DESIGN AND DEVELOPMENT OF AN ACTIVE LANDING GEAR SYSTEM FOR ROBOTICALLY ENHANCED SURFACE TOUCHDOWN

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ABSTRACT

The recent developments in the course of Rosetta mission of landing a probe on a comet have utterly shifted the concept of active landing gears from desired system functionality to necessity in future planetary exploration missions. Active landing gear has been identified by ESA as one of the key technological challenges in the framework of a European Mars Phobos Sample return Mission. Within the frame of Phootprint mission, the ESA-funded REST activity (Robotically Enhanced Surface Touchdown) has the clear objective of designing an actively compliant landing gear for low gravity environments (Phobos) and developing and testing a scaled prototype of it.

The preliminary outputs obtained during the first two phases of the project are presented, i.e. a state-of-the-art analysis of past and present developments in the field of active landing gears with their feasibility traced with respect to the requirements derived for the REST system in the initial phase of the activity. A simulation campaign for validation of the proposed concepts shall be performed within the second phase of the project, while the reduced degree-of-freedom prototype development and manufacturing together with its testing on an air-bearing table shall follow in the subsequent phases.

1. INTRODUCTION

ESA's Phootprint mission is a candidate mission of the Mars Robotic Exploration Preparation (MREP) Programme, with the main objective of acquiring and returning a sample from the Mars moon Phobos, after a scientific characterisation phase of the moon and of the landing site.

The Phootprint spacecraft is composed by several modules as depicted in Figure 1. The system design is not closed and thus, the design here presented is still preliminary.

- A Landing Module (LM) carrying the ERV & ERC, performing the transfer to Mars, the Mars orbit insertion and phasing manoeuvres to reach Phobos vicinity, the operations around and on Phobos, including landing and sampling
- An Earth Return Vehicle (ERV) performing the Mars escape, the transfer back to Earth and the ERC release few hours before re-entry
- An Earth Re-entry Capsule (ERC)

The REST system is being designed by taking into account the following considerations:

- Safe landing of the spacecraft on Phobos;
- Reusability – avoid destruction or damaging at landing on Phobos
- Compactness – the system shall not exceed the envelope of the assigned launcher during the stowed configuration.

Tests are required for verification of the proposed design of an actively compliant landing gear for low-G environment. There are two main objectives of tests: validation of certain critical elements of landing gear design and acquisition of data required for calibration of dynamical model of landing gear, which will be used for numerical simulations of REST system. The tests will be performed on reduced degree of freedom test set-up (one landing leg with two translations and one rotational degree of freedom) which will make use of air-bearing technology in order to allow the REST prototype to land on a Phobos surface mock-up. Obtained tests results will be extrapolated and numerical dynamic model will allow understanding of the behaviour of the REST during the landing and surface activities.

The test set-up must allow at least simplified simulation of the actual surface touchdown of the REST prototype (model with reduced scale and d.o.f.). It is important (also for correlation with the numerical model) to reproduce not only the behaviour of one landing leg during landing, but to try to reproduce the behaviour of the REST system as a whole (e.g., its stability and tendency to flip over). In order to reproduce landing dynamics test set-up must allow motion of the landing gear prototype towards mock-up of Phobos surface and unrestricted contact with this mock-up.

2. LOW-GRAVITY LANDING REQUIREMENTS

The major requirements for the REST system are to provide safe landing on the surface of Phobos in micro-gravity conditions and ensure the required attitude, stability and dynamic properties to allow surface operations (i.e. during sample acquisition and robotic arm motion).

In order to capture the REST requirements, a reference scenario was defined at the beginning of the activity:

- The REST system serves as a landing gear for the Moon Mars sample return mission
- The spacecraft that will incorporate the REST system shall be compatible with the Ariane 5 and Falcon 9 launchers
- the REST system shall carry another 2 modules (ERV &ERC)

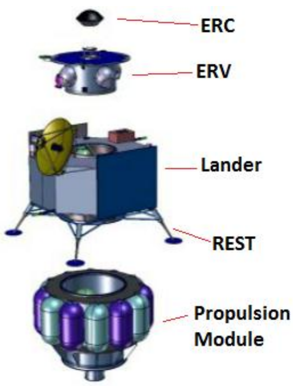

Figure 1. Phootprint Lander configuration (source: ADS)

As the overall system design is currently at an early stage, the critical interface requirement derived for REST states that the system shall be compatible with all the mission-related proposed platforms, according to the industrial studies performed up to date. The configurations are described in Figure 2.

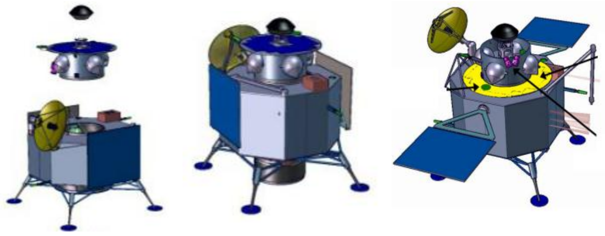

Figure 2. Spacecraft configurations: Left: ADS direct launch, Center: ADS GTO launch, Right: TAS-I direct launch (source: ADS, TAS-I)

The design driver requirements for the REST system are:

- Safe landing on Phobos (1 landing required)
- Impedance-controlled absorption of the impact/settling forces and compensation of residual elasticity, assuring: (1) no crash at landing, (2) no tip over at landing, (3) no rebound after landing
- Deployment of the landing legs (under investigation) and ability of re-levelling the lander platform
- The rejection of vibration induced by sampling devices, fuel sloshing, robotic arm actuation and firing of hold-down thrusters.

In order to provide for a safe landing, the REST system shall be able to cope with all the loads and shocks generated during landing. It is also necessary that the landing loads transmitted in the Lander structure shall be low enough so that no equipment or instrument will be damaged. The term of “safe landing” implies that Lander shall not suffer integrity damages or operational malfunctions due to landing. According to the initial simulations, the maximum kinetic energy to be dissipated at touchdown is estimated at 500J, with a peak during the 1st second and a total actuation time of between 5 and 30 seconds, considering the parasitic elasticity of the soil.

The “no rebound” after landing is a critical condition given the low-gravity environment of landing. “No Rebound” is considered here as the ability of the system to maintain always a positive or zero velocity of the spacecraft towards the surface. The requirement related to no tip-over implies that the energy necessary to topple the lander needs to be higher than the horizontal component of the impact energy. Additionally it is evident that the CoM projection on the sub-lander surface shall not exceed the perimeter delimited by the landing gear pads (footprint).

The primary approach investigated during the activity for minimizing/eliminating the rebound consist in avoiding restitution of the damped energy during landing: as evidenced by previous studies [1] this energy can be absorbed either passively – through shock alleviation techniques: plastic deformation of crushable materials, friction attenuator, spring-damper mechanisms, hydraulic or pneumatic attenuators or cyclic plastic deformation materials; either actively - through controlled actuators.

As the landing site has not been completely defined yet, the system needs to cope with a significant range of surface environmental conditions and landing scenarios, the worst case scenario stating a clearance for boulders of up to 50cm in diameter and 25deg sloped terrains.

Since one of the Phootprint mission’s objectives is to safely return to Earth samples of Phobos surface, the landing gear is also required to provide stability during sampling by cancelling all the induced vibrations. There are multiple sources of disturbing forces, such as sampling induced torques and moments, fuel sloshing in tanks, firing of hold-down thrusters and also residual elasticity in the Lander’s structure determined by the intermittent thruster firings.

3. ACTIVE LANDING GEAR TECHNOLOGIES

Compliant mechanisms are being studied for vibration isolation systems, in order to cancel undesired disturbances, resulting in attenuated output amplitude. This study is limited to low frequency isolation, because the use of compliant mechanism in an active vibration isolation system has the greatest advantage in the low frequency range. According to [2], vibration isolation systems can be categorized in various ways, but the most common is according to control schemes: passive, active and semi-active systems (Figure 3).

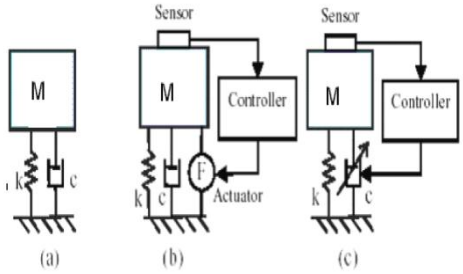

Figure 3. Simple models showing basic elements in different types of vibration isolation systems: Passive, Active and Semi-active [3]

The Passive solution is formed by elastic elements and a damping element, used to limit the amplitude of vibrations and to dissipate energy away from the system. A passive system cannot be adjusted while the system is in operation. For this reason, the vibration transmissibility depends on the disturbance frequency. Figure 3 shows a plot with a typical transmissibility function, for a passive system. According to this, it can be stated that a passive system is only effective for disturbances with frequencies much higher than its natural frequency. For this reason, adjusting the system damping parameters involves a trade-off between isolation at different frequencies and the resulting overall performance.

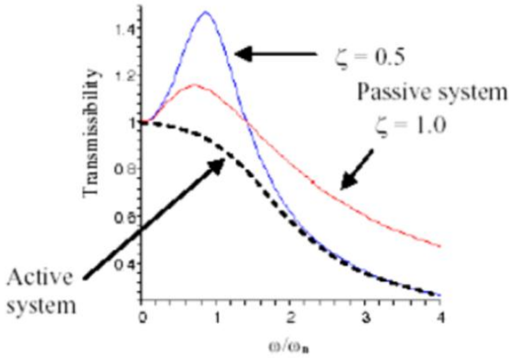

Figure 4. Vibration transmissibility comparison graph between passive and active systems

An active vibration isolation system uses external energy, to directly cancel energy in the system, by using actuators, sensors and controllers. The transmissibility plot of a typical active system is shown as a dashed line in Figure 4.

A semi-active system combines features of a passive system and an active one. Semi-active systems are passive elements whose properties such as damping ratio and stiffness can be varied so that the control can be implemented without adding external energy into the system, except a small amount of energy required to change the properties of the actuators.

According to [3], the ideal damping system is a passive one with a very low stiffness, leading to low natural frequency so that the natural frequency is always below the operative ranges. However, this situation is not possible in the vertical direction because such a low vertical stiffness will lead to high strokes that will cause the collision of the probe with the ground.

1.1. Applications in aeronautics

In [4] an investigation is conducted for an active landing gear for aircraft vibrations isolation, due to landing impacts and runway excitations. This application uses an oleo-pneumatic shock strut, similar to the ones used in landing gear systems for aircrafts. The motivations are previous investigations, involving real-time feedback of the ground input to the landing system, that show that active control, greatly reduces impact and fatigue loads experienced by the aircraft as well as vertical displacements.
Active control landing gear systems are still in the theoretical and experimental stage and they have not been introduced into real aircrafts because of many practical issues involving safety, design and production.
Figure 5 shows the model used in [4] for the creation of the nonlinear mathematical model to study the performance of an active landing gear system, implementing the dynamic equations in SIMULINK.

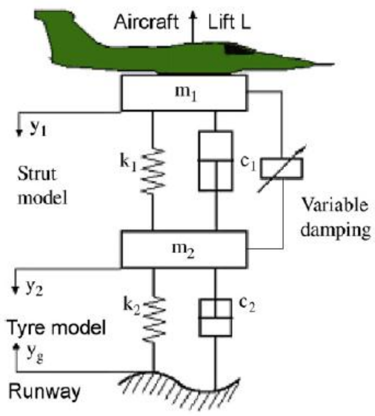

Figure 5 Dynamic model of an aircraft landing gear system [4]

1.2. Applications in space

In [5] an investigation is conducted to determine the performance of a variable damping shock absorber with semi-active vibration control, for space applications. It is focused in reducing the vibrations transmitted to on-board instruments due to shocks generated by pyrotechnic actuation devices that produce high frequency, high amplitude shocks, as well as vibrations transmitted during the launch process.
Passive isolation systems are effective for shock attenuation, however, they are not the best choice for launch vibration suppression, because they cannot adapt to environmental changes due to their fixed parameters.

On the other hand, active systems are a very attractive solution because they overcome the passive weaknesses, the cost is higher and the reliability is reduced due to some phenomena, such as spillover, specially when the exact dynamic characteristics of the structures are not determined.

Finally, the semi-active solution seems promising for space applications because it has advantages in both passive and active systems. The performance of a semi-active system is much better than a passive one because the damping force is controlled. Moreover, the robustness of the semi-active system is higher because energy is always dissipated by passive components.

In [6] a complete analysis, covering the design of legged landing gears and ASA design is presented. This paper remarks the importance of not using oils and freezable fluids in space applications. For this reason, proposes the use of electromagnetic actuators that not only solve problems related to temperature variations but also offers a very simple control architecture. (Figure 6).

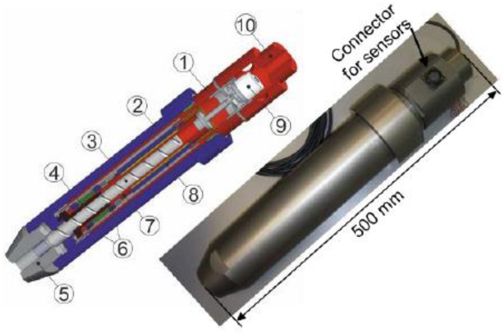

Figure 6: ASA design [6]

The results show that the proposed actuator increases the efficiency of the landing gear, allowing it to be reusable, but also enabling leveling of the lander attitude and allowing hopping mobility.

1.3. Earth applications

The most common terrestrial applications in which active suspensions are used are related to railway and automotive applications.
In [7] a studied is carried out by Eindhoven University, in collaboration with Swedish mechatronics company SKF for the design of automotive electromagnetic active suspension system. The proposed solution will provide additional stability and maneuverability by performing active roll and pitch control, during cornering and braking, as well as eliminating road irregularities.

Figure 7: Electromagnetic suspension prototype developed by Eindhoven University [8]

The firm Bose, has recently presented the Bose Suspension System [9], that uses a linear electromagnetic motor and a power amplifier at each wheel. The bidirectional power amplifier allows power to flow into the linear electromagnetic motor and allows power to be returned from the motor. It is said that this suspension system requires less than a third of the power of a typical vehicle's air-conditioning system (Figure 8).

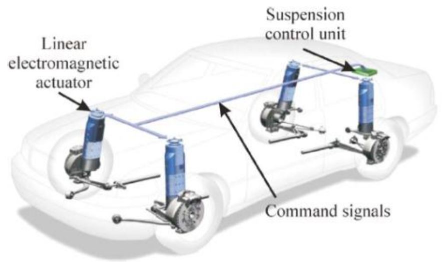

Figure 8: Bose suspension system

The railway industry has been closely related since the early nineties to magnetic suspensions, but paying attention to magnetic levitation more than in vibration absorption. In the frame of these applications, the German Monorail of 1934 was the first vehicle provided with magnetic levitation. Then, in 1984 another railway was developed by the UK using magnetic levitation and induction propulsion. In 1987 the German Transrapid exhibition vehicle was used to transport passengers. Finally, in 2004 the German-Chinese collaboration led to the Transrapid 07 that was a vehicle operating between Shanghai and its airport.

Figure 9: Transrapid 09 at the Emsland test facility in Germany (Source: Wikipedia)

4. TESTING ENVIRONMENT

4.1. Functional Engineering Simulator (FES)

Dynamic analyses will be run with the use of the REST Functional Engineering Simulator (FES). The FES is currently being implemented on a Matlab/Simulink infrastructure, which will allow reproducing the Phobos environmental interactions including all the dynamics and kinematics aspects.
Monte Carlo capability from the FES and high-fidelity models of the soil interaction are implemented in order to identify the maximum forces (worst case) exchanged between REST and the spacecraft with sufficient confidence level.

The architecture of the REST FES is composed by the following main elements:

- **Phobos models** which includes Dynamic and Kinematic Enviroment, such as Phobos gravity and Phobos specific soil interaction models currently under investigation. The tuning of some of the quasi-experimental soil interaction parameters will inevitably follow some simple test results from the experimental setup on the air-bearing table.
- **Lander dynamics** which include the main spacecraft dynamics, meaning at least fuel sloshing, forces transmitted from engines and from the sampling tool, residual elastic energy after impact and during firing of hold-down thrusters.
- **REST mechanism** which includes the multibody simulation of the legs and all their elements, including the control of the active actuators. Multibody simulation is implemented in dedicated tools such as SimMechanics in order to ease its integration through, for instance, S-Function within the Simulink-based FES. This module is envisaged to include detailed characterization of the active and passive elements of the landing gear system, whose transfer functions and dynamic constants (adapted to mass-spring-damper models) will be tuned after experimental tests.

The simulator is aimed to be implemented so that the user will be able to easily configure parameters that will be tuned along the REST design.

4.2. Air bearing table

Tests are required for verification of the proposed design of an actively compliant landing gear for low-G environment. There are two main objectives of tests: validation of certain critical elements of landing gear design and acquisition of data required for calibration of dynamical model of landing gear, which will be used for numerical simulations of REST system. Tests will be performed on reduced-d.o.f. test set-up which will make use of air-bearing technology in order to allow the REST prototype to land on a Phobos surface mock-up. Obtained tests results will be extrapolated and numerical dynamic model will allow understanding of the behaviour of the REST during the landing and surface activities.

Two landing legs will be tested as the REST prototype. Scale of the prototype will be reduced to fit into the existing facilities. Prototype of the landing gear will be placed on an air-bearing cart. Coefficient of friction of planar air-bearings is very small ($\sim 10^{-5}$), thus objects supported on air-bearings can move and rotate freely on the table surface. As a result microgravity conditions can be simulated in one plane. To simulate low-gravity conditions of Phobos during landing of the Phootprint Lander granite table will be slightly tilted ($\alpha \approx 0.05$ deg). Air-bearing cart will be accelerated to the required touchdown velocity by means of the spring-launcher system. Then, contact of the landing gear with a mock-up of the Phobos surface will occur and behaviour of the REST prototype during the landing and surface activities will be tested. Conceptual design of the air-bearing test set-up is presented in the Figure 10.

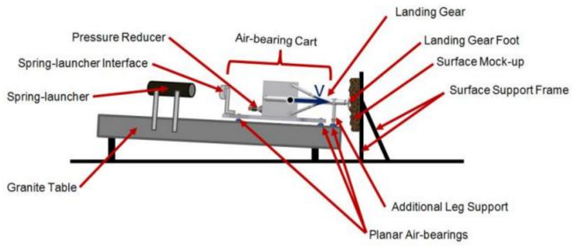

Figure 10. Conceptual design of the air-bearing test set-up.

The air-bearing cart, on which the landing gear prototype will be placed, will be supported on three air-bearings that form a three-point stance. Air-bearing cart will give freedom of planar motion for the REST prototype. Two-legged landing gear prototype will operate in one plane only (parallel to the table surface), thus it is possible to use additional planar air-bearings (two or four) to support struts of the landing gear and reduce forces acting on the legs. Design of the landing gear prototype will take into account these additional supports and system based on resilient suspension plates will be used to compensate for vertical misalignments

between components of the system (all air-bearings must be ideally coplanar in order to allow proper operation of the bearings and free planar motion of the system).
Air-bearings based on porous media technology will be used. In such bearings pressurized air is supplied through a hole on a side of the air-bearing and airflow is then controlled across the entire bearing surface through millions of holes in the porous carbon. Air pressure remains almost uniform across the whole surface, as the air flow is automatically restricted and damped. In contrast to classic air-bearings where the air is distributed through many small orifices, porous air-bearings are immune to scratches and hard to clog. Reliability of air-bearings system is important for the planned test set-up. Schematic view of the planar air-bearing based on porous media technology and picture of the actual planar air-bearing available at CBK are presented in the Figure 11.
Three planar air-bearings of the air-bearing cart and planar air-bearing of the additional leg supports will be supplied with compressed air (0.6 MPa) from one gas canister located horizontally on the base of the cart. Gas canister located on the cart will be equipped with a pressure reducer and controlled manually (cart must be designed in such a way, that will provide easy access to the canister). Preliminary design of the proposed air-bearing cart is presented in the Figure 12. The air-bearing cart will be based on a plate, to which most components will be fixed. Landing gear legs will be located on the opposite vertical plates, similarly to the configuration of the considered Phootprint lander. The air-bearing cart support structure will carry loads acting on the landing gear mounting points during contact with the Phobos surface mock-up.

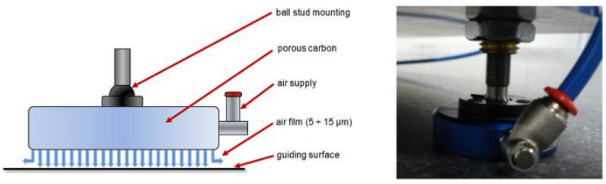

Figure 11. Schematic view of the planar air –bearing based on porous media technology (left) and picture of the planar air-bearing available at CBK (right).

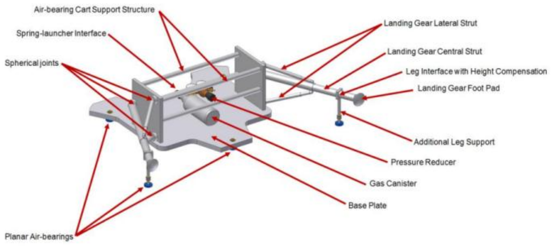

Figure 12. Preliminary design of the air -bearing cart with two-legged prototype of the REST system

During touchdown simulation the REST prototype will make contact with the Phobos surface mock-up, which will stand in a vertical position. During simulation of surface activities the landing gear will rest on the mock-up due to the inclination of the granite table that reproduces low-G conditions. Mock-up of the surface will consist of a base plate attached to a vertical metal frame. This base plate will be covered by a Phobos surface analogue, i.e., soil simulant fixed to some material reproducing surface features of the Martian moon.
Test set-up will be equipped with measuring equipment on the air-bearing cart (measurements of positions of linear joints of the REST prototype and of torques and forces acting in these joints). Position and orientation of the REST prototype during approach, landing and surface activities will be measured with motion capture system that could track markers on the air-bearing cart.

5. CONCLUSIONS

Preliminary dynamic analyses are to be concluded under the REST Functional Engineering Simulator taking into account the Phobos environment, lander dynamics and multi-body simulation of the legs and all their elements. Within the above context, it is fundamental that the correlation between REST FES simulations and the prototype experimental campaign on the air-bearing table is as close to the reality as possible, in order to have a validated simulator. The simulator, together with the conceptual system design and prototype developed within the frame of this activity shall serve as baseline for raising the REST system TRL to level 5 in the upcoming activities.

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