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Robot for managing safety-critical operations of CALLISTO at Landing Pad in CSG

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The CALLISTO Vehicle is a flight demonstrator for future reusable launcher stages. The program involves three countries and their space organizations: CNES for France, DLR for Germany and JAXA for Japan. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches. The challenge is to develop, all along the project, the skills of the partners. This knowhow includes Products and Vehicle design, Ground Segment set up, and post-flight operations for Vehicle recovery then reuse.

Focusing on operations in French Guiana and CSG, the Vehicle recovery operations just after flight at Landing Pad pose unique safety related challenges. Indeed and ahead of clearing access to operation staff, it has to be ensured that Vehicle is safe enough. Whatever the operational scenario is, the challenge is (i) how to deal with the required duration for getting Vehicle safing-critical operations completed and (ii) how to provide functions requested for running these operations properly up to their end.

From Vehicle design standpoint, there are two opposite options:

- To have Vehicle travelling during flight with devoted extra reserves for getting the safety-critical operations completed after landing (electrical power e.g.),
- To get the Vehicle as light as possible and manage the post-landing operations with an external means.

One primary motivation for CALLISTO is to fly and collect real world data over the largest flight envelope possible (altitude and speed). Having in mind that the rocket engine of CALLISTO is off-the-shelf product, the single way to explore the maximized flight envelope is to minimize Vehicle dry mass and maximize propellant loading accordingly. Therefore, CALLISTO team looks for minimizing mass budget of ancillaries including electrical power generation & distribution e.g.

This paper details first general information about CALLISTO Ground Segment, Vehicle and operations in CSG. This introduction is useful for further comprehension of robot-based scenario in Lift-Off Pad and Landing Zone. Then, it is showed how CALLISTO team reached the point where Robot becomes the smartest option for operations after landing from both Vehicle design optimization, Vehicle reusability and staff safety perspectives. Additionally, it is explained why this choice is a direct opportunity for simplifying operations and also Mechanical Ground Support Equipment at Lift-Off Pad. Finally, the robot baseline is briefly described.

Abbreviations

CALLISTO	:	Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations
CSG	:	Guiana Space Center
EGSE	:	Electrical GSE
ELM	:	Multi-Launcher (launch) Complex
FCS/A	:	Flight Control System/Aerosurfaces
FCS/R	:	Flight Control System/Reaction
FCS/V	:	Flight Control System/Vectoring
FGSE	:	Fluidics GSE
GHe	:	Gaseous helium
GN2	:	Gaseous Nitrogen
GSE	:	Ground Support Equipment
LH2	:	Liquid Hydrogen
LOX	:	Liquid Oxygen
LP	:	Lift-off Pad
MGSE	:	Mechanical GSE
RLV	:	Reusable Launch Vehicle
VPH	:	Vehicle Preparation Hall

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1. Introduction

CALLISTO is a demonstration project of recovery and reuse of core stage(s) of space launch system: it is research, technology and system demonstration oriented. It takes off and lands vertically at same place (or very nearby from Lift-Off Pad) and is supposed to be flown several times in a row. It will be operated in CSG, the European spaceport located in French Guiana.

When compared to a Heavy-class Launcher (weight at take-off beyond 700 metrics tons and height as much as 50-60 meters tall), CALLISTO is a small vehicle: 3+ metric tons at lift-off and 10-15 meters high.

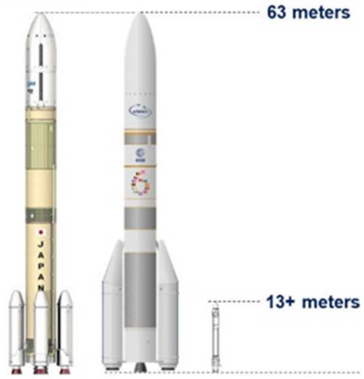

Figure 1 : CALLISTO sizes vs. Heavy Lift Vehicle

From operations standpoint and according to background history of CSG and its heritage in operating launch systems for 50+ years, to have Vehicle returning back home is the brand new life phase to manage. It is especially challenging from (staff) safety perspective:

- Tanks venting and possible propellant leakages induce a high risk in area around the Vehicle (several dozen meters).
- After having landed, the Vehicle "mechanical" stability is depending on several factors including wind effect and behavior of the damping system vs. touch-down impact.

Such conditions and few other issues require looking at different options for mastering these operations and maintain excellent safety standards.

2. Ground segment: brief description

CALLISTO Vehicle is operated at CSG in French Guiana inside Launch Complex dubbed ELM (French acronym for Multi-Launcher Launch Complex) located nearby Ariane 5 Launch complex. It takes benefit from:

- retrofitted installations of Diamant site operated in the seventies or more recent Ariane installations,
- and services offered by CSG Launch Range for Launch systems operated locally.

On the other hand, the activities are subject to the safety regulations applied to CSG, which are both a source of high constraints and a high value benefit of the demonstration.

Vehicle itself will be prepared ahead of flight and maintained afterwards at Vehicle Preparation Hall. It is located very nearby the Lift-off Pad and Landing zone (see figure below). Being so close from each other helps in optimizing operations and reducing duration of time around.

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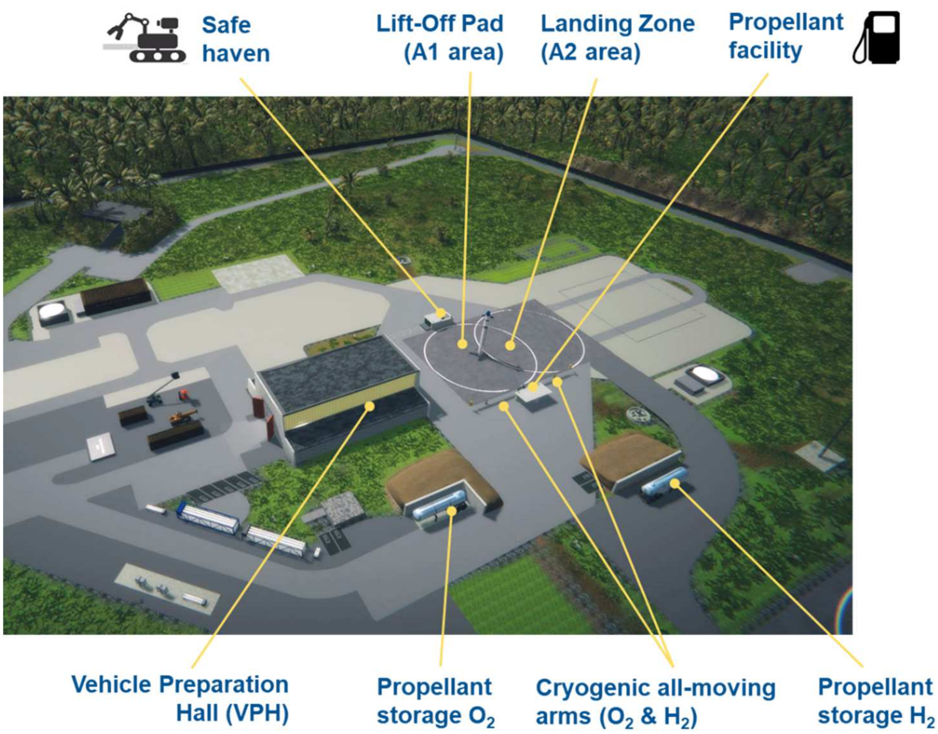

Figure 2 : ELM Launch complex – focus on primary installations for CALLISTO

Beside infrastructures themselves, there is a devoted Command & Control center located away from place where flight happens. And, in addition, there are three different Ground Support Equipments.

The Fluidics GSE supplies cryogenics (liquid oxygen and hydrogen), standard fluids (nitrogen, helium, compressed air), and H2O2 propellant for FCS/R (see chapter below).

The Electrical GSE supplies electrical power and different test benches for avionics and rehearsal of communications being wireless or not.

Last but not the least and concentrating on Mechanical GSE required at Lift-Off Pad and Landing Zone, it includes:

- transport means and tooling including crane(s),
- a small-sized lift-off table,
- the MGSE for disconnecting Vehicle safing functions ahead of Vehicle lift-off (see chapter afterwards describing briefly part of the Ground Segment-To-Vehicle interfaces),
- twin horizontal cryogenic arms (for Vehicle loading of liquid oxygen and hydrogen) that are full moving items for getting Lift-Off pad cleared ahead of flight and landing itself (see Figure 3 below),

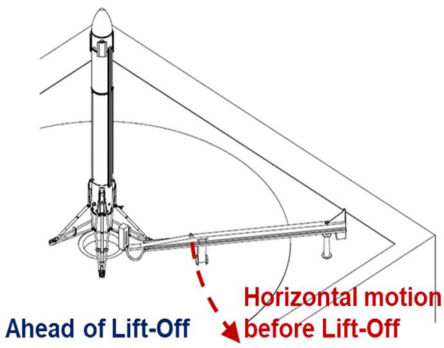

Figure 3 : All-moving cryogenic arm(s) at Lift-Off Pad

3. CALLISTO Vehicle at a glance

The CALLISTO Vehicle is a single stage architecture and features a rocket propulsion system mixing liquid oxygen and hydrogen with a turbo-pump fed engine. Its Flight Control System combines (i) an engine Thrust Vectoring (FCS/V), (ii) a set of 4 aerosurfaces (FCS/A) located at Vehicle's top and (iii) a Reaction Control System (FCS/R) as well. The FCS/A is electrically powered for unfolding maneuver during flight and then surface deflections. The FCS/R is a cold gas and pressure fed/blow down system. Its Landing System features a set of 4 fully deployable (landing) legs being pneumatic powered. Its damping system is made of honeycomb located in each leg primary strut, so it may result in tilted Vehicle after landing.

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It is designed to have a capability to reach the transonic speed regime using a single rocket engine and to return to its home base and being reused several times. The vehicle configuration with the aerosurfaces and the landing legs deployed is figured below.

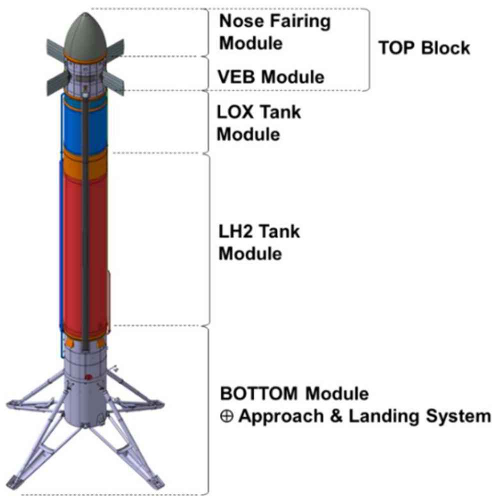

Figure 4: Vehicle configuration

Concentrating on carrying load structures including propellant tanks and pressurized vessels (vessels storing helium, H2O2 and propellant tanks), they feature safety factors that are space standards and are low when compared to other transport vehicles. Therefore, it imposes specific safety based limitations for operations involving staff as soon as filling operations start at lift-off pad and as long as vehicle is not in a safe and stable state after flight.

For managing properly rocket propulsion system during flight and its reuse over several flights, Helium is used for pressurization of propellant tanks during flight, fluidic circuits flushing after flight at Landing Zone and command/control of some valves (pneumatic power).

As for any vehicle, electrical power generation & distribution system may be quite heavy and any option for reducing its mass budget and volume is welcome: it will be shown that usage of robot helps later in this paper.

In addition, it does not feature any autonomous active Thermal Control System of the different compartments, namely TOP volume above LOX Module (see figure above), the volume in between two propellant tanks and the BOTTOM volume. It especially means that heat generated from (i) on board products (avionics especially), (ii) engine jet flow when braking combined with rapid internal repressurization at descent, has to be controlled with passive designs during flight. Ahead and after flight, there is the need for conditioning these compartments. This conditioning function relies on cold gaseous nitrogen circulating in the 3 compartments and supplied from Ground Segment.

As figured below, a set of connectors is located at rear side of the vehicle for interfacing with Ground Segment at Lift-Off Pad and Landing Zone.

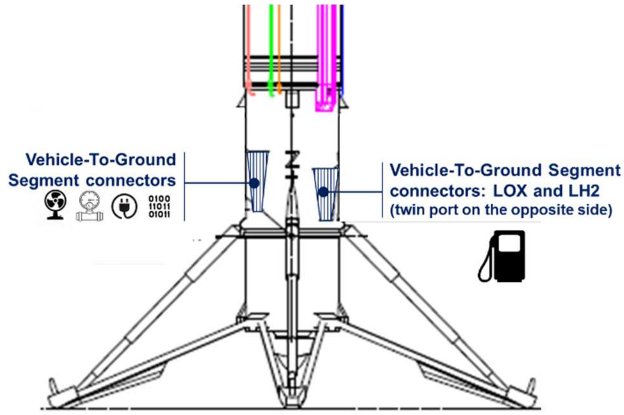

Figure 5: Vehicle-To-Ground Segment interfaces at Lift-Off Pad/Landing Zone

They include:

- transfer of cryogenics propellants (Lift-Off Pad only) to Vehicle (from storage area),
- extra loading of Helium High Pressure Vessels,
- keeping electrical power generation system fully loaded,
- conditioning function of Vehicle compartments,
- wired data communications,

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In this paper, these interfaces and their functions only are looked at for managing their connection at Landing Zone and disconnection ahead of Lift.Off.

4. Overview of operations in CSG

In case of a RLV-like vehicle as CALLISTO is, there are four primary phases to be run at spaceport for getting (i) a flight completed and (ii) readiness for next flight:

- indoor preparation and/or refurbishment operations of Vehicle for next flight at Vehicle Preparation Hall,
- Operations at Lift-Off Pad including loading of propellant tanks especially;
- Flight itself,

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- After flight, operations for getting vehicle safed at Landing Zone and ready for transfer to VPH after flight.

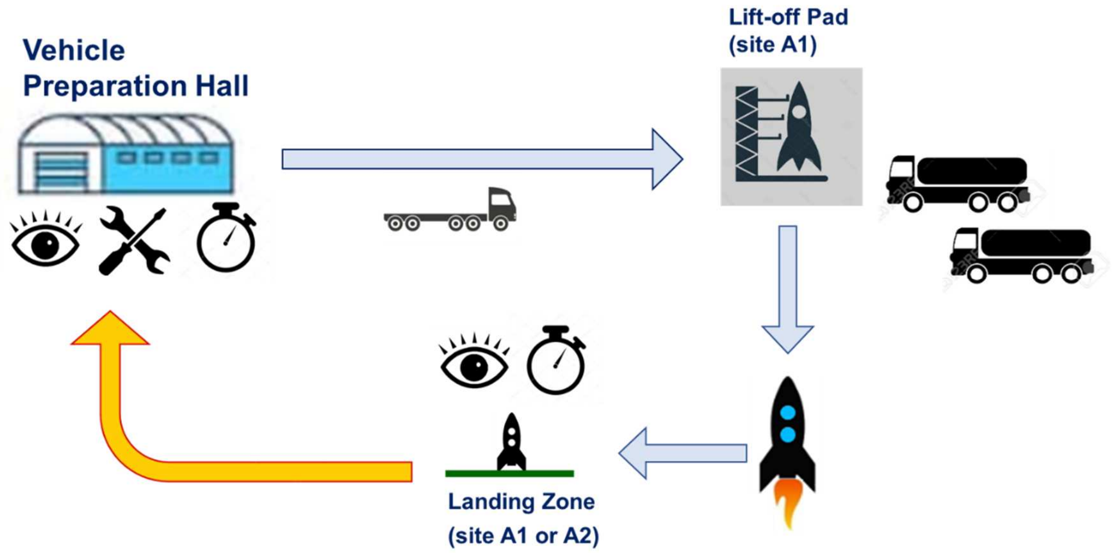

Figure 6 : set of operations - simplified

For CALLISTO team in charge of defining and managing operations in CSG, the greatest challenge for defining ground-based operations is this latter phase since it will be the first time that such life phase for a space vehicle will be experienced in CSG. The post-landing phase is Vehicle reuse-critical and, for operating staff, safety-critical. That is the basic rationale for giving special care to this set of operations. Thanks to lessons learned collected over last five decades in operating various Launch systems in CSG, experience in managing aborted lift-off events helps also in defining these operations.

5. Operations after landing: how to manage safety of operators around vehicle

After landing event, numerous safety-critical conditions prevent easy access to staff close to vehicle. Most safety-critical ones are figured hereafter.

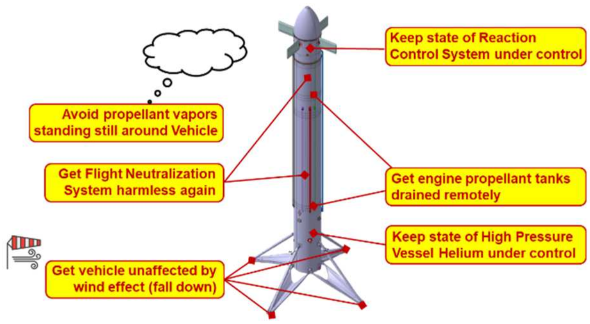

Figure 7 : set of most safety-critical conditions after landing

One major risk for staff getting close to vehicle after landing is the gaseous hydrogen vapor cloud emanating from Vehicle and possible fire and/or vehicle explosion.

Following flight and for getting vehicle ready for transfer back to Vehicle Preparation Hall from Landing Zone, the operations are broken down in 5 primary phases to be completed ahead (se also figure below):

- fully and short automated sequence for starting safing phase of vehicle systems,
- afterwards, remote operations from Control/Command Center via wireless communications are initiated for further step in vehicle safing,
- connection of the 4 safety-critical functions for sustaining vehicle health (see chapter 3),

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- remote operations benefiting from hard connection to FGSE and EGSE for getting vehicle safing completed,
- staff operations at Landing Zone for getting Vehicle ready for transfer to Vehicle Preparation Hall.

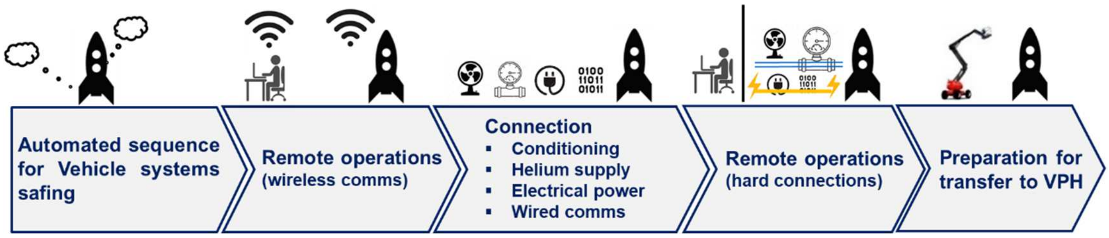

Figure 8 : set of primary operations after landing

Concentrating on phase devoted to connection of the four safing-critical functions in between Vehicle on one hand and FGSE and EGSE on the other hand (see end of chapter 3 above), there are two options: manually with staff close to Vehicle for connecting hard interfaces or remotely piloted with a Robot.

Both options are figured below:

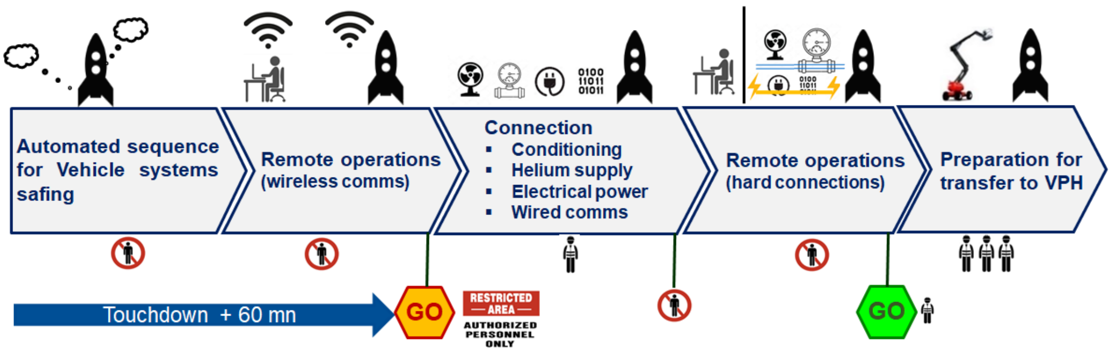

Figure 9 : set of primary operations after landing – scenario relying on staff for reconnections

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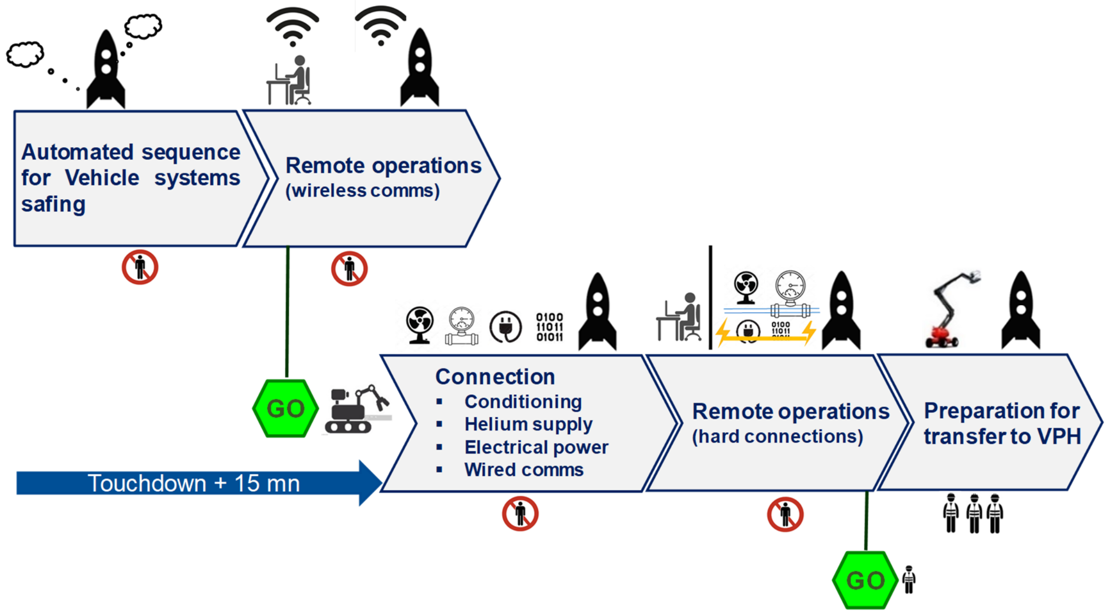

Figure 10 : set of primary operations after landing – scenario relying on robot for reconnections

There are pro and cons with both options according to different criteria:

- safety of operations when staff is around,
- reliability of operations in case of Robot-based scenario and different failure cases,
- cost of operations: purchase of robot, modifications to GSE and training of staff for remote operations,
- faster reconnection with Robot resulting in vehicle design optimized with more compact electrical power generation system e.g.,
- same positive trend for avionics items being less thermal environment stressed and then increased reusability with conditioning function reconnected more rapidly with a robot,
- innovation in CSG and operations for reconnecting Vehicle safing-critical functions.

6. Operations ahead of lift-off: opportunity relying on robot

At Lift-Off Pad and for managing the off-nominal situation of aborted flight, attention has to be paid to safing-critical function of Vehicle as it is the case for reconnection after flight.

The rationale for disconnecting Vehicle-to-Ground Segment interfaces as late as possible ahead of flight is as the same as for re-connection operations after landing:

- minimize Vehicle electrical power budget,
- improve reuse capability of heat-sensitive products (avionics e.g.),
- master vehicle state in case of aborted lift-off.

Therefore, there are two options:

- mechanical GSE that would disconnect Vehicle safing function at lift-off (when vehicle starts to have a vertical motion) in so-called positive time. Such choice, which is standard for most launchers, is compulsory for managing properly and safely off-nominal conditions and then aborted lift-off and what happens just afterwards;
- second option relies on a robot. Then these Vehicle safing functions are disconnected ahead of lift-off and may be easily reconnected in case of aborted flight without staff around Vehicle at Lift-Off Pad.

MGSE option is figured below with two different positions “before/after (lift-off)”, the major constraint being to have the Lift-Off Pad completely cleared after lift-off since, for some flights, Vehicle is supposed to land as same place.

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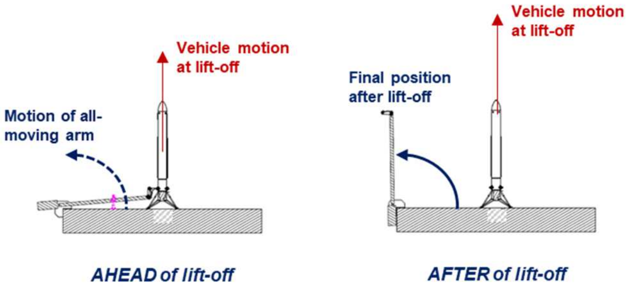

Figure 11 : all-moving arm for supplying gas and electrical power to Vehicle at lift-off pad

The disconnection of four functions is supposed to happen when Vehicle starts to move (lift-off) and the all-moving arm rising up around a rotating axis located outside the area where the vehicle is supposed to land at end of flight.

The two resulting scenario "all-moving arm vs. robot" with sequence of operations at Lift-Off Pad are figured below. Dashed orange box directly indicates difference in between two sequences

In case of all-moving arm-based scenario, the disconnections happen after engine ignition (thrust setting at 40% of full thrust) and last Vehicle health check leaving open the option to disrupt flight and keep safing-critical functions remained connected. For such off-nominal situation, the vehicle would then stay in safe state for indefinite time leaving the sequence of lift-off abort scenario properly completed.

For scenario relying on robot, the safing functions are disconnected much earlier for leaving time to Robot to clear the area and reach parking station away from Lift-Off Pad. In case of aborted flight, it would easily travel back to Vehicle as it would do so after landing.

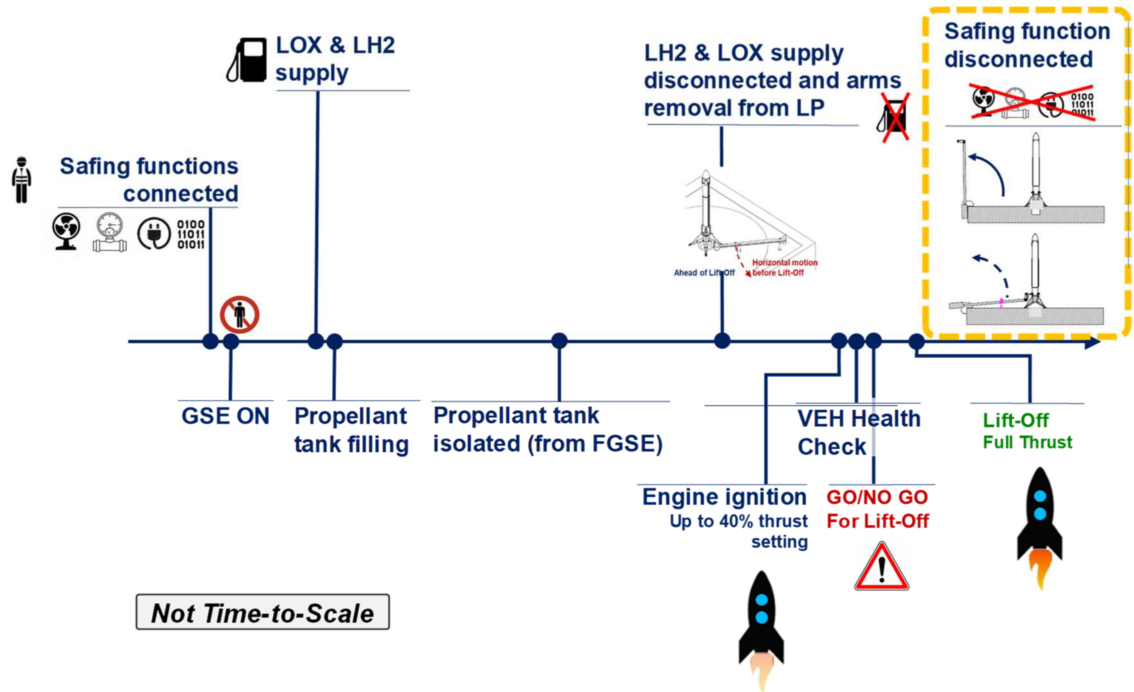

Figure 12: operations at Lift-Off Pad – scenario relying on MGSE disconnected AFTER Vehicle starting to move (vertical motion)

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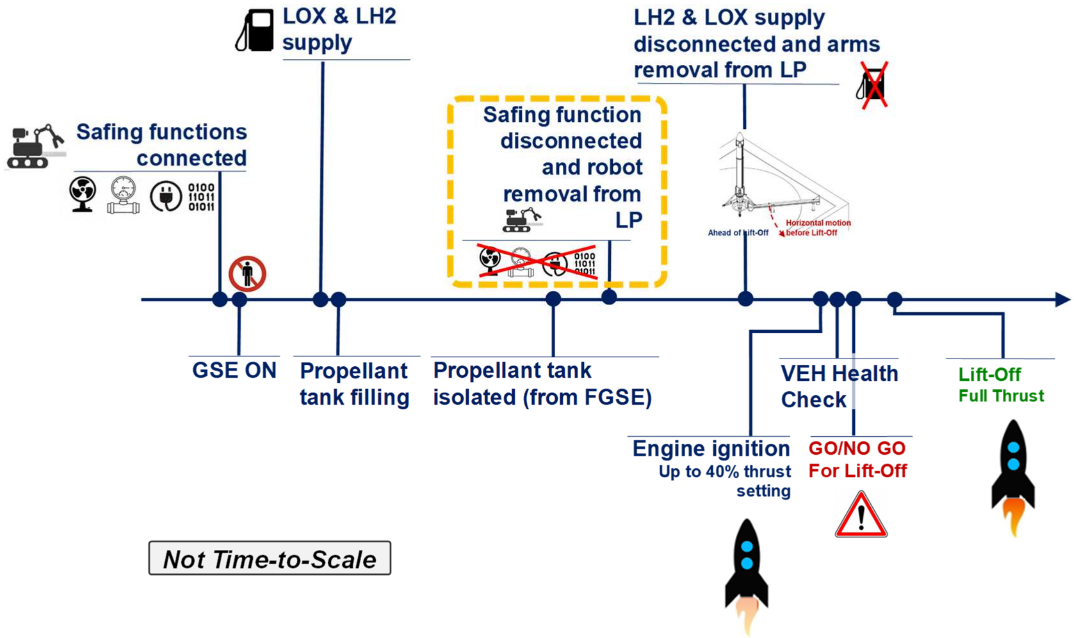

Figure 13: operations at Lift-Off Pad – scenario relying on robot disconnected PRIOR TO Vehicle starting to move (vertical motion)

7. Synthesis: robot-based operations

During a Request of Information managed by CNES earlier in the project and thanks to a set of initial requirements, it was checked that numerous and experienced companies may provide a Robot-based solution relying on existing building blocks: rover, robotic arm, etc… It was also made clear to CNES that operating manually and remotely a Robot is a real benefit for CALLISTO-like Project. When compared to industry and conditions indoor a factory, the situation after landing is much less easier to predict and to have human-in-the-loop is a valuable degree of freedom.

So conclusion of the trade-off became straightforward:

- For operations ahead of lift-off, a Robot is easier to design and more reliable to operate when compared to an all-moving arm supposed to disconnect Vehicle safing-functions after lift-off (aka in positive time),
- For operations after landing, the reconnection operations are faster and much more safer since no operating staff nearby Vehicle is required.

Installing a robot for operations at Lift-Off Pad and Landing Zone imposes:

- a devoted small-sized building for protecting and preparing Robot for a given flight. It is also the place for connections with networks of the Ground Segment or GSE: gaseous nitrogen, gaseous helium, electrical power, data communications,
- safe haven where the Robot is stationed during flight and where it travels to (ahead of flight) and from (after landing),
- interface with Command/Control Center from where the Robot will be remotely operated for re-connection operations after landing or aborted flight.

Current robot baseline combines off-the-shelf products (rover, elevating arm and robotic arm). The rover itself is small-car sized and figured below.

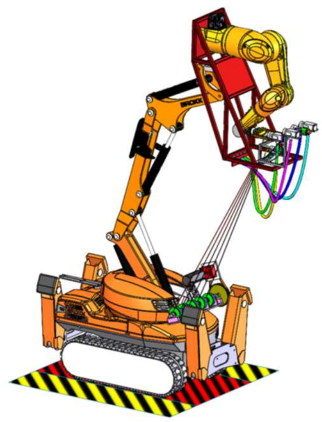

Figure 14 : robot in motion – artist's view – Courtesy Cybernetix

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8. Conclusion: status

After completion of the Request for Proposal in late 2021, the contract is running with a supplier much experienced in providing Robots for extreme conditions operations (under water, nuclear plants, etc…) and a demonstration step is in preparation for Q3 2022. The direct and running dialogue in between teams of CNES and supplier is also the occasion to further detail the set of requirements and then to get a step beyond in optimizing the overall System: interfaces in between the Ground Segment and Vehicle, the robot and the sequence of operations themselves at Lift-Off Pad and Landing Zone.

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