LET THE DLR SCOUT ROVER FLIP: PARAMETER STUDY SIMULATIONS

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ABSTRACT

The DLR Scout rover is symmetrical about the horizontal plane and can drive upside down equally well as upright. The rover was designed such, because its intended area of applications, planetary caves, is very difficult to access and navigate through, tipping over is just a matter of time. Entrance through skylights or drops inside the cave can cause the rover to end upside down with a high probability. There are however reasons to prefer being upright, mainly payload. There is thus motivation for the rover to be able to flip itself, on its own or along an obstacle, in a controlled way. In order not to put the prototype at risk and for repeatability, a simulation parameter study is performed, with a few validation points using hardware. Results show that the rover is able to flip itself on a flat plane, when the wheels abruptly turn quickly in opposite directions on both rover sides. This maneuver is currently not possible on the prototype for safety reasons. The flip simulation along an obstacle shows that a simple inclined plane is enough, with higher success rate the faster the wheels turn. Other parameters like friction or the introduction of a ditch in front of the inclined plane, have little to no impact. Driving on the side of an inclined plane to induce a roll movement into the rover, mostly is unsuccessful in simulation (sliding or ending on one side) but mostly is successful with the prototype because imperfections are enough for the rover to end upside down if it comes to rest on a side.

Key words: planetary exploration rover simulation, multibody simulation, rimless wheel rover, driving performance, parameter study, planetary caves, lava tube, DLR Scout rover.

Figure 1: The DLR Scout rover prototype

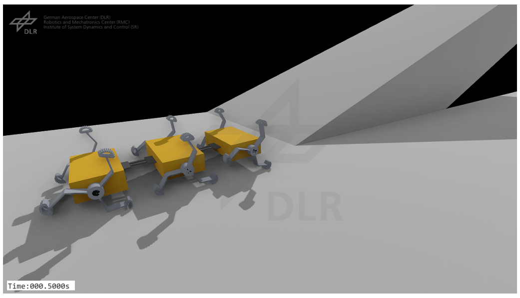

Figure 2: The DLR Scout rover simulation

1. INTRODUCTION

The DLR Scout rover, Figure 1, has been in development at the Institute of System Dynamics and Control (SR) for the last years [L$^+$21]. It is built of, in general, three modules, each module has an axis with rimless wheels whose spokes are compliant. The rimless wheels and compliant "backbone" are key for the terrain traversability of the rover and key to survive drops, most likely necessary to enter planetary caves. The design also takes into account that the rover may end upside down, it is symmetrical about the horizontal plane (driving axis and wheel axis), at least considering the locomotion subsystem. While it can drive upside down, there are subsystems that are not symmetrical to the horizontal plane and thus have a preferred top and bottom side. For example, the camera image is easier to interpret (for autonomy and human in the loop) and the primary antenna is on the top side (the antenna on the bottom side is backup only). Similarly, some payload instruments, e. g. for spectroscopy, may not be omnidirectional like a thermometer. While it is not a complete show stopper should the rover end upside down, there are good reasons to investigate the possibility for the rover to flip itself around. Answering whether, and if so how, it is possible, is subject of this text.

Development of the Scout rover is driven by modeling, simulation and optimization. Through all phases, a high-fidelity simulation model is developed along the prototype [PL22, P$^+$22]. It currently mainly focuses on the locomotion subsystem, since this is the major driver of development, but is also used for software testing. In fact, much of the firmware for control engineering etc. is exactly equal for simulation and prototype. This is one of the strengths of the Modelica language that is used on the Scout rover. This reduces the risks on the prototype while speeding up software development, ultimately saving time and money overall. This strategy is also beneficial for the research question at hand where many similar and repeatable tests are to be run in a short time, tests that in addition would set the prototype to strain.

The answer to this question is not trivial, not finding a way to flip the rover does not mean that it is impossible.[1] Further, there is not much literature to review because most often rover kinematics and control algorithms are designed such that the rover does *not* flip. See [FBB18] for a study researching ways to protect a rover from tip-over. Also, [S$^+$22] tries hard to avoid flip on a rover similar to Scout.

Two parameter study simulations are done here. The first attempts to make the rover flip on its own, that is only by systematic actuation of the drives on a plane. The second attempts to find an obstacle (block, slope, . . .) where driving on it makes the rover flip with high probability.

2. SIMULATION MODEL

2.1. Rover Model

The simulation model of the rover has already been detailed in [PL22]. Only a short summary is given here.

The rover simulation is implemented in Modelica[2] inside the Dymola IDE[3]. It is one rover of the DLR SR **R**over **S**imulation **T**oolkit *RST* [HBB17]. Foci are on locomotion and contact dynamics with ground and obstacles.

The simulation model follows the modular structure of the rover with three modules with two rimless wheels each and compliant "vertebrae". All bodies are rigid with appropriate dimensions and mass, flexibility is introduced with rotational springs between segments of the vertebrae or the spokes of the rimless wheels. Similarly, flexibility in the feet is modeled by springs with one translational and one rotational degree of freedom between the lower end of the spoke and the rigid foot model. All parameters were verified against the prototype.

The drives are implemented in an idealized version, that is velocity signals from the controller are exactly applied to the mechanical simulation of the wheels. However, gear losses are implemented in a simplified way following the data sheet to have a more realistic estimate of torque demands. For the present study acceleration limits, generally present in the control logic, were disabled for the first investigation when the rover is on a plane and attempts to flip using drive action only. The reason being, that the questions to be answered are about the torque requirements on drives to successfully flip, not whether the current prototype is able to perform such a feat.

2.2. Environment Model

Ultimately, the Scout rover is going to be operated away from Earth, still the gravitational acceleration for this parameter study is $1\,\mathrm{g}$. This permits qualitative validation with the prototype on the Scout test area. However, a simulation study with Moon or Mars gravity is a possible future work.

Two different contact dynamics models are used, one very simple for the flat plane, one more advanced when several obstacles are to be considered. They're two of the several models for contact dynamics calculation and terramechanics that build the *Contact Dynamics* external library to RST [BPB23].

The very simple first model is implemented directly into Modelica using a so-called `ElastoGap`, a spring damper combination that can lift off on one side. The normal force is nonlinear with exponent 1.5 as already established by Hertz in 1882 [Her82]. The spring constant is set high, i. e. hard soil, to maximize the chance for the rover to flip. The tangential force is a simple Coulomb friction whose parameter μ is one parameter to variate.

The advanced contact model uses the same equations of Hertz and Coulomb in combination with an **M**inkowski **P**ortal **R**efinement *MPR* contact detection between the rover parts and environments [Fis18]. This library is implemented in C and included to Modelica as external library. This permits to combine advantages of Modelica (rigid body dynamics simulation, compilation for efficient simulation, integration algorithms) with C code (manipulation of objects, efficient collection handling). Again, the normal force model is chosen to be relatively stiff while the Coulomb friction parameter will be subject of the parameter variation.

The Contact Dynamics external library also provides generators for natural surface shapes using random numbers that have certain properties described by numbers from real planetary surfaces. But this will not be used for the present study in favor of artificial surface with steps and slopes on a flat plane. The reason is that the question to be answered, aims at finding certain categories of obstacles that are favorable for the rover to flip. However, a simulation study with random natural surface shapes is a possible future work.

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[1] « absence of evidence is not evidence of absence. »
attributed to William Wright (1887), Dugald Bell (1895), Martin Rees (1972), Carl Sagan (1977) and others

[2] `https://modelica.org/`

[3] `https://www.3ds.com/products-services/catia/products/dymola/`, accessed September 22, 2023

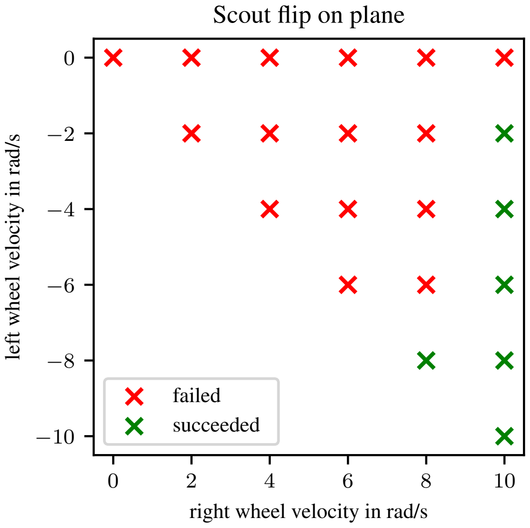


Figure 3: Scout flip on plane as function of right (ccw) and left (cw) wheel velocities

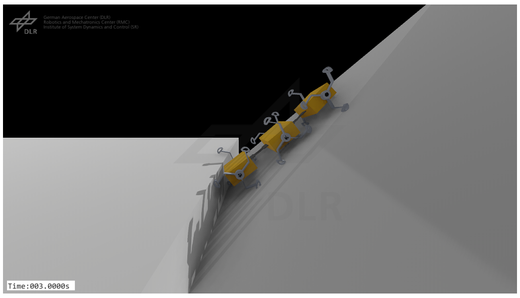
3. RESULTS

3.1. Flip on a Flat Plane

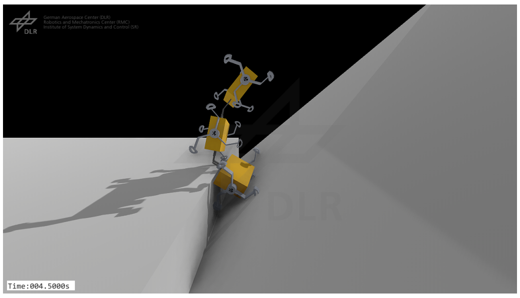
The first study considers the rover only, there are no obstacle on the completely flat and level ground, hence the very simple surface contact model. The goal is to find the most promising set of commands to the wheels to make the rover jump and have a roll movement of 180°. The six rimless wheels are individually actuated by angular velocity signals, but to keep the search space manageable, wheels on the same side always turn at the same rate. More precisely, the following speeds are applied: $0\,\mathrm{rad\,s^{-1}}$, $2\,\mathrm{rad\,s^{-1}}$, $4\,\mathrm{rad\,s^{-1}}$, $6\,\mathrm{rad\,s^{-1}}$, $8\,\mathrm{rad\,s^{-1}}$ and $10\,\mathrm{rad\,s^{-1}}$. Because the Scout rover is symmetric, not all combinations are needed, only the upper right triangle.

Figure 3 shows the outcome of the parameter study simulations with red crosses indicating that this combination of left and right wheel speeds didn't manage to make the rover flip, while green crosses indicate success. As said, only the upper right triangle is shown but the results can be mirrored along the diagonal. It's interesting that flip is not possible if wheels on one side don't move at all. The second obvious result is that there is a threshold between $8\,\mathrm{rad\,s^{-1}}$ and $10\,\mathrm{rad\,s^{-1}}$ for flip success or failure. The sliding friction parameter between rover feet and soil was varied as well, with no impact on the results.

Whether the prototype can flip in this way following the commands identified in the parameter study, remains an open question for the future as the current soft- and hardware doesn't permit such high velocities or abrupt accelerations. Currently the maximum wheel velocity is $2\pi\,\mathrm{rad\,s^{-1}}$ by software and limited to a finite acceleration by hardware. The acceleration is probably high enough as has become evident from hours of operation experience. Future iterations will consider this study's outcome in laying out drives and implementing controllers.



(a) Initial position



(b) Successful flip

Figure 4: Scout rover front flip simulation with parameters slope 40°, ditch depth $0.1\,\mathrm{m}$, rover target velocity $0.75\,\mathrm{m\,s^{-1}}$, phase shift 60°, friction 0.3

3.2. Flip along an Obstacle

3.2.1. Obstacle completely in front of the rover Because the requirements on the drives of the prototype for a flip maneuver on a flat plane can't be fulfilled currently, and may not be in the near future, research for an obstacle onto which the rover can flip is undertaken. Experience from operating the prototype rover in the test field and in natural environment as well as prior simulation campaigns has narrowed down the kinds of obstacles that can lead to a successful flip. The rover needs to start highly pitched on a slope and then turn its wheels forward. This can already induce enough energy for the rover to slip, but to make it easier, a little ditch in front of the slope can help to fasten the rear module. Figure 4 shows one set of parameters where the flip simulation is successful.

Three to six values for each of the five parameters are defined and all combinations tested. The simulation runs store whether the flip has been successful or not, and the evaluation shows the success rate dependent on each parameter separately. The following parameters are varied:

- Inclination of the plane: 25°, 30°, 35°, 40° and 45°
- Depth of the ditch in front of the inclined plane: $0.00\,\mathrm{m}$, $0.05\,\mathrm{m}$, $0.10\,\mathrm{m}$ and $0.15\,\mathrm{m}$

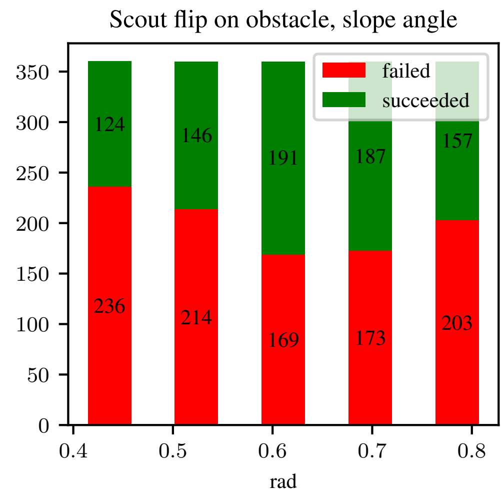


Figure 5: Scout flip on obstacle as function of slope angle

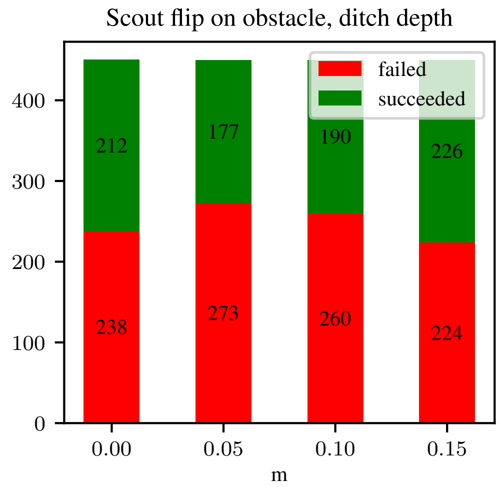


Figure 6: Scout flip on obstacle as function of ditch depth

- Rover target velocity, that is the velocity in case of zero slip: $0.25\,\mathrm{m\,s^{-1}}$, $0.50\,\mathrm{m\,s^{-1}}$, $0.75\,\mathrm{m\,s^{-1}}$, $1.00\,\mathrm{m\,s^{-1}}$, $1.25\,\mathrm{m\,s^{-1}}$ and $1.50\,\mathrm{m\,s^{-1}}$
- Angle between wheels on the same axis and between wheels on adjacent axes: $0°$, $15°$, $30°$, $45°$ and $60°$
- Friction between feet and ground: 0.3, 0.5 and 0.7

Figure 5 to Figure 9 show the results of the parameter study simulation. It's interesting to note that there is no parameter value that completely prevented the rover to flip, remember for example that in subsection 3.1 the wheels not turning on one side always resulted in no flip.

Figure 5, the angle of the inclined plane, shows a shape in form of a parabola with a maximum of success at $35°$, i. e. $0.6\,\mathrm{rad}$. Actually a good result, because long slopes higher than this but not close to vertical are rare.

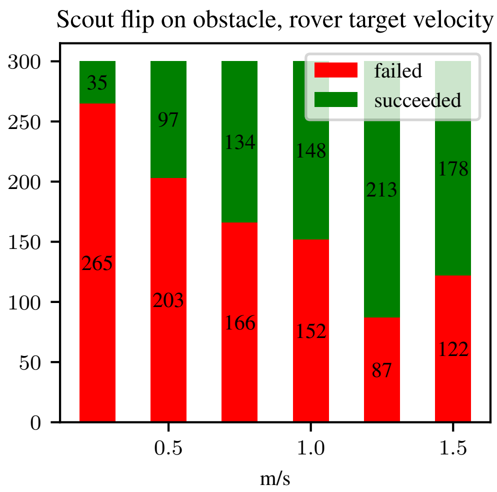


Figure 7: Scout flip on obstacle as function of target velocity

Figure 6, the depth of the ditch in front of the inclined plane, shows only little impact with better performance at the extremes. This is not the expected result and it seems that the introduction of the ditch, which was thought to improve the results, in the end was not necessary.

Figure 7, the rover target velocity, that effectively controls the wheel turn rate, basically shows that flip is more probable the faster the wheels turn. This intuitive result conforms to the larger amount of energy introduced into the system. However, the success rate at the highest target velocity is smaller than at the next to highest velocity.

Figure 8, the phase angle between wheels on the same axis and between wheels on adjacent axes, also has a shape similar to a parabola. The best flip success rate is achieved at middle shift values. Both zero and maximum shift angles resulted in fewer flips. When the shift is at its maximum, the rover moves smoothest and thus experiences fewer flips. When the shift is zero, the middle and rear modules of the Scout rover also have large movements away from the slope, resulting in fewer flips.

From Figure 9 it is obvious that the friction parameter has no impact on the flip success, as long as the slope angle is so high, that the rover slides. This was anyway the case in all tested combinations.

3.2.2. Obstacle partially in front of the rover One further intuitive way to flip the rover along its roll axis, is to drive on the edge of a slope such that the wheels on one side are on the slope while those on the other are not. Figure 10, the continuation of Figure 2, shows this in simulation. This obstacle arrangement proves to not be able to make the rover flip in simulation reliably. It slides down over the edge without flipping when the slope is low or high. For the slope around $20°$ the flip is not complete and the rover ends on its side. From there, the

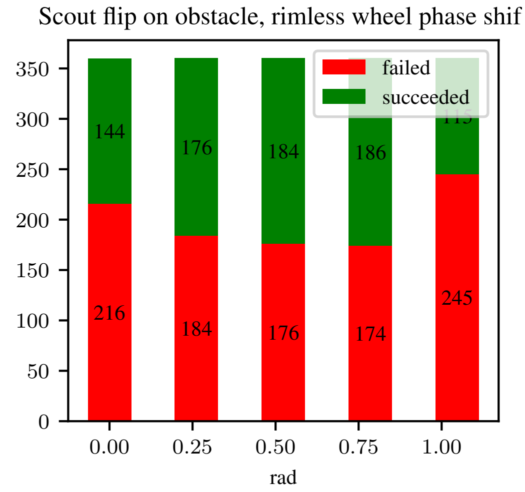


Figure 8: Scout flip on obstacle as function of rimless wheel phase shift

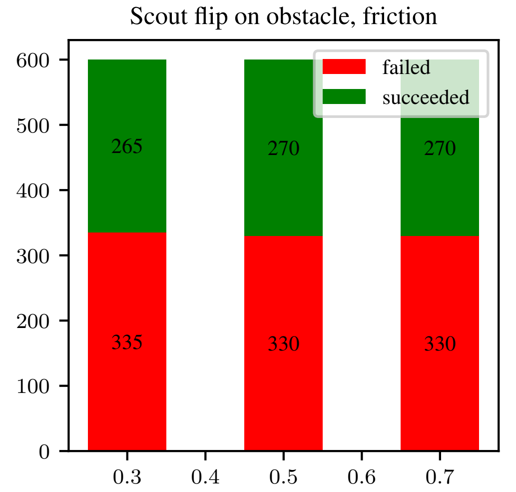


Figure 9: Scout flip on obstacle as function of friction

perfect simulation model can't put itself on its feet. The prototype however has shown numerous times that it can do that thanks to the imperfections in rover and ground.

4. VALIDATION

The current software on the prototype sets relatively tight limits on the maximum acceleration and speed of the drives to protect the rover from itself, it is strong enough to break its spokes and swirls sand and stones around, also on itself. For these reasons, prototype tests to validate the results of subsection 3.1 are not performed. However, the values identified in this study may lead to changes in hard- and software in future iterations.

Flip tests on obstacles on the other hand, can safely be done with the prototype, though only at relatively low speeds. The test area outside the Scout lab has a slope with hard ground which, in contrast to section 3.2.1, has a step and not a ditch to overcome first. This was chosen, because such obstacles are more frequent in caves, the target area of operation of Scout.

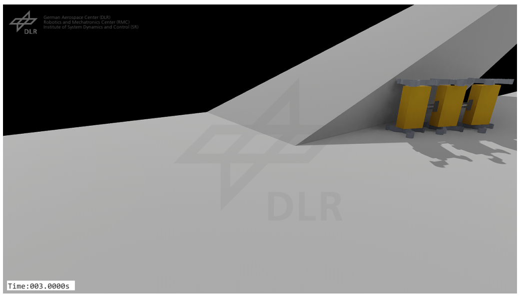


Figure 10: Scout rover side flip simulation, continuation of Figure 2, compare with Figure 12, the simulation can't free itself from this incomplete flip situation

Figure 11: Scout rover flip on step

Figure 11 shows the Scout rover prototype on this obstacle. In this case, the rover flipped, but in most attempts the rover climbed the step, which confirms the difficult repeatability of hardware tests. Recreating the obstacle in simulation (step instead of ditch before inclined plane), has results similar to section 3.2.1 with the most important parameters for success being again a fast target velocity and a high inclination after the step. The step height has little impact, just as the ditch depth, suggesting a high inclination is key for flip on an obstacle.

Figure 12 shows a qualitative validation for the simulation study of section 3.2.2. Here again, repeatability is difficult. In 50 % of the tests the rover performs the intended flip, in 40 % of the tests the rover ends as it started, and in the remaining 10 % the situation as depicted in Figure 12 happens: the rover ends on its side. When the Scout rover is on its side, activating the wheels introduces enough instability for the rover to end on its feet. So in half of the remaining 10 %, the flip is successful, while in the other half, the rover ends in the starting position. Flip success without the intermediate resting phase on the side depends mostly on where the Scout rover falls from the obstacle, the higher the more likely the flip.

(a) A short time before the fall

(b) Incomplete flip, the prototype can free itself

Figure 12: Scout rover side flip

5. CONCLUSION

Two parameter studies have been done with the simulation model of the DLR Scout rover to estimate how it may be able to perform a flip maneuver, either on its own or with help of obstacles.

Flips without obstacles are possible if the wheels on one side turn in the opposite direction than those on the other side. Success sets demands on speed and acceleration too high for the current soft- and hardware of the prototype. Thus, this result can't be validated.

Flips on obstacles mostly depend on the angle of an inclined plane on which the rover can't climb (too low friction). The success rate is highest, the faster the wheels turn (all at the same speed). Adding a ditch or a step before the inclined plane affects this result only slightly. Validation of this simulation is not exactly possible, because the test area was laid out to recreate conditions in caves or lava tubes, where slopes are either lower than identified by the simulation study or close to vertical which does not help when the task is to let the rover flip. Nonetheless the findings of the parameter study simulations are useful for the further development and future investigations using the hardware DLR Scout rover.

The highest success rate with the prototype is achieved when the obstacle induces a roll motion and fall, even if the rover comes to rest on its side as in Figure 12. From there imperfections in ground and rover are enough to induce instability such that actuating the drives quickly brings the rover back on its feet, with $50\,\%$ chance to be upright. Ironically, this situation is more difficult to recreate in simulation. Most often, the simulated rover slides down to the side before the roll is enough to flip, probably because the friction characteristics of the rover are more complex than the simple Coulomb friction in the simulation model. The other times, the rover in fact rolls until it lands on the wheel side from which the simulation model can't free itself to end upright or upside down because of the perfectly flat ground and rover building blocks. This suggests further work in this direction.

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