ACTIVE DEBRIS REMOVAL SYSTEM BASED ON POLYURETHANE FOAM

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ABSTRACT

Space debris is an increasing problem. 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 for civil people on Earth.

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 new technologies for the mitigation of space debris are under study: for what concerning the removal of debris the use of laser to give a little impulse to the object and push it in a graveyard orbit or to be destroyed in the atmosphere. Another solution is the use of a satellite to rendezvous with the space junk and then use a net to capture it and destroy it in the reentry phase. In a parallel way the research is addressed to the study of deorbiting solutions to prevent the formation of new space junk. The project presented in this paper 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. It is possible to perform two kind of mission:

1) Not controlled removal: the two components are designed to react producing a low density, high expanded, spongy foam that incorporates the debris. The A/m ratio of the debris is increased and in this way also the ballistic parameter. As a consequence, the effect of atmospheric drag increases and the orbit life time is reduced.

2) Controlled removal: the reaction of the two components leads to a high density, medium expanded, rigid foam. The idea is to create a link between the satellite and the object: in this case the deorbit is performed by the cleaner satellite propulsion, in a smaller time compared to the first configuration.

Several tests and designs are in implemented to achieve the goals of the research

INTRODUCTION

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 for people on Earth [1]. In this scenario 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 [2]. The space debris environment is routinely monitored by radar and optical observation systems (e.g. [3-7]). Currently 19000 debris larger than 5 cm are tracked, while 500000 smaller than 1cm are estimated. 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 could be enough to remove only 5 big debris a year. Even if it could be appear relatively a little regarding to the big amount of debris, recent technology didn't show yet the feasibility of removal. Many of these are now under study: one of that consists in the use of lasers to give a little impulse to the object and push it in a graveyard orbit or to be destroyed in the atmosphere [8-9]. Another solution is the use of a satellite to rendezvous with the space junk and then use a net or a robotic arm to capture it and destroy it in the reentry phase. Using nets or arms, the catching phase is complicated by the possibility of the debris to move freely. The technology presented in this paper is studied as a possible solution for space debris mitigation, permitting to perform many removal strategies. The reported results came from years of studies on polyurethane foam application for debris removal, started with Redemption experiment, part of ESA Rexus programme and led by the Space Robotic Group of the University of Bologna.

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THE FOAM

The system is based on a particular polyurethane foam, developed for the purpose. The foam is generated by a chemical reaction of 2 liquid components. The result of reaction is CO2 that allow to inflates the compounds, which expands. After the expansion, start the solidification. 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. The test consisted in realize the reaction in a vacuum chamber and observe the result. The test give two main results. The first one was confirming of the possibility to use the foam in space environment, the second one, unsuspected, 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 gasses produced by the reaction. [10][11][12]
The foam is produced by the reaction of two liquids mixed together (Figure 1). 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.*

Fig. 1 Vacuum Test of the foam

To test the possibility to use the polyurethane foam for grabbing the debris, was performed on adhesion test: The test has been performed on aluminium, the most common material of space debris. Two aluminium beams have been cross-linked together by casting on them the foam (without incorporating the beams to verify just the adhesion). 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 2 *Chemical modification of the foam*

In order to test the foam on a sounding rocket was performed also a thermal test to ensure that the liquids survive to the climatic condition. The two reagent supported without problems the cold/hot cycle, passing from -19°C to 70°. The cycle was repeated 3 times on the same samples and after made them react. The result was a normal reaction. [11]

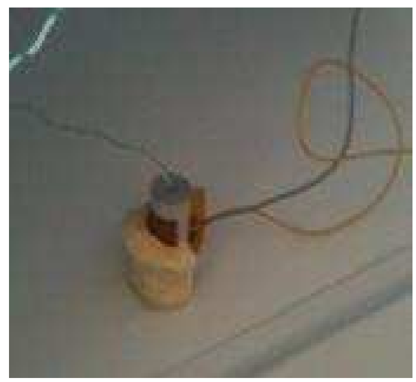

Fig 3 Thermal test of the material

ADR SYSTEM

To test the foam in space, the foam was boarded on the Rexus sounding rocket, in frame of ESA Rexus/Bexus educational programme. The name of the experiment was REDEMPTIOM ((REmoval of DEbris using Material with Phase Transition: IONospherical tests)). [10] [11] [12]. To test the material was developed a system for release automatically the foam.
The system called “test cell” had a sector in which the piston is actuated by linear springs, a sector containing the tanks of the two liquids with a heating syste,, an electronic valve and an expansion room for the foam.
The test cell is provided with its own tank, separated from the other ones, consisting in a double syringe (an heating system providing to keep the liquids at the operating temperature): it contains the two reagents in separated bodies, and has a plunger that simultaneously pushes them out. The valves between the tanks and the

mixers avoid that the reagents come in contact before the spring release time.
Redemption experiment flown on board of Rexus12 rocket the 18th march 2012. Unluckily, the rocket, had a malfunction and was not possible to deploy the foam. By the way the foam releasing system, passed, without problem, all the test campaign to be accepted and integrated on the rocket.

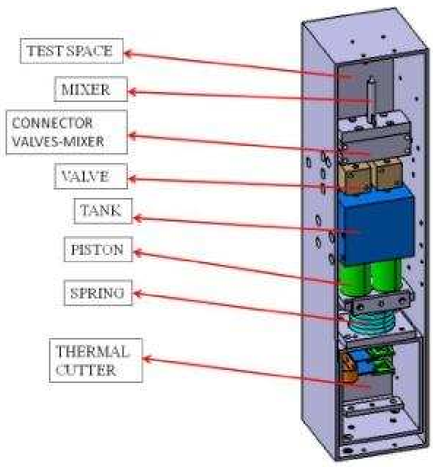

Fig 4 *Redemption foam Release system*

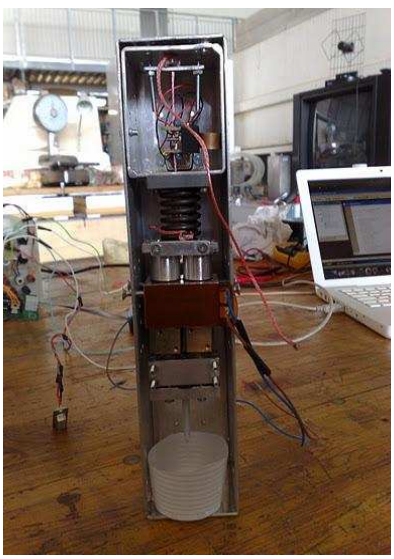

Fig 5 Prototype of test cell

Redemption experiment flown on board of Rexus12 rocket the 18th march 2012. Unluckily, the rocket, had a malfunction and was not possible to deploy the foam. By the way the foam releasing system, passed, without problem, all the test campaign to be accepted and integrated on the rocket.

Fig 6 Rexus 12 Rocket

CUBESAT MODULE

The possibility of in orbit testing of the system concept suitability and performance could be provided by boarding a sample of the developed foam and spraying system on a nanosatellite. Many university and research institution developed nanospacecraft for testing innovative technology in orbit, taking advantage of the low cost involved and the possibility of accepting some risks in the mission [13-18]. The wide spread of the Cubesat nanospacecraft standard enhanced the nanospacecraft mission performance further, lowering the cost and improving reliability, due to the system standardization and the possibility to perform multiple spacecraft launches [19-22].
Starting form Redemption, the foam realising system was engineered to be used like a foam sprayer for the space debris and to be boarded on nanospacecraft and in particular on Cubesats. The foam can be used as a space debris remediation system, based on the concept of drag augmentation [23]. The ADR system (figure 7) [10] consists in a mechanical device that performs all the required operation to shoot the foam against the debris. It's possible to identify four main parts: the first is composed of two separated tanks where the two liquid components are stored; the second is represented by the actuator system, composed by two plungers moved using a compression spring; the third consists of two electrovalves in order to control the spring activation, while the last part is a static mixer where the liquids are mixed and the reaction starts. When the system is engaged the spring is totally compressed and kept locked by the two electrovalves that also guarantee the isolation of the components from space vacuum. The two tanks are properly equipped with flexible thermal heaters in order to bring the two fluids at the correct temperature (~ 50°C) for the reaction before activating the system. [23]

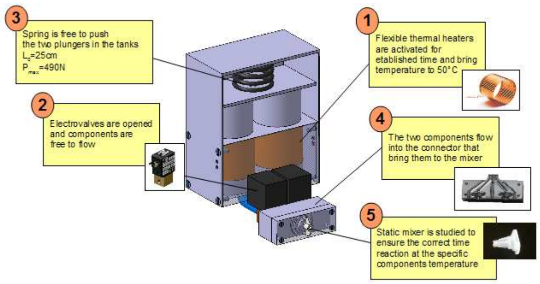

Fig 7 ADR System engineered for Cubesat Use

MISSIONS CONCEPT

This ADR system is suitable to be integrated on satellite of different classes (from nanosat to big satellite). With the foam it is possible to plan 2 different mission of debris removal. Controlled and not controlled removal mission. [25] [26]

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 increasing its aspect mass ratio (Fig.8).

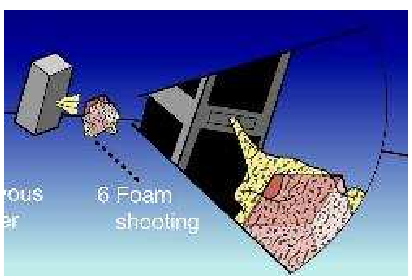

Fig.8 Example of debris capture[1]

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 [10]) in which it's possible to underline that it depends from the ballistic parameter B; where 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[10]

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

Eq.2 Ballistic Parameter[10]

It's important to understand the behaviour of the foam in vacuum condition and absence of gravity, designing the shooting system in order to obtain an omnidirectional expansion , creating a sort of baloon attached to the debris. For this solution has been defined a specific chemical formulation suitable to achieve the desired behaviour in space condition.

Also the quantity of foam has to be carefully established to avoid that the increase of volume ((and so mass) function of r^3) nullifies the increase of area (function of r^2): for each debris it's necessary to evaluate the tipping point in the aspect mass ratio growth. Despite that, one of the disadvantages of this solution is related to the fact that to deorbit big debris it's necessary a huge quantity of foam, increasing mass and costs of the mission. This kind of solution could be interesting for small debris. In that case would be possible to provide one big satellite of multiple ADR system, removing more debris with only one mission

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Controlled Removal

This kind of mission consists in creating a rigid link between the cleaner satellite and the debris. In that way it's possible to use the deorbiting devices of the cleaner satellite or, better , a dedicated propulsion system to accomplish the removal. In that case the foam is used to strongly connect the two objects after the rendezvous maneuver. In that case it's obvious that the success of the link depends on the mechanical properties of the foam instead of the expansion ratio. This kind of foam is the one designed for Rexus12 experiment (Fig.9).

Fig.9 Adhesion test in normal condition

The great potential of this solution is due to the possibility to grab a moving object that can't be controlled. Most of the problem 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.

In this kind of mission there are no limits to the size of the debris that, even if it's very large, can be attached with multiple cleaner satellite. In that way this technology can represent a great solution for space debris mitigation, helping to remove the 5 big debris a year that can stop the population growth [2].

It is clear that these procedure forces to sacrifices the cleaner satellite that has to be to deorbited with the debris, increasing in that way the incisiveness of costs to make multiple removals

CONCLUSION

The concept to use polyurethane foam to perform ADR mission or to make deorbit the space debris is demonstrated. The foam was qualified to fly on board of sounding rocket but still need to make a microgravity test. By the way the releasing system of the foam is ready to fly also on board of cubesat, and if the satellite will be provided of the necessary sensor to report the result, the cubesat can be a good platform for the space test of the system. If the test will show positive results it is possible to start a developing of the system for big satellite with lager operational possibility. The potential of this foam technology can drive multiple missions and solutions and put the bases of a new key technology for the Active Debris Removal.

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