

Guidance and Control Strategy for the CALLISTO Flight Experiment

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Abstract

In order to make access to space more affordable for both scientific and commercial activities the German Aerospace Center (DLR), the Japan Aerospace Exploration Agency (JAXA) and the French National Centre for Space Studies (CNES) joined in a trilateral agreement to develop and demonstrate key technologies for a future reusable launch vehicle. In the joint project CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) a reusable vertical take-off, vertical landing rocket is developed as a demonstrator for a reusable first stage. The test flight operations will take place at the Guiana Space Centre (GSC), in French Guiana.

This paper gives a textual overview of the control strategies of the DLR/JAXA guidance and control subsystem for the CALLISTO test flights. The main assumptions adopted for design and simulation will be illustrated, and an overview of the foreseen mission profiles will be given. The missions consist of multiple flight phases having different aerodynamic configurations of the vehicle: the ascent phase, the boost-back maneuvers, the aerodynamic phase, and the powered descent and landing phase. We describe the sequence of events and the high-level G&C mode for each phase, including the criteria for the phase transitions as evaluated by the on-board computer. To autonomously control the vehicle during the different flight phases multiple classic and modern control methods are utilized. Finally some simulation results based on a preliminary G&C design are being discussed.

1. Introduction

The need for a more affordable and versatile access to space for both scientific and commercial activities is boosting the efforts of several companies towards the development of partially or fully reusable rockets. In the United States companies such as SpaceX¹⁵ and Blue Origin¹⁴ are already actively flying reusable rockets like the Falcon 9 and the New Shepard, and foresee the development of more ambitious vehicles, like the Starship and the New Glenn, which maiden flights are foreseen in only a couple of years. These vehicles are the natural evolution of a renewed interest towards vertical take-off, vertical landing (VTVL), which had its origin in the first flights of the McDonnell's DC-X.³ New successful experiments were performed years later by SpaceX's Grasshopper,¹⁶ and Masten Space's Xombie.¹⁸

Also outside the United States the interest in these technologies is increasing. The German Aerospace Center (DLR) worked on the development and the testing of a small demonstrator vehicle (EAGLE) based on an air breathing engine that successfully demonstrated multiple lift-offs, hover and landing capabilities.^{7,11} The Japan Aerospace Exploration Agency (JAXA) is working on the development of the RV-X demonstrator vehicle, with ground tests performed at the Noshiro Rocket Testing Center,⁴ which will be soon followed by flight tests. One important driver for the increasing interest and development of VTVL demonstrators is to create test environments for key technologies needed by operational reusable VTVL first stage.² Testing and demonstrating these technologies on smaller demonstrators allow reducing risks of developing future large scale reusable stages. One of these key technologies is pinpoint landing G&C. This is a key-capability for reducing time and cost of recovery and refurbishment operations, and to provide a significant reduction of costs to bring payloads into orbit.⁵ At the same time similar control technologies play a

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large role towards a more ambitious space exploration program: A more autonomous system able to achieve pinpoint landing accuracy allows to distribute a large payload, impossible to deliver with one flight, on multiple missions, and therefore also supports the autonomous exploration of other celestial bodies, including manned missions to the Moon and Mars. In the context of this international interest the trilateral program CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations)¹ between DLR, JAXA and CNES becomes an important step in this direction for Europe and Japan. This project aims at developing the capability to autonomously fly, return and successfully land a rocket that can be fully reused, and the joint efforts of the three agencies will culminate in a demonstrator that will perform its first flights from the Guiana Space Center (GSC), in French Guiana. The three agencies share the development effort in a fair manner considering respective know-how and maximizing the synergies with previous projects. The CALLISTO program is also a chance of investigating, developing and demonstrating different strategies and solutions within a common project. For the G&C subsystem two development lines run in parallel, one being jointly developed by DLR and JAXA, the second one by CNES and industrial subcontractors. The navigation system for CALLISTO is developed by DLR as a successor of the INS/GPS Hybrid Navigation System (HNS) that flew on SHEFEX-2,¹⁷ which is also scheduled to fly on DLR's next REusability Flight EXperiment (REFeX).^{10,12}

This paper describes the overall guidance and control strategy that DLR and JAXA are jointly studying for CALLISTO. The paper is structured as follows: first the vehicle architecture and the mission scenario are described. The description includes sequence of events, as well as the transition logic and an explanation of the four phases of flight. Then, we provide a high-level overview on the different guidance and control techniques currently under development for the first flight test. Finally, the steps foreseen for the next two years are described and motivated.

2. Vehicle Description

The CALLISTO vehicle has a longitudinal length of about 13 m and a diameter of about 1 m. CALLISTO uses liquid hydrogen (LH₂) and liquid oxygen (LOX) as propellants. The main engine generates roughly 40 kN of thrust and can be modulated until about 40% of its maximal thrust. The engine is mounted on a gimbaled system to allow to control the thrust vector pointing direction. During the active propulsion phases this guarantees full pitch and yaw control capability which is used for translational control. The roll control is realized mainly through a set of Reaction-Control thrusters which is installed at the top of the vehicle. During the non-propelled phases three-axes control is achieved through a set of four aerodynamic fins which are mounted in a "+" configuration. The active landing system of CALLISTO is comprised of a set of 4 foldable legs. An impression of the vehicle is shown in Fig. 1. Taking into account the deployment states of the fins and the legs and the state of the main engine we identify six relevant configurations of the vehicle, as shown in Fig. 2, over the course of the different flight phases which are elaborated in the next section.

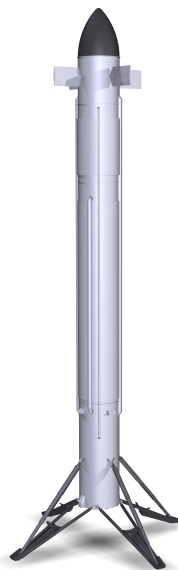


Figure 1: CALLISTO experimental vehicle.

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Configuration		Phase Applicable	Fins	Landing Legs	Thrust Plume
FFO (C0)		<u>Ascent and Powered Tilt-Over:</u> MEIG#1 – MECO#1	Folded	Folded	Thrust Plume
FFN (C1)		<u>Ballistic</u> MECO#1 – Fin Deploy	Folded	Folded	No Thrust Plume
UFN (C2)		<u>Ballistic:</u> Fin Deploy – MEIG#2 <i>and</i> <u>Aerodynamic Descent:</u> MECO#2 – MEIG#3	Unfolded (Deployed)	Folded	No Thrust Plume
UFO (C3)		<u>Brake Boost:</u> MEIG#2 – MECO#2 <i>and</i> <u>Approach Boost:</u> MEIG#3 – Legs Deploy	Unfolded (Deployed)	Folded	Thrust Plume
UUN (C4)		<u>Landing:</u> Legs Deploy – MECO#3	Unfolded (Deployed)	Unfolded (Deployed)	Thrust Plume + Ground Effect
UUN (C5)		<u>Landed (Park):</u> After MECO#3	Unfolded (Deployed)	Unfolded (Deployed)	No Thrust Plume + Wind Stability

Figure 2: CALLISTO configurations.

3. Mission Scenarios

CALLISTO is foreseen to be launched from French Guiana. Two different mission scenarios are under study:

3.1 Downrange Landing

The first scenario is referred to as *Downrange (DR)*. After the ascent flight, roughly at peak altitude, the main engine is cut-off (MECO) and the vehicle performs a coasting arc. A tilt-over is performed to attain an engine-first attitude. After the tilt-over the engine is re-ignited (Main Engine Ignition or MEIG) to significantly alter the ballistic impact point to match the selected landing zone on a barge, which is located close to the coast. The vehicle performs an aerodynamically controlled descent, crossing the trans-sonic regime. Finally, at an altitude of typically 2-3km, the engine is re-ignited again and the vehicle lands on the barge. The main phases of the *DR* scenario are depicted in Fig. 5.

3.2 Return-to-Launch-Site

The second scenario is referred to as *Return-to-Launch-Site (RTLS)*, in which CALLISTO will invert the direction of the horizontal velocity through a boost-back burn before the beginning of the aerodynamic return flight during which the vehicle loops back to a landing site which is close to the original launch site.

The qualitative altitude profiles of both scenarios are compared in Figs. 3 and 4. The *DR* scenario has a higher altitude than the *RTLS* scenario and its duration is slightly longer.

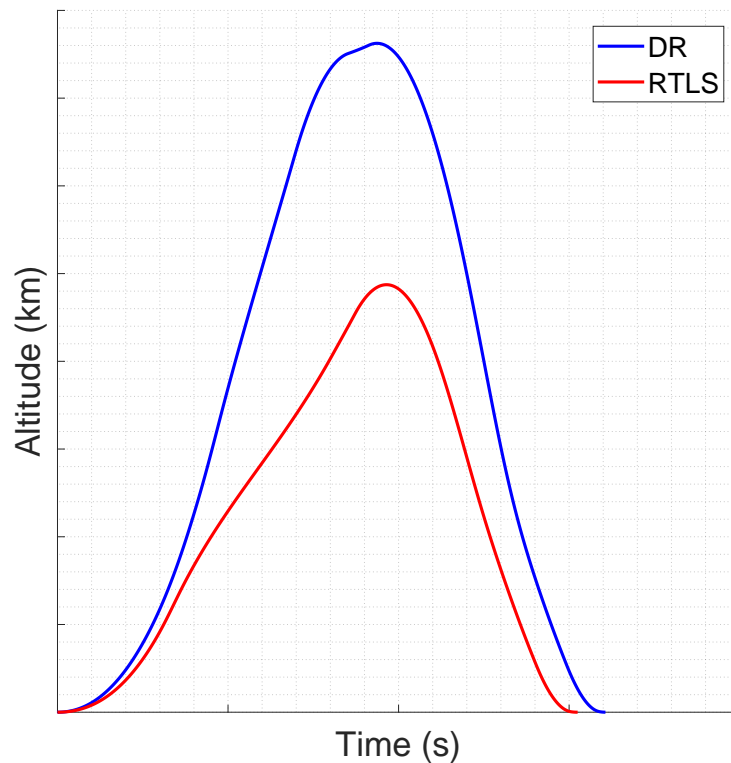


Figure 3: *Downrange* and *Return-to-Launch-Site* altitude comparison.

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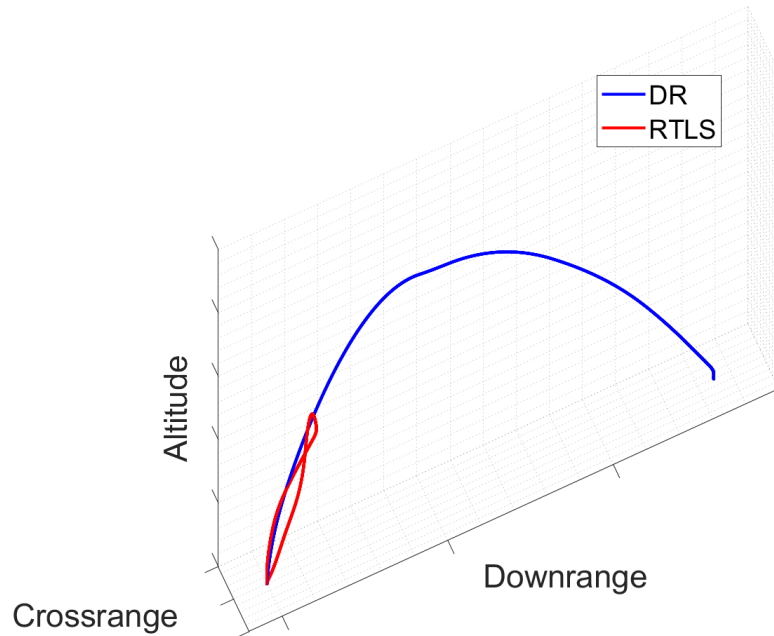


Figure 4: Downrange and Return-to-Launch-Site profiles.

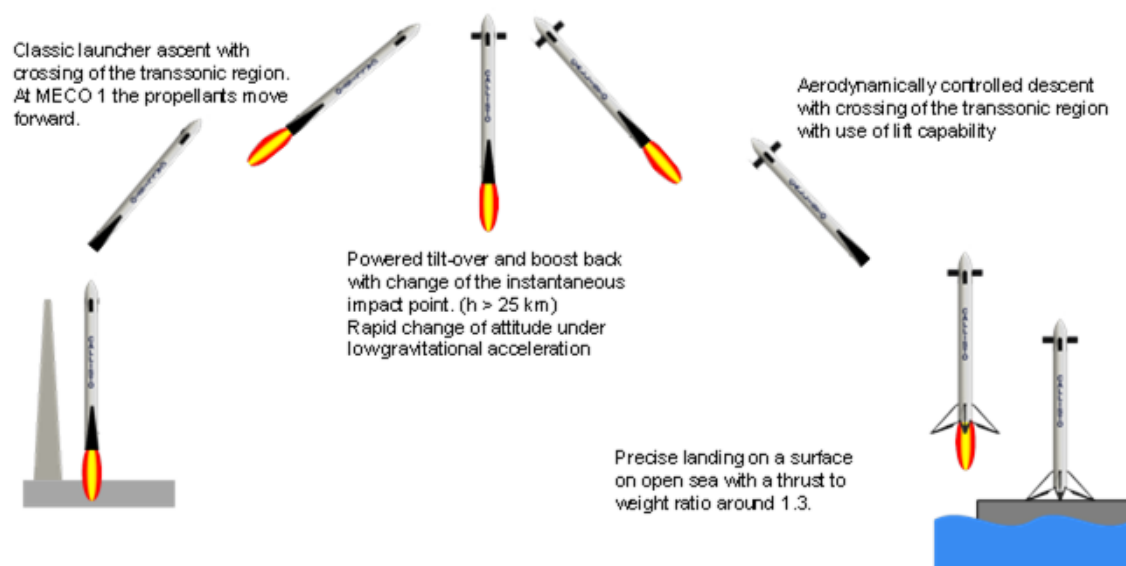


Figure 5: Event sequence for the Downrange scenario.

4. Guidance and Control Strategy

4.1 G&C Architecture and Control Design Approaches

The control system consists of the guidance function which computes and evaluates the trajectory and the control function which tracks the trajectory and determines the actuator commands. Depending on the flight phase the trajectory can be fixed and pre-computed or it can be generated on-board in real-time.

The control system is based on a point-wise linearization of the equations of motion on the nominal trajectory. A common approach to flight control systems is classical Proportional-Integral-Derivative (PID) control, which has the basic structure shown in Fig. 6. The outer 'guidance' loop controls translational motion and generates attitude angle commands corresponding to the forces to control the trajectory. The inner 'attitude control' loop, on the other hand, controls the rotational motion and generates the commands to be sent to the control devices such as TVC, RCS, and fins to generate the required torques. The control gains of the guidance and control modules are selected so that the closed-loop bandwidths of the inner and outer loops are properly separated. The resulting control parameters are evaluated to have appropriate stability and response by analysis in the frequency domain and non-linear simulation.

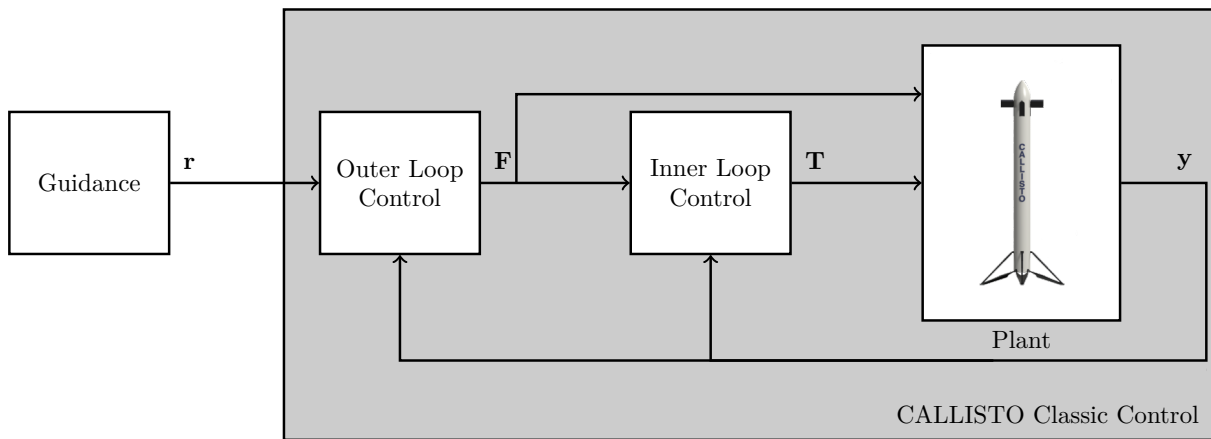


Figure 6: Classic control for CALLISTO.

In addition to classical control design robust control methods based on the H_∞ -norm are investigated for CALLISTO. In the last thirty years robust control techniques have found huge consensus and several applications both in industry and research. This success is justified by the capability to accurately satisfy a set of requirements by imposing some constraints in the frequency domain, together with the high degree of automation that this family of methods has reached to date (e.g., by means of Matlab's *hinfsyn* synthesis routine). However, this methodology also has some historical drawbacks, which have partially limited an otherwise wider utilization. The most important one is the tendency to generate high order controllers. While in classical methods like Linear Quadratic Regulators (LQR) and PID the controllers are low-order Linear-Time-Invariant (LTI) systems based on static-gains, in H_∞ control the resulting controller has at least the same order as the augmented plant, which implies that, in case of complex systems and/or high-order weighting functions the optimization process might lead to a controller of a large degree. To cope with this drawback the structured H_∞ control technique can be employed. The main difference with respect to classic H_∞ control is that its control structure is not autonomously determined by the synthesis routine, but is rather provided beforehand by the designer, which defines a *controller template*. A different control synthesis routine, e.g., Matlab's *hinfsstruct* computes a controller which will be as close as possible to the original H_∞ controller, but within the limits imposed by the template. This design method provides an ideal way of trading-off between a full-order controller and simpler structures, like PID controllers, which can be later populated with gains obtained from the structured H_∞ synthesis.

The state-space representation is applied to schedule controllers based on LTI systems obtained from the linearization of the non-linear model. A meaningful variables (e.g. dynamic pressure, Mach number, non-gravitational velocity or altitude) can be adopted as scheduling parameters. The concept of adopting a known controller structure allows a smoother transition from a well-known control architecture (e.g. PID), which can be preserved, to robust controllers, with all benefits associated with the latter, as in e.g. Navarro et Al.^{8,9} A typical control architecture based on this concept is depicted in Fig. 7.

The augmented plant consists of a set of state space matrices which include the vehicle's dynamics and weighting variables, which represent tuning parameters that are needed to specify the requirements for the vehicle over the

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different flight phases. While the controller uses a simple PID-like structure the tuning is based on the synthesis of a more complex H_∞ controller.

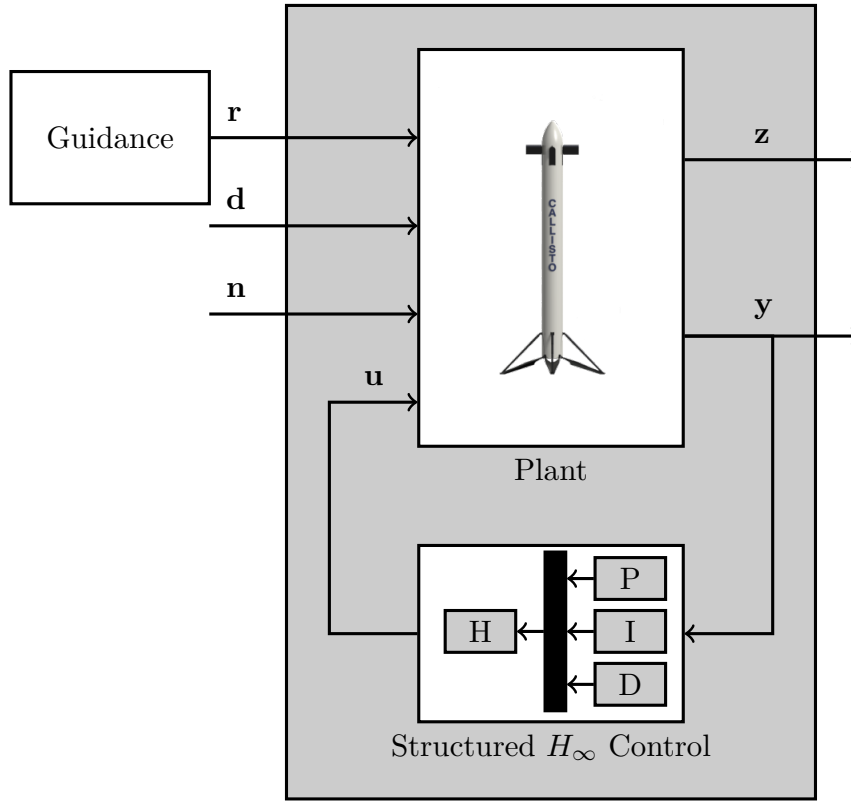


Figure 7: Generalized Structured H_∞ control for CALLISTO.

4.2 Onboard Flight Phase Management

During the flights CALLISTO will perform all the operations autonomously, so no tele-commanding of the vehicle from ground for G&C purposes is foreseen. The GNC software tracks and commands the flight modes using a finite state automaton which we also refer to as Mission and Vehicle Management (MVM). The automaton nodes correspond to the GNC modes and the connection to the possible mode transitions. Each transition has a set of well defined guard conditions. Upon fulfillment of these conditions a transition of the flight mode can be initiated. Preliminary flight mode transition conditions are stated in table 1, where t_T^A , t_A^B , h_B^A , h_A^L are constants that depend on the trajectory. The active control channels that are used during the different flight phases are shown in Table 2. On this purpose note that an important assumption for the G&C is that the controllers for each phase are independently designed. According to the phase that the vehicle is flying a specific controller is run, and at the transition between phases a discrete change of control strategy occurs.

Table 1: Mission Vehicle Management Transition Logic.

Phases	Transition Condition
Takeoff \rightarrow Ascent	$t \geq t_T^A$
Ascent \rightarrow Boostback	$t \geq t_A^B$
Boostback \rightarrow Aerodynamic Descent	$h \leq h_B^A$
Aerodynamic Descent \rightarrow Landing	$h \leq h_A^L$

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Table 2: Phases of flight and control allocation for different configurations.

Phase	Thrust Magnitude	Thrust Pointing	RCS	Fins
Takeoff	fixed	active	active	inactive
Ascent	active	active	active	inactive
Boostback	active	active	active	inactive
Aerodynamic Descent	inactive	inactive	active	active
Landing	active	active	active	inactive

4.3 Guidance Strategies

4.3.1 Takeoff

At the beginning of the launch phase the main engine throttle level is set to a predefined constant value for the first seconds of flight. After the vehicle has reached a safe altitude, the MVM transitions to ascent mode.

4.3.2 Ascent

CALLISTO's ascent guidance system is based on a pre-calculated trajectory that includes the reference attitude commands to steer the vehicle to follow the nominal position and velocity trajectory. During ascent flight, the vehicle relies on the forces and torques generated by the adjustment of the throttle level and TVC (Thrust Vector Control) deflections for both position and attitude tracking. A first tracking controller was designed based on the full 6 degree of freedom (DOF) equations of motion using LQR synthesis. This design technique however does not allow to account for uncertainties nor considers frequency domain characteristics of the bending modes or of the actuators on design level. A second, currently developed controller uses a robust control H_∞ design. Following Simplicio et. al¹³ and Navarro-Tapia et. al⁸ the design is based on the separation of the pitch and yaw dynamics, while the roll motion is handled by a separated control loop.

4.4 Boost-back Burn

In the RTLS scenario, the engine continuously burns while changing attitude by gimbal control and reversing the flight direction toward the launch site (Powered Tilt-Over). In the DR scenario, after the first MECO, the vehicle performs a ballistic flight where the angles of attack are kept near zero by using Reaction Control System (RCS) and then carries out the second burn while changing attitude to get into a ballistic trajectory toward a landing platform on the open sea. In both scenarios the attitude commands prescribed for each sub-phase are computed based on a numeric prediction of the drag landing point (DLP).

The CALLISTO mission objectives include the demonstration of a boost-back maneuver. In the CALLISTO project, a boost-back maneuver is defined as a propulsive maneuver with the goal to change significantly the shape of the trajectory and specifically to move the DLP back towards the launch site. The DLP is defined as the point where the vehicle would land if the flight is continued with only the drag impacting the trajectory.

On this purpose, an onboard algorithm to numerically predict the DLP in real time to achieve the mission objective has been developed. In the present algorithm, DLP positions are computed with the 4th-order Runge-Kutta method by using the drag coefficient at an angle of attack of 180 deg for UFN (C2) configuration. DLP position data is used to determine the timing of the MECO in the boost-back maneuver. A second algorithm estimates the time-to-go until DLP is reaching a target position and issues the MECO command at the moment when the time-to-go becomes zero. The possibility to reuse the DLP prediction and time-to-go estimation algorithms to MECO at the end of the ascent phase for the DR scenario is currently under investigation.

4.5 Aerodynamic Flight

During the aerodynamic phase the vehicle does mainly use the fins for control, as the main engine is switched off. The only way to control the position of the vehicle during this phase is by means of aerodynamic forces, which are generated by posing the vehicle with given angle with respect to the air-flow. The relative attitude with respect to the wind vector modulates the lift and the drag according to models predicted by CFD (computational fluid-dynamics).⁶ The attitude control loop generates the required torques by using the fins mounted on the vehicle.

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Difficulties connected with this phase are due to the uncertain involving the aerodynamic force and torque coefficients, which directly translate into an uncertain in the main control channels of CALLISTO. Moreover, wind has to be taken into account, as strong gusts or shears can lead to significant deviations from the nominal angles of attack, and a trade-off between load relief and tracking performance need to be considered.

Structural limits must also be included in the design of the guidance and control system to preserve the integrity of the vehicle (e.g., the dynamic pressure cannot exceed some prescribed upper bound, and the deflections of the fins must be limited to avoid excessive aero-thermal loads). Finally, the error at the end of the aerodynamic phase cannot exceed some thresholds. This conditions is required to ensure that during the following powered phase no large divert maneuvers, which go beyond the capabilities of the remaining on-board fuel, are needed to successfully complete the mission.

One of the main technological G&C branches that are currently under investigation by DLR and JAXA for CALLISTO is convex optimization. Convex optimization is a special sub-field of numerical optimization, in which the cost function, as well as the equality and / or inequality constraints are convex. This special property, which can be interpreted as a generalization of the linearity property, allows solving most of convex problems very quickly, opening the doors for the application of optimization-based techniques to real-time critical applications. In the frame of CALLISTO the trajectory generation, together with the feed-forward controls required to track the trajectory itself can be computed by using convex programming. The adoption of these techniques is especially appealing for critical phases of flight, such as the aerodynamic phase, characterized by large atmospheric and aerodynamic disturbances, and the landing phase, where an ad-hoc optimal trajectory is fundamental for propellant-management while satisfying the final requirements in terms of attitude, position, and velocity for a safe touchdown. An example of solutions obtained for the landing part of the trajectory by using convex optimization is depicted in Fig. 8(b).

4.6 Landing

For the landing guidance and to compute end-time the landing burn also different algorithms based on convex optimization and numeric prediction are investigated.

At the end of the aerodynamic phase (e.g., between 2 and 3 km of altitude) the engine is reignited and the powered descent and landing phase begins. The vehicle can therefore use again the thrust to control the position, but the aerodynamic forces, although less intense than the previous phase, must be accounted for, especially in the first part of this flight phase. As in the case of the ascent phase, a coordination of TVC and RCS ensures full control of the attitude in this phase as well. The vehicle flies towards the prescribed landing, and great care must be given to the final conditions immediately before the touchdown. A perfect coordination of thrust, position and velocity is in fact required to ensure that the impact does not exceed the structural loads that the legs can withstand. The lateral error that can be tolerated is also critical, especially for the downrange scenario, and a very small attitude error is allowed, to exclude the risk that the vehicle tips over right after the ground contact.

5. Preliminary Results

In this section preliminary results for the closed-loop end-to-end scenario are shown. Moreover, some trajectories obtained in presence of errors for the aerodynamic and the landing phases are depicted. Specifically, Fig. 8(a) shows some closed-loop results for the aerodynamic phase, while Fig. 8(b) describes some closed-loop results obtained for the powered descent and landing segment of the mission in presence of uncertainties in terms of position, velocity, attitude and angular rate. The errors were in the order of 30 m for each position component, 15 m/s for each velocity component for what regards the translation. For the rotational dynamics errors were in the order of 10 deg and 5 deg/sec on each axis. All the values refer to 3- σ dispersions.

It is possible to see during the aerodynamic descent that all the trajectories converge towards the interface point where the landing phase begins. In Fig. 8(b) the vehicle decelerates until reaching the landing position with prescribed vertical velocity and attitude.

A first example of end-to-end closed-loop trajectory for the two scenarios can be observed in Fig. 9(a) and 9(b).

The trajectory is tracked over all the phases of flight. A small deviation with respect to the nominal solution can be observed in the higher part of the DR trajectory, due to slight differences between the assumptions adopted for the generation of the reference solution and the current full nonlinear model. The differences are compensated for in the descending part of the trajectory until reaching a safe touchdown on the barge. For the Return-to-launch-site profile larger errors are observed if compared to the Downrange scenario during the landing phase. Currently Proportional-Derivative laws are implemented for inner and outer loop, with a separation in closed-loop bandwidth of approximately one order of magnitude. Note that in this phase it is not meant to actively rely on fins as feedback actuators. Their use is in this phase only limited to feedforward trimming device during the first part of landing sequence, when the dynamic

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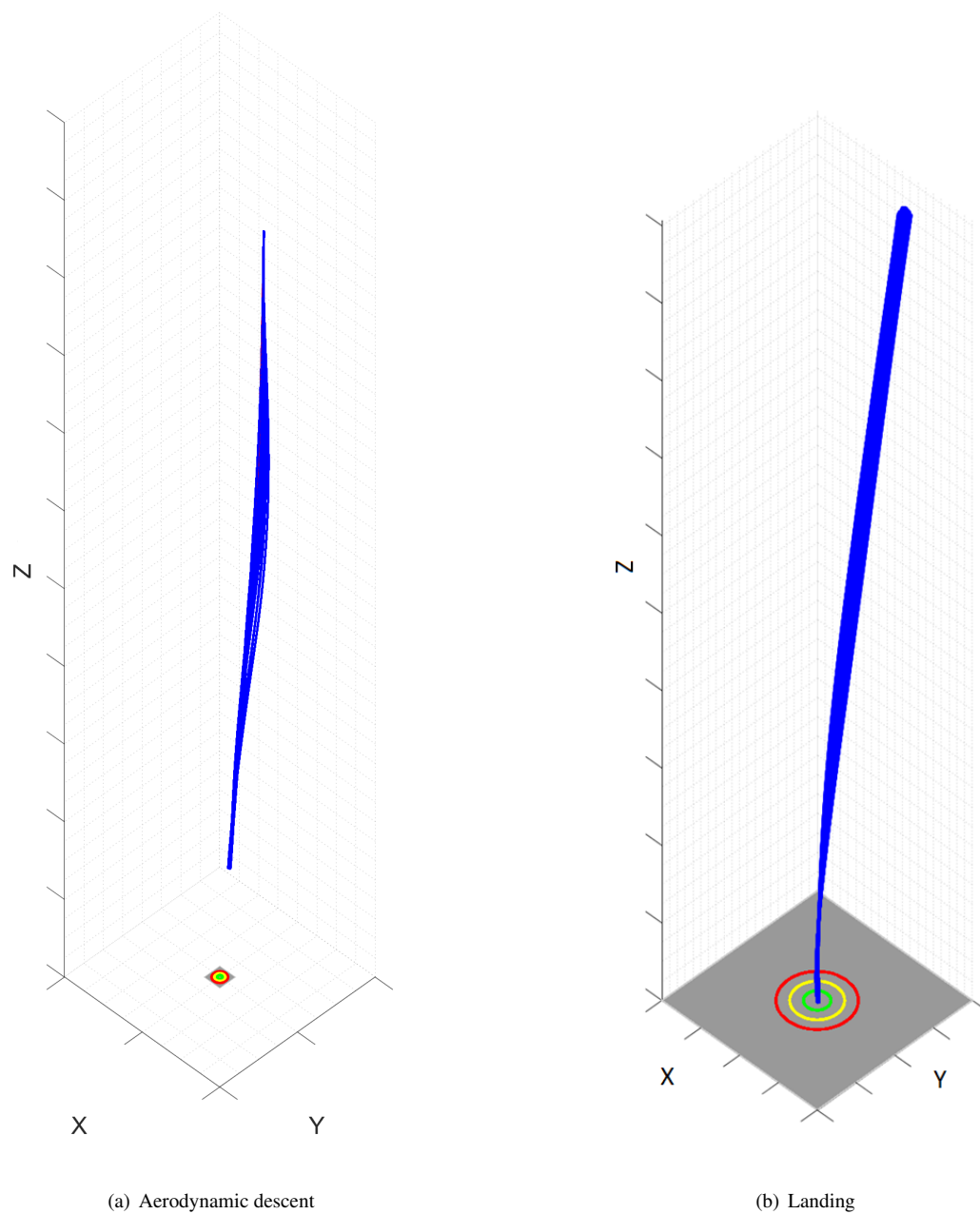
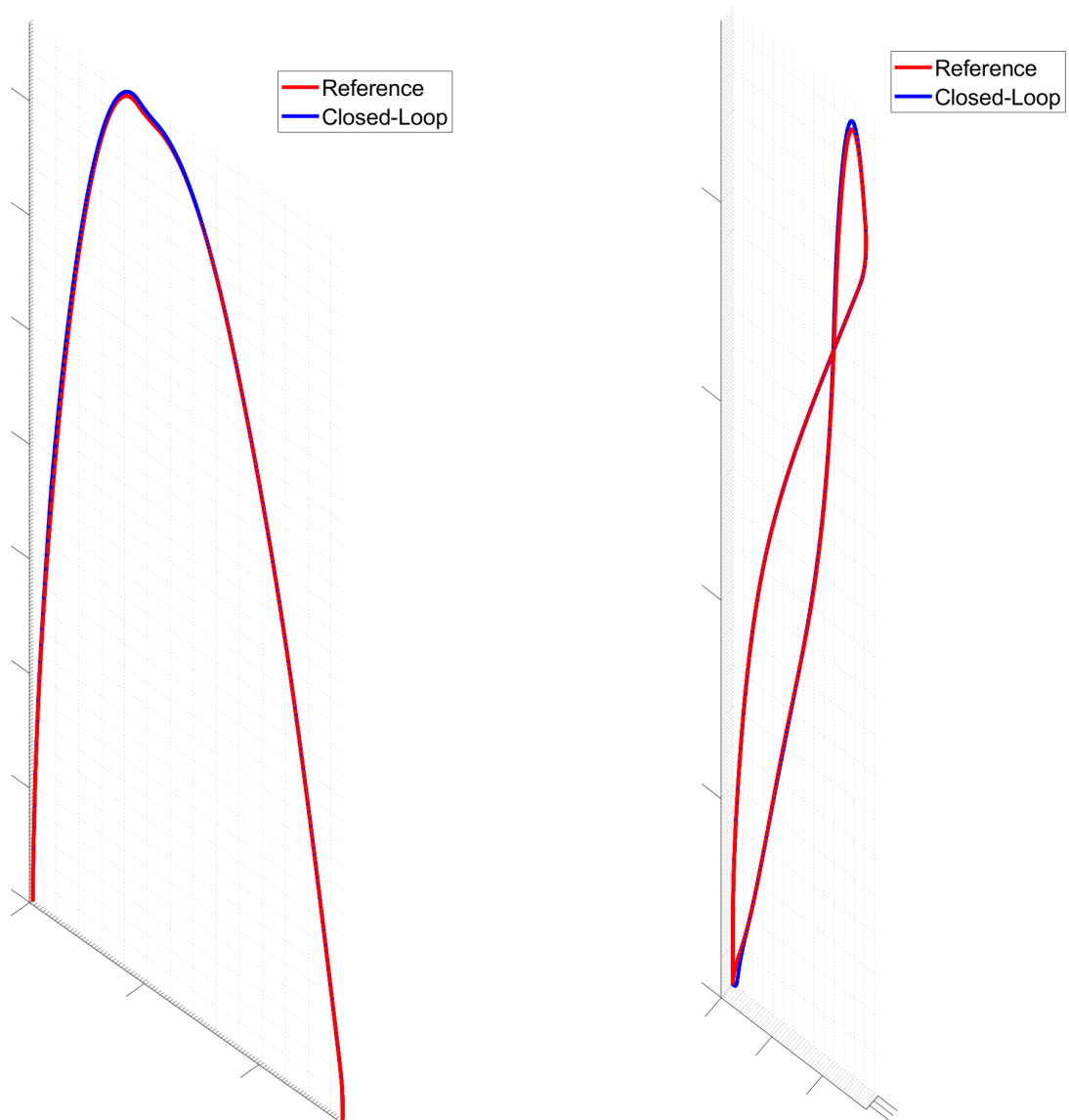


Figure 8: Examples of trajectories for aerodynamic and landing phases

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(a) Downrange scenario.

(b) Return-to-launch-site scenario.

Figure 9: End-to-end closed-loop trajectories

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pressure is still large enough to guarantee acceptable efficiency of the aerodynamic surfaces. When the dynamic pressure drops below a given threshold fins are no longer used. Over the entire landing sequence attitude feedback control is allocated on TVC for pitch and yaw axes, and RCS for roll control. These results will be compared with more robust control techniques in the next project phase. Moreover, a full Monte-Carlo campaign aiming at evaluating the performance of all the G&C algorithms will be run. Effects will include, among the others, uncertainties on mass and inertia, aerodynamic properties of the vehicle, as well as actuators misalignment and atmospheric disturbances.

Conclusions and Future Outlook

In this paper we gave an overview about CALLISTO, a trilateral project aiming at accelerating the development of reusable technologies. The cooperation between DLR, JAXA, and CNES will culminate in a series of demo flights to be performed at the Guiana Space Center. Two different scenarios have been illustrated, namely the Downrange scenario and the Return-to-launch-site scenario. Several G&C related key technologies currently under investigation for the development of the G&C subsystem have been briefly introduced. Finally some preliminary simulation results have been shown and evaluated qualitatively.

The G&C system for CALLISTO is complex due to multiple flight phases and vehicle configurations which require to bring together different control strategies and technologies. The performance requirements to achieve pinpoint landing accuracy are high for the entire GNC chain. The state dispersion accumulated during the ascent phase, coasting and tilt-over has to be completely attenuated for a successful pinpoint landing. This requires a G&C system which is robust and which can support a large flight envelope by accurately planning the burn phases taking into account the accumulated state error. For this purpose DLR and JAXA investigate guidance methods that allow an accurate real-time numerical prediction and update of the entire trajectory. These methods are combined with control techniques which are robust to changes of the operating point as resulting from the guidance trajectory update. This will allow to recover from state error during the atmospheric return flight and to achieve a high accuracy at the beginning of the landing phase to finally ensure pinpoint landing capability.

The next steps for the DLR/JAXA CALLISTO G&C development will be a detailed evaluation of the end-to-end G&C performance, as well as worst-case and flight safety analyses. Moreover the phase transition conditions will be refined, in particular the explicit dependency on time shall be replaced with a criterion involving one or more measurable states.

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