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NEMS and MEMS technologies in RLV maintenance operations

Massimo FERLIN, Michal KURELA***
*Olivier LEHMANN****
**CNES Launcher Directorate Innovation Launcher System Paris-France*
Massimo.ferlin@cnes.fr
***CNES Launcher Directorate LOS French Guiana*
Michal.kurela@cnes.fr
****FEMTO Engineering - FEMTO-ST / AS2M*
Besançon (FRANCE)
olivier.lehmann@femto-st.fr

Abstract
NEMS (Nanoelectromechanical systems) and MEMS (Microelectromechanical systems) have already demonstrated their capabilities in the medical domain for in body inspections, operations and treatment of diseases. Selected NEMS and MEMS state-of-art technologies could be used for inspections at Guiana Space Center without dismounting and sending to Europe for industrial check. A few examples of micro and nano equipment's such as µrobot (µtools), µ ornano camera, for detection and data collection are underlined in the article and a preparation tests campaign is prepared according to precise specifications coming from RLV equipment. This feasibility study is the first attempt to use these technologies in order to cope with the MRO RLV and start to contribute at a maintenance characterization economic model.

1. Introduction

Prometheus [20][19] and Callisto [1][1] are two keys elements of European future launcher preparatory roadmap according to CNES. If the first represents the future European engine in the RLV domain, the second is a system demonstrator project to master the RLV end-to-end operations. Both of them have the objectives to demonstrate the capacity of the efficient maintenance.

Historically in European space industry the launchers maintenance was not a priority because of their expendable nature. The maintenance has been concentrated in the ground segment and in very small part of launcher's subsystems lifecycle from production to final chronology, only in acceptance tests or integration operations at European Spaceport at Kourou in French Guiana.

With introduction of the RLV the maintenance has become a very important specification not only in order to refly the launcher but it represents an important factor for its economic model. The product lifecycle for the RLV launcher is much bigger than for the expendable one and the lessons learned of US Space Shuttle show the complexity of aspiring RLV systems to optimize its exploitation costs and reliability.

The maintenance is strongly related to the technologies used and adopted in the engine design or stage of the RLV launcher and to the production organization. In Europe the product lifecycle is strongly impacted by the geography. All the production is situated in Europe while the European Spaceport is situated in French Guiana in South America. Because of that particular situation, the historical tendency is to reduce the maintenance requirement by design (increasing margins, concept simplification, …) while in many cases it is not the optimal solution. The alternative is to identify the innovative maintenance means directly in French Guiana. They need to be applicable after landing directly at the spaceport without any strong support from the industry equipment's and experts situated at more of 8000 km.

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2. RLV engine maintenance risk analysis and launchers' lessons learned

The maintenance of RLV's made an important part of Space Shuttle lessons learned □[16]~~[16]~~□[17]~~[17]~~. While initial idea from 1970s was to produce high cadence launcher to orbit with low recurrent costs, in the end the significant feature of Space Shuttle was its complexity in technical definition and concept of operations. Other arguments included erroneous market analysis, overestimating the need for that kind of service and a trade-off that sacrificed the actual reusability against the non-recurrent cost. All that led to explosion of recurrent cost of space shuttle launches. However the experience of Shuttle, being the first almost RLV system in exploitation, provided numerous specifications to include in design of RLVs □[17]~~[17]~~□[18]~~[18]~~, including:

- Importance of having a full understanding of the operational environment
- Establish periodic and preventative maintenance, inspection and checkout plan for critical flight hardware to reduce the likelihood of failures. Checkout testing intervals should be set based on component criticality and system functionality requirements.
- Importance of a robust and thorough Corrective Action process that avoids extensive latitude for accepting repeated failures without preventive corrective actions.
- Design systems for ease of leak checking and operational verification

Driving from that experience as well as from aeronautic standards in the framework of Prometheus and Callisto programs the maintenance needs were evaluated by taking into account launcher's lifecycle for feared events identified in the preliminary RAMS analysis. That analysis is taking into account functional stage cycles and physical particularities (typically properties of LOX/LH2, LOX/CH4). The lessons learned from concurrent launch failures and production technical facts also serve to identify the feared events that can be addressed by maintenance, such as:

- Pollution in the fluid circuits of the stage, following the wear or phenomenon's due to propellants behavior
- Aggravated pre-existing structural defects leading to leaks or decreasing the structural reliability
- Geometric non-conformities following the cycling phenomenon's

Following the screening of innovative technologies, the means of preventive maintenance include the implementation of HMS systems and planned exchange of certain components which have reduced lifetime. However, in aim to avoid launcher misconfiguration and costs of complex MAIT (Manufacturing Assembly Integration and Test) operations in French Guiana, the alternative means for MRO (maintenance, repair and overhaul) in-situ are needed. That concerns such components as thrust chambers, auxiliary power units, and turbomachines.

CALLISTO (fig.1) □[1]~~[1]~~ is a flying demonstrator of reusable rocket that will be operated at Guiana Space Centre (French Guiana) in 2022. 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. Its development is an opportunity to test the innovative MRO means.

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

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Beyond RLV needs and up to some degree the maintenance plays the role even for the expendable launchers, since their equipment's are tested before flight and sometimes they fail leading to the additional equipment refurbishment, exchange and test operations. Depending on the test instance (equipment, stage, launch campaign) the impact on the overall launch campaign can be very important.

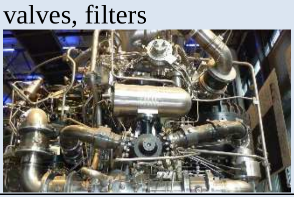
The inspections are a classical quality tool to assure the conformity of the launcher equipment with the definition that is qualified and foreseen by the launch operator. Yet after specific milestones (integration of upper stages, closing the human doors, integration of specific equipment's, engine fire testing) they are impossible without putting a strong strain on the planning and costs of the campaign.

The deconfiguration following the failure of a specific equipment can have very important impact on the justification of the flight worthiness. That constraint is true during all phases of the life of the system concerning both basic building blocks and the whole launcher that is in the synchronized sequence waiting on the launch pad. Contrary to the appearances the failure on low level subsystem level in its manufacturer premises could impact the parallel launch campaign flightworthiness if the issue requires to inspect or alter the concerned subsystem on the launcher, that is fully integrated. Often that very alteration will lead to deconfiguration requiring a specific justification by specific engineering studies, increasing the cost and delay of launch. In similar way the parallel development of future evolutions of the system sometimes reveals fortuitous failure cases (notably in case of hardened tests) impacting the system of previous definition in exploitation.

Often the problem comes from the technical limitations of the Non Destructive Inspection (NDI) means, such as endoscopes, portable radiography. It includes their length, diameter, the bad luminosity in the zone to be inspected, particular behavior of the items to be inspected (bad visibility of additive manufacturing powder wrt. X rays)

Following the analysis of above examples of failure cases, the following 4 families of maintenance targets were defined:

Table 1: Families of launch system maintenance targets and their particularities

No.	Family of maintenance target	Dimensional particularity	Examples	Expected maintenance action
A	Fluid lines of the engines and propulsion functional system fluid equipment's	Diam. several mm Length several meters Varied geometry	Engine feed system, stage pressurisation lines, their valves, filters 	inspections, refurbishment of defects of structures or specific coating materials, declogging, cleaning the pollution.
B	Engine equipment's specific circuits "on the table" nondestructive inspection	Diam: 1-2mm Length several meters Varied geometry with numerous strong bendings	Regenerative circuits of combustion devices of very small diameters (Thrust chambers, gaz generators), turbomachines 	Inspections, refurbishment of defects of structures or specific coating materials, declogging, cleaning the powders and other pollutions accumulated in the cavities (typically post additive manufacturing de-powdering and decontamination)
C	Inaccessible launcher cavities of the after integration operations	Diam: several dozens mm Length of several meters	Engine Thrust Frame equipment's on its inner side, equipment plate	Inspections, limited testing (metallisation, continuity, helitest, x-rays, etc.), revalidation (apply the

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				mechanical couple, connect a connector, etc.)
D	Ground segment equipment's,	Diam: of dozens on mm and several km length	inaccessible ducts and cavities, fluid lines and their equipment's 	inspections, refurbishment of defects of structures or specific coating materials, declogging, cleaning the pollution

The above mentioned problems require nonstandard solutions to break through the maintenance costs taking into account temporal and space constraints imposed on RLVs. The small robotics had been investigated for that purpose.

3. NEMS/MEMS robotics state of art

NEMS (Nanoelectromechanical systems) and MEMS (Microelectromechanical systems) have already demonstrated their capabilities in the medical domain for in body inspections, operations and treatment of diseases. Their use in industry is uncommon. Selected NEMS and MEMS state-of-art technologies could be used for inspections without dismounting and sending to Europe for industrial check. A few examples of micro and nano equipment's such as µrobot (µtools), µ or nano camera, for detection and data collection are underlined.

Globally the state of art of the micro and nano robots can be classified in terms of applied technologies in the following manner (with referenced bibliographic examples):

Table 2 nano and microrobots technologies versus applications

Robot Technology	**Launch system application (§2)**				**TRL**
	A	**B**	**C**	**D**	
Means of displacement					
w/o contact magnetic□[2] ~~[2]~~	x	X			3
transporting fluid □[3]~~[3]~~	x	x		x	9
surface contact □[4]~~[4]~~	x	x		x	3
flying drone □[5]~~[5]~~		x	x	x	9
wheeled □[6]~~[6]~~			x	x	9
endoscopy/deployment □[7]~~[7]~~□[8]~~[8]~~	x	x		x	4
Sensors					
nano-cameras □[9]~~[9]~~	x	x			1
endoscopic laser pointing □[10]~~[10]~~	x	x		x	5
LGRUT (Long Range Ultrasonic Testing) □[11]~~[11]~~		x		x	5
multimode optical fiber □[13]~~[13]~~	x	x			2
EMAT (Electromagnetic Acoustic Transducers) □[12]~~[12]~~		x		x	3
Refurbishment actioners					
Laser □[10]~~[10]~~	x	x		x	5

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The actual bibliography is much richer than several presented examples, but they show already that it is possible to address with use of robots the needs identified in §2. In particular the Concentric Tube Robots □[7]~~[7]~~ and endoscopic laser pointing were identified as a good target for a preliminary experimentation on space industry component items (corresponding to maintenance targets A and B). The former one can be seen on fig.3 hereafter and the endoscopic laser pointing, equipped with light source and visual light camera is depicted below□[14]~~[14]~~:

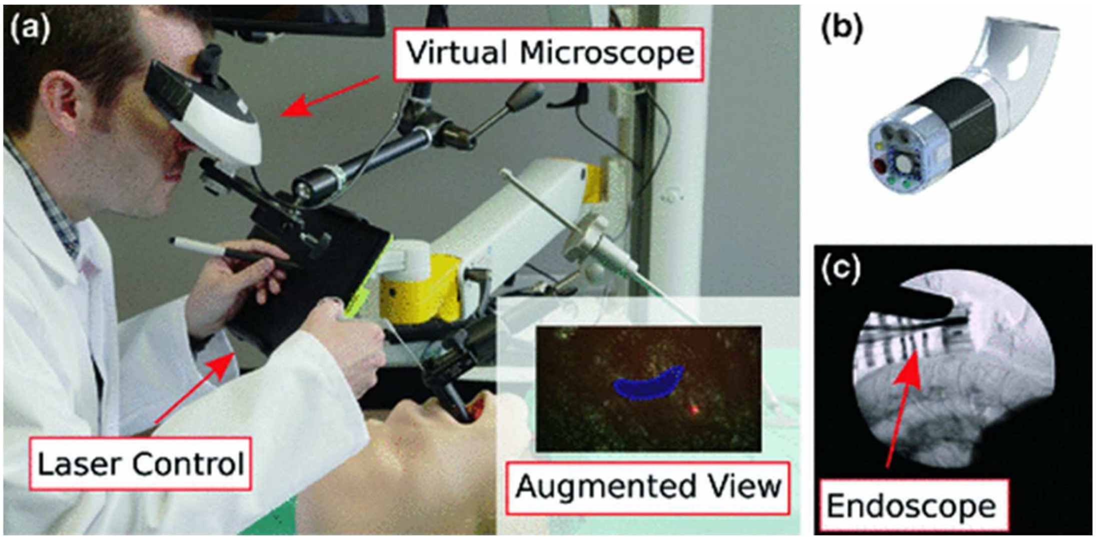

Figure 2 µRALP endoscopic laser

The bigger robotic systems (several dozens of centimeters) were not really a focus in this study despite their very high technical maturity, since the miniaturization limits were of the biggest interest.

Other robotic means represent lowest TRLs, typically addressing the inspection of very narrow, curved canals geometries over long distance. There are numerous problems to overcome their limitations in terms of instrumentation type that can be associated with such concepts and their technological contradictions (for example use of electromagnetic field for inspection of metallic pieces) even though the biomedical applications drive the development of that kind of nanorobots associated with inventive sensors (use in conjunction of X-ray and pressure sensor in □[20]~~[20]~~).

The actioners applicable for localized manufacturing are limited mostly to the application of lasers, even though there are trials to develop innovative solutions for microfabrication with micro-actioners such as wire construction □[15]~~[15]~~.

4. Additive manufacturing test item definition

With current demand for efficiency in material and energy usage, new manufacturing techniques such as Additive Layer Manufacturing (ALM) processes (also known as powder bed methods) are the subject of great current research interest. The materials that can be made through ALM processes are very different in nature. The essential principle of the process translates a 3D image held in a computer into a metallic part, with very low levels of wastage or final machining required. The processes have arisen from rapid prototyping, where a computer-aided design (CAD) model is created and formed into a solid part by adding layers (hence additive layer manufacturing, ALM). These methods were first applied to polymers, although some were adapted to produce as said metal parts. The powder can be recycled back into the process. The metal products could and can be used with efficient results in terms of thermo-mechanics properties and very interesting geometries and gain in mass and production costs. In rocket space domain the ALM is already in use and exploitation for example at RocketLab, Nasa, Spacex. According RocketLab,[21] all the essential components of the rocket have been 3D printed using the EBM (Electron-Beam Melting process). EBM uses an electron beam as the power source instead of a laser to 3D print metal. An electron beam melts metal powder layer by layer in a high vacuum and can achieve full melting of the metal powder. This method can produce fully dense metal parts and can retain the characteristics of the material. This method actually allowed the company to manufacture inexpensive engine parts, with a 24H printing time production for their main engine.

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In our case the ALM production is an opportunity in order to realize the NEMS and MEMS inspection robot's solutions and verify these new type tools and check at the same time the inner quality ALM production parts as future perspective realistic situation. The choice of the ALM production is determined by the fact that on one hand we would like to test in a challenging and innovative environment as specified in §2, on the other it is the simplest way to figure out the realistic specifications both for our space systems and potential robotic means.

The following specification had been proposed to test the inspection capacity for the benefit of Callisto and Prometheus project:

- Environment: ambient temperature, standard humidity foreseen inside the maintenance hall in the Guiana Space Centre : ~50%.
- Materials: Inconel Copper, Inox (engine), alloys of Al, Ti and carbon fiber composites for a stage.
- Geometries: holes mostly with diameters 5-10 mm, some specific holes are 2,5 mm.
- Inspection depth: 2 m max. (engines). Stages can require several dozens of meters.
- Curves : in the engine the curves can be up to 90° on very small distances (<2-5 mm, turbines blades)

The test pieces are as follows:

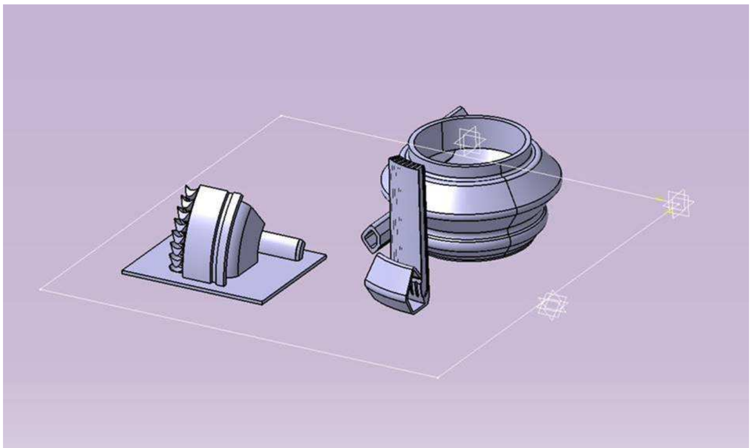

Fig.3 Inspection test pieces

They address the first two (out of 4) families of maintenance inspection problems identified in the previous chapter. The products showed in the figure 3 represent generic turbopumps parts, generative circuit parts and other sensitive components. They represent identified needs in terms of inspection for reusable engine between the flights.

5. Preliminary specification for inspection robot

The review of past lessons learned, the NEMS/MEMS state of art allows to propose the specification of the robot to be tested. For the 3 additively manufactured items (fig.3) it is foreseen to use the robot with concentric tubes (CTR) using the fiber camera, light source for visual inspection using the principle "follow the leader". The figure below depicts the example of such robot □[7][7]:

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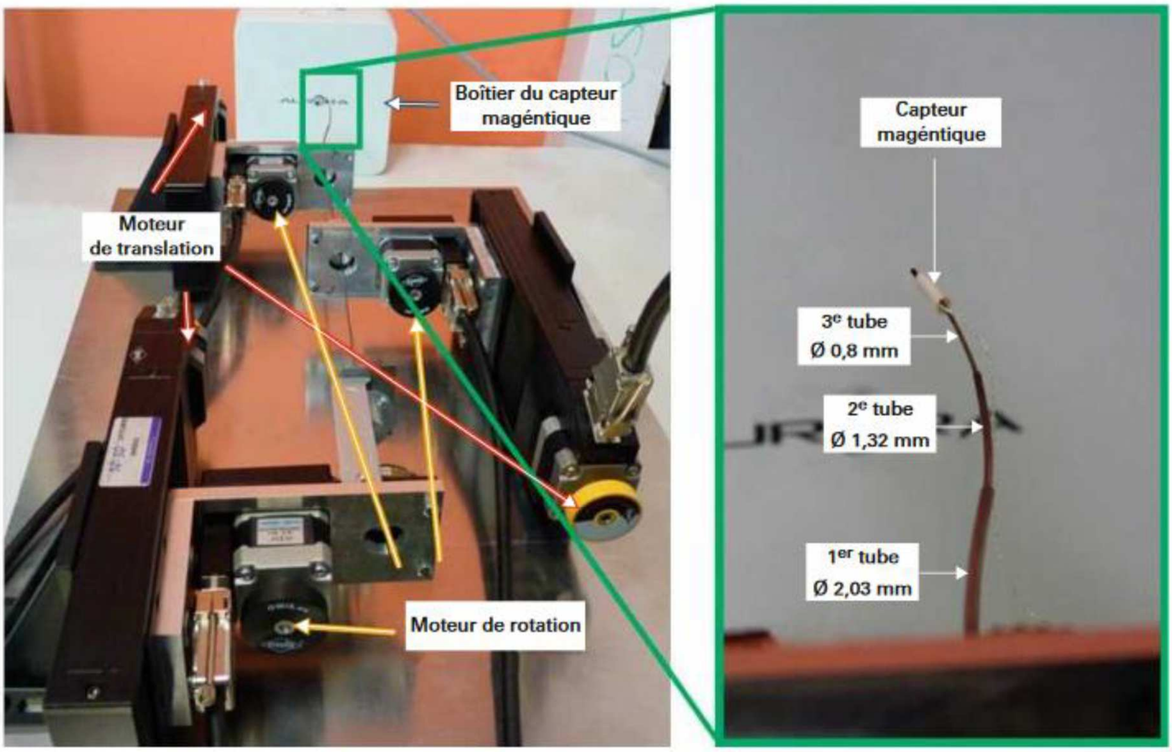

Fig.4 Concentric Tube Robot

The dimensions of the robot end part will be compatible with all those 3 items, but it would require to use different number of tubes for each application. The current capacity of CTR is 10cm max, its longer tubes could go to 2 meters corresponding to the target need, but the friction stresses become predominant in such a configuration while the tubes are motorized in such a way that they could move by torsion and flexion with respect to other tubes. The CTR robots are basically tele operated: the model of command is embedded in robot system to allow generating the required movements.

Existing solutions addressing all those needs show that there are no “showstopper” technological obstacles to resolve.

6. Preliminary test plan

The test plan for our robot solution is supposed to treat a wide feasibility study. The main objectives of the tests are:

- Use of MEMS and NEMS solutions in rocketry domain in the MRO asset for the first time
- Determine the consistency of the solution (displacement, vision and repair criteria) and improve the TRL
- Determine the feasibility inspection and repair solution for future RLV use and prepare the follow up demonstration
- Determine also an opportunity maintenance or inspection solution for the actual launcher expandable exploitation

In the §4 CAD drawings the major constraints and realistic geometries were introduced coming from our experience in Prometheus and other rocket propulsion engines. In addition to that the specific defects could be introduced for failures NDI testing, based on the past production, exploitation anomalies and critical points. Also the preexisting, non-ALM launcher representative pieces will be inspected for comparison.

The detailed content of the test plan is still under definition using this classical iter:

1. Analyze the robot inspection product
2. Design the Test Strategy (Risk analysis, test logistics and integrations and function analysis)
3. Define the Test Objectives
4. Define Test Criteria

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5. Resource Planning
6. Plan Test Environment
7. Schedule & Estimation
8. Determine Test Deliverables

To finalise it we have to further progress in ALM production (§4) and the test robot assembly (§5) which are necessary steps for our test campaign. Those are the objectives of the next months to be supplied for a test campaign that should start in late 2019.

7.Perspectives

The solutions developed in the framework of current experimentations could be further evaluated for Prometheus engine MRO. Callisto demonstration could use them to inspect the internal cavities of that reusable stage and consolidate its maintenance operations test plan during the test campaign in French Guiana.

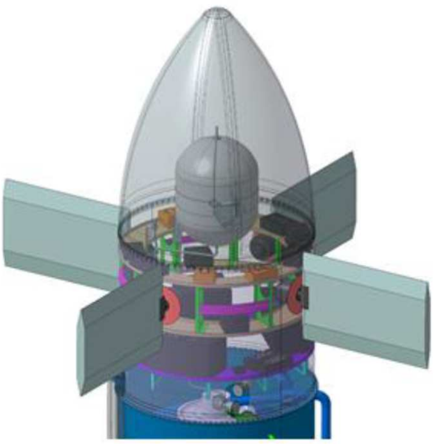

Fig.5 Callisto stage cavities

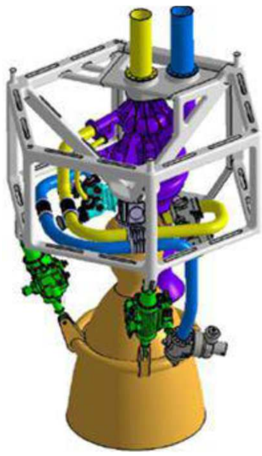

Fig.6 Prometheus engine

Fig.7 Ariane Next reusable stage

Future Themis reusable stage is supposed to take an advantage from Callisto to include even more ambitious demonstration of multi-engine bay inspection with objective to limit potential MAIT operations.

The specific solution for a 4th problematic of ground segment maintenance monitoring is to be yet defined, knowing that bibliography in §3 indicates very high TRL rich past experience on that subject (typically the pipe drones). The launch table with its chambers inerted and submitted to the ATEX environment is an interesting target for such future application. The solutions similar to autonomous small wheeled robots [6][6] could be further investigated in dedicated ground segment maintenance study.

The inspections of the very small diameter organs are a challenge for a future development of low TRL NEMS robotics. Going beyond inspection and being able to actually perform the localised repairs on inspected zones is also a difficult task considering current limited solutions.

8. Conclusions

The investigations performed up to now allowed us to define the potential robotic systems responding for all identified needs. In particular, the inspection of the engine fluid equipment's is specified with existing MEMS means, notably CTR robotic intelligent endoscope issued from biomedical domain. The performance of presented test plan with proposed specimens will allow confirming its operational applicability for RLV maintenance and could also bring solutions for actual expandable launcher systems production inspections and maintenance in launch campaign

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