DESIGN OF THE MMX ROVER ATTITUDE CONTROL SYSTEM FOR AUTONOMOUS POWER SUPPLY

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ABSTRACT

The Martian Moons eXploration (MMX) mission led by the Japan Aerospace Exploration Agency (JAXA) aims at studying Phobos and Deimos. It includes a small rover that will explore Phobos, carried out jointly by the French Space Agency (CNES) and the German Aerospace Center (DLR).

With its fixed solar array, the rover does not receive enough energy in nominal driving orientation to recharge its battery. Therefore, an attitude control system manages the rover orientation, using the locomotion system and a sun sensor. The specifics of the control loop such as movements limitations or tranquilization periods are due to the dynamic interactions with the regolith.

This paper presents the attitude control system (SKA) architecture, through the various challenges encountered: limited design flexibility with major changes during the development, small knowledge of Phobos' expected soil, very tight schedule to meet the JAXA delivery date. The design drivers were to create the simplest and most robust system to orient the rover in order to maximize the battery recharge, while ensuring the rover stability and addressing the above issues. A particular focus is made on the preliminary simulation results. Finally, the way forward is outlined with the SKA development and validation steps.

1 MMX ROVER MISSION DESCRIPTION

The Martian Moons eXploration (MMX) project led by the Japan Aerospace Exploration Agency (JAXA) aims at studying Phobos and Deimos, with a launch planned for mid-2024. This ambitious mission will make observations and measurements of Mars and its moons from quasi-satellite orbits and flybys, return samples from Phobos' soil back to Earth, and explore the surface of Phobos thanks to a small rover (about 25kg) [1].
The rover is a cooperation between the French Space Agency (CNES, Centre National d'Etudes Spatiales) and the German Aerospace Center (DLR, Deutsches Zentrum für Luft- und Raumfahrt). Released from the mother spacecraft, it will study the terrain properties before the MMX landing. The internal structure of the rover contains all the core elements and the scientific instruments.

Mounted to the chassis, four legs and four wheels that can rotate around their joints constitute the "locomotion system" allowing the rover to move on the ground. Once deployed, the Solar Array (SA) is fixed at the top of the chassis. Figure 1 presents the rover along with the "Explo" frame attached to the rover body. The frame origin O_{Explo} is located at the center of the four shoulders plane.

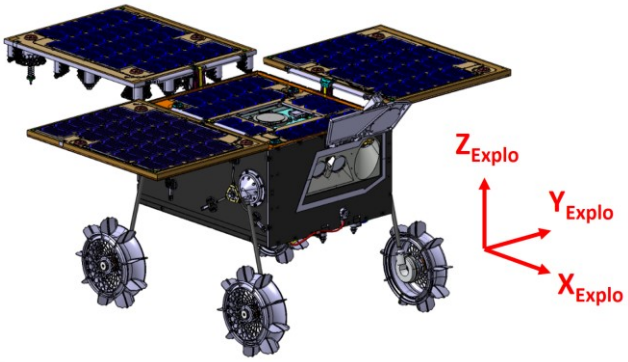

Figure 1: MMX Rover and Explo frame (© CNES)

The rover will separate from the spacecraft during a landing rehearsal, dropped at about 30 to 40 m from Phobos ground, with an expected impact velocity of about 0.7 m/s. After falling and enduring many expected but uncontrolled bounces, it will autonomously reorient itself to reach an upright position, open the SA and perform a first attitude control to recharge the battery. This sequence, called SLUD for "Separation, Landing, Uprighting and Deployment", is facilitated by Phobos' very low effective gravity (3-7 mm/s² accounting for centrifugal acceleration and Mars tides) [2].

After a commissioning phase, the exploration and various scientific experiments [3] will begin: landscape observation with two navigation cameras (NavCams), study of the interactions between the wheels and the regolith with two wheel cameras (WheelCams), surface mineralogy analysis using a Raman spectrometer ("RAX"), thermal properties analysis thanks to a radiometer ("MiniRad"). Note that the rover is primarily a technological demonstrator of driving in milligravity, autonomous navigation, and nanosatellite technologies use for the deep space exploration.

2 ATTITUDE CONTROL to INCREASE the ROVER ENERGY

The survival of the MMX Rover on Phobos depends on its ability to recharge its battery. Continuously moving the rover to optimize the SA orientation would consume more energy than the potential gain of tracking the Sun, and increase the risk to get stuck in the regolith. During the battery charge, the rover should not move but rather have an orientation optimizing the received flux over a Phobos solar day (Phod).

The battery charge is very dependent on the rover landing site, composed of the landing date and landing coordinates. Mars' distance to the Sun and the Sun declination vary with the landing date, while the geodetic latitude changes the mean elevation at which the Sun is seen. Note that the geodetic latitude is not defined with respect to a hypothetical ellipsoid fit to Phobos but as the angle between some average plane fit to a local terrain of Phobos and the equator of Phobos. Due to Phobos' irregular form, it is essential to consider such geodetic coordinates and not the geocentric coordinates.
The triangles of Phobos' shape model [4] are used for preliminary average computations. During the rover operations, a more refined model should be available to define a Regional Reference Plane (RRP) that best fits the terrain characteristics of a given region. This RRP permits to define the

Topocentric North Frame (TNF) where Z_{TNF} is along the RRP normal pointing outward Phobos, and X_{TNF} belongs to the RRP and points to the North. This frame is particularly useful for attitude estimation (see section 4.2).

The potential energy gain (or recharge) at battery level over a Phobos day (lasting about 7.6 hours) is evaluated for the considered landing sites. The mission is ensured with a minimum of 10Wh battery gain per Phod considering that the rover is idle.
The worst case dimensioning the analysis happens just after the SLUD phase, when the rover battery charge is very low (around 30%), the landing site corresponding to a thermal cold case, with a local terrain inclination (LTI) that can reach 20°. In that case, reaching the full battery charge would take about 10 Phod with a +10Wh charge per Phod.

Figure 2 shows the battery gain over a Phod on a flat ground (0° LTI) considering no rover inclination (the SA normal is then equal to Z_{TNF}). The white areas show the landing sites where the SLUD survival is compromised, and in the darkest blue areas the mission may be delayed due to slow recharging.
Taking into account an unfavorable local terrain inclination of 20° is almost directly equivalent to shifting the map from 20° on the geodetic latitude ordinate axis. This considerably narrows the acceptable landing sites. Therefore, an attitude control is necessary to compensate the unfavorable LTI and increase the accessible areas on the battery gain map. Note that the energy situation is easier in the mission next phases with a smaller expected LTI after the rover first moves.

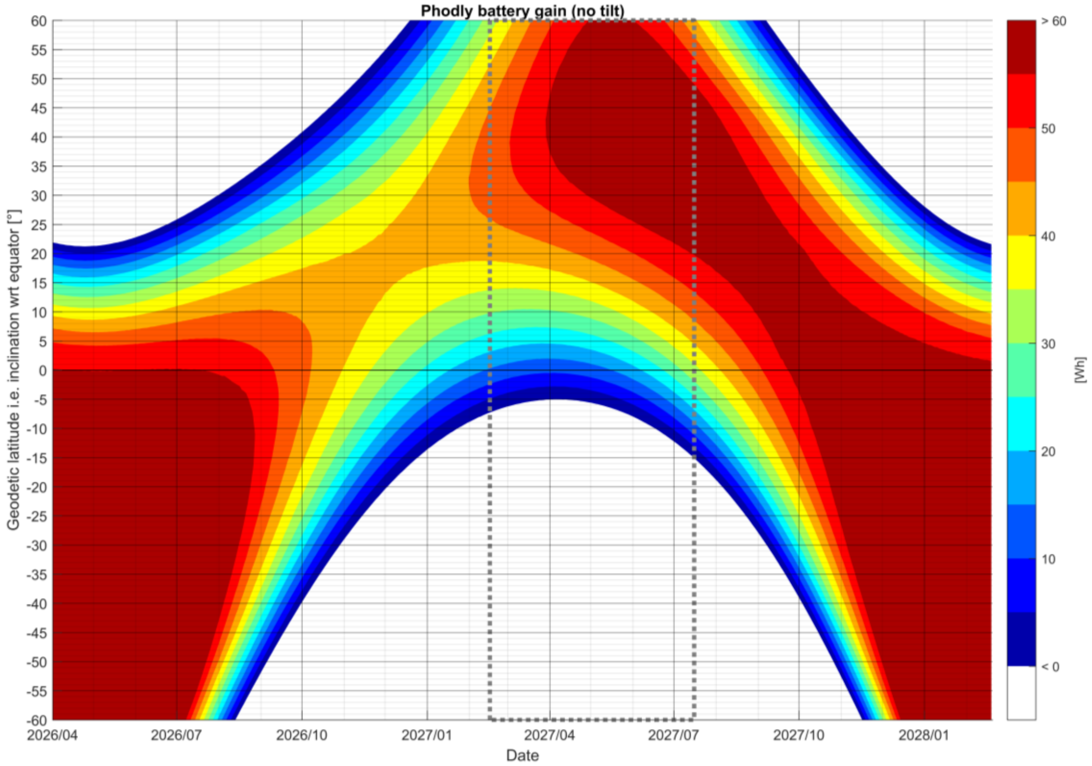

Figure 2: Battery gain over a Phod, no local terrain inclination

For attitude control design, the power received at SA level is considered rather than the battery gain. This permits to disregard the potential electrical and SA design changes (diode and regulation system losses). Therefore, the energy is evaluated as the average power received at SA level over a Phod, per square meter, divided by a Phod duration. This metric is simply referred to as the "average power".

3 ATTITUDE CONTROL LOOP SPECIFICS

3.1 The locomotion system as an attitude actuator

The SA orientation is ensured by the attitude control system named “SKA” (Système für die Kontrolle of the Attitude). The SA being fixed to the rover body, the whole rover attitude is modified using the locomotion system (its legs), based on the attitude measurements.

The locomotion is developed by the DLR Institute of Robotics and Mechatronics and is described in details in [5]. The locomotion electronics mainly include a control PCB, including a FPGA and a SpaceWire communication interface, and two power inverter PCBs, all regrouped in a module called “Loco Ebox” located inside the rover internal structure.
The actuators (four legs and four wheels) are mounted to the side panels of the chassis, and include 3-phase brushless direct current motors. The torque and position sensors of the motors and joints are connected to the Loco Ebox using shielded cables.

The angular position of the legs defines the rover attitude [6] and a good knowledge of these leg angles is therefore important. Hall sensors are associated to the motors to count the increments, and potentiometers on the joints can also give an absolute angular position. Depending on the locomotion control software (LOCO) configuration, these angular measurements can be compared, prioritized, etc. Then the leg angular positions are stored in the On-Board Computer (OBC) non-volatile memory.

The LOCO is a partition of the OBC that permits to create a consistent command of the eight separate actuators. Various control modes are implemented for the actual mission on Phobos (driving, alignment, uprighting, inching modes) or for AIT tests (direct motor, pass-through modes) [6]. The SKA uses the alignment control mode to orient the rover body towards a given direction, while controlling the rover body height to avoid damaging the lower instruments and to ensure stability.

The ideal plane containing the four wheels’ contact points is called the locomotion reference plane (Fig. 3) with n_{ref} its upward normal. The reference frame is defined such that $Z_{reference} = n_{ref}$. $X_{reference}$ and $Y_{reference}$ are such that $Y_{reference}$ is aligned with the projection of Y_{Explo} onto the reference plane. This frame is expected to be one of the most stable ones relatively to the regolith after an alignment. The distance h between O_{Explo} and the reference plane is used to characterize the rover height.

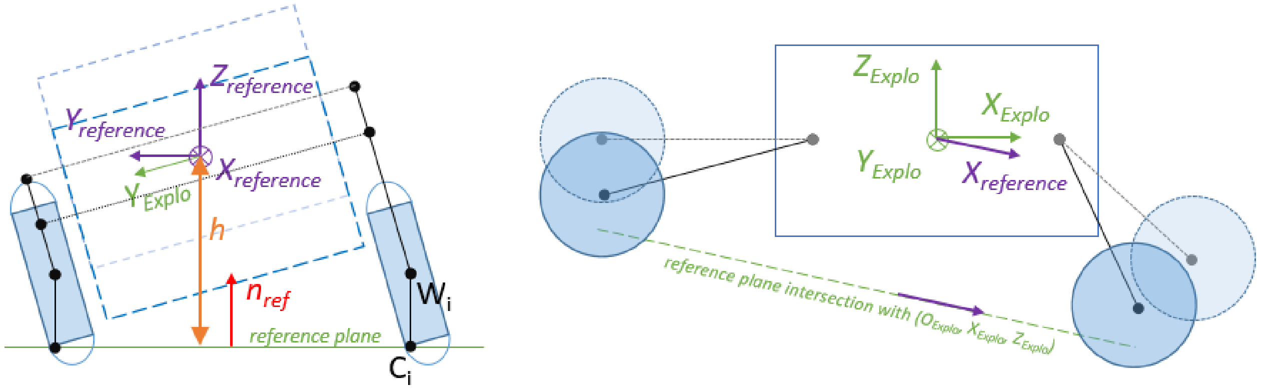

Figure 3: Locomotion reference plane, Reference and Explo frames, wheel contact points (Ci)

When used as a command for an alignment move sent to the LOCO partition, n_{ref} and h are respectively called n_{des} (desired normal) and d_{des} (desired distance). To fully specify the four legs positions based on n_{des} and d_{des}, the additional constraint of choosing preferentially an outward solution (to improve stability) is implemented in the LOCO partition. Note that the wheel motors are also commanded during the alignment in order to get a zero slip rolling movement.

Other useful notions to compute the attitude control command are:

- the ground clearance: smallest distance from the locomotion reference plane to any (bottom) corner of the rover chassis.
- the rover tilt: angle between Z_{Explo} and n_{ref}
- the rover tilt azimuth: oriented angle (around n_{ref}) from $X_{reference}$ to the projection of Z_{Explo} on the reference plane (see Fig. 4)

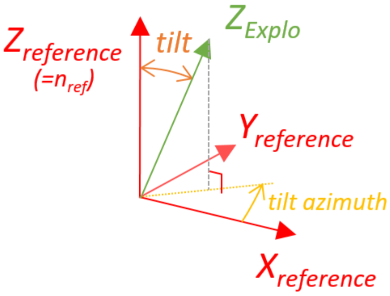

Figure 4: Rover tilt and tilt azimuth

3.2 Environment constraints

The interactions between the rover wheels and Phobos' regolith during a movement can potentially increase the sinkage of the rover wheels into the ground and even lead the rover being stuck in the regolith. To limit this effect, the rover movements must be limited at several levels. As mentioned before, instead of correcting the rover attitude along the solar day, the attitude control loop's purpose is to position the rover at a unique attitude that will optimize the battery charge over a Phod. Then the rover might keep this attitude for several Phods until the battery is fully recharged.

Moreover, SKA movements should be commanded only if the potential correction benefit is stronger than the potential attitude disturbance due to the ground interaction. And even then, the number of movements and the range of motion must be minimized. The control strategy takes into account these elements by defining several thresholds before triggering a SKA movement and by limiting the number of correction movements.

To move safely the rover in milligravity, only very slow movements can be commanded (about 1°/s leg rotations and 1mm/s linear velocity). To limit the unwanted dynamics effects, a tranquilization duration is foreseen after each rover movement so that the rover and its surrounding soil settle into a steady state before another measurement and movement phase.

4 INITIAL DESIGN

4.1 Constraints and general principle

The SKA design was heavily constrained from the start: preliminary studies did not show the need for an attitude control. With the initial hypotheses, no matter its attitude, the rover would gain enough energy to accomplish its mission. Therefore, the initial layout did not take into account attitude control inputs. Then the mission analysis refinement highlighted the need for an attitude correction. Due to the already advanced stage of the project, the SKA design flexibility was limited. The locomotion system became the actuator of the control loop. Two sensors were preselected: a Sun Acquisition Sensor (SAS) on the rover top and a Fiber-Optic Gyroscope (FOG) inside the rover internal module.

Lens R&D's BiSon64-ET SAS is an analog sensor, based on four photodiodes that generate four currents Q_1 to Q_4. Those currents are processed using barycentric formulas (Eq. 1) and correction coefficients (C_a, C_b) to compute the SAS angles α and β [7], and then the Sun direction. This sensor, usually used for nanosatellites missions, can withstand the temperature range required for the mission. It specifies an accuracy of 0.5° 3σ using the provider's calibration tables and a 59° field of view (FoV). The FOG will not be described in this article as it has been removed from the final design.

$$\frac{Q_1 + Q_4 - Q_2 - Q_3}{Q_1 + Q_2 + Q_3 + Q_4} - C_a = \frac{\tan(\alpha)}{\tan(\alpha_{max})} \quad , \quad \frac{Q_1 + Q_2 - Q_3 - Q_4}{Q_1 + Q_2 + Q_3 + Q_4} - C_b = \frac{\tan(\beta)}{\tan(\beta_{max})} \qquad (1)$$

The control loop starts with a 3-axis attitude estimation based on the SAS and FOG measurements. Then a target "heliotrope direction" is determined for the SA normal, thanks to an energy map providing the expected energy gain over a Phod for a given rover orientation. Finally, the command to modify the rover attitude towards the heliotrope direction while ensuring the rover stability is computed and sent to the LOCO partition.
The global strategy is to perform several iterations of the above steps, separated by tranquilization phases allowing the rover to settle into a steady state.

4.2 Attitude estimation

The 3-axis attitude estimation is based on a QUEST algorithm (with a bypass strategy to handle the 180° singularity). When the rover is still, the FOG measures Phobos' rotation vector. Meanwhile, the SAS measures the Sun direction. Both measured vectors are converted to Explo frame (see Fig. 1).
The 2019 corrected IAU model of Phobos' rotation [8] is implemented on-board, which permits to define the change of frame from EME2000 inertial frame to True Phobos Fixed Frame (simply referred to as PFF) with α Phobos's North pole right ascension, δ Phobos's North pole declination and W rotation of the prime meridian around Phobos's North pole (Eq. 2).

$$M_{EME2PFF} = \begin{bmatrix} -\cos W \sin\alpha - \sin W \sin\delta \cos\alpha & \cos W \cos\alpha - \sin W \sin\delta \sin\alpha & \sin W \cos\delta \\ \sin W \sin\alpha - \cos W \sin\delta \cos\alpha & -\sin W \cos\alpha - \cos W \sin\delta \sin\alpha & \cos W \cos\delta \\ \cos\delta \cos\alpha & \cos\delta \sin\alpha & \sin\delta \end{bmatrix} \quad (2)$$

The TNF and PFF are linked through the landing site geodetic longitude ϕ and geodetic latitude θ (Eq. 3). Besides, a Sun ephemeris seen from Mars (considering the center of Mars instead of the real position on Phobos induces a negligible error) is implemented. It is based on a polynomial formula that matches the JPL ephemeris with a precision better than 0.05° 3σ.
These models permit to compute the Sun direction and Phobos' rotation in TNF to feed the QUEST algorithm. Filtering the measurements, a few minutes are necessary to get a correct estimation of the rover attitude in TNF.

$$M_{PFF2TNF} = \begin{bmatrix} -\cos\phi \sin\theta & -\sin\phi \sin\theta & \cos\theta \\ \sin\phi & -\cos\phi & 0 \\ \cos\phi \cos\theta & \sin\phi \cos\theta & \sin\theta \end{bmatrix} \qquad (3)$$

4.3 Energy map and next targeted heliotrope direction

The determination of the optimal heliotrope direction is based on a “sky map” of the average energy that the PCDU is expected to deliver over a Phod in function of the normal to the SA in TNF. As this energy map slightly varies over time, it is computed as a first step of each heliotrope sequence. The raw energy values are obtained by accumulation at a regular time step, taking into account the loss of efficacy of the solar cells at high sunrays incidence and the effect of self-shadowing (worst case among rover headings). This integration also considers a conservative constant 10° horizon elevation and the losses due to the diode and regulation system for a representative working point and consumption scenario. When evaluating the average energy for a given direction and angular uncertainty, the worst case over the corresponding uncertainty cone is computed.

At the start of the heliotrope sequence and at the end of each iteration, the new target orientation is computed by travelling inside the energy map, incrementally following the energy gradient until the targeted energy threshold or maximum amplitude is reached (the energy map is previously smoothed to remove any local maximum), or until no stable pose further increases the expected energy value. This iterative process takes into account the increasing uncertainty due to the amplitude of the alignment move, and ignores unfeasible or unstable orientations (cf. §4.4). A more favorable orientation (energy-wise) than necessary is indeed targeted when the alignment realization error is expected to be high. Note that at each step, the evaluated direction is transformed into a full rover orientation by assuming that the reference frame stays fixed in TNF during the alignment.

4.4 Ensuring the rover stability

The stability of a given rover pose is checked by verifying that the estimated gravity direction stays inside the stability cone (cf. Fig. 6), composed of the 4 facets defined by the center of mass and consecutive wheel contact points. This check takes into account various uncertainties: position of the center of mass, estimation of the gravity direction and its variation upon a Phod, rover attitude, etc., and most notably an additional uncertainty to model the interaction with the regolith (increasing with the amplitude of the commanded alignment performed to reach this pose).

When evaluating the feasibility of a heliotrope iteration, the stability of the final orientation is first assessed, then the stability along the movement is checked (via a discretization of the evolution of the leg angles as computed by the LOCO partition, and considering an increasing uncertainty with the amplitude). The final rover height might be decreased, down to the minimum ground clearance allowed, in case of an initially detected stability risk.

4.5 Attitude estimation during landing

The last part foreseen in the initial SKA design is the SLUD attitude estimation. During the rover fall and bounces, the FOG is used to propagate the current rover attitude initialized with an attitude quaternion given by MMX spacecraft. Once the rover is stabilized, the use of the different changes of frame described in section 4.2 permits to get the rover attitude in the local frame (TNF) and in particular the “up” direction. The central software uses this information to compute the locomotion command that will reorient the rover to reach an upright position.

5 DESIGN CHANGES and JUSTIFICATIONS

5.1 Context

Many difficulties were identified during the rover Preliminary Design Review (PDR), including the difficulty to match the JAXA required delivery date, leading to an urgent need for simplification. In line with the nanosatellite philosophy, simplifying as much as possible, with no redundancy, to deliver a space system in a very short amount of time was vital, even if it meant taking more risks. That illustrates why the rover is indeed a demonstrator of this nanosatellite philosophy use for Exploration.

Descoping the FOG was key to improve the mass budget and to lighten hardware integration, but would have a strong impact on the SKA design. The attitude estimation during landing could not be performed anymore, so the rover had to be able to turn itself on the right face without knowing the "up" direction. A new sequence called "universal uprighting sequence" was designed and showed conclusive results, allowing to switch to this new baseline to put the rover on its feet. Besides, a SAS-only solution to control the rover attitude in deployed mode was studied. The next paragraphs present and justify this new approach. Note that removing the FOG means no more attitude estimation, then no more possibility to position the rover on the energy map and to assess the rover stability.

5.2 Simplification of the pointing strategy

The SAS-only control loop strategy stems from one main idea: if the rover orients himself towards the Sun at noon in Phobos local time, then the resulting rover attitude should be favorable for the battery charge. The Sun trajectory is rather regular from East to West, with a maximum elevation depending on the landing site. Consequently, this rover positioning provides an energy gain close to the energy map optimal, for it gives a very balanced illumination of the SA over the Phod.

Simulations are run to evaluate the energy loss for all the possible landing sites in comparison to the previous design. This analysis is performed for the SLUD, the most critical phase in terms of attitude control. From a same rover pose, the computation of the energy expectancy of the two pointing methods is compared. This computation takes into account the least favorable rover configurations (worst-case reachable rover tilt, energy-wise worst-case initial local terrain inclination).

Figure 5 presents the energy expectancy losses for the considered landing sites if the pointing at noon strategy is used instead of the energy map pointing. In most areas, the losses are negligible, which supports this new pointing strategy. The areas with high energy deltas (up to about 8 Wh per Phod) are very local, and actually only occur in areas where the total energy value is already comfortable (Fig. 2). Hence, this less optimal pointing has an acceptable impact on the energy gain. It considerably simplifies the SKA development in order to match the JAXA deadlines, and allows to cut out the FOG from the attitude control. Therefore, this solution has become part of the final SKA design.

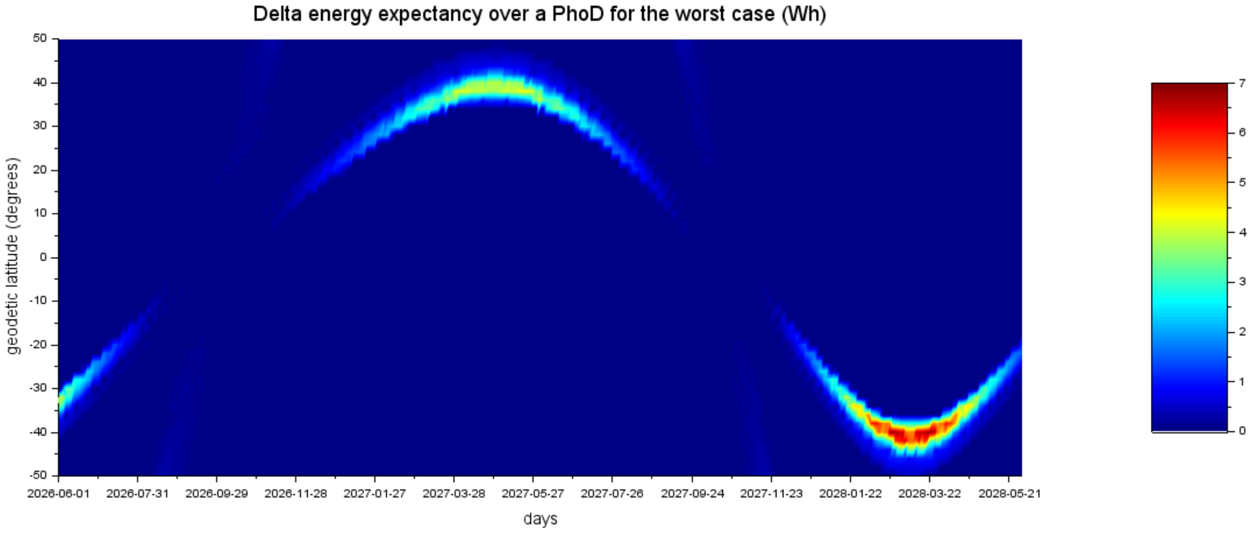

Figure 5: Energy losses when pointing the Sun at noon instead of the energy map pointing

This method has other advantages: since it does not require 3-axis attitude estimation, the attitude command is immediate for it only depends on the instantaneous SAS measurements, and several correction iterations can be performed quickly. It is a simple and robust strategy, and a good trade-off in terms of battery charge performance, design complexity and accepted risks.

However, it constrains the operations workflow: the rover cannot move after midday for it is the start of the battery charge phase. All the rover movements (driving) must be performed in the morning.

5.3 Simplification of the stability assessment

Without 3-axis attitude estimation, the gravity direction cannot be assessed anymore. Then the stability margin introduced in §4.4 cannot be computed to ensure that the rover does not tip over. Instead, the concept of “raw stability margin” is defined for a given rover pose as the half-angle of the biggest cone around [G, -Zreference) residing entirely inside the stability tetrahedron (Fig. 6).

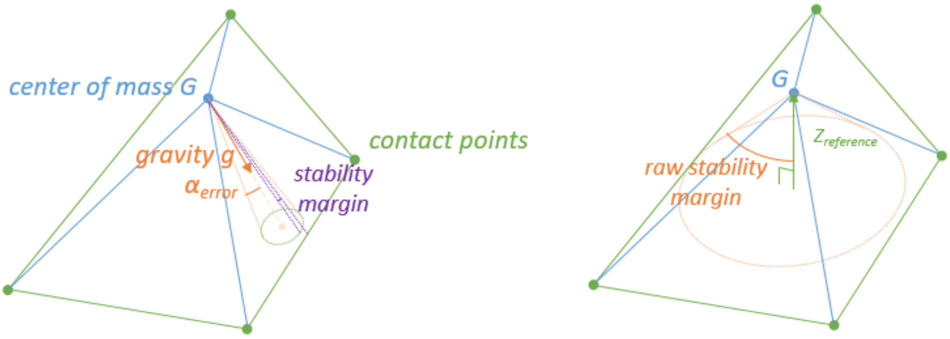

Figure 6: Difference between the stability margin (left) and the raw stability margin (right)

Preliminary simulations performed on the DLR robotics simulator [9] show that the angle between the local anti-normal at rover scale $-Z_{\text{Reference}}$ and the gravity vector g should remain lower than 30° in most rover and terrain configurations. Then a sufficiently large raw stability margin (computed taking uncertainties on G actual position) can serve as an indicator to assess the stability of the rover.

For a given ground clearance, the raw stability margin decreases when the tilt increases. The raw stability margin also slightly varies with the tilt azimuth (at the lowest for tilt azimuths near the front and back directions). Figure 7 shows in blue the worst-case raw stability margin over all tilts and tilt azimuths, and in orange the worst-case considering a limitation of the tilt.

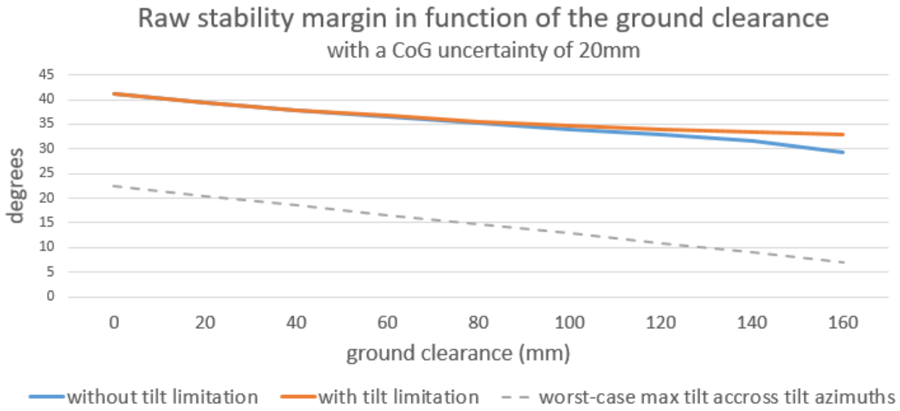

Figure 7: Evolution of the worst-case raw stability margin in function of the ground clearance

This permits to construct a stability domain, defined by a maximum ground clearance (and optionally a slight limitation of the tilt in the front and back directions) inside which any rover pose is stable, under the considered assumptions on the terrain and other uncertainties. Additional Monte-Carlo simulations are performed to verify that the rover remains stable (i.e. presents a high enough raw stability margin) during alignments between any two poses inside this domain.
Note that the maximum ground clearance cannot arbitrarily be lowered, as a minimum safe distance to the regolith shall be kept for the instruments safety. Two stability domains are then defined:

- One for the SLUD with low ground clearances: instruments not exposed, high expected LTI,
- One for the exploration phase with higher ground clearances: shutters opened, driving sessions expected to have led the rover in flat areas with lower LTI.

6 FULL DESCRIPTION of the FINAL SKA DESIGN

6.1 Heliotrope sequence

Figure 8 presents the SKA control loop and the main interactions between the subsystems, which are primarily the SAS and the locomotion system.

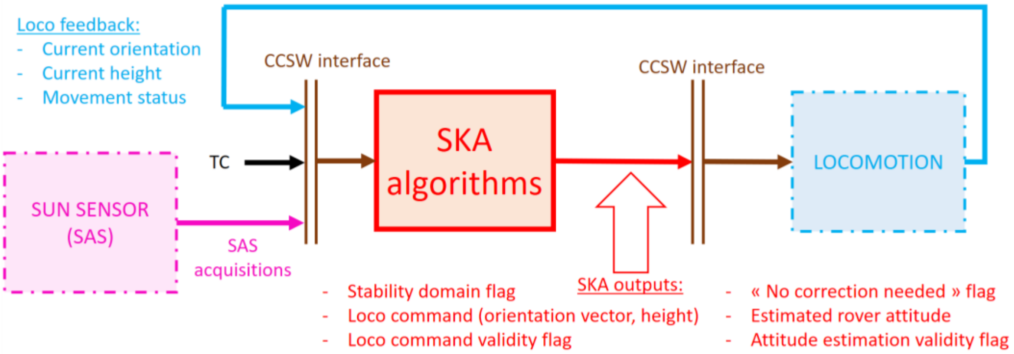

Figure 8: SKA control loop

The chain of event performed by the SKA to maximize the battery charge is called the heliotrope sequence (Fig. 9). To ensure the rover stability, the movements are separated in two phases. First, a lowering movement permits to move the rover in the ground clearance range associated to the stable zone. For instance, if the rover finishes its driving sequence with all its legs almost vertical (no tilt), then it lowers its chassis and keeps the same attitude. Then, the rover executes several movements to align the SA normal with the Sun direction (pointing loop), while staying in the safe ground clearance range. Figure 10 presents several examples of the heliotrope positions. Finally, the last phase of the sequence is dedicated to 3-axis attitude estimation.

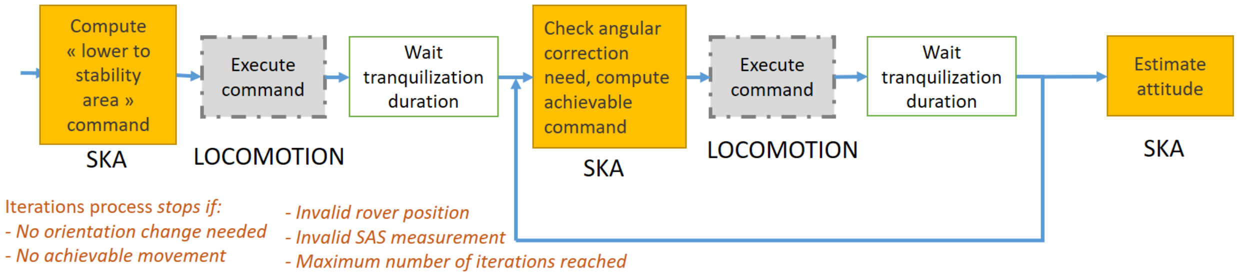

Figure 9: Heliotrope sequence

Figure 10: Rover in possible heliotrope positions

6.2 Lowering movement

The lowering command is computed with the following successive steps:

1. Check if the current rover pose is in the stability domain, by computing the rover ground clearance, tilt and tilt azimuth, and taking into account a ground clearance margin due to the locomotion system control error.

2. If it is not in the stability area, compute the SKA command (d_{des}, n_{des}) to put the rover at the maximum acceptable ground clearance in the allowed range without changing the rover tilt.

3. If it is not possible to preserve the tilt, put the rover at minimum ground clearance with the maximum acceptable tilt (in the current tilt azimuth) and compute the new SKA command.

4. Cancel the SKA command if predefined minimum thresholds (height, orientation) are not reached, otherwise send it to the LOCO. This prevents the execution of a too small movement.

6.3 Pointing loop

The pointing loop is composed of the following elements: SAS measurements processing, ideal correction computation, locomotion command computation.

To process the SAS measurements, the validity of the four photodiode currents is checked and the currents are averaged. They are then calibrated (gain, offset) based on the OBC temperature. The SAS angles α and β are derived from the currents (Eq. 1), these angles are calibrated to correct spatial error using calibration tables provided by the SAS manufacturer. Finally, the SAS angles are combined to compute the Sun direction in rover "Explo" frame, named *SunDirRov*.

An important point to be able to execute the above processing is to make sure that the Sun direction is indeed in the SAS FoV. To do so a combination of conditions on the photodiode currents and computation on SAS angles are evaluated. This aspect is particularly sensitive as for some landing sites (with the smaller solar fluxes), the expected currents at the FoV limit are close to the electronics residual currents. The parameters of the SAS processing need to be carefully chosen and will require to be refined with a better knowledge of the expected landing site.

The ideal command angle is restricted to *maxComAngle* (Eq. 4) to prevent rover movements that would be too big and could lead to bury the rover wheels in the regolith. *comAngle* is then compared to a threshold ("AngThreshold") in order to cancel commands that would be too small. The resulting z_{target} direction (in Explo frame) is then computed and associated with an "orientationChangeNeeded" flag that will enable or not the locomotion command computation.

$$\begin{cases} SunAngle = \mathrm{acos}(SAnormal \cdot \mathrm{SunDirRov}) \\ comAngle = \min(\mathrm{SunAngle}, MaxComAngle) \end{cases} \tag{4}$$

The locomotion command is computed with the following successive steps:

1. z_{target} is converted in Reference frame since this frame is assumed to stay roughly fixed in TNF during the rover movement.

2. Using the conversion relations between the Reference and the Explo frame (§ 3.1), the SKA command (d_{des}, n_{des}) is computed. Similarly to the lowering command, the purpose is to put the rover at the maximum acceptable ground clearance with the target tilt. If it is not possible, the rover is put at minimum ground clearance with the maximum acceptable tilt.

3. Finally, the new expected z_{Explo} is compared to the current one and if the angular correction is too small, the SKA command is canceled.

6.4 Attitude estimation

Attitude estimation is not mandatory anymore to control the rover attitude, but it stays useful for the mission and for the auto-navigation partition to readjust regularly their attitude estimation.

The attitude estimation method is similar to the initial design. However, the FOG measurement is replaced by a second SAS measurement: instead of having two different sensors, the same sensor is used twice at two distinct moments. This technique can be used because once the rover is pointed towards the heliotrope direction, it will not move again until the battery is sufficiently charged. Moreover, since the pointing has to be done around noon in Phobos local time, it means that the Sun should stay in the SAS field of view at least a few hours more.
Two SAS measurements of the Sun direction are combined with two Sun directions calculated thanks to the on-board ephemeris model, giving an estimation of the rover orientation relatively to Phobos local frame. Potential improvements of the estimation include taking into account several points on the Sun path instead of only two, it is particularly suitable with the QUEST algorithm.

6.5 Operating the SKA

Regarding Command & Control, two SKA TCs are defined: *SKA_lowering* and *SKA_pointing*. They are scheduled close to noon LTST (Local True Solar Time) on every Phod. A table listing all the noon LTST dates is provided to the operations team. The *SKA_pointing* TC contains in particular an angular threshold “maxSunAngle” to which is compared the *SunAngle* variable. This mechanism with two angular thresholds creates a customizable control through the different phases of the mission.

The high level angular threshold “maxSunAngle” permits to trigger or not the heliotrope sequence depending on the high level mission and mobility goals: either limiting the rover’s movements as much as possible or getting a very good rover attitude.
The low level angular threshold “AngThreshold” limits the number of correction movements once the heliotrope sequence is launched; again balancing between simply coming back to an acceptable coarse attitude or allowing several correction movements until the rover attitude is very close to the target. This mechanism gives a good flexibility and will permit to adapt the control strategy depending on the feedback gained from the rover interaction with the regolith and the pressure on energy levels.

7 PRELIMINARY SIMULATIONS RESULTS

Preliminary SKA simulations have been performed using the rover Robotic Simulator, made by the DLR Institute of System Dynamics and Control. This simulator provides a multibody dynamic simulation and is based on the rover CAD model [9]. The ground is modelled with a soft deformable soil and includes rocks. It permits then to model the wheels sinkage and movement blockages due to rocks. The random generation of the ground is based on the project terrain requirements.

A preliminary modeling of the SAS and the Sun trajectories allowed to simulate the heliotrope sequence for the considered landing sites. Only the pointing part was studied in these simulations, in order to evaluate the survival to the SLUD.

To process the simulations data (about 4000 simulations), a critical point was to discard the unrealistic failure cases: the terrain being randomly generated, there are cases where the rover is dropped onto a rock that is too big or in a bad rocks configurations. Such cases should not be considered because the rover uprighting would probably have failed or moved the rover further. Criteria to discard those simulations without removing representative ones were compared and set up to process the data.

Figure 11 presents the average power gain for each landing site. The gain is particularly important at low latitudes. For the high latitudes, there are cases where the gain is null or negative. This is expected because the pointing strategy (Sun direction at noon LTST) is not optimal (see Fig. 5) but a good average pointing strategy. What this graph does not show is that for the high latitudes, the energy expectancy is already much higher than the minimal threshold (see Fig. 2), therefore a little degradation will not endanger survival. The landing site will be decided shortly before the landing and so it was necessary to have a pointing strategy working for all possible landing sites. Moreover, a way to get closer to the optimal pointing direction (as it would be computed on the initial energy maps), will be to slightly modify the heliotrope sequence time of the day.

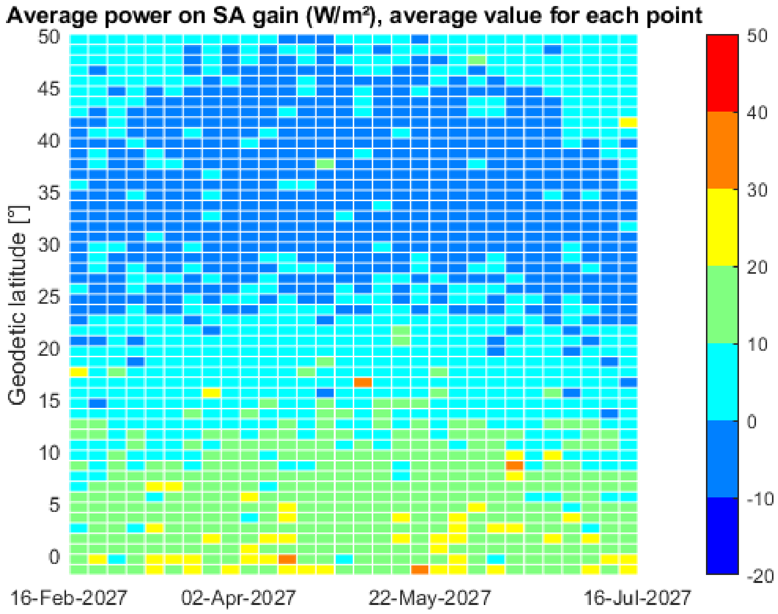

Figure 11: Average power gain after heliotrope sequence

Figure 12 presents the survival before and after the heliotrope sequence (comparing the average power expectancy to a preliminary 140W/m² threshold). As seen before, the interest of the heliotrope sequence appears mainly at low latitudes, and survival is ensured for most of the landing sites after the heliotrope sequence. It is due to a bad set of events when the minimum threshold cannot be reached: at low latitudes, the rover tilt needs to be higher and it can become limited by the stability constraint. On such sites, very unfavorable local slope and rocks configurations, leaning the rover far from the heliotrope direction, prevent it to reach the minimum average power expectancy threshold.

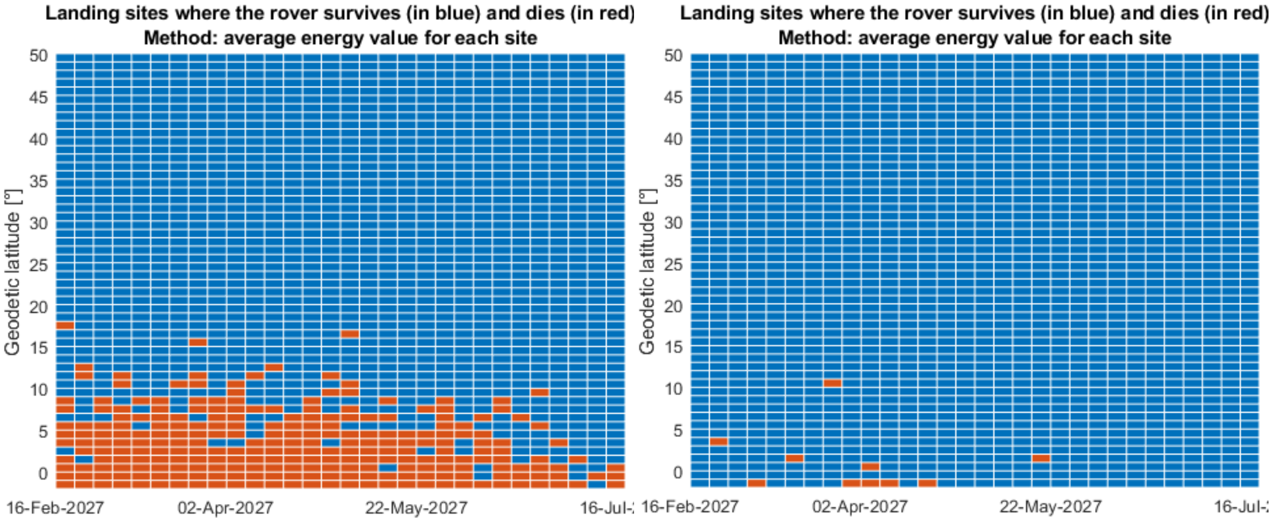

Figure 12: Survival before (left) and after (right) the heliotrope sequence

The angle between the SA normal and the Sun direction decreases of about 10° in average after the heliotrope sequence. This pointing efficiency is consistent with the order of magnitude of the potential rover tilt (up to about 18°). It is important to remember that for some latitudes the Sun direction is far from reachable, the only thing that can be done is to get closer to the Sun direction – which improves the energy gain – but the Sun angle can never be close to 0° without the rover tipping over.

The stability margin globally decreases after the heliotrope sequence : this is expected since the rover starts with no tilt and ends up tilted which is obviously less stable. However, the minimum stability margin value obtained (22° 3σ) is sufficient to ensure the rover safety. Note that the rover is automatically put at minimum acceptable ground clearance for these SLUD simulations. The bottom shutters being closed, there is no risk to damage the instruments and staying at minimum ground clearance allows to reach the highest tilt for this energetically critical phase.

The needed number of iterations was difficult to predict as it is linked to the way the rover interacts with the soft soil and the rocks. The results show that most heliotrope sequences only need two to three iterations to reach a pointing accuracy lower than the minimum angular threshold (set to 2°).

8 WAY FORWARD

The development and validation of the SKA partition are already at an advanced stage, though a simple outline is given here.

Two versions of the SKA partition are foreseen, a preliminary (but functional) one for the AIT tests, and another one to be charged on the rover before the MMX launch.
The SKA partition is composed of a core module called *SKA_tools*. It is developed, validated and the embedded code is generated using Matlab/Simulink. The SKA partition interfaces and the two SKA TCs, are defined by the SKA architect but coded directly by the flight software team. This distribution permits to meet the very tight schedule of the project.

The algorithms performance simulations and the functional validation of the SKA partition will be run on a numerical simulator including the whole SKA partition, the DLR Robotic Simulator and several other models (ephemeris, SAS model, etc).

Besides, the SAS acquisition chain performance has been assessed through several hardware tests including tests in thermal chamber. The DLR is responsible for the locomotion system qualification, it is presented in [10].

During the AIT, the SKA chain is assessed at several levels. On the FlatRover, the residual currents of the SAS acquisitions are checked as well as the signs for both the SAS and locomotion system. On the rover PFM, the same checks are also performed. Once the rover is assembled with the main parts needed by the SKA, a global SKA loop test is performed, using the real on-board SKA partition. The SAS is illuminated by a torch lamp, the loco commands are computed and executed. The movements of the legs are monitored and compared to predictions.

The last point of interest is the difficulty encountered for the tuning of some SKA software parameters. The minimum ground clearance is complicated to tune because of the very small knowledge of Phobos' expected soil. This parameter must compensate the wheels sinkage, the presence of rocks and the soil deformation. It is interesting to set it as low as possible because it allows a higher tilt (leading to a better energy gain) and a better stability. However, if it is set too low, it will endanger the chassis bottom including the rover instruments, and possibly the SA. This is just one example of some difficult system trade-offs that will need to be done before starting the mission.

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