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Simple and Small De-orbiting Package for Nano-Satellites Using an Inflatable Balloon

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The paper proposes a de-orbiting system using inflatable balloon especially dedicated for nano-satellites. The system consists of a balloon of laminated aluminum film, gas supply system and electronics system which inflates the balloon when a certain signal comes from the satellite at the end of its life time. The balloon, once deployed, keeps its shape even after the gas expires. The package can be very small, low-cost and requires very little power for activation, which makes this system very attractive especially for university education satellites for which the satellite weight/size as well as cost are major concern. The BBM system has been developed and several ground experiments have been performed including deployment in vacuum environment and thermal cycle tests. We recognized that this system concept is viable and very promising as a de-orbiting system in the future when the satellite is ordered to have some method to avoid becoming space debris.

Key Words: Inflatable System, De-orbiting System, Nano-Satellites, Debris Removal

1. Introduction

Space debris problem is getting worse and worse, and in near future, it may be required that every satellite should have a certain measure to de-orbit at the end of its lifetime and go into the atmosphere within a certain period of time such as 25 or 30 years. However, the stringent space, weight and power budget of micro/nano-satellites would make it impossible to implement thruster systems or other sophisticated de-orbiting mechanism on the satellites. CubeSats, which are 10 cm cubic satellites with 1 kg weight, are typical examples which will remain in orbit for very long time, sometimes more than a century, if without such "a de-orbiting system," and for which it would be almost impossible to implement any conventional de-orbiting systems like thrusters.

This paper proposes a simple, small and low power consuming de-orbiting system using an inflatable balloon, especially for 1kg CubeSat class to 20kg nano-satellites (Fig.1). The whole system is packed into a small case of less than 10cm x 10xm x 5cm (for CubeSat) or 18 cm x 18 cm x 5 cm size (for Nano-sat) attached to the satellite, with one power line connection to the satellite. During the satellite lifetime, the balloon remains folded with a special manner within the case, requiring no power. At the end of satellite lifetime, the satellite begins sending very small power to the de-orbiting system and this power is accumulated in a condenser inside the de-orbiting system. When the accumulated energy becomes a certain level, a gas cylinder's closed outlet is got open and a out-going gas unfolds and inflates the balloon. Then the balloon becomes a spherical shape with a certain diameter, and will remain its shape even after the inside gas goes off. This balloon reduces the ballistic coefficient tremendously and reduces the orbital life time less than, for example, 25 years. There are several methods proposed up till now to deorbit satellites after their life time, including electric dynamic tether or deploying a membrane type structure. Comparing with such methods, the important features of this system is its simplicity, low power consumption and low cost.

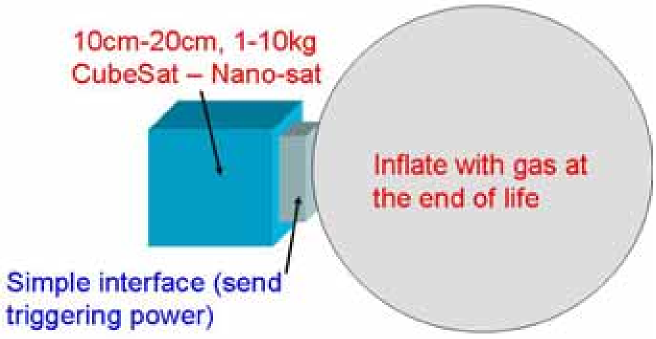

Fig.1. De-orbiting package using inflatable balloon.

The key technologies of this de-orbiting system include material of the balloon surface which can be folded and will keep its flexibility inside a small package during the satellite lifetime, and will remain its shape for several decades after deployment in the space environment, how to fold this balloon into the small volume, and how to control the deployment process including opening of the gas tank, gas pressure/flow control and opening of the package door, etc. These technological issues have been solved partly using ground based technologies and know-how of material vendors. Vacuum and temperature cycle experiments have been performed which showed very promising results as to the system under development.

2. Requirements for De-orbit Balloon Package

2.1. Balloon Size

Figure 2 shows the relationships between satellite weights, balloon size and the time to de-orbit from 800km altitude circular orbit. 10kg and 5kg represent typical weights for nano-satellites and 1kg for CubeSat respectively. In order to de-orbit 5kg and 1kg satellite within 25 years, the required diameter of the balloon should be 73 cm and 33 cm respectively. From these results, we set the target size of the balloon as 73 cm and 33 cm in BBM. For this calculation, the drag coefficient of the balloon is set at 2.2, and standard atmospheric density model is used.

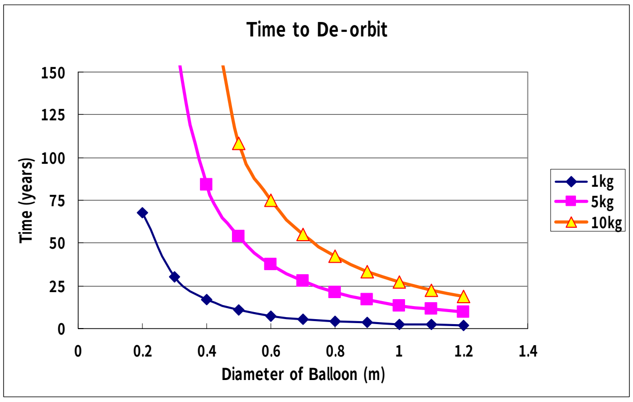

Fig.2. Time to de-orbit from 800 km altitude with various satellite weight and balloon size.

2.2. Package Size

The package size of the de-orbiting system should be as small as possible to make the impact on the satellite design small. For example, a package attached to CubeSat which is 10cm cubic size should preferably be 10cm by 10cm with 3-5 cm thickness. The gas storage and supply system with some electronics should be packed within this size.

2.3. Endurance against Thermal Cycle

The balloon is after deployment subject to thermal cycle on the orbit. As de-orbiting requires very large period such as 25 years or more, the number of thermal cycles which the balloon should survive will easily surpass 100,000. The balloon material and the way to make it rigid should be carefully selected so that the balloon shape can be kept under these thermal cycles. How to validate this endurability of the balloon is another big issue, because the test will require very long period and the mixture of various aspects of space environment is hard to simulate on the ground. For this reason, in-orbit demonstration and long term test would be highly desirable.

2.4. Reliability of the Total System

Finally, reliability of the total de-orbiting system should be considered. Especially, the reliability that the system does not deploy the balloon at the wrong timing is more important, because it changes the orbit during the mission period. However, this requirement can be mitigated for such satellite as educational ones which do not have so strong desire as to the orbit selection.

3. System Concept for De-orbiting Balloon Package

3.1. Overall System

Figure 3 shows one example concept of de-orbiting balloon package, which we have been using as BBM (Breadboard model). The package consists of gas tank with a certain gas to inflate the balloon, pipe and valve system, a folded balloon, some electronics system which triggers the inflating process when a certain command comes from the satellite, and some support structure. The folded balloon is stowed between the case and the cylindrical wall which constitutes a boundary between the surrounding balloon part and the central tank and electronics part.

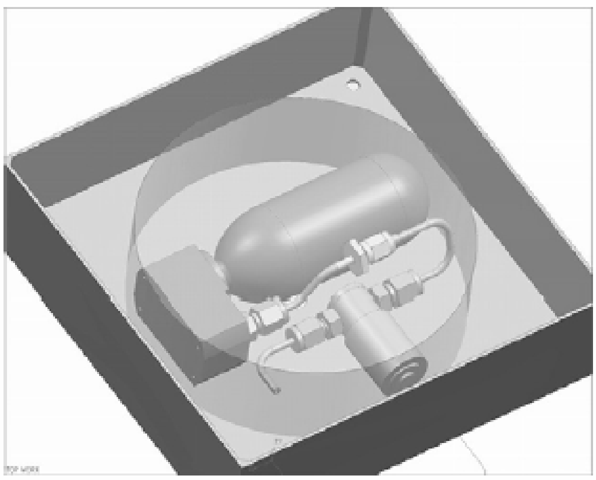

Fig.3. BBM for de-orbiting balloon package.

3.2. Inflatable Balloon Material

As the material of the balloon, we have selected laminated aluminum film. The laminated materials are Poli-Amid (PA) and Poli-Ethilen (PE). The layered structure of this film is described in Table 1.

Table 1. Laminated alminum film layered structure.

Material	Thickness (μm)	Density (g/cm^3)	Area Density (g/m^2)
Al	6	2.71	16.3
PA	15	1.14	17.1
PE	50	0.94	47.0
Total	71	1.13	80.4

This laminated film has the following preferable characteristics:

1) Low weight (only 135g and 28 g for ϕ73cm and ϕ33 cm balloon respectively)
2) Being airtight
3) Possibility to fold and deploy without severe damage
4) If a plastic deformation occurs at the end of the deployment with a certain level of inside pressure, then the balloon can keep its shape. The inside pressure to realize this plastic deformation is 3kPa for ϕ73cm balloon and 6kPa for ϕ33cm balloon.

3.3. The Way to Fold the Balloon

Figure 4 shows the folding lines for the ϕ73cm balloon. The balloon is made by connecting 8 streamline-shaped patches and two octahedron-shaped patches at north and south poles, just like a typical beach ball. The balloon is folded inside and outside reciprocally at the folding lines in Fig. 4. Fig.5 shows the midway, and Fig.6 shows the final shape of the folded balloon[1). As verified in the deployment experiment described later, this folding method is excellent in that it does not make the deployment process stacked at any point.

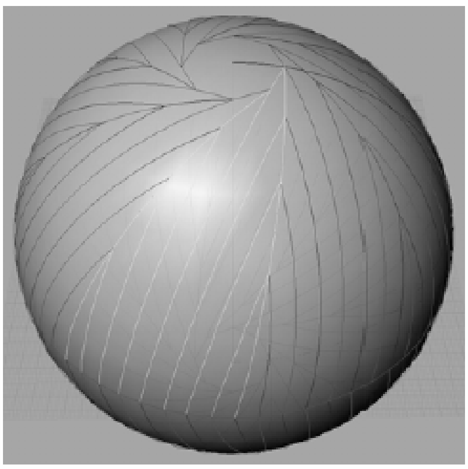

Fig. 4. Folding lines on the balloon.

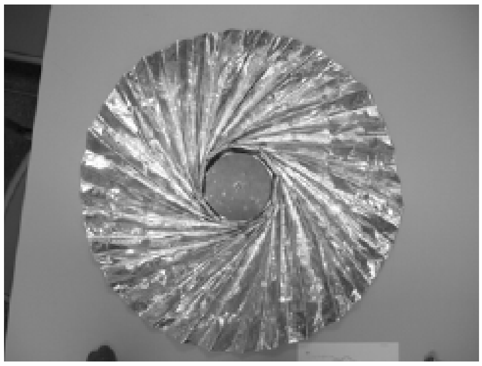

Fig. 5. Half folded/half deployed balloon.

Fig. 6. Fully folded balloon.

3.4. Gas Supply System

A small N_2 mini-cartridge tank which is typically used for beer server has been adopted in the first model. For ϕ73cm balloon, NTG off-the-shelf gas cartridge of 95 cc (initial inside pressure is 19.2-19.8 MPa) has been found suitable as it provides 9kPa pressure when the ϕ73cm balloon is fully deployed. Mass of the gas is 20.4g and the mass of the tank is 233g. The major issue in case of using this cartridge is that the initial tank pressure becomes very large, which bears the following problems;

1) Initial large pressure may make the deployment process too fast and give damage to the balloon material.

2) The cartridge should be fully closed during the satellite mission life, say for 2 to 5 years. If the inside pressure is large, it is difficult to close by electric valve, and so pyro-type valve would be required.

As to 1), a proper usage of orifice during the gas supply line is promising. As to 2), pyro-valve is not a good choice because it is very expensive as well as bulky and heavy. We have several alternatives for pyro-valve based system, and continue searching for the most appropriate choice.

4. Preliminary Ground Test

In order to examine the feasibility of the proposed system, we have conducted two preliminary ground tests: deployment test in a vacuum chamber and thermal cycle test in a thermal bath.

4.1. Deployment Test in a Vacuum Chamber

The objective of this test is to examine if a folded balloon can be smoothly deployed by the pre-specified gas pressure. Figure 7 describes the gas supply system for this experiment. In order to close the valve to shut the air stream from the high pressure N2 tank (19.2MPa), a piezo valve was used. This valve can be switched on/off with arbitrary interval, which make it possible to control the gas flow into the balloon. A vacuum chamber of the Department of Aeronautics and Astronautics, University of Tokyo was used. Figure 8 shows the experimental setup inside this vacuum chamber.

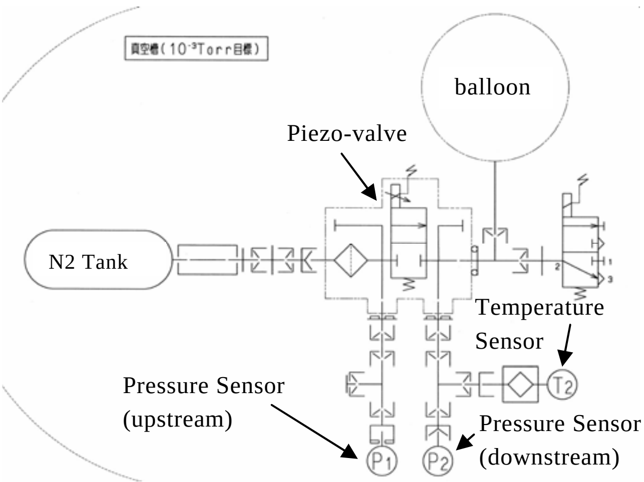

Fig.7. Gas supply system for deployment experiment.

Fig. 8. Setup inside the vacuum chamber.

The deployment experiment was conducted four times; two different gas flow settings for ϕ33cm and ϕ73cm balloons respectively. In the first run (case 1), the piezo-valve was kept open, which means the gas cartridge's initial high inner pressure is directly propagated into the balloon. In the second run (case 2), the piezo-valve was switched on/off manually to slowly deploy the balloon, with the objectives to find out the minimum flow rate to deploy the balloon without stacking. Figure 9 shows the history of balloon deployment for ϕ73cm in Case 1. The initial tank pressure is 16MPa and the final pressure in the balloon is 120kPa. The balloon deployment took about 0.7 sec.

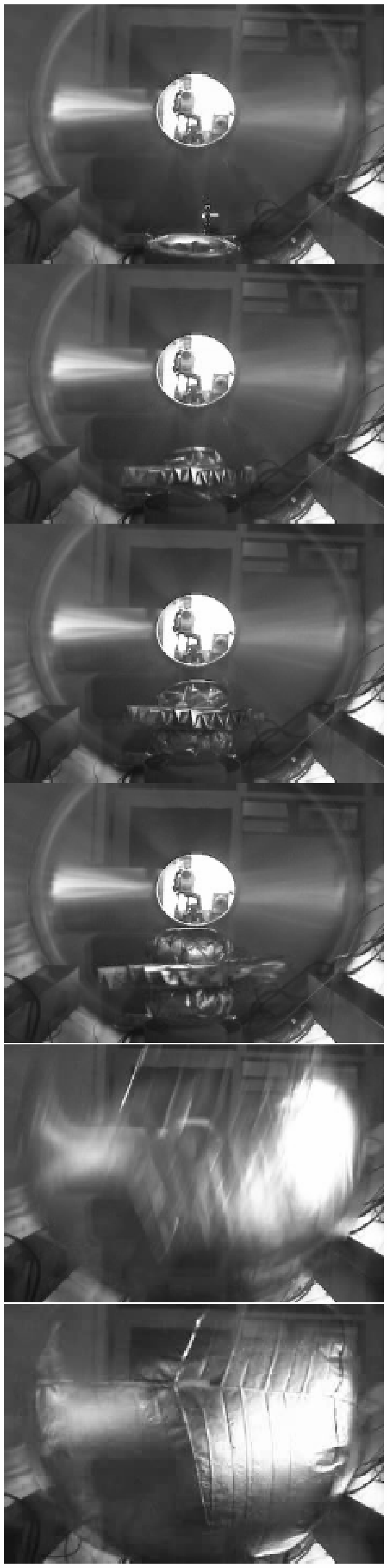

Fig.9. Balloon inflation process (ϕ73cm, Case 1).

Figure 10 shows the deployment process of ϕ33cm balloon in Case 1 and Case 2. From these experiments, we obtained the following findings.

Fig. 10. Inflation process of ϕ33cm balloon.

Left: Case 1
Initial tank pressure: 2MPa final pressure: 28kPa
Interval of photos: 0.2 sec
(at 0.6 sec, the connection between the balloon and the floor disconnected)

Right: Case 2
Initial tank pressure: 2MPa
final pressure: 10kPa
Interval of photos: 0.6 sec

1) The initial gas flow rate has significant effect on the balloon inflation speed. Without control of this flow rate, the balloon has inflated so fast just like explosion, which may give some damages to the balloon.
2) As to the final pressure inside the balloon, 10kPa is enough for ϕ33cm balloon.
3) The quicker the inflation process becomes, the more symmetrical the shape of the balloon becomes during the inflation process. This is because in the quick inflation the inertial force dominates the dynamics while the friction has larger effects in slow inflation.

It has been indicated that proper profile control of the flow rate (or pressure of the supplied gas) is required to secure the reliable and smooth inflation of the balloon.

4.2. Thermal Cycle Test

The balloon is subject to the long and many thermal cycles in the orbit. The inside gas will expire soon and so the balloon has no air inside for a long time. So we don’t have to worry about the effect of the inflation/condensation of the inside gas. However, the thermal cycles may exert inflation/condensation effect on the aluminum laminated film, which may change the shape of the spherical balloon.

We simulated the temperature changes of ϕ33cm balloon in orbit, assuming several parameters for the absorption (α) and emission coefficient (ε) of the aluminum laminated film. Emission coefficient is rather predictable, and it is set at 0.3 which is typical value for aluminum film. However, α depends on the surface status of the film, and is parameterized between 0.03 and 0.11. Table 2 shows the relationships between the maximum and minimum temperature of the balloon and the absorption coefficient (α) and the eclipse rate. Figure 11 shows the equilibrium temperature in direct sun-light for various α. As the shape of the object is spherical, the equilibrium temperature in the sun light does not depend on the sun angle, which coincides with the maximum temperature in Table 2 for 0 % eclipse rate. For 40 % eclipse rate, the maximum temperature is not so high as this equilibrium temperature for α between 0.03 and 0.07 because of the shortage of the sun-shining time. It should be noted that the lowest temperature depends on the orbit and so cannot be controlled, while the highest temperature can be controlled to some extent by designing α of the film.

Table 2. Balloon maximum and minimum temperature in 800km altitude Earth orbit (℃).

α	Eclipse 0%		Eclipse 20%		Eclipse 40%	
	Min	Max	Min	Max	Min	Max
0.03	5	5	-40	4	-67	-2
0.05	43	43	-22	43	-55	40
0.07	71	71	-12	71	-49	70
0.09	93	93	-5	93	-45	93
0.11	112	112	0	112	-42	112

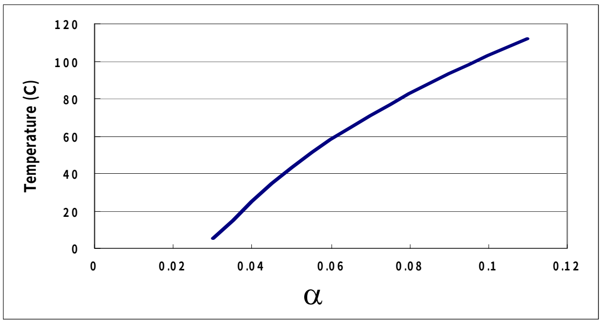

Fig. 11. Equilibrium temperature in sun light.

Figure 12 shows one example of the temperature change in orbit for a certain value of α, ε and eclipse rate. The temperature changes between -12℃ to 71℃ with cycle time of about 100 minutes. This value is used for the model of temperature change in the thermal bath experiment.

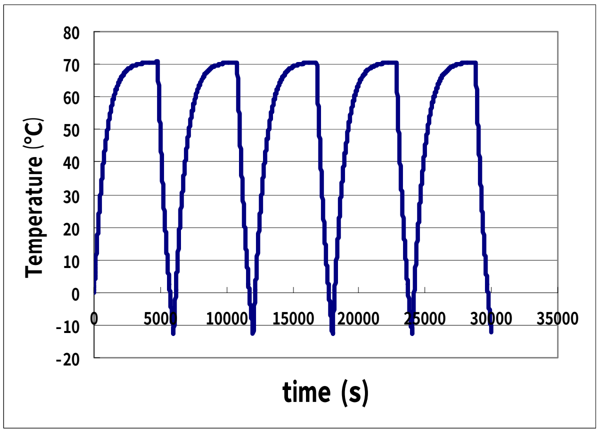

Fig.12. Temperature change of ϕ33cm balloon in orbit (ε:0.3, α:0.07, Eclipse rate:20%).

Figure 13 shows the change of the balloon shape before and after several hundred thermal cycles. The upper raw of pictures show the balloon at the maximum temperature timings and the bottom raw show that at the minimum temperature timings. The difference from the real situation is that there is air outside and inside the balloon. The figure shows that the balloon at highest temperature has larger wrinkles than the lowest temperature case. This seems to come from the difference of thermal extensibility of the three laminated materials (PA, PE and Aluminum) whose effect appears more in high temperature. However, long duration tests with far more cycles under vacuum environment would be needed to evaluate the thermal effect more precisely.

The balloon system should endure more varied space environment than mere thermal cycles. That includes 1) vacuum, 2) ultra violet ray, 3) radiation, 4) particles such as atomic oxygen, 5) debris, etc. It would be difficult or almost impossible to simulate on ground the complex space environments consisting of all of these aspects. Therefore it is highly required to have it tested in real Earth orbit for a long duration.

5. Conclusions

This paper proposes simple and low cost de-orbiting system for such nano-satellites that cannot implement de-orbiting thrusters or other sophisticated de-orbiting systems. Currently, even such satellites that do not have de-orbiting system can be launched into Earth orbit, but in near future, it may be highly possible that such satellites are prohibited to be launched. The proposed system provides one of very promising methods of giving chance to such satellites. The feasibility of exploding balloon with compressed air has been confirmed, and the next tests to do include in-orbit endurance test of the balloon shape under complex space environment. We plan to test the system in near future on nano-satellite developed by University of Tokyo.

References

1) K.Senda, et.al. Inflatable Deorbit Balloon Using Work Hardening of Metal-Laminated Film, *51st Joint Symposium on Space Science and Technology, JSASS,* Sapporo, 2007

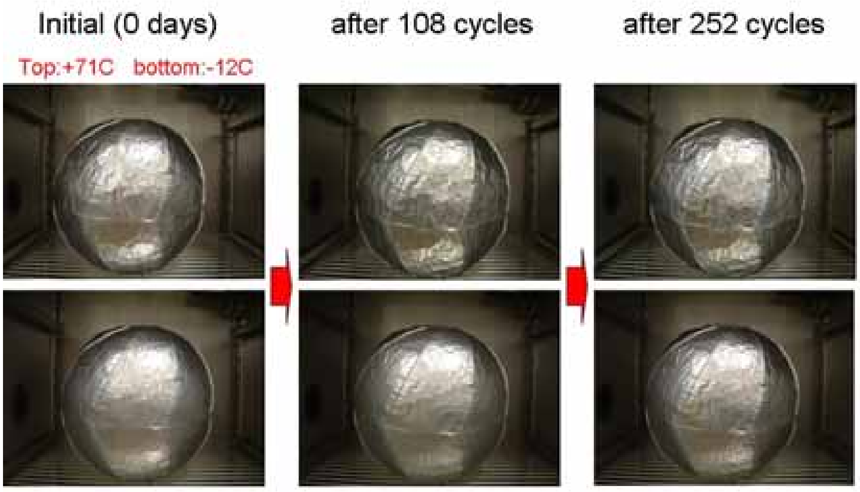

Fig.13. Change of the balloon shape in thermal cycle test.