AUTOMATED DESIGN OF LIGHTWEIGHT EXPLORATION ROVERS

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ABSTRACT

In the recent years, vehicle-environment modelling techniques and powerful simulation tools have been used exhaustively to design wheeled rovers. In spite of that, rover preliminary design is still very dependent on human designer. It is also well-known that human analysis of a complex vehicle dynamics is very time consuming, which implies in a simplified analysis of just a few useful operating conditions. It compels strict achievement of requirements without a deeper investigation of performance optimization potential during preliminary design phase. Our in-house developed rover optimization tool allow us to achieve a reasonable configuration having mobility and locomotion requirements and a given suspension concept as inputs. It reduced drastically the time usually devoted to synthesize some rover parametric configuration. We show the results optimized rovers under our scenario-oriented multi-objective optimization concept. The results are assessed through parameter variation studies to evaluate: allowable volume to place the center of mass of the vehicle, sensitivity analysis, Pareto frontier relating important metrics two by two, and figures of merit illustrating mapping of the design parameters into the criteria space. This research generates two branches of special interest: applicability of the current results (other than straight forward construction of the obtained suspension); and further development of the optimization tool.

1. INTRODUCTION

The first thing needed to accurately represent a rover driving on some representative scenario is the interaction modelling between vehicle and its environment**.** This was done in our previous works [2] through contact modelling. Multibody simulation tools are able to simulate the relative movements of the mechanical parts of the mechanical suspension. These are the main building blocks used to dynamically describe a rover driving on some environment. This current work shows some results of an automated design in the context of the ROV-E (Ligthweight Technologies for Exploration Rovers) project. Modelling and simulation were used exhaustively in order to synthesize a specific geometric configuration of the rover's suspension. The following sections describe setup and execution of the automated process as applied in the case of a rover with ExoMars type suspension. It goes from optimization setup and results in section 2 through sensitivity analysis and scenario choice in section 3. Preliminary results in automatic generation of multibody structures are shown in section 4. This is the first step in an effort of a complete automated design of exploration rovers without a-priori knowledge of the suspension type.

2. OPTIMIZATION SETUP AND RESULTS

Scenario-oriented optimization [5] is very meaningful when one takes locomotion requirements into account. The requirements can be translated into scenarios, where simulations can be executed to evaluate the performance of a given concept. An optimization run with a reduced number of scenarios is able to produce a compliant design; this process relies on the experience of a human designer to suitably select meaningful scenarios. In the present case 12 requirements were taken into account. Not only driving situations like crosshill, downhill, excessive sinkage, and slippage, but also explicit constraints are specified in these requirements which limit: mass, volume through deployment configuration, and static stability in all directions. The 12 requirements were mapped in 19 scenarios which are capable to evaluate them. The mapping is not one to one because some of the requirements have to be verified by simulation when the rover drives forwards and backwards. As an example, figure 1 illustrates two simulation scenarios which are verified driving forward and backward. Each scenario can be used to compute one or more objective function. The objective functions are assigned to each scenario during the optimization setup. Some of the commonly used objective functions are: travelled distance, average consumed power, accumulated sinkage, height of the center of mass, and overall mass.

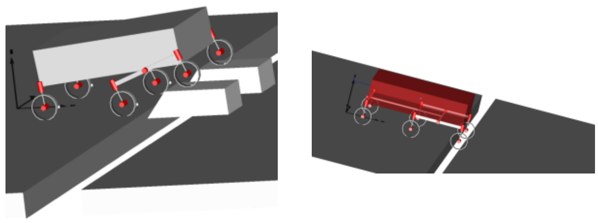

Figure 1. Rover surmounting two obstacles (left), trespassing crevasse (right)

Up to this point we have a minimal set of scenarios with the respective objective functions assigned. It is capable to capture the performance of the vehicle in very specific situations interesting to the mission. The vehicle is simulated in all 19 scenarios at each iteration of an optimization loop (see figure 2).

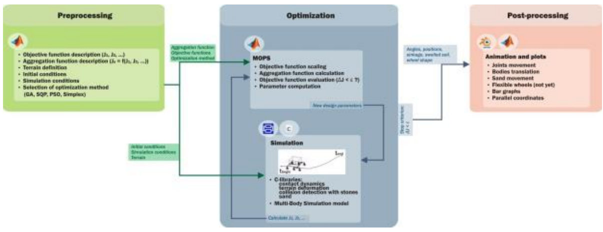

Figure 2. Optimization loop

The global optimization algorithm used was differential evolution, it had a population size of 10 individuals and took 166 iterations to find a solution. When the solution of the 19-scenario (19S) case is compared with a simpler 7-scenario (7S), a difficult trade-off takes place. The 19S rover achieves smaller values for 28 objective functions (in a total of 39 distributed over the 19 scenarios) better than 7S rover simulated in the same 19 scenarios. The 19S rover is 3kg heavier than the 7S rover, but allows a body with higher center of mass to be placed over the suspension. The parameters can be compared in the table 1.

Table 1. Comparison (nominal, 7S, and 19S) of ExoMars type suspension configurations according to parameters in figure 3

Parameters	ExoMars [m]	ExoMars 7S [m]	ExoMars 19S [m]
d_{rp}	1.080	1.071	1.032
$d_{bf} + d_{br}$	0.640	0.715	0.777
b_w	0.100	0.050	0.050
r	0.125	0.125	0.125
h_{wb}	0.198	0.198	0.198
b_v	1.270	0.958	1.177
Vertical distance from suspension to CM of the rover	0.100	0.174	0.205
Total Mass	119kg	114kg	117kg

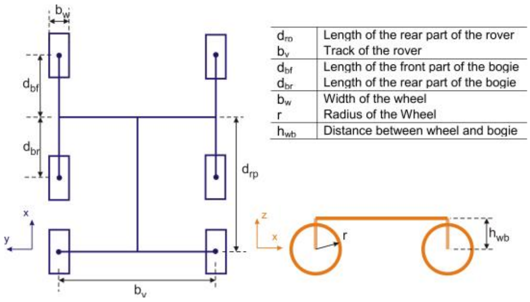

Figure 3. Parameters to be optimized in the ExoMars type suspension

Figure 4 shows the normalized outcomes for power and mass concentrated about the optimal solution. Each point means a rover configuration, several configurations achieved power (average power in all scenarios) and mass measures better than that of the optimal configuration (the 19S rover). But these configurations are unstable or achieved worse values in other metrics.

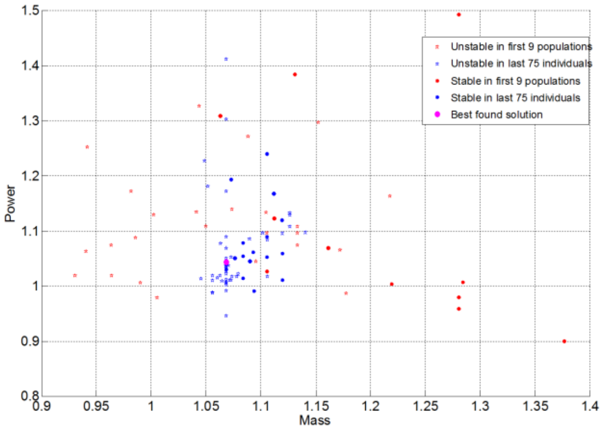

Figure 4. Figure of merit: average power through scenarios and overall mass

Figure 5 shows that the 19S rover is in the limit of the mass-sinkage compromise while stability can still be achieved.

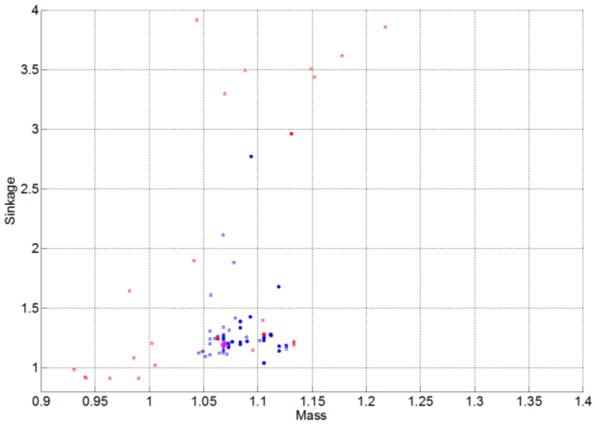

Figure 5. Figure of merit: average sinkage through scenarios and overall mass

Figure 6 shows some configurations better than 19S, but these achieved worse results in the other figures of merit.

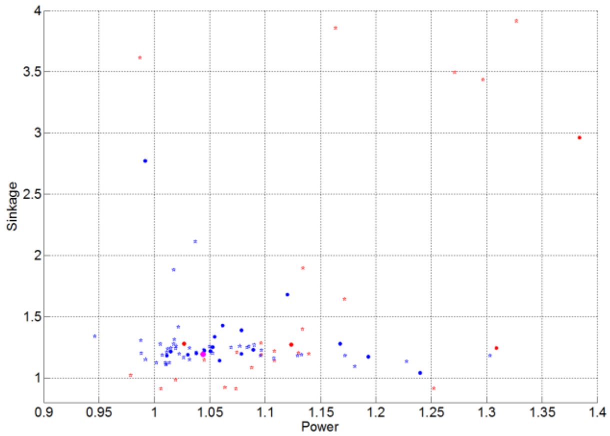

Figure 6. Figure of merit: average power and average sinkage through scenarios

If one takes just the stable configurations and those with an acceptable sinkage value, i.e. configurations which are prone to safe locomotion (without achieving immobility or unstable behavior), Figure 7 can be plotted. The best result is achieved by 19S rover, although MOPS (the in-house Multi-Objective Parameter Synthesis tool developed at DLR and used in this work) uses the sum of squares as aggregation function, the solution is also the best considering average power, average distance, and average sinkage summed with the other specific measures.

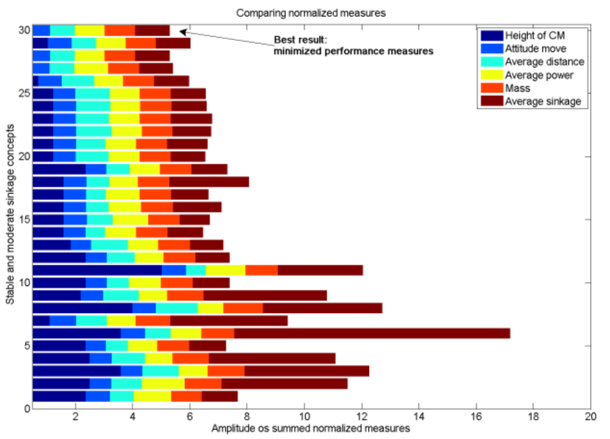

Figure 7. Barplot of the solutions which are prone to safe locomotion

There is one solution relatively close to the 19S rover. In case of quadratic sum the difference is much larger. When the aggregation function is used during optimization, this is amplified and the difference between 19S rover (number 30 in figure 7) and number 28 in figure 7. This is mainly caused by the mass, rover number 28 is 12kg heavier than the optimal one. The other measures are comparable, the allowed height of center of mass is about 10cm lower. In other words, 19S is absolutely the best choice in the ensemble generated by differential evolution algorithm. The performance of the nominal rover, optimized 7S, and optimized 19S are compared as shown in figure 8. As minimization of the metrics indicates best performance, we conclude that the 19S rover is a reasonable choice

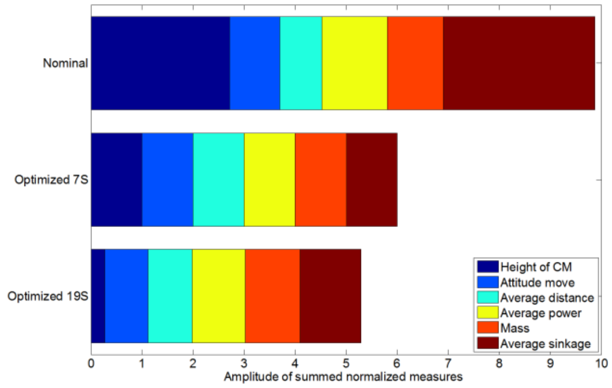

Figure 8. Performance of nominal, optimized 7S, and optimized 19S ExoMars suspensions compared

3. SENSITIVITY ANALYSIS AND SCENARIO CHOICE

Automated rover design aided by dynamic simulation and optimization algorithms becomes a complex task as multiple requirements are involved [1,3,4]. Multiple requirements imply multiple objectives to be optimized. The end solution of an optimization frequently needs trade-off and further simulations to decide which solution is the best (or most suitable to the set of requirements). The amount of scenarios, kinds of objective functions, and parameters to be optimized are always chosen by the human designer. Thus, the result also relies on the experience of the designer to choose representative scenarios, objective functions which really measure the performance of the vehicle in a meaningful way, and a set of parameters to which the objective functions are sensitive.

Note that a bad choice would cause sluggish convergence or even achievement of not meaningful results. An optimization takes $n \times i$ minutes, where n is the mean duration time of all scenario simulations in minutes, and i is the amount of iterations. A well-tuned one-scenario optimization takes approximately four to five days to converge to some solution. A 19-scenario for example would take too much time to converge. This problem was solved by implementation of distributed computation. The 19-scenario optimization for example took five days to be accomplished.

A common method to choose suitable objective functions, scenarios, and parameters is to perform simple simulations with the candidate scenarios and parameters and perform sensitivity analysis. Figure 9 shows the result of one analysis comparing the sensitivity of four objective functions to five distinct design parameters.

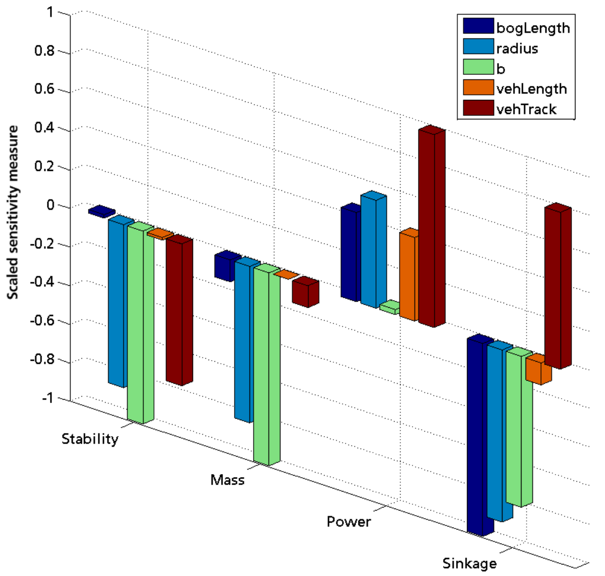

Figure 9. Sensitivity analysis around some starting configuration

But the sensitivity analysis is not sufficiently general because it is carried out around some point, in figure 9 it is around the starting configuration. Other simulations are required to define the sensitivity about interesting solutions. Another kind of sensitivity analysis is related to the impact of the scenario on some performance measure. Some scenarios evaluate some objective functions in a complete different way than others. Vehicles surmounting stones in sandy environment will certainly consume much more power than the same vehicle driving straight ahead on bedrock. This is another kind of sensitivity, which can be evaluated like in figure 10.

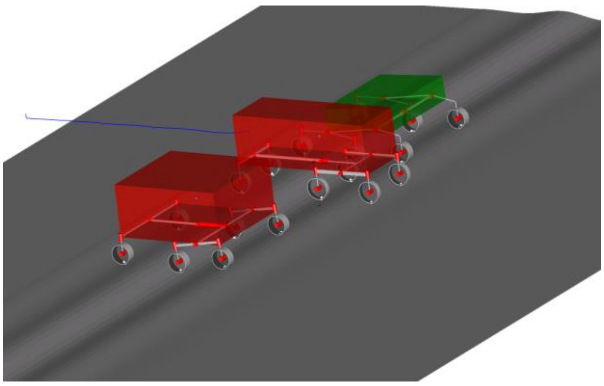

Figure 10. Three rovers on undulating terrain

Different configurations of the same suspension or different types of suspension are simulated on some scenario. Simulation results are compared against each other to draw conclusions about how sensitive is some objective function to that scenario. One of the stored variables of the simulation illustrated in figure 10 is that of figure 11.

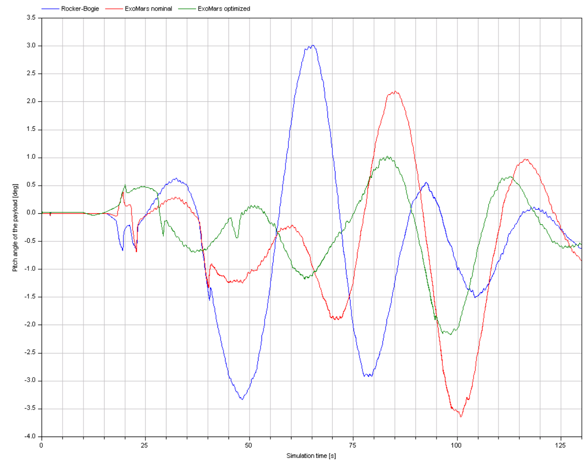

Figure 11. Pitch angle of the vehicles on undulating terrain.

There is a considerable change in the amplitude and phase of the stored pitch angles of the payload. This simulation was employed to define undulating scenario as an important candidate to evaluate the damping of the payload by the multibody structure. This analysis is repeated through several scenario candidates. At the end, a set of scenarios is chosen and assigned to the pertinent objective functions. In the 7-Scenario case the scenario-objective function assignment is that of figure 12.

Scenario	Overall mass	Average power	Accumulated sinkage	Stability	Traveled distance	Attitude path
A	✓	✓	✓	-	-	-
B	-	✓	✓	-	-	-
C	-	✓	✓	-	-	-
D	-	-	-	✓	✓	-
E	-	-	-	✓	✓	-
F	-	-	-	✓	-	-
G	-	-	-	✓	-	✓

Figure 12. Scenario-objective function assignment

In fact, like in figure 12, in a scenario-oriented approach, a few objective functions are added as the number of scenario increases. The same objective function evaluated on a different scenario is considered as another objective function. In figure 12, six objective functions become 14 objective functions. The vehicle suspension and the assignment structure (as in figure 12) are the main inputs to start the optimization of a rover.

The beginning of the optimization process relies on the ingenuity of the designer, mainly due to the configuration of the suspension. The interconnection of the multibody structure is considered here as sufficient to synthesize a new rover suspension composed by joints and rigid connections. The next section describes some advances in the initial effort to generate automatically the multibody structure itself.

4. INITIAL EFFORTS IN SUSPENSION SYNTHESIS

Currently, the multibody structure of the vehicle cannot be modified neither optimized. A given structure can just have its geometric parameters optimized. The idea is to make automatic also the generation of the multibody structure. The steps to do this are two:

1. Feasibility constraints to generate concept set.
2. Post processing.

The feasibility constraints defined in this first attempt to automate the multibody structure generation are: path between each wheel and payload shall exist; joints shall not remain alone, they have to be connected to at least two objects; all objects shall be connected. The results of the previous step can be further improved through post processing: select configurations in the Pareto frontier; eliminate redundant configurations: configurations which connect to each other, and joints which are already connected to the payload.
Two objective functions are computed and assigned to each concept in order to generate a figure of merit and allow Pareto Frontier's analysis, these are:

- Complexity metric 1:
  $$\frac{\text{Total number of connections}}{\text{Number of connections among joints}}$$
- Complexity metric 2:
  $$\text{Number of connections among joints}$$

Both complexity metrics shall be minimized. As an example, consider figure 13. Several multibody structures were generated. The well-known Rocker-Bogie and ExoMars were also automatically generated.

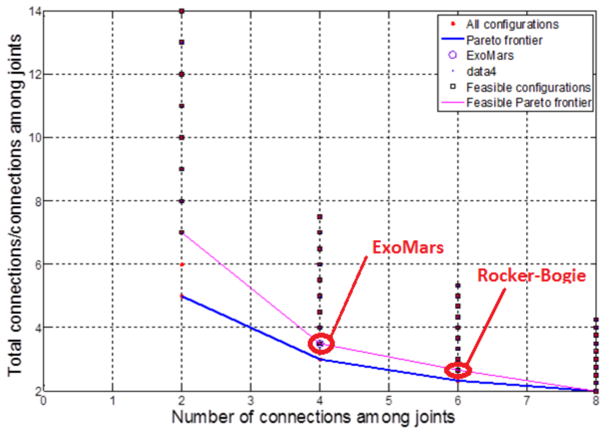

Figure 13. Evaluation of automatically generated suspensions

According to the proposed complexity metrics, ExoMars and Rocker-Bogie configuration are exactly on the feasible Pareto Frontier. From the point of view of a human designer these are reasonable concepts, this agrees with the result provided by the automatic generation. The set of concepts (suspension configurations) can now be used as input to the optimization process to define an optimized rover both in the point of view of optimized geometric parameters and interconnection of the multibody structure.

5. CONCLUSION AND OUTLOOK

This work shows how automated design of rovers was carried out using the scenario-oriented approach. Scenarios, objective functions, and parameters to be optimized are defined during the optimization setup. Using global optimization algorithms, aggregation function, and dynamic simulations, the geometric parameters of some multibody structure are synthesized in order to minimize the given objective functions simultaneously. This process is well-known from our previous works [1,3-5] and was successfully applied in the context of the ROV-E project, specifically to the ExoMars type suspension. Results were shown here to illustrate analysis through figures of merit and trade-off of the obtained solutions. The current level of design automation is already very useful, but some human dependant tasks are being automated as well. This is the case of the automatic generation of a suspension concept (or suspension configuration). Section 4 introduced some results of our current effort in automatic multibody structure generation. Next steps of this work are: integration between automatic multibody generation and optimization process; automated scenario selection. These are identified as research directions to obtain faster, lighter, and more efficient rovers as the design time is reduced.

6. ACKNOWLEDGEMENTS

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