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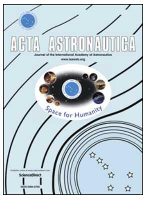

Rosetta lander Philae – Landing performance and touchdown safety assessment

Lars Witte [a,*], Reinhard Roll [b], Jens Biele [c], Stephan Ulamec [c], Eric Jurado [d]

[a] German Aerospace Center (DLR), Bremen, Germany
[b] Max Planck Institute for Solar System Research (MPS), Göttingen, Germany
[c] German Aerospace Center (DLR), Cologne, Germany
[d] Centre National d'Etudes Spatiales (CNES), Toulouse, France

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ABSTRACT

This paper describes the simulation and analysis work on Rosetta lander Philae's touchdown dynamics which was done to support its Landing Site Selection Process. The simulation part consists of a numerical multi-body simulation to describe Philae's touchdown dynamics. Suitable performance metrics in conjunction with Monte Carlo trajectory data from the flight dynamics analysis yields landing area specific landing gear performance and safety figures. These were then incorporated into the site selection process with regard to landing system performance margins and touchdown safety. While Philae finally made a nearly successful landing the actual flight data were used to review and discuss the applicability of the presented simulation and analysis scheme.

1. Introduction

Philae is the landing element of ESA's Rosetta mission to comet 67P/Churyumov–Gerasimenko [1,2]. Philae has a total mass of about 98 kg and carries a payload of 10 scientific instruments to the comet's surface. The lander is equipped with core avionics consisting of the central data management system, S-band communication (relayed via the Rosetta orbiter), and the power distribution system with primary and secondary batteries. The body structure is made from carbon fiber and aluminum honeycomb and is covered with the solar array. The body contains a fly wheel for attitude stabilization during descent as well as a cold gas hold-down thruster (ADS, Active Descend System) to support the touchdown. The landing gear subsystem is a foldable tripod made from carbon fiber tubes and includes several elements to enable a safe landing coping with uncertain surface and soil conditions. These include a central electro-mechanical damping system which is attached to the lander body, and ice screws in its landing feet. Anchoring harpoons are an additional means which were intended to fix Philae to the surface and stay there. The landing gear has a mass of about 10 kg and a footprint diameter of 3.08 m in the deployed condition. The lander itself and its payload are described in more detail in several publications such as [2]. The landing gear subsystem and its dynamics are specifically described in [3]. An adjustable ejection device on the Rosetta orbiter releases and pushes off the lander a pre-planned trajectory. The lander then descends ballistically towards its designated landing site.

The 12th of November 2014 marked then the first landing of a spacecraft – the lander Philae – on a comet. The push-off from the Rosetta orbiter and descend towards the selected landing site »Agilkia« were nominal during

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* Correspondence to: German Aerospace Center (DLR), Institute of Space Systems, Robert-Hooke-Street 7, 28359 Bremen, Germany. Tel.: +49 421 24420 1127.
E-mail addresses: lars.witte@dlr.de (L. Witte), roll@mps.mpg.de (R. Roll), jens.biele@dlr.de (J. Biele), stephan.ulamec@dlr.de (S. Ulamec), Eric.Jurado@cnes.fr (E. Jurado).

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the actual landing attempt. Touchdown occurred very close to the targeted landing site coordinates. This event was preceded by a Landing Site Selection Process (LSSP) which led to the selection of »Agilkia« [4]. A landing gear performance and touchdown safety assessment was made in the frame of this site selection process. This paper describes the analysis tools and methods developed for this assessment. Note, that the analyses assumed a working ADS.

A high-fidelity multi-body simulation of the lander – described in Section 2 – represents the landing gear dynamics and system response upon touchdown. The lander kinematics and force laws implemented in the model which determine the touchdown dynamics are introduced in this section. Performance metrics and safety figures are defined in Section 3 to measure the success of a particular landing case and the remaining landing gear performance margins. Site and landing scenario specific expected values for a safe landing and its margins are derived from this analysis in conjunction with Monte Carlo trajectory data from the flight dynamics analysis (Section 4).

The actual landing – however – was hampered by failures of both the hold-down thrust and the anchoring harpoons. Consequently, the lander bounced-off the surface after initial touchdown and drifted to its final, unintended landing position [5]. Section 5 of this paper reviews the touchdown simulation and assessment process in view of the actual landing taking into account also the subsystem failures.

2. Philae touchdown dynamics simulation

The purpose of a high-fidelity touchdown (abbreviated: T/D) simulation is to provide an accurate representation of the lander dynamics and surface interaction upon touchdown. Such an engineering simulation has already been used during the design and development phase of the lander in 1996–2002. These early simulation are described in [6]. An experimental landing test campaign [3] was done to review the landing performance and to be incorporated into the operations planning of the upcoming landing. This test campaign made use of a new test facility to provide data beyond those available during the design, development and qualification of Philae. The numerical simulation was newly set up with improved fidelity in view of new landing gear test data and findings from this campaign. The simulation is checked and validated against these experimental data.

The landing system is modeled as a multibody mechanical system. Its implementation uses the commercial multibody simulation software tool SIMPACK [7]. Model elements are bodies, joints or constraints and forces. Bodies represent the geometry and mass properties of the lander, joints or constraints are connecting the bodies and determine the degrees of freedom of the complete assembly. The resulting multibody topology is depicted in Fig. 1.

The force elements act on the various bodies according to certain force laws (e.g. the thrust profile of the Active Descend System ADS). Control logic is implemented to mimic the onboard logic which detects the touchdown event and initiates events such as the firing of anchoring harpoons and the ADS activation. The following functionalities and forces are represented:

2.1. Damper assembly

The electro-mechanical damping device (Fig. 2) translates the damper stroke into a rotation which drives an electric generator. The electrical energy is then dissipated within a resistor. The resulting damping force F_d depends on the relative actuation velocity v_d between the landing gear assembly and the lander body and is described by a complex transfer function (Eq. (1)).

$$\hat{F}_d = \frac{k_D \cdot (j\omega + \delta)}{j\omega^2 + j\omega\delta + \omega_0^2} \cdot \hat{v}_d \qquad \text{with } \omega_0^2 : \frac{\sigma^2 k_D}{I_R} \text{ and } \delta : = \frac{d}{I_R} \tag{1}$$

The moment of inertia of all of the rotating elements is collectively described by I_R, whereas k_d stands for the stiffness of (primarily) the cables, σ is the spindle thread pitch and d is a damping coefficient. The quasi-stationary transfer behavior (Eq. (2)) shows that the damping force is linearly proportional to the velocity with $b = 567$ N s/m. A detailed description of this assembly and its dynamics is given in [3].

$$\hat{F}_d = \frac{d}{\sigma^2} \cdot \hat{v}_d = b \cdot \hat{v}_d \tag{2}$$

2.2. Footpad–soil-contact

This force law models the comet surface as a kind of granular material (dust/ice agglomerates). Its compressive strength provides the resistance against the penetrating feet as the surface yields. The adopted soil force model is the simplest imaginable for granular beds in micro-gravity, thus with no depth-dependence. Dynamical resistance is neglected. The penetration resistance $F_{s,norm}$ of any lander element is then given by the compressive strength s_c of this idealized material times the penetrating cross section $A_v = 0.017$ m^2 (Eq. (3)). This area is mainly determined by the two soles of each foot, see [8]. The landing feet are retained by the shear forces between the comet material and the ice screws of the lander. The retention force is given by material's shear strength s_s times the side wall area $A_h = 0.0069$ m^2 of the penetrating object (Eq. (3)). The assumed strength values – compressive $s_c = 7$ kPa, shear $s_s = 1$ kPa – are taken from [8]. The model above is consistent with laboratory measurements (slow horizontal drag of a test body in a granular medium under 1 g, [9]) but not with assumed tri-directional compression because the particles cannot evade to the sides when an object is penetrating as in [10]. While these parameter assume a lower bound for a weak surface in the simulated landing scenarios, a second case considers a hard, nearly rigid ice crust with a compressive strength of $s_c = 2$ MPa. The ice screws are not extended and the footpad penetration is negligible. Consequently, with $A_v = 0$ this case, there is no

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