill placement. Because of the nature of drill placement (position and heading coupling), a different strategy may be required for this application.

Both Navigation and Path planning as are also achieved through algorithms of the image processing family with similar implications to Perception (§2.3.1).

2.4. Traverse Monitoring

All the functions previously described ensure the Rover safety by planning to avoid dangerous areas and by following such a path. However, in the event of a failure not timely detected, an unforeseen environmental anomaly or non-visual safety threatening areas (eg. slippage), mission success must be granted by not jeopardising the Rover safety. This is traditionally achieved by the Failure Detection, Isolation and Recovery (FDIR) function which has a peculiar nature for a Rover. FDIR is responsible for all safety aspects, but in the context of this paper (Mobility), one only focuses on Rover safety linked to its motion.

FDIR uses a family of PUS (Packet Utilisation Standard) services that are used to monitor key parameters of the system and to adequately react to, ensuring Rover safety. FDIR by itself does not produce the data that needs monitoring, it only monitors data and adequately reacts to it. If data linked with the motion of the Rover (eg. slippage) needs monitoring which is not directly available from equipment or functions otherwise required, there is a need to derive such data. Another reason for deriving data to be monitored is reasonable segregation of data used to drive and data used for ensuring Rover safety (eg. tilt angle is used to determine a terrain model to plan a safe path but it also cannot exceed a safety threshold – if incorrect it could allow the Rover to plan an assumed safe path over a safety threatening area). The function that allows elaborating this additional data requiring monitoring ensuring Rover safety whilst traversing the terrain is designated “Traverse Monitoring”.

3. FUNCTIONAL ARCHITECTURE & EQUIPMENT

3.1. Architecture

The summary of the ExoMars Mobility Functional Analysis presented in §2 allowed identifying the top level functions needed to ensure mission success. These

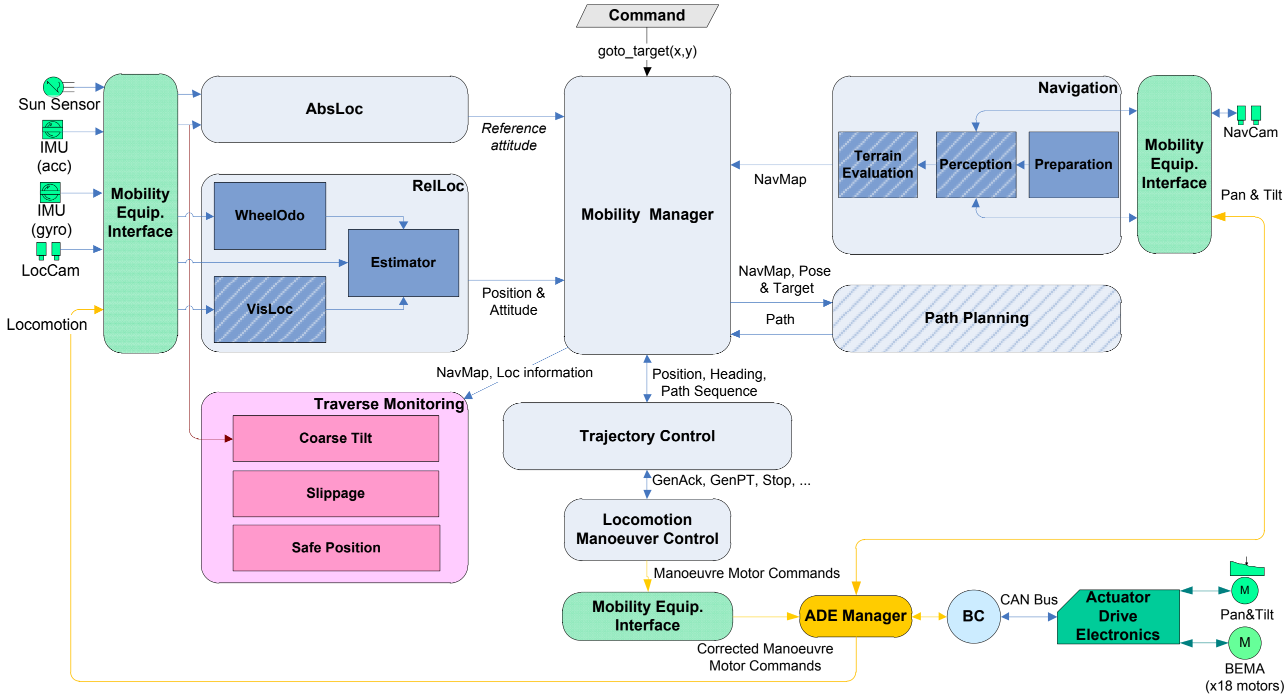

Figure 3. ExoMars Rover Mobility Functional Architecture

functions need to be organised in a rationalised architecture, considering their interdependencies and/or interactions, the operational needs and the implications of HW feasibility (sensors and actuators).

Fig. 3 presents the ExoMars Mobility functional architecture which can be compared with the MER one in [1] (mostly reused for MSL). One of the key functions intentionally omitted in §2 is the Mobility Manager - §2 focuses on the core functions. This need becomes clearly apparent when structuring and organising the more specific functions. Its role is to correctly sequence all functions, check conditions for mode transitions, adequately initialise functions, etc. Fig. 3 also depicts further functionally inside the top level functions identified in §2.

A key additional function is the Mobility Equipment Interface (MEI). This function is in charge of transforming equipment data into engineering units, apply calibration to telemetry and commands, express data in the right frame, and complement Equipment low level FDIR as necessary. Refer to Fig. 3.

3.2. Equipment

3.2.1. General Considerations

As for all space programs mass is a severe constraint on equipment. This goes hand in hand with volume constraints. In addition, for the ExoMars Rover, equipment needs to be low power because of the very limited source of energy that degrades over its lifetime also due to dust deposition on the solar cells.

These needs, together with the low temperatures for external units, planetary protection and high cleanliness requirements, present significant challenges for the ExoMars equipment, Mobility units included.

3.2.2. Mobility Units

The equipment necessary for Rover mobility is not always exclusive to this Sub-System. Naturally, the wheels, its actuators (inc. sensors), the bogies and associated harness are the Mobility actuator (BEMA: Bogie Electro-Mechanical Assembly). This would be the equivalent to thrusters or reactions wheels on a spacecraft. However, the control electronics of those actuators are also used to control other mechanisms of the Rover such as Solar Arrays for example. The ADE together with BEMA are designated “Locomotion”.

A Sun sensor has been baselined because of its simplicity of use to the Absolute Localisation function – it directly provides the Sun direction which is used to initialise the Rover heading on the MLG frame. The Sun sensor is an external equipment and is therefore subjected to the extreme Martian temperatures and dust deposition- consequently it is not free of risks but those are understood and managed. It is used only for Mobility purposes.

The accelerometer is used to obtain an absolute reference of the Rover roll and pitch (or/and tilt angle) by measuring Mars gravity vector. It resides inside the Rover (thermally controlled) and therefore is not subjected to the extreme Mars temperatures.

The gyroscope is used to propagate the Rover attitude. This information is used to complement Visual Localisation (VisLoc - refer to §2.1) by allowing to propagate the VisLoc attitude output between visual frames in such a way that Trajectory Control always has heading information. The gyroscopes output is also used for consistency check with the VisLoc output since, unless there is a failure in one of them, they should be compatible to each other.

The accelerometer and gyroscope might be packed as a single Inertial Measurement Unit (IMU).

The Localisation Cameras (LocCam) are used by VisLoc providing 1024x1024 (or 512x512) 8-bit panchromatic stereo images as the Rover moves: the ExoMars Rover does not stop to take localisation images or to process them, it does it all on the move. The LocCam are also an external equipment and are therefore exposed to the challenging Mars temperatures and dust. The cameras are tilted down by 18º which also allows dust to naturally fall off as the Rover moves.

Figure 4. ExoMars Cameras (Neptec Design Group)

The Navigation Cameras (NavCam) are of the same design as the LocCams and often the driver in terms of design requirements. The reason for this is that they are used by Perception-Navigation-Path Planning chain which is in charge of ensuring a safe and efficient path for the Rover to drive and meet the 70m/sol, one of the most challenging requirements for the Rover. Both the horizontal and vertical Field of View of the cameras is 65º, the cameras stereo baseline is 150mm after a careful trade-off by ASU of the Perception/Navigation functions performance. The NavCam are mounted 2m above the ground on top of Pan and Tilt Mechanism (PTM) which is an integral part of the Deployable Mast Assemble (DMA).

The Pan & Tilt Mechanism is used to orient the NavCam in such a way that the terrain in front of the Rover is imaged without gaps. More than the actual orientation of the NavCam, it is the knowledge of this orientation that is critical. Indeed, that information is required by Navigation when constructing the corresponding 3D terrain model. Errors in this measurement translate into terrain errors, which translate into margins that reduce the number of viable paths for the Rover to drive over.

3.2.3. Redundancy

In §3.2.1 the stringent mass constraints on the mission were already alluded to. Indeed, this has led the ExoMars consortium to tailor the mission success criteria leading to a very selective redundancy strategy. This is not unprecedented. It is important to mention at this point that NASA/JPL Mars Science Laboratory (MSL, otherwise known as Curiosity) is generally not redundant, only some very selective redundancy exists. ExoMars is expected to have wider redundancy, but still very limited. Additionally, the ExoMars on-surface mission is required to last at least 180 sols (~6 months), which for most equipment is a "small" duration.

The Rover must be able to deploy and egress from its lander platform. Once this is achieved, only "rudimentary" mobility needs to be achieved after a single failure. Without presenting or discussing the details, this implies the following for the Mobility related equipment:

Table 1. Mobility Related Equipment Redundancy

	Redundant	Not Redundant	Partially Redundant
Sun Sensor		X	
Gyroscope		X	
Accelerometer	X		
LocCam		X	
NavCam		X	
ADE			X
BEMA			X

4. MOBILITY MODES & OPERATIONS

4.1. Mobility Levels of Commanding

In the previous section one has referred to higher and lower autonomy/driving modes that the operators may use. The functional architecture established above (§3) enables hierarchizing the functions allowing different levels of functionality, i.e., of autonomous driving.

Fig. 6 presents the ExoMars Mobility levels of commanding which exploit the Mobility functional architecture and modularity. The top level (LC_NOM) corresponds to maximum autonomy, where all functions are used. This level corresponds to the nominal operational mode where operators provide a target in MLG frame for the Rover to autonomously reach. It corresponds to the lowest Rover net speed.

The Rover also has to follow a WISDOM (Water Ice and Subsurface Deposit Information On Mars) subsurface scanning pattern that is pre-loaded or uploaded by ground for science reasons. Both for this operation as for drill placement, it is to be assumed that the terrain is safe for development and testing purposes. Nevertheless, operationally, one still wants to check if the path is safe. Hence, in this case, Mobility does not produce a path but still produces all information that would allow it to produce a path. That information is then used to check the safety of the commanded path before driving over it – using the "Safe Position" sub-function of Traverse Monitoring in Fig. 3. This corresponds to (LC_CHECK_PATH).

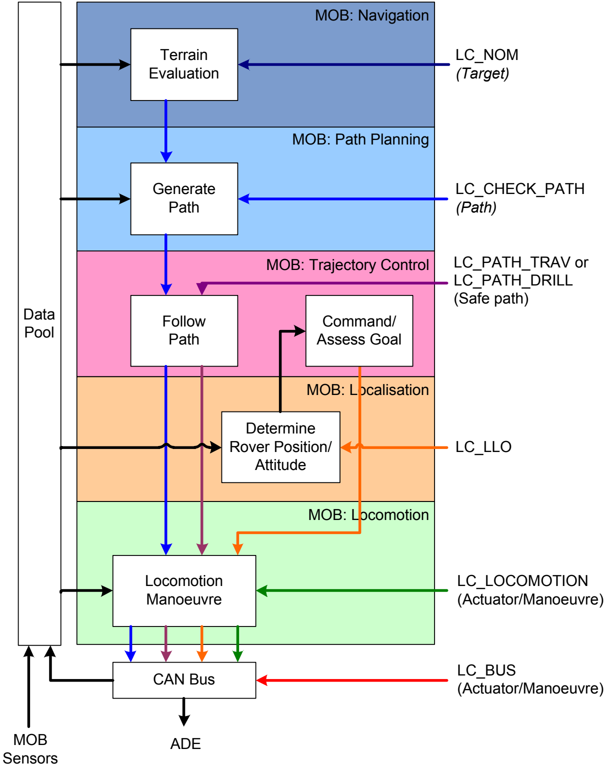

Figure 5. Mobility Operational Hierarchy

Going down the level of the levels of autonomy, the Rover can also follow a path without the checks mentioned above (LC_PATH_TRAV or DRILL) – in this case there is still closed-loop Trajectory Control. This is followed by ground directly commanding open loop manoeuvres such as Ackermann geometries to follow (duration or distance limited – latter still requires localisation) or Point Turn manoeuvres (LC_LLO). If one drops localisation, only duration-limited manoeuvre are then possible (LC_LOCOMOTION). This level also allows for direct commanding of each actuator. Finally, in a much reduced mode, it is possible to bypass most of the functionally and directly command at bus level each actuator (LC_BUS) – it is anticipated this will never be used, but it is present in the design for robustness.

4.2. Mobility Modes

Fig. 7 presents the ExoMars Rover Mobility Modes and Sub-Modes. The levels of commanding summarised in §4.1 are also depicted allowing the reader to relate functionality as commanded by ground to the operational modes.

As the name indicates, in ABS_LOC mode, Mobility executes the Absolute Localisation function initialising the Rover attitude in the Mars Local Geodetic frame. This also includes the MEI functions associated with the Equipment used (accelerometer and Sun sensor).

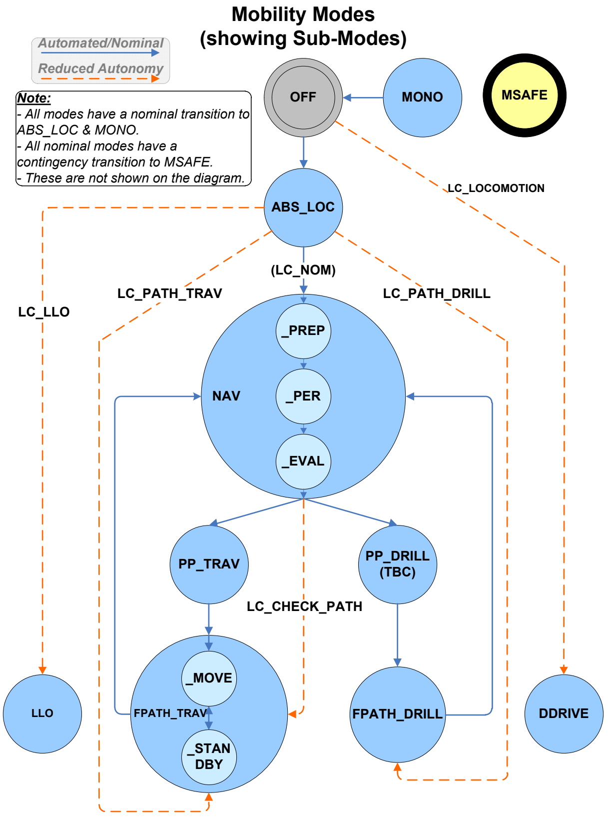

Figure 6. Mobility Operational Modes & Sub-Modes

Once an attitude estimate is ready, the Mobility Manager will transition to the Navigation mode as soon as the Rover Vehicle overall is ready to start motion (eg. it may need to wait for the actuator to be warm). The Navigation mode includes three sub-modes.

In the NAV_PREP sub-mode, the Rover status is assessed with respect to the commanded target to conclude if it has completed its traverse. If not, the sequence of Pan & Tilt angles is determined to take the NavCam images.

The NAV_PER sub-mode corresponds to the Perception function presented in §2.3.1. In addition, since NavCam pictures are taken as determined in NAV_PREP, it also needs the NavCam MEI. The NavCam MEI includes the auto-exposure algorithm for example.

Afterwards, the NAV_EVAL sub-mode corresponds to the Navigation function summarised in §2.3.2. This is a very complex algorithm and its description is outside the scope of this paper.

Once NAV mode is complete, a path can be planned. Following the different constraints for normal Traverse (drive) to reach a Rover target, and to place the drill tip, different algorithms and associated mode are reserved: PP_TRAV for traverse and PP_DRILL for drill placement. This corresponds to the Path Planning function summarised in §2.3.3.

The ABS_LOC, NAV and PP_TRAV/DRILL modes are performed with the Rover not moving.

The Rover is now able to start moving towards its target using the path just calculated. This is performed using the FPATH_TRAV/DRILL mode. In order to follow a path the Rover needs to know where it is with respect to the path and, in case of deviation, it needs to be able to correct for it. The former function is localisation summarised in §2.1, the latter function is Trajectory Control summarised in §2.2. Both functions are used together to follow the path.

The FPATH_TRAV includes two sub-modes. The FPATH_TRAV_MOVE is when the Rover is moving. During FPATH_TRAV_STANDVY, the Rover temporarily interrupts following its path in order to perform an accurate WISDOM scan which occurs every 0.1m and lasts ~30s. This has no operational equivalent during the drill placement. Once a path segment is complete and the Rover reaches the waypoint, it transitions back to NAV mode and the process repeats.

The remaining modes have specific characteristics and are not nominally used. The LLO mode is the one allowing ground to directly command manoeuvres with duration or distance as a constraint (LC_LLO) – used for Rover locomotion deployment and egress from the lander platform. In DDRIVE mode the operators directly command manoeuvres but only a duration constraint can be given. MONO is a mode only used during deployment of mechanisms whilst still on top of lander platform, such as solar panels or DMA – it uses the IMU to register telemetry outputted by the IMU MEIs for ground to have more options to determine successful deployment.

The MSAFE mode is the defined as the mode Mobility transitions to in case of FDIR triggering. It is not yet defined and it may be the same as Mobility OFF mode, where Mobility equipment and functions are not used.

5. ROVER SAFETY WHILST MOVING

Naturally, FDIR is about more than just safety linked with Mobility/motion. However, in the context of this paper, one only focuses in safety linked with Mobility.

Tab. 2 presents a list of feared events associated with the motion of the Rover on a terrain with associated causes.

In addition to Tab. 2, any equipment may stop providing data or start providing erroneous data. Depending on the failed equipment, consequences are different but its direct detection method is similar.

With the presented Mobility design, there are feared events that can be prevented and others that can only be detected. The Perception-Navigation-Path Planning functions are used to detect safety threatening areas and to plan a path avoiding them. Nevertheless, one also needs to consider the case where these may fail and still meet the mission objectives. As Tab. 3 demonstrates, on top of the prevention made by planning a safe path, monitors are needed to ensure the Rover is kept safe.

Not all data to be monitored is directly available by the functions used for driving. Therefore, for those which aren't directly available, they need to be calculated. This is achieved by the Traverse Monitoring (TMON) function (§2.4).

Table 2. Mobility Feared Driving Events

Feared Event	Cause
Loss of stability whilst driving	Steep slope
	Combined rock & slope
	Cliff
Collision	Mars surface: terrain
	Deployment & Egress: lander
Stuck	Loose soil
	Large rocks
	Combined rock, slope, soil
	Overhang
	"Sit" on top of rock
Unsafe geometry (wheel in the air)	Combined rock, slope, soil

Monitors in Tab. 3 are safety monitors, they are not checking for Mobility performance. They are set to trigger when that may represents a threat to the Rover, not when a particular value is not within the expected performances. Therefore, when these trigger, the FDIR reaction is to stop the Rover and transition to MSAFE.

There are other cases that do not threaten the Rover safety and are therefore autonomously handled as nominal events. Over-reacting and transitioning to MSAFE in these cases would certainly compromise the mission since the Rover would not move until ground operators recover the situation, which could take several sols.

For example, Trajectory Control has an error that normally does not exceed a threshold (eg. 0.2m). Nevertheless, it is not because the Rover is at the edge of the 0.2m that this is dangerous since there is no reason to assume a safety-threatening obstacle is present at that point. In this case, before exceeding that threshold, the Rover autonomously stops and transitions back to NAV mode. This will lead to re-planning a path with new adequate margins and the Rover will then follow it. If there was indeed a safety-threatening obstacle, this would be detected in this new NAV mode. If a way out is not found in this additional waypoint, then it is a legitimate reason to trigger FDIR and wait for ground to recover the situation.

Another example is precisely linked with finding a way out at a waypoint. A path in front of the Rover as it initially stands (eg. cul-de-sac), may not exist. However, there might be a path on the side or by backtracking. The Rover Mobility in this case performs a series of Point Turns until finding a path (the Rover does not autonomously drive backwards). Only in the case a path cannot be found it will trigger FDIR, stop, transition to MSAFE and wait for recovery by ground.

Table 3. Key Mobility Monitors

Monitor (in addition to Navigation)	Who feeds FDIR	Preventable by Navigation
No data from unit	MEI	No
Erroneous data from unit	MEI	No
Inconsistent data from units	MEI	No
Bogie angle	MEI	Yes
"Absolute" Bogie angle	TMON	Yes
Coarse Tilt Angle	TMON	Yes
Fine Tilt Angle	Localisation	Yes
Slippage (Visual and non-visual position consistency)	Localisation / TMON	No
Visual and non-visual attitude consistency	Localisation	No
Relative and Absolute attitude consistency	Localisation	No
VisLoc Tracking Lost	Localisation	No
End and beginning of sol: attitude consistency	Localisation	No
Rover current position wrt unsafe areas in FPATH*	TMON	*Uses NAV data*
Rover current position wrt unsafe areas in LLO	TMON	No

6. CONCLUSION

In order to provide ESA with a vehicle capable of contributing to the objective of explaining the origin of the Universe and of life, ASU has been developing the most autonomous Rover ever for the surface of Mars. Its mobility is a key capability since it allows autonomously accessing interesting science sites. The GNC subsystem has reached a TRL6 in August 2011 becoming one of the pillars of the ExoMars programme. Specifications for the flight SW has started and it is scheduled to be complete first half of 2014. It will be followed by testing on ASU Mars Yard with benches such as the one in [4], extensive testing and verification in validated simulators exploring a maximum of combinations. Launch is scheduled in May 2018.

The ExoMars Rover Mobility will exceed the current level of autonomy of MER and MSL. This is not only performed for a technological objective: this capability will be exploited for the unique payload of ExoMars.

7. REFERENCES

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