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Smart Operations in ATEX RLV Environment

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Abstract

The paper presents the safety logic analysis in the remote operation handling with regard to analysed specific and critical cases of the vehicle landing and its safely recovery. A few cases are analysed in details taking into account the results of tests campaign in ATEX environment of the LOX and LH2 storage and productions areas realized with an ATEX drone at European Spaceport in French Guiana in 2018. These results have notably demonstrated the feasibility of detection of gas leaks, thermal isolation defects and hot points before authorizing the approach of any human operator to the launch vehicle. The state of art infrared and optical sensors is presented in order to anticipate and foresee inspections operations for the vehicle landing.

1. Introduction

Since the beginning of the development of the Callisto reusable demonstrator project, the CNES has brought in evidence the importance of safe recovery of the vehicle. In recent years the repetitive successes of Space-X's launch vehicles have validated the feasibility of the reusable launch vehicles. However certain aspects are yet to be improved, such as the use of more efficient fuel, typically LOX/LH2 or LOX/LCH4 instead of kerosene. Beyond that, the tests flights campaigns will be take place at European Spaceport in French Guiana under the responsibility of CNES. That opportunity brings the difficulties concerning the reliability and safety of the launch vehicle due to the physical nature of LH2 and LCH4 especially for the transient phases of launch and landing. In our work we aim to analyse those difficulties under RAMS angle and to propose the innovative solutions.

The Callisto demonstrator has an engine working with the couple LOX-LH2 and the CNES has the historical experience in ground operations with this propellant but only with expandable rockets. The reusable launch vehicle brings a new set of dangers to be treated, notably the difficulty to recover the level of safety allowing the presence of personnel around the stage, i.e. neutralization of energy sources or putting on the safety barriers against catastrophic risks.

The phase by phase analysis had been performed in the framework of Callisto and ArianeNext projects in aim to define the preliminary safety specifications. In result, we have identified the set of traditional approaches to launch vehicle safety evaluation such as explosion modelling, the functional evaluation of fuel, pressurization gas and energy consumption as well as the material safety features, such as venting check valves and potential concepts of ground/board interfaces. All of them suppose a risk of landing pad destruction that is superior to the risk of launch pad destruction, since the environment cannot be controlled as well as on the launch pad. It has been put in evidence that new technologies in the frame of remote operations handling could reduce that risk to the vehicle recovery taking into account the ATEX (explosive atmosphere) environment.

In the last years in other industrial domains especially in the chemical and petrol ones, the ATEX environment has been very well mastered in terms of operations in respect of international safety rules. Among the technologies already

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qualified and actually operational all-around the world, there are the remote flying and terrestrial drones. Selecting the most mature solution, CNES decided to test the flying drone. The challenge was using such a drone, that could limit the risks provoked by its own failure modes in the ATEX zone and that could be accepted by existent French and international legislation (i.e. French Space Operations Act, aviation law, ATEX legislation). It was possible thanks to the study realized by ALTEA Solutions (ex Xamen Technologies) leader in the ATEX operations environment.

In the article at first it is presented a safety logic analysis in the remote operation handling with regard to analysed specific and critical cases of the vehicle landing, then it is put in evidence all the remote handling operations that could be realized in order to safely recover the vehicle in identified nominal and accidental conditions and master the critical steps taking account of associated risks.

A few cases are analysed in more detail and the article will focus on the flying ATEX drone solution taking into account the results of test campaign in ATEX environment of the LOX and LH2 storage and productions areas realized with the ATEX drone at European Spaceport in French Guiana in 2018. The state of art infrared and optical sensors have been used in order to anticipate and foresee the actual optic and thermal inspections foreseen for the vehicle landing. These results have notably demonstrated the feasibility of detection of gas leaks, thermal isolation defects and hot points before authorizing the approach of any human operator to the launch vehicle.

In the last part the article will present the innovation logic related to other technologies available such us ATEX terrestrial and robots for physical operations on ground/board interfaces and automatic flying drone’s solutions. A bibliographic status concerning the exploitation in space RLV domain is also presented. The article will conclude on what has been demonstrated and which are the development axes in order to safely operate on RLV environment.

2. Risk analysis post landing

CALLISTO (fig.1) is a flying demonstrator of reusable rocket that will be operated at Guiana Space Centre (French Guiana) in 2022 [25]. After lift-off in French Guiana Space Range (CSG) it is supposed to return to a specific landing site, either located on ground or on the maritime barge.

Figure 1: Callisto on barge after landing and drone in operation (Simulation)

Based on the preliminary definition of Callisto vehicle, the following operations plan had been established for each phase of the mission [26]:

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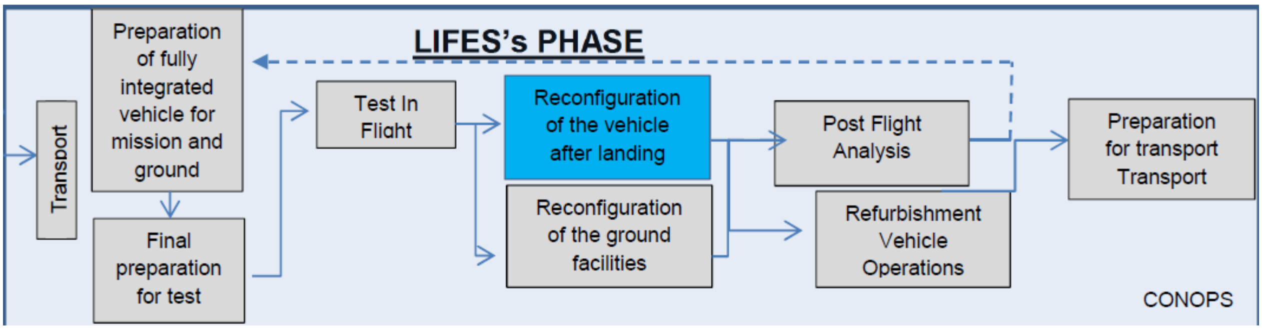

Figure 2: Callisto Operations Concept

In terms of risk for personnel on ground the final preparation for test and after landing phase are considered as the most critical phases. The initial status of the vehicle after landing includes vehicle stationary on ground, engine stopped and purged by automatic on board sequence, landing legs deployed and blocked, TVC (Thrust Vector Control) switched off, the residual propellants mass is still present, LH2 tank is pressurized to flight level in GH2, LOX tank is pressurized to flight level in GHe, RF emissions are active.

The final state after reconfiguration should allow the access of personnel with respect to French Space Operations Act (FSOA – LOS in French).

In conjunction with Functional Analysis that allowed to perform a full operational cycle risk analysis, here after the following main catastrophic feared events were identified for that state:

Table 1: Principal feared events in the safety

Feared Event	Potential Causes	Effect
Failure of approach and landing system –	Mechanism failure following excessive accelerations, efforts, icing wrt ambient humidity	vehicle tilting - loss of mechanical integrity
Gaseous hydrogen degassing and ignition from energy source	Degassing through relief valves and presence of hot points	Explosion
Gaseous oxygen degassing	Degassing through relief valves and presence of hot points	Oxygen saturation of specific materials, increased inflammability
LH2 and LOX tanks pressure burst	Relief valves failure	Explosion
Reaction Flight Control System (RFCS) leaks (H2O2)	Valves failures	Fire and organic irritation in the presence of persons
High pressure systems burst (GHe, H2O2 RFCS)	Pressure regulation failure following the choc of landing	Loss of mechanical integrity
Batteries failure		Explosion, Fire
RF emissions in the presence of persons	Non inhibition of RF emissions	Irradiation
Untimely activation of flight neutralisation system on ground	Non inhibition of flight neutralisation system on ground	Explosion
Untimely thrust vector control movement	Non inhibition of TVC system	Injury of persons
Cold points -	Cryogenic fluids leak, isolation default	Burns of persons
Hot points on the engine after shutdown	Insufficient thermal dissipation	Burns of persons
Propellants or helium leak	Valves failure	Anoxia

In terms of the mitigation actions the following needs were identified among others:

- The vehicle safety status to authorize personnel operations after landing or aborted flight shall be accessible without requiring vehicle power sources (electrical and pneumatic). Considering the simplex architecture an off-nominal procedure should be defined in accordance with vehicle status when unpowered or in case of communication absence between flight vehicle and Ground Segment.

- Vehicle mechanical stability should be assessed and guaranteed considering vehicle verticality, leg assembly integrity (e.g. status of crushable parts) and leg latching status.
- The risk of significant leakage of LH2/LOX in presence of persons, it concerns ground fluid interfaces reconnection after landing and in case of aborted launch following ground fluid interfaces disconnection. Launch System shall be FS/FS (Fail Safe/Fail Safe) against that risk.
- Vehicle wall temperature measurement should be done to characterise the hot and cold spots
- Simple relief valves are foreseen for the outgassing potentially constituting potentially the Single Points of Failure with respect to the risk of tanks burst. While the system is designed to minimise the auto pressurisation slope, the qualitative (FS) means (for example redundancy of relief valves) should be foreseen for risk criticity reduction.
- Outgas interfaces should be remotely operated and reported to Ground
- Untimely activation of the engine nozzle must be FS/FS. One barrier shall be fitted with a disabling device
- All connections have to be accessible without Mechanical Ground Support Equipment as much as possible

These are numerous and sometimes mutually exclusive requirements to put the safety barriers but not to put persons in the danger and not to impact the reliability and performance of the vehicle. They induce the need of alternative means of risk reduction impacting both for measurements and action. The remotely controlled robots and drones are proposed as a potential mean to solve the above technical contradictions.

3. Concurrent lessons learned and robots' application antecedents

In the concurrent industries the robotic solutions were already applied to address some of the risks identified here above in numerous applications and extreme conditions, such as firefighting, mining, military, nuclear, explosives mitigation. Very extensive studies exist about those applications

In the space industry in May 2016 after a sea landing, on board video of the drone ship showed the Falcon 9 booster moving on the deck due to the ship's roll [3]. The booster shifted several meters before being stuck to the fence. Luckily for SpaceX, booster had not tipped over. It should be noted that this near-accident occurred by calm weather with a roll amplitude of approximatively 4 degrees.

To prevent this event to happen again, the first measure was to immobilize the stage by hooking the engine bay up to the deck. This secures the stage during the return journey but require that workers operate next to a potentially unstable stage. Then SpaceX introduced the "Roomba" (or "OctaGrabber") robot which stabilised the booster, once it is stationary on the drone ship [13][14].

Figure 3: Octagrabber on OCISLY (c: Stephen Marr)

Figure 4: Octagrabber on OCISLY (c. The Aerospace Geek)

Beyond space domain the robots were used in treatment of nuclear accidents, such as Chernobyl [2]or Fukushima [1] the remotely controlled robots were used to move, film and perform measurements in highly encumbered radioactive zone, and even in the tentative of decontamination by physical displacement of radioactive debris [4][5]. Chernobyl case demonstrates the deliberate people's exposure on the catastrophic risk [9] (use of soviet soldiers, surnamed "liquidators" for the tasks of nuclear debris cleaning) , the very situation that the robotic means are supposed to mitigate.

On the frontier of firefighting need and nuclear installations a modular robot i-TIM is in exploitation in CERN installations [12]. It includes measurement chain (radiation, vacuum leaks, photogrammetry), the actuators (robotic arm for manipulation of cameras and sensors in LHC tunnel) and fire extinguisher.

Due to presence of explosive atmosphere coal mining is one of key sectors where ATEX robots develop [6][8] to be applied for inspection in underground coal mine areas after a catastrophic event. The typical accident zone contains increased levels of harmful gases like CO and CO2 and explosive gases like CH4 in addition to a decreased level of Oxygen. The entire gallery or roadway is filled with dust and smoke, or water in case of inundation, hindering the visibility of rescue personnel. The temperature can be above 60 degrees C. In terms of tunnels geometry an important slope can be encountered and different obstacles. Telerescuer robot presented in [6] addresses those issues and discusses the impacts of the ATEX certification on the robot design.

Outside of accidental applications the article [10] presents the tested application of the industrial autonomous robot certified for ATEX for the petrochemical installations thermal imaging survey and fluid equipment manipulation. The valve manipulation operation involves sensor-based movements which implies that the robot trajectories have not been programmed a priori.

The drones (UAVs) and robots were widely applied in the energy, infrastructure (roads, bridges) and petrochemical industries for the inspection of installation status [19], [21]. The detection of industrial gases, such as methane had been also already tested for application on UAVs [24]. The Argos competition organised by Total is one of the most notable recent initiatives in this domain [22][23].

In terms of emergent solutions there are trials to develop “soft” robots without electrical actuators for use in offshore oil and gas environments due to the ATEX compliance, low cost, and resilience to extreme environments[7]. The drones were also applied to inspect HVAC conduits in the industrial installations with caged structure to protect those installations from drone operations, while being equipped with infrared and optical cameras for detection of maintenance problems [20].

The use of effort sensor and, haptic interfaces with industrial robots [11] is another way to address the problematic of non-preprogramed robot behaviour and to satisfy potential need to manipulate the mechanical interfaces.

The above sample of robotics applications demonstrate that it is potentially possible to address with use of robots the needs identified in §2 and excluding the presence of personnel in the landing zone of Callisto demonstrator, while the launcher hazardous systems are not completely neutralised. The more detailed technical trade-off is necessary to consolidate the feasibility of that goal.

4. Flying ATEX drone solution

The ATEX environment [15][18] concerns an explosive atmosphere and it is defined as a mixture of dangerous substances with air, under atmospheric conditions, in the form of gases, vapours, mist or dust in which, after ignition has occurred, combustion spreads to the entire unburned mixture. Atmospheric conditions are commonly referred to as ambient temperatures and pressures. That is to say temperatures of –20°C to 40°C and pressures of 0.8 to 1.1 bar.

Explosions can cause loss of life and serious injuries as well as significant damage. Preventing releases of dangerous substances, which can create explosive atmospheres, and preventing sources of ignition are two widely used ways of reducing the risk. Using the correct equipment can help greatly in this.
In the RLV environment the ATEX risk is present and the operations post landing must cope with this specific dangerous constraint.

Among the different solutions to operate in remote handling according the safety rules, we focused on the Flying ATEX drone solution. This solution takes advantage from the petrol and chemical domain where ATEX working area are present and since a few years ATEX drones (according to specific certification) are used in order to check the status of infrastructures and equipment but also perform analysis with regard to the corrosion status of structures and thermal analysis. The Technical Readiness Level of that solution is very high and application is common for petrochemical industries. This solution presents many advantages for the respecting of the safety rules, for example safety distance from dangerous area, and have rapid checks status of a vehicle in the RLV domain to take quickly a right decision. For this reason, the CNES decided to start a feasibility study and perform the test campaign in a real ATEX environment at Guiana Space Centre.

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Figure 5: ATEX Drone in operation

The post landing RLV needs must be respected by the drone specifications with respect to the risk analysis presented in §2. They are presented in the following table:

Table 2: Drone specifications wrt RLV post landing operations

Function	**ATEX zone 2 area means and conformity**	
	Optic 20Mpx	Thermography
F1: to contribute to monitor the vehicle		
F1.1 : to contribute to external visual inspection	Sony RX100+ optic zoom x3,6, resolution 4,5/5cm at 150m altitude	Flir Vue Pro 640 13mm 9Hz, from -4deg to 550deg.C, photo & video, optic zoom x2, x4
F1.2 : to calculate the surface temperature	n/a	
F1.3 : to contribute to detect hot points on vehicle skin <300 deg.C	n/a	
F1.4 : to contribute to detect a cold cloud around the vehicle <-70 deg.C	n/a	
F2: to perform operations in remote mode		
F2.1: to transport batteries close to the vehicle capability m<30kg	yes, up to 2kg	
F2.3: to move and deposit mass on vehicle legs m<20kg height <0,5m		
F3: to perform operations autonomously		
F3.1: to localize the vehicle in space	Yes	
F3.2: to approach to vehicle equipment’s		
F3.3: to go back in a safe mode		
Constraints		
CF1: capability to operate in explosive atmosphere ATEX	Yes	
CF6: to operate in night conditions		
CF10: to transmit in real time		
CF11: to operate on an unstable surface, barge in open sea		
CF12: to operate on slope and obstacles		
CF13: to operate on the vehicle without impact		

The ATEX drone solution used for this test is indicated in the following table with its main characteristics:

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Table 3: Drone ATEX characteristics

Topics	Drone (LE 4-8X Dual ATEX
Type	8 propellers
Power	electric
Mass dry (without payload)	4,6 Kg
Dimensions (max)	102 cm
Take-off	vertical
Altitude max	400 m
Time flight	10 min
Distance max	2,5 Km
Number of pilots	2
Velocity max	60 Km/h
Range of temperature (operation)	-5° to 100 ° Celsius

5. Test campaign at Guiana Space Centre

In the frame of the feasibility demonstration among the main objectives there were all compulsory authorisations necessary for this type of operation. The area of operation is an industrial LH2 and LOX production and storage site with ATEX zones. The site is inside the Guiana Space Centre. That means we are in a classified SEVESO High Level site in a restricted and secured area. The authorisations necessary came from the CNOA (National Centre of Aeronautical Operations- French-Air Force), the DGAC (General Direction of Civil Aviation), the local French Air Force commander, the CNES Security department, the CNES Cybersecurity department, the CNES Safety department and the safety officer of the local industrial site. We can specify that the operation in ATEX zone in a Classified SEVESO site demands that the pilots must have all the security clearances requested and the drone must be ATEX certified according the international rules of the European Directives for controlling explosive atmospheres. In accordance with the authorities the flight plan was specified and accorded and the main risk analysis is presented here after in the following table:

Table 4: Drone operation Risk AnalysisN°	Phase	Material in use	Risk	Safety Precautions
1	Take-off	Drone and its sensors	1 engine in failure (autorotation)	Safety Distance of 15m
2	flight	Drone and its sensors	Navigation system failure	Flight plan preparation- Check of the system before take-off- In case of falling, open the parachute (automatically or by the pilot)
3	Flight- Distance to close to objective (inspection)	Drone and its sensors	Impact with the objective	Parachute opening automatically or by pilot
4	Flight- The pilot feels unwell (illness)	Drone and its sensors	Drone uncontrolled	The drone automatically will stabilize itself at its altitude. The second pilot will put the drone at its starting position
5	Flight- Magnetic Saturation	Drone and its sensors	GPS failure or breakdown	Switch of piloting in manual mode (without GPS) and landing. Changing of flight plan and take-off arear
6	Flight- Strong wind in the inspection area	Drone and its sensors	Punctual Instability unexpected	Deportation of the objective. Wait of the end of the gusty winds period. Restarting of the mission if the situation has improved (and acceptable) V<20km/h
7	Flight- Bird impact	Drone and its sensors	Drone Rotation and falling	Parachute opening automatically or by pilot

8	Flight- High tension line impact	Drone and its sensors	Falling	Parachute opening automatically or by pilot
9	Flight-Signal problems (emission and receiving)	Drone and its sensors	Drone Stabilization	Automatic control system to “go home”. The drone goes back and lands at the take-off point
10	Take-off-Battery trouble	Drone and its sensors	Drone Immobilization	Battery change
11	Take-off-Battery trouble (fire)	Drone and its sensors	Drone on fire	Keep clear the zone from people and await the natural extinction of the fire on the drone
12	Flight-Battery trouble	Drone and its sensors	Loss of control of the Drone	Parachute opening automatically or by pilot through the system X-SAFE with its independent power alimentation
14	Flight	Drone and its sensors (payload)	The sensors stalled	The sensor is maintained by a back-up joint solution. Emergency landing procedure
15	Flight-Battery trouble	Drone and its sensors	Battery Explosion	Parachute opening automatically or by pilot through the system X-SAFE with its independent power alimentation

The main descriptive of the Safety operation procedure of the ATEX drone is the following:

- Emergency landing
- Fail Safe on transmitter and receiver with a fly back at the take-off point in case of radio failure and/or transmitter failure (« Home point » via Fail Safe said « RTH »).
- In case of overtaking the flying zone threshold (altitude) a sound and visual alarm.
- Visual and sound distance alarm Battery level visual and sound alarm XSAFE system activation automatically or manually with the parachute opening in case of serious incident. U buzzer will indicate the drone descent by parachuting. Impact energy inferior of 69 joules, the parachute is of 6 square meter and the velocity of 3,6 m/s.
- Home lock function: the drone flies back to initial point with a simple
- Course lock function, the drone can move in translation without any attitude controlling
- ATTI mode in case the GPS is lost the drone maintain the altitude but the pilot maintains the position manually in case of strong wind in order to stabilize it:
- The two pilots function in case of emergency, while one keeps clear the area of eventual personnel present, the other will control the drone.

The surveyed ATEX zone activity was the LOX and LH2 production and storage area which are presented in the following pictures taken during the operations (LOX on the left and LH2 on the right):

Figure 6: LOX and LH2 production plants at CSG

The main objectives for these tests operations were:

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- Technical and organisational feasibility of the flying check operation
- Visual inspection (direct and by post data treatment) of infrastructures (shocks, evident anomalies)
- Thermal inspection (direct and by post data treatment) of infrastructures (performances validation, micro leaks)

For what a thermal vision could provide as result in the cryogenic domain an example is the following picture realised in a previous operation in another cryogenic production site:

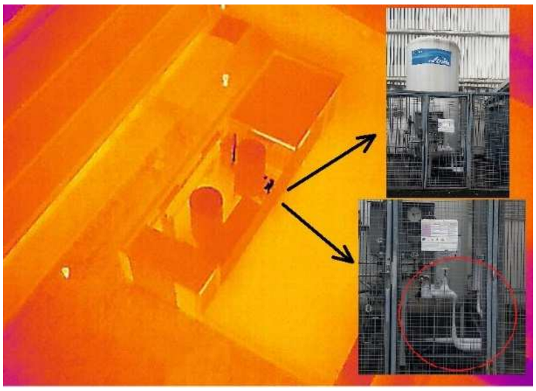

Figure 7: Example of leak detection in a cryogenic production

The saturation of the sensor provides an evident result in case of leaks, in the thermal picture the black spot in the middle. In our case we were quite confident of no particular leak but the results have brought other type of anomalies. The output data provided were 52 optic pictures and 107 thermal pictures in about 15 minutes of flying operation. Coming from the 107 thermal pictures we can put in evidence some examples of results:

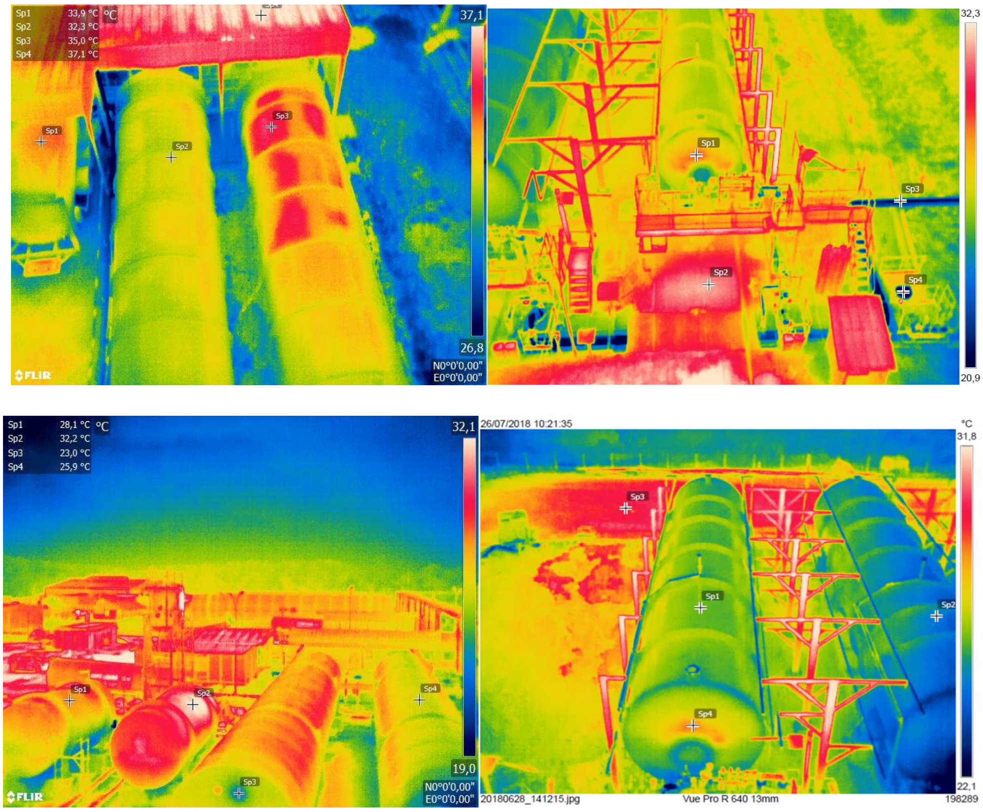

Figure 8: Results example coming from the 107 thermal pictures taken during the ATEX operation

The thermography was live as well during the operation in the ATEX zone (for the pilots) but as mentioned a post treatment has been realised by a software provided from the sensor IR company.

The temperatures in the surveyed zones were treated in relative and not in absolute values, since they depend on the angle of camera with respect to the filmed object, the light and sensor thermal range. The drone surveys were performed early in the morning, before the Guiana's strong daylight altered the detected temperatures. The good operational knowledge of the installation expected thermal behavior is necessary with conjunction to alternative measurements (for example localized thermal sensors) to adjust the measured values with more detail.

The main results are:

- No strong anomaly detected or leaks like in the previous example
- Anomalies were found in the He, LOX and LH2 sites, concerning a loosing of a layer tightness in a few tubes, tanks and infrastructures.

The last point has brought a crosscheck and confirmation analysis of some hypothesis in the industrial production process. In particular, in the storage containers and some tubes the sizing of the structures are dimensioned in order to maintain a certain temperature, normally a double thermal wall layer with a vacuum inside. The temperature variation on the structures shows and confirms these type of anomalies which are important for the maintenance plan or in case of preventive maintenance.

These results were very useful and positive for the LOX and LH2 producer in particular for the local Safety Officer and production responsible, providing consistency at a certain analysis evaluation of the production. These results even if were consistent and direct useful for the maintenance goal in a ATEX area, they represent an important feasibility confirmation of the consistency of the Safety post landing RLV operation and moreover for the Callisto project. In the next paragraph we put in evidence how these results represent a solution for smart operation in RLV domain.

6. Tests Results at benefit of RLV post landing

We have seen in the paragraph 2 and 4 the details for Callisto (RLV demonstrator) concerning the feared events in the post landing operations and the needs specifications in order to prevent against catastrophic or major risks.

In a frame of smart operations in post landing RLV, taking into account the results achieved in the ATEX flying drone at Guiana Space Centre and the analysed state of art in the drone (flying and terrestrial one) domain, we can put in evidence:

- Complete transposition of the drone exploitation from petrol chemical industrial domain in the space transportation
- Flying drone operability in dangerous area and ATEX one with specific certifications and compatibility of RLV post landing operations
- Thermography sensors for thermal characterisation of vehicle structures easily transportable and operational by flying drone.
- Visual inspection after landing thanks to HD optic sensors
- Drone Pilot Safety distance compatible with safety distance of a RLV post landing.

It is necessary to precise that the domain of robots, drones, sensors and telecommunication is highly dynamic and the improvements come frequently and are consistent. From one year to another the robots and drones' capabilities increase enormously. For this reason, in a RLV development or in the Callisto roadmap could be useful to take advantage of this.

In the ATEX domain we can affirm that for the flying drone actually it is available:

- Optic definition is about of 50Mpx with a zoom X30
- Gas detection camera type "Gasviewer " MUAV 3234 □[16] for natural gas such as methane, propane but also oxygen
- Thermal IR sensor FLIR type (like G300A and GF 320) □[17] for thermography. (analysis software provided with)

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For both terrestrial and flying ATEX drone solution what is very innovative is:

- Remote operation. Automatic intervention plan and teleoperation by pilot in case of specific case
- Data communication direct to a cloud for rapid exploitation instead of data recording on card
- Encrypted transmission data
- Improving data management and cloud computing for quick calculation and post treatment.

7. Preliminary specification for a Callisto robot

The review of Callisto demonstrator risk analysis, the state of art and the experimentations with ATEX drones in French Guiana drive the following set of macroscopic requirements towards potential demonstrator robotic system for "after landing" safety phase:

- Detection of cold and warm points, visual inspection, GH2, GOX concentration, hydrogen combustion
- Perform operations autonomously (localise the vehicle in space, approach it, be able to revert in safety state)
- Perform operations in remote mode -
    - Transport and connect the fluid and electrical interfaces by rotational movement, control mechanical loads applied on the vehicle few meters above ground level.
    - Move and deposit mass on engine legs
- Operate in the unstable, heated surface with slopes and obstacles
- Operate in ATEX environment both on ground or maritime barge in French Guiana tropical environment
- Autonomous power during several hours of operations.

Current follow up activity consists of a trade-off defining a specific solution able to satisfy the most of those needs (typically a drone working with "terrestrial" robot) and evaluating its preliminary design and test logic to be demonstrated in parallel of Callisto demonstration programme. The expected result is supposed to have a positive impact on the overall operational concept of the target launch system, its availability, reliability and cost, while satisfying the safety rules and French Space Operations Act. Potentially it could allow to simplify the launcher interfaces with ground segment.

8. Conclusions

Starting from a Callisto evaluation risk analysis post landing and conops some critical events have been put in evidence and some solutions have been provided to secure the post landing operations for Callisto but also in general for RLV. Some important elements of the state of art of solutions in use of robotics in space, petrochemical and nuclear domains operations have been presented.

We have focused on the preliminary solution of using of a ATEX flying drone which has been tested. It has been described and studied with some results tests the ATEX operations at Guiana Space Centre. The main goal was the feasibility and demonstration of smart operations with the help of a ATEX flying drone in order to prepare Callisto test campaign and solve the safety operations which will be necessary after the post landing. The main results are the:

- Complete transposition of the drone exploitation from petrol chemical industrial domain in the space transportation
- Flying drone operability in dangerous area and ATEX one with specific certifications and compatibility of RLV post landing operations
- Thermography sensors for thermal characterisation of vehicle structures easily transportable and operational by flying drone.

A few details have been showed concerning the thermography sensors certified ATEX and drone compatible and its capabilities in terms of thermal details which could useful for RLV.
Some evaluations and results have been presented concerning the actual and next close robot capabilities for post landing domain such as the importance of the communication and data management.

The review of RLV operational needs, state of art solutions and experimentations in situ in French Guiana allowed us to propose the preliminary requirements specification towards the robot tailored for Callisto demonstrator. The corresponding potential technical solution trade-off is ongoing.

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References

[1] CNET, How robots are cleaning up Fukushima's nuclear disaster https://www.youtube.com/watch?v=mhQixNlLF_k, 05/03/2019

[2] Institute of Safety Problems of Nuclear Power Plant (Ukraine), Robot inside Chernobyl's Sarcophagus - Робот в Чернобыльском Саркофаге https://www.youtube.com/watch?v=U5Ib2efNWDY, 29/03/2009

[3] Space X, How Not to Land an Orbital Rocket Booster , https://youtu.be/bvim4rsNHkQ?t=80 , 14/09/2017

[4] E. Potemkin ; P. Astafurov ; A. Osipov ; M. Malenkov ; V. Mishkinyuk ; P. Sologub 1992: Remote-controlled robots for repair and recovery in the zones of high radiation levels. Proceedings 1992 IEEE International Conference on Robotics and Automation

[5] Qihao Zhang et al 2018, Research Progress of Nuclear Emergency Response Robot, IOP Conf. Ser.: Mater. Sci. Eng. 452 042102

[6] Novak, Petr & Kot, Tomas & Babjak, Ján & Konečný, Zdeněk & Moczulski, Wojciech & Rodriguez, Angel. (2018). Implementation of Explosion Safety Regulations in Design of a Mobile Robot for Coal Mines. Applied Sciences. 8. 2300. 10.3390/app8112300.

[7] T. Mahon, Stephen & Buchoux, Anthony & E. Sayed, Mohammed & Teng, Lijun & A. Stokes, Adam. (2019). Soft Robots for Extreme Environments: Removing Electronic Control.

[8] Wang, Yong & Tian, Peng & Zhou, Yu & Chen, Qing. (2018). The Encountered Problems and Solutions in the Development of Coal Mine Rescue Robot. Journal of Robotics. 2018. 1-11. 10.1155/2018/8471503.

[9] Yablokov, Alexey. (2009). 7. Mortality after the Chernobyl Catastrophe. Annals of the New York Academy of Sciences. 1181. 192-216. 10.1111/j.1749-6632.2009.04828.x.

[10] D. A. Anisi, E. Persson and C. Heyer, "Real-world demonstration of sensor-based robotic automation in oil & gas facilities," 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, CA, 2011, pp. 235-240.

[11] A. Cirillo, P. Cirillo, G. De Maria, C. Natale and S. Pirozzi, "A proximity/contact-force sensor for Human Safety in industrial robot environment," 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Wollongong, NSW, 2013, pp. 1272-1277.

[12] M. Di Castro, M. L. B. Tambutti, M. Ferre, R. Losito, G. Lunghi and A. Masi, "i-TIM: A Robotic System for Safety, Measurements, Inspection and Maintenance in Harsh Environments," 2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Philadelphia, PA, 2018, pp. 1-6.

[13] Eric Ralph, SpaceX debuts 'Optimus Prime' Robot, successfully recovers Falcon 9 1029 for the second time, 29/06/2017,https://www.teslarati.com/spacex-debuts-optimus-prime-robot-successfully-recovers-falcon-9-1029-second-time/

[14] Emre Kelly, 'Robot' spotted on SpaceX drone ship as Falcon 9 first stage arrives at Port Canaveral, 30/06/2017, https://eu.floridatoday.com/story/tech/science/space/2017/06/29/robot-spotted-spacex-drone-ship-falcon-9-first-stage-arrives-port-canaveral/439348001/

[15] ATEX and explosive atmospheres, http://www.hse.gov.uk/fireandexplosion/atex.htm, accessed 16/06/2019

[16] Portable camera - GasViewer P 3234 – Datasheet, https://www.gasviewer.eu/products/portable-camera-gasviewer-p-3234/datasheet/, accessed 16/06/2019

[17] FLIR, https://www.flir.com/, accessed 16/06/2019

[18] Directive 94/9/EC of the European Parliament and the Council of 23 March 1994 on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A31994L0009, accessed 16/06/2019

[19] W. Wu, M. A. Qurishee, J. Owino, I. Fomunung, M. Onyango and B. Atolagbe, "Coupling Deep Learning and UAV for Infrastructure Condition Assessment Automation," 2018 IEEE International Smart Cities Conference (ISC2), Kansas City, MO, USA, 2018, pp. 1-7.

[20] A. Borik et al., "Caged Quadrotor Drone for Inspection of Central HVAC Ducts," 2019 Advances in Science and Engineering Technology International Conferences (ASET), Dubai, United Arab Emirates, 2019, pp. 1-7.

[21] Rise of the robot in offshore operations, 10/01/2018, https://www.oedigital.com/energy/item/16834-rise-of-the-robot-in-offshore-operations

[22] Elaine Maslin, The robot race, 01/05/2017, https://www.oedigital.com/component/k2/item/15234-the-robot-race

[23] Argos Challenge, Total, https://www.total.com/en/dossiers/argos-challenge-building-tomorrows-oil-and-gas-robot , accessed 16/06/2019

[24] L. Tao, D. Pan, L. Golston, K. Sun, S. Saripalli and M. A. Zondlo, "UAV-based laser spectrometer to quantify methane from agricultural and petrochemical activities," 2015 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, 2015, pp. 1-2.

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[25] O. Diaz Lopez, S. Lopez Moreno, J. Desmariaux, 2018, CALLISTO project - mechanical architecture and structural design challenges in the frame of a reusable first stage demonstration vehicle, 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018, IAC-18.D2.6.4x47124,

[26] O.Frenoy, T.Hiraiwa, Concept of Operations - CALLISTO demonstrator, 2019, 8th European Conference for Aeronautics and Space Sciences