REDEMPTION:
AN EXPERIMENT ON SOUNDING ROCKET TO TEST A SYSTEM FOR ACTIVAL DEBRIS REMOVAL – REXUS12

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ABSTRACT

REDEMPTION (REmoval of DEbris using Material with Phase Transition: IONospherical tests) is a student experiment aiming to propose a feasible solution for Active Debris Removal. Completely conceived, designed and realised within the Space Robotic Laboratory (SRL) of the second Faculty of Engineering of Bologna University "ALMA MATER STUDIORUM", REDEMPTION was selected to participate in REXUS/BEXUS 2012 Programme. This programme was realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload was made available to students from other European countries through collaboration with the European Space Agency (ESA). REDEMPTION experiment base-concept is definitely up-to-date, as at the moment space debris problem is one of the most challenging space research fields: currently the situation of debris population is quite critical, because every new collision produces at its time other satellite fragments, raising the total number of debris and making the probability of a new impact more likely (the Kessler- Syndrome). Due to the complexity of the task, no feasible solution has been found so far. One of the most critical aspects to be solved in debris removal framework is how to connect the debris to be removed to the cleaner satellite. On this matter, through REDEMPTION experiment, students aim to evaluate the feasibility of an ADR system based on a polyurethane foam. The foam under evaluation is generated starting from two liquid reagents, which need to be mixed to produce a polymeric structure that after a short time becomes solid and rigid. The opportunity to launch the experiment onboard REXUS rocket allowed verifying the behaviour of the foam in near space conditions, that is, milli-gravity and vacuum conditions. REDEMPTION flew in the space on board of REXUS12 Rocket on the 19th March 2012. In this paper the educational aspects of the project and the technical details regarding the three sub-experiments which constitute REDEMPTION module are depicted. As well, the results of the launch campaign are discussed, drawing the conclusions of the project.

INTRODUCTION

Space debris is an increasing problem[1]. The exponential increase of satellite launches in the last 50 years has determined the problem of space debris, especially in LEO. The remains of past missions are dangerous for both operative satellites and human activity in space. But not only: it has been shown that uncontrolled impacts between space objects can lead to a potentially dangerous situation . It is possible to reach a situation of instability where the big amount of debris could cause a cascade of collisions, the so called Kessler syndrome, resulting in the infeasibility of new space missions for many generations. Currently 19000 debris larger than 5 cm are tracked, while 500000 are smaller than 1cm. Leo polar orbit represents the most critical and risky area. In spite of that, the gravity of the situation and of the numbers listed above is offset by the apparent easy solution to the problem: recent studies indicates that to stop the population growth, it could be enough to remove only 5 big debris a year. Even if it could appear relatively a little effort with respect to the big amount of debris, recent technology did not enable active debris removal.

The project faces the problem of how to deorbit an existing debris, applying the studies about the use of polyurethane foam developed by Space Robotic Group of University of Bologna. The research is started with the Redemption experiment, part of last ESA Rexus program. The foam is composed by two liquid components that, once properly mixed, trig an expansive reaction leading to an increase of volume whose entity depends on the chemical composition of the two starting components. The idea is to create a link between the satellite and the object. [8]

MISSIONS CONCEPT

This ADR system is suitable to be integrated on satellites of different classes (from nanosats to big satellites). With the foam it is possible to plan 2 different missions of debris removal: controlled and not controlled removal mission. [6] [7]

Not Controlled Removal

The target of the "not controlled" removal consists in altering its passive deorbiting time: after the rendezvous maneuver, the debris is shooted with the ADR in order to attach to it a certain volume of expanded foam, as to increase its aspect - mass ratio (Fig.1).

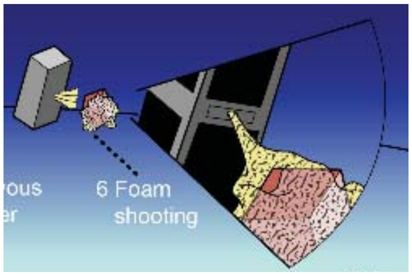

Fig.1 Example of debris capture

Thanks to the foam's property, in fact, it is possible to greatly increase the wetted surface area in relation to a minimal increase in mass. For this kind of mission it is necessary to define specific foam properties to maximize the expansion ratio reducing in that way the mechanical properties that are not relevant for the purpose. The reduction in terms of orbital decay time (t_f-t_0) is expressed by the following formulas (Eq.1 & Eq.2) in which it's possible to underline that it depends from the ballistic parameter B; r_0 is the starting orbit radius, H is the scale height of the atmospheric model, A is the wet surface, m is the mass, C_d is the drag coefficient and μ is the Earth gravity constant

$$(t_f - t_0) = \frac{H}{B\sqrt{\mu r}} \frac{1}{\rho(r_0)}$$

Eq.1 Orbit lifetime[2]

$$B = c_d \frac{A}{m}$$

Eq.2 Ballistic Parameter[2]

Controlled Removal

This kind of mission consists in creating a rigid link between the cleaner satellite and the debris. In that way it is possible to use the deorbiting devices of the cleaner satellite or, better , a dedicated propulsion system to accomplish the removal. In this case the foam is used to strongly connect the two objects after the rendezvous maneuver. It is obvious that the success of the link depends on the mechanical properties of the foam instead of the expansion ratio.

The great potential of this solution is due to the possibility to grab a moving object that cannot be controlled. Most of the problems of active debris removal solutions (above all robotic arms) are connected to the trouble in catching a spinning object: the foam technology allows to resolve these problems allowing to incorporate the object, whose spin can even promote adhesion of the foam.

THE FOAM

The system is based on a particular polyurethanic foam, developed especially for the purpose. The foam is generated by a chemical reaction of 2 liquid components. The product of reaction is CO_2, that allows to inflate the compounds, which expands. After the expansion, the solidification starts. The process of foam generation and formation is really rapid, and is completed in some seconds.

In order to test the capability of the foam to work in vacuum, a test was performed (Fig 2). The test consisted in realizing the reaction in a vacuum chamber and observing the result. The test gave two main results. First of all, it was confirmed the possibility to use the foam in space environment; then, the second finding, was that there is the possibility to modify the reaction to have different level of hardness of the foam, by the regulation of the quantity of gas produced by the reaction (Fig 3). [2] [3] [4]

The foam is produced by the reaction of two liquids mixed together. The speed of reaction and quality of the foam are influenced by the starting temperature of the reagents: this is why after several tests it has been decided to require 50°C at the moment of the fluid injection. The chemical formulation of the foam has been developed and calibrated by the producer, *Duna Corradini Group.*

The foam has never been space qualified, so it has been decided to test it on a sounding rocket programme. Rexus programme was very suitable for this purpose.

Fig. 2 Vacuum Test of the foam

Fig 3 *Chemical modification of the foam*

To evaluate the possibility to use the polyurethanic foam for grabbing the debris, an adhesion test was performed. This test has been performed on aluminium, the most common material space debris are made of. Two aluminium beams have been cross-linked together by casting on them the foam (without incorporating the beams, but just to verify the adhesion, see figure 4). The link was characterized by an interface surface of about 2000 mm^2. It has undergone subsequent load test, by increasing the suspended mass step by step. As a result, the maximum load supported by the link is about 6,3 kg.

Fig.4 Adhesion test in normal condition

In order to test the foam on a sounding rocket also a thermal test was performed, in order to ensure that the liquids would have survived to the climatic condition. The two reagents survived without problems the cold/hot cycle, passing fom -19°C to 70°. The cycle was repeated 3 times on the same samples. After the cycle, the reaction was started. resulting in a nominal reaction (Fig 5). [3]

Fig 5 Thermal test of the material

One of the liquids of the foam is very sensible to the humidity and the water. This was discovered during test campaign, in particular during the bench tests of the experiment. As mitigation to this possible problem, the experiment was assembled before the flight in a controlled humidity room.

FOAM RELASING SYSTEM

To test the foam in space, the foam was boarded on the Rexus sounding rocket, in frame of ESA Rexus/Bexus educational programme. [2] [3] [4] [5]

To test the material, a system for the automatic release of the foam was developed. The system called "test cell" (fig 7 and fig 8). Each test cell has its own not pressurized tanks, which are made from metallic material, separated from the other ones, and a double syringe. The syringe contains two reagents in separated containers and has a plunger that simultaneously pushes them out in a static mixer (provided my Maxver). The valves between the tanks and the mixers are important in order to avoid that reagents come in contact before the right time.

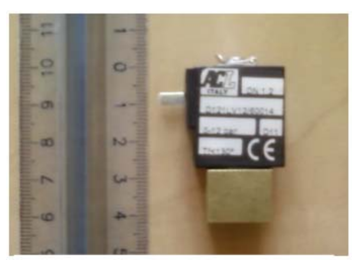

Fig.6 Electrovalves provided by ACL

A dedicated connector between the valves and the mixer was designed; it allows sending the two liquids from the syringes to the inlet of the mixer. The reagents are pushed out of the tanks using springs which are opened by thermal cut system. There is a safety dynema wire to keep the spring in position without applying force on the pistons. This is a redundancy system because the electrovalves (Fig. 6) are enough strong to support the pressure of the spring.

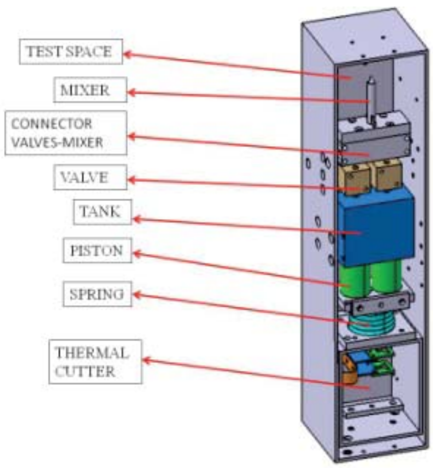

Fig 7 *Redemption foam Release system*

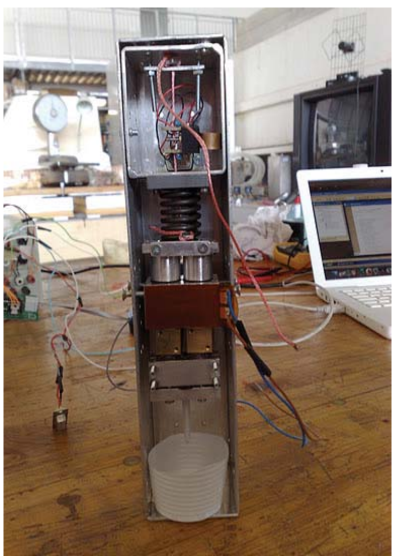

Fig 8 Prototype of test cell

Thermal cut is powered by battery pack. The liquids need to be heated to reach 50°C using a heating system powered by the external umbilical, for this the test cell were provided with kapton heaters film (provided by FrancoCorradi srl). These heaters are structured as a tape that had to be applied directly on the surface to heat. The power of the heaters was chosen to meet the operational conditions of the launch site; ESRANGE in Kiruna, where external temperature was expected to be between -10 and -20°C. For this reason, the heating system was tested inside a freezer. The heaters (Fig 9) had to rise the temperature of the liquids from -18 to 60°C. After the test, 60 Ohm heaters were chosen (15W for each one). Each test cell is aimed to test a different kind of foam with a different chemical formulation.

Fig. 9 Thermal control system based on kapton film

REDEMPTION MODULE

The REDEMPTION experiment module is composed by five Test Cell, with three different experiments. Inside the module there are four cameras to record the deploy and the evolution of the foam and thermal sensor to register the temperature of the foam. Three cameras are connected to an internal digital recorder and one camera to the tv channel of the rocket (fig 10).

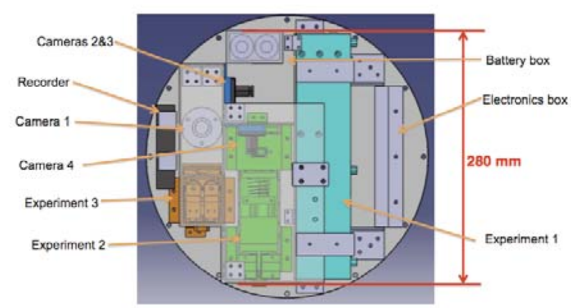

Fig 10 Overview of Redemption module from above

Three test cells are filled with three different kind foam with different proprieties. The aim of experiment is to evaluate the best expansion ratio and the speed of hardening of the foam. The expansion ratio is checked through the cameras and the hardening through the thermo sensor. The rigidity and the mechanical

properties of the foam depend on the temperature of the foam. Having data on temperature evolution means to have data on mechanical proprieties of the foam.
The second experiment consists in a free spray experiment where foam is sprayed in a free space to check the disposition of the foam. Basically the liquids, when are in space condition, without gravity, are disposed in bubbles. The foam starts its reaction and solidification in the same moment of contact between the liquids. It means that the foam just outside of the mixer, it is already under solidification. It is expected that, through this reaction, the foam will not assume a shape of a bubble just outside the mixer but that it will be possible to spray on the Plexiglas surface located at 5 cm from mixer. The importance of this instrument is that it will give data on the feasibility of an ADR mission with this system.
The last experiment consists in inflating a structure with the foam [5]. This structure is a kind of sock that allow the gases of the reaction to go out form the fabric, to guarantee that the inflation is provided only by the foam. In future, it may be possible to use foam to inflate larger structure.

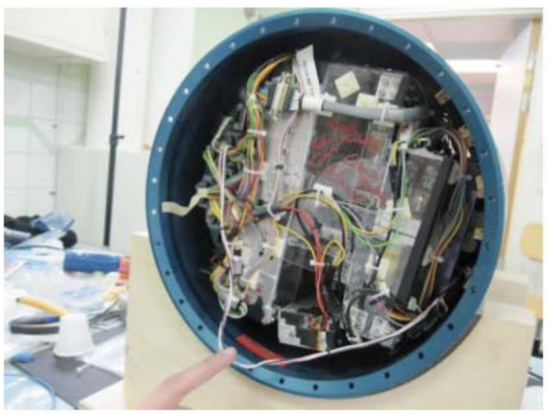

Fig 11 Redemption module fully integrated in the skin

The Redemption module (Fig 11) was also provided with a safety plug for the tests. Redemption is a “one shot” experiment. After the production of the foam, it has to be completely opened, cleaned and reassembled. The safety plug was used to avoid accidentally deploy of the foam during the tests (Fig 12).
The module was provided by an anti leak system. It was covered by polycarbonate around the test cell to avoid foam and liquid leakages. The polycarbonate (provided by Mareco plastic) was sealed. There was also a sponge on the bottom with the capability to absorb the entire amount of liquids present in the module. [2]

1 Fig 12 safety plug of Redemption

TESTS ON THE MODULE

Redemption experiment had to pass different tests to be integrated on Rexus12 sounding rocket.
The first test was the vibration test. Redemption module performed vibration test at ZARM Laboratory of DLR in Bremen. During this test the tanks of the foam were filled with water. Using water is a conservative way to make this kind of test, because water is less viscous and dense than the foam liquids: if water leakages were not registered, the experiments can be considered safe also for the foam. The vibration test went as expected,with no leakages detected; the experiment was ON during the vibrations, to simulate the launch conditions. During the vibration test, from the internal cameras of the experiment, also some videos of the vibrations of the test cells were recorded. The initial and last resonance vibrations were very similar. Only one screw from the video recorder (a commercial component of the experiment) was affected by vibrations. As a solution to this problem, all the screws from commercial components were glued and the test was considered as passed (Fig 13).
The integrations test was performed just after the vibration test. All the experiment of the rocket were integrated, and it was performed a cold countdown. Again all the part of the experiment were working nominally and there no conflict with others experiments or Rexus modules was detected.

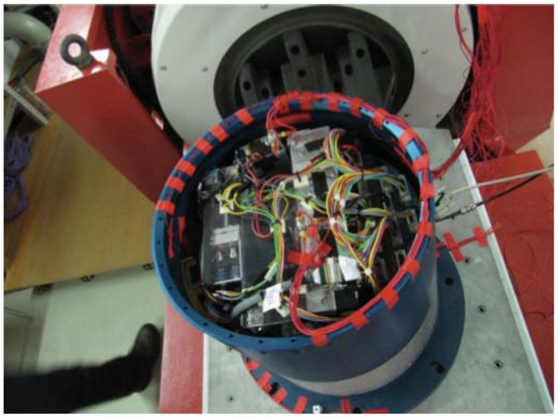

Fig 13 Redemption module at vibration test in ZARM

The bench tests were performed after a couple of week. This test gives a lot of important information about the liquids. The tests consisted in the integration of the payload with the service module and the recovery system, two cold countdowns and one “hot” countdown where all the experiments had to run. The test was in part failed because the liquids did not pass trough the electro valves. After an investigation it was discovered that the problems were caused by some water trapped inside the valves. The valves used during the bench tests were the same used during the vibration test, where water was used. The valves, after the vibration test, were dried but were not open. The little amount of water inside the internal pipes of the valves was enough to make a reaction with one of the two liquids and to stuck the fluids (Fig 14). During the bench test al systems worked nominally and the problem was just the reaction of the liquids with water, so there was no need to change the experiment design. For mitigate the humidity problem, it was decided to avoid any contact with water or humidity of the liquids and of all parts that had to be in contact with reagents. [2]

Fig 14 Effect of the humidity on one of the liquids

LAUNCH CAMPAIGN

REDEMPTION flown on board of Rexus12 on 19 march 2012. To avoid the humidity problems all the components that during the experiment had to be in contact with liquids was replaced with new components in a special room provided by SSC (Space Swedish Corporation). Redemption was totally dissembled and reassembled. In this room the humidity never exceeded the 15%. During the filling operation of the syringes only one person was present, to avoid the rise of the humidity level due to the number of people in the room (fig 15). [4]

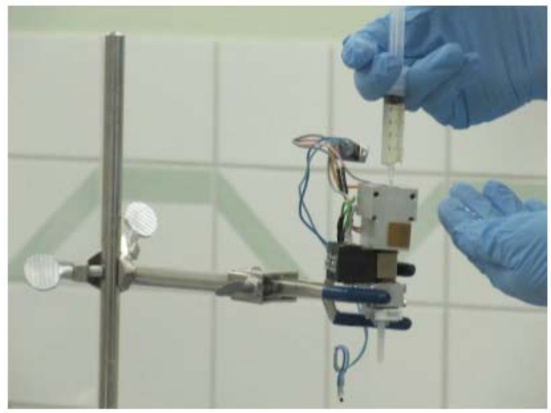

Fig 15 Selfshoot in dry room during the filling operations

Then, Redemption (Fig 16 and Fig 17) was integrated with the payload and sub systems of the rocket. It was performed a ground test before the integration of the engine and all was nominally. The launch window was scheduled three days after from the integration. During the Test Countdown Redemption lost the TV channel camera, which was working during the bench test. After a discussion it was decided anyway for the GO.

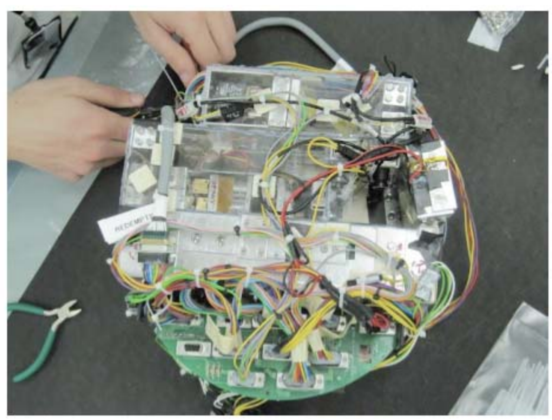

Fig 16 Redemption reassembly operations

During the pre launch the condition of the experiment were nominally. The temperature of the liquids were 60°C, thanks also to the hot air blower on Redemption module provided by SSC. During the countdown the signal to switch off the Redemption heater (powered by the umbilical) was delayed after the switching to internal battery of the rocket. It means that the internal rocket battery powered heaters of Redemption. This situation was meant to be avoided to not discharge the battery of the service module; during the preparation of the launch campaign it was indeed a requirement of the launcher. At the moment of LiftOff Redemption lost its telemetry that never came back during all the flight. Moreover Rexus12 (Fig 19) also showed problems. The recovery system did not work and the payload crashed instead of soft landing. From the analysis of the telemetry of the rocket it was clear that the problem on Redemption experiment was not due to a communication problem but to a failure on the Redemption power line.
After the recovery of the module it was possible to start an investigation. The structure of the experiment (produced by MCM spa) and the testcells survived to the crash. There were no leakages from the system. Test cells were still intact. To be sure that there were no problems of humidity some test cell were fired with success. The main board broke at the crash, but giving powering it directly from the cable of the module it was possible to detect a power consumption, so a problem in harness was excluded (Fig 18).

Fig 17 Payload of Rexus12 fully integrated

Moreover the camera that was not working during the test countdown was working after the crash.
The investigation did not show a reasonable cause of the power failure from the part of Redemption module. One of the possibility could be that the microcontroller did not survive to the G loads. Anyway the micro controller survived without problem to the vibration test and it was successfully used in previous REXUS missions.
On the digital recorder, the registration was interrupted just in the moment of the liftoff and it is not possible to see any vibration. Unluckily the micro controller was physically damaged by the crash and it was not possible to check it to rule out a failure at lift off.

Fig 18 Investigation after the crash: PCB damaged

CONCLUSION

Redemption experiment flown on board of Rexus12 rocket the 18th march 2012. Unluckily, the experiment lose the power at lift off. The analysis indicates that the rocket may had some malfunction, but it was not possible to find an exact cause of the issue.
In any case, the foam releasing system passed without problems all the test campaign before being accepted and integrated on the rocket.
The structure survived the launch and the crash, and after the recovery the mechanical system was still in working condition. The heating system also was maintained the temperature or the reagents before the launch as expected.The liquids did not create any problem to the rocket even after the crash, and the anti leak measures worked as expected.
Even if all the ground test show that the experiment can work, a test on milli gravity condition is still required to prove the feasibility of the ADR system based on polyurethanic foam. For these reason the team is still looking for a flight opportunity.

Fig 19 Rexus 12 Rocket

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