MAIN FUNCTIONAL TESTS OF CALLISTO'S LANDING SYSTEM – TOUCHDOWN AND DEPLOYMENT

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ABSTRACT

Reusable launch vehicles will inevitably face the challenge of a safe touchdown, which is essential to fulfil the re-usability objectives. Before touching down, the deployment of landing legs within a harsh load environment needs to be mastered. The engine plume, the aerodynamics, and vehicle dynamics influence the deployment dynamics, while the induced torques and forces must be carried by the central core structure and compensated by the Guidance Navigation and Control system. Once the deployment is mastered, the landing system's main function is enabled, allowing a safe transition from flight to ground. At the arrival gate, which marks the handover from deployment to touchdown phase, the vehicle's attitude and dynamic state is afflicted with uncertainties. The landing system must handle the majority of these states and provide tip-over stability, sufficient ground clearance, load attenuation capability, and the energy absorption capability that is required to dissipate the residual kinetic energy of the vehicle at touchdown. Understanding the complex dynamics of a landing system therefore requires, beside numerical tools, tests on landing leg level.

Within the CALLISTO project, single leg touchdown and deployment tests were performed in the Landing and Mobility Test Facility (LAMA) located at the German Aerospace Center in Bremen. These tests experimentally investigated the deployment and touchdown performance of the development model of CALLISTO's Approach and Landing System (ALS), which is driven by a pneumatic deployment system. The deployment tests verified the functionality of the pneumatic deployment system and the entire functional chain starting from the reception of the deployment signal through to completion of the transient deployment phase. The energy absorption and the load carrying capability of CALLISTO's landing leg were assessed on the single leg drop test stand. The resulting test data were used for the validation process of the developed simulation tools, which were used for generating predictions and assess the deployment and touchdown dynamics at both the landing leg and vehicle level. This paper presents the conducted deployment and touchdown tests and how these tests incorporate into the landing system verification program.

1. INTRODUCTION & CALLISTO PROJECT

Currently, several launch vehicles are under development worldwide with the goal of cost reduction by re-usability. Examples of these launch systems include SpaceX's Starship (USA), Deep Blue Aerospaces Nebula-M Rocket (China), and MaiaSpace (France). All these launch systems share a common feature: they employ deployable landing legs, offering the advantage of a significantly reduced projected area when stowed compared to the deployed configuration. To capitalize on this benefit, the landing leg system requires a novel deployment mechanism that is relatively new to the space industry. While common deployment operations in space industry have been conducted in near-vacuum or low-density atmospheric conditions, the landing system of a reusable launch vehicle (RLV) must perform its deployment in a dense atmosphere, near sea level and subsequently pin-point land the vehicle on

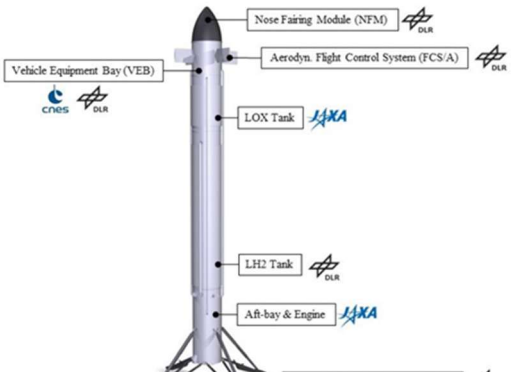


Figure 1: CALLISTO sub-scale booster demonstrator. Responsibility shares between partners

ground. This presents unique challenges compared to previous missions and operational environments. Subsequently, after the deployment, the vehicle needs to master the touchdown dynamics that are afflicted to vehicle state uncertainties.

To gain a better comprehension of the characteristics of RLVs regarding the required design and operations, and to mature the required key technologies, CNES of France, DLR of Germany, and JAXA of Japan have chosen to combine their expertise in the CALLISTO project (Cooperative Action Leading to Launcher Innovation in Stage Toss-back Operations). The trilateral partners aim to develop, build, and test a subscale reusable first stage demonstrator vehicle. Responsibility and tasks are distributed based on the expertise and knowhow of the partners. An overview of this sharing is illustrated in Figure 1 and well described in [1-4]. The Approach and Landing System (ALS) is under the responsibility of DLR. In addition to developing, building, and testing it, a major contribution is the simulation of the landing leg's dynamic behaviour.

The following section describes the ALS main structure and the deployment subsystem, followed by a description of the ALS main functions. The last section explains how physical tests and virtual simulations incorporate into the landing leg development program.

2. APPROACH AND LANDING SYSTEM

During ascent and descent, the landing legs are folded and secured against the vehicle. Just before touchdown, they are deployed via the pneumatic deployment subsystem. Once fully extended, two latching mechanisms located at the segment interfaces of the telescopic struts engage to prevent retraction under external loads. The legs remain locked in place until manual reset, after successful touchdown, by the ground operational staff. These two configurations are illustrated in Figure 2. Additionally, the legs are equipped with an ablative thermal protection system (TPS) to withstand the intense thermal conditions experienced during the final approach and landing phase.

2.1. Landing Leg Structure

The ALS consists of four deployable inverse tri-pod landing legs and a deployment subsystem. The primary and secondary strut are attached to the vehicle's aftbay and transmit flight, deployment, and touchdown loads. The telescopic primary strut consists of three cylindrical carbon fibre reinforced plastic (CFRP) segments that slide coaxially within one another, providing a compact stowed volume (expansion factor of 3). Two passive latching mechanisms lock the segment-to-segment degree of freedom in fully deployed state. The extension is initiated by the deployment subsystem. Once the primary strut is pressurized the pneumatic force drives the segments outwards.

The third segment is divided into two sub-parts that enclose a crushable energy absorption element. Upon touchdown, when the crush load is exceeded, the crushable element absorbs the residual kinetic energy of the vehicle by plastic deformation of the energy absorption element.

The aeroshell is formed by the secondary strut outer hull. Contact with the landing site is established via the rubberized footpad. Beside the main structural

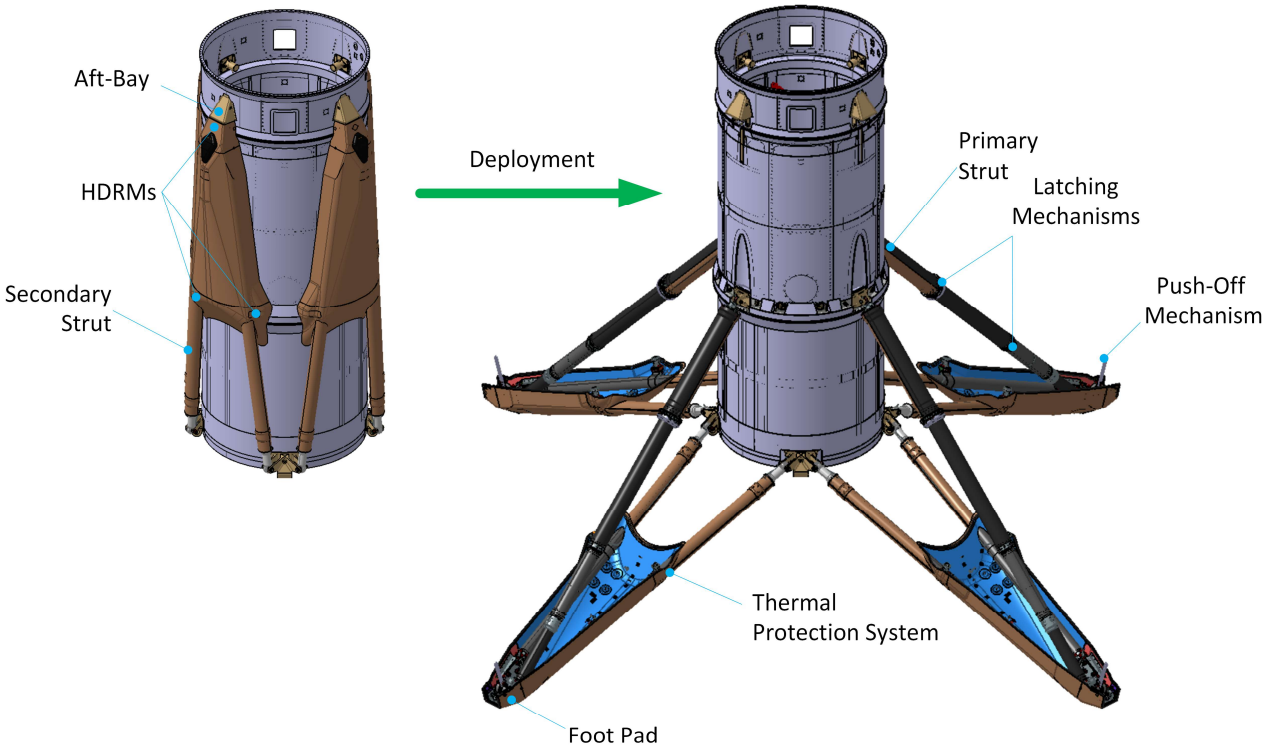


Figure 2: ALS subassemblies. Left figure shows the stowed and right the deployed state.

parts, the landing leg structure entails a thermal protection to protect the structure from heat loads generated throughout all flight and ground phases. CALLISTO's load carrying structure development has been studied in [9].



Figure 3: Falcon 9 asymmetric deployment dynamics. [adapted from Bob Montanaro (https://lunarcabin.com/) with permission]

2.2. Deployment Subsystem

The pneumatic deployment subsystem combines equipment and actuators for extending the landing-leg struts. It is composed of a high-pressure storage vessel, an isolation valve, a pressure-relief valve, a fill-and-drain valve, tubing, electromechanical release mechanisms, and the associated pneumatic telescopic strut actuators (primary strut). A deployment controller is integrated into the subsystem; it receives the deployment command from the launcher's onboard-computer (OBC), converts it into an opening signal for the isolation valve, fires the hold down release mechanisms (HDRM), and routes key instrumentation data, system pressure, HDRM status, and latch status, to the launcher's OBC [5]. These components are accommodated within CALLISTO's aftbay, as shown in Figure 4. This architecture was selected because it brings the following technical advantages:

- Limited mechanical and fluidic interface management – No fluidic interface to the rocket propulsion system for helium supply and the push-off is mounted directly on each leg, reducing the number of mechanical interfaces with the launcher.
- Pneumatically driven actuators provide the ability to modulate the generated pneumatic force, enabling adjustment of pneumatic force for a range of deployment conditions.
- Asynchronicity mitigation – By adjusting the actuator force, the relative timing of the landing legs can be limited.
- Reliance on COTS flight-heritage components – All major elements (valves, tubing, HDRMs) are commercially available, flight-tested parts, ensuring high reliability and simplifying procurement and qualification.
- Re-usable and field resettable deployment system, as no single use components are implemented. Reduces MRO duration and hence increases economic efficiency

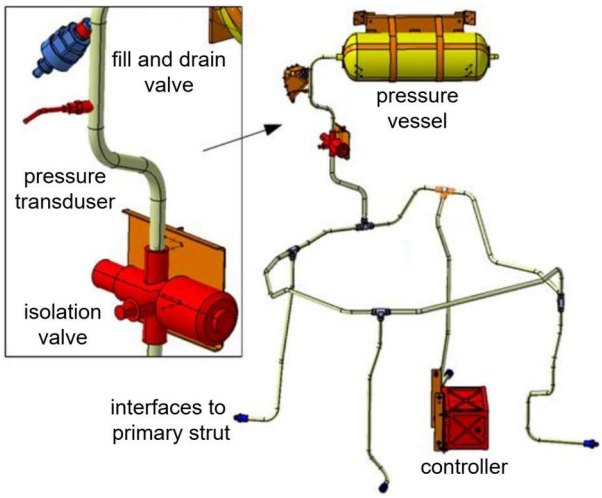


Figure 4: Aftbay internal components of the ALS deployment subsystem equipment.

3. LANDING GEAR MAIN FUNCTIONS

The ALS supports the vehicle in standing autonomously without the need for ground support equipment. Upon touchdown, the ALS landing gear fulfils the following primary functions: (1) absorbing the remaining kinetic energy, (2) ensuring both dynamic and static tip over stability, (3) maintaining ground clearance, and (4) attenuation of loads transferred to the vehicle's aftbay. In general, the ALS facilitates a safe transition from flight to ground state.

A necessary pre-condition for these functions is a successfully deployed landing system. To ensure this, the deployment subsystem needs to fulfil the following functions: (1) to keep the landing gear in stowed position until deployment initiation, (2) to maintain the landing gear in deployed position after deployment finalisation and during touchdown. (3) to provide sufficient amount of energy to deploy successfully and (4) to release the landing legs within a pre-defined time window.

The deployment and, in particular, the touchdown functions are vehicle level capabilities that require holistic analysis on vehicle level.

3.1. Deployment Challenges

The landing system of a RLV must withstand a harsh, highly unsteady load environment. The loads arise from the complex interaction of aerodynamics and engine plume with the leg structure, from a large spectrum of possible deployment conditions, and from the vehicle-induced accelerations that

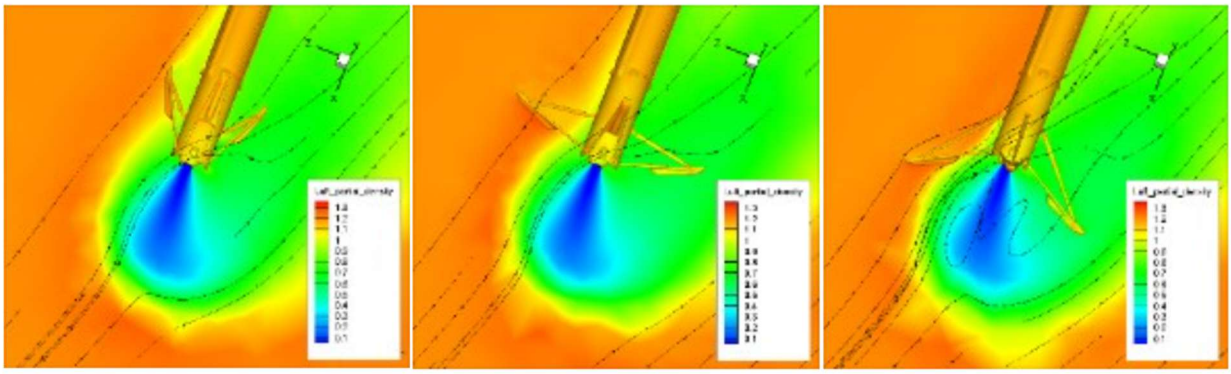


Figure 5: Flow field around ALS. One leg is oriented leeward and is therefore covered with plume, whereas the windward oriented leg faces the full dynamic pressure.

occur during the descent. Because the magnitude and orientation of these loads are tightly coupled to the chosen descent trajectory, the deployment dynamics are sensitive to approach trajectory-design decisions. Figure 5 illustrates the asymmetric flow field around CALLISTO's landing leg at different opening angles, which contributes to the non-linear load environment [7,8]. An example for an asymmetric landing leg deployment caused by the non-linear load environment has been observed during Falcon 9 landings. An example of the NROL-76 mission is shown in Figure 3.

This highly non-linear environment and the criticality of this function require high-fidelity numerical simulations, to predict the deployment dynamics and understand the influences. DYNOS (Deployment dYnamics OptimisatioN Simulation) has been developed within the course of the development of the ALS and used for the definition of specifications and for deployment dynamics studies. A block-diagram of this tools is shown in Figure 6.

The influences on CALLISTO's deployment dynamics have been studied in [6]. Here, it is shown that deployment dynamics are not only influenced by the product parameter (vessel, pressure, timings, friction, …) but mainly on vehicle dynamic states parameters such as:

- Non-gravitational acceleration – higher value, leg tends to open faster
- Angle of attack profile – AoA =/= 180 deg leads to asymmetric load environment, leeward oriented leg opens faster
- Approach velocity – defines the absolute value of the aerodynamic forces
- Angle of roll – Defines which legs are lee- or windward oriented.

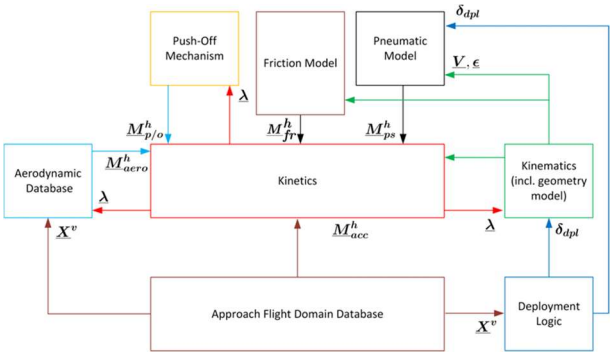


Figure 6: Block diagram of the DYNOS deployment dynamics simulator, with coloured blocks representing sub-models, and arrows indicating the data flow

3.2. Touchdown Challenges

The safe transition from flight to ground state is considered a primary prerequisite for fulfilling the objectives of an RLV. The touchdown, which follows the successful deployment and latching of the landing legs, is regarded as the culmination of this vehicle state transition.

The vehicle's touchdown dynamics are driven not only by the landing gear and engine characteristics but are also influenced by the vehicle's dynamic state at the handover from the approach phase to the landing phase. The initial vehicle dynamic states are defined by the trajectory design, whereby the translational and angular velocities, and consequently the kinetic energy to be absorbed by the landing gear, are prescribed. This dynamic state is affected by Guidance Navigation and Control (GNC) system dispersions, by which the number of possible dynamic states to be handled by the landing gear spans a broad parameter space. This dispersion is determined by the control capability of the GNC system.

Induced interface forces at touchdown are attenuated by the energy absorption system, whereby the residual kinetic energy is also absorbed through the plastic deformation of the honeycomb cartridge. The number of touchdown cases to be analysed is increased by product-related uncertainties, caused for instance by manufacturing imperfections or varying foot pad friction coefficients. Additionally, the touchdown dynamics are influenced in a non-linear manner by fluid-structure interactions, such as residual propellant sloshing [10,11], and the elastic properties of the central core.

The vehicle's touchdown dynamics are impacted by the combination of all the aforementioned performance drivers. The majority of possible touchdown conditions must be handled by the landing gear, wherein tip-over stability, ground clearance, load attenuation capability, and energy absorption capability must be ensured.

The touchdown dynamics are rendered a complex function by the sheer number of possible initial vehicle states at the handover from the approach phase to the landing phase, combined with

uncertainties related to the landing gear. Numerous possible touchdown conditions are generated by these factors collectively. Experimental coverage of all possible conditions at the vehicle level is cost-intensive. Therefore, high-fidelity numerical simulations are indispensable. Given the extensive number of variables and associated uncertainties, a statistical Monte Carlo simulation strategy was utilised to efficiently explore the large parameter space.

4. DEPLOYMENT TEST CAMPAIGN

The landing-leg deployment test campaign is organized around a set of objectives that verify functional performance, safety-critical features, and provide the data required to validate the deployment simulator:

- to verify the deployment function
  - to demonstrate the capability to transform pneumatic power into mechanical power
  - to verify the mechatronic functional chain
  - to check whether ALS can withstand induced latching loads
  - to maintain the deployed configuration
  - to check whether ALS can successfully latch within its application domain
- to characterise induced load level
  - HDRM release induced shock
  - latching shock
  - end stop induced forces
- to gather test data for deployment simulator validation

4.1. Test Stand & Instrumentation Concept

The testing of the leg's deployment functionality and its performance characterization are conducted in the Landing and Mobility Test Facility (LAMA, DLR Bremen) and utilising a dedicated deployment test rig. This test stand is depicted in Figure 7 and is configured to accommodate a single leg assembly, the pneumatic sub-assembly and the landing gear controller as well as laboratory instrumentation for the acquisition of test data. External forces are represented by a system of counterweights acting via cable pulleys on the respective leg assembly to represent external forces. This mass is defined as the net effect of non-gravitational forces and dynamic pressure. The counterweight system adds inertia to the tested landing leg, whereby the landing leg deployment dynamics are fundamentally altered compared to the flight dynamics. Different qualitative characteristics are exhibited by the counter-force compared to the expected net load of aerodynamic forces and non-gravitational acceleration.

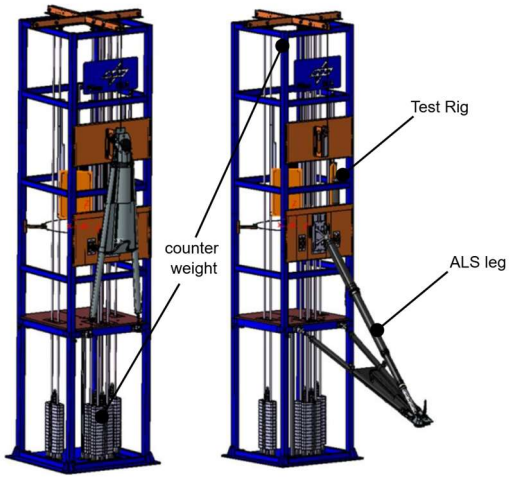


Figure 7: Deployment Test Stand. Left: Stowed leg. Right: Deployed leg. The ALS leg is connected via a rope with the counterweight.

4.2. Performed Deployment Tests

To verify the deployment function, multiple tests with increasing levels of integration were performed. Initially, the pneumatic flow parameters were characterised at different pressure rates. Additionally, the stiffness and damping characteristics of the structure were determined using strain gauges during a partial unfolding test with an initial secondary strut opening angle of approximately 100°.
The electromechanical functional check-out of the deployment system (excluding the primary strut and push-off) was performed to ensure correct timings of the deployment functional chain. As a secondary outcome, safety-related features, such as the pressure relief valve, were verified during the deployment test campaign.
Finally, the full deployment test campaign was performed under different test conditions. A cautious approach was applied, whereby the first deployment was performed at low speed and successively increased to high speed with varying test parameters up to a 130 kg counterweight and a vessel pressure ranging from 2 to 8.5 MPa. A summary of the total number of tests is presented in Table 1.
For each test, the latch state signals of both latching mechanisms were checked to verify the secure engagement of the primary strut. The induced shock levels were calculated and analysed.

The resulting leg deployment opening angle evolution in comparison with the simulated case with DYNOS is shown in Figure 8.

Table 1: List of performed tests within the scope of the deployment test campaign.

Test	Number of tests
Parameter characterisation tests	4 (2x structural,

	4 pneumatic)
Landing Gear Controller functional test	1
Safety valve functional test	1
Deployment tests	14
Total number of tests	21

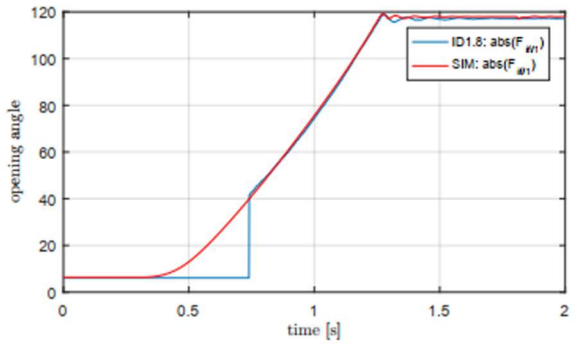


Figure 8: Opening angle vs. time. Blue line represents the measured opening angle, whereas the red line the simulated opening angle evolution.

5. TOUCHDOWN TEST CAMPAIGN

CALLISTO's goal is to perform multiple flights, beginning with low-energy (hover-like) test flights, followed by a cautious increase in flight velocity and altitude to high-energy demonstration flights. For each flight the nominal touchdown conditions differ and, additionally, the vehicle's dynamic state is subject to uncertainties. These project-driven constraints define the application domain of the ALS and hence influence the test definition.

The CALLISTO ALS development program involves single-leg drop tests at DLR's LAMA in Bremen, complemented by numerical touchdown simulations, with the following objectives:

- to characterise the dynamics of the landing-leg assembly
- to demonstrate the energy-absorption capability
- to demonstrate the load-attenuation capability
- to demonstrate the load carrying capability of a landing leg
- to generate test data for correlation of the LANDing SIMulation (LANDSIM) tool

Together, these objectives provide a comprehensive assessment of the landing leg's dynamic behaviour, energy dissipation, force attenuation, structural capacity, and simulation fidelity.

5.1. Test Stand & Instrumentation Concept

The LAMA comprises the single leg drop Test stand, which consists of a rail tower on which a sledge can slide. The device under test, in this case the ALS leg, is attached to the sledge. Depending on the required touchdown orientation, the sledge can incline the ALS leg in multiple directions (pitch & yaw). The energy at touchdown is adjusted by the initial height of the sledge and the total mass, which can be adjusted with weights. The landing site surface can be simulated with, e.g., a concrete slab. Figure 10 illustrates the single leg drop test stand with its subassemblies and the ALS landing leg.

For the characterisation of the interface load environment induced by touchdown dynamics, the interfaces between the ALS landing leg and the sledge were equipped with force sensors at the primary strut interface and acceleration sensors at the secondary strut interfaces.

The dynamic behaviour of the ALS landing leg is acquired with acceleration sensors at the footpad and HDRM interfaces. Furthermore, the sliding of segment 3b into 3a caused by the crushing of the energy absorption element is recorded with a laser sensor. The sledge is equipped with a laser sensor to capture the vertical movement and dynamics of the sledge/ALS landing leg assembly.



Figure 9: ALS deployment sequence of the ALS attached to the deployment test stand in the LAMA. The left image depicts the stowed configuration, with the sequence progressing to the right, showing the stages of deployment. (0°, 25°, 45°, 90°, ~ 110°) Please scan the QR-code for a full deployment video (link to youtube.com).

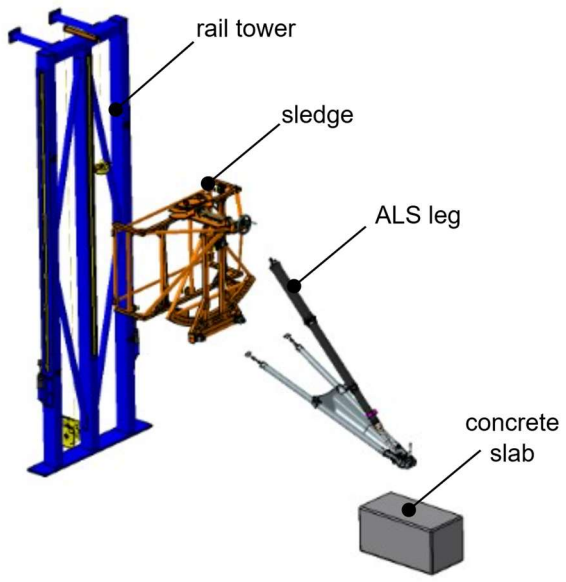


Figure 10: Explosion drawing of the Single Leg Drop Test Facility.

5.2. Performed Touchdown Tests

During the landing leg development process, two dedicated development test campaigns have been performed. Based on the test results, feedback has been systematically forwarded to the design iteration loop. The test campaigns incrementally increased the touchdown mass and velocity to evaluate performance under, in terms of load, progressively more demanding landing conditions. Throughout all tests, the mechanisms maintained fully engaged, ensuring the load path from footpad to the interfaces. In initial state the landing leg attached to the sledge is elevated to the desired height and released upon the reception of the release signal. The initial and final state are illustrated in Figure 11.

To capture the range of vehicle attitudes and leg attachment positions encountered during real landings, the legs were tested at various inclination angles. Additionally, different crush-force levels were applied to verify energy absorption capabilities across varying crush extents. Structural integrity was continuously monitored throughout the testing, while the function of the latching mechanisms was thoroughly checked to confirm reliable operation.

The results demonstrate that performance aligns with intended design objectives. As illustrated in Figure 12, a plateau of plastic absorption is observed following a rapid increase in primary strut load, with dynamic oscillation occurring until the system comes to rest. These findings confirm that the ALS landing leg can provide effective energy absorption capability without compromising structural integrity and that it successfully reduces induced forces transmitted to the vehicle.

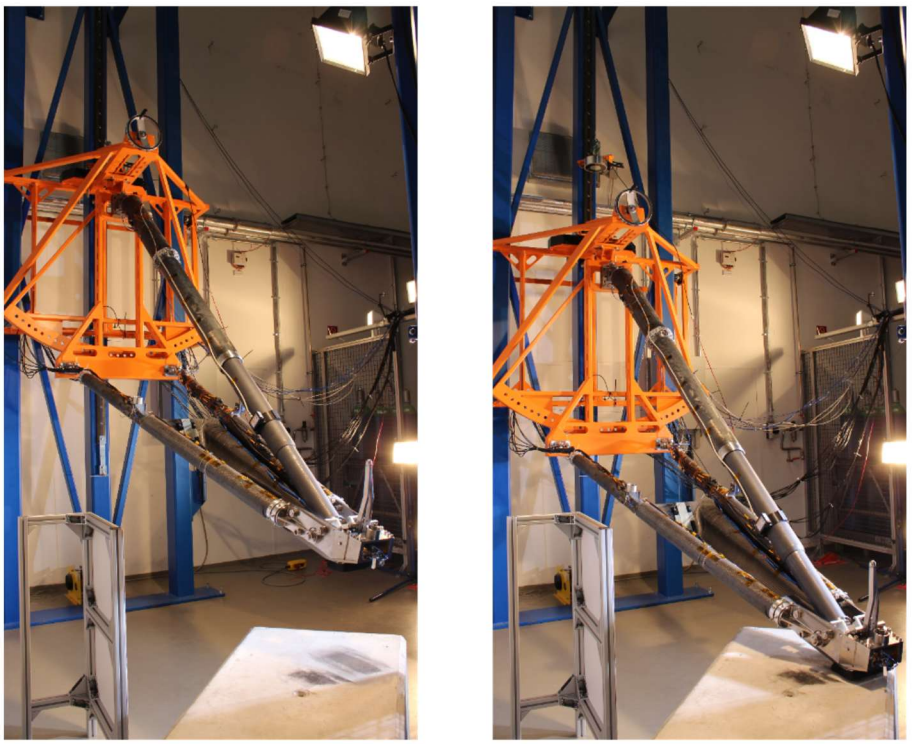


Figure 11: Left: Prior to touchdown. Right: After touchdown, leg in rest, honeycomb crushed

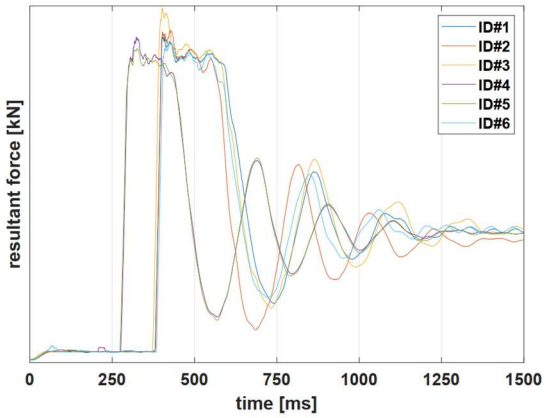


Figure 12: Primary Strut resultant force of performed drop tests. The time line starts with release of the sledge, followed by a free flight phase and rapid increase of the force, which marks the contact between foot pad and concrete slab. The plateau indicates the energy absorption. Please note the force values on the y axis have been omitted for confidentiality.

6. INCORPORATION OF LANDING GEAR MAIN FUNCTIONAL TESTS INTO CALLISTO'S LANDING SYSTEM DEVELOPMENT PROGRAM

The single leg functional tests described in the preceding sections cannot be utilised to verify the main landing gear functions, as it is not possible to reproduce the vehicle dynamics or the complex aerodynamic load environment on a test stand, due to highly non-linear external loads and vehicle dynamics.

A development process based on three pillars, as illustrated in Figure 13, was applied to the ALS development, comprising physical functional test campaigns conducted in the LAMA, numerical simulation tools, and the environmental context, which defines the initial vehicle dynamic state in addition to the external load conditions for the landing leg deployment.

The ALS is represented as both a physical development model for testing purposes and as a numerical model in this development process. The touchdown and deployment functions are simulated with the LANDSIM and DYNOS simulations tool. These tools are used to generate single leg deployment and touchdown test predictions. The subsequent single leg touchdown and deployment tests are performed in the LAMA. The generated test data is utilised for the validation of the numerical simulation tools. This loop involving the generation of test predictions and the feedforward of test data for the validation of simulation tools is iterative.

The vehicle level simulations are performed with the same numerical tools, however, the full landing system is incorporated. The external context is defined by the third pillar. This contains the vehicle's initial state at the beginning of the landing phase. Additionally, the broad approach flight domain is defined within this pillar as well. The numerical simulation results are post-processed and, in cases where landing gear functions are violated, the conclusions are fed back as engineering constraints. For instance, in the case of deployment dynamics, constraints are defined in terms of maximum allowable interface forces or induced disturbance torques and forces. A holistic analysis of the landing leg system is facilitated by this process.

7. SUMMARY

This paper discusses the challenges and testing of reusable launch vehicles, specifically focusing on CALLISTO's ALS. One of the primary challenges for RLVs is achieving a safe transition from flight to ground phases, which requires mastering the deployment of landing legs in a harsh load environment. The deployment of landing legs is sensitive to trajectory parameters such as non-gravitational acceleration, angle of attack, approach velocity, and angle of roll.

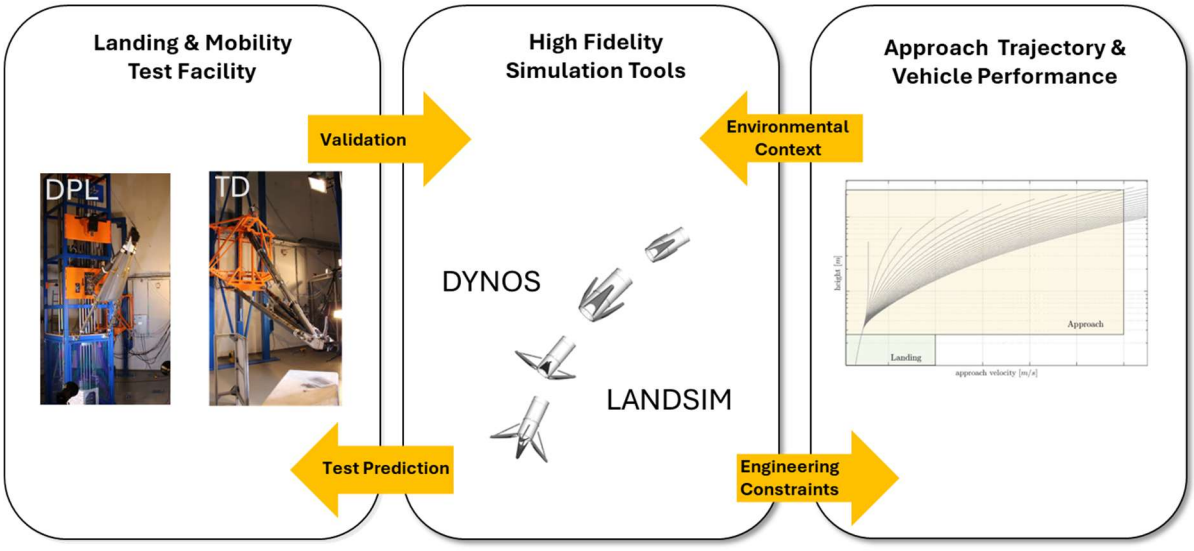


Figure 13: Three pillar development process of the CALLISTO Landing Gear.

The paper describes the ALS of CALLISTO, which includes a pneumatic deployment subsystem and deployable inverse tripod landing legs. The system is designed to absorb the residual kinetic energy of the vehicle during touchdown while maintaining stability and ground clearance.
The paper highlights the complexity of deployment and touchdown dynamics, which are influenced by aerodynamics, engine plume, trajectory design, and vehicle-induced accelerations. High-fidelity numerical simulations and Monte Carlo methods were employed to explore the large parameter space of possible touchdown conditions.
In conclusion, the CALLISTO project represents a significant step towards the development of reusable launch vehicles, with a strong emphasis on testing and simulation to ensure safe deployment and touchdown. The results of the tests demonstrate the effectiveness of the ALS in absorbing energy and reducing induced forces, validating the design and performance of the landing system.
The development process relies on three pillars: functional test campaigns, numerical simulation tools (LANDSIM and DYNOS), and the environmental context. The tests were conducted at DLR's Landing & Mobility Test Facility (LAMA) and included deployment tests and single leg drop tests. The results of these tests were used to validate the numerical simulation tools.
The functional test campaigns of CALLLISTO's landing system ALS were presented and how their results contribute to the overall landing system development strategy. The criticality of the deployment function was explained and rationales for the numerical deployment simulator given. The touchdown is one of the main functions of an RLV. The criticality and influences coming from GNC and trajectory design were shown.
In short, landing (deployment and touchdown) is a system level capability with unique load cases that require novel high-fidelity tools and novel development approaches to master a safe transition from flight to ground phases.

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