Design and Verification of a Robust Release Mechanism for CubeSat Deployables

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***Abstract*—The design of a simple and reliable release mechanism for deployables on CubeSats is presented. The design relies on a thermal knife to sever a Dyneema thread, releasing a spring loaded deployable. Details of the design, technical challenges, and the results of in-orbit testing of the final design are described.**

***Index Terms*—deployable, nanosatellite, cubesat, satellite, burnwire, hot knife, thermal knife**

I. Introduction

Many CubeSats require systems to release deployable onboard systems such as booms, antennas, or folding solar panels. Traditional solutions using frangible or flammable materials, such as frangible bolts or paraffin actuators, used on larger spacecraft to trigger deployment, are not suitable for CubeSat applications when deployed from the International Space Station (ISS) [1], which requires astronauts to carry the spacecraft through crewed compartments. In this paper, the design of a simple and reliable mechanism for releasing spring loaded deployable systems on CubeSats is described. Before launch, the deployable feature is held in a stowed position by a Dyneema thread. When the release mechanism is activated, a thermal knife is powered, melting the thread and allowing deployment. Successful deployment is verified by the release of a microswitch otherwise held closed by the stowed deployable. Threads and thermal knifes are often used to secure deployable features on CubeSats, however, material selection and physical design vary somewhat [2]–[4]. Justification for the choices made in this design are given. The final design was tested in orbit for the application to deploy a fluxgate magnetometer boom on the Experimental Albertan Satellite #1 (Ex-Alta 1) CubeSat. Technical challenges encountered and potential improvements for the design are discussed.

II. Mechanical Design

The release mechanism, illustrated in Fig. 1, holds the stowed deployable in a machined cradle made with glass fiber reinforced polyether ether ketone (PEEK) plastic. The cradle is fastened, using stainless steel machine screws, to a PCB substrate that is mounted on the outside face of the spacecraft. Each end of the Dyneema thread is held securely between two pairs of stainless steel washers. The thread runs from the first pair of washers, underneath the thermal knife element, over the deployable, and through a small stainless steel eyelet, to the other pair of washers. The eyelet ensures that the tension on the thread leaving the pair of washers is primarily parallel to the surface of the PCB. To add redundancy, several threads can be used. The spring force of the deployable feature holds the thread firmly against the thermal knife to ensure good thermal contact.

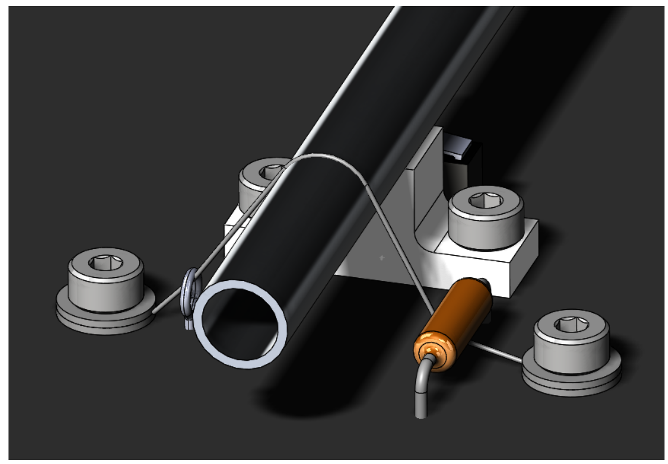

Fig. 1. Rendering of the deployment mechanism.

TABLE I
Material properties for thread selection

Material	*Longitudinal Tensile Modulus*	*Longitudinal Tensile Strength*	*Melting Point*
Kevlar (49) [5]	154	2800	550
Kevlar (29) [5]	61	2800	450
Dyneema [5]	115	3500	150
Nylon-6 [6]	2 ~ 4	45~90	220
	(GPa)	**(MPa)**	**(°C)**

III. Thread Design

Several materials were considered for the thread including Dyneema, Kevlar, and Nylon. The melting point, tensile strength, and longitudinal tensile modulus of each of these materials, summarized in Table I, were considered.

Dyneema thread has a high tensile strength, and has a relatively low melting point of 150 °C. These qualities make Dyneema an appropriate material for this application. In particular, a low melting point makes it easier for the thermal knife to cut the thread without risking thermal damage to nearby components on the spacecraft. A higher tensile modulus such as that of Kevlar (49) is desirable to minimize stretching of the thread while the deployable is stowed, but the high melting point of Kevlar make it an unsuitable choice. Dyneema has some sensitivity to degradation from prolonged atomic oxygen (AO) exposure [7]. In most cases deployable systems such as antennas are released promptly after the initial deployment of the spacecraft, minimizing the risks of premature deployment due to AO effects. In applications where significant AO exposure will be a major concern, alternative thread materials should be investigated.

A. Release Verification

A microswitch is fastened directly behind the PEEK cradle with stainless steel machine screws, underneath the stowed deployable. The microswitch, which supplies digital signaling to a microcontroller. is held closed by the deployable until it is released. After receiving the signal from the opened switch or a time-out, the microcontroller turns off the thermal knife. This event can be recorded in the telemetry data. The microswitch should be carefully positioned to maximize travel of the switch lever, reducing the risk of the switch opening erroneously due to small movements of the deployable prior to its release.

IV. Thermal Knife Design

To release the stowed deployables, electrical current is supplied to the thermal knife. Ideally the thermal knife should quickly become hot enough to cut the thread, but never get hot enough to risk damage to the rest of the spacecraft. An ideal system should quickly achieve the melting temperature needed to sever the thread, avoid failure from prolonged actuation, and not cause thermal damage to surrounding components. Four different thermal knife solutions were considered including Nichrome wire, epoxy coated helical metal film resistors, silicone coated helical metal film resistors, and self limiting positive temperature coefficient (PTC) heaters. The strengths and weaknesses of each of theses options are discussed in this section.

Out of the four options considered, the best solution was the silicone coated helical metal film resistor because it is easily mounted on a PCB substrate, is convenient for wrapping the thread around, and minimizes the potential for thermal damage. The power supplied to the resistor should be sufficient to ensure prompt deployment but low enough to avoid damage. This may require some experimentation in individual applications.

A. Nichrome Wire

Nichrome wire is widely used as a thermal knife for deployables. The lack of insulating coating allows excellent thermal contact between the Nichrome wire and the thread. However, Nichrome wire is fragile and difficult to fasten securely because traditional solder will not bond well to Nichrome wire.

B. Self-limiting PTC Heater

Self limiting PTC heaters passively converge to a calibrated temperature and are typically used for prolonged heating applications [8]. In nominal operation, a PTC heater should naturally maintain it's temperature within a safe operating range, reducing the risk of damage to the spacecraft from excessive heating. However, the gradual convergence to a set temperature results in unacceptably slow deployment on the order of $10 \sim 20\,\mathrm{minutes}$. This will result in additional heating of sorrounding components that are otherwise protected by interfaces with low thermal conductivity. It may also be problematic if the energy required to power the heater over a long period is significant compared to the small battery capacity of the CubeSat.

C. Epoxy Coated Helical Metal Film Resistor

Thru-hole helical metal film resistors are an attractive option because they are widely available, easily mounted on a PCB substrate, and are conveniently shaped for wrapping a thread around. The epoxy coating on the outside surface of the resistor increases the thermal resistance between the resistor and the thread. To quickly achieve the desired temperature at the surface of the epoxy coating within an acceptable time period, the helical metal film should be sufficiently hot. This high heat can cause warping or melting of the epoxy coating making this option unsuitable.

D. Silicone Coated Helical Metal Film Resistor

This solution is similar to epoxy coated helical metal film resistors, but with a silicone coating more tolerant of high temperatures. These resistors are typically intended for high temperature applications and in some cases are rated to operate up to $230\,^{\circ}\mathrm{C}$ [9]. This increased temperature tolerance reduces or eliminates warping or melting of the coating due to excessive heating of the internal helical metal film. The operating point (resistor value and supply voltage) should be carefully chosen to avoid excessive heating.

The specific component we used was CPF182R000FKE14, an $82\,\mathrm{ohm}$ resistor manufactured by Vishay with a power rating of $1\,\mathrm{W}$. To ensure rapid melting of the thread, allowing a short duty cycle, we exceed the $1\,\mathrm{W}$ rating. With a maximum supply voltage of $16.8\,\mathrm{V}$, the maximum power dissipation was $3.5\,\mathrm{W}$.

V. Technical Challenges and Considerations

Deployable release mechanisms should be simple and reliable. Thorough testing is needed to uncover weaknesses in the design. In this section, some problems and significant considerations concerning that arose throughout the evolution of the design are discussed.

A. Powering Resistors Beyond their Power Rating

In general, the power rating of resistors is chosen by the manufacturer to ensure safe operation in normal ambient thermal conditions. To achieve sufficient heating (which would be excessive in the typical application of resistors as components in a circuit) using regular through-hole resistors, it is typically necessary to power the resistor beyond the manufacturer's recommended power rating. This increases the likelihood of the component failing. This problem is reduced with the use of Silicone coated resistors that are specifically intended for demanding, high heat applications and therefore have a greater tolerance for excessive heating and therefore typically have much higher recommended power ratings. Depending on the application, it may still be necessary to exceed the recommended power rating, but the risk of failure is still significantly reduced by using components designed for high heat applications. In our design, using an $82\,\mathrm{ohm}$ resistor with a power rating of $1\,\mathrm{W}$, the maximum power dissipated by the resistor was $3.44\,\mathrm{W}$, assuming a maximum supply voltage of $16.8\,\mathrm{V}$.

B. Thread Beading and Catching on Eyelets

Our initial design had an eyelet between the resistor and the deployable, minimizing the mechanical load on the resistor, but causing deployment failures during testing. As the Dyneema thread is melted by the thermal knife, the molten polymer accumulates on the severed end of the thread and hardens. If the thread then passes through an eyelet, this excess material may catch on the eyelet, preventing deployment. This issue also poses a risk to deployables that are very thin, or that have sharp edges that could easily catch or hook onto the excess material. The configurations shown in Fig. 1 and Fig. 2 are designed to be immune to this potential problem. Anyone attempting to reproduce this work should take care to do the same.

C. Heat Damage to PCB Substrate

During prolonged heating of the hot knife, thermal damage to the surrounding area is a major concern. The PCB substrate surrounding the hot knife, and the solder joints holding it in place are vulnerable to excessive heating. To minimize this risk, materials with a higher melting point such as polyimide PCB substrate are worth considering.

D. Failure of Release Verification Microswitch

This deployment release mechanism was tested in orbit aboard the Ex-Alta 1 CubeSat. This satellite had nine deployables including four antennas, four needle Langmuir probes, and an elbowed fluxgate magnetometer instrument boom [10] which were all held in place whilst stowed using the deployment system described here. Deployment occurred nominally except for issues with the microswitch which was intended to detect deployment of the elbowed fluxgate magnetometer boom. Fig. 2 shows a cross-sectional view of the elbowed boom in its stowed configuration. One possible cause for this failure was stretching of the Dyneema thread which resulted

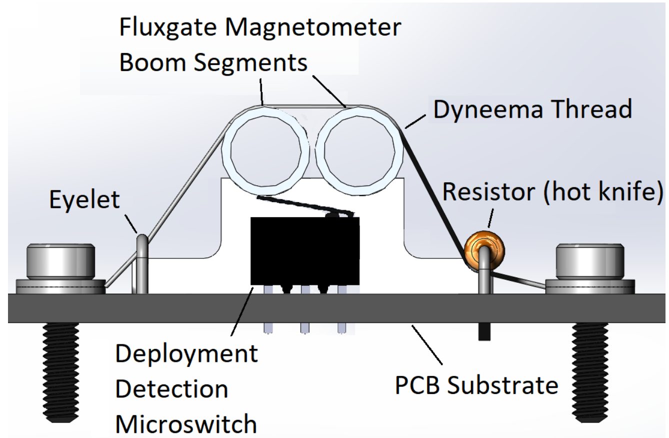

Fig. 2. Cross-section of the stowed elbowed boom

in a release of the microswitch, implying boom deployment, whilst the boom in fact remained stowed. The tension on the thread arising from the deployment springs on the magnetometer boom was higher than that of the other deployables, and securing the two elements of the boom required a longer thread. These factors would have increased the possibility of the thread stretching, potentially resulting in the microswitch falsely reporting that deployment had occurred. One way to mitigate this issue in the future is to add a feature that will maintain tension on the thread, absorbing any slack caused by stretching. Dyneema fiber has a negative coefficient of thermal expansion [11] so lengthening due to heating is not a likely cause of this issue.

VI. Potential Improvements

A. Solder and Substrate Selection

Selecting a thread material with a suitably low melting point does reduce the risk of thermal damage to surrounding components by reducing the heat required from the hot knife. However, if actuation is prolonged (on the order of tens of minutes) due to environmental factors or malfunction, it is possible that thermal damage will still occur at the mounting points of the thru-hole resistor. To avoid this problem, it would be ideal to select solder (such as pure lead) and PCB substrate material (such as polyimide [12]) with sufficiently high maximum operating temperatures. These maximum operating temperatures should be equal to or higher than the $230\,^{\circ}\mathrm{C}$ maximum operating temperature of the silicone coated hot knife resistor.

B. Locking Resistor Leads

If excessive heating causes the solder to melt, it is possible that the resistor will separate from the PCB substrate. To avoid this risk, a resistor with formed locking leads, as shown in Fig. 3 could be used to increase the force needed for separation, making the design more reliable. Alternatively, the resistor leads could be looped through a second set of mounting holes as shown in Fig. 4. Although we haven't tested this, it may also improve durability if the resistor is secured using high temperature epoxy as shown in Fig. 5 on both end faces of the resistor.

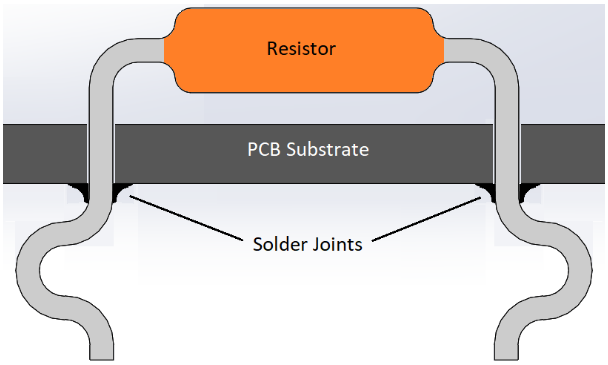

Fig. 3. Through-hole resistor with formed locking leads

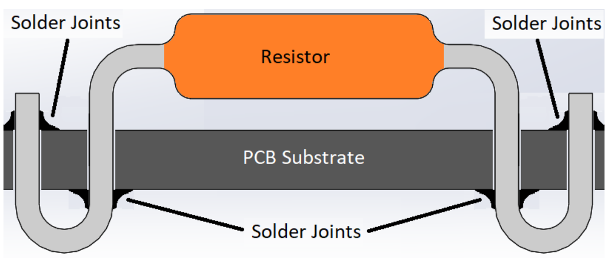

Fig. 4. Through-hole resistor with additional mounting holes to improve durability in-case excessive heat causes the solder joints to melt

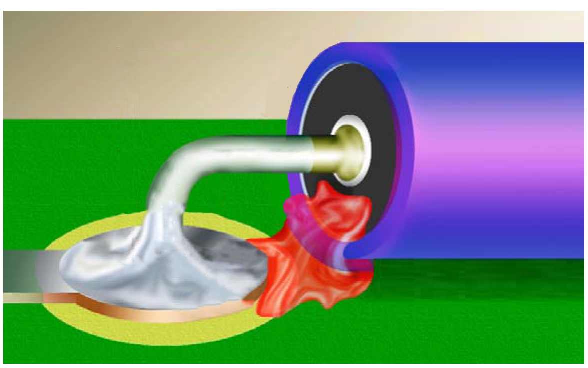

Fig. 5. Through-hole resistor with high temperature epoxy on both end faces (adapted from [13])

VII. Conclusion

The design presented here represents a low cost and low risk, space validated, design for the release of deployable systems on nanosatellite and CubeSat applications. The design may have widespread utility for low cost CubeSat projects such as those being developed by University student teams. The risk of thermal damage to surrounding components on the spacecraft is minimized by using a thread with a relatively low melting point.

One release verification sensor comprising a microswitch was prematurely triggered on-orbit prior to deployment, most likely as a result of stretching of the thread holding the boom in place before deployment. This weakness could be mitigated be including a feature to maintain tension on the thread. Further improvements are possible with more exhaustive consideration of material properties and mechanical design.

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References

[1] T. Prejean, "NanoRacks cubesat deployer (NRCSD) interface definition document (IDD)," NanoRacks, Tech. Rep. NR-NRCSD-S0003, Jun. 2018.

[2] G. F. Brouwer, W. J. Ubbels, A. A. Vaartjes, and F. T. Hennepe, "Assembly, integration and testing of the DELFI-C3 nanosatellite," in *59th IAC*, no. IAC-08-D1.5.6, Glasgow, Scotland, Oct. 2008.

[3] S. Jeon and T. W. Murphey, "Design and analysis of a meter-class cubesat boom with a motor-less deployment by bi-stable tape springs," in *52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Denver, CO, 2011, pp. 1–11.

[4] K. Nakaya, K. Konoue, H. Sawada, K. Ui, H. Okada, N. Miyashita *et al.*, "Design & development of flight model and future plan," in *21st International Communication Satellite Systems Conference and Exhibit*, Yokohama, Japan, 2003, pp. 1–10.

[5] J. Pilling. (2006, Apr.) Mechanical properties data. Dept. of Metallurgy, University of Manchester. [Online]. Available: http://www.mse.mtu.edu/ drjohn/my4150/props.html

[6] (2003) Young's modulus - tensile and yield strength for common materials. Engineering ToolBox. [Online]. Available: https://www.engineeringtoolbox.com/young-modulus-d_417.html

[7] M. M. Finckenor, "Comparison of high-performance fiber materials properties in simulated and actual space environments," Marshall Space Flight Center, techreport, Jul. 2017.

[8] S. Azechi and T. Nakamura, "Electrically conductive silicone rubber composition," US patentus 6 734 250B2, May, 2004.

[9] "Metal film resistors, axial, industrial power, precision, flameproof," Vishay Dale, Tech. Rep. 31021, Dec. 2016.

[10] D. M. Miles, I. R. Mann, M. Ciurzynski, D. Barona, B. B. Narod, J. R. Bennest, I. P. Pakhotin, A. Kale, B. Bruner, C. D. A. Nokes, C. Cupido, T. Haluza-DeLay, D. G. Elliott, and D. K. Milling, "A miniature, low-power scientific fluxgate magnetometer: A stepping-stone to cube-satellite constellation missions," *Journal of Geophysical Research: Space Physics*, vol. 121, no. 12, pp. 11,839–11,860, 2016.

[11] A. Yamanaka, T. Kashima, M. Tsutsumi, K. Ema, Y. Izumi, and S. Nishijima, "Thermal expansion coefficient of unidirectional high-strength polyethylene fiber reinforced plastics at low temperature," *Journal of Composite Materials*, vol. 41, no. 2, pp. 165–174, 2007.

[12] "85n polyimide laminate and prepreg," Arlon EMD, Tech. Rep., 2009.

[13] *Workmanship Standard for Polymeric Application on Electronic Assemblies*, NASA Std. NASA-STD-8739.1A, Rev. 2, Mar. 2011.