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RCET: ROVER CHASSIS EVALUATION TOOLS

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ABSTRACT

A set of tools is being prepared in the frame of ESA activity [18191/04/NL] labelled: "Mars Rover Chassis Evaluation Tools" to support design, selection and optimisation of space exploration rovers in Europe. This activity is carried out jointly by Contraves Space as prime contractor, EPFL, DLR, Surrey Space Centre and EADS Space Transportation. This paper describes the current results of this study and its intended used for selection, design and optimisation on different wheeled vehicles. These tools would also allow future developments for a more efficient motion control on rover.

INTRODUCTION AND MOTIVATION

A set of tools is being developed to support the design of planetary rovers in Europe. The RCET will enable accurate predictions and characterisations of rover performances as related to the locomotion subsystem. This infrastructure consists of both S/W and H/W elements that will be interwoven to result in a user-friendly environment.

The actual need for mobility increased in terms of range and duration. In this respect, redesigning specific aspects of the past rover concepts, in particular the development of most suitable all terrain performances is appropriate [9]. Analysis and design methodologies for terrestrial surface vehicles to operate on unprepared surfaces have been successfully applied to planet rover developments for the first time during the Apollo LRV manned lunar rover programme of the late 1960's and early 1970's [1,2]. Key to this accomplishment and to rational surface vehicle designs in general are quantitative descriptions of the terrain and of the interaction between the terrain and the vehicle. Not only the wheel/ground interaction is essential for efficient locomotion, but also the rover kinematics concepts.

In recent terrestrial off-the-road vehicle development and acquisition, especially in the military, the so-called 'Virtual Proving Ground' (VPG) Simulation Technology has become essential. The integrated environments previously available to design engineers involved sophisticated hardware and software and cost hundreds of thousands of Euros. The experimentation and operational costs associated with the use of such instruments were even more alarming. The promise of VPG is to lower the risk and cost in vehicle definition and design by allowing early concept characterisation and trade-off's based on numerical models without having to rely on prototyping for concept assessment. A similar approach is proposed for future European planetary rover programmes and is to be enabled by RCET.

The first part of this paper describes the methodology used in the RCET activity and gives an overview of the different tools under development. The next section details the theory and modules used for the simulation. Finally the last section relates the first results, the future work and concludes this paper.

METHODOLOGY

The RCET will be a database driven software application dedicated to rover simulation, augmented by two dedicated H/W testbeds. 3-D rover simulation is part of the RCET because it is the best way to have an irrefutable comparison of different rovers and locomotion concepts without need of manufacturing them. However, this simulation requires a 3D CAD model not available in the first design phases and takes a long time with current PC's when the simulation precision is high. In this case, it becomes practically not possible to perform a parametric analysis for optimising the vehicle. For these reasons, a set of 'parametric tools' is also part of the RCET and will allow design and simulation of rovers in a short time.

The parametric tool will allow the characterisation of locomotion performances of rovers at early stage of the design process and first-order trade-off studies. This set of application consists mainly of a 2D-rover simulator that uses a tractive prediction module for computing the wheel/ground interaction. A user interface will allow design of 2D-rover and 2D-terrain and a report generator will be specially developed to understand the influence of internal parameters of the locomotion performances. In conclusion the parametric tools will allow to have, in a short time, a rough assessment of the viability of a given vehicle structure concept and allow optimising the rover structure. Then the 3D-simulator will be used for validation of the rover concept w.r.t a full 3D environment.

Test and measurement of wheels and rovers is complementary to the simulation, for calibrating the applications and for validation purposes. Two different testbeds, one dedicated to a single-wheel characterisation and another for the rover system-level locomotion performance evaluation, will be used in the development and tests phases of mobile structures. The two testbeds allow validating experimentally the tractive prediction application, which inherently involve several aspects that are difficult to model. In particular the power consumption and, in general, the locomotion performances are investigated. This strong interaction between H/W and S/W during the calibration, validation and utilisation phases of the RCET requires an architecture that allows data exchange in an easy way.

RCET ARCHITECTURE AND FUNCTIONALITY

To generate useful reports for both H/W and S/W tools and allow irrefutable comparison of different rovers and locomotion concepts, the different RCET modules need to interact together. In particular for estimating the simulation precision and calibrating the different applications, data comparison has to be done between both real measurement and simulation. For this purpose, the communication between the integrated tools will be done via database entries and by communication with processes of the MMI.

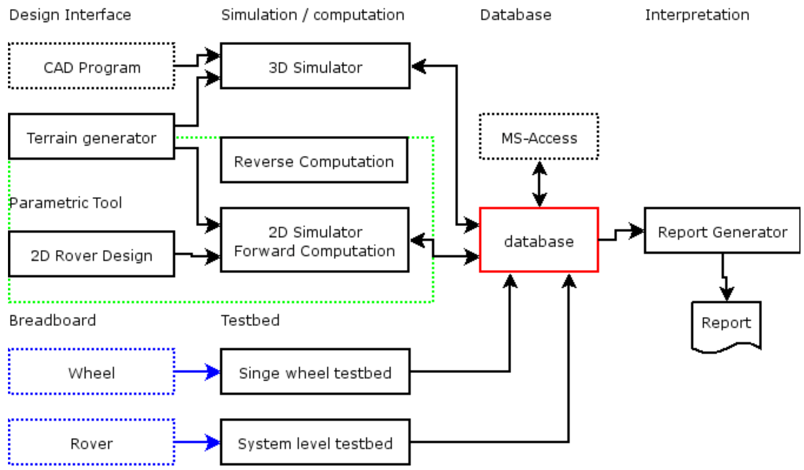

Figure 1: RCET architecture and tools interaction

WHEEL GROUND INTERACTION THEORIES

An important aspect of designing planetary rovers is the consideration of the soil physical properties such as soil shear strength, compressive strength, bearing capacity, penetration resistance, etc. The most important soil parameters are related to shear strength quantified by the Mohr-Coulomb relation.

The Bekker analysis provides the basis for determining the theoretical performance of a vehicle traversing on a particular soil. The soil shear strength *(τ)* is characterised by soil cohesion *(C_o)* and internal friction angle *(ϕ)* quantified by the Mohr-Coulomb law such that the shear stress is defined as:

$\tau = C_o + \sigma \tan \phi$ *(σ = normal stress)*

The soil thrust *(H)* provides the tractive effort. The maximum tractive thrust available from the soil over a vehicle contact area *(A)* is given by the Bernstein-Bekker equation [10,11]:

$H = A\, C_o + W \tan \phi$ *(W = vehicle weight)*

The soil thrust will be modified by slippage. Slip *(s)* is a function of tractive force and is dependent on vehicle velocity *(v)*. It is defined as follow [3]:

$s = |\,(r\omega - v) / r\omega\,|$ *($r\omega$ = wheel rotational speed* and *v = wheel velocity)*

Motion resistance *(R)* can be decomposed as follow:

$R = R_c + R_b + R_t + R_g$ *(compaction, bulldozing, tyre hysteresis and gravitational resistance)*

Finally the Drawbar pull *(DP)* is the difference between soil thrust *(H)* and motion resistance *(R)* and it defines trafficability:

$DP = H - R$

More details related to terramechanics theory can be found in [8, 10, 11 and 12].

A tractive prediction module will be part of the RCET and can be easily integrated in future simulation applications. It incorporates modified Bekker equations that are solved numerically for a given wheel, soil and load. As main input, this element requires the wheel characteristics, the normal force and the soil parameters. The main outputs are the soil-wheel interaction parameters: wheel sinkage and drawbar pull.

First the simulation application has to find the load repartition for each wheel and the contact angle between the wheels and the ground. The tractive prediction module will return the maximum traction force for each wheel for a given slip, and thus the corresponding load torque acting on the wheel. In vehicle operations, the torque applied to each wheel is a control-dependent parameter. Usually, for planetary rovers with low speed motion, the motion control is with constant torque (open loop motion control) or constant speed (speed motion control).

ROVER LOCOMOTION PERFORMANCES METRICS

The locomotion metrics have to be defined to evaluate rover's capabilities to perform motion on a given terrain. The rover objective for planetary exploration is to bring the scientific instruments to a specific site in order to examine geology, mineralogy or exobiology on other planets [9]. The best rover is considered as the one that can transport the scientific P/L and reach the goal by appropriate motion on a specific and unknown terrain with less power consumption, mass and volume requirement in storage configuration as compared to competing concepts.

The RCET evaluate the rover chassis independently of the navigation strategy and software. Because the functionality of a chassis is linked to the terrain, the locomotion metrics can only define which is the best rover for a specific mission. The main RCET proposed metrics are:

The **mean free path is** the expected straight line path distance that the rover can follow over a given terrain before a heading change is required.

The **drawbar pull** (net pulling force) is the soil thrust reduced by motion resistance. Expended for either acceleration or slope climbing.

The **mean maximum pressure** is related to the ground pressure incurred by the vehicle and is important since a given terrain can only support a certain maximum load without excessive vehicle sinkage.

The **minimum required slip** is needed to allow motion against resistive forces from soil (i.e motion resitance); it should be as small as possible for best efficiency and thus low energy consumption. The slippage is also important for the navigation system.

A **minimum friction coefficient** is required to negotiate a given reference terrain is the key metrics to compare suspension mechanisms (kinematics).

The **energy consumption per unit distance** is important for the power management and has to be minimised by the rover kinematics, control and by appropriate wheel design in particular in rough terrain and when turning.

The different simulation tools can output even more detailed data than these metrics. For this reason, the architecture design allows to store all data in a database. This feature provides flexibility for further data analysis and the possibility to plot graphics according to the user's specific needs.

ROVER SIMULATION METHODOLOGY

There are two main simulation methodologies. A mathematical description of the rover allows solving directly the Newton-Euler equations. If the resolution of the equations can be computed in an very fast time (real time), the main disadvantage is that the equations are different for each rover and are not trivial to establish [7]. The other possibility is to have a general structure description based on joint definition between two solids. To allow easier rover description, the RCET is based on this second principle and investigated mathematical sub-structure description for reducing simulation time .

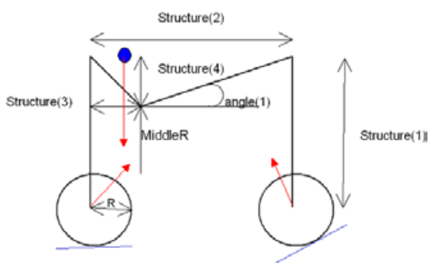

Figure 2: Parametric rover structure description with normal forces

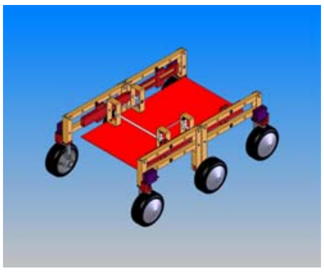

Figure 3: 3D model of the rover CRAB (EPFL)

RCET ROVER SIMULATION

As shown in [Figure 2], the rover structure (or chassis) is described with bodies connected to each other with joints. The articulated rigid body structure can then be simulated using a stable integrator. In the RCET, the structure design in 2D is done with a dedicated rover design interface which is part of the parametric tools. Computing the normal force applied on each and utilisation of the tractive prediction module for establishing the wheel/ground interaction parameters does the rover simulation. The simulation time increases with the required precision so that simulation in real time is no more possible. The results will be post-treated with the appropriate application, e.g. plotting user defined graphics, printing of the performance evaluation sheet or generating a movie of the simulation run.

When a CAD model of the rover is available, a 3D simulation can be performed with the help of RoverGen, a 3D simulator for SolidWorks, which uses COSMOS/Motion developed by ADAMS®. The software comprises of a user-friendly interface developed by the study team using a Windows® interface. All the needed parameters are inputs in the front-end interface, which are directly transmitted to the simulator for conducting a simulation run using those user-defined parameters. The performance matrix gives an indication of the capability of an individual concept to perform motion on a predefined terrain under a fixed set of operating environmental parameters.

RCET TESTBEDS

During development of mobile vehicles for use on planetary surfaces it is essential to validate locomotion performance in laboratory conditions to allow repeatability of experiments. For RCET, a single wheel testbed [Figure 4] and a rover system-level testbed [Figure 5] are being developed. Both testbeds feature soil bins filled with appropriate Martian soil simulant. The main testbed purpose is to measure vehicle tractive ability (i.e. drawbar pull) on simulated surfaces and under controlled conditions. Investigations of obstacle negotiation performance as well as of soil slope climbing can be easily accommodated in the system-level testbed by rock placements and by preparations of appropriate slopes from the soil, respectively. The measurements will allow hardware characterisation but also calibration of the mathematical models incorporated in the RCET software part. This second task is essential because theoretical prediction and corresponding sizing of the locomotion subsystem is intrinsically difficult since a number of uncertainties are involved whenever dealing with soil-like materials.

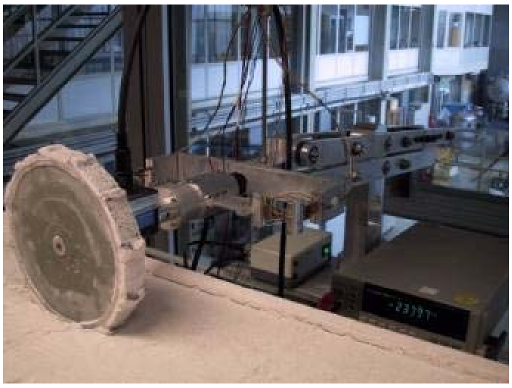

Figure 4: Single-wheel testbed at DLR

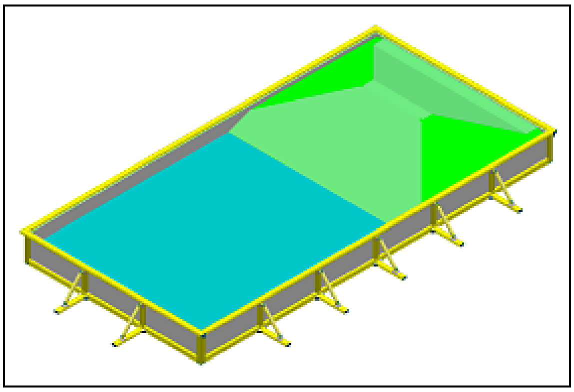

Figure 5: RCET system-level testbed CAD model

ROVER PERFORMANCE EVALUATION

The rover performance evaluation will be made on the basis of the locomotion metrics described before. Presently, preliminary results and experience from the team lead to the conclusion that the best structure for a wheeled, long range Mars rover is achieved by an in-line six wheeled configuration (i.e. three wheels on each side), a result obtained previously by other investigators as well. The load repartition of the wheels has to be equal on level terrain for best locomotion performance. Furthermore, the structure should be chosen such that an appropriate adaptation to the terrain is possible and that a capacity exists to turn on the spot. Not only the ground clearance is important but also the relation between the motion of the CoM (Centre of Mass) related to the wheels motion and the normal forces distribution on the wheel/soil interface. Every structure is very sensible to the position of the CoM and this has to be taken into account during the rover design phases.

STATE OF THE ART AND FUTURE WORK

Presently, a large variety of simulation tools are available and used in industry or even for entertainment purposes. The first category can be used for rover 3D simulation with some accommodation. The second one gives interesting visual results in real time but the physical results are far away from reality, in particular because the wheel ground interaction model is too simple. A third possibility for rover simulation is to establish the mathematical equations for the specific application. If this way is used by some robotic laboratories [LRP, EPFL, Tohoku] the time and knowledge required to write the equations for each rover is not adapted to the RCET needs. This is why the team adapted the two first S/W categories to meet the requirements related to the mobile robotic world. In addition, the work provides two testbeds for measurement of the H/W and validating the S/W.

The parametric tool kernel is adapted to a 3D mathematical rover description and therefore can be used as a real time 3D simulator for motion control. Legged structures can also be simulated with an additional module for controlling the leg motion. As the parametric tool manages a 3D environment, integration of sensor models can be added to allow simulation of the navigation system and associated algorithms.

Not only the normal forces repartition and the wheel design influence the locomotion performance, but also the torque applied to each wheel. Thanks to the simulation application, it becomes possible to find out the optimal torque for each wheel that maximises the traction (torque control). A study on this subject has previously been carried out by EPFL and is described in [7]. Preliminary results described in [7] show an increase of motion capability when using a torque-based motion control, only achievable with the help of real time simulation applications.

CONCLUSION

A rover is a system whose objective is to perform motion from a starting point to the target. In a planetary exploration mission, the rover has to carry a scientific payload on an unknown terrain to a predefined target, usually in a power and energy constrained environment. In this case, the highest-level performance metric is the capacity of the rover to achieve the mission. For this, the rover structure, motion control and autonomous navigation level is essential.

The RCET set of tools under development is presently limited to wheeled structures and navigation considerations are out of the scope of the project. However, the RCET applications dedicated to rover simulation and augmented by two dedicated H/W testbeds help to design, select and optimise rovers. The large variety of wheeled mobile structure concepts can be evaluated at early phases of the design process. The parametric analysis supports the optimisation of the structure and the selection of the appropriate actuators for a dedicated mission (w.r.t the terrain). A full 3D simulation of the rover chassis evaluates the locomotion performance of the rover for validating the concept. And finally, after manufacturing, the wheel and rover can be functionally tested in an appropriate locomotion test environment.

The tools developed during this activity will be useful for the development and test of future rover chassis for planetary exploration and in particular for the planned ESA mission ExoMars. Additional functionalities are planned to be incorporated in the tools from the team members, especially for a better motion control and to allow hardware in the loop (import for measurements of real data from rover demonstrators). In conclusion, the RCET is not only a complete set of tools for rover chassis evaluation and design, but also a sound basis for further development related to rovers and mobile structures for planetary exploration.

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