

CRAB – EXPLORATION ROVER WITH ADVANCED OBSTACLE NEGOTIATION CAPABILITIES

Thomas Thueer, Pierre Lamon, Ambroise Krebs, Roland Siegwart

*Autonomous Systems Lab, ETH Zurich
ETH Zurich, Autonomous Systems Lab, Tannenstrasse 3
8092 Zurich, Switzerland*

{thomas.thueer, pierre.lamon, ambroise.krebs, roland.siegwart} @ mavt.ethz.ch

ABSTRACT

Many exploration rovers have been proposed in the past, but none was compared to other systems. Therefore, this paper not only introduces the locomotion concept CRAB, but also compares it to other rovers regarding obstacle negotiation capabilities. Instead of relying only on simulation, a comparison was also performed with real breadboards. In reality the CRAB is compared to RCL-E (Concept E by RCL); the simulations include the MER (Mars Exploration Rover by NASA) as well. The simulations predict significantly superior performance of CRAB compared to RCL-E, which is confirmed by the tests on hardware. The performance of CRAB and MER is similar; however, the CRAB has the same behavior in forward and backward motion because it is a symmetrical structure, while the MER has significantly inferior performance in backward motion.

Keywords: *CRAB, exploration rover, design, simulation, hardware test, locomotion performance*

INTRODUCTION

With the ExoMars mission approaching, the need for a high-performing rough-terrain robot becomes real. Several wheeled suspension systems have been proposed in the past years for this kind of application ([1-4]). While NASA's rocker bogie rovers have shown that they perform well on the Martian terrain, other rovers still lack prove of applicability. Even though many simulation and test results have been presented and show good performance for these rovers, their performances have never been compared. The comparison based on the available data is difficult because the parameters are too different, e.g. external dimensions, number and diameter of wheels and total weight. Thus, claims of having the best performing rover are difficult to justify.

In this paper, the rover CRAB, which is a design of the Autonomous Systems Lab (ASL) is not only presented, but also compared to other rovers regarding obstacle negotiation capabilities. The comparison has been performed in simulation and with real breadboards. In simulation, the CRAB is compared to NASA's Mars Exploration Rover (MER) [5] and Concept E (RCL-E) by RCL and VNIITRANSMASH ([6], [7]). In reality, only the breadboards of CRAB and RCL-E were available. In order to properly compare the different structures, they were normalized according to specific rules, the metrics were precisely defined and all tests conducted under identical conditions.

The simulations were performed using the 2D simulator which was developed as part of the Rover Chassis Evaluation Tools (RCET) framework [8]. Thanks to the simplicity to change parameters of the rover model, it was possible to perform a parametric analysis on the CRAB suspension system to increase its locomotion performance. This paper shows the evolution of the CRAB and how it was possible to eliminate strong drawbacks of the initial design by using simulation.

The metrics used in this work are imposed by the parameters output by the simulator and the sensors on the breadboards. However, they are chosen such that they best describe the performance of the rovers.

ROVER DESCRIPTION

This section introduces the rover CRAB. The idea of the locomotion concept, as well as its evolution from the first implementation to the current version of the breadboard is described and explained in detail. Since one of the objectives of this work is the comparison of the CRAB with other rovers, the RCL-E and MER are also briefly described below.

All systems discussed in this work are passive locomotion concepts with six motorized wheels and equal load on all wheels while on a flat surface. The centre of mass (CoM) is placed accordingly in the longitudinal direction and at the same height on all systems. The same set of wheels was used for both breadboards.

The Rover CRAB

The CRAB is a system which 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 a rocker which includes a rotational joint in the middle. The structure is fully symmetrical. A differential mechanism between the left and right suspension levels the pitch angle of the chassis.

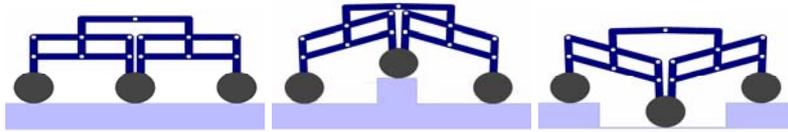


Fig. 1: Locomotion concept CRAB

The first implementation of the concept CRAB deviates slightly from the original concept as it is depicted in Fig. 1. The changes were imposed by certain constraints from a former project like modularity of the mechanical parts and the requirement for simple modification of dimensions in the future. The resulting modified structure, CRAB I, is depicted in Fig. 2.

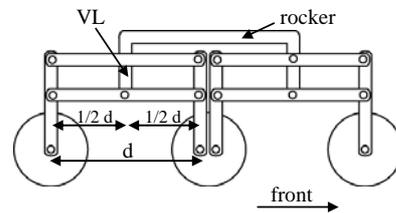
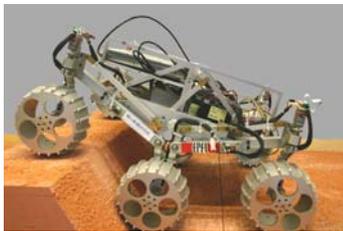


Fig. 2: CRAB I (modified back bogie on the obstacle)

The vertical middle links (VL) are positioned in the middle of the bogies at $1/2 d$ from the middle wheels which causes equal load distribution on both wheels of the bogies. However, the middle wheels take twice the load compared to the front and back wheels because they are connected to the front and back bogies. Another modification concerns the rocker and the back bogie. In order to respect the constraint regarding simplicity of the mechanics, the middle joint on the rocker was removed. As a consequence the back bogie had to be modified to avoid hyperstaticity. This was realized by connecting the back bogie with only one joint to the rocker which slightly changes the kinematical behavior of the bogie.

Unfortunately, while these modifications simplify the mechanical structure, they also reduce the locomotion performance. The simulations with the simulator POT (Performance Optimization Tool) revealed that the changes on the back bogie did not only influence kinematical properties, but also affected static properties in a negative way. Additionally to the performance reduction, the increased load on the middle wheel was not compliant with the general objective to have equal load on all wheels. Based on these drawbacks, the need for a more complex breadboard, fully incorporating the initial concept CRAB, became obvious and led to the breadboard CRAB II depicted in Fig. 3.

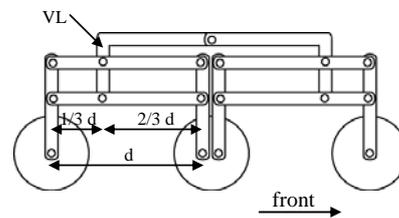


Fig. 3: CRAB II (two identical parallel bogies in front and back)

On CRAB II, the load is distributed evenly on all wheels because the VLs are placed at $2/3 d$ from the middle wheel. The front and back bogies are identical. The rocker which connects both bogies is divided into two elements with a rotational joint in the middle. Thus the system is fully symmetric. Version II of CRAB performs better than version I on the benchmark obstacle, in simulation and reality.

The Rovers RCL-E & MER

Concept E was proposed as a baseline for further development of a Mars rover locomotion system after evaluation of several different concepts. Fig. 4 shows a photo of the real 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 kinematical elements like the rear bogie can be suppressed because they don't act in the plane of the 2D view.

RCL-E consists of three parallel bogies. One is mounted on each side at the front of the chassis and hosts the front and middle wheels. The third bogie is mounted at right angle to the other bogies at the rear of the chassis. It serves as a leveling mechanism, thus the system doesn't need a differential mechanism. The CoM is situated right above the middle wheel, which creates equal load on all wheels.

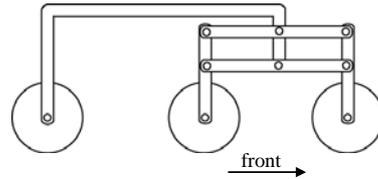
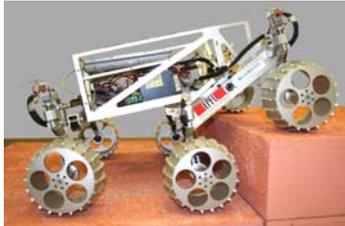


Fig. 4: RCL-E (parallel bogie on the front)

RCL-E is an interesting approach which keeps the mechanism simple (no differential). The breadboard was built as it was proposed in the ESROL-A report, except for some modifications that were imposed by external constraints (e.g. size of the rover, same wheels as on the CRAB) but didn't change the kinematics of the rover.

The MER (Spirit / Opportunity) are the most well known rocker bogie type rovers (Fig. 5). The design has six wheels of which the front and back wheels are equipped with steering capability. It is an asymmetric design in longitudinal direction; the distance between the wheels is not equal. In order to have equal load on all wheels the horizontal position of the CoM is slightly shifted forward.

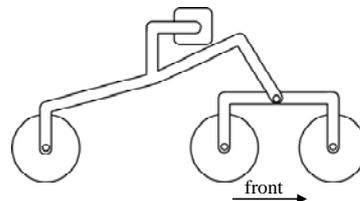


Fig. 5: Mars Exploration Rover Spirit of NASA

LOCOMOTION PERFORMANCE

This paper describes the evaluation of the locomotion performance of the CRAB and compares it to the performance of other rovers. Thus, it is important to be sure that the mechanical systems are comparable, i.e. that they have the same characteristics, and to define criteria that can be used to characterize the rover and allow drawing an objective conclusion about the rover's performance.

The metrics used to qualify the performance of the rovers are the torque requirement, the needed minimum friction coefficient to maintain the equilibrium and the slippage. The first two are discussed in detail in [9], where the friction coefficient is defined as the ratio between the tangential and normal force at the wheel-ground interaction. Slippage causes energy consumption without making the rover move forward and it deteriorates the odometry, therefore it has to be as low as possible.

In order to compare two vehicles, one has to be normalized with respect to the other because the original design propositions differ in many ways. Unfortunately, this procedure does not correspond to a simple scaling because the ratios between various elements of 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 a maximal terrainability, the rover mass is equally distributed on all wheels and the CoM at the same height on all rovers. These constraints provide excellent conditions for a rover comparison with a precisely defined benchmark test.

All tests were performed on the same terrain. The benchmark obstacle was a step of a height equal to one wheel diameter. The step is considered a very critical obstacle for a wheeled vehicle because of the vertical inclination which has the highest demands regarding kinematics and force distribution. Further, every phase of the climbing can be observed independently because the obstacle negotiation is not influenced by the obstacle's dimensions (like on a simple bump).

SIMULATION & HARDWARE SETUP

The Performance Optimization Tool (POT), which was used in this work to compare the performance of the different concepts in simulation, is described in detail in [10]. The POT can be used to quickly compare existing designs [9] or to design and optimize new structures in an efficient way.

The POT is based on a static model, which makes calculations very fast. Since exploration rovers typically move slowly (< 10 cm/s), dynamical effects are negligible and a quasi-static model is appropriate [11]. Since the rover has one DoF, controlling such a structure would require only one single motor. In reality, in order to increase the terrainability, every wheel is driven by a motor. As a result, there is an infinity of solutions that keep the rover in equilibrium. An optimization criterion has to be defined in order to select one solution. Reference [12] proposes, among different strategies, equal friction coefficients on all wheels to maximize traction. This is the approach adopted in the POT.

The results of the static analysis depend on the mechanical design only. No implementation of a control algorithm and no simulation settings like speed or torque interfere. This is an advantage of the quasi-static approach and allows the best possible objective analysis of the rovers' performance.

The breadboards of CRAB and RCL-E were designed in such a way that the same electronics, motors and wheels can be used for both systems. This modular design allows for quick setup and test of different locomotion concepts. The main dimensions of the breadboards are listed in Table 1.

Table 1. Main dimensions of breadboards

	Unit	CRAB	RCL-E
Total mass	[kg]	35	32
CoM	x_{CoM}	0.32	
	y_{CoM}	0.21	
Wheel track	[m]	0.65	
Wheel diameter	[m]	0.2	

The hardware tests were performed on a step obstacle of 0.2 m height, equal to the wheel diameter. Two different coatings with different friction coefficients were used for the experiments. One material has a rough surface and allows the wheel grousers to hook tightly into the terrain. The second material is rather soft (carpet like), however, its structure also permits the metal grousers to hook into the terrain. The main difference is the rover behavior when slip occurs. Slip on the second material is rather smooth, while on the rough surface slip is gruff and bumpy. All test runs were started from the same position and stopped when the back wheel was on top of the step. Runs 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. Two different controllers were used: regular velocity control and the wheel synchronization control algorithm introduced in [13].

OPTIMIZATION OF THE CRAB

As mentioned previously, the existing CRAB breadboard did not correspond to the original concept due to various reasons. However, two potential drawbacks were identified and simulation was used to verify this assumption. The effects of the modifications on the performance were analyzed independently in order to find out, if both characteristics have to be changed in a mechanical redesign.

The first analysis concerned the influence of the modified back bogie. Table 2 contains the maximal values for torque and required friction over a whole simulation. They show that the modified bogie has a negative impact on the locomotion performance. The maximum friction 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 middle lever of a regular parallel bogie is connected with two joints to the bogie, the modified version contains only one. On the one hand the two joints on the regular parallel bogie allow transmitting a torque between bogie and system, on the other hand the single joint connection on the modified bogie allows a rotation about this point, which results in a

different kinematical behavior. While the first difference becomes visible in the simulations, the kinematical differences still need further research.

Table 2. Maximum values CRAB (comparison of bogie types)

	Max. friction [-]	Max. torque [Nm]
CRAB II	0.64	6.0
CRAB I	0.90	7.7

The second analysis concerned the influence of the unequal load distribution on the wheels. Table 3 confirms a better locomotion performance of the original concept. It was to be expected that an equal load distribution leads to lower traction and torque requirements, since the load is partially taken off one wheel and distributed on to the other wheels. In the case at hand, the maximum values occur for the 1/2 – 1/2 configuration while the middle wheel with the heaviest charge is climbing the step. In the case of the 2/3 – 1/3 configuration the middle wheel is relieved and the peak occurs while the back wheel is climbing up (the maximum value being significantly lower).

Table 3. Maximum values CRAB (comparison of load distribution)

	Max. friction [-]	Max. torque [Nm]
CRAB II (1/3 – 2/3)	0.64	6.0
CRAB II (1/2 – 1/2)	0.73	6.6

According to these results a full redesign of the existing breadboard’s suspension system was highly recommended to profit from the full potential of the CRAB regarding locomotion performance.

ROVER COMPARISON (SOFTWARE & HARDWARE)

This section describes the results from simulation and hardware testing and compares the results of the two approaches.

Simulation

In simulation, all three rovers, introduced above, were compared. Fig. 6 depicts the results for maximum friction and torque requirements. The peaks in the figure appear every time one of the wheels has to climb the step. For better understanding, the maximum values for every peak are listed in Table 4.

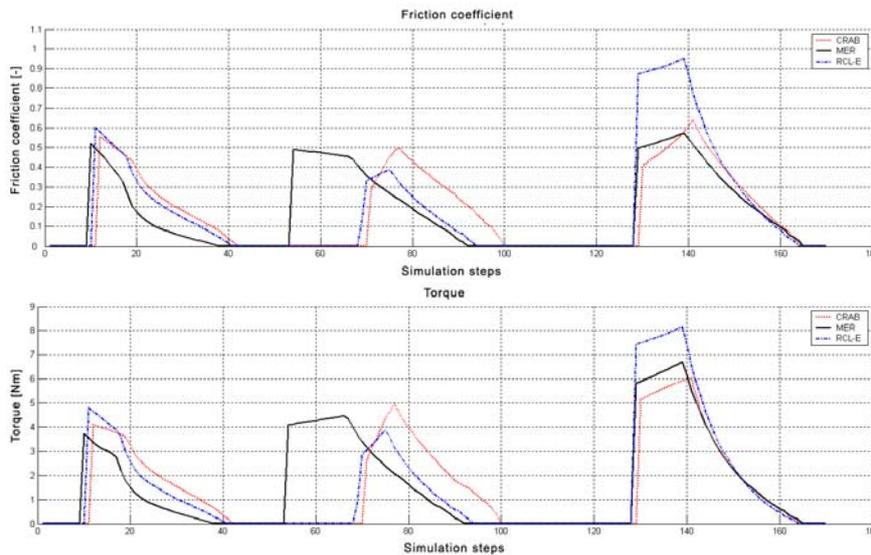


Fig. 6: Friction coefficient (top) and torque (bottom) for CRAB, MER and RCL-E

The maximum values (bold) for all rovers appear in the third column, i.e. that they all need the biggest effort when the last wheel is climbing the step. Regarding friction MER has the best performance, regarding torque CRAB performs best. The difference between these two rovers is roughly 10% for both criteria. RCL-E needs significantly higher friction coefficient and torque to climb the obstacle. The values in Table 4 show that the main problem of RCL-E is the

back wheel which takes too much load because it doesn't have any compliance in longitudinal direction (which corresponds to a fixed link to the main body of the rover).

Table 4. Peak values of friction coefficient and torque

	Max. friction coefficient [-]			Max. T [Nm]		
MER	0.52	0.49	0.57	3.75	4.47	6.7
CRAB	0.56	0.5	0.64	4.1	4.95	6.03
RCL-E	0.6	0.39	0.95	4.81	3.86	8.17

The CRAB has a symmetric suspension, whereas MER hasn't (unequal distance between the wheels; small bogie with big rocker). Therefore CRAB's performance is the same for forward and backward motion. The performance for forward and backward (see Fig. 5 for definition) motion of MER on the same obstacle is depicted in Fig. 7. It is clearly visible that the backward performance is significantly worse. Apparently, the asymmetrical design leads to very good forward, but rather bad backward performance. This can be disadvantageous in case the rover has to get out of a dangerous situation and is not able to turn in order to perform the maneuver.

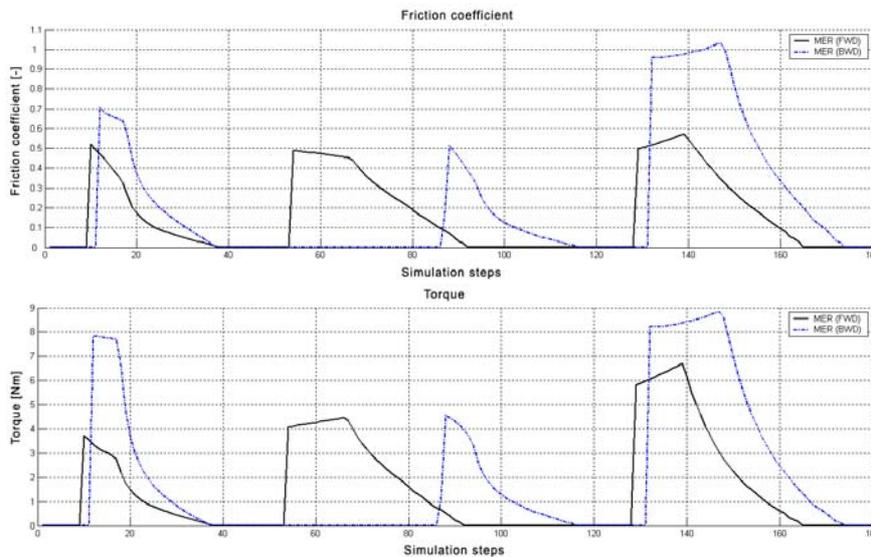


Fig. 7: Comparison MER forward and backward

Hardware

For each test¹, the current provided to each motor and the wheel encoder values were logged. The current graphs (Fig. 8, left and right side of the rover) show three significant peaks over the whole test run, which appear when a wheel has to climb the step. The different currents between the wheels at every peak are caused by unequal load distribution and kinematical constraints. Current saturation occurs, if a wheel is blocked; negative currents show that the wheels are fighting each other in certain positions. Both phenomena are caused by kinematical constraints. In the interval between the peaks the currents descend significantly because rolling resistance is the only force opposing the movement.

In Table 5, the summary of the tests performed with the CRAB is presented. The CRAB always succeeded climbing the obstacle on both types of terrain surface and with both types of controller. The mean value of slippage was 30.2 cm which corresponds to a slippage of 5 cm per wheel over a traveled distance of 120 cm.

RCL-E wasn't able to climb the obstacle with exactly the same motor configuration (standard settings) as CRAB. No test run was successful because the rover always got stuck when the last wheel tried to climb the step. Apparently the provided motor torques were not strong enough. The measurements of such a test are depicted in Fig. 9 on the left graph. Around second 22, the front and middle wheels start slipping, while the back wheel is blocked (saturation). The rover failed to reach the top of the step and the test had to be aborted.

¹ Videos available at: <http://asl.epfl.ch/~thuer/ASTRA06>

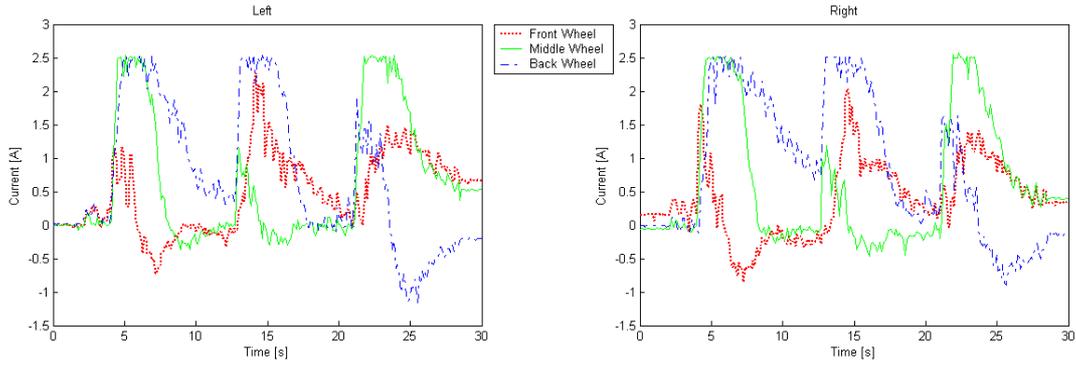


Fig. 8: Motor currents for left and right side (CRAB)

Table 5: Test results CRAB

Terrain surface		Rough		Soft	
Controller	Velocity	x		x	
	FIDO		x		x
Success rate		100 %	100 %	100 %	100 %

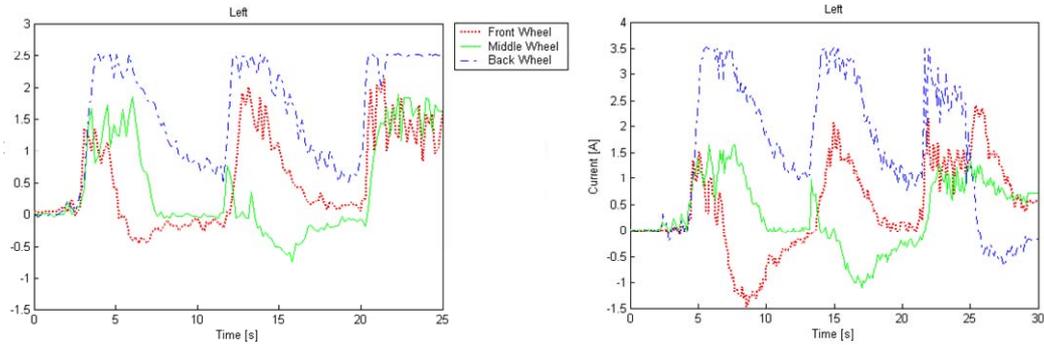


Fig. 9: Motor currents (RCL-E): back wheel blocked (left); successful climbing (right)

Table 6: Test results RCL-E

Terrain surface		Rough		Soft	
Controller	Velocity	x		x	
	FIDO		x		x
Success rate		33 %	0 %	50 %	80 %

In consequence, the current limits were increased (2.5 A \rightarrow 3.5 A) to provide bigger peak torques (8.6 Nm \rightarrow 12 Nm) in the critical situations. The summary of the tests performed with RCL-E with the changed motor configuration is presented in Table 6.

RCL-E succeeded in roughly 50 % of all tests. The performance was significantly better on the soft terrain surface. The controller influenced the performance in both directions depending on the test. The mean value of slippage was 41.9 cm which corresponds to a slippage of 6.9 cm per wheel over a traveled distance of 120 cm.

The right side of Fig. 9 shows the current measurements of a successful test. However, the noisy signal between seconds 22 and 25 reflects the shaky behavior that could be observed as the back wheel slipped repeatedly on the vertical surface before the rover finally got up on the step.

The fact that RCL-E failed almost half of the tests even with the modified motor configuration shows that the success not only depends on the provided torque, but also on the traction between wheels and ground. Apparently the friction coefficient of the test terrain has a critical impact for RCL-E.

Comparison

The simulation results predict significant differences between the rovers. They show advantages and drawbacks of the designs, as well as the performances relative to each other. The match between the results of the simulator and the experiments with the breadboards is excellent. The ranking for each performance metric is the same in simulation and for the tests. It is interesting to note that the specific weaknesses of one of the chassis detected during the design phase are clearly identified during the tests. Thus, the test results not only allow a comparison of the chassis, but they also confirm the predictions from simulation.

Even though the POT is only 2D and relies on a static model, some important characteristics of the rovers, predicted with the POT, could be verified with the hardware tests. Under equal conditions the CRAB climbs the step easily while the RCL-E gets stuck when the back wheel tries to climb the obstacle. Fig. 6 shows a significantly higher demand of RCL-E for torque. Even with increased torque RCL-E fails several times because its requirements regarding friction are very high. Both of these characteristics could be observed with simulation.

CONCLUSION & FUTURE WORK

A new locomotion concept called CRAB was presented in this paper. Its complex mechanical structure was explained and the evolution of the breadboard described. In order to put its obstacle negotiation capabilities in a bigger context, the CRAB was compared to other rovers in simulation and hardware. Its performance is similar to the one of the MER, however, thanks to its symmetrical structure the CRAB performs equally in both directions. The hardware tests confirmed the predictions from simulation. CRAB passed all tests successfully, while the conditions proved to be difficult for a rover with higher demands for traction and torque. Further studies on kinematics and dynamics will have to be performed to get a complete picture of the CRAB's performance.

ACKNOWLEDGMENTS

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