Design and Development of a Miniature SMA-Based Hold-Down and Release Mechanism for CubeSats

Rahul Yadgirkar
TakeMe2Space
Telangana, India
r.vortex@tm2.space

Sharat Reddy
TakeMe2Space
Telangana, India
sharat@tm2.space

***Abstract*—This paper presents the design and experimental validation of a compact, resettable Hold-Down and Release Mechanism (HDRM) actuated by Shape Memory Alloy (SMA) wire for CubeSat-class spacecraft. The mechanism supports general payload deployment tasks including solar panels, antennas, and deployable booms and fits within a 45 × 22 × 6.5 mm aluminum enclosure. A mechanical slider, driven by the contraction of a NiTi SMA wire, disengages a friction-locked dual-cylinder release nut. A compression bias spring provides passive reset, enabling repeatable operation. The system includes a detector switch to confirm successful actuation, enabling basic closed-loop feedback. The design is electrically actuated using direct current and eliminates the shock, debris, and single-use limitations associated with pyrotechnic and burn-wire systems. Initial testing under ambient conditions demonstrates sub 2 second actuation time with reliable release and reset behavior. The proposed HDRM offers a reusable, non-pyrotechnic solution for low-shock deployment in space-constrained satellite platforms, with further qualification testing planned under thermal-vacuum and vibrational conditions.**

***Index Terms*—SMA actuator, HDRM, CubeSat, solar panel deployment, nonpyrotechnic release**

I. INTRODUCTION

Miniature satellites such as CubeSats have enabled low-cost access to space for scientific, commercial, and educational missions [1]. As these platforms evolve, the demand for compact and reliable subsystems has increased significantly, especially for payload deployment. Among these subsystems, Hold-Down and Release Mechanisms (HDRMs) play a critical role in the security of deployable structures such as antennas, solar panels, and deployable booms during launch, and in ensuring their controlled release once in orbit [2].

Conventional HDRMs often rely on pyrotechnic devices or resistive burn-wire systems. Although effective, these approaches introduce several limitations: pyrotechnics produce shock and debris, complicate mechanical integration, and are non-reusable; burn wires are power intensive, difficult to inspect, and typically single-use [2], [3]. These drawbacks are especially problematic for space-constrained missions where safety, reusability, and modularity are priorities.

Shape-memory alloy (SMA)-based actuators offer a compelling alternative. These materials, commonly made from nickel-titanium (NiTi) alloys, exhibit a unique thermomechanical behavior in which they return to a predefined shape when heated above a critical transformation temperature [4]. This contraction is driven by a solid-state phase change from martensite to austenite, allowing SMA wires to generate high force in a compact form factor. Their ability to produce smooth, silent motion without complex mechanical systems makes them ideal for use in space-constrained environments. SMA systems are electrically simple, low-shock, and inherently compact traits that align well with CubeSat constraints [5].

This work's significant contributions include:

- The development of a miniaturized, resettable SMA-based HDRM with a right-angle actuation geometry, enabling a 6.5 mm profile suitable for space-constrained CubeSat platforms.
- Integration of a friction-based mechanical locking and release system with SMA actuation, offering a low-shock, reusable alternative to traditional pyrotechnic and burn-wire mechanisms.

The rest of this paper is structured as follows: Section II discusses previous research and existing implementations. Section III outlines the proposed mechanism and its design rationale. Implementation details and experimental results are presented in Section IV. Finally, Section V concludes the paper

This work was supported by TakeMe2Space.

and suggests directions for future work.

II. Background and Existing Work

A. Traditional HDRMs

Hold-Down and Release Mechanisms (HDRMs) are widely used in space systems to restrain deployable structures such as solar panels, antennas, deployable booms, or sensors during launch, and to release them once in orbit. Conventional HDRMs rely heavily on pyrotechnic devices or resistive burn-wire mechanisms, both of which have limitations in terms of reusability, safety, shock generation, and integration complexity.

B. Pyrotechnic and Burn-Wire Limitations

Pyrotechnic HDRMs, such as explosive bolts and separation nuts, are single-use and produce significant pyroshock and debris, which can compromise sensitive electronics and mechanical assemblies on board small satellites [2], [7]. While they offer high reliability and simplicity, their drawbacks such as the inability to perform functional checks pre-launch and the risk associated with handling explosives make them less desirable for missions that demand modularity and safe integration.

Burn-wire mechanisms, although electrically simpler and safer than pyrotechnics, suffer from slow actuation times and thermal inefficiencies. They also typically support only one-time actuation, limiting their use in scenarios that require resettable or multiple deployment cycles [3], [8].

C. Emergence of SMA-Based HDRMs

To address these issues, researchers and aerospace engineers have explored non-explosive actuators (NEAs), particularly those based on Shape Memory Alloys (SMAs). SMA devices utilize the thermally induced transformation between martensite and austenite phases to produce mechanical motion. Because of their compact size, high force-to-weight ratio, and silent, shock-free operation, SMA-based HDRMs have gained attention in recent years [4].

One of the earliest and most recognized implementations is the Frangibolt™ actuator [9], which uses an SMA cylinder to fracture a preloaded bolt upon heating. While effective, it is a destructive approach and does not support reusability. More recent developments have focused on resettable SMA mechanisms. These include pin-puller devices, SMA-actuated latch systems, and segmented nut releases. These mechanisms offer advantages such as modularity, low actuation noise, and suitability for CubeSat integration [5].

D. Novelty of the Present Work

The design space for SMA HDRMs has expanded to include compact geometries and mechanical amplification strategies. A study by Thurn and Simon [5] demonstrated a miniaturized SMA wire-based HDRM suitable for nanosatellite deployment, highlighting the role of thermal design, spring biasing, and wire crimping techniques. However, most published designs remain either linear or rely on direct axial actuation.

In contrast, the present work introduces a compact HDRM employing a Right Angle Pull configuration [6], redirecting the SMA contraction force orthogonally through a slider mechanism. This approach provides a thin, planar actuation layout suitable for ultra-compact enclosures and supports reusability through a passive bias spring. The design builds on prior SMA HDRM concepts while introducing a novel mechanical layout and a customized friction-locked release nut, broadening the applicability of SMA-based release systems in tightly constrained satellite structures.

III. Proposed Approach

A. Overview of Mechanism Architecture

The proposed Hold-Down and Release Mechanism (HDRM) is designed to provide a compact, resettable, and non-pyrotechnic alternative for small satellite deployment systems. Central to the mechanism is a NiTi Shape Memory Alloy (SMA) wire that actuates a slider mechanism in a Right Angle Pull configuration [6]. This design choice enables the redirection of the SMA's axial contraction into lateral slider motion, allowing the mechanism to remain extremely thin, measuring only 6.5 mm in profile.

B. Slider and Release Interface

The slider is the core mechanical element that transmits the SMA contraction force. It is guided within machined channels and features an embedded pin that mates with a dual-cylinder friction-locked nut. During actuation, the SMA wire pulls the slider rearward, disengaging the locking pin from the nut. Once released, the nut allows the constrained structure (e.g., a solar panel or antenna) to deploy.

C. Reset and Bias Mechanism

A compression bias spring is integrated into the mechanism to provide passive reset functionality. After actuation, once power is removed and the SMA wire cools, the spring restores the slider to its original forward position, re-engaging the locking geometry for repeated use. The preload from the spring is selected to be lower than the maximum contraction force of the SMA wire, ensuring reliable release without compromising reset strength.

The actuation forces within the mechanism are illustrated in the free body diagram shown in Figure 1. The diagram highlights the contraction direction of the SMA wire, the opposing preload from the compression spring, and the resulting stroke of the slider. This visual representation clarifies the mechanical balance between driving and restoring forces, which is critical to ensuring both successful release and repeatability.

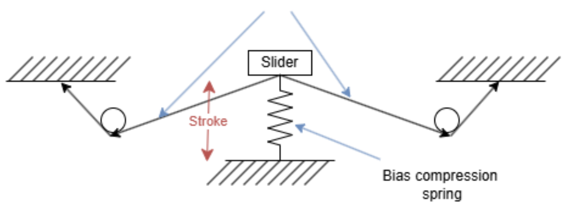

Fig. 1. Free body diagram of the HDRM slider mechanism showing SMA contraction force, compression spring preload, and slider stroke.

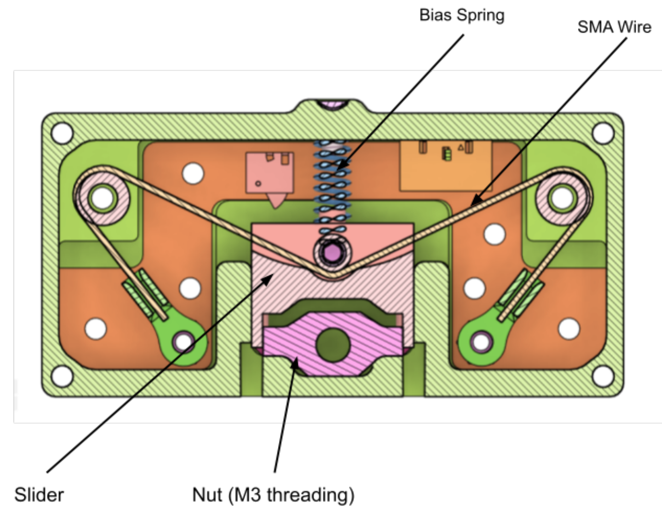

Fig. 2. 3D CAD model of the proposed HDRM showing internal components including the SMA wire, slider, compression spring, and locking nut, enclosed within the compact aluminum housing.

D. Mechanical Advantages and Integration Benefits

This architecture significantly reduces mechanical complexity and part count compared to traditional latch or bolt-style HDRMs. The Right Angle Pull geometry eliminates the need for long axial stroke volumes, which is ideal for CubeSats where vertical space is at a premium. Furthermore, the planar design simplifies stacking and mounting within satellite frames.

The overall mechanism is modular, low-shock, and scalable. It can be integrated into a variety of payload release scenarios beyond solar panels, including deployable antennas, deployable booms, or drag sails. The design is also inherently safe for handling, testing, and reset, allowing for multiple ground test cycles before final deployment. Figure 2 illustrates the overall layout of the HDRM mechanism in CAD, highlighting the internal actuation path and packaging efficiency.

IV. Implementation and Results

A. Fabrication and Assembly

Initial prototypes of the mechanism were developed using 3D printing for rapid iteration and geometric validation. However, surface roughness inherent to additive manufacturing led to mechanical issues such as slider jamming and inconsistent friction at contact points. These drawbacks significantly impacted early actuation reliability and underscored the importance of precision fabrication. To address this, the final prototype was machined from aluminum, which provided the necessary tolerances and smoothness for reliable sliding motion.

To further enhance operational reliability, a PTFE sleeve was added around the SMA wire path. This non-metallic barrier prevents the SMA wire from contacting surrounding aluminum components, reducing thermal losses, mechanical wear, and the risk of electrical shorting.

The prototype HDRM was fabricated using CNC-milled aluminum 6061 for the structural enclosure due to its favorable strength-to-weight ratio and space-grade machinability. The SMA wire used for actuation is a 0.5 mm diameter NiTi alloy, crimped at both ends using crimps to ensure electrical and mechanical reliability. The slider and the dual-cylinder friction nut were precision machined to allow smooth disengagement under SMA tension. A compression spring was selected and dimensioned such that its preload was sufficient for full reset after actuation while remaining lower than the SMA's generated force. Figure 3 compares two stages of the HDRM prototype. The top image shows the machined enclosure and locking components before SMA installation. The bottom image presents the fully assembled mechanism, including routed SMA wires through PTFE sleeves and the integrated compression spring.

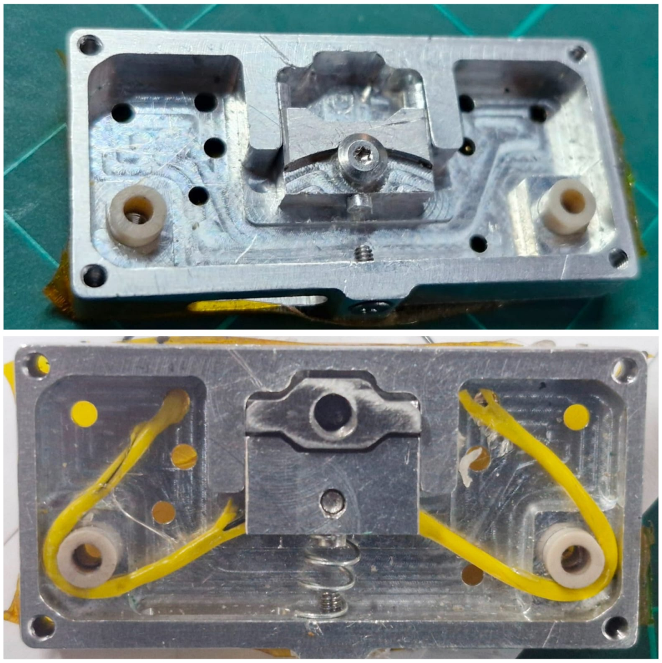

Fig. 3. HDRM prototype. **Top:** Slider and locking nut interface prior to SMA wire installation. **Bottom:** Fully assembled prototype with SMA wire routed through PTFE sleeves and compression spring installed.

A. B. Electrical Actuation Setup

Direct current was used for resistive heating of the SMA wire during initial testing. A benchtop power supply operating at 5V was used to drive the contraction, with future versions planned to incorporate PWM control via a low-side MOSFET driver for improved thermal efficiency and current regulation.

To verify successful actuation, a miniature detector switch rated for low outgassing was mechanically integrated into the mechanism. This switch is triggered when the slider reaches its fully retracted position, providing a reliable signal that the HDRM has completed its release stroke. The system thereby achieves basic closed-loop functionality, allowing the deployment event to be confirmed electrically without external sensing. This feature is particularly beneficial for flight systems that require independent verification of deployment status.

No thermal insulation or advanced control electronics were included in the preliminary tests, as the focus was on mechanical reliability and actuation repeatability.

C. Functional Testing

Actuation time was consistently measured under 2 seconds in ambient lab conditions. The mechanism showed full slider retraction and successful nut release in each of five consecutive cycles. The reset function via the bias spring worked reliably after SMA cooling. The holding force of the nut under preload and its resistance to accidental displacement during handling were evaluated, although no additional locking was implemented in this prototype.

TABLE I
KEY SPECIFICATIONS OF THE PROPOSED SMA-BASED HDRM

Parameter	**Value**
Dimensions (L × W × H)	45 × 22 × 6.5 mm
Actuation Time	$<$ 2 seconds
SMA Wire Length	64 mm
SMA Wire Diameter	0.25 mm
Weight	$<$ 20 grams
Power Input	5 V DC
Enclosure Material	CNC-milled Aluminum 6061
Reset Mechanism	Compression Spring
Insulation Layer	PTFE Sleeve
Reusability	Yes (Resettable)
Release Preload	Approx. 4 N (SMA pull force)
Maximum Preload	Approx. 1200 N (lock interface limit)

D. Future Testing Plans

The prototype is scheduled for vibration and thermal vacuum (TVAC) testing to qualify its mechanical and thermal robustness for space deployment. These tests will also evaluate electrical insulation integrity, wire fatigue behavior, and reset repeatability under representative orbital thermal gradients.

The results thus far demonstrate the feasibility of the HDRM design for low-shock, resettable deployment in small satellite missions.

V. CONCLUSION

This paper presented the design, development, and initial validation of a compact, resettable Shape Memory Alloy (SMA)-based Hold-Down and Release Mechanism (HDRM) tailored for CubeSat applications. The proposed design leverages a linear SMA actuator integrated with a mechanical slider and friction-locking nut assembly, offering low-shock deployment in a miniature 45 × 22 × 6.5 mm form factor.

The final prototype, machined from aluminum, addressed early performance limitations encountered with 3D-printed models, particularly those related to surface roughness and mechanical interference. The inclusion of a PTFE sleeve further enhanced the reliability and insulation of the SMA actuator. Bench testing confirmed actuation times under 2 seconds with consistent release and reset behavior.

While preliminary results in ambient conditions demonstrate functional repeatability and mechanical integrity, future work will focus on qualification through thermal vacuum and vibration testing. The results support the feasibility of this approach as a viable alternative to traditional pyrotechnic and burn-wire systems, enabling safer and more reusable deployment strategies for space-constrained satellite missions.

REFERENCES

[1] J. Puig-Suari, C. Turner, and W. Ahlgren, "Development of the Standard CubeSat Deployer and a CubeSat Class PicoSatellite," in *Proc. IEEE Aerospace Conf.*, 2001.

[2] B. Wang, J. Zhu, S. Zhong, W. Liang, and C. Guan, "Space deployable mechanics: A review of structures and smart driving," *Materials & Design*, vol. 237, p. 112557, Jan. 13, 2024, doi: 10.1016/j.matdes.2023.112557.

[3] D. J. Hartl and D. C. Lagoudas, "Aerospace applications of shape memory alloys," *Proc. Inst. Mech. Eng., Part G: J. Aerospace Eng.*, vol. 221, no. 4, pp. 535–552, 2007.

[4] S. Dahake, N. Awate, and R. Shelke, "Design and analysis of release mechanism using shape memory alloy for spacecraft," in *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1206, no. 1, p. 012012, Nov. 2021.

[5] S. Reershemius, K. Sasaki, and T. Sproewitz, "The development of a self-resetable, low-shock hold-down and release mechanism,"

[6] DYNALLOY, Inc., *Technical Characteristics of FLEXINOL® Actuator Wires*, Technical Datasheet.

[7] J. Lee and J.-H. Han, "Separation and Release Devices for Aeronautical and Astronautical Systems: A Review," *Int. J. Aeronaut. Space Sci.*, 2024.

[8] A. Thurn, S. Huynh, S. Koss, P. Oppenheimer, S. Butcher, J. Schlater, and P. Hagan, "A Nichrome burn wire release mechanism for CubeSats," in *Proc. 41st Aerospace Mechanisms Symposium*, 2012.

[9] TiNi Aerospace, "Frangibolt® Non-Pyrotechnic Separation Device," Product Datasheet.