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Performance comparison of rough-terrain robots - simulation and hardware

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Abstract

The design of a rover for a specific environment is a complex procedure which requires modeling a chassis and evaluating it with specific criteria. This is the aim of the Performance Optimization Tool (POT) presented in this paper. The POT enables the comparison and optimization of a rover chassis in a quick and efficient way. The tool is based on a static approach including optimization of the wheel torques in order to maximize traction. Tests with real hardware were performed to validate the POT. Two different rovers, CRAB and RCL-E, were assessed in simulation and hardware with respect to specific, well defined metrics. In simulation, their performances were compared to the rocker-bogie-type rover MER. CRAB and MER showed similar performance, while RCL-E had significant problems with the benchmark obstacle. A very good match between simulation results and real measurements was achieved.

1 Introduction

To design an all-terrain vehicle that is optimally suited for a given environment is a difficult task. The problem is inherently complex due to the large set of design variables to consider and a lack of information about the target terrain. This is especially the case for planetary exploration missions. The optimization of a particular design is tedious because the variables are coupled. As such, the optimization of one particular aspect of the design can have a negative influence on another. Moreover, at an early stage of the design phase there may be a large variety of candidate vehicle designs, and the selection of the most appropriate is usually not straightforward. Thus, it is important to quickly reduce this set in order to avoid a detailed evaluation of too many alternatives. Indeed such a process would imply the design of the mechanical components of the chassis for complete simulation, breadboarding and testing, which is both costly and time consuming.

In this paper, a framework is proposed to speed-up the optimization of a given structure for a rough terrain environment and to assess the performance of various concepts. An evaluation tool called Performance Optimization Tool (POT) (Krebs, Thueer, Michaud & Siegwart, 2006) has been developed for this purpose. Contrary to more sophisticated simulation tools which require CAD models and heavy computational power, the POT allows for quick modification and evaluation of the models. Thanks to the limited computation requirement, the POT provides results quickly and enables parametric analyses. By following a normalization process (e.g. equal wheel diameters, mass, footprint, etc.) it is then possible to compare the performance of different chassis and select the best candidate, which can be optimized using the same tool.

The computations are based on a static model of the rovers. The wheel torques are optimized such that the friction, needed to maintain the static equilibrium, becomes minimal (Iagnemma & Dubowsky, 2000). The POT is the first tool adopting this approach, where the mechanical equations are generated automatically for each model and provides easy-to-use interfaces for rover creation, simulation definition, and visualization of the results. The POT cannot be
directly compared to existing dynamic simulators because the underlying model is different. Dynamic simulators can provide steady state results as well, if used appropriately, but they represent one arbitrary solution while the POT calculates the best one. The output from the POT requires a different, more abstract, kind of interpretation because it is static and includes torque optimization. It reflects the full locomotion potential of a system regarding obstacle climbing and does not depend on specific simulation settings.

A standardized methodology for comparing and benchmarking all-terrain vehicle performance is missing in literature. When new concepts are presented, emphasis is put on their good performance, however, comparison with other vehicles is widely neglected. This paper takes a step in the direction of standardized benchmarking and compares two rovers in simulation and hardware under equal conditions. With the help of the POT, the obstacle climbing capabilities of the systems were analyzed. In order to validate these results the rovers were tested in reality and their performance measured. The locomotion systems used in this work are the CRAB of the Autonomous Systems Lab (ASL) and the Concept E (RCL-E), which was proposed to the European Space Agency (ESA) by RCL and VNII TRANSMASH (Kucherenko, Bogatchev & Van Winnendael, 2004). Since both concepts are related to the rocker-bogie-suspension type rovers by NASA, their performance was also compared in simulation to a scaled version of the Mars Exploration Rover (MER) (Lindemann & Voorhees, 2005).

This paper is structured as follows. Section 2 gives an overview of the software tools that can be used for performance evaluation of all-terrain robots and the POT is introduced. Section 3 describes the chassis that have been modeled and manufactured for this research work. The approach adopted to assess the performance of a given structure and to compare different concepts is presented in section 4. The simulation results and experimental measurements, validating the predictions of the simulator, are discussed in sections 5 and 6. Section 7 contains a comparative analysis of the two approaches. Finally, sections 8 and 9 conclude the paper and describe future work.

## 2 Software tools

The ideal way of comparing mechatronic systems is to build and test them in hardware. However, since this approach critically affects time and costs of the development, simulations are an unavoidable solution. When selecting a simulation tool, one must consider the constraints of the available tools in order to find the appropriate software. Below, an overview of some of the more frequently used tools used in vehicle simulation, along with their characteristics for rover evaluation is provided. This is followed by an introduction to the POT, which describes its advantages and why it provides valuable information about the systems that existing tools cannot.

### 2.1 Existing software

The tools presented in this section are all dynamic simulators. While Adams, RCAST, and ROAMS are 3-dimensional simulators, WorkingModel 2D (WM2D) is restricted to 2 dimensions. The 3D simulators require an extensive amount of preparation before a model can be simulated. The WM2D provides an easy-to-use interface that allows for simple set-up of simulations including rovers and the environment. The Open Dynamics Engine (ODE) is a special case because it is not based on exact mechanics.

- Adams (MSCSoftware, 2006) by MSC Software is a very well-known multi-body system simulation tool and is considered the standard in many industry sectors. It is based on the Newton-Euler formula and uses the Euler-Lagrange equations to set up the equations of motion. The software solves a system of differential-algebraic equations using the latest numerical methods. Nevertheless, processing the results can...
be time consuming and processor intensive. Adams can load rovers of any topology; however, it takes a tremendous effort to design a new model and prepare a simulation.

- **RCAST** (Bauer, Leung & Barfoot, 2005) is a dynamic simulator dedicated to a specific rover and is therefore not an appropriate tool for extensive rover comparison. In any case, the simulator has some very useful features like advanced models for wheel-ground interaction, sophisticated control algorithms or models of electronic components.

- **ROAMS** (Yen, Jain & Balaram, 1999; Jain et al., 2004) is an advanced simulation tool as well. It has similar features like RCAST. Adapting it to different rover types and preparing simulations requires a big effort which is a disadvantage for rover comparison.

- The Working Model 2D (Design-Simulation, 2006) is a dynamic 2D simulator. Its capability to detect collisions of bodies makes it very suitable for simulation of wheeled robots on rough terrain. Different rovers can be designed and loaded into the simulation environment easily. However, in order to obtain good results from dynamic simulations, some parameter tuning is required, e.g. the wheel-ground interaction properties need to be defined correctly and control parameters need to be adapted to the respective system. This complicates fast, extensive and automated comparison of a wide selection of rovers.

- The Open Dynamics Engine (Smith, 2006) is a software framework that aims more at fast and reality-like simulations rather than representing precisely the dynamics of the simulated system. This is reflected in the model which works with force accumulators to move bodies and constraints to represent joints. ODE is a good tool to test algorithms such as path planning, but it is not appropriate for rover comparison with regards to real mechanical properties.

### 2.2 Introduction to POT

The POT is part of the Rover Chassis Evaluation Tools (RCET, (Michaud et al., 2004)), which provide a set of both software and hardware tools used to evaluate the performance of rovers. The different tools aim at supporting the designer during the various stages of the development.

The POT is used in an early phase of the rover design process. During this phase of development, information about the final design is limited, CAD models are not available and thus complex simulation tools like Adams cannot be properly used. There may be a wide range of candidate suspension systems and time for the development is usually short. The POT provides a means to quickly create models graphically, compute their performance and enable a first-level comparison.

![Figure 1: Difference of input-output relation between POT and dynamic simulators in general use.](image)

The development of the POT was motivated by the lack of a tool combining generic model creation, high processing speed and integrated optimization of wheel torque. Using more sophisticated simulation tools for rover comparison would be extremely time consuming and
would require a lot of processing power, while the effort needed to prepare the models would be cumbersome. WM2D is the tool that comes closest to the POT but a very important feature differentiates them (Figure 1). The POT looks for the static equilibrium state of the rover, which makes its simulations fully independent of any control algorithm. Thus, only the performance of the suspension mechanism is evaluated. The POT can be used to quickly compare existing designs or to design new structures in an efficient way (Thueer, Krebs & Siegwart, 2006). The goal of the POT is to allow the user to select the best design and adapt it for a particular application through a parametric study. The tool is not able to automatically change or adapt designs; however, it offers a framework to easily modify the tested mechanisms, which allows for manual optimization. Data from 3D simulation tools are complementary and used later in the development of the rover. Figure 2 depicts the high-level architecture of the POT and its modules. The main modules are: the user-interface to design rovers, the 2D simulator that handles the simulations, and the player that allows visualizing the rover’s states. External applications like MATLAB can be used to display the numerical results.

Figure 2: POT architecture: overview of different modules with internal and external communication channels.

The POT is based on a static model, which makes calculations very fast. Since exploration rovers typically move slowly (< 0.1 m/s), dynamical effects are negligible and a static model is appropriate. The results of the static analysis depend on the mechanical design only, as no implementation of a control algorithm or simulation settings, such as velocity, interfere. This is an advantage of the static approach as different control strategies or even different implementations of a controller lead to different performance of a mechanical structure in dynamic simulation. Thus, the POT allows an objective and unbiased analysis of the rovers’ performance. The other strong simplification of the POT is the 2D modeling of the rovers. This simplification is valid for several reasons. First, when steering is neglected, wheeled robots have a mobility of one. This corresponds to a trajectory in a vertical plane which is what the POT models with the 2D assumption. Furthermore, most rovers are symmetrical and have the same suspension mechanism on both sides. The 2D model avoids static indeterminacy that occurs in the third dimension, if no flexible elements are modeled. Additionally, obstacle climbing is a critical situation, therefore steering should be avoided. Such a special scenario is not important for performance evaluation at this stage of the development. Thus, linear obstacles cover most of the relevant cases of obstacle negotiation and provide important information for the evaluation of suspension systems.

### 2.2.1 Simulations

A simulation, in the context of the POT, mainly requires two elements: a rover and a terrain. At the beginning of the simulation, the rover is placed at a starting position on the terrain. Its state is retrieved from the kinematics engine and passed, together with the system of mechanical equations, to the solver which computes the tool’s outputs for this simulation step.
The obtained forces and torques are those which maintain the rover in static equilibrium. For the next simulation step, the rover is moved forward a short, well-defined distance along the terrain and the process is repeated. Since the POT is static, the visible movement in the simulation is not a result of the computed forces. The rover is placed at every successive position from the beginning to the end of the terrain. The state of static equilibrium is then calculated and forces and torques are stored in a database. Each simulation step is independent from one another.

2.2.2 Generation of rover models

The POT provides a Graphical User Interface (GUI) which enables the creation of a rover using predefined elements such as wheels, bars, parallel bogies, different types of joints, etc. These elements can be linked together at specific points and the type of link can be set to joints that are fixed, free-moving or motorized. Based on this model the static equations are generated automatically by the software. Using this approach, it is possible to model and generate the system of equations for any passive mechanical structure in 2D.

Once the rover model is established, it is validated before use in the simulation. This is done applying Grübler's formula (Grübler, 1917):

\[ f = 3 \cdot (n_B - n_G - 1) + \sum f_{Gi} \]  

with \( f \) = degrees of freedom (DoF), \( n_B \) = number of bodies, \( n_G \) = number of joints and \( f_{Gi} \) = DoF of joint \( i \). The mechanical structure of a 2D rover must have a total DoF \( f \) equal to one (Lauria, Shooter & Siegwart, 2003).

2.2.3 Under-constrained problem

Since the rover has one DoF, controlling such a structure would require only a single motor. In reality, in order to increase the terrainability (Apostolopoulos, 2001), every wheel is driven by a motor. As a result, there are an infinite number of solutions that keep the rover in static equilibrium. For example, a rover with \( n_B \) bodies, including \( n_w \) motorized wheels, corresponds to the following system (reduced form):

3·\( n_B \) Equations
3·\( n_B \)+\( n_w \)=1 Variables

This means the system is under-constrained by \( n_w \)-1. An infinite number of solutions exist and one has to be selected. This solution has to reflect the goal of the simulator, which is to express the capacities of the mechanical structure of the rover. A criteria for optimization is defined in order to proceed with the selection of a solution.

2.2.4 Optimization criteria

Among different strategies, equal friction coefficients on all wheels has been proposed to maximize traction. The idea is to have the ratio of tangential and normal forces (Figure 3) as low as possible by selecting the correct set of torques.

\[ T : \text{Wheel torque} \]
\[ N : \text{Normal force} \]
\[ R : \text{Tangential force} \]
\[ r : \text{Wheel radius} \]

Figure 3: Definition of the friction coefficient (\( \mu \)) as ratio of tangential (R) and normal force (N).

In the case of a real rover control, slippage on the \( i^{th} \) wheel can be avoided if:
where $\mu_0$ is the static friction coefficient, $R_i$ and $N_i$ the tangential and normal force, respectively. Although $\mu_0$ is difficult to determine because it depends on the wheel-soil interaction, minimizing $G_i$ reduces the slippage risk. Therefore, the traction limitation $F$ for the rover is defined by the worst $G_i$.

$$F = \max(G_i)$$

The highest traction possible is reached when $F$ is minimal, and this case corresponds to $G_i$ equal for all wheels. In order to find this solution within the POT, a fix-point-based algorithm is used with the following criteria:

$$H = \min(\sum_i (G_i - \bar{G})^2)$$

where $\bar{G}$ is the mean of all $G_i$. $F$ is minimal when the difference between every $G_i$ is minimized. This in itself corresponds to the criteria H.

Finally, the criteria G is introduced. $G$ is equal to $F$ if the optimization H is applied. It is of interest because, speaking in mechanical terms, this solution means that a mechanical structure cannot achieve more traction in a given situation. Therefore the criteria qualifies the performance of rovers which is important in the context of the POT (Lamon, 2005).

### 3 Chassis description

Breadboards of CRAB and RCL-E were used during this project. Both rovers have articulated suspension systems like NASA’s rocker-bogie-type Mars Exploration Rovers. Therefore a comparison with the MER would be of interest, since the MER has been successfully used in an exploration mission. Unfortunately, there was no rover available with the same rocker-bogie suspension configuration like the MER. This is why the performance comparison of the three mentioned rovers could only be completed in simulation.

CRAB, RCL-E and MER are all passive locomotion concepts with six motorized wheels and equal loading on each wheel while on a flat surface. CRAB and RCL-E have equal distance between the wheels, thus the center of mass (CoM) is placed above the middle wheel. This is not the case for MER which has unequal distance between the wheels. Consequently the CoM is placed such that each wheel is loaded equally. The height of the CoM is the same on all systems.

#### 3.1 CRAB

The CRAB concept follows the idea of using parallel kinematic elements like parallel bogies, as used by its two predecessors at ASL: the Shrimp (Siegwart, Lamon, Estier, Lauria & Piguet, 2002) and the SOLERO (Michaud et al., 2002). Both have excellent obstacle climbing capabilities. They make use of one parallel bogie on each side and a fork element at the front with parallel kinematics and an internal spring. However, these designs have significant drawbacks. E.g. the wheels are arranged along three tracks. Thus it is impossible to turn properly on the spot because only the middle track with front and back wheel has steering capabilities. Furthermore, the volume for instruments and payload is significantly reduced compared to systems that have all wheels arranged in only two tracks. Another drawback is the spring in the front fork that is used to exert the required force for climbing a step, but is too weak to support the weight of the vehicle on the way down. There is no compliance between body and rear wheel which takes, therefore, a significant amount of the load when the other wheels are on an obstacle. This requires large torques from the motors for climbing. Hence, a new system was designed that builds on the positive elements and attempts to eliminate the problems that have been encountered in previous rover designs.
The result is the locomotion concept CRAB (Figure 4 and Figure 5), a system that is based mainly on parallel bogies of which it has two on each side. They are connected at the bottom next to the axis of the middle wheel and at the top through an articulated rocker. A differential mechanism between the left and right suspension levels the pitch angle of the chassis.

![Figure 4: Locomotion concept of CRAB consisting of two parallel bogies linked with an articulated rocker.](image1)

Figure 4: Locomotion concept of CRAB consisting of two parallel bogies linked with an articulated rocker.

![Figure 5: Breadboard of ASL rover CRAB climbing a step obstacle of 0.2 m height during testing.](image2)

Figure 5: Breadboard of ASL rover CRAB climbing a step obstacle of 0.2 m height during testing.

Two implementations of the locomotion concept CRAB appear in this work to show how the POT contributed to the evolution of the breadboard.

3.1.1 CRAB I

The CRAB I breadboard which already existed at the ASL deviated slightly from the original concept. The changes were imposed by certain constraints from a former project, such as the modularity of the mechanical parts and the requirement for simple modification of dimensions.

The schematic view in Figure 6 depicts the suspension of CRAB I. The chassis’ vertical links (VL) were positioned in the middle of the bogies at 1/2 d from the middle wheel, which enabled equal load distribution on both wheels of the bogies. However, the middle wheel took twice the load with respect to the front and back wheels because it was connected to both the front and back bogies.

Another deviation concerned the rocker and the rear bogie. In order to respect the constraint concerning simplicity of the mechanics, the middle joint on the rocker was removed. As a consequence, the rear bogie had to be modified in order to avoid static indeterminacy. This was realized by connecting the rear bogie with only one joint to the rocker, which changed the kinematic behavior of the bogie.

Simulations with the POT confirmed the poor performance of the existing structure and demonstrated the need to change the breadboard mechanics. While the original design simplified the mechanical structure, it also reduced the locomotion performance. The simulations revealed that the changes on the rear bogie did not only influence kinematic properties, but also affected static properties in a negative way. Moreover, the increased load on the middle wheel was not consistent with the objective of having equal load distribution on each wheel.
3.1.2 CRAB II

CRAB II (Figure 7) corresponds to the original concept. The load is distributed evenly on all wheels because the VLs are placed at 2/3 d from the middle wheel. The front and rear bogies are identical. The rocker that connects both bogies is divided into two elements, with a rotational joint in the middle. Thus the system is fully symmetric.

3.2 RCL-E

Concept E was proposed as a baseline for further development of a Mars rover locomotion system after evaluating several different locomotion topologies. Figure 8 shows a photo of the breadboard at ASL and a schematic view of the structure. The 2D representation has the same behavior as the real rover as long as it remains on a symmetric obstacle. Transversal kinematic elements like the rear bogie can be suppressed because they do not act in the plane of the 2D view.
RCL-E’s suspension consists of three parallel bogies. There is one on each side at the front of the chassis on which the front and middle wheels are mounted. The third bogie is mounted at right angles to the other bogies at the rear of the chassis. It replaces a differential between the left and right suspension and serves as a leveling mechanism. The CoM is situated right above the middle wheel, which creates equal loading on each wheel.

RCL-E is an interesting approach which keeps the mechanism simple (e.g. no differential). However, the concept does not allow for extensive optimization. Therefore the breadboard was built to the proposed specifications, but with respect to some external constraints (e.g. dimensions, use of same wheels as on the CRAB).

### 3.3 MER

The MERs (Spirit / Opportunity) are the most well-known rocker-bogie-type rovers (Figure 9). The design has six wheels of which the front and back wheels are equipped with steering capability. It is an asymmetric design in the longitudinal direction; the distance between the wheels is not equal. In order to have equal loading on each wheel, the horizontal position of the COM is slightly shifted forward.

As it was mentioned before, no hardware tests could be performed with a MER breadboard, therefore all descriptions and results in this article refer only to the simulated MER. Note that, contrary to the real MER, the front side of the simulation model was chosen at the bogie side as depicted in Figure 9.

![Figure 9: NASA’s Mars Exploration Rover, Spirit.](image)

### 3.4 Rover models

This subsection describes the models that were derived from the breadboards and used in the simulations with the POT.

Since the POT works in 2D, the rover models must be adapted accordingly. This basically concerns the mass of the rover, which has to be divided by two because both suspensions on the real rover (left and right) take half of the total mass, assuming that the rover remains on a symmetric obstacle.

Even though the POT allows assigning mass properties to each element of the model, masses are given only to the wheels and the main body. This is considered sufficient due to the fact that at this point in the design, the user does not know the final design of the suspension, which in any case only represents a small fraction of the rover’s total mass. However, the total mass is known because it should be given in the list of requirements.

In order to compare the breadboards, they were designed to be as similar as possible with respect to mass, CoM, footprint, wheel type, and wheel diameter. The final mass differs slightly because of the different suspension designs. The other components, i.e. wheels, motors, controllers, batteries, and computer, are the same for both breadboards. These characteristics are reflected in the POT models. Figure 10 depicts the parameters for the models and Table 1 lists the respective values. Note that the exact dimensions of the MER are not available in literature, therefore the dimensions may slightly differ.
Figure 10: Geometrical parameters for a rover.

Table 1: Physical data of CRAB, RCL-E and MER.

<table>
<thead>
<tr>
<th>Unit</th>
<th>CRAB</th>
<th>RCL-E</th>
<th>MER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>[kg]</td>
<td>17.5</td>
<td>15.8</td>
</tr>
<tr>
<td>Main body mass</td>
<td>[kg]</td>
<td>13</td>
<td>11.3</td>
</tr>
<tr>
<td>Wheel mass</td>
<td>[kg]</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Main body position</td>
<td>( x_b ) [m]</td>
<td>0.315</td>
<td>0.331</td>
</tr>
<tr>
<td></td>
<td>( y_b ) [m]</td>
<td>0.277</td>
<td>0.283</td>
</tr>
<tr>
<td>CoM</td>
<td>( x_{CoM} ) [m]</td>
<td>0.324±0.005</td>
<td>0.344</td>
</tr>
<tr>
<td></td>
<td>( y_{CoM} ) [m]</td>
<td>0.215±0.005</td>
<td>0.215</td>
</tr>
<tr>
<td>Wheel distance</td>
<td>( l_a ) [m]</td>
<td>0.324</td>
<td>0.389</td>
</tr>
<tr>
<td></td>
<td>( l_b ) [m]</td>
<td>0.324</td>
<td>0.259</td>
</tr>
<tr>
<td>Wheel track</td>
<td>( t ) [m]</td>
<td></td>
<td>0.648</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>( \phi ) [m]</td>
<td></td>
<td>0.2</td>
</tr>
</tbody>
</table>

4 Locomotion Performance

When talking about rover performance, the following question typically comes up: “Which rover has the best performance?” To answer this question, two important aspects must be considered:

1. Are the mechanical systems comparable? Do they have the same characteristics?
2. What criteria can be used to characterize the rovers? Do the criteria allow drawing an objective conclusion about the rover’s performance?

The following subsections make reference to these two aspects and explain how these issues can be treated.

4.1 Normalization

There exist a large number of vehicles which have different characteristics, but underline the same objective: locomotion on rough terrain. To select a design for a particular application, the performance of each selectable vehicle should be compared. This is possible only if all vehicles comply with the same constraints. Therefore, normalization is required.

For obvious reasons, it would not make sense to compare the performance of MER with the one of a vehicle like a Hummer or any Sports Utility Vehicle (SUV). There are too many differences between the vehicles in terms of dimension, size, wheel diameter, number of wheels, weight, power, etc. To compare vehicles, one has to be normalized with respect to the other. Unfortunately, this procedure does not correspond to a simple scaling because the ratios between the various elements in the rovers can be different.
In this work, wheel type, number of wheels and mass of the rovers are equal. The footprint of the rovers is also identical while placed on a flat ground. In order to have maximum terrainability, the rover mass is equally distributed on all wheels. These constraints provide excellent conditions for a rover comparison with a precisely defined benchmark test.

### 4.2 Performance metrics

In this subsection the metrics used to qualify the performance of a rover are described. The rover with the best overall rating concerning these metrics is defined to have the best performance.

- **Torque requirement**
  The maximal required torque is an important factor. A higher torque will require a bigger motor, which adds weight to the rover and consumes more energy. Thus, the rover with the lowest required torque is best.

- **Minimum friction coefficient**
  For a given state of the rover, which is determined by the shape of the terrain, the structure that requires the least amount of friction to maintain equilibrium is the best performing structure. The needed friction coefficient $\mu$ is defined below as the ratio between tangential ($R$) and normal ($N$) force ($T$: wheel torque; $r$: wheel radius).

  $\mu_{\text{needed}} = \frac{R}{N} = \frac{T \cdot r}{N}$

- **Slippage**
  Slippage consumes energy without making the rover move forward, and it has a negative impact on the odometry. Therefore the rover with the least amount of slippage is the best performing structure.

### 5 Simulation results

The simulation results section is divided into two subsections. First, the results are presented, which show the advantages of CRAB II compared to CRAB I. Second, a comparison is made between the three locomotion systems: CRAB, RCL-E and MER.

All simulations were performed on the same terrain. The climbing abilities of the suspension mechanisms are very important in the context of all-terrain rovers, therefore the benchmark obstacle was a step of a height equal to one wheel diameter. The step is considered the most critical terrain for a wheeled vehicle because of the vertical inclination which has the highest demands regarding kinematics and force distribution. Furthermore, each phase of the climbing can be observed independently because the obstacle negotiation is not influenced by the obstacle’s dimension (like on a simple bump).

#### 5.1 Improvements on the concept CRAB

As mentioned previously, the existing CRAB I breadboard did not correspond to the original concept for various reasons. In order to determine the potential drawbacks of CRAB I, it was compared in simulation with CRAB II. The simulations revealed serious disadvantages which could be traced back to the changes discussed above. Hence, a redesign of the mechanics was necessary before performing the hardware tests.

To find out if both changes with respect to the original concept, i.e. load distribution and bogie type, were important enough to be considered in the redesign of the breadboard, their effects on the performance were analyzed independently.

- The first analysis concerned the influence of the special bogie. The table below contains the maximal torque and $G$ values over an entire simulation.
Table 2: Maximum values of G and torque for CRAB (comparison of bogie types).

<table>
<thead>
<tr>
<th></th>
<th>Max G [-]</th>
<th>Max. torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRAB I</td>
<td>0.90</td>
<td>7.7</td>
</tr>
<tr>
<td>CRAB II</td>
<td>0.64</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The maximum values in Table 2 show that the special bogie has a negative impact on the locomotion performance. The maximum G increases by roughly 29% and the maximum torque by 22%. The reason lies in the different ways the two types of bogies interact with the rest of the system. While the vertical lever of a regular parallel bogie is connected with two joints to the bogie, the simplified version contains only one. On the one hand, the two joints on the regular bogie allow for transmission of a torque between the bogie and the system. On the other hand, the single joint connection on the special bogie allows for a rotation about this point, which results in a different kinematic behavior. While the first set of differences became visible in the simulations, the kinematic differences still require further research.

- The second analysis concerned the influence of the unequal load distribution caused by the position of the vertical middle lever on the parallel bogies. For this study, the CRAB II was modeled in two slightly different configurations: VL (see Figure 7) at 2/3 d and 1/2 d from the middle wheel.

Table 3: Maximum values of G and torque for CRAB (comparison of load distribution).

<table>
<thead>
<tr>
<th></th>
<th>Max G [-]</th>
<th>Max. torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRAB II (VL at 1/2 d)</td>
<td>0.73</td>
<td>6.6</td>
</tr>
<tr>
<td>CRAB II (VL at 2/3 d)</td>
<td>0.64</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 3 confirms a better locomotion performance with VL at 2/3 d. It was expected that an equal load distribution leads to lower friction and torque requirements. This is because the load is partially taken off one wheel and distributed to the others. In the case at hand, the maximum values occur for the 1/2 d configuration when the middle wheel with the heaviest charge is climbing the step. In the case of the 2/3 d configuration, the middle wheel is relieved and the peak occurs while the rear wheel is climbing up (the maximum value being significantly lower). As a consequence, the 2/3 d configuration was recommended not only from a terramechanics point of view but also from an obstacle negotiation point of view to improve the locomotion performance as defined previously.

According to these results, a full redesign of the existing breadboard’s suspension system was considered necessary.

Simple, qualitative tests for verification demonstrated that the mechanical changes brought the predicted improvements. While the breadboard with the old suspension (CRAB I) always got stuck with the middle wheel on the step, the CRAB II was able to climb a step obstacle at height of one wheel diameter. Unfortunately, no valid measurements were taken with the CRAB I configuration.

Because the CRAB I suspension was not used anymore after the redesign, the name CRAB always refers to the CRAB II configuration in the following sections.

5.2 Rover comparison: CRAB, RCL-E, MER

The results from the comparison of the three rovers are presented in this subsection. In Table 4 the maximum values provide a short summary of the performances with respect to the metrics: maximum G and maximum torque. Since these peak values only contain limited information, it is necessary and also very instructive to take a look at the performances over the entire simulation run as shown in Figure 11 to Figure 13.
The results from the POT are quite special. For a three-wheeled rover (in 2D) on a step obstacle, three peaks represent the phases of the wheels climbing the step. Because of the static model, torque, tangential force, and G values are zero between the peaks (the displacement of the rover is not caused by the forces). In each of these phases however, the normal forces maintain a certain value representing the current load distribution on the wheels. There is only one curve for G because the optimization criterion H leads to equal G_i (Eq. 4).

Table 4: Maximum values of G and torque in simulation. Note that "forward" and "backward" are defined with respect to the definition of "front" in Figure 9.

<table>
<thead>
<tr>
<th></th>
<th>Max G [-]</th>
<th>Max. torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRAB</td>
<td>0.64</td>
<td>6.0</td>
</tr>
<tr>
<td>RCL-E</td>
<td>0.95</td>
<td>7.3</td>
</tr>
<tr>
<td>MER (forward)</td>
<td>0.57</td>
<td>6.8</td>
</tr>
<tr>
<td>MER (backward)</td>
<td>1.03</td>
<td>8.9</td>
</tr>
</tbody>
</table>

The values in Table 4 show that MER (forward) has the best performance in terms of G (0.57), while CRAB performs best in terms of torque (6.0 Nm). The difference between these two rovers is roughly 12% for both criteria. RCL-E, however, needs significantly higher G (+66%) and torque (+21%).

As pointed out above, the last peak is the most critical. Therefore it is interesting to take a closer look at the wheel ground contact forces at this moment. It is striking to note that just before touching the step with the rear wheel, MER and RCL-E both have equal loading on the front and middle wheels (segment d). As soon as the rear wheel touches the obstacle (at the simulation step marked by e), MER displaces most of the load to the middle wheel, while the load remains equally distributed on RCL-E. This discrepancy can be explained with the different bogie types, which seem to have an influence not only on the kinematics of the

![Figure 11: Maximum G values for all rovers. Segments a, b and c mark the climbing of front, middle and back wheel respectively.](image1)

![Figure 12: Maximum torque values for all rovers. All systems have biggest peak when last wheel is climbing the obstacle.](image2)
system, but also on the statics. The graph shows that the load distribution of MER is more favorable, allowing the front and middle wheel to contribute more to the rover’s equilibrium, which results in better performance in terms of G and torque. This is confirmed by analyzing the load on the rear wheel in this situation, and since the wheel is on a vertical surface (at the simulation step marked by f), this corresponds to the last peak of the tangential force graph. RCL-E has significantly more load on the rear wheel (8.2 kg) than MER (4.3 kg) and CRAB (5 kg).

Figure 13: Normal and tangential forces per wheel for all rovers. Normal force distribution of RCL-E and MER similar in d and completely different in e; CRAB and MER take significantly less load on the rear wheel (f).

6 Hardware tests

6.1 Experimental setup

The breadboards were designed in such a way that the same electronics, motors and wheels could be used for all systems. This modular design allows for a quick setup and test of different locomotion concepts.

The locomotion control runs on a regular laptop that is mounted on the rover. The motion commands are input by means of a graphical user interface on a remote laptop and sent to the rover through a wireless connection. Both computers are running the Linux operating system. The onboard computer uses the mobile robot control framework GenoM (Mallet, Fleury & Bruyninckx, 2002) for taking care of the various control tasks. Maxon motors of type RE-max are used in combination with the appropriate Maxon EPOS motor controllers. The power supply is managed by a custom energy board, which was developed at ASL; this board is equipped with extended measurements capabilities such as voltages and currents.

Two different types of controllers were implemented. The first being a regular velocity control (referred to as Velocity), makes use of the velocity profile mode of the EPOS controllers. The second is an implementation of the wheel synchronization algorithm (referred
to as FIDO) described in (Baumgartner, Aghazarian & Trebi-Ollennu, 2001), which aims at synchronizing the wheel speeds based on the traveled distance of each wheel. Once a desired speed is set, the variations in wheel speed and in other disturbances are handled by FIDO. The controller updates each wheel speed independently for an overall better behavior according to:

\[ V_{i_{\text{set}}} = V_{\text{nomin}} + \Delta V_i \tag{6} \]

and

\[ \Delta V_i = F_{\text{syn}} \left( V_{i_{\text{set}}} \right) \tag{7} \]

where \( i \) is the wheel number, \( n \) the number of wheels, and \( t \) the time index.

It is clear that the mobility of a rover, especially its terrainability performance, does not only depend on the mechanical structure but is also strongly correlated to the control strategy. The best strategy would be torque control, which is based on the static approach. Such a controller distributes the torques on the wheels proportionally to their respective normal forces in order to reduce the slippage risk and optimize the rover mobility (Lamon & Siegwart, 2005). However, such a controller needs to know the state of the rover in detail, including the contact angles of the wheels. The wheels used in these tests were not equipped to sense the contact and therefore, torque control could not be implemented.

The tests were performed on a step obstacle of 0.2 m height which is equivalent to the wheel diameter. Two different coating materials with different coefficients of friction were used for the experiments. One material has a rough surface and enables the wheel grousers to hook tightly into the terrain. The second material is relatively soft (carpet like), but its structure also permits the metal grousers to hook into the terrain. The difference lies in the behavior of the rover during slippage. Slip on the second material is smooth, while on the rough surface slip is bumpy.

All tests were initiated from the same position and stopped when the rear wheel was on top of the step. Trials were interrupted when the rover remained stuck for approximately 5 seconds because of blocked or slipping wheels. At least three runs were performed per test. A test is defined as a combination of rover, terrain, and controller type.

6.2 Experimental results

The measurements of electric current and motor encoder values provide important information about the rover’s behavior. For each test, the current consumed by each motor and the wheel encoder values were logged. A typical example of a test with the CRAB is depicted in Figure 14.

The electric current graphs show three significant peaks over an entire test run, which appear when a wheel is climbing the step. The first peak (at the time marked by g) corresponds to the front wheel climbing the obstacle. The same shape can be observed for the middle and rear wheels, which correspond respectively to the second and third peak (at times marked by h and i). The difference in electrical current between the wheels at each peak is caused by unequal load distribution and kinematic constraints. During the interval between the peaks, the currents are significantly reduced because rolling resistance is the only force opposing the movement. Negative currents indicate that the wheels fight each other in certain positions due to kinematic constraints. In the worst case these constraints can block a wheel which leads to current saturation. Such a situation is visible at the time marked by i in Figure 14 where the middle wheel is blocked. As a consequence, in order to reach the input velocity, the controller increases the wheel torque up to the limit, which causes the current to rise to 2.5 A.

\[ \text{Videos from the tests available on http://www.asl.ethz.ch/people/thueert/personal/JFR} \]
The torque value applied at each wheel can be obtained from the corresponding value of the electrical current. The current is multiplied by the torque constant of the motor, the gearbox ratio, and the efficiency of the gearbox:

\[ T = I \cdot K_{motor} \cdot R_{gearbox} \cdot \eta_{gearbox} \]  

(8)

with \( \eta_{gearbox} = 70\% \), \( R_{gearbox} = 190 \) [-] and \( K_{motor} = 25.8 \) [mNm/A].

Figure 14: Motor currents and traveled distance for the left and right side of CRAB.

The wheel encoder values can be used to compute the distance traveled by each wheel (Figure 14).

\[ D_{distance} = \frac{\Delta_{encoder} \cdot 2 \cdot \pi \cdot r}{N_{pulse} \cdot R_{gearbox}} \]  

(9)

with \( N_{pulse} = 2000 \) [pulse/turn], \( R_{gearbox} = 190 \) [-] and \( r = 0.1 \) [m].

Slippage can be calculated based on the wheel encoder values. It can be defined as the difference between the traveled distance of the rover (ground truth) and the wheel odometry. The ground truth is very difficult to measure accurately. Therefore, relative slippage was used in this work which is the difference between the measured distances of the wheels. Slipping wheels do not contribute to the motion of the rover, i.e. energy consumed in slipping wheels is wasted. Furthermore, slippage is bad for the odometry. Therefore, slippage must be avoided.

Slipping wheels can be detected in the distance graph of Figure 14. E.g. at the time marked by i the following situation occurs: kinematics impose very low speed on the front and middle wheel (horizontal movement on top of the obstacle) while the rear wheel climbs the step (vertical movement). The graph shows that the middle wheel slows down (lower slope), while the front and rear wheel keep turning at the same speed (slope remains constant). This means that the distance measured by the front wheel encoders is mostly slippage because the mechanical constraints of the structure keep the distance between middle and front wheel constant.
6.2.1 Tests with CRAB

The tests performed with the CRAB are summarized in Table 5.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Terrain</th>
<th>Rough</th>
<th>Soft</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIDO</td>
<td></td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

The CRAB reached the goal and always overcame the obstacle. Therefore, the global success rate was:

\[ SR_{\text{CRAB}} = 100\%. \]

In terms of slippage, the mean result over all runs was:

\[ \text{Slip}_{\text{CRAB}} = 0.302 \text{ m}. \]

This corresponds to a slippage of 0.05 m per wheel over a traveled distance of 1.2 m.

6.2.2 Tests with RCL-E

The RCL-E never reached the goal with exactly the same motor configuration as the CRAB. No test run was successful. The global success rate was:

\[ SR_{\text{RCL-E}} = 0\%. \]

The typical electrical current consumption is depicted in Figure 15.

![Figure 15: Motor currents for left and right side (RCL-E). In segment j the back wheel is blocked while the others slip.](image)

The first two peaks indicate no difficulties encountered while the front and middle wheels climbed the obstacle. In segment j, the rear wheel was blocked (current saturation) at the bottom of the step while the front and middle wheels slipped (oscillating current graph). The test run was stopped because the RCL-E failed to reach the top of the step.

In order to obtain data over a successful test run with the RCL-E, the current limit of the controllers was increased from 2.5 A to 3.5 A. This modification enabled the motors to provide sufficient wheel torque needed to climb the obstacle. The new maximal torque on each wheel was:

\[ T_{\text{max}} = 12.04 \text{ Nm}. \]

The current consumption of the RCL-E climbing the step with this new limit is displayed in Figure 16.
Figure 16: Motor currents for left and right side (RCL-E, increased current limit). In segment k the back wheel is climbing the step. Slipping of the other wheels is clearly visible.

The rear wheels climbed the step in the critical section marked by k. One can note a very noisy current signal in this phase. This is due to the fact that the wheels slipped at first inducing a very unstable current consumption.

The summary of the tests performed with the RCL-E is presented in Table 6. Only tests performed with the electrical current limit increased to 3.5 A are included.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Velocity</th>
<th>Terrain</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIDO</td>
<td>33%</td>
<td>Rough</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>Soft</td>
</tr>
</tbody>
</table>

The global success rate of the RCL-E was:

\[ SR_{RCL-E} = 47\% . \]

In terms of slippage, the mean result over all the runs was:

\[ Slip_{RCL-E} = 0.416 \text{ m}. \]

This corresponds to a slippage of 0.069 m per wheel over a traveled distance of 1.2 m.

6.2.3 Discussion

The results presented in the previous section show that the CRAB performs much better than the RCL-E. The CRAB passed all the tests whereas the RCL-E reached the goal only in 47% of all test cases.

It was also observed that the movement of CRAB was smoother and less shaky than the one of RCL-E. The shaky behavior deteriorates the odometry, which is reflected in the slippage metric. Thus, this value is 38% higher for RCL-E than for CRAB.

The results clearly show that the torques required by RCL-E to pass the step are higher than those required by CRAB. With the same motor configuration for both rovers, the RCL-E’s rear wheel was always blocked when attempting to climb the step. The success rate of 47% was achieved only by increasing the electrical current limit.

For the successful test runs, the average current consumption of the RCL-E’s rear wheel while climbing the obstacle (Figure 16, section k) lies in between the limits of the two motor configurations, 2.5 A and 3.5 A. The mean value is about 3 A, which corresponds to a torque of approximately 10.3 Nm. Although this current was not the highest during the test, the torque of 10.3 Nm can be considered the maximum torque required by RCL-E to overcome the step for two reasons:

1. The first two wheels are able to climb the step with lower torques. This is shown in Figure 15 where the currents are limited to 2.5 A.
2. The highest currents appear when wheels are blocked due to physical constraints. In this case, the torque on each wheel is increased to keep up with the desired velocity. This results in peak current and saturation of the motor, even though the wheel does not contribute to the rover’s movement. This kind of peak appears in Figure 16 only before section k.

Finally, the results in Table 5 and Table 6 show that the different controllers did not affect the performance. The FIDO algorithm might be a very useful controller but its effect is not sufficient for such a big obstacle as the step used in the tests.

7 Analysis simulator – hardware

To validate the results of the simulator, two different mechanical designs were modeled and their performance evaluated using both the POT and real breadboards. There are several interesting elements that are observable in the work presented here. The most important ones are described below in the four subsections. The first two analyze the main metrics from a qualitative point of view. Quantitative analysis is made in the third subsection. Finally, the fourth subsection provides a summary of all the analyses.

7.1 Torque requirement analysis

During the experiments, the CRAB passed the obstacle with a torque limit of 8.6 Nm. The RCL-E could not do so with this limit. Under equal conditions, the CRAB climbed the step easily while the RCL-E got stuck when the rear wheel tried to climb the obstacle. Section j in Figure 15 shows that the rear wheel was blocked and that the current reached the prescribed limits. Since the front and middle wheels could not generate more traction, the rear wheel required a significantly higher torque, which could not be achieved with the motor configuration. Thus the rover failed the test objective. For RCL-E to succeed in climbing the obstacle the motor configuration was changed and the torque limit increased to 12.04 Nm. These results confirm the predictions by the POT which state a significantly lower torque requirement for CRAB. In fact, Table 4 shows that the POT computes maximum torques of 6 Nm for the CRAB and 7.3 Nm for the RCL-E. The discrepancy between simulated and measured values is caused by the simplifications within the POT model. However, the performance ranking of the mechanisms based on the torque metric was validated with the hardware tests.

Another interesting element can be seen in Figure 12. The peaks of the torque values corresponding to RCL-E’s front and middle wheel climbing the obstacle are lower than the highest peak of CRAB. It suggests that being given a certain torque limit, if the CRAB is able to pass the step, the first two wheels of the RCL-E should be able to do the same. This was confirmed by the real test results as the RCL-E got stuck only when its rear wheel had to climb the step. Again, this proves that there is valid and valuable information resulting from the comparison of rovers with the metrics applied in the POT.

7.2 Max G analysis

Both rovers can climb the step if the motors provide enough torque, however this does not constitute equal performance. Table 4 lists the needed G for CRAB and RCL-E as 0.64 and 0.95 respectively. This means that there is a higher risk for RCL-E than for CRAB to slip or even get stuck due to slippage. Given that sufficient torque is provided to climb the obstacle, there is a higher probabilistic chance that RCL-E cannot create sufficient traction on a specific terrain. Thus these predictions are similar to those above, but the critical issue is traction not torque.

When enough torque is available, the hardware results show that the RCL-E rover is able to climb the step thanks to the increased current limit, but not in all test runs. This is reflected in
the global success rate $SR_{RCL-E}$ of 47%. It seems that the coefficient of friction for the terrain is too close to the G required by RCL-E. Since the G required by CRAB is sufficiently low and enough torque is provided, it never gets stuck due to slippage and reaches an $SR_{CRAB}$ of 100%. Table 6 shows that the performance of RCL-E is slightly better on carpet. This means that this terrain has a higher friction coefficient and offers more grip. However, the hardware tests also confirm that CRAB requires a lower G than RCL-E. The comparison of mechanisms in POT based on the G metric also proved to be valid.

7.3 Numerical results

Although the same tests were performed in both types of environments, the conditions were not exactly the same. The static model neglects inertial effects and does not include rolling resistance. The mechanical structure is represented by point masses and internal friction is not modeled. The real rover has to deal with effects like reduced efficiency of the gearboxes, coarse terrain surface, and implementation of the control algorithm. As a consequence it cannot be expected that the simulation results exactly match the hardware results. However, in an optimal case the results only differ by an offset and scaling factor caused by neglected constant effects. Under these conditions, the simulations not only allow for qualitative predictions but also provide some input regarding the quantitative hardware results. Thus, it is important to analyze how simulation and hardware results correlate in order to allow locomotion performance prediction of rovers based on simulation.

As mentioned earlier, the RCL-E breadboard requires a torque of 10.3 Nm, which is 40% bigger than the 7.3 Nm resulting from simulation. If the computed peak torque for the CRAB (6.03 Nm) is also increased by 40%, a new maximal torque results:

$$T_{MaxNew} = 6.03 \text{ Nm} \cdot 1.4 = 8.46 \text{ Nm}.$$

The prediction based on the simulation results and the difference of 40% between test and simulation state that CRAB needs a maximal torque of 8.46 Nm to climb the obstacle. This value is lower than the 8.6 Nm, which the motors could provide in the initial configuration. This in turn is lower than the torque needed by the RCL-E. Thus, it is not surprising that CRAB climbed the obstacle while RCL-E did not with a 2.5 A current limit. Here as well, a correlation between POT and real tests is clearly visible.

7.4 Summary

Following the simulations, the CRAB was expected to perform better regarding both G and torque metrics. This was verified in hardware tests that confirm the strong correlation between simulation and reality. Therefore, it can be claimed that the CRAB offers a better terrainability than the RCL-E.

The match between the results of the simulator and the experiments with the breadboards is very good. The ranking for each performance metric is the same in simulation and reality. It is interesting to note that the specific weaknesses of RCL-E detected during the design phase also appeared during the real tests. The simulations predicted a high torque and friction requirement for the rear wheels to climb a step and this was confirmed when the breadboard failed to climb the obstacle.

Therefore, it can be concluded that the POT is a validated tool that can be used for chassis comparison and optimization.

8 Conclusion

Comparison between rover chassis has been widely neglected in literature. This may be due to the fact that breadboarding is expensive and most simulation tools are more complex than necessary for a level-one design phase. Therefore, the rover evaluation tool POT was introduced in this article and validated by means of real hardware tests. The validation was
performed on two different rovers, which enabled comparison between their performance both in simulation and in hardware.

The POT was developed to provide engineers with a tool that makes quick evaluation of different structures possible. The tool allows for comparison at an objective level because the results depend only on the physical structure of the vehicle and are independent of other factors which are required in dynamic simulators, like the implementation of a control algorithm.

The decision to re-develop the breadboard from CRAB I to CRAB II was reinforced by the use of the POT. The promising predictions of the tool were proved to be right by hardware tests. Furthermore, thanks to the POT analysis of the rovers CRAB, RCL-E and MER, significant differences in performance could be observed. The precisely defined metrics, minimum requirements regarding friction (G) and torque, allow for performance classification, while additional outputs from the tool such as contact forces, help to understand these results.

According to the evaluation with the POT, the performances of CRAB and MER were similar, while RCL-E had significant problems when the rear wheel had to climb the step obstacle. Unfortunately, no breadboard of the MER type was available, which is why the POT results could be confirmed only for CRAB and RCL-E. According to simulation results, RCL-E required significantly higher friction and torques than CRAB. Both predictions were confirmed during hardware testing. On the one hand, the hardware tests revealed that, under equal conditions, CRAB was able to climb the benchmark obstacle, while RCL-E got stuck with only front and middle wheel on the step. The wheels were blocked because of insufficient torque. On the other hand, with increased motor torque, it was observed that RCL-E slipped and repeatedly failed to climb the obstacle due to missing traction. The comparison showed superior performance of CRAB with respect to RCL-E in simulation and hardware.

The POT provides valuable information for the design or optimization of a locomotion concept. The hardware results validate the POT and emphasize the necessity to make use of it during the development of rough-terrain robots.

The quantitative analysis showed that the calculated torque values are roughly 40% below the measured torques. This was to be expected because the POT is based on ideal rover models and adopts the static approach. However, the real measurements allow for better understanding of the values that the POT provides. For the future, this experience will help to derive more precise conclusions from POT analyses. The match of qualitative predictions and the discrepancy of absolute values between simulation and reality add to the initial idea of a tool that supports comparison and optimization in an early phase of the rover development, rather than a simulator that yields the accurate behavior of a system.

9 Future work

As it was already done in simulation, it would be very interesting to extend the comparison in hardware with MER in order to classify the performance of CRAB and RCL-E with respect to MER. Since the performances of CRAB and MER are quite similar in simulation, a direct comparison on real breadboards could also yield useful information about the accuracy of the results of the POT.

At the moment, the POT supports optimization of a structure by providing results quickly and allowing for simple modifications of the model. In the future, extended functionality could include automatic changes of certain design parameters, e.g. position of the vertical levers on the parallel bogies of CRAB.

Instead of adding complexity to the POT, like extension of the model to 3D and asymmetrical obstacles, future work might rather focus on how the approach adopted in the POT can be further used. Torque optimization was proposed in order to improve motion control of rovers.
Such a control needs information about the state of the rover and the wheel-ground contact angles in order to perform the optimization of the torques. At the moment, the breadboards are incapable of providing this type of information. Therefore tactile wheels must be developed before an improved motion control can be tested on hardware.

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References


