From Structure to System: Multifunctional 3D-Printed Satellite Architectures

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Abstract

Additive manufacturing offers significant potential for the development of highly integrated and cost-effective satellite structures. This research aims to evaluate the viability of monolithic 3D-printed satellite structures for space applications, with a focus on integrating mechanical supports, electrical routing, and electronic functionalities directly into the primary structure. By leveraging the monolithic nature of additive manufacturing, structural elements such as brackets and supports are printed as part of the structure itself, reducing part count (such as bolts or screws), and assembly complexity.

The methodology involves the design and fabrication of multiple structural prototypes, followed by numerical analyses to assess mechanical behaviour and structural integrity. In parallel, experimental integration tests are conducted to evaluate mechanical compatibility, electrical functionality, and interface robustness. Two electrical integration approaches are investigated: embedding cables within internal structural channels to reduce integration complexity and embedding printed circuit boards or conductive paths within the structure to partially or fully replace traditional cabling.

The expected outcomes include a validated assessment of the mechanical and electrical performance of multifunctional 3D-printed structures, identification of key design trade-offs, and guidelines for future implementations. The results of this work are directly applicable to CubeSats and other small satellite platforms, enabling more compact, robust, and scalable spacecraft architectures.

Keywords

3D Printed, Multifunctional, Embedded Cables, Embedded PCBs

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Acronyms/Abbreviations

PCB	*Printed Circuit Board*
OCB	*On Board Computer*
EPS	*Electric Power System*
BMS	*Battery Management System*

1. Introduction

Additive manufacturing has emerged as a transformative technology in the aerospace sector, offering new possibilities for the design and production of highly integrated and cost-effective satellite structures. Its ability to fabricate complex geometries without the constraints of traditional manufacturing enables the development of multifunctional components that combine structural, electrical, and electronic functionalities within a single monolithic system.

Conventional satellite architectures typically rely on many discrete parts, including mechanical fasteners, separate structural supports, and extensive cable harnesses. These components increase system mass, assembly complexity, and potential failure points. Additive manufacturing provides an opportunity to address these limitations by enabling the direct integration of structural elements such as brackets, mounts, and supports into the primary load-bearing structure, thereby reducing part count and simplifying assembly processes.

This research investigates the feasibility of monolithic 3D-printed satellite structures for space applications, with a particular focus on integrating mechanical and electrical functionalities into a unified architecture. The study explores the potential of embedding electrical routing and electronic components directly within the structural design, aiming to replace or reduce conventional wiring systems.

To achieve this, multiple structural prototypes were designed and will be fabricated using additive manufacturing techniques. Experimental tests are conducted to assess mechanical compatibility, electrical performance, and interface reliability. Two approaches for electrical integration are examined: (i) the embedding of cables within internal structural channels to minimize assembly complexity, and (ii) the integration of printed conductive pathways or electronic components within the structure to partially or fully eliminate traditional cabling systems.

The objective of this work is to provide a validated assessment of the mechanical and electrical performance of multifunctional 3D-printed satellite structures, identify key design trade-offs, and derive guidelines for future implementations. The findings are particularly relevant for CubeSats and other small satellite platforms, where mass, volume, and integration efficiency are critical constraints, and may contribute to the development of more compact, robust, and scalable spacecraft architectures

2. Embedded Cable Integration in Monolithic 6U CubeSat Structures

A key objective of this study is the integration of electrical cabling directly within a monolithic 6U CubeSat structure manufactured using a thermoplastic polymer. The baseline architecture consists of a lightweight isogrid-based structural design incorporating a 3U payload volume, with the remaining volume allocated to subsystems and structural interfaces. The primary innovation lies in the incorporation of internal routing channels intended to accommodate electrical harnessing within the load-bearing structure itself, thereby reducing external wiring, improving packaging efficiency, and maintaining a monolithic design philosophy, Figure 2.1.

To evaluate the feasibility of this approach, a series of simplified prototypes were manufactured featuring internal cable routing paths embedded within structural elements. These experimental models were used to assess manufacturability, cable insertion feasibility, and routing constraints under realistic geometric conditions. The study considered both closed-channel and open-channel routing strategies.

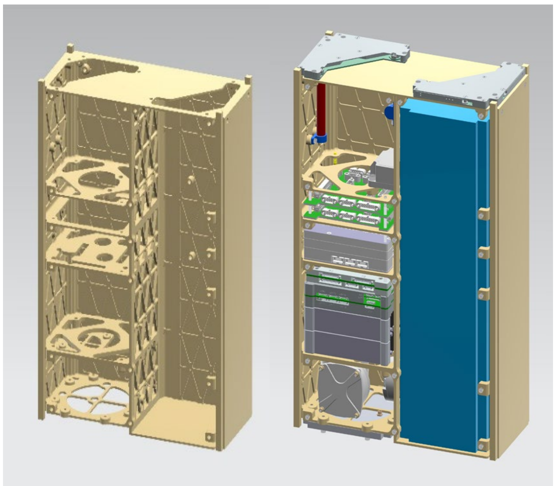

Figure 2.1 Embedded Cable Structure

2.1. *Closed-channel routing approach*

In the closed-path configuration, cables are intended to be fully enclosed within internal structural channels during or after the printing process, this conceals them completely, provides a cleaner appearance, and keeps the cables secure and protected against vibration and interference with other components Experimental results indicate that this approach introduces several significant constraints. First, cable insertion is only feasible when connectors are not attached, as rigid terminal geometries prevent passage through curved or confined channels. This imposes a requirement for post-routing termination, increasing integration complexity at subsystem interfaces.

Second, the minimum radius of curvature within the embedded channels is a critical design parameter. Excessive curvature leads to increased friction and insertion resistance, while insufficient curvature risks damaging cable insulation or conductors. A sufficiently large bending radius is therefore required to ensure smooth insertion and long-term reliability. In addition, a dedicated guiding mechanism or insertion aid is necessary to facilitate cable routing through extended or complex paths, particularly in non-linear geometries.

Despite these measures, the closed-channel approach does not significantly reduce overall assembly complexity when compared to conventional spacecraft harnessing. In practice, insertion becomes a sequential, constrained process that offsets the intended benefits of integration.

A further limitation is the inability to route multiple cables through a single channel. Due to space constraints and mechanical interference, only one cable can be reliably inserted per path. As a result, electrical routing for different subsystems must remain fully separated, increasing the number of required channels and further constraining the structural design.

2.2. *Open-channel routing approach*

To address the limitations of closed channels, an alternative open-channel routing strategy was investigated. In this configuration, partial openings in the structure allow cables to be inserted after manufacturing, including pre-terminated cables with connectors. This approach improves integration flexibility and enables multiple cables to share a common routing path, reducing the total number of dedicated channels required.

However, this design introduces a structural penalty. The presence of open grooves or partially removed material in the isogrid significantly reduces local stiffness and load-carrying capacity. This weakening effect is particularly critical in regions subjected to bending or concentrated loads, where uninterrupted load paths are essential for structural integrity. Furthermore the open paths increase the risk of cables loosening due to vibration.

Consequently, a trade-off emerges between electrical integration efficiency and mechanical performance. Increasing openness improves harness accessibility and routing flexibility but compromises the inherent advantages of monolithic additive structures.

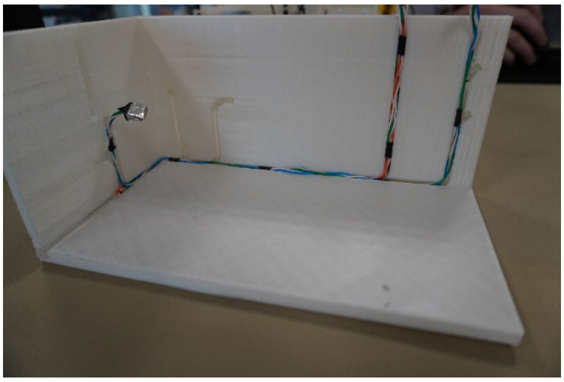

Figure 2.2 Open-channel prototype.

2.3. *Design implications and routing constraints*

From a design perspective, embedding cable routing within a monolithic structure introduces additional constraints beyond traditional spacecraft layout considerations. In addition to component placement and subsystem accessibility, designers must account for internal routing continuity, channel intersection avoidance, and structural reinforcement requirements.

Specifically, internal paths must be carefully designed to avoid clustering multiple cables in proximity, unless sufficient structural reinforcement is provided, as localized material removal can significantly degrade mechanical performance.

As a result, routing optimization becomes a coupled mechanical–electrical design problem. Component placement must be coordinated not only to satisfy functional and thermal requirements but also to minimize routing complexity, reduce channel density, and avoid interference between electrical paths.

Overall, while embedded cable routing demonstrates potential for integration within monolithic 3D-printed spacecraft structures, the results of this study indicate that its practical implementation requires careful balancing of manufacturability, mechanical integrity, and system-level integration constraints.

3. Embedded PCB and Avionics Integration within the Structure

An alternative multifunctional integration approach investigated in this study involves the direct embedding of printed circuit boards (PCBs) within the primary load-bearing structure of a 6U CubeSat. The structural concept is based on a lightweight monolithic architecture, incorporating an isogrid reinforcement topology to maximize stiffness-to-weight efficiency while enabling functional integration. The configuration consists of a 3U payload section, with the remaining volume allocated to avionics, power systems, and supporting subsystems.

Unlike conventional spacecraft architectures, where PCBs are mounted on dedicated panels and interconnected via complex wiring harnesses, the proposed concept integrates electronic boards directly into structural slots within the printed frame. These slots are designed as open cavities within the isogrid structure, allowing for the insertion and mechanical retention of PCBs after manufacturing. Once inserted, the boards are secured to the structure using fastening or retention features integrated into the design.

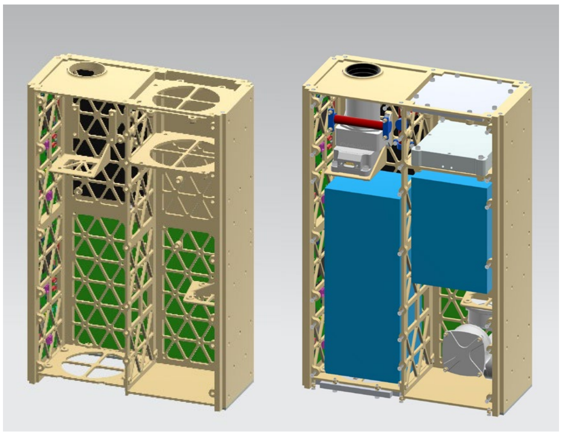

Figure 3.1 Embedded PCB structure.

3.1. *Integrated avionics architecture*

The primary objective of this approach is to replace traditional cable-based harnessing with structural electronic integration. This includes not only interface boards but also key avionics subsystems such as the On-Board Computer (OBC), Electrical Power System (EPS), and potentially additional functional boards such as power distribution or data handling units. By embedding these elements within the structure, the system transitions from a modular assembly of discrete components to a partially integrated structural–electronic platform.

A further extension of this concept includes the integration of energy storage elements, enabling a decoupled structural battery architecture [1][2][3]. In this configuration, battery modules are housed directly within dedicated structural compartments, reducing the need for external mounting systems and further increasing packaging efficiency.

3.2. Structural and design implications

While this approach offers significant integration potential, it introduces several design constraints. The most critical limitation arises from the need to physically insert PCBs into the structure. This requires that the structural openings be sufficiently large to accommodate the full dimensions of each board, including mounted components such as capacitors, inductors, or heat-generating devices. As a result, the surrounding structure must be locally reinforced or bulked out to maintain mechanical integrity, partially offsetting the mass savings achieved through integration.

The required slot geometry is therefore strongly dependent on the specific PCB layout and component selection, introducing a tight coupling between mechanical design and electronics design. Unlike traditional spacecraft design practices, where structures and avionics are developed in parallel but independently, this approach demands early-stage co-design to ensure compatibility.

Another critical challenge concerns electrical interfaces. Since PCBs must be inserted into the structure prior to final electrical connection, conventional connector systems are not directly compatible with this integration scheme. Instead, snap-fit or “click-in” connector solutions are required to enable post-insertion mating. However, most existing space-qualified avionics are not designed for such interfaces, necessitating the use of short bridging cables between structural PCBs and traditional subsystem connectors. This introduces a residual level of cabling and highlights the need for redesign of avionics interfaces to fully support structural integration concepts.

3.3. Assembly and integration considerations

From an assembly perspective, the embedded PCB approach is expected to simplify system integration compared to both conventional harness-based architectures and embedded cable routing strategies. The reduction in discrete wiring harnesses significantly decreases routing complexity and potential assembly errors. Additionally, the modular insertion of PCBs into predefined structural slots enables a more deterministic and repeatable integration process.

However, successful implementation depends heavily on precise mechanical tolerances and insertion planning. The sequence of assembly becomes critical, as PCBs must be installed prior to final electrical closure of the system. This requires careful definition of integration steps and may impose constraints on late-stage subsystem replacement or maintenance.

4. Fully Integrated “Structural Satellite” Concept (Future Work)

A long-term vision emerging from this research is the concept of a fully integrated “structural satellite,” where the distinction between structure, avionics, power system, and communication hardware is effectively eliminated. In this architecture, the 6U CubeSat is still manufactured using a high-performance polymer such as ULTEM 9085, but the structure itself becomes the functional backbone of the entire spacecraft, acting simultaneously as load-bearing frame, electrical bus, and subsystem host.

In this concept, the structure is no longer a passive mechanical support but an active multifunctional system. Conductive paths (e.g., printed copper traces or conductive composites) are embedded directly into the structural lattice during manufacturing, effectively transforming the frame into a distributed PCB [4]. As a result, traditional wiring harnesses are fully eliminated, and electrical interconnections between subsystems are inherently defined by the geometry of the structure itself.

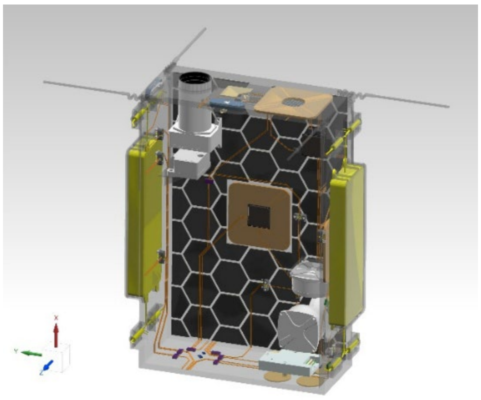

Figure 4.1 Fully Integrated “Structural Satellite” Concept.

4.1. Structure as an integrated avionics platform

In its most advanced form, the structure incorporates the full functionality of core spacecraft subsystems. The OBC, Battery Management System (BMS), and power distribution network are no longer discrete boards but are instead distributed functions embedded within the structural material. Electrical routing is achieved through integrated conductive paths, while connector interfaces are directly bonded or mechanically attached to predefined structural nodes.

Sensors can also be embedded directly into the structure, enabling distributed sensing of temperature, strain, vibration, and radiation exposure. This transforms the spacecraft into a continuously instrumented system, where structural health monitoring and mission data acquisition are inherently unified.

4.2. Structural energy storage and power integration

A key extension of this concept is the implementation of a coupled structural battery system [1][5]. In this configuration, energy storage materials are integrated into or alongside the load-bearing structure, enabling the satellite frame itself to function as both mechanical support and energy reservoir. This approach significantly reduces mass and volume while increasing system-level integration.

However, structural batteries introduce complex coupling between mechanical loading, electrochemical performance, and thermal behaviour. Mechanical stresses may influence electrochemical stability, while charge–discharge cycles may induce dimensional or stiffness changes in the structure. These interactions remain an open research challenge and require substantial advances in multifunctional material science.

4.3. Integrated communication and actuation systems

Communication systems, including antennas and potentially magnetorquers, are also envisioned as printed or embedded elements within the structure. Antenna geometries could be realized as conductive patterns integrated along external or deployable structural surfaces, eliminating the need for separate deployed appendages in some cases. Similarly, electromagnetic actuation elements could be embedded within structural regions, enabling attitude control functionalities directly from the spacecraft frame.

Deployable mechanisms, where still required, would be printed or structurally integrated, minimizing discrete mechanical assemblies and reducing deployment failure risks.

This level of integration leads to a fundamentally different spacecraft paradigm, where the satellite behaves less like an assembly of subsystems and more like a unified "living structure." In this analogy, the structure acts as the body, while distributed electronic and functional elements act as embedded organs and nervous systems. Electrical pathways resemble neural networks, structural loads resemble musculoskeletal functions, and sensing capabilities resemble distributed perception.

5. Conclusions

This work has explored a progressive pathway toward highly integrated 6U CubeSat architectures enabled by additive manufacturing, ranging from embedded cable routing to structural PCB integration, and ultimately to a fully multifunctional structural satellite concept. Across all investigated approaches, a common objective has been the reduction of assembly complexity and part count through increased physical and functional integration within a monolithic additively manufactured structure.

The embedded PCB approach presents a promising step toward fully integrated satellite architectures. Compared to embedded cable routing, it offers improved assembly simplicity and higher functional integration, with the potential to incorporate complete avionics and power systems within the primary structure. However, these advantages come at the cost of increased structural complexity around PCB interfaces, larger local volume requirements, and the need for redesigned electrical connector standards. Despite these challenges, the concept demonstrates strong potential for future small satellite platforms, particularly satellites with strict volume constrains.

More broadly, all proposed integration strategies are subject to significant challenges and uncertainties. Critical issues include thermal management of embedded electronics in vacuum environments, mechanical reliability under coupled structural–electrical loading, manufacturing limitations in multi-material additive processes, radiation-induced degradation, and reduced system repairability and modularity. Addressing these challenges will be essential for the practical realization of multifunctional structural spacecraft.

Despite these limitations, the fully integrated structural satellite represents a compelling long-term vision for spacecraft design. Future advances in multi-material 3D printing, conductive composites, structural batteries, and embedded electronics may enable incremental realization of this concept. The evolution from conventional harness-based systems to embedded cables, then integrated PCBs, and ultimately fully functional structural systems reflects a continuous transition toward maximum physical integration, progressively reducing system complexity while increasing functional coupling.

In the next phase of this project, a full structural prototype will be manufactured, and integration and assembly tests will be performed to validate the proposed concepts. If the work is extended further, future efforts will focus on detailed structural analysis, mechanical optimization, and the investigation of thermal and radiation effects, as the current phase is primarily focused on design definition and integration feasibility.

Acknowledgements

This work has been funded by the European Innovation Council (EIC) under the Horizon Europe EIC Pathfinder Programme through Grant Agreement No. 101161603 (E.T. COMPACT).

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