Planetary Rover Localization Design: Antecedents and Directions.

Javier Hidalgo, Jakob Schwendner and Frank Kirchner

Abstract— **This paper describes the localization problem in planetary rovers and its influence in the mission success. This manuscript gives an overview of the localization subsystem from a system level perspective and its impact on mission operations. It discusses current problems on the design of proper sensor fusion scheme and addresses future challenges which needs to be pursued in order to move forward planetary rovers into more intelligent vehicles for future planetary missions.**

I. INTRODUCTION

The performance of autonomous navigation for planetary rovers depends highly on the robustness and reliability of the localization subsystem, which is responsible for closing the navigation control loop while driving [1], [2], [3], [4], [5], [6]. In order to estimate with enough accuracy the position and attitude of the rover while driving, several different sensors have to be incorporated on-board and their individual outputs to be combined in a sensor fusion framework [7], [8]. Relative position information relates the current position of the rover to one or more of its previous positions. Absolute position information on the other hand relates the rover position to a globally referenced map of the environment. While relative positioning is similar between terrestrial and space applications, terrestrial systems can in many situations make use of absolute reference systems like GPS. Robotic applications in planetary exploration fail to benefit from GPS and accurate long term localization systems are needed for the mission success. Due to inherent sensor errors and computation cost, sensor fusion techniques would be used to estimate the resulting position and attitude more accurately than if each sensor was considered individually. Three different kinds of sensors are normally considered in a rover mission, (1) wheel odometry, (2) cameras and (3) inertial sensors, since those sensors are nominal in the majority of current rover designs [9], [10], [11]. Additional types of sensors have also been considered for integration in mobile exploration systems. Sun-sensors [12], [13], [14], which are cheap in mass and power requirements can provide information on the heading of the rover without the need to pan the main camera. Further, 3D sensors [15] provide dense distance images of the environment with greater accuracy, higher distance and less computing power compared to stereo processing. However, they use up a lot of power and mass and currently have a low technology maturity level for space applications.

Many analyses in the field of sensor fusion and localization for aerial and terrestrial vehicles have been carried out.

The needs of a localization subsystem on-board a planetary rover has several similarities with the ones on terrestrial vehicles as well as conventional spacecrafts. However, they have significant differences in terms of operational constraints and dynamics. Although, the search for accurate and efficient sensor fusion algorithms for robot and vehicle localization has been performed during many years and takes part in many field of engineering, no quantitative performance analysis or theoretical feedback in the context of planetary rovers has been proposed and a significant lack of information exists on how to design a sensor fusion scheme to accurately propagate planetary rover position and attitude. This manuscript analyzes the current state of the art and derives directions for future designs.

II. RATIONALE

The engineering process of a planetary rover is a concurrent design which involves several iterations and phases presenting many challenges during the whole process. The rover system design is driven by mission requirements and environmental constraints that affect the final rover concept. To give an example, thermal cycles are a big issue in Mars driving to do as much as possible as soon as possible. Different philosophies and approaches are usually taken based on a number of criteria such as redundancy, technology maturity (Technology Readiness Level - TRL), mass, simplicity, reliability and accuracy. In this scenario different subsystems contribute to the design of the whole rover: locomotion, power, thermal, OnBoard Data Handling (OBDH) and others which iterate on the rover design and concepts. A powerful engineering methodology and a better understanding of the subsystem performance and details improve the complete

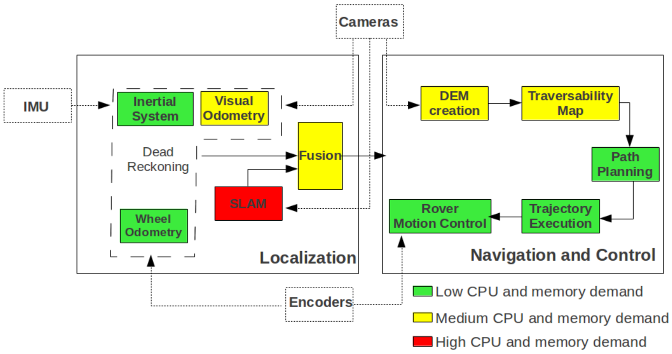

Fig. 1: Schematic representation of a nominal localization subsystem with the different components and its OBDH demands.

DFKI - Robotics Innovation Center Robert-Hooke-Str. 5, 28359 Bremen, Germany, `javier.hidalgo_carrio@dfki.de`, `jakob.schwendner@dfki.de`, `frank.kirchner@dfki.de`

design process. Mobile robots are sometimes referred to in the space domain as ground spacecrafts. However, there are many differences and peculiarities that make the rover design a unique case. Among all the subsystems that constitute a planetary rover, three are critical during the design due to their influence on the mission success. These subsystems are (1) locomotion, (2) power and (3) Guidance Navigation and Control (GNC). Power needs to be properly sized up since it is a crucial subsystem affecting the performance of the rover as well as scientific instruments. Locomotion and GNC are together mentioned as mobility. More specifically, GNC is responsible for three main functions, (1) guidance (2) navigation (including localization) and (3) control, which altogether are essential for rover autonomy (see Fig. 1). This manuscript is centered in the localization. Accurate rover positioning is basic for many other subsystems affecting rover safety, operations and level of autonomy. Further information about autonomy for planetary rovers can be found in [16] and [17].

Nowadays, the localization problem requires a more elaborated analysis and a further understanding in order to identify its impact and aid in future rover designs. It will be argued in the rest of this manuscript.

III. ANTECEDENTS

The most complete and reliable localization scheme for planetary rovers is up to now onboard in the Mars Exploration Rovers (MER) and it will be soon the coming Mars Science Laboratory (MSL). Surface Attitude Position and Pointing (SAPP) is the rover component in charge of calculating and propagating rover attitude and position estimation, using and combining different techniques and sensory information. SAPP is further explained in [18] and carries out the propagation of rover pose depending on three commands defined in the Attitude Acquisition Machine and triggered from ground depending on rover operations. The localization subsystem computes and propagates attitude using gyros integration and additional support from Sun elevation information on the camera images. Also accelerometers data in static regimen is provided. The rover position is propagated using wheel odometry and no accelerometers are used in this step [19]. Conventional wheel odometry remains good on simple terrain, flat and level ground, being computationally inexpensive. Spirit only accumulated 3% position error over 2 km of driving on level ground [20]. Quantitative ahead images from previous sol (Martian day - 24.6 hours) allow offline further terramechanics simulation from the ground, giving valuable aid in wheel odometry and the type of maneuvers to perform. However, it is not possible on complex terrains and when ahead images are not available. MER mission did not consider visual odometry from camera images in the nominal localization scheme by SAPP. The high slippage observed while driving on Mars surface forced engineers to include visual odometry in successive subsystem updates. Maimone *et al* reported in [21] the use of visual odometry based on Structure-From-Motion algorithms using stereo images computation. Stephen *et al* give also in [22] an analysis of applicability of Visual Odometry in planetary rovers. Visual features are deduced and tuned for corner detection. Proper stereo matching of the selected features and feature tracking together with the successive motion estimation are computed onboard the rover. The incorporation of visual odometry into the localization framework addressed a significant advance allowing the rover to navigate through more challenging terrains increasing the number of science targets to analyze. The application of visual odometry turned out to be a fundamental capability on demanding terrains, typically loose/mixed terrain and/or slopes of 10% and higher, measuring slips as high as 125% when it tried to drive up more that 25 degree slope [2], [21]. Slippage detection is a complicated task and soil parameters are involved. It is documented in [20] how Spirit reached 100 % slippage (no forward progress) on a 16 degree slope and only few meters ahead had only 20% slip on a 19 degree slope with no discernible difference in the character of the surface.

The penalty of using visual odometry is the computation cost and the associated power consumption. Visual odometry takes between 2-3 minutes to process stereo pair images on the RAD6000 (35 MIPS) processor of the MER rovers, and 60% of overlap between image pairs is required, limiting turning maneuvers. It affects daily operations and degrades the performance of the whole rover mobility [20] [23]. The localization subsystem has a direct impact on rover trajectory, planning, speed, distance to traverse, ground operations and scientific return. Direct driving speed for MER is about 124 m/h when benign terrain and ahead images are available for planning from ground. When visual odometry is activated rover speed goes down to 10 m/h and a maximum of 6 m/h is achieved when working in cooperation with autonomous obstacle avoidance [20]. This difference in speed between using one or another localization mode clearly points to the need of improving and analyzing the design of future localization schemes. This fact has an important consequence on rover mobility and operations. MER can travel 50 m in 25 minutes using direct driving and take up to 8 hours using visual odometry and obstacle avoidance for the same distance. For this reason the use of visual odometry and obstacle avoidance was limited considerably in both Mars rovers. Therefore, different localization solutions were remotely switched for MER mission, using visual odometry when it was extremely necessary and having direct impact on the level of autonomy. This fact enhances the necessity for future missions of using visual odometry together with other sensor information in an intelligent and autonomous closed-loop manner without human intervention from ground, reducing then the human factor, waiting times and communication windows to Mars.

IV. MOTIVATION

Mars is the single most attractive solar system site for its wide scientific investigations, in particular the evidence of life. The European Space Agency (ESA) is involved within the Mars Robotic Exploration Program (MREP) for the next major step on the red planet. Within MREP a

Sample Fetching Rover (SFR) has been studied, which in comparison to ExoMars has much harsher requirements regarding traveling distance and localization accuracy. In terms of Research and Development (R&D), ESA has been developing some technologies under the General Support Technology Programme (GSTP) and funded mission studies as part of the MREP and in particular in the Mars Sample Return (MSR) programme together with NASA. This future robotics Mars context means moving the European space programme far out of its technological comfort zone.

Future ESA rover missions plan to travel longer and faster than past rovers. MER covered ∼15 km in ∼7 years while next rover missions plan a traverse range of ∼20 km in ∼6 months. Traverse requirements will drastically drive the design of the platform and its mobility system. As mentioned previously, mobility is used as a term for the locomotion system together with the GNC system to emphasize and recognize the interleaved nature of these two systems. For example, a more capable locomotion system decreases the need of obstacle avoidance, decreasing the complexity of the GNC system. This analysis has not been carried out properly in the literature although Allouis *et al* give a general system engineering overview of the problem in [24]. Increasing the size of the locomotion system is a suitable solution to improve mobility and fit the traverse requirements. However, mission constraints in term of mass and volume do not allow for a complex locomotion chassis and actuators. A more capable locomotion system, such as that of the MSL with 50 cm wheel diameter, would allow offline fast path planning using the HiRISE imager, (30 cm/pixel ground resolution) decreasing complexity in the obstacle avoidance algorithm. Nevertheless, mission constraints always drive the rover design and an imperative improvement of the GNC system is required for future missions where a lighter rover (a fifth of the ExoMars rover) takes part of a more complex mission scenario than MSL. While ExoMars rover mass envelope is about 300 kg, SFR is less than 80 kg, having a direct penalty in the locomotion system and increasing the complexity of the GNC system. Traverse requirements are much higher with reduced mission lifetime in order to fulfill the cache return operations of MSR. Different rover masses and traverse requirements of some current planetary rover missions are summarized in Fig. 2.

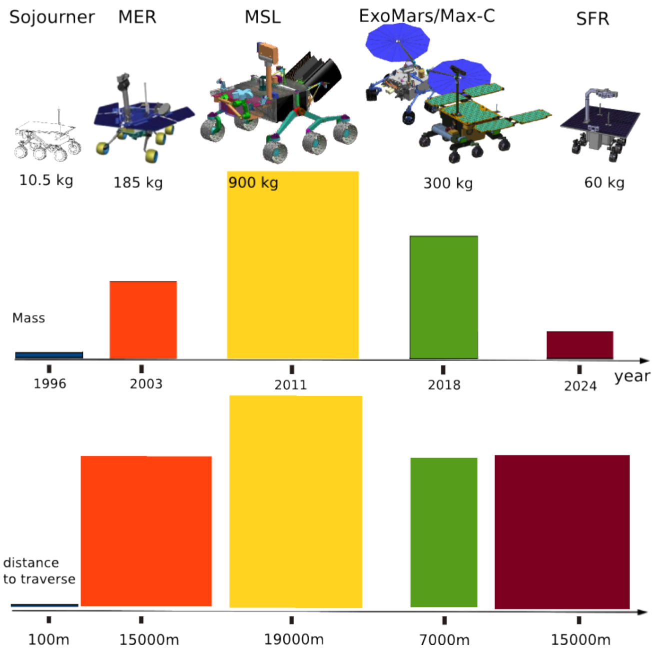

Fig. 2: Comparison of mass and distance to traverse by each rover for past, current and future missions. The bars are properly sized. SFR has small mass and a high requirement in distance. It forces a more capable navigation subsystem in the design.

While Mars undoubtedly is a primary target for exploration missions involving mobile robotic systems, the Moon has also regained attention from the scientific community, as well as several space agencies and private entities that currently pursue exploration missions. Since the Luna 24 mission in 1976, there have been no attempts of controlled landing on the surface of the Moon. Multiple missions using either orbiters or impactors (SMART-1, SELENE, Chang'e-1, Chandrayaan-1, LCROSS, LRO) have however verified the existence of volatiles like water in the lunar south polar region. This is interesting both from a scientific point of view as well as the application for in-situ resource utilization scenarios. Currently ESA is planning a precursor mission to the lunar south pole to be launched in 2018 [25], mainly to verify technologies in the area of soft precision landing. This mission had a rover content during the first phases of the mission, which was later removed due to mass constraints. Multiple experiments using the rover where planned in this phase, which required high localization accuracy of 0.1% of the overall distance traveled. The total distance was planned to be 10 km. Another study has been funded by the DLR, to have a scaled down rover on the Next-LL mission, in the 10 kg class [26]. This rover only has to travel a distance of 100 m away from the lander, and has no particular accuracy requirements with regards to localization. It needs however to be able to return to the lander autonomously, and thus traverse the 100 m without operator intervention. This requires a consistent localization and mapping component with appropriate accuracy. Both the Chinese and the Indian space agencies are also currently planning lunar rover missions to be launched this decade.

Fig. 3 compares the different speed of pass, current and future rover missions. It is important to mention that the comparison considers 2.25 hours of driving for a locomotion sol and no movement during a science sol. MSL and ExoMars nominal average speed are set with autonomous navigation capabilities in contrast to previous missions in which *direct driving* was employed, not using visual odometry and other autonomous behaviors. SFR would take this improvement one steep further. It is an imminent necessity to find effective data fusion schemes in order to deduce rover position and orientation in a prolonged and adaptive manner that ensures the desired speed. Mars rover missions have demonstrated

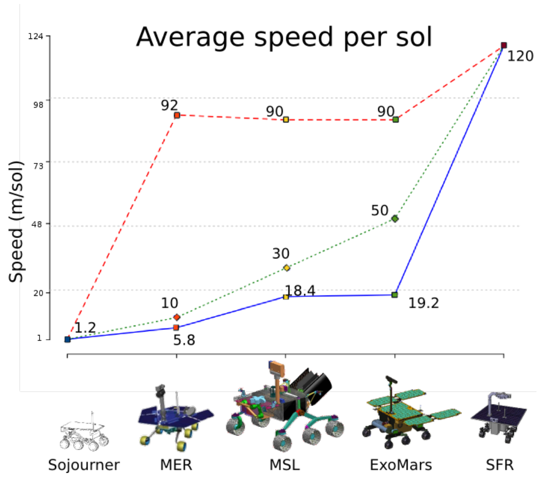

Fig. 3: Rover speed for different planetary missions. The lowest line is the average mission speed taking into account locomotion and science sols. Upper and middle lines only consider locomotion sols, being the maximum average and nominal average speed respectively. The graph shows rover speed variation depending on the localization and navigation mode which is dictated by surface and soil conditions as well as information from the previous sol. MER maximum average speed is 92 m/sol considering that speed peak is 124 m/h in *direct driving* and 96 m/h using *path selection*. However autonomous capabilities with visual odometry on MER decreased the speed considerably (6 m/h). MSL speed has been designed to 90 m/sol and 30 m/sol for maximum and nominal average but considering autonomous capabilities. ExoMars requirement in phase-B2 drived the rover to a nominal speed of 50 m/sol. The total time available in the SFR mission for traversing 15 km is a maximum of 125 sols, resulting to a minimum rover speed of 120 m/sol.

that geometric and non-geometric hazards could stop entirely the motion of the rover due to its physical properties and are difficult to detect remotely from Earth [19]. It entails a higher level of autonomy in localization with more sophisticated sensor fusion solutions which combine data from different sensors and information from diverse subsystems as well as taking advantage of better sensor developments.

T. Biesiadecki *et al* introduced an overview study in [20] about the impact that different navigation and localization modes affects rover autonomy and mission planning. Some authors as Huntsberger *et al* [5] reported upcoming developments at NASA/JPL for next missions with special emphasis in precision navigation in relatively long distances and improvements in mobility operations. Schenker describes in [27] the importance of surface mobility to space science addressing some key problems in advancing performance of future planetary rovers.

The localization subsystem needs more rigor during the missions studies. Fig. 4 depicts an example of the Navigation-Locomotion loop for a planetary rover. The loop is comprised by two phases (1) the Processing/Path Planing phase and (2) the Locomotion phase. The former is responsible for the stereo image acquisition and the processing. The trajectory planing is the output of this phase and the beginning of the Locomotion phase. The distance traveled during the Localization phase has an average of 2 meters depending on rocks density distribution [28], [29]. The distance is measured by the localization subsystem during the Locomotion & Localization phase, being a key process on the loop. The energy budget and execution time of the Locomotion phase have only considered the motor energy consumption and rover speed. The consumption of the localization subsystem and its influence on the whole loop performance have been neglected. This assumption has to change in future designs and the localization subsystem will take more importance on closing the loop during the trajectory execution as variations in speed are depicted in Fig. 3.

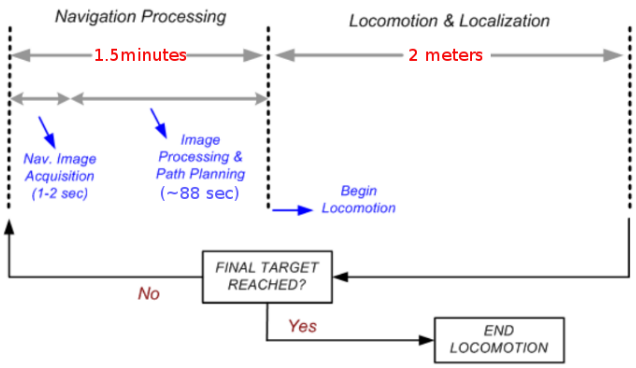

Fig. 4: Rover navigation cycle during a typical mission study.

V. FUTURE DIRECTIONS

The key problem in localization is to find a robust and reliable data fusion scheme which properly fits nominal mission constraints. Rover pose needs to be locally (dead reckoning) and globally consistent using satellite imaging and digital elevation map creations offline from ground. This will increase mission success and reliability. Learning from MER experience, MSL wheels have tread pattern in order to leave an impression on the soil surface in morse code. The idea behind is to post-process by looking back with the cameras and analyze the distance traversed. However, the availability to process this extra information in real time and close the loop by the rover is still to discover. Different sensory data and information has to be processed and incorporated to solve the problem as well as to support the trajectory execution and the rover motion control.

A multi-sensor fusion approach needs to be developed taking into consideration sensor reliability, error characterization, power consumption and computation cost working towards a robust and accurate localization scheme that could be used nominally on rover mission scenarios. The goal is to minimize power consumption and intervention from the ground allowing desirable rover autonomy, localization robustness, accuracy and reliability.

A. *Localization Subsystem Design*

In order to enable the design of such mobility systems, it is necessary to find the fundamentals and knowledge gaps in the design of planetary rover localization scheme. Because reliance on a single data source can lead to ambiguity and uncertainty. Data fusion can improve (1) representation (2) certainty (3) accuracy and (4) robustness. Some topics are essential in order to achieve the desired localization performance.

1) Adaptability: A suitable solution in localization scheme is to move from the current static solution towards a dynamic process. The localization problem has been addressed as a static problem. It has been discussed in the paper that it is not and depends on several variables as energy, sensor accuracy as well as surface and soil conditions. A full feedback approach, which is currently done by the ground control (operator refinement) depending on the information available from telemetry data. Adaptability in the localization subsystem would improve the performance as it has been demonstrated for the path planning problem by Helmick *et al* in [30].

2) Intertwine with Resource Management: A formal duality exists in the control part of sensor fusion mentioned as resource management. It is the counterpart of the sensor fusion process defining the control response corresponding to the state estimation of the data fusion levels. Figure 5 shows these relationships, *sensors* observe the environment and are the inputs to the *data fusion* which estimates and orients the rover to decide actions, which are performed in the *resource management*. Finally, the *resource management* actively affects the rest of components actuating in the system and in the environment via the *response systems* component. In robotics terminology, the resource management is the compendium of all the rover subsystems that actively affect rover mobility. They are trajectory execution, rover motion control, navigation and path planning. In this analysis only the subsystems that affect rover mobility are considered, even though in reality it has impact on all the subsystems especially those ones affecting rover autonomy. A better connection between the localization subsystem and the rest of subsystems needs to be developed to improve the performance as it has been done for control of systems. The localization fusion scheme needs to be driven by the data and the resources available. The resource management is driven by the performance objectives (mission requirements and scientific interests).

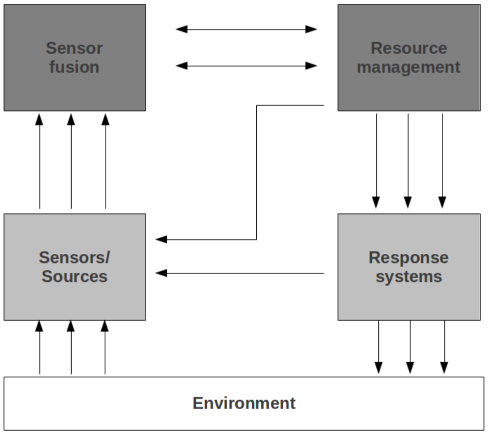

Fig. 5: Sensor fusion and the intertwine with resource management. Data fusion is the subsystem of combining data and information to estimate rover pose. Resource management is the subsystems to perform rover control, navigation and planning.

TABLE I: JDL levels and the proposed adaptation for rover localization.

JDL Level	**Localization functionality**
Level 0: signal/feature assessment	Sensor signal processing. Visual feature extraction.
Level 1: entity assessment	Data registration. Rover navigation kinematics. Stereo feature matching. Feature tracking.
Level 2: situation assessment	Relation among sensory information Recursive state estimation. Gaussian and nonparametric filters.
Level 3: impact assessment	Sensor fusion evaluation Relation among data information (other subsystems)
Level 4: process assessment	Adaptive control of the fusion process Interaction with other levels and subsystems

3) Data Fusion System Engineering Approach: Data fusion is a complex discipline and not many functional studies have been developed. The Joint Directors of Laboratories (JDL) began an effort to codify the terminology related to data fusion [8], [31]. A system engineering approach is desired for solving a *goal-driven* localization problem in a systematic manner. The JDL data fusion *functional* model has been designed to facilitate understanding of types of problems for which the data fusion is applicable and to define a useful partition of solutions. Partition into levels reflects significant differences in datatypes, resources, models and inferencing. The JDL levels are not necessarily performed in sequential order and two or more levels may need to be integrated into common nodes to increase performance.

JDL levels together with the localization functions/tasks to perform in each level are depicted in Table I. However some changes need to be done to adapt this model to the robot localization problem. An entity is considered here as a rover localization estimation from a sensory data type (i.e.: inertial measurements, visual motion estimation and navigation kinematics). This entails some perspective changes with regards to the JDL nomenclature. The multi-sensor data fusion is performed at level 2, which it is the current rover pose. Level 4 has been discussed by the sensor fusion community several times in early versions [32]. It is considered here for the localization problem in order to perform the *adaptability* of a particular solution. Currently, this evaluation is done by the ground control station (level 5, operator refinement) which is not considered part of the localization problem and more a human supervision for the overall mission performance.

VI. CONCLUSION

Besides the requirements of a particular mission scenario a reliable localization system is a desire. However, a sophisticated localization system will have a direct impact in the power system and therefore affect the whole rover design. It is crucial to analyze proper data fusion algorithms as well as previously testing on ground by means of prototypes. This manuscript has presented the future directions and approaches to achieve these objectives. (1) The localization subsystem needs some studies to be properly included in the Navigation&Localization loop design. (2) Adaptability without ground control intervention is desired as well as better dependence on other subsystems. (3) Intelligent use of the resources and sensors available. (4) Establishing test and evaluation criteria to compare alternative methods. In order to evaluate in comparison to an agreed-to baseline (e.g., without fusion capabilities or adaptability) and if the contribution of a localization scheme while holding other factors fixed contributes some marginal or piecewise improvements to the overall rover.

The presented guidelines for planetary localization design are globally applicable and should lead to design localization subsystem that better fulfill with more capable planetary missions.

VII. ACKNOWLEDGMENTS

This work presented here is part of the European Space Agency (ESA) Networking Partnering Initiative (NPI), grant no. 4000103229/11/NL/PA and partially funded by the German Space Agency (DLR), grant no. 50 RA 0907, with federal funds of the Federal Ministry of Economics and Technology (BMWi).

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