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FOOTPAD-TERRAIN INTERACTION TESTS WITH THE ROBOTIC LANDING AND MOBILITY TEST FACILITY (LAMA)

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Since the start of ESA’s NEXT Lunar Lander program the development of a landing vehicle for moon or other planetary bodies has become focused. In the Framework of ESA’s “Landing System Development” lead by TAS-I the German Aerospace Centre (DLR) performed a series of tests to study the interactions between a landers footpad and the surface of a celestial body during touchdown. This paper will give an overview of the actual development status and the results obtained from the test.

To size the Footpads a hardware test campaign is needed to evaluate the behaviour of the dynamic interaction with the soil during touchdown. The produced data serves as a basis for correlation with the multi-body simulation tools. A further objective is to optimize size and shape of the pad. The footpads have to be big enough to ensure a stable stand and to avoid that the lander is subsiding too deep into the soil. On the other side the footpad has to be as small as possible caused by mass requirements. With these tests it is possible to build up a parametric model and simulate further designs to get to a lightweight landing gear subsystem.

To measure and correlate the occurring energy effects, the simulated touchdown had to be split up in two test modes. The first one investigated the momentum exchange at the initial impact. Therefore a footpad with a specific mass, represented by an overlaying barrel filled with sand, has been dropped from a robot flange to impact the soil either vertically or at an inclined angle. The second test mode simulated the slideout phase. A landing leg adapter was attached to the robot flange with the footpad slightly touching the ground and pulled through a soil bin at a constant velocity, with the footpad maintained either at constant depth of penetration or under conditions of constant vertical load.

I. INTRODUCTION

The touchdown of a landing probe is a critical step within the landing phase of a planetary spacecraft. Therefore many studies and numerical models have been developed to explain the dynamics between the spacecraft and the planetary terrain. To prove these models, real hardware tests have been performed. In this paper the setup of a test program to validate numerical models for footpad-soil interaction is presented. A further goal of these experiments was the optimisation of the Footpads shape. Therefore multiple footpads have been used and the friction as well as the dynamical behaviour has been evaluated.

The by far most extensive investigation of the footpad soil interaction has been carried out on behalf of (at that time) NASA’s Manned Spacecraft Center in the forefront of the Apollo lunar landings [RD1]. The used model assumes four major processes of energy exchange acting during three phases – initial impact (figure 1.1, A), slideout (B) and the static equilibrium. The processes are impulse exchange with the soil, displacement drag, increase in mechanical bearing strength and friction in the pad/soil interface.

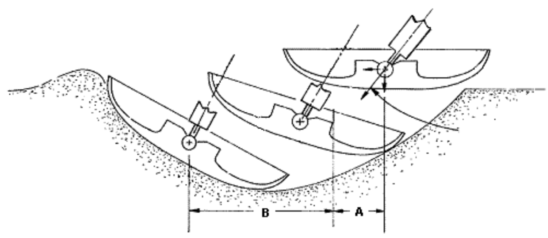


Fig. 1.1: Impact and sliding phase

The impact and slideout phase are described consistently by a differential equation whose parameters are related to soil properties and footpad shape [RD2]. These equations have been the basic for the setup of this test programme. Parameters for the drag coefficient (Cd) and the mechanical strength coefficient (Cms) are on one hand dependent from the soil properties and on the other hand from the shape. By varying these parameters the values for Cd and Cms can be determined.

II. OBJECTIVES

The overall goal of these tests was to find out the optimal size of the footpads and therefore the lightest solution for the landing legs. The footpads have to be big enough to ensure a stable stand and to provide the lander of being dug too deep into the soil. On the other side the footpad has to be as small as possible caused by mass requirements. With the ground clearance requirement the length of the landing leg has to be adapted with regard to the penetration depth of the pad. Therefore the optimal footpad size is the one with the lightest combined mass of leg and pad which comply with this requirement.

Tests have been made to investigate the penetration behaviour for the different footpad designs. With these tests it is possible to build up a parametric model and simulate further designs.

III. REQUIREMENTS

The test set-up provided an environment in which a correlation between the performed tests and the previous numerical simulations could be achieved. Therefore relevant parameters for the simulation of the touchdown dynamics of the Lander had to be identified. A list of parameters for soils is given in Table 1. Two types of soil have been used to see footpad's behaviour also on lunar soil simulant. Nevertheless the fine grained moon soil simulant (MSS-D) only has been used in the small soil bin for the drag tests (see chapter V.II.). The choice was driven by manageability reasons. Too fine grained soils are difficult to handle. They build dust clouds, when they are moved, which affect the measurement equipment and other parts of the test facility.

Soil Properties	Lunar Soil	WF34	MSS-D
Cohesive strength [kPa]	0.44-0.62	0.06	0.01
Soil bulk density [t/m^3]	1.4-1.6	1.4	1.3
Young's modulus [kPa]	~180	1900	1000
Poisson's ratio [-]	~0.35	0.15	0.35
Bulk modulus [kPA]	Not measured	905	3333
Shear modulus [kPa]	Not measured	826	370
Internal friction angle [°]	42	32±2	31±2

Table 1: Relevant parameters for lunar terrain and terrain simulants [RD5, RD6]

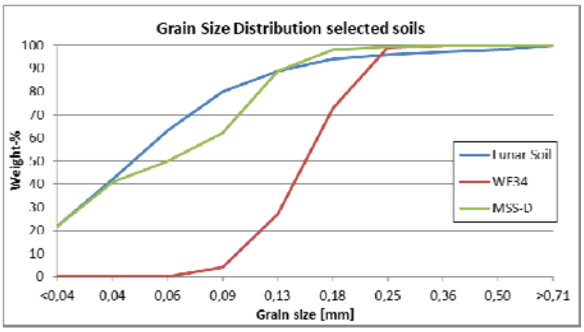


Fig. 1: Grain size distribution of lunar soil and two selected soils. About 40 percent of lunar soil is smaller than 40 µm, 90 percent is smaller than 130 µm.

As it can be seen, the values for the simulants are in the range but not exactly the lunar soil. This is not problematic as long as the numerical simulation uses the same simulant properties.

Pad (MoonNEXT)	Estimated mean value	Range
Vert. velocity	2 m/s	±1 m/s
Horiz. velocity	1 m/s	0 - 1 m/s
Attitude	2.5 deg	±2.5 deg
Attitude rate	0.5 deg/s	±0.5 deg/s
Mass	200 kg	125 – 300 kg

Table 2: Relevant parameters for touchdown simulation [RD3]

The resulting mass of the Lander, landing on one leg with pitched angle, is in the range of 125 kg to 300 kg. However 800 kg is the full Lander weight, but won't act fully on one leg.

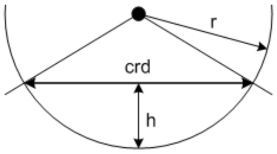
To generate reproducible outputs, the test conditions have to be exactly adjusted. The compliance of the footpad parameters are provided by the test equipment which reaches a high accuracy of the predefined velocities and attitudes. The soil on the other side needs a special treatment to guarantee a constant property which is described in section VI.II.

IV. FOOTPAD SHAPES

The purpose of a footpad is to guarantee a safe touchdown and stable stand on the surface of a planetary body especially for landings with a horizontal velocity component. Furthermore the footpads prevent the spacecraft of being dug too deep into the soil so that the landing leg will be working as a lever for toppling the lander. For a stable landing it is therefore recommended that the footpad shall slide over the surface when the S/C lands with horizontal velocities.

Investigations during the development of the Lunar Module (LM) [RD1] have shown that spherical profiles provide good characteristics during the impact and sliding phase. Furthermore the footpad shall have a symmetrical shape to guarantee the same behaviour in every direction of motion. During the development tests, different sizes and shapes have been tested so that the effects of the footpads could be investigated and conclusions to the stability criteria could be extracted.

In the case of using a spherical shape, the spherical radius (r) is strongly related to the ratio of the selected values for footpad height (h) and chord (crd) of the sphere (see eq. 1).



$$r = \frac{4h^2 + crd^2}{8h} \quad [1]$$

In the following table the four used footpads are presented. The pads have dimensions of 30 cm respectively 40 cm in diameter and a constant height of 4 cm. The suggested sizes are derived from previous planetary landing missions (e.g. Surveyor).

crd = 40 cm	
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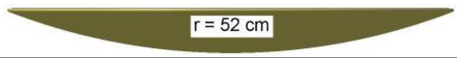
crd = 40 cm	
crd = 30 cm	

Table 3: Footpad shapes

Overall there are two kinds of shapes, the spherical ones and the flat plate with roundings on the edges. The radius of the sphere depends on the height and cord of the pad (see eq. 1). In this case it differs from 30.1 cm to 52cm.

V. TEST MODES

To get feasible data from the test campaign, the real touchdown dynamic has to be analysed and assigned to a simulated test environment. As said in section I., the touchdown is dominated mainly by four effects of energy transmission over three phases, which are shown in Table 4.

	Impulse exchange	Displace-ment drag	Mechanical bearing strength	Pad/soil interface friction
Initial impact	X	X		
Slide out		X	X	X
Static equilibrium			X	X

Table 4: Energy effects at touchdown

To measure and correlate the occurring energy effects, the simulated touchdown had to be split up in two test modes. The first one investigated the impulse exchange at the initial impact. Therefore a footpad with a specific mass has been dropped from the robot flange (see section VI.) to impact the soil. The second test mode simulated the slideout phase. A landing leg adapter has been attached to the robot flange and has been pulled through a soil bin at a constant velocity, with the footpad maintained either at constant depth of penetration or under conditions of constant vertical load. In this chapter the two used test modes are described.

The logic for the execution of the tests is to vary significant parameter and correlate them with the system model. By this means each footpad design has been tested at two different weights respectively forces at two different soils. The impact has been additionally tested on hard ground for adjusting the simulation. The attitude of the footpad has also been varied and observed as well as the vertical and horizontal velocities. The slope of the terrain doesn't have any effect on the analysis. By proceeding in this way it is possible to build up a parametric model for the footpad design in order to find the best solution for the design of the landing gear.

V.I. Impact test

A full-scale impact test (or drop test) is necessary to measure the dynamical soil reactions on a footpad impacting into the soil either vertically or at an oblique angle with the soil surface at a controlled impact velocity. Equipment design is such that the impacting footpad falls free before touching the soil material. The test equipment allows varying the impacting mass, impact velocity and angle of impact. It was designed to measure vertical loads on the footpad, pitch attitude, three-dimensional accelerations, impact velocity, and displacement of the footpad.

The tests results are used to validate the numerical model for the landing phase A (impact phase).

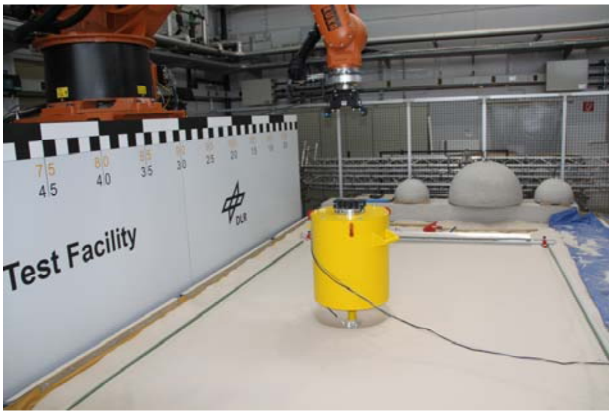


Fig. 2: Impact Test Equipment after dropping

Fig. 2 shows the drop test configuration. The system is essentially a dummy mass (to simulate the full or fractional weight of the Lander) with an attached footpad which is dropped by a pneumatic parallel gripper from a robot moving horizontally on a rail track. The gripper is mounted to the robot flange and releases the test object at a pre-programmed point of time, when the robot has reached its final horizontal velocity of up to 1 m/s. Due to earth's gravity, the vertical touchdown velocity is adjusted by the height on which the gripper releases the test object and the angle of impact can be set by varying the horizontal respectively vertical velocity. The attitude of the test object is adjusted by the robot hand flange before the release. The hinge axis of the footpad has one rotational degree of freedom and can be tilted till 30° and counteracts the attitude of the leg in a way that the pad is parallel to the ground. It is also possible to secure the hinge at certain positions in steps of 10°.

The instrumented footpad (Fig. 3), containing a 3-axis-accelerometer, a potentiometer to measure pitch angles and a 3-axis-force sensor, is mounted under the pivoting hinge which carried the leg and the mass dummy. The footpad has been used for both test modes. The test mass is a cylindrical container and can be adjusted by filling in sand from the soil bin. The whole test object weight is adjustable in the range of 125 kg to 300 kg. In this case 300 kg is also the maximum payload mass of the test object, caused by the configuration. Cables used for power and data of the sensors have been lead away from the dropped foot. The test object itself has been attached through an interface to a form fitting gripper jaw. The gripper is controlled by a 5-port/2-way valve which receives its lock/release signals from the robots realtime controller and is actuated by two impulsive solenoids. All drops have been performed above the 10 m x 4 m soil bin with the WF34 soil. To simulate landings on a rock, a special concrete terrain has also been prepared.

V.II. Drag test

The drag test equipment has been used to measure the dynamic soil resistance forces acting on an instrumented footpad moving horizontally through the soil bed. This movement is representing the phase B of S/C touchdown (sliding phase, Table 4). Thereby two options of executing this test have been foreseen. In the first option the footpad has been pulled with a constant velocity at a constant depth of penetration which generated a variable force on the pad that could be measured. In the second option the force has been hold constant by the robot controller and the depth of penetration has been measured. Both options have been performed in order to observe differences in the behaviour.

In Fig. 3, the instrumented footpad and the robot with suspension are shown. Like at the impact test, the robot moves sidewise on a rail track and presses the footpad into the soil. The pad is instrumented to measure forces with a 3-axis-force sensor, mounted on the center-bottom of the foot, accelerations with an accelerometer and the pitch-angle with a linear potentiometer, mounted directly in the hinge axis.

The connection to the robot has been realized by a steel cylinder containing the harness from the footpad sensors. On the flange of the robot there is the Force-Torque-Control sensor which measures forces and torques in all three axes. The robot itself contains a controller which measures the actual position and time (83 Hz) and compensates stiffness effects (Position accuracy: 0.15 mm). With these data, velocities or accelerations can be derived. A digital camcorder videotapes the whole test run and can also be used to determine velocities.

All instruments, bearings, and push rod assemblies has been protected from the soil and dust during tests by encasing the system in a plastic boot. The boot has been fixed to the footpad and strut with band clamps.

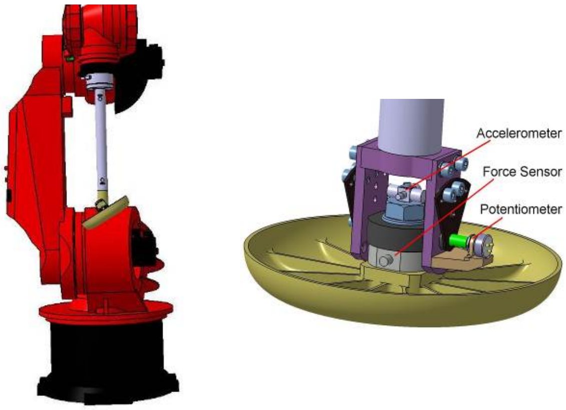


Fig. 3: Instrumented footpad

The motion of the robot has been composed of an acceleration phase (1 m), a constant speed phase (1.5 m), and a deceleration phase (0.5 m).

VI. TEST FACILITY

The tests have been performed at the Landing & Mobility Test Facility (LAMA) at the DLR-Institute of Space Systems in Bremen, Germany. The LAMA facility consists of five major elements, which are a standard type 6-axis industrial robot system (KR500) plus a rail track used typically for factory automation purpose, a suspension device to mount rover or lander, a controller to set up, control and maintain the experiment conditions, a soil bin containing the planetary soil simulant and a test cell which integrates all elements and provides the necessary infrastructure.

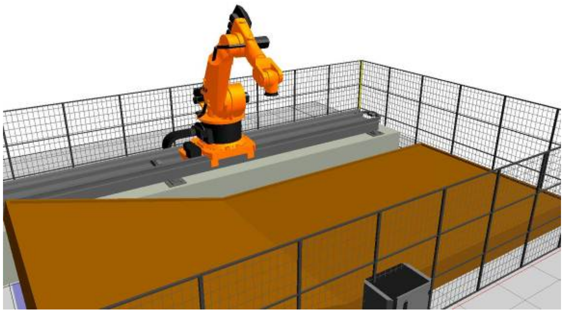


Fig. 4: LAMA test cell

The original purpose for this facility is the provision of a test bed to study vehicle-soil-interactions (i.e. tip-over stability of landing vehicles or terrain accommodation for rovers) in a reduced gravity environment by weight offloading of the robot system.

VI.I Robot system

The key element of LAMA facility is the heavy-duty class robot KR500 [RD4]. The main reason for using an industrial robot is to provide a fully active, self-supporting and in the use cases highly flexible device for setup and maintaining load scenarios and test object handling. The nominal static load bearing capacity of this robot is 500 kg. The KR500 sits atop a rail track system provided by a KUKA KL1500-2 linear axis, allowing a lateral travel distance of 12 m (see Fig. 4).

VI.II. Soil bin

The drop tests have been conducted on a 4 m x 3 m wide part of the LAMA soil bin. With special soil preparation methods and a sand glazer (Fig. 5) the underground had the same characteristics at each test run.

Fig. 5: Test bed for the drop tests

The drag tests have been performed in a 3.2 m x 1.2 m wide soil container located on top of the bigger 10 m x 4 m soil bed. The reason for using a smaller soil bin than the already existing test bed was that the soil could easily be prepared and exchanged. Also for the drag test mode the soil has been treated in a special way so that every test run had the same starting conditions (Fig. 6).

Fig. 6: Test bed for the drag tests

VI.III. Data acquisition concept

The measuring instruments have recorded vertical and horizontal displacement, horizontal velocity, accelerations, attitude, and loading of the instrumented footpad.

A central DAQ unit has been used to synchronize data from three main areas during test operations. This was first of all the test object itself where test mode specific analog sensors such as potentiometer, force sensor and tri-axial accelerometer are mounted on predefined positions. Second, external video cameras have been used for test documentation and subsequent motion analysis. And third, the robot controller itself delivered data about its hand position and orientation as well as forces and torques in the hand root.

VII. TEST RESULTS

VII.I. Drop test results

The drop tests revealed the influences of different footpads at the initial impact. In the table below the behaviour (penetration depth, maximum applied forces and accelerations) of the four footpads at same test conditions can be seen. Note, these results are only exemplary for the complete test campaign, but the other test cases showed similar correlations.

Pad Diameter [mm]	Shape	Sinkage [mm]	F_{max} [kN]	a_{max} [g]
300	spherical	126	13.2	6.3
300	flat	115	13.6	6.1
400	spherical	80	25.0	12.5
400	flat	66	28.3	13.8

Table 5: Penetration depth and forces for selected footpads (mass=200kg, Vz=3m/s)

The test showed following results:

- Comparison of same shape and different size: Smaller footpads sink 55%-75% deeper in the soil than the bigger ones, but the forces and accelerations are only 50% of those. This is an expected result as a smaller pad has less resistance to the soil and the energy can be dissipated more slowly.
- Comparison of different shape and same size:

Spherical footpads sink 10%-20% deeper in the soil than the flat ones; the forces are only 3%-12% smaller and the maximum accelerations are independent from the shape.

VII.II. Drag test results

For the interpretation of the drag test data one test case was selected and compared with the four footpads. In this scenario the pads slid with a constant depth of 30 mm and a constant velocity of 1 m/s through the soil bin. The presented values are all mean values from three test runs of the same kind.

Pad Diameter [mm]	Shape	$F_{z,mean}$ [N]	$F_{x,mean}$ [N]	Pitch [°]
300	spherical	153	-130	2
300	flat	68	-75	-3.3*
400	spherical	490	-290	5.4
400	flat	388	-310	1

Table 6: Drag test results (*: only two of three tests)

It can be stated that spherical pads have 25%-125% higher vertical and lateral loads than flat pads while sliding through the soil. The values for the pitch angle differ from test to test. Especially for the flat pads it is not clearly defined in which direction the footpad will swivel in the sliding phase. The spherical pads however always pitch up in the direction of lateral motion.

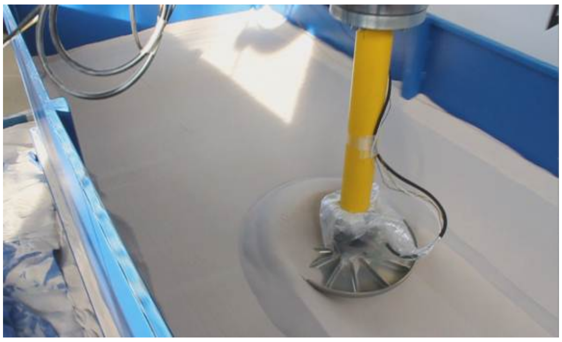


Fig. 7: Footpad sliding through the soil bin

VII.III. Accuracy of test results

A detailed description of the accuracy of the test data is given in [RD7]. An overall summary is presented in this section.

The values shown in the table below were obtained by taking the average of the mean deviations of each test case.

The soil properties and their deviations have been determined in a separate test campaign and are presented in [RD8].

	Error [%] (Drop Test)	Error [%] (Drag Test)
Sinkage	1.1	n/a
Force	2.6	8.7
Acceleration	2.9	n/a
Pitch	n/a	32.4

Table 7: Total Error summary of recorded parameters

It can be seen that the values obtained from the drop tests are very precise. The errors in the determination of the drag test values are significantly higher. Especially the pitch angle has a considerable range of dispersion which comes from the indefiniteness of the flat footpad in which direction it pitches while sliding through the soil.

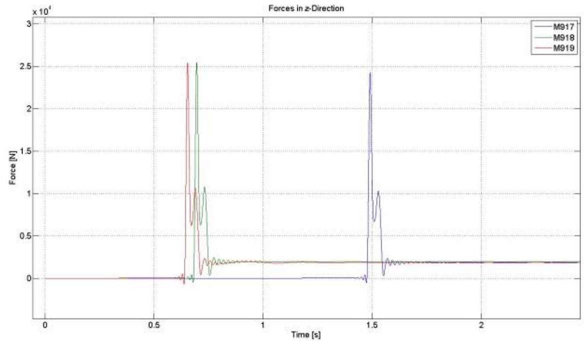


Fig. 8: Force curves of three drop tests at same test conditions

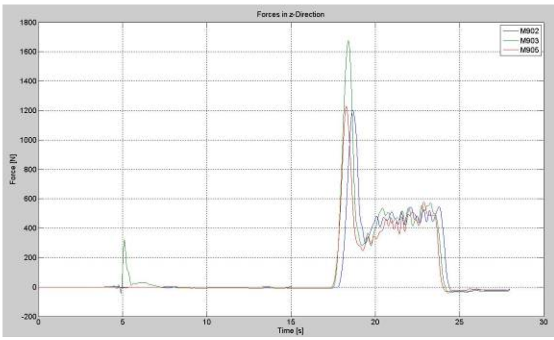


Fig. 9: Force curves of three drag tests at same test conditions

The main influences of the errors in the test data is caused by the soil properties. Small deviations in the preparation of the soil will lead to large differences in the soil resistance. The errors from the drop test are much smaller than the drag test data because the kinetic energy absorption is much higher and small differences in the preparation will have fewer effects on the footpad.

VIII. DISCUSSION

On the basis of the test data it can be seen that the spherical pads tends to penetrate deeper into the soil at the initial impact but have higher contact forces while sliding through the soil. This attitude can be interpreted as a counteraction of the pad of sinking deeper into the soil. The spherical shape therefore leads to an upward motion within the sliding phase which are suppressed here by the robot interface and showed themselves in the higher force levels.

As expected, a larger pad is more resistant to soil penetration than a smaller pad. This is valid for both test modes.

It can be concluded that spherical pads are more robust of penetrating the soil with horizontal velocities. They will slide atop the surface plane rather than sinking deeper into it. The size has to be adapted in order to fulfil ground clearance constraints. A raise in the size of 78% leads to ~60% less sinkage.

IX. CONCLUSION & OUTLOOK

The representation of the final landing phase of a spacecraft has been performed by splitting up the phase in two test modes. The first one investigated the initial impact into the soil by dropping off a footpad from a robot on a rail track. In the second test mode the sliding phase has been represented. A footpad attached to the robot hand flange has been pulled through the soil and the reacting forces have been measured.

The tests have been performed at the Landing and Mobility Test Facility (LAMA) of the DLR institute of space systems in Bremen. The test setup provided confident data to select a footpad shape for future Moon or Mars missions.

The next steps have to be the correlation of the experimental gained data with adequate multi-body simulation tools and later on the integration to a system level simulation. The simulations should lead to a trade between size (mass) of the pad versus soil penetration depth, loads and landing stability.

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