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Comprehensive Locomotion Performance Evaluation of All-Terrain Robots

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Abstract – Information about the locomotion performance of known rovers is sparse. A comprehensive evaluation of wheeled passive systems is presented in this work. It is based on a static 2D approach that includes optimization of the wheel torques in order to minimize the required friction which is an important performance metric. The evaluation comprises well known rover concepts and new suspension systems. The performance of the systems is compared and interesting effects of some concepts are discussed in more detail including torques and load distribution. The rovers MER (NASA) and CRAB (EPFL) show good performance which is topped only by the eight wheeled DoubleSpring system.

Index Terms – Rover, All-Terrain Robots, Locomotion Systems, Robot Design, Space Robotics.

I. INTRODUCTION

Autonomous vehicles in uneven terrain need to rely on efficient suspension mechanisms that allow negotiating obstacles of different kinds, while consuming the least energy possible to extend the time of autonomy.

There are two categories of suspension systems: active and passive. The first one can be subdivided into legged (e.g. Honda's ASIMO [1]) and wheeled (e.g. Octopus [2] of the Autonomous Systems Lab (ASL) at EPFL) systems. Active suspensions need actuators to change their state and adapt it to the terrain according to the information from the sensors on the rover. Active systems have great potential, however the required control system is very complex and the whole system susceptible to failure. Passive suspensions adapt to the terrain only through the applied contact forces and internal mechanical constraints which simplifies the control structure significantly and reduces the chances of failure of important components. Therefore our work focuses only on wheeled, passive suspension mechanisms.

Various locomotion systems with wheels have been proposed in the past. A broad overview can be found in [3]. Even though all rovers are designed to perform well in rough terrain, each design has its advantages and drawbacks. Unfortunately, information about the locomotion performance of the different rovers is sparse. To our knowledge very little test or simulation data are available. Additionally, the information that can be found is hard to compare because the rovers have different dimensions, the applied simulation techniques yield different outputs or the research teams use different metrics.

This work presents the first step towards a complete performance evaluation of most known wheeled, passive locomotion concepts. As a first approximation a quasi-static model was chosen. This is a legitimate approach because rovers generally operate at very low speeds. The main metric which was used is the minimum friction coefficient that a rover needs to climb a certain obstacle. This is a very important characteristic because the lower this value the smaller the chances that the rover slips or gets stuck in an unknown environment. Since all wheels of rovers are equipped with motors the locomotion system becomes hyperstatic. In order to find the minimum friction coefficient an optimization on the wheel torques is performed. Further parameters such as maximum torques and load distribution on the wheels are also considered in the discussion.

II. OPTIMIZATION TOOL

The results in this paper were obtained using an extended version of the 2D optimization tool (POT) [4] that was developed at our laboratory in the frame of the ESA (European Space Agency) project "Rover Chassis Evaluation Tools" (contract no: 18191/04/NL/PM). The POT is used for parametric studies because it is fast and allows quick modification of design parameters. It automatically generates the mechanical model of the rover, simulates the movement, performs the optimization and saves the output in a database.

III. QUASI-STATIC MODEL

It is important to do simulations of complex mechanisms before building prototypes. There are different approaches to simulate rovers, e.g. motion simulation tools like Adams®, dynamical models, kinematics analyses or quasi-static models. All of them have advantages and drawbacks, which make them more apt for specific purposes. This work aims at comparing a large number of concepts, therefore it is reasonable to start with a simple model in order to reduce work for model building and processing time.

Rovers in general move at low speeds (< 10 cm/sec) and inertial effects are very small. It is common sense that the quasi-static model, which considers only static forces and torques, is a good approximation. Ref. [5] has shown that the results are sufficiently precise to be included in a control algorithm to reduce slip significantly.

Since the model is based on static equations only, rolling resistance is one of the parameters which are not included in the model (as a consequence torques are zero when all wheel-ground contact angles are zero). Hence the torque values resulting from the model cannot be directly used for the rover design. However, this does not pose a problem because the model is used for comparison, not to obtain absolute values.

The selected model has significant advantages. The approach leads to the best possible performance the rover can achieve because the forces and torques are calculated by performing an optimization on the friction coefficient. The approach does not depend on control algorithms because the model is static. Thus the results are not influenced by the implementation and tuning of control parameters. The defined metric (friction coefficient) is an abstract value and the wheel ground interaction is represented by the relation between normal and traction force. This way the model remains independent from soil properties as they are needed for models incorporating Bekker's equations [6] and the results get a more general meaning.

Deriving the mechanical equations for a quasi-static model of a wheeled rover is a challenging task, especially when the rover contains parallel structures and closed kinematic loops. It is important to analyze the mobility of the rover using Grubler's mobility equation [7] which states for the 2D case that

$$f = 3 \cdot (n_B - n_G) + \sum_i f_{Gi} \quad (1)$$

with f = degrees of freedom (DOF), n_B = number of bodies (without ground), n_G = number of joints and f_{Gi} = DOF of joint. The mobility of a rover in the plane must be $f = 1$.

Because all wheels are motorized rovers become hyperstatic mechanisms with

$$f = 1 - n_w \quad (2)$$

where n_w = number of wheels. Thus, $(n_w - 1)$ wheel torques can be freely chosen and the best solution can be found using an optimization algorithm.

The goal of the optimization is to choose a set of wheel torques such that wheel slip is minimized. Slip should be avoided because it is a loss of energy and introduces error in the navigation, thus the performance is reduced. Rovers risk to get stuck, if too much slip occurs. Slip depends on the friction coefficient (μ) which can be expressed as ratio between normal (N) and tangential (F) components of the contact force:

$$\mu = F / N. \quad (3)$$

Ref. [8] has shown that the best solution corresponds to the situation when the required friction coefficient is equal for all wheels. Therefore the selected optimization criterion is the minimization of the variance of the friction coefficient of every wheel which can be written as

$$\min \sum_i (\mu_i - \bar{\mu})^2 \quad (4)$$

with $\bar{\mu}$ = mean friction coefficient. The optimization outputs the set of wheel torques which requires the smallest friction coefficient in order to keep the rover in a stable state.

A dynamic simulation requires speed or forces as inputs and provides the behaviour of the system as an output. Contrary to this, the movement is not inherent in the static model. Therefore it is crucial to understand that a mechanically valid rover state is the input to the model and the simulation outputs the required forces to maintain this state. Further, it is necessary that all wheels are always in contact with the ground. The aim of the tool is to find the best performance possible which cannot be the case if not all the wheels touch the ground.

IV. PERFORMANCE METRICS

As it was mentioned above, the definition of metrics is difficult since outputs vary depending on the simulation type. This section describes the metrics that are used while working with the quasi-static model. When choosing the metrics one has to be aware of the fact that dynamics, hence speed and acceleration, are not considered in the quasi-static model. Thus it is not possible to predict performance regarding power and duration for the traveled distance. Slip can not be predicted neither.

A. Minimum Friction Coefficient (μ)

The minimum friction coefficient needed to climb an obstacle describes the locomotion performance in terms of terrainability [9]. The smaller this value the smaller the chances that the rover encounters a situation in a real environment where the soil does not support the needed traction, the wheels start to slip and the vehicle may not even be able to advance.

B. Minimum Wheel Torque (T)

This metric addresses the motor requirement. Motors are dimensioned with respect to the maximum required wheel torque. As a consequence, a rover that requires less torque, needs a smaller motor. Small motors add less weight to the rover and consume less energy, both important factors, especially on space missions where energy is limited and additional weight increases costs for transport.

These two metrics are scalar values. This allows easy comparison, if a lot of results are available. However, scalar values contain limited information, thus it is important to analyse the curves describing the friction coefficient and the wheel torque over the full simulation to understand the performance. Therefore diagrams are displayed in the results section instead of simple values. The minimum friction coefficient, as well as wheel torque can be derived from them.

It is important to point out that the metrics "minimum friction coefficient" and "minimum wheel torque" correspond to the maximum values in the diagrams because they describe minimum requirements, meaning that the rovers need at least this value to maintain the current position.

The commonly known metric “maximum step height” provides information only about the performance on a specific soil. Because the presented approach is independent from soil properties, this metric can not be used.

In order to understand the behavior of the rovers it is essential to include the normal and tangential components of the contact forces in the evaluation.

V. ROVER CONCEPTS

The evaluated rover concepts are presented in this section. Asymmetric structures (in longitudinal direction) were assessed in forward and backward mode. The front of a rover is defined as being on the right side of the schematic drawings below.

The models used in the 2D simulator consist of bodies represented by point masses and joints that are ideal. The structure is considered massless, only the wheels have masses as well as the body that represents the chassis with payload. This assumption is sufficiently realistic, because the mass of chassis and payload is much bigger than the mass of the structure.

The selection of assessed locomotion systems contains known rovers as well as new propositions. All systems have equal load on all wheels while on flat ground. Most of the rovers have six wheels, some new propositions have eight wheels. It is important to point out that rovers with four wheels on each side need steering capability on at least three wheels per side (independent steering [9]) because the middle wheels make proper coordinated steering impossible. The additional weight for the steering normally is considered as a disadvantage, unless the system can compensate it with significantly superior performance; however this work is not affected by this subject because it deals only with the 2D case, thus no steering.

To allow a proper comparison, the different concepts had to be normalized. Different rules for normalization have been proposed [10], however none of them being applicable because too many parameters interfere, such as wheel diameter, mass and outer dimensions. Scaling all parameters equally can lead to absurd results. Because the MER is the only rover that was ever used on a real mission it was taken as reference. The other systems were adapted in a way that they all have the same length, mass, wheel diameter and vertical position of the center of mass (COM) as the MER by keeping equal load on all wheels. This approach is supported by the fact that the evaluation is about concepts of locomotion systems, not fully designed rovers.

A. Mars Exploration Rover (MER)

The MER (Spirit / Opportunity) are the most well known rocker bogie type rovers. The design has six wheels, whereas the front wheels are equipped with steering capability. It is an asymmetric design, 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. Other robots like Rocky7 [11], FIDO [12] and Sojourner [13] are based on

very similar locomotion systems with small changes (e.g. unequal load on wheels).

Fig. 1: Mars Exploration Rover (MER) of NASA

B. SOLERO

Fig. 2: SOLERO of ASL (EPFL)

The SOLERO [14] (similar to Shrimp [15]) has one parallel bogie on each side and the characteristic fork containing a spring in the front. The back wheel is linked to the main body without compliance. The front and back wheels are equipped with steering capability, whereas the middle wheels slip while turning. In order to have equal load on all wheels the COM is shifted slightly backwards and the spring constant is chosen accordingly.

C. CRAB

Fig. 3: CRAB of ASL (EPFL)

The CRAB has two parallel bogies connected at the bottom through the middle wheel and at the top with a rotational joint to prevent hyper-statism. The vertical middle levers of the bogies are placed at a $2/3 - 1/3$ ratio from the middle wheel in order to distribute the weight of chassis and payload evenly on all wheels because the COM is exactly above the middle wheel.

D. RCL-E

The RCL-E [16] has one parallel bogie on each side in front. The back wheels are mounted on a transversal parallel bogie that serves as a levelling mechanism in case of asymmetric obstacles. However, this mechanism has no influence on 2D terrains and can be replaced by a rigid link between chassis and back wheel without changing the kinematics of the rover. The COM is situated above the middle wheel.

Fig. 4: Concept E (RCL-E) of Rover Science and Technology Company (RCL; a VNIIT Transmash subsidiary) developed for ESA

E. RCL-C

Fig. 5: Concept C (RCL-C) of RCL developed for ESA

The RCL-C has a bogie between back and middle wheel, whereas there is a structure with a joint in between middle and front wheel. Both these elements are connected with a joint to the chassis forming a closed kinematical loop. The COM is situated above the middle wheel.

F. CRAB-S

Fig. 6: CRAB-S (new concept)

The CRAB-S concept is similar to the CRAB, but the parallel bogies were replaced by regular bogies and connection joints were added to the bogies to provide the required degrees of freedom. The system is symmetric with the COM in the middle.

G. CRAB-8

Fig. 7: CRAB-8 (new concept)

The CRAB-8 concept is an eight wheeled suspension system that makes use of two parallel bogies on each side which are connected to the chassis. The system is symmetric with the COM in the middle.

H. DoubleSpring

Fig. 8: DoubleSpring (new concept)

The DoubleSpring concept makes use of springs like the SOLERO. It consists mainly of a chassis with two wheels on each side and wheeled trailer-like structures in the front and back. Compression springs between chassis and trailers help to distribute the load evenly on all wheels. The system is symmetric with the COM in the middle. (The shown configuration has a very limited ground clearance, a problem that can be easily solved when designing the real mechanics.)

All concepts need a differential mechanism between both sides (in 3D) to level the chassis' inclination angle except for RCL-E which has a parallel bogie in the back for this reason.

VI. SIMULATIONS AND RESULTS

A step obstacle of the same height as the wheel diameter was chosen for all simulations. It is a very challenging obstacle regarding performance and allows analyzing the different steps of obstacle negotiation individually (decoupled information). Results from other obstacles can be significantly influenced by their dimensions (e.g. bump). The outputs from the step obstacle give information about the real limits of a locomotion system.

Most of the concepts were assessed in different configurations as well as in forward and backward mode. RCL-E and CRAB were also tested in variants that adopted the unequal wheel distances of MER. A similar change was applied to CRAB-8 by making the bogies of different lengths. In this section, however, only the best results are shown. All six and eight wheeled locomotion systems are compared among each other, followed by some interesting specific results.

The peak values in the graphs below occur when a wheel has to climb the step (see Fig. 9 for an example). The maximum values per peak and rover are listed in TABLE 1 and TABLE 2.

Fig. 9: Example car on step

Fig. 10: Friction coefficient of six wheeled systems

TABLE 1
μ peak values of six wheeled systems

	Max μ per peak			Variance
MER	0.65	0.5	0.6	0.15
CRAB	0.62	0.55	0.68	0.13
RCL-C	0.74	0.44	0.59	0.3
CRAB-S	0.64	0.7	0.82	0.18
RCL-E	0.65	0.48	0.87	0.39

Fig. 10 shows the friction coefficient of the six wheeled suspensions. According to the results one can distinguish three groups: MER and CRAB with $\mu < 0.7$; RCL-C with $\mu < 0.8$; CRAB-S and RCL-E with $\mu > 0.8$. It is interesting that some systems require the biggest friction coefficient when the front wheels is against the step, while it is the back wheel for others, but never the middle wheel. Further, the variance of the peaks per rover varies between 0.13 (CRAB) and 0.39 (RCL-E). In the case of the RCL-E the third peak is very dominant, decreasing the performance significantly. This kind of information can be used to detect potential for optimization of the system.

Fig. 11 shows the friction coefficient of the eight wheeled systems and SOLERO, whose 2D model has four wheels too. Since the load of these locomotion systems is distributed on more wheels than on the six wheeled suspensions it was to be expected that they would show superior performance. This is confirmed by TABLE 2. The performance of SOLERO and CRAB-8 is similar to the good results of MER and CRAB, while the maximum value of the DoubleSpring system is significantly lower at 0.55.

Fig. 11: Friction coefficient of eight wheeled systems and SOLERO

TABLE 2
μ peak values of eight wheeled systems and SOLERO

	Max μ per peak			Variance
DoubleSpring	0.46	0.29	0.55	0.26
SOLERO	0.46	0.58	0.43	0.63
CRAB-8	0.51	0.35	0.69	0.52

Fig. 12: Torques of SOLERO

The variance of the peaks of CRAB-8 is quite big (Fig. 11). The system has problems when the third wheel has to climb the step because the load on this wheel is too big in this situation. SOLERO has a similar problem with the back wheel. This can not be detected though by analyzing the friction coefficient only, because the last peak is not much higher than the second one. However, the peaks of the torques (Fig. 12) clearly show that the load is strongly unbalanced: 28 Nm, 39 Nm, 44 Nm, 66 Nm. The source for this problem is evident; there is no compliance between the chassis and the back wheel.

The following example of MER moving forward and backward shows the importance of direction for asymmetric systems. While MER shows very good performance moving forward, the requirements regarding friction are quite bad when going backwards (Fig. 13). The analysis of the normal forces reveals that the middle wheel takes hardly any load at the first peak when moving backwards, so it can only contribute little to make the rover advance. Additionally, the load on the back wheel at the last peak is much bigger in backward than in forward mode which leads to poor performance.

Fig. 13: Comparison of friction coefficient of MER forward and backward

Fig. 14: Comparison of normal forces of MER and RCL-E

Fig. 15: Normal forces of DoubleSpring

If RCL-E is further adapted to MER dimensions (COM slightly advanced, unequal distance between wheels), the two concepts in general differ only in the type of bogie. The influence of the bogie type on the performance is surprising (Fig. 10). The normal forces in Fig. 14 display the different behavior of the two concepts. Their force distribution in zones A and B is quite different. Additionally, the tangential forces show that the load at peak three is almost 1.6 times bigger for RCL-E.

Finally, a special phenomenon of DoubleSpring has to be mentioned. When the first wheel is on the vertical part of the step, the second wheel almost loses contact with the ground (Fig. 15), because the spring force becomes too big and tries to lift the rover chassis. However this has no negative influence on the performance as it was shown above. Decreasing the specific spring constant would solve this issue, but the equal load distribution on a flat surface would be lost.

VII. FUTURE WORK

The approach will be extended to 3D in order to assess the performance on asymmetric obstacles and the case of a rover hitting the obstacle at an angle. Kinematical aspects must also be analyzed to complete the evaluation. Finally the results will be verified on existing and new rover breadboards.

VIII. CONCLUSION

An extensive locomotion performance evaluation was presented in this work. Because the approach is quasi-static and an optimization searches for the ideal solution, the results are independent from control algorithm and soil properties, therefore allowing comparison on a more abstract level and showing the real potential of a locomotion system. The friction coefficient is an important parameter because it provides information about the probability if a rover will slip or even get stuck. Therefore it is used as main metric.

MER and CRAB showed the best performance of the six wheeled concepts. Even though RCL-E appears to be quite similar to MER in 2D, the analysis of the forces shows that the behaviour is different, leading to significantly inferior performance of RCL-E.

As it was to be expected the eight wheeled concepts perform very good. The performance of the DoubleSpring concept is even outstanding, the springs transferring some of the load successfully to the trailer-like parts in the front and back.

The presented approach provides valuable information about the locomotion performance and suits very well for the early phases of the evaluation process of locomotion systems.

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