Study on Strategies for Planetary Exploration within the HG-Project "Planetary Evolution And Life"

Caroline Lange
German Aerospace Center (DLR)
Institute of Space Systems
Robert-Hooke Strasse 7
28213 Bremen, Germany
+49 421 24420-159
caroline.lange@dlr.de

Aravind Seeni
German Aerospace Center (DLR)
Institute of Robotics and Mechatronics
Münchener Strasse 20
82234 Wessling, Germany
+49 8153 28-1082
aravind.seeni@dlr.de

Abstract—The search for life and water on other planetary bodies is of high interest for the space science community. [1] [2] Since 2008, Helmholtz Association (HG) supports a project, the so-called Helmholtz Alliance for "Planetary Evolution and Life", which was set up with members consisting of planetary scientists and engineers. In this project, members aim at solving some of the important questions on how life formed, evolved on Earth as well as potentially on other extraterrestrial bodies. We, the engineers are concerned with mission concept and systems design in order to assist the scientists by identifying solutions through innovative and feasible mission concepts. As this work is always driven by the science objectives on one hand and the technological capabilities on the other hand, we developed a science-driven approach to mission design. A review of the options of available technology and limitations of state of the art technology will be presented in this paper.

A survey of all scientists in the alliance was made to understand science objectives and an appropriate mission concept is chosen. One such mission concept is the "Mars Cave Explorer" that was conceptualized based on the need to explore sub-surface caves on Mars. This mission uses a rover to carry a set of miniaturized robots onboard. The optimization approach followed for designing the main rover follows a Genetic Algorithm, an evolutionary algorithm as a systems engineering tool. It is used for identifying suitable design parameters iteratively. Also the challenges faced by the rover designer for cave exploration on Mars is studied and described.

[1] 978-1-4244-7351-9/11/$26.00 ©2011 IEEE.
[2] IEEEAC paper # 1359, Version 2, Updated January 11, 2011

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1. INTRODUCTION

The Helmholtz Alliance "Planetary Evolution and Life" has been established in 2008 as a Germany-based consortium of planetary scientists from well known institutes such as the German Aerospace Center (DLR) Institute of Planetary Research or the Max-Planck institute for Solar System Research. The main focus of this alliance is the investigation of the concept of habitability. This includes questions such as whether or not extraterrestrial life exists, how the evolution of the planets is and has been influencing planetary habitability and what might be the role of life in stabilizing habitable conditions. The six main topics of the alliance covered are:

(1) Biosphere-Atmosphere-Surface interactions and Evolution,

(2) Interior-Atmosphere Interaction, Magnetic Field, and Planetary Evolution,

(3) Impacts and Planetary Evolution,

(4) Geological Context of Life,

(5) Physics and Biology of Interfacial Water,

(6) Tools and Strategies for Exploration Missions for Planetary Habitability.

The main questions of the latter topic, where the here presented research is integrated, are (i) How can life or traces of extant or extinct life, like biomolecules or pre-biotic compounds, respectively, be detected on other planets and moons - within our solar system and beyond? (ii) Which missions, tools, sensors have to be developed for their detection and measurements? (iii) How can geophysical parameters and other environmental conditions be measured that have a bearing on habitability?

This paper will give an overview over how these questions have been approached so far, by providing the results of a survey or questionnaire that has been sent out to all the participating researchers and was aimed at gaining some insights into the main objectives for habitability-focused exploration missions, the type of science payload and need. Section 2 will give an overview over the survey and its results, which were incorporated into our ongoing mission design work. Section 3 will present the subsequently performed technology review that showed us the major options and also identified some technological gaps that may be tackled during the running period of the Helmholtz Alliance. Section 4 will subsequently present a suite of proposed mission concepts that use novel methods such as using the discarded heat shield of an atmospheric entry vehicle as useful platform to carry a suite of scientific instruments. A prudential thought of retaining a mobile robot for achieving mission objectives for one particular mission and the methodology of design optimization of the respective robot will be discussed in section 5. In section 6 we will conclude and present an outlook for the next half of the running period of the alliance.

2. A SURVEY FOR A SCIENCE DRIVEN APPROACH TO MISSION DESIGN

Approach

As mentioned earlier, the main tasks in Topic six (see above) of the alliance were to define and study new mission concepts for the exploration of planetary habitability, as well as to provide innovative solutions to robotics, mobility and instrumentation problems. To bring in a science-centric view, early in the course of this work the engineers in topic six established the need to interview the scientists across all the other disciplines regarding their scientific objectives for the question of habitability in the solar system. This was done mainly to establish a common understanding for such a mission and was hoped to provide valuable input into the engineering work of Topic six.

The survey was structured in a way to gather as much requirements as possible for a future mission design. Thus it comprised not only the scientific objectives in general, but also the suggested target body, target terrain, target material, material manipulation requirements, mobility requirements and approximate measurement duration. Also, input for suggested instruments including their characteristics such as payload maturity was requested. The survey was sent to the scientists in the alliance via email and provided an Excel-spreadsheet for response. Furthermore, the questionnaire was published online at the homepage of the Alliance. The survey was open for about half a year.

Results

Though the survey provided only limited output, the following will give a short interpretation of the results that were obtained from the twenty replies. Replies came from all the different topics within the Alliance, thus showed a great variety of scientific objectives ranging from the characterization of the interior structure of planets to the search for biosignatures. Regarding the target bodies, however, a clear result was that the majority of replies referred to Mars and Europa as the preferred planets. This shows that regardless the variety of research topics, these two bodies are in unison the most interesting targets for habitability and life. Regarding the target material, the replies showed that icy material might have the highest potential for future investigations with more than 50% of the replies mentioning this target material. As for the question of mobility, a tie was estimated between the more global approach and the local point investigations. No tendencies were recognizable regarding the questions of target terrain and material manipulation requirements.

3. TECHNOLOGY REVIEW – ELEMENTS AND OPTIONS OF MISSION DESIGN

A next step on the way to mission concept design for planetary habitability was a technology review that was supposed to give an overview over the options and limitations of the state of the art exploration technology. Candidate concepts for this review comprised all types of mobility (aerial, roving, rough terrain) but also subsurface access as well as Networks and sample return as more complex solutions.

Table 1 provides an overview over the obtained results that include state of the art, main requirements and enabling technologies for future optimization or enabling of the respective missions.

Table 1: Results of the technology study

Concept / Problems	State-of-the-Art	Main Requirements[1]	Enabling Technologies
High surface mobility	Pathfinder; MER on Mars (24 km travelled distance, 35 m/hr in rocky terrain – 7% rock abundance [1],[2]); ExoMars and MSL detailed studies (5-20 km proposed distance) [3]	High body coverage; high variability of the terrain; long mission duration; onboard communication with orbiter (no relay from lander) with high data rate (due to increased data volume); power generation in various terrains and latitudes	Power: Lightweight solar panels, lightweight high power batteries, fuel cells; Increased lifetimes of components and subsystem → advanced materials; innovative mobility concepts → hoppers, balloons; autonomy
Access to rough regions	Several concepts for terrestrial applications (DLR Crawler, DFKI Scorpion [4]) - all in demonstration state	Low mass and size (light-weight structures and instruments); Fault tolerance and robustness of locomotion S/S (subsystem); adaptability to various types of terrain; high autonomy; power generation for various environmental conditions; communication without line-of-sight contact with orbiter	Innovative Mobility concepts, e.g. walkers; Miniaturization including the application of MEMS (microelectromechanical systems); advanced autonomy and cooperation concepts; modularization
Aerial vehicles	VEGA Venus balloons 1984: 2 superpressure balloons, 46.5 h mission duration, 54 km altitude [5]; Titan Tandem/TSSM Mont-golfière Phase-0 study: 6 months lifetime at 10 km altitude [6]	High surface coverage; atmospheric composition measurements & imaging (with high resolution); long mission duration; lightweight power system; materials (e.g. fabric) resistant to environment; high autonomy	Power: Lightweight solar panels, lightweight high power batteries, fuel cells; small volume propulsion concepts; autonomous state estimation, autonomous altitude control and navigation; advanced materials
Access to subsurface aquifers (deep subsurface)	Terrestrial demonstrators (incl. ExoMars drilling technology development for ~2m depth, [7]); concepts only for deeper drilling	Single or very few sample locations; access to deep subsurface (O(km)); Mars: high latitudes; small, lightweight instruments; long mission duration; long communication ranges; power generation without solar flux in the subsurface; high pressures, low temperatures;	Robust coring, drilling, hammering mechanisms; miniaturization of instruments; autonomy; power transmission over large distances or advanced power S/S (RTG, fuel cells etc.); advanced comm concepts; strategies for chip removal and bore-hole stabilization; steering concepts
Access to ice layers	Terrestrial research probes (applied at arctic ice, to be applied at Lake Vostok) of 10-12 cm diameter; access subsurface to about 1 km depth [8]	See access to subsurface aquifers; exception: access deep subsurface (O(100m)) in ice-soil mixture	See access to subsurface aquifers; combined melting and drilling technology with low power consumption
Access to subsurface oceans	Terrestrial research probes for analogous environment (to be applied at Lake Vostok); terrestrial ocean vehicles in general (AUVs and ROVs) with similar requirements	Low mass and size; local investigation of the ocean; long mission duration; water environment; communication in water required; unknown temperatures and high pressures; no solar flux for power generation; hazard avoidance and highly autonomous science	MEMS technology (miniaturization of instruments); advanced power subsystems (RTG, fuel cells, highly capable batteries); autonomous science and hazard avoidance
Networks / simultaneous investigation of several targets	MetNet concepts [9], NetLander for Mars [10]	Simple, small, robust individual vehicles; high surface coverage and good lander dispersion; geophysical instrumentation; long mission duration; synchronization of all vehicles	Synchronization techniques; surface to surface communication; miniaturization
Sample return	Return of samples from: comet Wild-2 with Stardust (using Aerogel) [5]; the Moon (Apollo and Luna) [5]; asteroid ITOKAWA by Hayabusa [11]	Single location, multi-point or local sample gathering; sampling instruments; short mission duration; high power demands; Mars: ascent in atmosphere; stringent planetary protection demands (sample handling, chain of contact), high velocity Earth re-entry	ISRU; Mars ascent technologies; planetary protection strategies wrt. contamination avoidance

[1] regarding system mass and size, mission surface coverage, types of terrain, types of measurements/instrumentation, mission duration, communication, thermal aspects, power demands, data handling and autonomy, planetary protection, others

4. MISSION DESIGN CANDIDATES

Sample Missions

Based on the results obtained in the survey and in the technology study, we identified a range of mission candidates that not only incorporate the suggestions given in the survey but are also supposed to go beyond the current large agencies planning. This kind of concept car approach was established with the constraints of looking into the future of 20 years and beyond, as well as giving programmatic and cost aspects only a secondary role. However the main theme remains the Alliance topic of “planetary habitability and life. Thus all missions are outlined to enhance the scientists’ knowledge regarding this leading theme. The following four missions are currently favored for further research:

Titan Geophysical Network—Titan, due to its interesting chemistry, is a key to understanding the origin of life and its formation. One major step into understanding this body is the characterization of its interior processes and geophysical parameters. Especially geophysics on Titan will help in understanding the atmosphere-surface-interior interaction and their processes as well as the environmental processes. Such processes are best explored using a network. Via a global distribution of several small landing packages simultaneously performing geophysical measurements we could investigate these global processes that cannot be assessed with a single point measurement. Though the dense atmosphere on Titan simplifies the landing compared to a landing on Mars, the aspect of the delivery of a network is not trivial in terms of timing of the release of the separate landers, e.g. during the final orbital approach phase, or the separation itself. Both aspects should be very well studied to guarantee a lander dispersion that is optimized for the measurement of the geophysical parameters.

One possible solution for a small geophysical landing package has already been studied: the ‘Geosaucer’-type of lander. This concept shows a high-risk but feasible approach of bringing geophysical instrumentation to Titan’s surface. The instruments package and its supporting subsystems were designed to hitchhike in the heatshield of the Montgolfière of the Tandem/TSSM mission (See Figure 1, [12]). Such an approach is in principle feasible for all future missions going to Titan and could be supplemented by a standalone Network mission with dedicated landers.

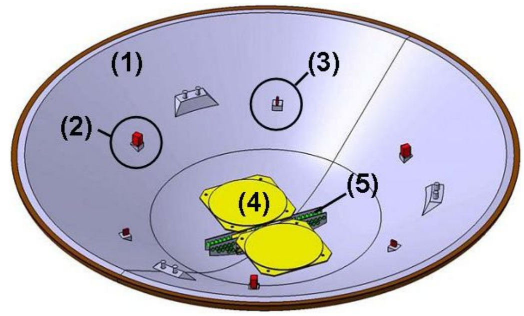

Figure 1: ‘Geosaucer’ configuration for the Tandem/TSSM Montgolfière heatshield—(1) Heatshield structure, (2) Magnetometer, (3) Seismometer, (4) RS-Beacon and Antennae, (5) Batteries

Mars Earthworm-Type Deep Drilling—After the investigation of the shallow subsurface, the deeper subsurface (several tens to hundreds of meters) will be the next big thing in Mars exploration. Such a mission could allow assessing the planet’s climate history, finding subsurface aquifers and eventually finding signs of organics and life that are enclosed and preserved in the several billion years old ice. Especially the Southern hemisphere and the region of the Mars Polar Lander landing site are good candidates for such a mission [13]. The main aspects for a study of such a mission comprise the investigation of the drill technology as well as the support structure.

Europa Multipoint Subsurface Probing—Forward looking to a scenario beyond the next 20 years, after the first supposedly small landing package has been exploring a single point on the surface of Europa, there will be the need for a mission probing the subsurface to find traces of life and organics that cannot be found on the surface due to the high radiation. Keeping in mind the difficulties and the duration of the transport of such a type of lander to the surface of Europa, there is a strong justification for a multipoint probing strategy at different places on the surface. The high radiation environment on Europa, however permits a long-lasting roving traverse to different locations. Also, the absences of an atmosphere, as well as the low gravity, make a hopping-type of approach more feasible. The details of such a mission concept will be studied as ongoing work to be performed within the Alliance. A schematic is shown in Figure 2.

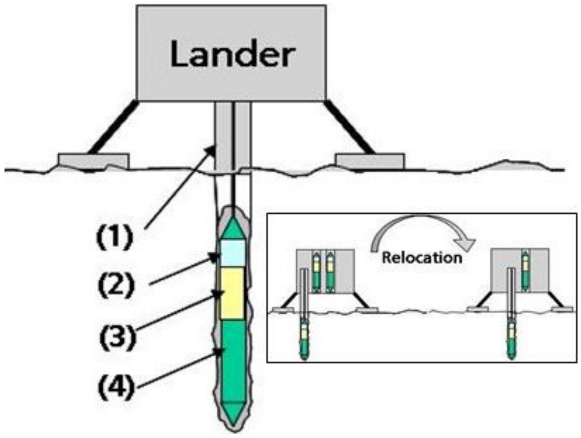

Figure 2: Europa Multipoint Subsurface Probing—(1) Subsurface probe launch tube, (2) Tether storage unit, (3) Instrument unit, (4) Hammering Unit

Mars Cave Explorer—Caves on Earth contain various forms of microbial life to be assessed in an undisturbed status, since they provide a protected environment despite or precisely because of their limited accessibility and incidence of light [14]. Analogous, on Mars caves could provide one of the few areas where extant life may have been preserved or may be even possible today, protected from surface hazards, such as micrometeoroids or UV radiation and large temperature variations [15]. Cushing and Titus only recently identified some of the potential caves on Mars proposing that they are either formed as lava tubes or hybrid volcano/tectonic fracture networks [16]. The observed lava tubes also provide skylights, i.e. entrances to the subsurface, a possible starting point for a mobile robotic subsurface explorer. The following section describes a deeper investigation of robotics and mobility elements design for the Mars Cave Explorer concept.

5. Robotics and Mobility Subsystem Design

The Mars Cave Explorer mission involves exploring the sub-surface ice caves on Mars, studying the ice deposits as well as investigating potential life signatures. This is an important mission in the astrobiological and human exploration context, because if accessible, caves could serve as a potential source of much needed water.

Main rover design

Achieving mobility of payload on remote planetary surfaces such as Mars through robots is a valuable mission element especially for planetary scientists. It is hard to determine local terrain nature prior to the mission since it is nearly impossible to determine the local terrain conditions such as soil properties using available remote sensing imagery, thermal imagery etc. In addition, factors such as landing accuracy and difficulties in estimating the robot path and corresponding nature of terrain that the rover would traverse contributes to uncertainty. An ideal terrain condition would be smooth soil, covered with little rocks and soil that offers sufficient traction and provides low wheel sinkage when pressure is exerted. However, as seen in earlier missions, the terrain may be rugged and surrounded by boulders even near the landing zone. In addition, the terrain nature inside the cave is hardly known. Furthermore, at a gravitational acceleration of 3.71 m/s^2, mobility is not similar to as on Earth. Consequently, robotic exploration of caves is complex and carries high risks of mission failure. The exploration of caves requires innovative solutions, for example agile robots able to traverse unknown terrain that may be populated with many rocks, or other methods to get instruments into the cave interior. Also the system has to withstand the harsh temperature conditions. Advanced inter-communication links between robots are necessary for communication and the robot must have advanced vision systems for navigating in the dark. These systems have not been tested in remote operational conditions in space and therefore impact overall system reliability and mission success rate. Since it is clear that mission failure risk should be minimized, a main wheeled rover that would carry a set of miniaturized robots (micro-robots) onboard and releases them at the entrance of the cave is thought. Wheeled rover systems and components, in general possess substantial technological maturity. The micro-robots on the other hand possess highly agile mobility characteristics. One possible solution for such micro-robots has been described by Dubowsky et al. [17]. The micro-robots shall be designed with advanced vision and communication systems that feed or transmit useful data retrieved from the sensors from inside the cave to the main rover present outside. In this paper, particular focus is given only to the conceptual design of the main rover and would be explained in detail. Design of the micro-robot and the mechanism for releasing them from the main rover to the entrance of the cave i.e. a conceptual multi-joint robotic arm are not discussed and are left to further work.

Power and thermal control

Since the only task of the main rover is to carry the micro-robots to the cave entrance, it may be designed with systems that are reliable and available off-the-shelf. For mass and power budgeting, we propose a method that would allow efficient selection of appropriate technologies using a trade selection process. Mosher [18] reported that choosing technologies could be efficiently performed using a Genetic Algorithm (GA). GA is a stochastic global optimization technique that is used to identify a global optimum solution that satisfies user defined design and performance requirements. It was originally developed by Holland in the 1970s. Originally found as useful to enhance computer program structures and performance, GA later was introduced by Goldberg as a meta-heuristic, numerical optimization technique [19]. Charles Darwin's famous theory of evolution of life is driven by the following processes – reproduction, natural selection along with maintenance of diversity of individuals. GA basically works similar to the life evolution process by working with a collection of solutions that reproduces, undergoes crossover and mutation. Each of these steps is mathematically programmed in a GA to create and alter individuals or solutions.

Here we use GA as an optimizer for trading technologies and designing the rover's power and thermal control subsystems. The GA used for this purpose is Genetic Optimization Systems Engineering Tool (GOSET) v.2.3, courtesy of Sudhoff S. D., Purdue University [20]. The parameters are varied by GA over a certain number of iterations, fed back to find a better solution each time until a set of performance measures becomes acceptable. The GA uses the trades that are coded as design variables and arrive at a possible solution until a set of criteria is satisfied. The technological options are traded for lower mass and higher reliability based on a multi-objective optimization approach. A generic multi-objective optimization problem may be stated as follows:

minimize $\mathbf{J(x,p)}$ where $\mathbf{J}= [J_1(\mathbf{x}), J_2(\mathbf{x})\ldots J_z(\mathbf{x})]$ (objective functions) s.t.
$\mathbf{g(x,p)} \leq 0$ (vector of m_1 number of inequality constraints, $[g_1(\mathbf{x}) \ldots g_{m1}(\mathbf{x})]^T$)
$\mathbf{h(x,p)} = 0$ (vector of m_2 number of equality constraints, $[h_1(\mathbf{x}) \ldots h_{m2}(\mathbf{x})]^T$)
$x_{i,LB} \leq x_i \leq x_{i,UB}$ (side constraints specifying lower and upper bound limits of i^{th} design variable)

where $i = 1,\ldots, n$, $\mathbf{x} \in S$. $\mathbf{x}$ is a solution vector of n design variables $[x_1 \ \ldots \ x_i \ \ldots \ x_n]^T$ and $\mathbf{p}$ is vector of fixed parameters. S is the decision solution space.

Table 2: Technology options (trades)

Design trade	Options
Array type	Non sun-tracking fixed array, sun-tracking inclinable array
Solar cell type	Ordinary Si, high efficiency Si, single junction GaAs, dual junction GaAs, triple junction GaAs
Battery type	NiCd, NiH_2, NiMH, AgZn, Li-ion
Thermal coating	Mylar Type-1, Mylar Type-2, Teflon, Kapton

A single experimental cycle of a rover is one complete set of science experiments performed by the rover within a certain time. The rover is equipped with essential power and thermal sources to survive on the surface. In order to know the power and thermal system design requirements, the power generation and thermal budgets are identified for one complete experimental cycle. Based on the budget, the systems are sized. The nominal and peak power requirements for rover operations is estimated and provided in Table 3.

J_1, the mass, is the summation of power and thermal subsystem masses that consists of solar cells, batteries, radiators etc. Both mathematical and parametric relationships are used to determine the mass. J_2, the power subsystem reliability is estimated based on empirical evidence of the failure rates of solar cell and battery types. Although failure rates for most of the solar cells and battery types are available in literature, rates for some of the types are not available. Therefore some realistic assumptions are made for some of the trades in the analysis. The technology options for power and thermal subsystems that are coded for the GA to process are listed in Table 2.

Table 3: Power requirement of main rover systems

Subsystem	Nominal power [W]		Peak power [W]	
	Day	Night	Day	Night
Mobility	25	-	150	-
Telemetry, Tracking and Command	30	-	250	-
Manipulation	45	-	80	-
Thermal Control	8	96	8	540
Navigation	20	-	20	-

Since the rover uses sunlight for power generation, it is important to know the amount of solar insolation available on the surface. Based on Appelbaum's solar radiation model [21], it is estimated that the surface (0° latitude, areocentric longitude = 90°) receives a solar insolation of 3807 Whr/m^2sol^{-1}. Based on the power requirements, battery charge demand, a minimum array area of 1.02 m^2 and battery capacity of 77 Whr is essential. An additional 300 Whr battery capacity margin is provided for egress/checkout after landing. The heat liberation of various components should be controlled. The battery, radioisotope heater unit and avionics dissipate 15 W, 10 W and 5 W of heat respectively.

The GA is run for 50 generations with a population size of 25. The crossover and mutation probability rates are set at 0.5 and 0.06 respectively. The final design solution is shown in Table 4.

Table 4: Best solution after 50 generations [GA: tournament selection; simulated binary crossover; elitism enabled]

Parameter	Solution
Array type	Fixed array (non-sun tracking)
Solar cell type	High efficiency Si
Battery type	Li-ion
Thermal coating	Teflon

The final result gives a rover with combined power and thermal subsystem masses of 49 kg and reliability of over 98%. The rover will be equipped with an array composed of high efficiency Si cells. The battery technology is Li-ion that is commonly used on rover missions.

In the next sub-section, the design optimization study of the main rover's mobility system is presented. The main design requirements of the main rover design, essential analyses and the design optimization adopted for realizing the concept is covered.

Mobility system

For the cave exploration scenario, a rover vehicle is required to be designed to carry the micro-robots and other subsystems. For the purpose of this paper and the design of this main rover we use the microbot design as described by Dubowsky [17] for reference. The total mass of the package to be carried by the rover along with supporting components amounts to 60 kg. The rover's slope capability requirement is 20º. The rover's only and primary mission objective is rolling to the entrance of the cave after lander egress. A simple four-wheel enabled system with two bogies on either side is sufficient for serving this purpose.

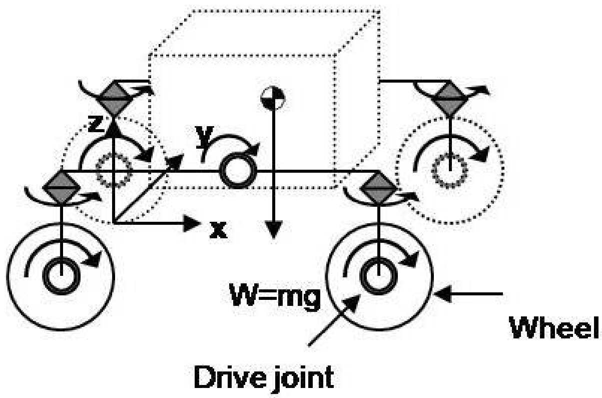

Figure 3: Dynamics model of vehicle

The dynamics model of the four-wheeled system is illustrated in Figure 3. This is a simplified model of the proposed rover that is considered for dynamic analyses. Initially, *Dymola* package that include *Modelica* library of active and passive components is used to develop a multibody vehicle model. It includes passive structural components and active motor controllers. Passive structural components are bogies, wheels, links made of Aluminium. The drive motor modeled for each wheel is a DC motor coupled to a reduction gear stage. Control systems are available for each wheel for driving. The controller implemented in all drive motors is a PI velocity controller cascaded with a PI current controller. Steering joints are also modeled similarly. The steering controller consists of a PD angular position controller cascaded with a PI current controller. Steering maneuvers is not assumed in the simulation, hence steering controller parameters are not considered for the optimization process, although the procedure is the same as in drive controller for optimizing the parameters.

The slope-terrain is modeled as ramp-shaped plane with the desired inclination, θ=20º. The slope conditions are coded into *Dymola/Modelica* runs for the vehicle to understand the motion path during simulation. The rover velocity on slope is 0.037 m/s. Contact equations between the wheels and surface are based on a compliant contact model given by Kraus et al. [22]. A point contact by the wheels with the terrain is assumed for calculation of wheel-terrain interaction forces.

Generic model development of desired vehicle is discussed so far. The next step would be analyzing the performance of vehicle by simulation. Here the states of the rover are found for different time steps. Basically the challenging issues while developing a rover are its ability to handle highly unstructured terrain, traverse with minimum friction requirement, low wheel slippage and power consumption. As in any other space missions, the total rover mass is also an essential factor driving the design process. In general, therefore, the problem can be treated as an optimization problem involving a key set of design criteria and constraints to be satisfied.

There are 12 design variables that define the optimization problem. The design variable vector, **x** consists of vehicle track length, wheel radius, wheel width, length, breadth and width of longitudinal bogies and traverse bogies. To optimize the mobility structure, we consider rover's mobility structural mass M_{rover} as the objective function (Eqn. 1).

$$\text{minimize } J(\mathbf{x}) = M_{rover} \tag{1}$$

There are three constraints imposed on the structure design problem. They are:

Longitudinal static stability angle (β_{long}) — Longitudinal static stability angle metric relates to the tip-over vehicle stability about the center of mass in the longitudinal direction of motion.

Lateral static stability angle (β_{lat}) —Longitudinal static stability angle metric relates to the tip-over vehicle stability about the center of mass in the lateral direction.

Average drive mechanical power (P_{mech}) —The average drive mechanical power is the average power requirement over duration *t*. It is the mean of the summation of the product of the wheel torque and angular velocity of all wheels over *t*. Since large mechanical power requires large electrical power for the drive joint, this metric indirectly constraints the electrical energy requirement for motion.

The above discussed criteria are specified as inequality constraints as shown in Eqns. 2, 3 and 4. Average mechanical power requirement is also specified as inequality constraint, g_3. This is because we indirectly place a constraint on the wheel size. A wheel of larger dimensions requires more torque for a given velocity than a smaller wheel. However a wheel of higher radius can scale larger obstacles.

$$g_1 = -\beta_{long} + 25 \leq 0 \tag{2}$$

$$g_2 = -\beta_{lat} + 30 \leq 0 \quad (3)$$
$$g_3 = -P_{mech} + 0.6 \leq 0 \quad (4)$$

A similar approach is followed for the motor controller design for minimum overshoot. The results from the structural optimization runs are taken for fixing the mechanical design of the rover. The objective here is to minimize the control overshoot, $O_{shootdrive}$. The objective function, $J(\mathbf{x})$ in this case is provided in Eqn. 5.

$$\text{minimize } J(\mathbf{x}) = O_{shootdrive} \quad (5)$$

There are three inequality constraints imposed on the motor controller design problem. The constraints are defined as follows:

Average longitudinal wheel slip (S_{long}) —It is the average slip, *s* by all n wheels in the longitudinal direction of motion (Eqn. 6).

$$S_{long} = \frac{1}{n}\int_0^t \sum_{j \in [1:n]} \left| s_j \right| \quad (6)$$

Drive motor control activity (CDact) —This constraint specifies the drive motor control activity (Eqn. 7).

$$CDact = max_{j \in [1:n]}\left(\left|\dot{u}_j\right|\right) \quad (7)$$

Average drive control error (CDerr) —It is the average of the control error, e suffered by the PI controller of all drive motors.

$$CDerr = \frac{1}{n}\int_0^t \sum_{j \in [1:n]} \left| e_j \right| \quad (8)$$

All three constraints are evaluated during the simulation run for time t. They are specified as in 9, 10 and 11.

$$g_1 = S_{long} - 0.1 \leq 0 \quad (9)$$
$$g_2 = CDact - 0.8 \leq 0 \quad (10)$$
$$g_3 = CDerr - 5 \leq 0 \quad (11)$$

In the final step, a GA search and optimization run is implemented that allows finding optimal solutions for active control and passive structural parameters that basically defines the vehicle. The parameters of mechanical structure and controllers undergo tuning during the optimization process. The optimization criteria consist of a set of constraints for both mechanical structure and controller design. The user has to decide whether the mechanical and controller parameters need to be optimized separately or simultaneously. Here we try to find solutions by considering the mechanical and control optimization problems separately. The equations of motion of the vehicle are understood and evaluated by *Dymola* and a time-response simulation for climbing the given slope is performed. The equations of motion are integrated for a simulation time (t) of 50 s with a step size of 0.001. The states of the vehicle are available for feedback control or constraint evaluation by the GA optimizer. The simulation is performed using dymosim, a command-level *Dymola* interface for MATLAB. With a population size assumed based on trial and error as 25, the design solution is obtained after 50 generations. The obtained result is tabulated in Table 2.

Table 5: Best solution results after 50 generations [GA: tournament selection; simulated binary crossover; elitism enabled]

Parameters	Value
Track length, *m*	1.48
Wheel width, *m*	0.10
Wheel radius, *m*	0.11
Wheel thickness, *m*	0.49
Bogie length, *m*	0.73
Bogie height, *m*	0.03
Bogie width, *m*	0.02
Vertical link length, *m*	0.27
Proportional velocity gain, *As*	2.0
Proportional current gain, VA^{-1}	1.22
Integral velocity factor, A^{-1}	0.01
Integral current factor, $VA^{-1}s^{-1}$	107.4
Rover mass, *kg*	99.4
Drive motor overshoot	5.5e-006

The result is a rover with the mobility structure of mass ~99 kg. The footprint of the rover is 0.73 x 1.48 m. The overall mass of the rover that includes all subsystems and payload is 160 kg.

General discussion on Microbot design requirements

It is assumed that the main rover releases a preallocated number of miniaturized robots (micro-robots) that are designed specially for exploring caves. Though the requirements are stringent, the design space of these robots comprises a few options. One possible solution is the microbot design configuration based on assumptions as suggested by Dubowsky et al. [17], but other options could also comprise the design of small wheeled or tracked rover, legged crawling systems or even non-mobile instrument packages.

The microbots described by Dubowsky are spherically shaped robots. They are self-contained systems that are designed with fuel cells for power generation and miniaturized phased array antenna for communication. Mobility is enabled by hopping, rolling and bouncing. The microbot is built with sensors such as imager, spectrometer, and chemical analyzer. The dimensions of the microbot as designed by Dubowsky are in the order of 10 cm in diameter and 100 g in mass. Dubowsky et al. states that the microbot is designed for exploring mars surface and narrow locations such as caves. They argue that releasing or deploying a large number of microbots would enable in-situ analysis of a vast surface area including caves. The mobility system technology is based on dielectric elastomer actuators powered by H_2/O_2 fuel cells. Since fuel cell is a non-renewable energy source, the lifetime of the robot is limited.

For cave exploration, thermal control of the robot is important. The science payload and other systems should withstand these conditions. This section of the paper would provide an overview of the design challenges for developing a micro-robot or any mobile system for exploring subsurface caves. It brings into view the problems that engineers would need to solve for performing exploration activities inside caves.

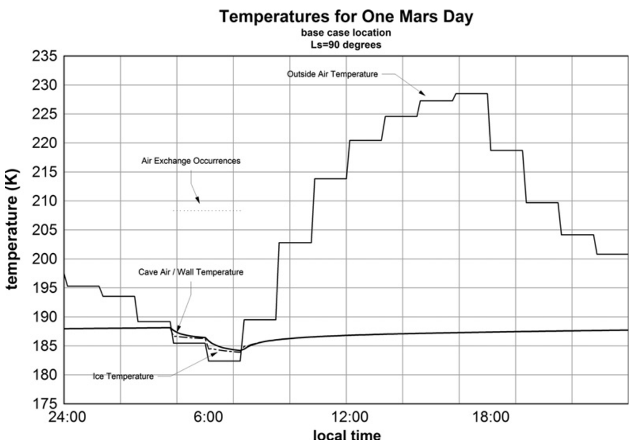

Figure 4: Illustration of diurnal temperature variation of outside air, ice, cave air and cave wall for one mars day [latitude = 0°, longitude = 0°, areocentric longitude = 90°]

First challenge would be the topographical conditions that exist inside and near the vicinity of the caves. The topography of the surface inside caves is thought to be unfriendly and rugged. The area near cave entrances is thought to be rocky and bouldered. Formations such as lave tubes are reported to have surface elevation variations. So generally, the surface would have irregularities with many obstacles, i.e. anything other than a smooth hard surface for effortless locomotion. To make matters worse for conducting science, there would be little or no sunlight reaching the interior of the caves. However, based on experience in terrestrial caves it is known that interesting biosignatures can already be found in the very vicinity of the cave entrance. Therefore it can be implied that a significant mobility performance will enhance the outcome of the cave exploration but is not ultimately required.

For cave exploration, it is very important to understand the physical conditions existing in the interior and exterior of a cave for designing reliable systems. The suitability of systems that are released into caves is based on their ability to withstand cold temperature and survive the harsh conditions. As mentioned by Williams et al. [23], the geometry of the cave dictates a certain circulation pattern between the cave and outside air. If the cave geometry allows an air circulation pattern that favours accumulation of cold air and expelling of warm air, then the cave will function as a “cold trap”. The presence of ice in the cave is perennial as ice is present through out the year with minimal loss during varied local temperature conditions over seasons. The caves are located sub-surface and air flow is maintained through a narrow entrance or chimney. Air exchanges between the cave and outside occurs when the outside air is coldest. This is usually prior to sunrise. During day the air inside the cave, ice and cave walls warm slightly due to surrounding cave wall material. The diurnal temperature variation can be clearly seen in Fig. 4 as illustrated by Williams et al. in his cave temperature variation model for one typical Mars day (areocentric longitude = 90°) at a base case location of 0° latitude by 0° longitude. The temperature inside the caves may reach as low as 183 K. Survival in such cold conditions requires special thermal protection for all systems and science payload. These factors should be considered while designing a micro-robot or any system to be operated inside caves on Mars.

6. CONCLUSIONS

The paper has reported our approach to identifying science requirements and corresponding mission design. Science requirements directly received from scientists in the Alliance helped us to develop mission concepts and perform the system design for elements such as rovers. Not only did the survey help us to develop technology requirements, but also increased our understanding of the scientists’ motives, their tasks and goals on other planetary bodies to answer their various quests in search for water, life, etc. that supports habitability. Subsequently four new missions of interest were concluded to have significant interest for the scientists and carry science benefits. As a start, we have analyzed the various technology options available in order to accomplish the mission objectives. One of the missions, the “Mars Cave Explorer”, which requires a vital robotic element, is chosen here for deeper discussion. After analyzing the mission scenario, an evolutionary approach was followed for conceptual design study of the rover for optimizing mechanical and control design parameters and the results are found to be satisfactory. Future studies will focus on the detailed design of all of the mentioned mission scenarios and the respective elements and subsystems. The output of four thoroughly studied mission concepts by the end of the study period of the Helmholtz Alliance is expected to significantly contribute to the overall success of the same. Furthermore, we will pursue our work on some detailed technological aspects, such as the subsurface penetration of icy material to extend our understanding of the implications of the technology on the system design.

ACKNOWLEDGMENT

The authors highly acknowledge the partial financial support provided by the Helmholtz Alliance within the framework of the project “Planetary Evolution and Life”.

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BIOGRAPHY

Caroline Lange *is a research engineer in space systems engineering at the German Aerospace Center, Institute of Space Systems in Bremen, Germany, where she started working at the Department of Exploration Systems in 2008. Currently she is involved in systems engineering for a small asteroid landing package, called MASCOT, mission concept studies within the Helmholtz Alliance and technology studies for future planetary exploration applications including ground penetrating systems (e.g. moles) and rover technology (e.g. wheels). Caroline has an engineers degree in Aerospace Engineering from the University of Stuttgart and is currently pursuing her doctorate in space systems engineering on the topic of modular, reconfigurable systems for planetary exploration.*

Aravind Seeni *is a research engineer working at the Institute of Robotics and Mechatronics, German Aerospace Center (DLR). His research interests are space systems engineering with applicability to conceptual study phase of missions. He works on computational tools that makes use of evolutionary algorithms for designing robust systems. His main involvement and contributions in the field, so far are in the following projects: Lunar Robotic Payload in cooperation with Kayser-Threde GmbH and Helmholtz Association supported project "Planetary Evolution and Life". He is a 2007 graduate of International Space University, France.*