Action Planner of Hybrid Leg-Wheel Robots for Lunar and Planetary Exploration

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Abstract— **In this paper, we propose an action planning algorithm and its evaluation method based on dynamic simulation for a novel type of hybrid leg-wheel rover for planetary exploration. Hybrid leg-wheel robots are recently receiving a growing interest from the space community to explore planets, since they offer an appropriate solution to gain improved speed and mobility on unstructured terrain. However, in order to fully reach the hybrid mechanism's potential, it is necessary to establish an optimal way to define when to use one over the other locomotion mode, depending on the soil conditions and topology. Even though this step is crucial, little attention has been devoted to this topic by the robotic community. The switching of motion mode, that is either wheel or leg are the actions to be planned, that we are considering in this paper. We aim at generating the safest and the least energy demanding path to reach a point of scientific interest. In order to define the optimal path with the set of switching actions required for the robot to follow it, the authors developed an action planning algorithm and a path evaluation method based on a four steps approach. First, an optimal candidate path on a rough terrain is generated based on topology and specifications' criteria functions. Then switching actions are defined along this path depending on the hybrid robot's performances in each motion mode. The next step is a dynamic simulation of the robot controlled to follow the path. Finally, the path is evaluated based on the energy profile spent by the actuators and calculated by the simulation. Demonstrations for the proposed technique are addressed along with a discussion on characteristics of the candidate path and the energy profile of the robot.**

I. INTRODUCTION

Planetary exploration to collect scientific data in order to increase our knowledge of the universe or prior to an establishment, requires efficient robot's surface mobility. Whereas the most commonly used technology to move on the surface of a planet is using wheeled mobile robots (rovers), the Space Exploration community is considering alternative technology to improve the mobility of the robots. An appropriate solution is to consider legged mechanisms like [1] but as walking is a very energy consuming locomotion mode, it is not appropriate for exploration. The ideal is then to use hybrid wheel-leg mechanism like [2]. In this case the robot is driving on smooth terrain, and walking when the soil conditions require it. However, in order to fully reach the hybrid mechanism's potential, it is necessary to establish an optimal mean to define when to use one or the other locomotion mode, depending on the soil conditions and topology. A great number of papers and books regarding path/motion planning issues, specific for leg robots [2] or mobile robots in general [3]-[5] has been addressed. Despite such intensive research, little attention has been devoted to define an optimal path considering the switch of locomotion mode for hybrid mechanisms. Whereas in this paper, we are focusing on LEON, a novel type of hybrid wheel-limbs robot, the proposed method applies to any hybrid wheel-leg robot.

A mission of ice water prospection in the Moon's craters is a possible target application for this work. As the craters of the Moon's poles are constantly in the dark, if the robot is not having any umbilical link to a solar power station on the rim of the crater, i. e. no way to charge batteries, planning the motion of the robot optimizing the energy cost is critical. The proposed planner aims to provide the optimal path considering the energy consumption between a starting point until the next point of scientific interest (POSI). The planner also defines in which motion mode the robot should be moving, and where to trigger the action of switching motion mode depending of the soil conditions. The full action planning process is reiterated after the POSI has been approached, scientific data collected and the new POSI defined by the scientific team on earth. Our approach is based on our previous work in [6] and consists in the four following points: 1) the path planning to derive potential candidate path, 2) the action planner to define which motion mode the robot should be and where to switch from one to the other, 3) the dynamic simulation in which a virtual robot is controlled to follow the candidate path in the appropriate motion mode, and 4) the path evaluation based on the dynamic simulation results.

In Section II, we describe the features of LEON, the novel hybrid wheel-limbs robot and a mission scenario. Section III describes an outline of the proposed technique for the action planning and path evaluation. Section IV describes the action planning algorithm and its criteria. The dynamic simulator, the simulation models, and their path following strategies are detailed in Section V. Finally Section VI is a case study, where a generated elevation map is used to generate and simulate two optimal paths obtained with different criteria.

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II. A NOVEL HYBRID HEXAPOD FOR LUNAR ICE WATER PROSPECTION AND EXPLORATION

After briefly describing a potential mission as an application of this work, we will focus on the description of the novel hybrid hexapod we are currently developing:

the Lunar Exploration Omni directional Netbot (LEON) [7] whose particularity is the ability to fold two of its limbs to transform them into wheels.

A. THE PROPOSED MISSION DESCRIPTION

The proposed mission we are considering for LEON, concerns the exploration of the Moon's pole craters seeking lunar water ice in permanently shaded areas. A lander where the robot is located, gets an elevation map of the crater to explore, by scanning it with a laser range finder during the descent phase, and is spotting some points of scientific interests (where signs of water are) with a spectrometer. The lander moons on the rim or inside the crater, the robot is deployed, and the prospection starts.

B. The Lunar Exploration Omnidirectional Netbot design

On lunar surface a mobile robot is expected to move either on deformable soft sandy terrain or uneven firm rocky terrain. Thus a suitable design for the locomotion mechanism is critical. Legged robots are known to be efficient on uneven rocky terrain, but they are energy consuming and have a relatively slow motion. On the other hand, wheeled robots are faster and less energy consuming, but need to be moving on a smoother terrain. Mobility on loose deformable soil is still extensively investigated for planetary exploration. In order to overcome these drawbacks preserving the advantages of both locomotion systems, hybrid robots represent a proper solution on highly challenging terrain as expected in the pole's lunar craters.

Previous research on hybrid leg-wheel system proposed solutions either with small wheels at the end of the legs [8], or owning both locomotion systems using them simultaneously (or alternatively) [9]. However neither of those approaches are well suited to lunar exploration. End tips wheels are usually reduced in size in order to assure a precise contact of the leg on the ground or have a retraction ability, but they prevent the mobility on soft terrain. On the other hand, keeping both independent mechanisms, leads to actuators redundancy and bulkiness. NASA's Athlete [2] is using wheels at the end of each of its six legs but the robot size is big enough to allow wheels with an appropriate diameter to deal with the soil. In contrast to these approaches,

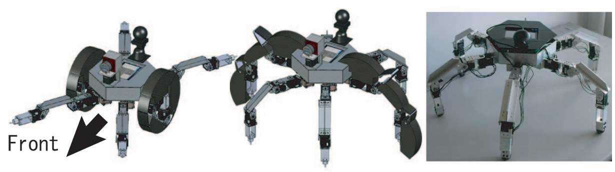


Fig. 1. CAD models of LEON and current implementation

we propose the LEON's novel design. LEON is a hexapod that can fold two of its limbs to transform them into wheels. In that way, LEON turns into a large wheeled robot as seen in Fig. 1. Its 3D structure is formed by a central body, with a hexagonal shape and six limbs, symmetrically distributed around the body. This allows a near omni directional motion on uneven soil and a grasping of the surface. The legs equipped with the necessary tools, can be used as well for simple manipulations in cooperation with other similar robots, for sampling returns, sensor positioning, and surface processing like digging, scratching, or piercing the soil even when in two wheeled mode.

Our novel type of hybrid wheel-leg robot needs to be able to switch from one configuration to the other by changing the two lateral legs into wheels and vice-versa. In order to do so, the two front and the two back legs are used to lift the body high enough so that the two lateral legs can fold in a combined motion to turn into wheels. Once this sequence is done, the supporting legs lower the body to let the wheels in contact with the ground. Then, the robot can be used as a differential wheels rover. The same procedure is done when switching from wheel to leg locomotion mode.

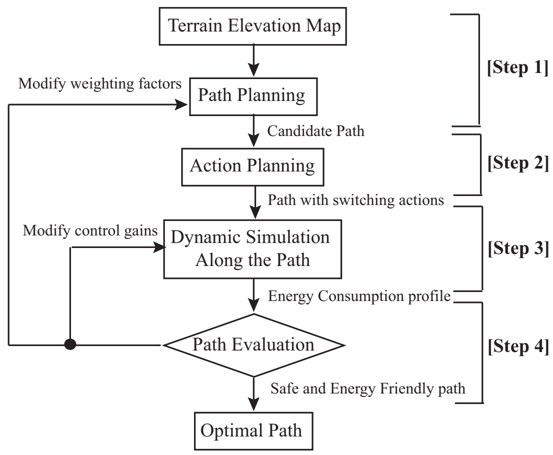


Fig. 2. Flow chart of the path planning algorithm and evaluation method

III. OUTLINES OF THE ACTION PLANNING AND EVALUATION METHOD

In order to define when a switching of motion mode should occur along an optimal path, we define the following action planner algorithm. The action planning and the evaluation process of the proposed technique is described in the flow chart on Fig. 2. As mentioned in section I, our approach is following four steps.

In the first step, after inputing a Digital Elevation Map (DEM) into the planner algorithm, the path planning problem is addressed as an extended version of a search of the minimal path. Then, a candidate path is obtain, giving the inputed DEM, using the Djikstra's algorithm [5].

In the second step, the algorithm reads the candidate path and checks for the switching conditions along it. When in wheel mode, the action planner is seeking for a soil condition requiring a leg mode motion, and when in leg mode, the planner follows several rules described in the next section to avoid getting back in wheel mode too often and to verify that the switching condition is possible.

The third step is the dynamic simulation carried out to define the energy consumption profile. The virtual robot is controlled to follow the generated path file upgraded with the set of actions to be taken. The simulator switches wheel and leg model and control them accordingly to the script defined in the previous step. The dynamic model of the robot in wheel mode and in leg mode will be discuss in section V. Here it is possible to discuss the path-following error as the robot might not follow accurately the candidate path and as the real time simulator ERode provides a visual rendering of the robot's trajectory on the challenging terrain.

In the fourth step, the candidate path is evaluated based on the result of the dynamic simulation. The evaluation criteria are the total energy consumption of the robot to reach the final destination, the accuracy to follow the path, and elapsed time/total travel distance from the initial point to the target destination.

IV. ACTION PLANNING ALGORITHM

Here we describe the criteria function to generate the path and the switching actions. It is assumed that we have a perfect, i.e. without uncertainties, knowledge of the terrain map. The terrain map is represented by a DEM, which is defined as a series of elevations at a grid's node n_i in (x_i, y_i, z_i), where i is the index of the node. This DEM-based terrain map can be measured by a Laser Range Finder (LRF) or a stereo camera system mounted on the robot. For our mission, due to the light conditions, a LRF mounted on the lander seems to be an appropriate solution.

A. Criteria Indexes

The objective function to find a candidate path is composed of three criteria indexes: terrain roughness, path length and inclination.

1) Terrain roughness index: The terrain roughness index aims to define a traversability over uneven terrain. The planner avoids to define the path over too rough zone that the robot would not be able to overcome even in leg mode. The terrain roughness index B_i is given as a standard deviation of the terrain elevation over a projection region of the robot R_i [4]:

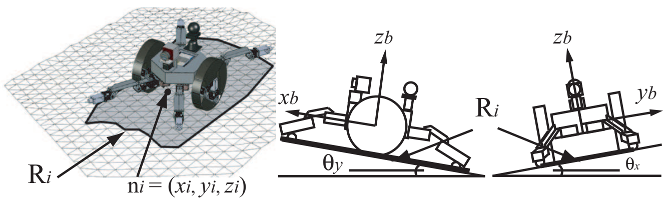


Fig. 3. Projection region on the terrain and inclination angles of LEON in wheel mode

$$B_i = \sqrt{\frac{1}{n}\sum_{R_i}(z(R_i) - \bar{z}(R_i))^2} \quad (1)$$

As shown in Fig. 3, the projection region R_i includes the set of terrain elevation points inside the region surrounded by the end tips of the legs spreads, in wheel motion mode. This projected area is wide enough to allow a transformation of locomotion mode. In equation 1, n represents the number of node inside the region and $\bar{Z}(R_i)$ denotes an average elevation in R_i. The rougher the terrain is, the larger R_i becomes.

2) Path length index: This index aims to define the shortest path from an initial point to a destination. The path length index L_i between adjacent nodes is calculated by:

$$L_i = |n_i - n_j| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \quad (2)$$

If the nodes n_i are not adjacent to the nodes n_i, L_i gets a large value.

3) Terrain inclination index: When the robot is climbing up a hill or traverse a slop of a crater, risks of slippage or tipping over increase. The index of terrain inclination aims to mitigate such risks. The terrain inclination angles are divided into two axis related to the robot body coordinates described in Fig. 3. An inclination angle around x-axis of the robot coordinates is denoted by θ_x, while one on the y-axis is θ_y. The indexes Θ_{xi} and Θ_{yi}, associated with each terrain inclination are respectively determined by the average inclination at the region R_i:

$$\Theta_{xi} = \bar{\theta}_x(R_i) \quad (3)$$

$$\Theta_{yi} = \bar{\theta}_y(R_i) \quad (4)$$

B. Objective Function for the Candidate Path

The above criteria indexes are weighted in order to define the $C(\mathbf{p})$ economical function to minimize, that generates a candidate path $\mathbf{p}$.

$$C(\mathbf{p}) = \sum_{i=\mathbf{p}}(W_B N_B B_i + W_L N_L L_i + W_{\theta_x} N_{\theta_x} \Theta_{xi} + W_{\theta_y} N_{\theta_y} \Theta_{yi}) \quad (5)$$

where, W_B, W_L, W_{θ_x} and W_{θ_y} are the weighting factors to give specific priorities between the terrain roughness, path length, and terrain inclinations. Note that W_{θ_x} or W_{θ_y} respectively take large enough values when the index Θ_{xi} or Θ_{yi} exceed threshold angles $\theta_{x_{max}}$ and $\theta_{y_{max}}$. N_B, N_L, N_{θ_x} and N_{θ_y} are constants to normalize each corresponding indexes and eliminate the dimensions. The path $\mathbf{p}$ consists of a series of neighboring nodes, $\mathbf{p} = \{\mathbf{n_{start}}, ..., \mathbf{n_i}, ..., \mathbf{n_{goal}}\}$.

A small index means that the robot is less affected by the criteria. For example the smaller W_B is, the less the planner will try to avoid rocks and boulders. Therefore the smallest the sum of the weighted indexes is, the optimal, as less hazardous the path is, and supposing that the objective function is a hypothetical distance function, the path planning problem is considered as a shortest path search. And considering that the minimum objective function derives the "shortest" path $\mathbf{p_s}$, the following equation can be defined:

$$minC(\mathbf{p}) = \mathbf{C}(\mathbf{p_s}) \quad (6)$$

We are using a Dijkstra algorithm [5] to derive $\mathbf{p_S}$.

C. Switching Condition Indexes

The default configuration for the robot is the wheel mode, as it is the one consuming the less energy and as the robot starts its mission from the lander in this configuration. The action planner will try to keep the wheel mode as much as possible along the candidate path, but will immediately plan a switch to leg mode as soon as the terrain is too rough for the wheels. Then it will try to get back to the wheel mode but in a very secure way, based on three criteria: terrain roughness, continuity, and safe switching space. The robot will not plan any switch back to wheel mode unless the three criteria are fulfill at the same node.

1) Terrain roughness criteria μ: The action planner is seeking along the candidate path, the soil conditions at each node of the trajectory using equ. (1). When the roughness condition is too high, the robot needs to keep or switch into leg motion: $\forall B_i, i \in \mathbf{P} = \{\mathbf{1}, ..., \mathbf{m}\}, \mathbf{B_i} \geq \mu \Rightarrow$ legmode, where m is the total number of nodes on the path, i its current node, and $\mathbf{P}$ the set of all the nodes along the path.

2) continuity criteria λ: This index allows the planner to verify that switching from leg mode to wheel mode, worth the time and energy spent in the transformation. λ avoids too frequent transformations along the path: $\forall B_i, i \in \mathbf{S} = \{\mathbf{j}, ..., \mathbf{m}\}, \exists \mathbf{l}, \mathbf{B_l} \geq \mu, (\mathbf{l} < \lambda \vee \mathbf{l} = \mathbf{m} \Rightarrow$ legmode$) \vee (l \geq \lambda \Rightarrow wheelmode)$. l is either the index of the first node since i to be requiring a switching to legmode, or the last node m, and j the index of the last switching node from wheel to leg. λ can be seen as a minimal distance between j and the next switch from leg to wheel mode. $\mathbf{S} \subset \mathbf{P}$

3) safe switching space criteria Δ : A safe region around the current localization of the robot might be necessary when a switching action occurs, especially for transforming Hybrid robots like LEON. The space Δ criteria aims to fulfill this requirement by verifying that when a switching of motion is planned at i, $R_i \leq \Delta$. If $R_i > \Delta$, there is no space for transformation, and the planner will check backward on the path for a place to switch. To do so, we iterate the process with $\forall R_{\tilde{i}}, \tilde{i} \in \mathbf{T} = \{\mathbf{k}, ..., \mathbf{i}\}, \mathbf{R_{\tilde{i}}} \leq \mathbf{\Delta}$ with $\tilde{i} = i - 1$ where k is the last recorded switching node. In the worse case, the planner will cancel its previously planned switch mode at the previous switching node k and keep a leg mode. Note that the segment $\mathbf{Q} = \{\mathbf{k}, ..., \mathbf{i}, ..., \mathbf{l}\}$ is defining an smooth area between two rough zones, we have $\mathbf{Q} \subset \mathbf{P}$, the number of element of $\mathbf{Q} \geq \lambda$ in leg mode.

Fig. 4 is an example output of the planer along a 20 nodes long path, with a $\mu = 0.3[m], \lambda = 3$ nodes and $\Delta = 1$ node.

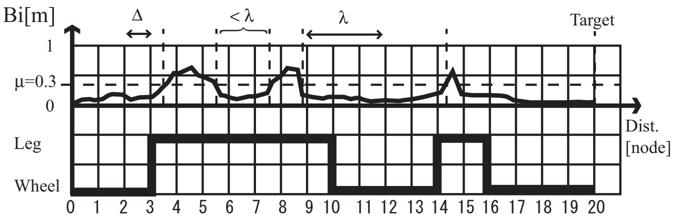


Fig. 4. Example of generated profile

V. THE DYNAMIC SIMULATOR ERODE

The dynamic behavior of the hybrid robot is analyzed along the candidate path with the dynamic simulator ERode, developed at the Space Robotics Laboratory of the Tohoku University. ERode is a physics-based simulation environment based on ODE (Open Dynamics Engine) library [10] , which allows one to easily create a virtual world, visualize it and run real-time interactive simulations. It also features convenient functions to control the appearance for realistic or scientific rendering, the values of dynamic parameters such as gravity, terrain properties, etc. Specifically, the dynamic model comprises two modules: the vehicle dynamics model and the leg/wheel-soil interaction model, which is based on the classical terramechanics approach [11]. In the reminder of this section both models are described in detail.

A. Vehicle Dynamics Model

The robot in the simulation was modeled according to our hybrid prototype Leon (see Fig. 1). Leon's overall weight is about 6 kg with a wheelbase of 0.2 m and a wheel radius of 0.1 m in wheeled configuration, and a hexagonal convex hull, enclosing the contact points, with a major and minor axis length of 0.25 m and 0.2 m, respectively, during legged locomotion. The height of the robot from the ground is equal to the wheel radius during wheeled mode, and 0.15 m for the legged configuration.

Given the candidate action plan, which is composed of a feasible path augmented with the set of instructions to switch from a locomotion system to an other, the dynamic behavior of the robot is numerically obtained by successively solving the following motion equation,

$$H \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \\ \ddot{q} \end{bmatrix} + C + G = \begin{bmatrix} F_0 \\ N_0 \\ \tau \end{bmatrix} + J^T \begin{bmatrix} F_e \\ N_e \end{bmatrix} \quad (7)$$

where H represents the inertia matrix of the robot, C is the velocity-dependent term, G is the gravity term, v_0 and ω_0 are the translational and angular velocity of the main body, q is the joint angle vector, F_0 and N_0 are the external forces and moments acting at the centroid of the rover, τ is the vector of the torques acting at each joint of the rover, J is the Jacobian matrix, $F_e = [f_{w1}, f_{w2}, ...f_{wm}]$ is the vector of forces applied at the m contact points by the external environment, N_e is the counterpart of F_e for the moments. Note that each external contact force f_{wi} is derived by the leg/wheel-soil contact model described later.

Equation 7 is a general equation, and can be applied to a vehicle with any configuration. The virtual robot can be considered dynamically equivalent to the real LEON prototype. Specific parameters of the robot kinematics and dynamics were experimentally-determined to match the behavior of the simulated model with the real system.

B. Wheel-soil Contact Model

During wheeled locomotion, the drive wheel contact forces can be decomposed into a longitudinal component F_x, usually referred to as the drawbar pull, a lateral component F_y, and a vertical component F_z. Based on the terramechanics theory [11]-[12], these components can be obtained as,

$$F_x = rb \int_{\theta_r}^{\theta_f} (\tau_x(\theta) \cos\theta - \sigma(\theta) \sin\theta) d\theta \tag{8}$$

$$F_y = \int_{\theta_r}^{\theta_f} (r \cdot b \cdot \tau_y(\theta) + R_b \cdot (r - h(\theta) \cos\theta) d\theta \tag{9}$$

$$F_z = rb \int_{\theta_r}^{\theta_f} (\tau_x(\theta) \sin\theta + \sigma(\theta) \cos\theta) d\theta \tag{10}$$

where b represents the width of the wheel, r the wheel radius, $\sigma(\theta)$ the normal stress beneath the wheel, $\tau_x(\theta)$ and $\tau_y(\theta)$ the shear stress along the longitudinal and lateral direction of the wheel. The contact region of the wheel on loose soil is determined by the entry angle θ_f and the exit angle θ_r. In addition, R_b is modeled as a reaction resistance generated by the bulldozing phenomenon on a side face of the wheel, and it is expressed as a function of the wheel sinkage h.

C. Foot-soil Contact Model

Similarly, in legged configuration the contact force components on each flat foot can be expressed as,

$$F_x = l_y \int_0^{l_x} \tau_x(x) dx \tag{11}$$

$$F_y = l_x \int_0^{l_y} \tau_y(y) dy \tag{12}$$

$$F_z = l_y \int_0^{l_x} \sigma_x(x) dx \tag{13}$$

where l_x and l_y are the longitudinal and lateral length of each foot.

D. Path following control strategies

During the simulation, the virtual robot is controlled to follow a path and switch from one mode to the other following the script generated by the action planner. A

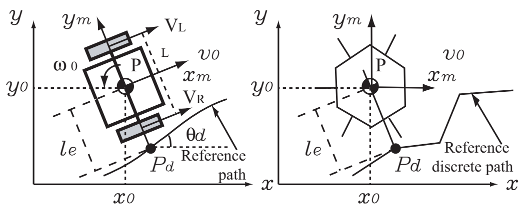


Fig. 5. Illustration of the path following control

general illustration of the path following problem is depict in Fig. 5. In wheel mode a differential wheel model is used where $\omega_0 = (V_R - V_L)/L$ and $v_0 = (V_R + V_L)/2$. V_R and V_L are left and right wheel velocities, L the distance between the two wheels, and ω_0 the angular velocity of the body. In leg mode, the robot is omnidirectional, and v_0 , the speed of its body, is the control parameter for the body's pose. The robot's position is denoted by P, the shortest distance projection of P to the reference path is P_d. Moreover, l_e is the signed distance between P and P_d (distance error); θ_d, the angle between the x-axis and the tangent to the path at P_d (vehicle's desired orientation in wheel mode); and θ_e, the orientation error in wheel mode $(\theta_0 - \theta_d)$. A feedback control law is applied, to satisfy in wheel mode both $l_e \to 0$ and $\theta_e \to 0$, or in leg mode only $l_e \to 0$.

VI. SIMULATION AND EVALUATION

In this section, we present results obtained using the proposed action planner. Two candidate paths augmented with the correspondent actions are analyzed, and the dynamic behavior of the robot is simulated along each of them through the ERode simulator. Then, the two action plans are compared in terms of travel safety, energy efficiency, total driving distance and travel time from the starting point to the final destination. Specifically, a global power consumption

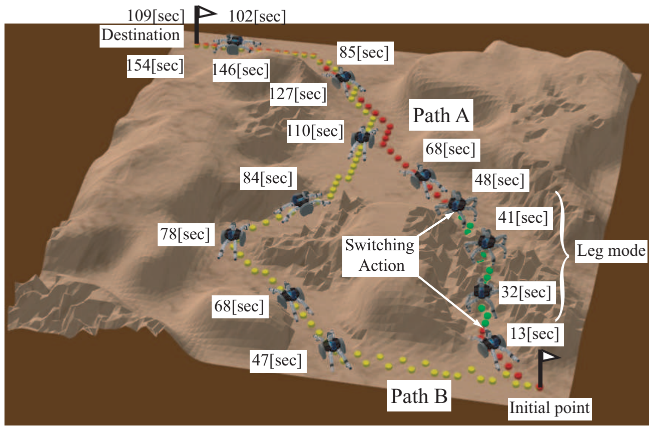


Fig. 6. Illustration of the path evaluation on ERode

TABLE I
SIMULATION SET UP AND RESULTS

Path #	W_B	W_D	W_{θ_x}	W_{θ_y}	Total length [m]	Elapsed time [sec]	U [N.m]
A	0.1	0.1	0.1	0.1	11.65	109	20.9
B	0.8	0.01	0.2	0.2	16.23	154	35.4

parameter U is defined as $U = \sum_{t_s}^{t_f} \Delta\bar{\Gamma}_{t_i}$, where t_s and t_f are the starting and final time along the path, and $\Delta\bar{\Gamma}t_i$ is the average energy consumption during a time iteration. $\Delta\bar{\Gamma}t_i$ is defined as $\Delta\bar{\Gamma}_{t_i} = \frac{1}{n}\sum_{j=1}^{n} \tau_j$ where τ_j is the torque at actuator j and n the total number of actuators or degree of freedom of the robot ($n = 20$ as we have 18 leg's actuators and 2 wheel's motors). Since, torque is roughly proportional to the electrical current in DC motors, we regard U as meaningful of the energy consumption of the robot along the path.

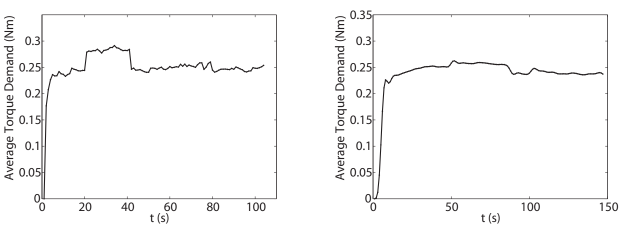
The procedure for action planning and evaluation is summarized as follows:

1) Input the terrain elevation map.

2) Choice of the weighting factors for cost function (5).
3) Extraction of a candidate path p_s based on (6)
4) Action planning along p_s, as described in Section IV.
5) Analysis of the dynamic behavior of the robot along p_s using the ERode simulator.
6) Path evaluation based on the energy consumption, safety, and travel time and distance.

The digital elevation map (DEM) used in Fig 6 is a 8 m $\times$ 8 m square with a grid of 50×50 equally-spaced terrain nodes. ERode is generating the DEM from an inputed gray scale image and is displaying the reference path computed by the planner, by colored dots placed on the grid nodes.

For this evaluation, two candidate paths were considered, obtained with a different values of the weighting factors summarized in Table I. Path B is shown by yellow dotes in Figure 6, whereas Path A is shown by red dots for the portion where LEON planned motion is in wheeled mode, and by green dots where it is planned to walk. Details of the length and inclination of the two paths are also collected in Table I. The weight indexes of Path A are well balanced and the result is a shortest traveling distance between start and destination, but at a cost of the traversal of a rocky area, along which Leon is set by the planner to switch into leg mode. The choice for path B was connected with the search for the safest path, along which the robot was able to traverse using only its wheeled locomotion mode. To generate path B, the roughness index has been set very high in comparison to the length one. In order to compare path A with path B,



(a) Path A (b) Path B

Fig. 7. Energy consumption

the dynamic behavior of Leon was simulated along each path using the ERode simulator. The time profile of the energy consumption parameter $\Delta\bar{\Gamma}_{t_i}$ is shown in Fig. VI, and the resulting total traveling time and energy consumption are collected in Table I. Path B is a more energy consuming path according to the simulation, even if Path A had to deal with a walking mode on a rough terrain. By simply looking at the torque profile, it is obvious to see that LEON was in leg mode from time [sec] $t \approx 21$ to $t \approx 41$ in path A. Beside this, the energy profile for path A is pretty constant proving that the terrain was relatively flat. On the other hand, for path B, we clearly see an increasing of the average energy consumption over the time from $t \approx 47$. The elevation map confirms that a slope is the reason. Then the tendency is inverted at $t \approx 84$ with an average torque lower than on a flat ground. This is the result of a descending slope. As a conclusion for this case study, Path A is the most appropriate choice as it consumes less energy and is faster than Path B to reach the POI.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we first presented a novel design of hybrid leg-wheel robot that folds two of its six legs to transform them into wheels. Then we addressed an action planner and its evaluation method for lunar/planetary exploration hybrid leg-wheel robots, considering the planning of switching of locomotion mode. The proposed technique has been composed of four steps: 1) a path planning to generate a candidate path, 2) an action planning to generate a script of switching of motion mode along the path, 3) a dynamics simulation in which the robot is following the path, and 4) a path evaluation based on the dynamic simulation results.

The proposed technique has been described through the analyze of two different paths for a given digital elevation map provided to the simulator and the planner by a gray scale image. The DEM can be generated by other mean like a stereo camera or a laser range finder for a real application.

More investigation can be conducted on the implementation of different soil characteristics in the planner, to have more accurate simulation results, as well as an automatic choice of the weighting factors for the cost function, based on the soil condition. For an onboard implementation of the planner the path searching method shall be quicker as well as an in-situ measurement system of the soil characteristics is required to be implemented as we are currently assuming to known them for the simulation process.

VIII. ACKNOWLEDGMENTS

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