Evaluation of mobility concept for a Martian-rover

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***Abstract*— Evaluation and comparison of locomotion performance of rovers is a difficult, though very important issue. In the first part of this work, three different rovers were analyzed. Based on a kinematic model, the optimal velocities at the actual position were calculated for all wheels and used for characterization of the suspension of the different rovers. Simulation results show significant differences between the rovers and thus, the utility of the chosen metric. The focus is then on a research aiming at implementing an enhanced control to drive the six wheeled rover CRAB based on an optimal set of torques. The results include testing and comparison of the controller with a standard velocity controller in simulation which showed very promising performance. Further, the development of a tactile wheel, which allows measuring the wheel ground contact angle, is described. This component completes the necessary hardware setup for real testing of torque control.**

I. INTRODUCTION

In the context of all-terrain exploration robotics, the locomotion performance of a rover is due to several factors.

First, there are the mechanical aspects of the locomotion system defining its mobility. This includes, for example, the number of wheels, the suspension system, and the size of the rover [1], [2]. Thus, it is obvious that a four wheeled rover has reduced performances compared to the well known Mars Exploration Rovers [3] (MER) rover in rough terrain. However, in most of the cases, the evaluation and comparison of locomotion performance of rovers is a difficult issue.

Then, the locomotion performance of a given rover is not only based on its mechanics but is also highly dependent on its ability to interact with the environment. Thus, the difference of a controller integrating or not the model of the rover will greatly affect its performance and behavior.

This paper addresses these issues as follows. Section II addresses the problem of the evaluation and comparison of locomotion performance of rovers and evaluate them using a new metric. Three rovers, MER, as a representative of the rocker-bogie (RB) system, CRAB and RCL-E are presented and compared. The next section presents an enhanced controller applied to the CRAB rover. It is an optimal torque control which aims at optimizing the rover traction and thus, increasing its terrainability. Section IV shows the development of a piece of hardware called tactile wheel. This was specifically developed for the CRAB and provides necessary input for the torque controller. The paper is concluded with the summary of this paper a content as well as the future work orientation.

II. ROVER COMPARISON

In this section the analyzed rovers are briefly presented and the kinematic modeling is explained. For reasons of consistency, the same rovers were selected for the kinematic analysis as in [1] where more information can be found about the systems. The selected rovers are shown in Fig. 1. The kinematic models were simplified such that they still respect the geometrical constraints imposed by the suspension system, thus maintaining identical behavior as the real rovers. Since the original rovers differ with respect to many parameters, they were all normalized to the approximate dimensions of the MER[1] with the same total mass (∼180kg), wheels (⌀0.25m), foot print (∼1.5m) and CoG. This normalization allows for a proper comparison of the suspension types regardless of terrain characteristics.

Rough-terrain robots usually consist of several rigid elements connected through joints of a certain number of degrees of freedom (DoF) resulting in a structure that has one system DoF. This allows the rovers to move along an uneven terrain without loosing contact (in most cases). Rigid body kinematics for closed loop systems was used to represent these characteristics and establish the rover models.

A. Metrics

It is important to have metrics that precisely define what is considered a good or bad performance. The metrics used in this study are described below.

1) Difference between input and optimal velocities: Δvel_{opt}*:* This metric is a measure for the risk of violation of kinematic constraints through deviation from optimal velocity. This is the case, e.g., if a simple velocity control is used which sets equal speed on all wheels.

$$\Delta vel_{opt} = \sum_{i=1}^{n} |\vartheta_{ref} - \vartheta_{opt_i}| \quad with \quad i \neq ref \qquad (1)$$

where ϑ_{ref} = velocity of reference wheel,
ϑ_{opt_i} = optimal velocity of wheel i,
n = number of wheels.

As it was mentioned above, uneven terrain leads to different optimal velocities on the wheels. If the controller is not able to set the velocities accordingly, slip occurs because kinematic constraints are broken. Δvel_{opt} is an indicator of how good a suspension system adapts to the terrain

[1]Nominal driving direction of MER (trailing bogie) in opposite direction to definition in Fig. 1.

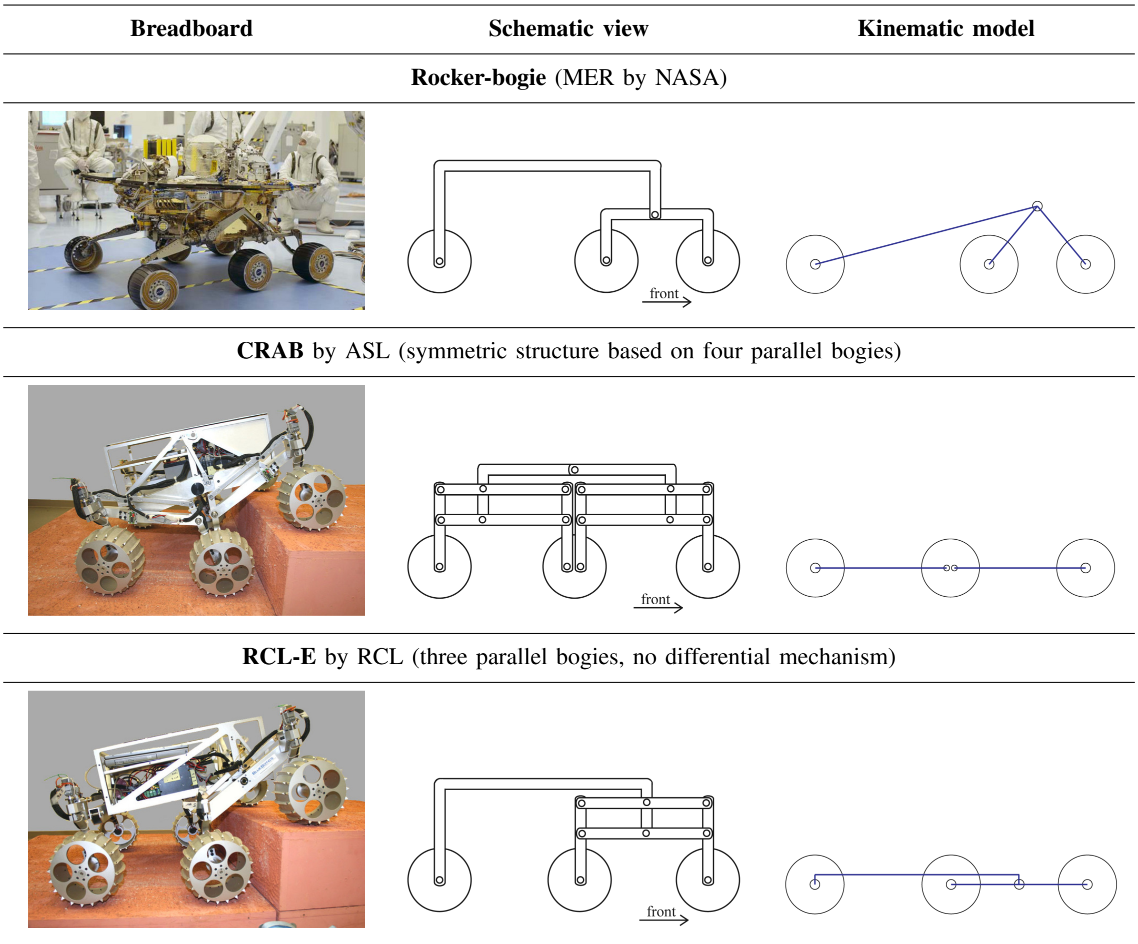

Fig. 1. Selected rovers: MER, CRAB and RCL-E.

while respecting kinematic constraints and not needing a sophisticated controller. If this value is small it is easier to control the rover because the kinematics impose similar wheel velocities, and the risk of slip is smaller.

2) Slip: Slip is defined as the difference between the displacement of a wheel measured at the wheel center point and the displacement derived from wheel rotation measurement with encoders.

$$\text{slip} = \sum_{i=1}^{n} |\Delta pos_{wheelcenter_i} - \Delta pos_{encoder_i}| \qquad (2)$$

Slip is bad for the odometry and it is a waste of energy because it does not contribute to the movement of the rover. Therefore this value must be small for good performance.

B. Simulation setup

All simulations of this section were performed using the software Working Model 2D (WM2D) by Design-Simulation [4]. It provides a nice graphical user interface (GUI) for easy definition of simulation runs. Fig. 2 depicts a normalized rover model on an randomly generated, uneven terrain. WM2D has an integrated interface to exchange data with Matlab in which the kinematic model is implemented. The motors are velocity controlled, i.e., constant velocity input.

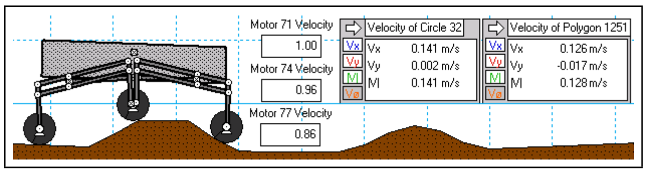

Fig. 2. Graphical user interface WM2D with CRAB.

C. Simulation results

The same simulations were performed for all three rovers under equal conditions. The results are presented in this section. First, the parameters that define a simulation are described.

- **Terrain**
  The selection of the terrains was motivated by the idea to have two distinct types: uneven terrain to represent a real environment (24m long, sinusoidal obstacles with defined max. height); artificial benchmark obstacle that allows analyzing what happens during obstacle negotiation due to decoupled climbing phases of the wheels (truncated pyramid, height equal to wheel diameter).
- **Control**
  First, the rovers were assessed with constant speed control, then the optimal velocity information was added

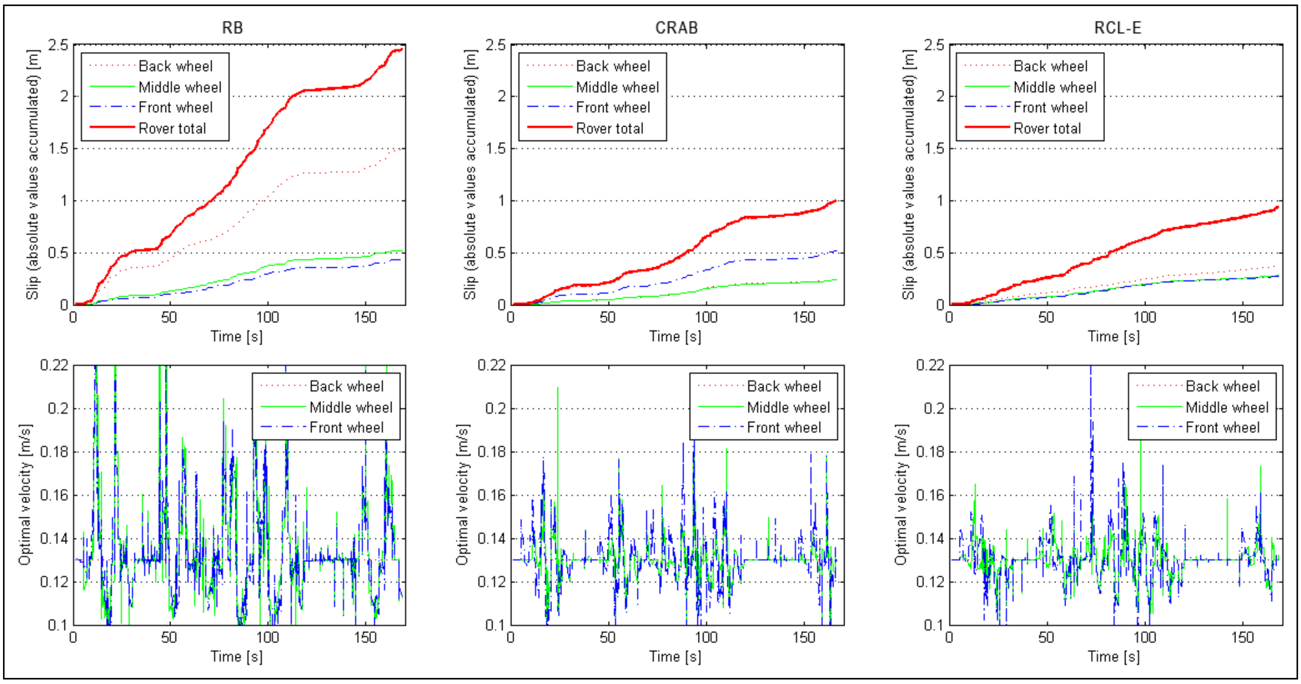

Fig. 3. Slip and optimal velocity of all rovers with rear wheel as reference.

to the controller (model-based).

- **Reference wheel**
  Indicates the wheel used as reference (1: rear; 2: middle; 3: front).

The results for test runs on artificial and uneven terrain are listed in TABLE I. The sum of the first metric Δvel_{opt} over the full simulation run is given. One can see that there is a significant difference between the performance of RB and the other rovers, CRAB and RCL-E. This means that the error would be much bigger on RB if a constant speed control was used on the rovers. In other words, RB has a higher need to adapt the wheel velocities in order to satisfy the kinematic constraints and reduce slip. This conclusion is supported by Fig. 3 where the total accumulated slip and the optimal velocities on uneven terrain are depicted. The curves show how Δvel_{opt} is reflected in slip measurements and that there is an important discrepancy between the performance of the RB and the other rovers. This metric cannot only be used to characterize the kinematic capabilities of a suspension type. The information about optimal velocities can also be included to compensate for the violation of kinematic constraints. Simulations have shown a significant improvement of performance for all rovers when the model-based controller was activated and the input velocities were adapted according to the optimal velocities from the kinematic model. The performances improved by values up to 70%, however, the relative ranking between the rovers remained the same.

III. Slip minimization by enhanced control

Most of the rovers are mechanisms which have a single degree of freedom (DOF) when neglecting their steering. They can move along a single trajectory, which is on a straight line or on a curve. Nevertheless in the context of exploration in rough terrain, the robots can face very challenging terrain and in order to enhance their terrainability, all their wheels are generally motorized. It follows that the CRAB, which is equipped with six motorized wheels for a mobility of one, is over-actuated and this means that there is an infinite number of solutions to control this DOF.

TABLE I

Results for metric Δvel_{opt}.

Rover	Δvel_{opt} [m/s]	
	Artificial terrain	Uneven terrain
RB	27.87	93.71
CRAB	12.17	37.53
RCL-E	12.72	35.69

The fundamental idea of the controller that this paper is concerned with consists of minimizing slip by efficiently distributing the torques on the wheels. The more a wheel is loaded, the higher the torque applied can be before it slips. For this reason, the controller is referred to as torque control. This approach is based on a static model of the rover that allows calculating the optimal torque for a given state. Since rovers move very slowly the static model is considered a good approximation.

The static model is based on the Newton-Euler formulation which states that in static state all forces and all torques are in a state of equilibrium. Setting up such an equation system for a 2D model is quite straight forward. If the model is to be extended to 3D, however, static indeterminacy becomes a problem.

A. *CRAB rover*

The CRAB rover is characterized by a mechanical suspension 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.

The mobility of a rover should be one and can be computed with Grübler's formula [5]:

$$MO = 6 \cdot n - 5 \cdot f_1 - 4 \cdot f_2 - 3 \cdot f_3 - 2 \cdot f_4 - f_5 \quad (3)$$

where MO is the mobility of the system (the rover in this case), n the number of mechanical parts and f_j the number of joints of all types ($j = 1 \ldots 5$).

The mechanical structure of the CRAB suspension system is composed of 30 parts and 41 pivot joints. To that, the six wheel-ground contacts have to be added which are assumed to be spherical joints ($DOF = 3$). Using these numbers the result of Eq. 3 is -43 for the CRAB's mobility instead of 1. This result is due to the multiples kinematic loops in the structure and redundancy of joints that provoke static indeterminacy. Therefore, the model has to be modified in order to conform to the mathematical constraints while preserving the real behavior (Fig. 4).

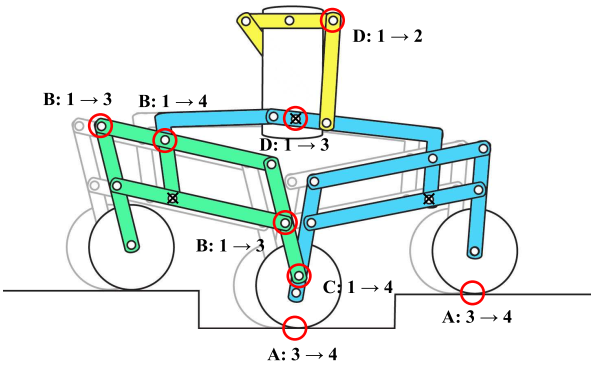

Fig. 4. CRAB rover schematic. All modified DOF joints in the model are indicated by red circles.

The first modification (A) concerns the wheel ground interaction as only two wheels out of the six can take lateral forces in order to avoid hyperstatism. Thus, four contacts are modeled as joints with 4 DOF instead of three. As a result only the left front and the right rear wheels take up lateral forces. In a next step (B) three joints of every parallel bogie (green) are given more DOF to be compliant with the constraints implied by these parallel mechanisms and the multiple loops induced. The third change (C) affects a single joint on each side of the structure. It concerns the loop formed by the parallel bogies and the articulated rocker (green and blue). Finally (D), the joints in the loop formed by the differential (yellow), the main body and the structures on both sides are modified to reduce the number of blocked DOF.

These changes lead to a CRAB model with a mobility of 1. Tests of the model representing various typical rover states showed that the equation system can be solved and the results conform to the rover behavior.

B. Equation system

The CRAB consists of 30 parts and can be characterized by 6*30 = 180 independent equations describing the static equilibrium of each body and involving 14 external ground forces, 6 internal torques and 165 internal forces for a total of 185 unknowns. The mechanical structure is considered massless whereas the weight of the main body and the wheels is taken into account.

As no interest is held in the internal variables, it is possible to simplify the equation system. The variables of interest are the wheel torques and the wheel ground contact forces which constitute a total of 20 variables and can be expressed by 25 equations. Nevertheless, the reduction of the system dimension comes with an increase of equation complexity. For this reason, 23 internal forces remain in the final equation system additionally to the forces and torques of interest.

C. Optimization

In order to solve such an equation system n-1 parameters can be chosen and input to the system (n = number of wheels). In the torque control algorithm this free choice is exploited in the sense that the torques are subject to an optimization algorithm. The criterion for the optimization can be described as minimization of the variance of the required friction coefficient G_i, as illustrated in Eq. 5. G_i is defined as ratio between tangential R_i and normal N_i contact force (Eq. 4) and its optimal value is equal for all wheels. The equation for the i^{th} wheel is:

$$G_i = \frac{R_i}{N_i} \quad (4)$$

The optimal set of torques $\vec{T}^{\star}$ is determined heuristically by Eq. 5 while respecting the mechanical constraints resulting from the rover structure.

$$\vec{T}^{\star} = \arg\min_{\vec{T}} \left(\sum_i \left(G_i(\vec{T}) - \bar{G}(\vec{T}) \right)^2 \right) \quad (5)$$

where $\bar{G}$ is the mean required friction coefficient.

This solution has the lowest friction requirements for the ground. The risk that the rover actually starts to slip in such a position is minimized although the terrain type is unknown. This solution corresponds to the best possible performance of the mechanical structure in terms of friction requirement.

D. Simulation

The simulations served several purposes: implementation and testing of the CRAB model; development of the control algorithms which will also be used on the breadboard; reproduction of former results adapted to current hardware (CRAB instead of the SOLERO rover [6]).

a) Controller: Different types of controllers for vehicles operating in uneven terrain have been proposed. In order to show the advantages of the traction maximizing control algorithm (torque control) it was compared to velocity control with wheel synchronization.

b) Torque control: The basic idea of the optimal torque control algorithm is to set torques according to the load distribution on the wheels in order to maximize traction. The static model presented above provides the torques that are needed to maintain the rover in a static state of equilibrium. In order to make the rover move, a PID controller which takes the velocity error as input and generates a correction torque as output is added to the control loop. The same control scheme as in [6] was used. This is depicted in Fig. 5.

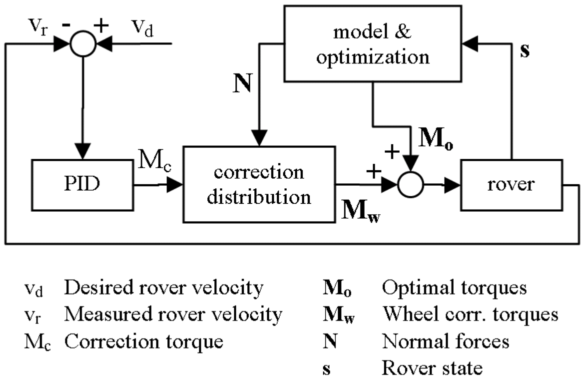

Fig. 5. Control scheme for optimal torques.

c) Wheel velocity synchronization: This algorithm aims at synchronizing the velocities of all wheels by detecting outliers, i.e. wheels that rotate at significantly higher speed than the others. Once the outliers are identified the mean rotation velocity of the wheels can be estimated more accurately. Based on the deviation of a wheel's rotational velocity from the estimated mean velocity a velocity correction term can be calculated [7].

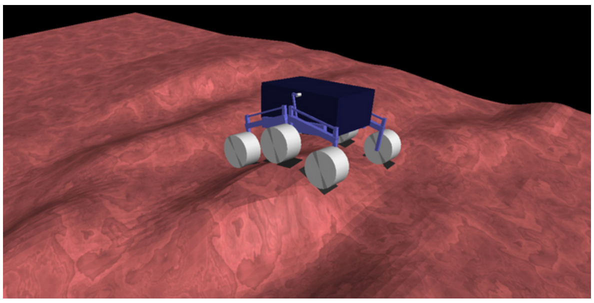

Fig. 6. CRAB rover during simulation.

E. Results

For the simulations, performed in ODE, [8] three different terrains were used. The rover was tested on all terrains, once with each controller. distance was slightly more than 4 m. An example is given in Fig. 7. which depicts the trajectories of the wheels and the rover body on terrain number 3. The terrains differ in number and size of bumps and are well suited for performance comparison. Three terrains are certainly not sufficient for a statistically complete analysis but the tests on those terrains provide enough data to illustrate the potential of torque control on uneven terrain.

The metric for the performance evaluation was slip. This choice was motivated by the fact that several aspects of a rover mission demand for as little slip as possible. Navigation is more accurate if the rover does not slip; since slipping wheels do not contribute to the rovers movement it is a loss of energy; slip can increase the risk of an operation failure due to loss of control over the vehicle.

There are two situations where slip occurs: the wheels are fighting each other due to uneven terrain or different velocities; the applied torque is too high and the ground cannot sustain the created traction. Torque control tries to avoid the latter by assigning bigger torques on wheels where the load is bigger because more traction can be generated.

The results of the simulations on the three terrains with both controllers ($\mu = 0.4$) are listed in Table 2. It can be seen that torque control helps reducing slip significantly. The improvement, however, depends on the terrain which is reflected in a range of 23 to 42% less slip. Even though this range is quite large, it promises a valuable gain in performance compared to the one of known, existing controllers.

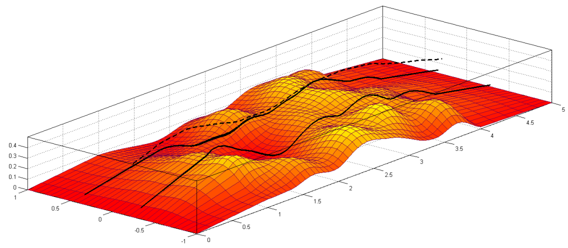

Fig. 7. Wheel and body trajectories on terrain number 3.

The total accumulated slip and the total slip per time step of all wheels together, while moving over terrain number 3, are depicted in Fig. 8. The graphs show the comparison between torque and velocity control, each for a different friction coefficient (0.4 to 0.6 top to bottom).

One can see that the rover slips less if driven with torque control but this difference decreases with an increasing friction coefficient. The more traction the ground can provide, the less important becomes the choice of the wheel torques. The remaining slip is mainly caused by wheels rotating at different velocities due to the uneven ground, not by lack of traction.

TABLE II

COMPARISON OF TOTAL ACCUMULATED SLIP WITH DIFFERENT CONTROL TYPES AND $\mu = 0.4$ (TOTAL TRAVELED DISTANCE OF ALL WHEELS TOGETHER $\approx 25m$).

	Control Type		
Terrain	Torque	Velocity	Diff
1	1.41 m	2.41 m	42 %
2	1.02 m	1.60 m	37 %
3	1.97 m	2.56 m	23 %

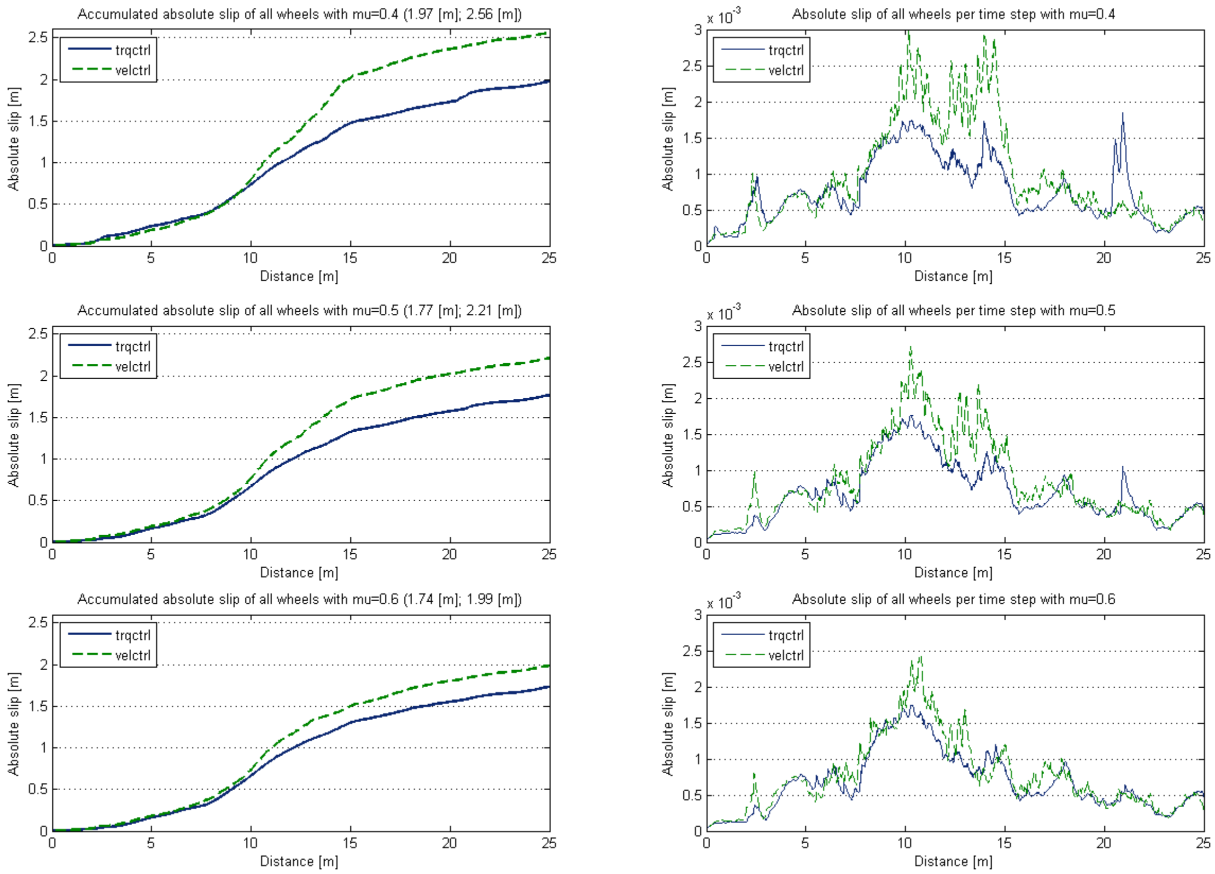

Fig. 8. Comparison torque and velocity control on terrain number 3. Total accumulated slip and total slip per time step ($0.01s$) with varying friction coefficient 0.4, 0.5 and 0.6 (top to bottom).

IV. Tactile wheel development

In order to implement and test the torque control algorithm on the real platform, it is necessary to get all the necessary inputs to the model. The actual actuator and sensory system of the CRAB rover is presented in this section and the sensors providing the needed information are described.

A. System overview

In order to use the model presented in section 2, the orientation of all parts of the suspension system are needed. This information can be either measured or computed based on measurements. The sensors used for this purpose are described below.

1) IMU: An Inertial Measurement Unit is mounted on the body of the CRAB. It provides the orientation (Euler angles) of the chassis.

2) Angular sensors: The relative angle between a permanent magnet and a sensor is measured. Six of them (three on each side) are positioned on specific joints of the bogies (marked with crosses in Fig **??**). The information they provide allows rebuilding the complete state of the suspension mechanism. This makes it possible to compute the relative orientation of all suspension parts in the rover coordinate system. In fact, four angular sensors would be sufficient for this task, but the redundant information sources provide a more reliable result.

3) Tactile wheels: Sensors that provide the information about the wheel ground contact angles. This input to the model is crucial to compute the optimal torques in uneven terrain.

B. Tactile wheel - mechanics

The tactile wheel detects objects, in general the ground or obstacles, which touch its external surface. A first tactile wheel was developed at the ASL for the Octopus rover [9]. It provided the contact angle by measuring the deformation of a rubber tire with several distance sensors inside the wheel. The same principle was to be used for the new wheel but the whole design should be better adapted to space mission requirements. Therefore the tire had to be replaced by a metallic ring. Further, the information about the deformation of the ring should be used for two different measurements. On the one hand its position should provide the wheel ground contact angle. On the other hand its magnitude should help derive the size of the applied contact force. Due to these additional constraints and the size and weight of the CRAB, a completely new design of the wheel was necessary. The presented tactile wheel is a flexible wheel, whose two basic elements, rim and ring, are made of metal. The rim is connected to the motor units output shaft. Spring elements transmit the torque from the rim to the flexible ring and keep the two elements at a well defined distance relative to each other. The selection of the spring elements was critical since they influence torque transmission and wheel deformation significantly. Four different concepts were tested and evaluated. They are depicted in Fig. 9: wheels a) and b), called MOVE and Sinus respectively, were developed by DLR [10], while c) and d) are ASL designs [11].

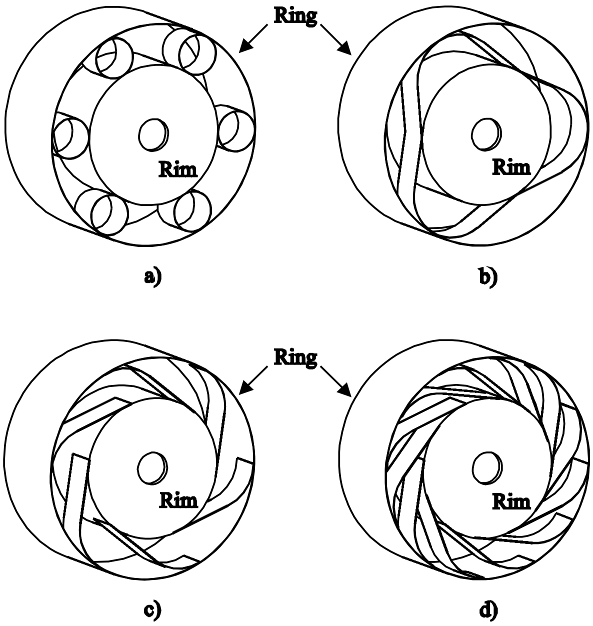

Fig. 9. Four spring concepts studied and tested for use in a metallic flexible wheel.

The arrangement as well as dimensions and thickness of the springs have an impact on the characteristic of the wheel. In order to measure deformations and characterize the wheels in terms of important properties like linearity and amplitude of the deformation a test bench was built.

The first inspected feature was the radial deformation of the wheel when exerting a radial force on the wheel at different angles. The desired characteristic was a homogeneous radial deformation. The second characteristic measured was the relative angular displacement of the rim with respect to the ring when applying a given torque to the rim. In the third test, the axial displacement of the rim with respect to the ring was determined. Ideally, both values should be as small as possible.

Another parameter of the wheel design was the number of rows of springs. Up to three rows with relative angular displacements of 30^o and 60^o were tested. The different spring concepts were not combined to additional designs.

The forces applied to measure the radial deformation were from $20N$ to $100N$ in steps of $20N$. This order of magnitude was defined based on simulations of the CRAB on a step obstacle performed with a 2D simulator [12]. An example of the test results is shown in Fig 10.a) and b) for the MOVE wheel and the iWheel12 respectively. It was to be expected that the curve of the iWheel12 would be more linear since it has more springs integrated. However, the tests revealed that it is necessary to have this number of springs to get the desired behavior that allows determining the applied force based on the amplitude of the deformation. Furthermore, it has to be pointed out that the design of the MOVE wheel does not allow increasing the number of springs enough.

The graphs of Fig 10 have different scales. The deformation of the iWheel12 is between 0 and $5.5mm$ and is smaller compared to the MOVE type results (i.e. between 0 and $9mm$). The iWheel12 is harder than the MOVE type wheel, but its deformation is more uniform, which is important. While the iWheel12 showed the smallest angular displacement in the second test, there were no noticeable differences of axial displacement in test three.

The results of the tests show the best performance of the iWheel12 with two rows of springs. Since the second row of springs points in the opposite direction a Sinus type configuration is formed as can be seen in Figure 11.a). Only two rows of springs are used, whereas it would be necessary to use four rows of Sinus type springs to have the same number of support points on the outer ring.

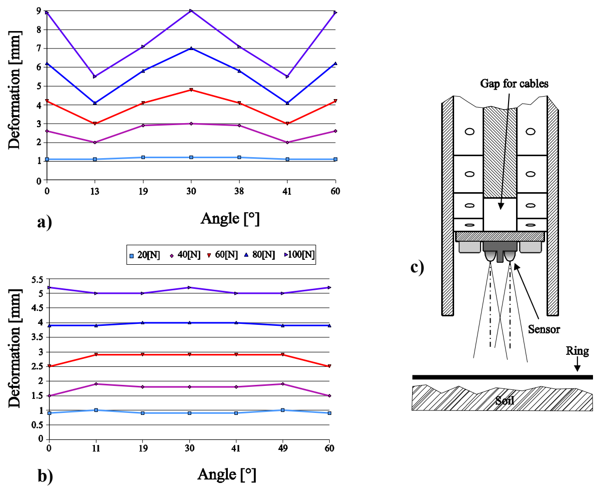

Fig. 10. Wheel deformation depending on the applied force. a) MOVE (2 rows of springs) b) iWheel12 (2 rows of springs) c) illustrates the measuring mechanism.

Fig. 11. iWheel12 flexible wheel a) Front view. b) Rear view with sensor rack.

The selected spring arrangement allows an increase in the number of supporting points without the need of adding more rows of springs inside the wheel. Only the number of springs per row has to be increased. This may be an option if the load on the wheel is increased.

C. Tactile wheel - electronics

To transform the flexible wheel presented in the last section into a tactile wheel, the deformation has to be measured. Therefore, infrared (IR) distance sensors were integrated inside the wheel. These are able to measure the distance from the sensor to the ring. A micro-controller drives the sensors and calculates the location and the degree of deformation of the wheel. Finally, it outputs the wheel ground contact angle.

The selection of IR sensors was a result of a comprehensive evaluation which included parameters like power consumption, size (volume) and mechanical complexity for integration. Two methods for the measurement of the deformation were considered. The direct method measures the distance between ring and rim. Physical principles suited for this method are return signal intensity measurement (light), triangulation (light), ultrasound, induction and linear potentiometer. The indirect method measures the real deformation on the ring or springs, for which strain gages could be used. The return signal intensity measurement was found to be the best solution for this specific application and the existing constraints. Inductive sensors are also an excellent mean to perform this task and have the advantage of not being sensitive to dust. Unfortunately these sensors are spatially too expensive and it would require a specific development.

The rack holding 19 sensors (Fig 11.b) is mounted on the non rotating part of the wheel assembly. The sensors are pointing downward (Fig.10.c) covering slightly more than 180^o, which is enough for the presented application. The rack also protects the sensors and limits the deformation of the ring.

V. CONCLUSION

In the first part, the rover locomotion performance was analyzed from a kinematic point of view. The main focus was laid on the characterization of suspension systems. Three different systems were compared based on two different metrics. The new metric Δvel_{opt} was introduced with the aim to characterize the suspension systems in terms of compliance with kinematic constraints while moving on uneven terrain. Slip was used as a second metric because it occurs when kinematic constraints are violated. The rovers CRAB and RCL-E performed well with respect to both presented metrics while RB's performance was significantly inferior.

In the following part, the current state of the CRAB robotic structure aiming at implementing an enhanced controller, using an optimal torque distribution, was presented. First, the rover model was set up which required a significant effort due to the complexity of the real system. The adaptation with respect to the real mechanical structure in order to obtain an equivalent model with a mobility of one was an intricate process. This model provides the basis to compute the optimal torques which minimize slip on the rover's wheels. The heuristic for the selection of optimal torques leading to equal friction requirements on all wheels was given. The controller itself uses the optimally distributed torques and adds a correction term based on the rover's velocity. It was compared to a standard velocity controller. It showed very encouraging results. The torque based controller had slip values reduced by 23 % to 42 %, depending on the simulation settings.

As this controller is supposed to be used on the real CRAB rover in the near future, the hardware has to provide all the necessary information which describes the rover's state. The last part of this paper presents the sensors available as well as the development of a tactile wheel. It is based on a flexible wheel whose deformation is measured to provide the wheel-ground contact angle. The next step lies in actually integrating the controller on the real platform and testing it. All the various components are now available, only their integration on the CRAB is missing. This is one of the main objectives of future research at ASL.

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