

Passive Deployment of Large-Area Membrane Aperture Using Modular Ring-Truss From 1U Stowed State

Ryan Paetzold
Materials and Mechanical Engineering
University College Dublin
Dublin, Ireland
ryan.paetzold@ucd.ie

Eoin Gahan
Materials and Mechanical Engineering
University College Dublin
Dublin, Ireland
eoin.gahaneg@gmail.com

Dylan Armfield
Materials and Mechanical Engineering
University College Dublin
Dublin, Ireland
dylan.armfield@ucdconnect.ie

Joseph Thompson
Materials and Mechanical Engineering
University College Dublin
Dublin, Ireland
joseph.thompson@ucd.ie

David McKeown
Materials and Mechanical Engineering
University College Dublin
Dublin, Ireland
david.mckeown@ucd.ie

The increasing demand for large-area functional surfaces in CubeSat platforms is constrained by strict volumetric limitations imposed by the 1U form factor. A compact deployable membrane system capable of achieving high deployment ratios from a single-unit stowed configuration is presented. The architecture integrates a modular collapsible ring-truss with an origami-inspired gossamer membrane, enabling controlled radial deployment and membrane tensioning. A compliant interwoven carbon fibre joint replaces conventional pin-based revolute joints, reducing mechanical complexity while enabling compact integration. Deployment is achieved through passive actuation using shape memory alloy (SMA) elements, eliminating the requirement for motors or release mechanisms. A hierarchical modelling framework is adopted, incorporating kinematic verification, finite element analysis, and multibody dynamic simulation. A reduced-order membrane representation is implemented within the multibody formulation to capture resistance and tension development. Results demonstrate repeatable and symmetric deployment with effective membrane tensioning within 1U constraints. Joint friction is identified as the dominant parameter governing deployment behaviour. The proposed architecture provides a scalable solution for large-area deployable systems in CubeSat applications.

Keywords: CubeSat, deployable structures, origami membrane, ring-truss, multibody dynamics, shape memory alloys, compliant mechanisms

I. INTRODUCTION

The CubeSat form factor imposes stringent geometric and volumetric constraints on spacecraft subsystems [1]. Within a single-unit (1U) configuration, available volume for deployable payloads is significantly reduced after allocation to primary structure and subsystems. This constraint limits achievable aperture size for power generation and sensing applications. Systems requiring large-area continuous apertures or membrane-based architectures, where stowage efficiency and deterministic deployment are critical, remain comparatively underexplored at CubeSat scale. Deployment mechanisms contribute significantly to mission failure rates in university-class CubeSats, with anomalies frequently attributed to subsystem malfunction [2]. At larger spacecraft scales, deployable structures have historically been a leading cause of in-orbit failure, resulting in substantial mission and financial losses [3].

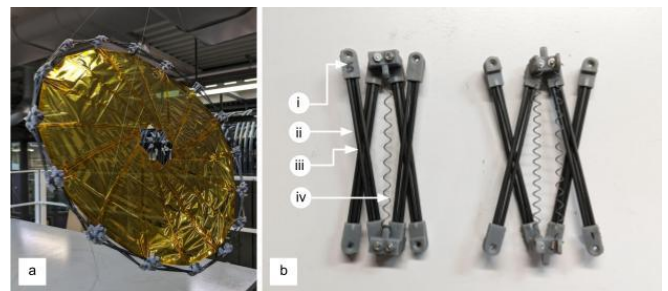


Fig. 1. Deployable Muira-ori folded origami flasher (a) and woven ring-truss assembly manufactured from an array of (b) truss assemblies consisting of (bi) 3D-printed fixtures, (b ii) CFRP members, (b iii) woven interface, (b iv) SMA actuator.

These risks are amplified at CubeSat scale due to reduced redundancy and tighter integration constraints. Origami-inspired folding methodologies offer high packing efficiency and controlled deployment characteristics [1,4]. However, their application within CubeSat membrane deployables remains limited due to manufacturing constraints, deployment reliability challenges, and the absence of compact supporting structures capable of providing geometric constraint and load transfer.

The present work addresses these limitations through the development of a deployable gossamer membrane system capable of generating a large aperture from a 1U stowed volume. The architecture integrates: (i) an origami flasher membrane, (ii) a scissor-based ring-truss, (iii) a compliant interwoven joint design, and (iv) a hybrid modelling framework combining experimental, finite element, and multibody approaches. Multibody dynamics modelling provides an effective framework for analysing articulated deployment mechanisms, enabling prediction of joint forces, constraint reactions, and transient motion [5–7].

However, conventional multibody formulations are not suitable for modelling thin membrane structures undergoing large deformation [8]. Finite element approaches have been used to analyse origami structures [8], but these methods remain computationally intensive and unsuitable for system-level analysis.

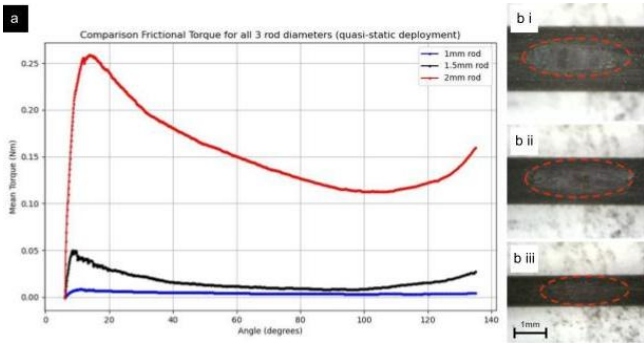


Fig. 2. a) Frictional torque between 2 mm, 1.5 mm and 1 mm CFRP longerons when deployed at 480mm/min over a 10 sec a 0°-90° orientation. (b) Occurrence of wear patterns on (b i) 2mm, (b ii): 1.5mm and (b iii) 1.0mm CFRP members.

A hybrid modelling strategy is therefore adopted, whereby membrane behaviour is approximated using reduced-order representations, while deployment kinematics are captured using multibody dynamics. This approach enables efficient evaluation of deployment forces, frictional effects, and membrane tensioning.

II. MATERIALS AND METHODS

A. Design and Configuration

As shown in Figure 1, the deployable system consists of a centrally stowed origami flasher manufactured from Kapton reinforced Mylar, providing high packing efficiency and deterministic folding. This membrane is coupled to a scissor-based ring-truss perimeter to address limitations associated with unsupported membranes, including poor out-of-plane stiffness and geometric instability. The ring-truss is composed of revolute scissor mechanisms designed to extend beyond the conventional 90° configuration, thereby increasing expansion ratio. The structure performs two primary functions: (i) deployment actuation through coordinated scissor expansion, and (ii) structural stiffening via uniform radial tensioning of the membrane. A compliant revolute joint based on interwoven carbon fibre rods replaces conventional pin-hinge mechanisms. This design eliminates discrete fasteners, reduces susceptibility to thermal-induced jamming, and introduces inherent frictional damping. The joint exhibits a single rotational degree of freedom governed by elastic deformation and contact interaction. Frictional resistance varies with deployment angle due to evolving contact conditions. Rod diameter is treated as a primary design parameter influencing stiffness, friction, and repeatability.

B. Characterization and Evaluation

A material testing system is used to impose prescribed displacement while measuring the corresponding force response. Torque is derived from measured force and joint geometry. Two deployment regimes are considered: (i) quasi-static deployment for baseline characterisation, and (ii) dynamic deployment over a 10s interval representing operational conditions. Finite element analysis is conducted to nonlinear approach is implemented to establish geometry, introduce contact interactions, and evaluate stress distribution under relaxed conditions.

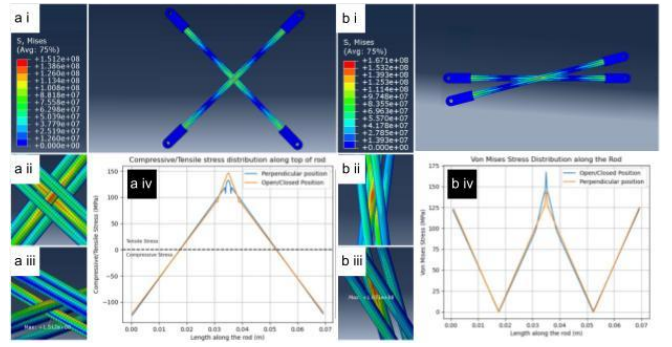


Fig. 3. (a i) distribution of Von Mises' stress in novel joint design when members are perpendicular. (a ii) distribution of stress at the interwoven section. (a iii) location of maximum stress at an interwoven point. (b i) Von Mises stress distribution in joint design in fully open/closed position. (b ii) Migrating accumulation of peak stresses as the closing angle of the truss assembly becomes more acute. (b iii) The occurrence and magnitude of localised Von Mises stress occurring at the interface of CFRP members in truss-assembly closed/deployed state.

System-level deployment is analysed using a Simscape Multibody model derived from CAD geometry. The model incorporates rigid-body kinematics, experimentally derived friction functions, and a reduced-order membrane representation. The membrane is modelled through equivalent rotational inertia and resistive torque applied at the central hub. Membrane folding behaviour is simulated using Grasshopper and Kangaroo Physics [9].

III. RESULTS AND DISCUSSION

A. Deployable Behaviour of the Ring-Truss-Membrane System

Deployment is observed to occur symmetrically across all configurations, with radial expansion proceeding without snap-through instability. Load distribution within the closed-loop truss maintains deployment uniformity. The absence of elastic snap-through behaviour contributes to smooth kinematic progression and reduced sensitivity to perturbations. Following deployment, the ring-truss constrains the membrane perimeter, inducing in-plane tension and resulting in improved planarity relative to unsupported origami structures [10].

B. Influence of Joint Friction on Deployment Dynamics

Joint friction is identified as the primary parameter governing deployment performance. Statistical analysis indicates that surface roughness variations are negligible ($p > 0.05$), with friction dominated by structural effects. A threshold behaviour is observed: below a critical friction level, deployment proceeds to completion; above this threshold, deployment stalls. Within the experimentally observed range, full deployment is consistently achieved. Increased friction results in longer deployment duration and higher torque, without inducing asymmetry or structural binding.

C. Quasi-Static Deployment

The torque-angle response exhibits a consistent profile, as shown in Figure 2 with minimum friction near the perpendicular configuration and increasing toward both open and closed states. This behaviour is attributed to evolving contact mechanics within the interwoven joint. Increasing angular deviation produces elliptical contact regions and higher normal forces due to bending deformation. Friction

magnitude scales with rod diameter due to increased bending stiffness and contact force.

D. Structural Validation

Flexural testing and finite element analysis confirm that friction scaling is governed by structural stiffness. Results are shown in Figure 3. Increased rod diameter results in elevated bending stiffness and increased contact force, producing higher frictional torque. Despite increased stresses, all configurations remain within allowable structural limits, confirming the viability of the compliant joint design.

IV. CONCLUSION

The proposed deployable system demonstrates suitability for CubeSat-scale applications. The hierarchical modelling framework enables efficient evaluation of deployment behaviour. The ring-truss architecture achieves symmetric and repeatable deployment while effectively tensioning the membrane, producing a stable planar configuration. Joint friction is identified as the dominant parameter governing deployment reliability, exhibiting threshold-dependent behaviour consistent with prior studies [1,11]. The frictional response is structurally governed, with bending stiffness dictating contact forces and resulting torque, as validated through flexural testing in accordance with ASTM D7264/D7264M-21 and EN ISO 14125:1998 [12,13]. The interwoven joint design provides predictable and repeatable performance within the operational range. The integration of kinematic design, experimentally derived friction modelling, and multibody simulation establishes a robust framework for the development of compact and scalable deployable systems.

ACKNOWLEDGEMENTS

This research was supported by the Disruptive Technologies Innovation Fund (Call 4) from the Department of Enterprise, Trade and Employment and administered by Enterprise Ireland (NSSPI: National Space Subsystems and Payloads Initiative - DT 2021 0353) and by Research Ireland (19/FFP/6777).

REFERENCES

- [1] Caldwell S. 6.0 structures, materials, and mechanisms. In: NASA [Internet]. 15 Oct 2021 [cited 23 Jan 2026]. Available: <https://www.nasa.gov/smallsat-institute/sst-soa/structures-materials-and-mechanisms/>
- [2] Caldwell S. 3.0 Power. In: NASA [Internet]. 8 Oct 2021 [cited 30 Mar 2026]. Available: <https://www.nasa.gov/smallsat-institute/sst-soa/power-subsystems/>
- [3] Surampudi R. Solar power technologies future planetary science missions. Jet Propulsion Lab Calif Inst Technol. 2017.
- [4] Selva D, Krejci D. A survey and assessment of the capabilities of Cubesats for Earth observation. *Acta Astronaut.* 2012;74: 50–68.
- [5] Swartwout M, Jayne C. University-class spacecraft by the numbers: Success, failure, debris. (but mostly success.). 2016 [cited 23 Jan 2026]. Available: <https://digitalcommons.usu.edu/smallsat/2016/TS13Education/1>
- [6] Rivera A, Stewart A. Study of spacecraft deployables failures. 19th European Space Mechanisms and Tribology Symposium (ESMATS) 2021. 2021. Available: <https://ntrs.nasa.gov/citations/20210020397>
- [7] Surampudi R, Elliott J, Blois J, Bugga K, Beauchamp P, Cutts J. Advanced energy storage technologies for future NASA planetary science mission concepts. 2018.
- [8] Bradford C. Update on starshade technology development: prospects for a future great observatory. 2022. Available: https://assets.science.nasa.gov/content/dam/science/astro/programs/exep/technology/tech-colloquium/files/ExEP_Colloquium_Starshade_20221116_final_1.pdf

- [9] Piker D. Kangaroo: Form Finding with Computational Physics. *Archit Design.* 2013;83: 136–137.
- [10] Pedivellano A, Sinn T, Raharijaona A, Kringer M, Gruber J, Lund T, et al. PowerCube: Design and development of a 100 W origami-inspired deployable solar array for NanoSatellites. *Small Satellite Conference.* 2022. Available: <https://digitalcommons.usu.edu/smallsat/2022/all2022/139>
- [11] Zirbel SA, Lang RJ, Thomson MW, Sigel DA, Walkemeyer PE, Trease BP, et al. Accommodating thickness in origami-based deployable Arrays1. *J Mech Des N Y.* 2013;135: 111005.
- [12] D30 Committee. Test method for flexural properties of polymer matrix composite materials. West Conshohocken, PA: ASTM International; 2021. doi:10.1520/d7264_d7264m-21
- [13] ISO 14125- Flexural test. Ascot: SAI Global;