MOBILITY AND TERRAIN ACCESSIBILITY ANALYSIS FOR HOPTER – AN UNDERACTUATED MOBILE ROBOT FOR PLANETARY EXPLORATION

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ABSTRACT

The article presents critical aspects of the complex mobility and terrain accessibility capabilities of the HOPTER - a novel hopping robot for low gravity planetary exploration. A system architecture comprises of three actuating legs arranged around a disc-shaped main body. The mechanism allows to store up to 50 J in each actuating leg which, given its mass of up to 10kg, should allow for jumps of several meters on Mars or Moon. Its horizontal symmetry makes it ready to jump without the need to reposition from the previous leap. The article provides an overview of the subsystems needed for successful locomotion and a description of the proposed architecture. Simulation and analysis of locomotion and terrain accessibility are focused on a single jump as well as in case of more elaborate situations, where more subsequent jumps are required. Aspects like jumping efficiency, system optimization, performance analysis are outlined in this article.

1. INTRODUCTION AND STATE-OF-THE-ART

The interest in planetary surface exploration is not stopping. New players are joining attempts to take part in space exploration and discover new worlds. This challenge requires novel forms of locomotion that would be capable of traversing not only on flat terrain (i.e. landers, rovers) but also more sophisticated environments, e.g.: undulated terrain or reduced gravity. Among available various forms of locomotion (divided into five applicable classes, i.e. wheels, tracks, legs, body articulation and non-contact locomotion [1]), hopping (the non-contact locomotion class) is one of the most efficient and universal way of mobility. This can be justified by a fact that hopping allows to manoeuvre over obstacles that are much larger than the robot itself, traction with the ground is not that important, and especially plays less important role with the decrease of gravity and is hardly dependent on atmospheric pressure (e.g. could be adopted to exploration of celestial bodies with and without atmosphere).

Currently there are several known or proposed solutions of hopping systems for space exploration. In most cases they are proposed for microgravity environments where could be used as a scout robot to reconnaissance surface of the celestial body. Among already implemented space flight systems we can list: PROP-F hopper for Russian Phobos-2 mission [2], MINERVA for Japanese Hayabusa mission [3], DLR's MASCOT for Hayabusa-2 mission [4] or Philae lander for ESA's Rosetta mission which essentially performed spectacular uncontrolled jumps on a surface of a comet [5]. Among prototyped and tested systems are, e.g. Hedgehog (JPL/Stanford) [6] or POGO (John Hopkins Univ.) [7]. All of those systems are focused on implementation to microgravity conditions (NEO, asteroids, comets, Phobos or other small moons).

There are several known concepts for higher gravity, e.g. Mars Reconnaissance Lander [8] or Hopper with SMA Actuator [9], but those platforms are relatively large or with limited controllability.

In contrary to those designs, we came up with an idea of HOPTER (Fig. 1) - a hopping robot for reduced gravity (including Mars or Moon), that would remain robust and energetic, could play a role of a scout robot for a larger rover or a lander, while being agile and well controllable.

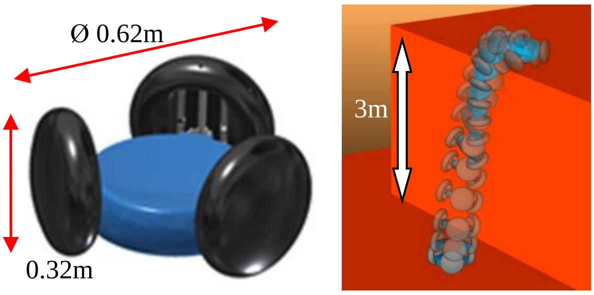

Figure 1. HOPTER visualization and its hopping sequence simulated in MSC.Adams (here jumping on a 3-meter cliff in Martian gravity is shown)

HOPTER's design and working principles differ from the known solutions. Analysis of scientific instrumentation for that robot was presented in [10]. In this article we focus on analysis of HOPTER's locomotion aspects, both from a perspective of a single jump as well as in case of more elaborate situations, where more subsequent jumps are required.

2. REQUIREMENTS AND MISSION SCENARIO

For the purpose of this article a case of Mars exploration mission is studied. Our scenario considers HOPTER as a scout robot to support operations of a mother lander or a rover and that could perform few kilometres traverse in terrain normally considered as a high-risk (e.g. crater, canyon). HOPTER would be capable of coming back to the lander/rover after accomplishment of reconnaissance and measurement sequence and stay available to assist the mission in further exploration.

Fulfilling such scenario would meet the general need for delivering scientific instrumentation to the areas normally not accessible for rovers. Secondly, the scout capabilities would significantly lower the mission risk of exploring undulated terrains. Worth mentioning is that due to lack of shear force with the surface this system should not have problems like complete stuck in loose material (i.e. compared to rovers). Finally, consideration of HOPTER in Martian case is convenient since, once solved for that gravity, the design could be utilized in lower- or microgravity cases. As a result it can provide significant advantage in terms of expected mission results and risk mitigation, and still constitutes small change in overall mass of power budget of the mission.

The main objectives and guidelines for the HOPTER development would therefore include: 1) system for higher gravity (Mars) to easily scale down to other gravities, 2) capability of operation in general unknown environment, considering dust protection, high vacuum, radiation and extreme temperatures, 3) development of light and low power device, that have significant efficiency allowing for high performance operation regardless environment.

This constraints the requirements for such platform to following: · the mobility platform shall take advantage of hopping principle (excluding problems with atmosphere presence or anchoring in unknown surface hardness); • shall be as light as 10 kg (first assumption); • shall operate also in Earth gravity (for the ease of experimentation designed for nominal jump of 1.5m vertically on Earth); • shall possess capacity for at least 3 scientific instruments; • shall have internal source of power allowing for 1000 jumps without a recharge (which would result in few kilometers of independent operation); • shall have compact envelope (here preliminarily assumed as 0.32 (H) x 0.62 (D) m); • shall possess high efficiency of robot-surface interaction (i.e. providing high enough impulse force to push it away from the surface, possessing relatively large contact area with the ground that would increase the surface pressure); • shall be controllable in 3D space (particularly giving possibility to choose direction of jump), have capability of traversing over objects higher than itself, stay effective in operation on various types of terrain, have capability of operation on a inclined terrain (e.g. by keeping low position of centre of the mass); • shall possess, or have potential to implement, various levels of autonomy (i.e. power autonomy, self-localization and decision making).

HOPTER is a system that is designed to meet that requirements. Its basic mobility features are shown in Fig. 2.

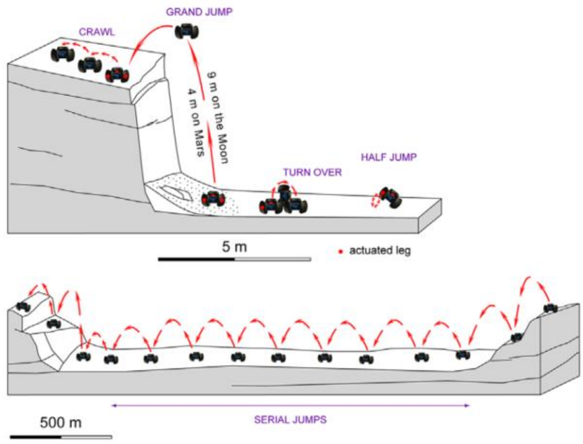

Figure 2. HOPTER's basic displacement strategies [10]

3. SYSTEM OVERVIEW

A locomotion system architecture comprises of three actuating legs evenly arranged around a disc-shaped main body. The mechanism allows to store up to 50J in each actuating leg, which, given platform mass of up to 10kg, should allow for jumps of almost 4m vertically on Mars, almost 9m on the Moon, and even much higher on small bodies under microgravity. Its horizontal symmetry makes it ready to jump without the need to reposition from the previous leap. The proposed system is shown in Fig. 3 in more details.

The actuation is in some sense similar to the implemented in mechanical mole type penetrators, developed by our group (e.g. Hammering Mechanism for HP3 instrument [11] or mole penetrator KRET [12]), where energy is slowly stored in drive springs (hence having significantly low power consumption - fraction of 1 W) and then rapidly released, creating high impulse force. As shown in Fig. 3, the actuating legs are off-centered which together with capability of storing different level of energy in individual leg, can generate and impulse force on the main platform directing it as desired in 3D space.

For the current design, energy is accumulated in set of springs which are compressed by a mean of DC motor motion through a ball screw system. The actuating legs are guided with respect to the main platform via rollers on a rails. While compressing the springs, the platform lowers itself and reaches the armed position. Release of the springs from the ball screw system is executed by an electromagnetic latch actuated accordingly on all of three actuating legs. The base platform is rapidly accelerated by the drive springs through pulling a tether connected on the other end to a rail of each actuating leg.

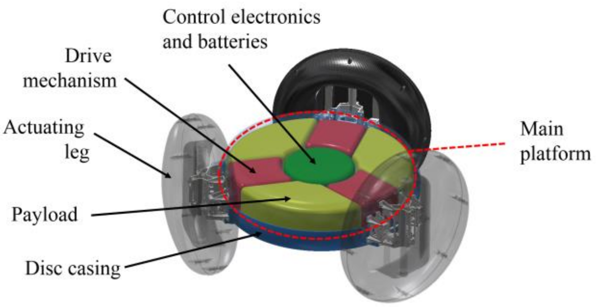

Figure 3. Design visualization of HOPTER, top of the cover and two front legs are semi-transparent to show interior arrangement

Drive mechanism is placed behind each leg. Central location is designated for control electronics and batteries. It is assumed that 12V/7Ah batteries could be used, which (assuming 50% of power transmission efficiency) would be enough to perform 1000 jumps on one charge. The volume inside the structure between actuating legs is assigned for scientific payload, which is expected to occupy approximately 20% of the mass budget of HOPTER.

At this stage of HOPTER development, subsystems like HOPTER to mother rover/lander communication are not considered.

4. SINGLE JUMP ANALYSIS

In order to be ready to operate regardless the side on which HOPTER lands, the main platform can lower with respect to the actuating legs by 55mm either way from the central (nominal) position (Fig. 4). After release of the drive springs platform is accelerated with respect to the actuating legs. The actuating legs are pressed against surface and the released energy is converted into kinetic energy of the main platform.

Figure 4. Left: nominal position of main platform to actuating legs. Right: armed configuration (all actuating legs equally loaded)

4.1. Jump efficiency

A 3D simulation model was developed using MSC.Adams software in order to analyse jump dynamics and preliminarily optimize system performance. A single jump is analysed in terms of the system efficiency with given mass distribution of the actuating legs to the main platform. In this case straight vertical jump was analysed, with HOPTER resting on a solid surface and height of a jump (indicator of an effective maximum potential energy achieved) was compared to the actual energy accumulated in the drive springs. The results are shown in Fig. 5. It can be seen that the efficiency of jump (percentage of achieved potential energy to accumulated in drive springs energy) depends nonlinearly on the ratio of the actuating legs mass to the mass of the main platform. Mass ratios greater than about 1:10 result in significant and rapid decrease of jump efficiency, therefore the actuating legs are desired to be as light as possible.

The system designed as outlined in Section 3 has mass of single actuating leg of about 0.6kg, which results in mass ratio of 1.8 : 10 and expected maximum jump efficiency of 81% on a solid surface.

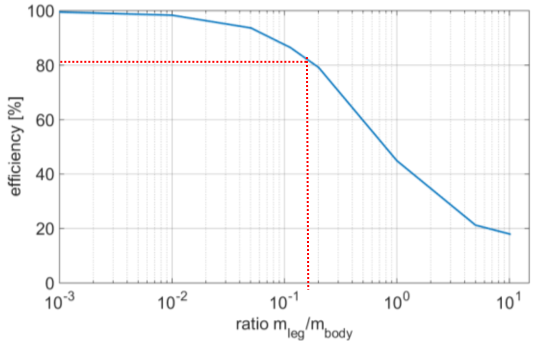

Figure 5. Simulated jumping efficiency as a function of mass ratio between actuating legs to main platform. Red dotted lines point current design characteristics

Interestingly, the actual performance of the HOPTER could be greater (in terms of height of jump), if we consider that mass of the actuating legs is fixed by design (0.6kg) and mass of the main platform is lowered. Given the presented in Fig. 5 efficiency relation of the mass ratio between actuating legs and main platform, we can calculate to which height HOPTER would jump on Mars if we could tune the mass of the main platform.

Apparently, as shown in Fig. 6, the product of system efficiency and height of the jump reaches maximum value for ratio of about 1:1 (mass of three legs to mass of main platform), even higher than for optimal efficiency mass ratio. The assumption is made that total accumulated energy remains constant for all cases (150 J). This is not necessarily realistic, since payload or other subsystems would need to be descoped in order to have adequately low system mass, nevertheless it is shown that the system can be more effective while being less efficient. Additionally it is better to keep lower mass of main platform than higher, despite the decrease of efficiency.

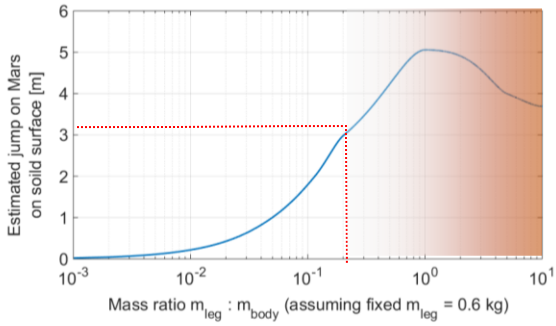

Figure 6. Expected height of jump as a function of mass ratio mass of actuating legs to main platform. Results for Martian gravity case on solid surface, assuming constant overall mass of actuating legs (1.8 kg = 3 x 0.6kg) and constant accumulated energy (150 J). Red dotted lines point current design characteristics. Shaded area indicates technically unrealistic design

4.2. Jump trajectories and lift-off angle

Different hopping trajectories are determined by releasing various levels of energy in individual actuating legs. This constraints potential performance, in a sense that horizontal jumps are from design less energetic than vertical ones. Projections of simulated hopping trajectories on a single plane for different total energy accumulated in drive springs are presented in Fig 7. Simulation results consider hopping on a solid and flat surface in Martian gravity. Configuration of actuating legs energies are provided in Tab. 1. From the plot in Fig. 7 could be seen that for about 150J of stored energy HOPTER could jump up to 3.2 m vertically. Maximum horizontal jump distance was achieved for cases with accumulated energy of 98-106 J reached is about 2.6 - 2.8 m (with maximum vertical elevation in range of 1.6 – 2.1 m).

Table 1. Configuration of drive springs loading cases for trajectories from Fig. 7

Ref. No.	**percent of maximum energy on individual leg [%]**			**Total energy in all legs [J]**
	1st leg	**2nd leg**	**3rd leg**	
# 1	25	0	0	12
# 2	50	0	0	25
# 3	98	0	0	49
# 4	11	11	0	11
# 5	98	11	0	55
# 6	98	32	0	65
# 7	98	50	0	74
# 8	98	98	0	98
# 9	98	98	15	106
# 10	98	98	36	116
# 11	98	98	50	123
# 12	98	98	88	142

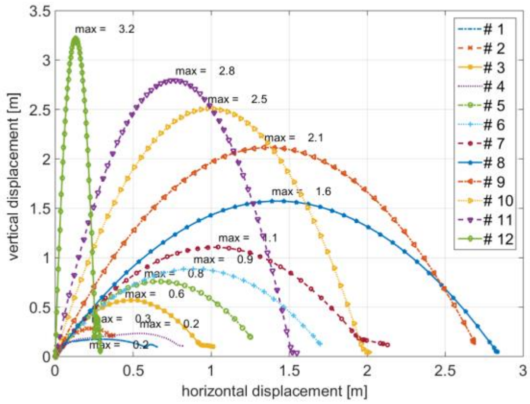

Figure 7. Simulated HOPTER jump trajectories in Martian gravity (assumed overall mass 10 kg and mass ratio of actuating legs to main platform 1:9). Plot numbers refer to data in Tab. 1

For realization of different trajectories an initial hopping angle can be obtained in any direction, varying from c.a. 65° to 90° (purely vertical jump with all equal energies released from actuating legs). Lower lift-off angle is possible when turning over mobility techniques are applied, which would potentially allow for slopes traversing. The idealized (assuming no slippage) sequence of turning-overs is shown in figure below – the ultimate angle at which HOPTER would remain stable on a slope is about 41° (for higher angles CM would be out of the statically stable configuration).

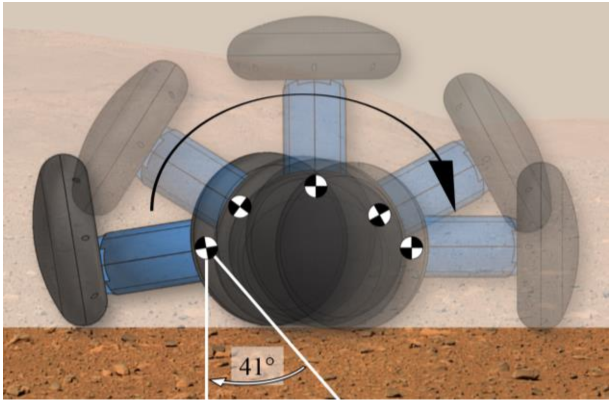

Figure 8. Turning over technique with indicated position of CM and maximum slope angle constraint

5. ACCESSIBILITY OF GEOLOGICAL SITES

As part of idea validation and system feasibility verification the analysis of platform capabilities in terms of surface locomotion and navigation was performed. This analysis is useful to build confidence about system, check validity of proposed locomotion solution and compare it in different configurations and environment conditions.

Mars environment is considered as most challenging in terms of accessibility due to the highest gravitational acceleration among bodies considered in the project.

Additionally for Mars case, high resolution surface data and rover mobility reference is available.

For the initial evaluation of platform mobility the static case is presented. In the 'static' evaluation number of modelled aspects is limited. The main interest is put on evaluation of reachability of cells in neighbourhood of take-off point and check of static stability in target cell. Due to the fact that platform dimensions are similar to available Martian surface data cell size, it is assumed that robot position is quantised to grid cell coordinates. Reachability analysis is based on projectile motion equations with constant gravitational acceleration (Martian for presented results) and set of platform related parameters is obtained from design assumptions and initial modelling analysis presented in previous sections of this paper. Robot related parameters set, that can be varied for evaluation, includes factors like: mass of the robot, energy dissipation factor, maximum jump energy, maximum lift-off angle, maximum drop height etc.

Only single, simple jump is used in this analysis, however, it is assumed that in general the platform is capable of many different actuation primitives from adjustment moves and flip-overs to complex state and time based jump sequences. Static stability is concluded based on comparison of local slope angle and maximum static stability angle parameter (value of 30° was set as more conservative over maximum 41° concluded during design analysis).

Surface contact dynamics is modelled only by non-directional, constant jump energy efficiency factor. In current simulation no influence of atmosphere (e.g. drag) is modelled. Platform is considered as point mass during flight and post landing tumbling behaviour is omitted. All these aspects are subject of ongoing development.

As an input data for the analysis we use stereo-pair of images in visual spectra obtained by HiRISE instrument working on Mars Reconnaissance Orbiter [13]. For presented here example PSP_009341_1715[1] data set was chosen as a scientifically interesting, while hardly accessible for traditional rover platform. Additionally, due to its geological history this area is an example of high accuracy, robust vertical resolution comparing to other. Based on input images Digital Elevation Model was computed and scientifically interesting places were identified. Due to limited computational resources only segments of this DEM were used for the study. In this paper results are presented for one segment which could be found under following coordinates: 65d43'12.19"W, 8d33'21.20"S (upper left corner) and 2243x2200 pixel size with ~0.5m horizontal and ~1m vertical resolution.

[1] *Contact between Wallrock and Light-Toned Layering in East Candor Chasma*: http://hirise.lpl.arizona.edu/PSP_009341_1715 credit: NASA/JPL/University of Arizona

The image with colour encoded elevation and outlined slopes is presented in Fig. 9. For used DEM following statistics describe value of elevation: min: 2257m, max: 2884m, mean: 2504.718 and stdDev: 155.274. In Fig. 10 histogram of calculated slope angle is presented.

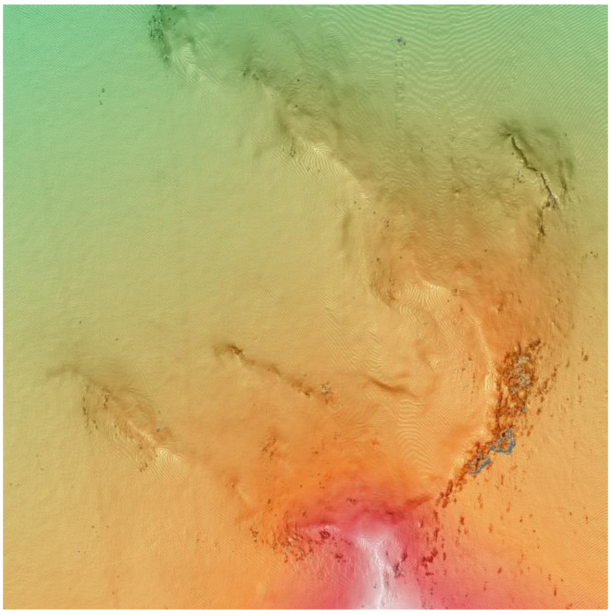

Figure 9. Input height map with outlined slopes (minimum elevation 2257m (green), maximum 2884m (red-white), slope shading is not representing local elevation change)

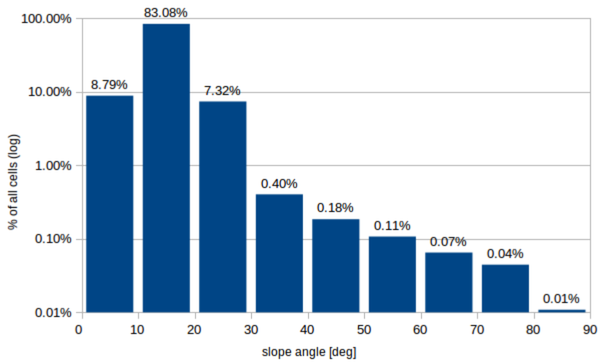

Figure 10. Histogram of slope angles calculated based on input DEM

Preprocessing of input DEM includes interpolation over cells with 'No Data' and computations to obtain local slope inclination. For DEM import and corrections gdal library tools are used[2]. Additionally elevation data is smoothed to compensate discontinuities due to vertical resolution. Based on preprocessed DEM normal-to-surface vectors, slope angles and elevation gradients are calculated.

Main part of the evaluation script is based on floodfill algorithm. In this algorithm, all possible transitions for current cell are identified and checked against modelled

[2] *www.gdal.org*

phenomena and algorithm is repeated for each reachable cell leaving transition evaluation data as a result. Additionally some optimisations are done to prevent algorithm from evaluating cells that are outside feasible range or checking transition again when not necessary. In presented work evaluation steps include: generation of feasible pair of initial lift-off velocity and its direction, check if this valid pair exists and if realisation of obtained solution is possible considering local terrain conditions. Generation of lift-off velocity parameters is based on distance from current to the goal cell, change in elevation between them, local inclination in desired jump direction and maximum take-off velocity and optimal angle limitations. Possibility to realize trajectory is checked by examining height of trajectory over terrain elevation and relative difference in elevation between start and goal point to assure that robot is not dropped from height greater than 3 times maximum jump height.

Most important output of presented evaluation is Accessibility Map (AM) which contains final evaluation status in each cell. For this study set of possible states includes:

- cell *'suitable'* - all checks ok
- *err_drop* - elevation difference too big to land safely
- *err_range* - take-off velocity not found due to distance, elevation difference
- *err_inclination* - take-off velocity not found due to too high platform inclination
- *err_stability* - static stability condition not met in goal cell
- *err_reachability* - cell not reachable from any stable position

For each cell of AM history of transitions during evaluation process is available which allows to debug and optimise solution as well as understand sensitivity drivers.

Accessibility Map for configuration discussed above is presented in Fig.11. Additionally AM content is presented in form of histogram in the Fig. 12. For this case more than 99% of cells is observable (could be observed e.g. by camera or other navigation sensors on board robot) from platform range distance of few meters. Presented AM image show that problematic cells (all different than reachable) are not clustered in big groups what suggests that are not representing uniform slope and spot big enough for platform landing ellipse can be found. Additionally most of the terrain is accessible or observable by approaching it from different directions. It is worth to remember that proposed platform design assume capability of tumbling motion and drop from significant height (~11m for Mars). For many places where platform is statistically not capable of landing in place, transition could be still considered with higher localization uncertainty measures. This could be true due to the fact that stable position can be supported by smaller scale local terrain roughness.

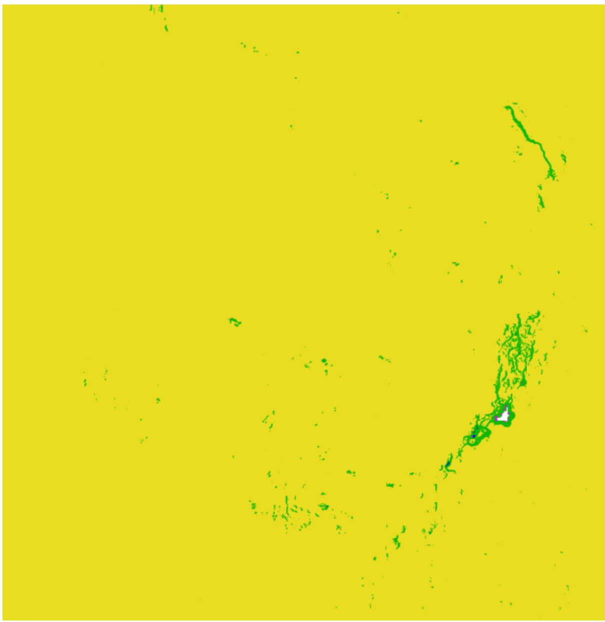

Figure 11. Output Accessibility Map (legend: 'suitable' - yellow; 'err_stability'- green; 'err_reachability' - white; 'err_range' - blue; 'err_drop' - violet; 'err_inclination' - red)

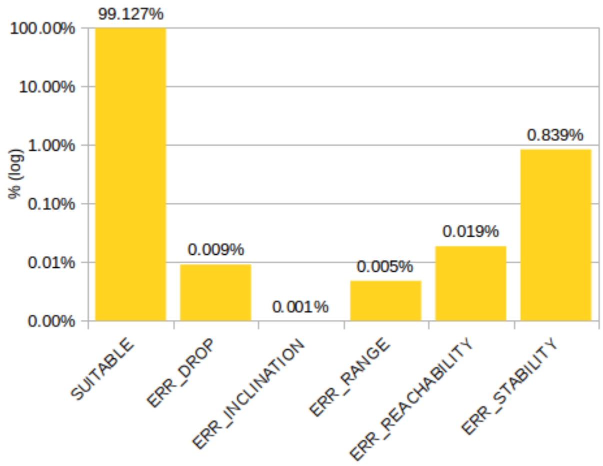

Figure 12. Accessibility Map histogram

From input data point of view significant impact on analysis has vertical resolution of DEM and quality of processing used for inclination estimation. Despite the fact that, input data was chosen considering its vertical accuracy, influence of DEM resolution could be observed in intermediate products (e.g. slope angle estimation). Local statistical analysis proved that in most cases this issue is not degrading evaluation results also due to the fact that system by design is capable to deal with terrain discontinuities. However, for development of more detailed aspects additional modelling need to be proposed.

Presented results are optimized for achieving maximum trajectory clearance and platform reachability by calculation lift-off angle that maximizes jump height. This approach is also the safest one in terms of robot-surface interaction because lateral forces during lift-off and landing are minimised. Developed software has wider scope and can be used for different optimization criteria e.g. to minimize energy, traverse time, uncertainties for take-off and landing, overall mission range etc.

6. CONCLUSION AND FURTHER WORK

The obtained research results show that HOPTER robot is a promising concept of mobility system for reduced gravity. Considered design of the system, including lightweight structure of actuating legs (here 0.6kg of individual legs) and about 10kg or overall mass can provide 80% of jump effectiveness. Performed simulations on the proposed design confirm effective performance in Martian gravity potentially allowing for jumps of about 3.2m high or up to 2.8m in range on solid surface. The limitations of the robot were identified, namely lift-off angle range is limited to about 40°. This is also a ultimate slope angle above which HOPTER becomes statically not-stable. Nevertheless, for such cases (i.e. slope grades of close to 45° or higher) different type of locomotion are likely to be considered, e.g. anchoring, climbing or tethered robots. As for a future study, it is planned to include different regolith characteristics as it is expected to have significant influence on jumping performance and design of the actuating legs.

In regards to the large scale terrain accessibility analysis, even though rough evaluation of planetary data was performed, it is a good exercise to understand challenges and opportunities for the proposed system. Presented results indicate level of usefulness of currently available data and highlight needs for further modelling of terrain (e.g. more robust slope modelling, roughness model, surface contact model) and system itself (e.g. surface contact dynamics). However, many inputs for next iteration of design (mass distribution, power estimation and efficiency), navigation subsystem (necessary sensor ranges, surface representation around the robot, kind of uncertainties to be considered for motion planning etc.) and mission concept (ranges in non-uniform terrain, mission lifetime impacting other subsystems etc.) were identified. Finally exercise was useful to initiate discussion and build common understanding of the system between engineers and scientists.

7. ACKNOWLEDGEMENTS

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