A reusable SMA actuated non-explosive lock-release mechanism for space application

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\textbf{ABSTRACT}
After the satellite is launched with the carrier rocket, it is necessary to separate the satellite from the rocket at an appropriate time to ensure that the satellite enters the intended orbit. In this process, it is vital to ensure a reliable connection and accurate separation. With the increasing use of microsatellite in orbit, the contradiction between the shock of separation and the requirement of the platform’s dynamic environment is becoming increasingly prominent. Therefore, the traditional pyrotechnic separation device can no longer meet the requirements.

This paper presents a reusable non-explosive release actuator using shape memory alloy (SMA) wire for high load and low shock. The system is based on the Fast Acting Shock-less Separation Nut (FASSN) technology. Using the shape memory effect of SMA, a biased SMA wire trigger has been developed, which is used as the driver source of the actuator. At the moment of receiving the electrical signal, the SMA wire generates stress and deformation. The trigger set free the constraints on the mechanical components, and the target is released. Experimental results indicate that the trigger device can unlock successfully and well meet the technical objectives.

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1. Introduction

The lock-release mechanism is a widely used device for spacecraft to accomplish related tasks. Their main function is to fix the movable payload, deployable accessories and separable tasks during the launch process, such as the separation of fairing, antenna deployment, solar array deployment and cabin separation, etc [1]. The spacecraft can only work normally after releasing. The lock-release device in this paper combines with the clamp-band system to lock the cabin section, wherein the upper frame is the cabin and the lower frame is the rocket, and the connection form is shown in Figure 1.

At present, most of the locking and releasing devices used on spacecraft are powered by pyrotechnics, represented by explosive bolts and cutters. The pyrotechnic device has an apparent unlocking impact during the action, and the device can only be used once [2], which has potential safety hazards. At the same time, it has many disadvantages, such as free matter produced by the explosion, inconvenient storage, and transportation, etc. With the development of precision payloads, the size of satellites has gradually been miniaturized and components have been concentrated in a limited space, which is very sensitive to vibration and shock. In order to overcome the limitations of traditional pyrotechnic devices, many countries have successively carried out research on non-pyrotechnic locking and releasing mechanisms. Including shape memory alloy devices [3–6], paraffin drives devices [7,8], thermal cutting devices [9–11], and the like [12,13]. Many of these devices have been tested in space and have been successfully applied to various types of tasks.

Among them, smart material shape memory alloy is widely used in locking and releasing devices because of its shape memory effect and high energy density. In this paper, a new type of lock-release device is also designed using shape memory alloy wire. Shape memory effects fall into two categories, one-way shape memory effects, and two-way shape memory effects. The one-way shape memory effect means that the SMA is loaded when the ambient temperature is lower than its phase transition temperature, and there is residual strain after unloading. If the SMA is heated at this time, the residual strain will disappear and the shape memory alloy will return to the condition before loading. The two-way shape memory effect

![Figure 1. Lock-release mechanism locks the upper and lower frames through the clamp-band system.](image-url)
Table 1. Technical objectives.

| Technical indexes       | Requirement                                                                 |
|-------------------------|-----------------------------------------------------------------------------|
| Applications            | Space environment                                                           |
| Trigger source type     | Non-explosive                                                               |
| Bearing capacity        | ≥15KN                                                                       |
| Unlock time             | ≤1s                                                                          |
| Device mass             | ≤900g                                                                        |
| Power supply requirements| Adapt to rocket power supply                                                |
| Reusable                | No components are damaged and no gas/debris is generated during unlocking. And can be reassembled and reused without replacing any components during reset. |

refers to the shape memory alloy can simultaneously remember the shape at high temperature and low temperature, i.e. After the SMA is heated to restore its original shape, if the temperature is lowered, the SMA can return to the state before heating [14]. However, two-way memory alloy has less application at present because of its strict requirements for two-way memory training and unstable performance. In this design, a one-way shape memory alloy is also used as the actuator of the device.

This paper introduces a lock-release device based on shape memory alloy, including the structural composition, working principle and working process of the device, as well as the design method of the main stressed components. At the same time, the prototype was processed and relevant functional verification and technical index tests were carried out, which verified the feasibility of the design idea.

2. Functional principle

In this article, the technical objectives the lock-release device should meet are shown in Table 1.

2.1. Components

The device is mainly composed of the SMA trigger assembly, the unlocking transmission assembly and the connecting and separating assembly. The structure of the device is shown in Figure 2.

![Figure 2. Device structure.](image-url)
The connecting and separating assembly includes screw, flywheel nut, bearing, etc. It is the main force-bearing structure of the device, and its main function is to realize the axial locking of the mechanism through threads. During the working process, the flywheel nut rotates at a high speed to unscrew the screw to realize unlocking, and the vibration and impact in the separation process are effectively reduced through the conversion of energy forms.

The unlocking transmission assembly mainly comprises a primary swing arm, a secondary swing arm, a Stopper and the like. During locking, the locking force is amplified by the multi-stage force increasing mechanism to achieve reliable locking of the connecting and separating components. When unlocking, quickly remove the constraint on the connecting and separating components.

The SMA trigger assembly includes a rotating ring, spring, SMA wire, etc. Its main function is to pre-tighten and limit the unlocking transmission assembly during locking to ensure the reliability of the connection. When unlocking, an unlocking force and an unlocking displacement are provided to trigger the unlocking transmission assembly to realize unlocking.

### 2.2. Release mechanism

The working process of the lock-release device is shown in Figure 3. When the device is locked, a preload is applied to the stressed screw through a pre-tightening nut, so that the stressed screw is elastically deformed. The preload is transmitted to the flywheel nut through the thread to generate torque, the load is further transmitted to the two-stage swing arm and gradually reduced and finally transmitted to the stopper. The second swing arm is limited by the stopper and limited to the first swing arm, the first swing arm limits the flywheel nut to maintain rotational kinetic energy of it. When power is applied, the SMA wire generates force to pull the stopper along the guide rail to release the limit of

![Figure 3. Separation process.](image)
the secondary swing arm, and then the first swing arm is released, and finally, the flywheel nut is free. In this process, the preload is released step by step, the strain energy stored in the non-self-locking thread is converted into the rotational kinetic energy of the flywheel nut, and the stressed screw moves linearly to separate the target.

The three main advantages of the device are:
- Non-explosive, fast to release: Triggered by SMA wire with small wire diameter, the unlocking response speed improves. Moreover, the structural damage and smoke pollution caused by the pyrotechnic explosion is avoided.
- Low shock: Shock reduction by conversion of stored strain energy into rotational Kinetic energy.
- Reusable: After the operation, the release actuator can be re-mated, and the system can be re-loaded without any replacement.

2.3. Design principles

The connecting and separating assembly is the key component for the high load of the device, and the locking and unlocking of the device are mainly realized through the combination and separation of threads between a screw and a flywheel nut. Considering the initial design conditions, it is necessary to lock two screws at the same time and ensure the synchronization of the unlocking of both ends. Finally, the scheme of flywheel nut rotating and two screws moving linearly is determined, and the principle is shown in Figure 4. Tighten the loading nuts at both ends and symmetrically apply the pre-tightening load to the two stressed screws. Through the non-self-locking thread between the two screws and the flywheel nut, the axial load on the screw is further converted into the torque of the flywheel. By constraining the flywheel nut, the device can be locked. In the working process, the unlocking transmission assembly releases the constraint on the flywheel nut. Due to the preload of the stressed screw, the flywheel nut rotates at a high speed, and the two screws move linearly to both sides with the limiting effect of the end cover, thus releasing the target.

(1) Design of core components

The screw is the key force-bearing component, which is designed according to the axial limit load of the device. One end of the screw matches with the flywheel nut through trapezoidal non-self-locking threads, and the thread parameters are shown in Table 2. By designing the angle of the thread, the locking strength and unlocking reliability of the device can be ensured at the same time. The other end of the screw matches with the

Figure 4. Connection and separation scheme.
loading nut through common threads for accurate loading. At the same time, arranging a spherical washer to ensure that the loading on both sides is on the same line. The hexagonal prism in the middle section of the screw cooperates with the guide structure to limit its rotation and avoid unloading. Installing a pair of tapered roller bearings on both ends to reduce the obstruction of flywheel rotation friction in the unlocking process and consider the influence of radial force generated by high-speed rotation and axial force generated by asymmetric loading process.

(2) Check of key parameters

The design principle of screw parameters is: where \( F \) is the input parameter (preload force in connection state), and \( d \) is the minimum design value of screw diameter. The screw is made of TM210A material. Here, \( [\sigma] \) is the allowable tensile strength of the material, \( [\sigma] = 1960\text{MPa} \).

\[
F = [\sigma]A = [\sigma] \frac{\pi d^2}{4} \quad (1)
\]

Checking on flexural strength of thread and it is denoted as

\[
M = \frac{F}{z} = \frac{F (d - d_2)}{2} \quad (2)
\]

\[
\sigma_b = \frac{M}{W} = \frac{F d - d_2}{\frac{2 \pi d_1 b^2}{6}} = \frac{3F h}{\pi d_1 b^2} \leq [\sigma_b] \quad (3)
\]

Here, \( [\sigma_b] \) is the allowable bending strength of the material, \( [\sigma_b] = 1340\text{MPa} \), \( z \) is the number of screw turns, \( h = d - d_2 \) represents the working height of the thread. \( b \) is the thread thickness, Trapezoidal thread takes \( b = 0.65P \). Checking on shear strength of threads and it is denoted as

\[
\tau = \frac{F}{\pi d_1 b z} \leq [\tau] \quad (4)
\]

Here, \( [\tau] \) is the allowable shear strength of the material, \( [\tau] = 670\text{MPa} \). Checking on anti-extrusion strength of thread and it is denoted as

\[
\sigma_p = \frac{F}{A} = \frac{F}{\pi d_2 h z} \leq [\sigma_p] \quad (5)
\]

Here, \( [\sigma_p] \) is the allowable contact strength of the material, \( [\sigma_p] = 1960\text{MPa} \). Checking on non-self-locking characteristics of threads and it is denoted as

\[
\rho' = \arctan(f') = \arctan\left(\frac{f}{\cos(\beta)}\right) \quad (6)
\]

### Table 2. Thread parameters of the release device.

| Parameters               | Value | Parameters               | Value |
|--------------------------|-------|--------------------------|-------|
| Nominal diameter \(d/\text{mm}\) | Tr14  | Lead \(Ph/\text{mm}\)    | 10    |
| Pitch diameter \(d_r/\text{mm}\) | 13    | Helix lead angle \(\Psi/\text{°}\) | 20.17 |
| Small diameter \(d_i/\text{mm}\) | 11.5  | Tooth angle \(a/\text{°}\) | 30    |
| Pitch \(P/\text{mm}\)      | 3     | Flank angle \(\beta/\text{°}\) | 15    |
| Threads \(n\)            | 5     | Screwing length \(H/\text{mm}\) | 20    |


Here, ρ' is the equivalent friction angle of the thread, and f' is the equivalent friction coefficient of the thread.

3. Performance test

3.1. SMA wire test

The device uses SMA wire to drive and test the performance of it in advance before unlocking. In practical application, the force and displacement output by SMA wire are important parameters. Different loads and operating conditions both have an impact on driving ability [15]. In order to test the output performance of the SMA wire driver under different conditions, designing a multifunctional SMA wire driver testing system. The test principle showing in Figure 5.

In order to ensure the stable performance of SMA wires, the same batch of SMA wires with a diameter of 0.4mm are selected (composition: Ni:54.94%, Ti:45.06%, phase transition temperature: 100°C), and several sections of SMA wires with a length of 120mm are intercepted. Before testing or practical application, the SMA wire is pre-stretched to 108% at room temperature, and then placed in a high-temperature box to undergo phase change shrinkage. This cycle is repeated for five times in order to train SMA wires to ensure stable performance during subsequent use. (During this process, the stress and strain properties of different samples shall be kept stable).

During the testing process, one end of the SMA wire is fixed on the tension sensor through the clamp, and the other end is fixed on the slide block through the clamp, and the slide block can slide along the slide rail. The other end of the slider is connected with a biasing spring to apply linearly varying load to the SMA wire, and a constant load can also be provided by hanging weight. The other end of the biasing spring is fixed on the spring fixing slide block. Using a laser displacement sensor to measure the

![Figure 5. SMA wire driver testing system.](image-url)
displacement of the slider, the strain of SMA wire can be obtained. The SMA wire is heated by electricity. The tension sensor and the laser displacement sensor should be able to work at the same time to collect stress and strain data corresponding to SMA wires at the same time. The driving force parameters corresponding to different heating currents of SMA wires at room temperature are obtained through many measurements, as shown in Figure 6.

It is worth noting that in actual space applications, not only the stability of SMA wire performance after different batches and multiple uses, but also the change of SMA wire performance after storage for a period of time need to be considered. However, this is not the focus of research in this article, so no further tests have been carried out.

3.2. Functional test

The functional test mainly verifies the rationality of the design, whether the movement form is in accordance with the expectation and whether the operation is smooth, etc. As shown in Figure 7, the unlocking device has an outer envelope size of 100 mm×100 mm×180 mm, and a mass of 890g, which meets the design index requirements. All parts can cooperate well and run smoothly.

The main purpose of the experiment is to verify whether the separation device can be unlocked as expected under the simulated loading condition. The experimental device is shown in Figure 8.

The device is composed of power supply, upper and lower loading plates, dragging plates, boosting mechanism and other parts. During loading, the device is placed on the bracket, the device is fixed with the loading frame through threads, and force is increased through a pulley mechanism, so that symmetrical loading of screws on both sides is realized, and axial unbalanced force is effectively avoided in the loading process. By changing the mass of the suspended weights, the unlocking function verification under different force loading conditions can be realized.

During the experiment, the SMA wire and the lead are connected through a clamping piece, and the SMA wire is electrified and heated by an external 5V voltage so that the

![Figure 6. Mechanical property test of SMA.](image-url)
SMA wire generates force and displacement. So as to pull the stop block, release the unlocking and transmission component, and further release the connection and separation component. The flywheel rotates at a high speed to separate the screw rods on both sides and realize unlocking. The process is shown in Figure 9.

3.3. **Static load test**

The lock-release device will overload during the launching process, so it is necessary to carry out the ultimate tensile bearing test of the device. The screw rods are fixed with the tension machine through a connecting piece to realize axial loading, and different loading values are set to verify the bearing capacity of the device. The experimental device is shown in Figure 10.
In the test process, the tensile machine is connected with the screw rod, and the tensile load range is set to 0 to 15KN to get the load-displacement curve of the device. As shown in Figure 11. Through experiments, it is verified that the mechanical properties of the device under different load-bearing states meet the requirements of technical indexes.

Figure 9. Unlocking process.

Figure 10. Ultimate load test experiment.
3.4. Separation time test

The unlocking time takes the moment when the SMA wire is energized as the starting point and the moment when the flywheel nut and the screw thread are loosened as the ending point. During the measurement, the timing controller is connected to the circuit, and the positive and negative poles of the power supply are connected to the screws on both sides. The timing controller is the control LED by the STM32F103C8T6 controller. One interface of the controller is connected to the led display screen to record the time. The SMA wire is connected to the power-on circuit, and the relay controls on/off. The normally closed circuit is connected with the left-hand screw and the right-hand screw, and the circuit is in an on state when the device is locked. When unlocking, the power-on circuit is switched on, timing is started, and SMA is heated to unlock. After successful unlocking, the two screws are disengaged from the flywheel, the normally closed circuit is disconnected, and the timing is finished. The unlocking time test process is shown in Figure 12.

During the experiment, the lock-releasr device is connected with a constant voltage source (5V) and is loaded with 2000N. The unlocking time is shown in Table 3.

![Load-displacement curve](image)

**Figure 11.** Load-displacement curve.

**Figure 12.** Unlocking time test.
The experiment was carried out at room temperature under atmospheric conditions. In the vacuum environment of practical application, the reaction speed of SMA wire will be faster. The living environment temperature range for connecting the unlocking device is ±70°C. In high-temperature environment, the time required to reach the SMA wire phase change temperature is shorter, the SMA wire reacts faster, and the unlocking time of the device will be shortened. On the contrary, in a low-temperature environment, the time required to reach the phase transition temperature of the SMA wire is longer, the SMA wire reaction will be slower, and correspondingly, the unlocking time of the device will also be longer. Therefore, the actual unlocking time is related to the space orbit temperature at which the device is located when the signal is received.

### 4. Conclusions

This paper introduces a lock-release device based on shape memory alloy, including the structural composition, working principle and working process of the device, as well as the design method of the main stressed components. At the same time, the prototype was processed and relevant functional verification and technical index tests were carried out, which verified the feasibility of the design idea. The technical indexes are shown in Table 4. The experimental results show that the performance parameters of the lock-release device can well meet the technical indexes in Table 1.

It is worth noting that before practical engineering application, there are still many confirmatory experiments to be done, such as vibration test, thermal vacuum test, etc. We will continue these researches in the near future.

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### Disclosure statement

No potential conflict of interest was reported by the authors.
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