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A Constraint-Driven Generative Design Methodology for Modular Actuated Robotic Components in Decentralized Manufacturing

Pedro Portugal*

Abstract

This work formalizes a constraint-driven generative design framework for actuator-integrated robotic components intended for decentralized additive manufacturing. Conventional topology optimization typically prioritizes structural efficiency while treating actuator integration, modular interfaces, and fabrication constraints as secondary considerations. In contrast, the proposed methodology encodes these requirements as first-order geometric and mechanical constraints prior to automated material redistribution. The framework defines preserved actuator geometry, bounded design envelopes, representative loading abstractions, and manufacturability-aware domains to guide structural synthesis within physically admissible regions. The mathematical formulation expresses the design task as a constrained mass minimization problem subject to equilibrium, stress, geometric preservation, and manufacturability conditions. By embedding engineering intent directly into the generative problem definition, the methodology ensures that synthesized geometries remain mechanically plausible, assembly-compatible, and fabrication-ready without post-hoc correction. This constraint-driven approach reduces design iteration overhead, improves reproducibility, and aligns generative outputs with the realities of consumer-grade additive manufacturing. Although motivated by actuator-integrated robotic links, the framework is architecture-agnostic and generalizable to a broad class of modular robotic components fabricated under distributed and resource-limited production environments. The approach provides a reproducible foundation for engineering-aware generative synthesis in decentralized robotic hardware development and supports scalable, accessible mechanical innovation across diverse applications and contexts globally.

Keywords: Modular robotics, actuated robotic components, constraint-driven design, generative design tools, decentralized manufacturing, additive manufacturing

INTRODUCTION

Legged robotic systems have been studied for their ability to navigate unstructured environments and maintain stability across various terrains [1]. Their inherent mechanical redundancy provides robustness against uneven ground and partial failures, making them attractive for exploration, inspection, and service applications.

Simultaneously, the mechanical complexity associated with legged locomotion, particularly at the level of actuated joints and load-bearing links, introduces significant challenges in design, manufacturing, and cost, which continue to limit broader adoption beyond research laboratories and specialized industrial contexts.

***Author for Correspondence**
Pedro Portugal
E-mail: pedroportugalsil@gmail.com

[1]Independent Researcher, Department of Mechanical Engineering, Querétaro, 76130, Mexico. (Formerly: School of Engineering and Sciences, Tecnológico de Monterrey)

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In parallel, additive manufacturing (AM), especially fused deposition modeling (FDM), has rapidly matured as a low-cost and flexible fabrication technology capable of producing complex geometries without dedicated tooling [2]. These capabilities enable rapid prototyping, customization, and decentralized production using accessible hardware. Despite these advantages, integrating AM into the mechanical design of robotic components remains challenging. Designers must balance printability, structural performance, material anisotropy, and assembly feasibility, particularly under decentralized manufacturing constraints, where access to industrial-grade materials, post-processing, and precision equipment is limited.

Recent studies have begun to explore the intersection of modular robotics and accessible fabrication technologies, recognizing that modular mechanical architectures can significantly reduce development costs and design complexity while facilitating reuse, repair, and adaptation [3]. At the component level, modular actuated links and joint assemblies allow robotic platforms to be reconfigured, repaired, or upgraded without a complete system redesign. Design-for-additive-manufacturing (DfAM) principles have been increasingly incorporated into such approaches, enabling faster iteration cycles and improved accessibility [4]. Nevertheless, much of the existing literature emphasizes high-level system architecture or application-specific demonstrations, with fewer studies explicitly addressing how decentralized manufacturing constraints, such as home-scale printers, limited material choices, and low-cost actuation, should be embedded directly into the mechanical and kinematic design of individual robotic components.

Concurrently, advances in generative design and topology optimization have highlighted the potential of automated tools for discovering structurally efficient geometries under specified loading and manufacturing constraints [5]. These methods have substantially reduced mass and material usage while maintaining mechanical performance. However, generative approaches alone often yield results that are mechanically impractical when isolated from functional requirements, such as interface geometry, joint alignment, and actuation topology. This limitation is particularly pronounced in actuated robotic components, where dynamic loading, precise joint kinematics, and anisotropic material behavior interact in ways that cannot be resolved through structural optimization alone. Consequently, purely generative solutions may conflict with manufacturability, assembly feasibility, or functional integration, underscoring the need for constraint-driven workflows that incorporate explicit engineering intent.

Beyond these general trends, recent research has increasingly emphasized modular and reconfigurable robot architectures to improve adaptability, maintainability, and resilience [6]. Studies on modular multi-legged robots have demonstrated how reconfigurable leg units can enable morphological adaptation, fault tolerance, and scalable design independent of a fixed body plan [7]. Procedural modeling and stability analyses further emphasize the role of individual mechanical modules, particularly actuated links, as critical units whose structural and kinematic properties strongly influence the overall system performance [8]. These developments align with broader efforts to lower the barrier to entry for legged robotics by simplifying the mechanical design and enabling replication outside specialized laboratories.

At the same time, design automation for AM has progressed toward integrating optimization algorithms and data-driven methods with generative geometry synthesis to better balance performance and manufacturability [9]. Generative tools have been successfully applied to industrial robotic components, demonstrating improved strength-to-weight ratios and reduced material usage while respecting AM constraints [10]. Nevertheless, a key gap remains in systematically guiding generative outputs with explicit engineering intent, particularly in robotic mechanisms where functional interfaces, joint kinematics, and actuation topology are non-negotiable. Without such guidance, generative design risks producing geometries that are optimal in isolation but unsuitable for integration into complex electromechanical systems.

Although topology optimization and generative design have been widely applied to mechanical components, their application in modular robotic systems fabricated under decentralized manufacturing constraints remains insufficiently formalized. Existing approaches typically prioritize structural optimality without explicitly embedding actuator integration, modular interface preservation, or consumer-grade fabrication limitations as primary design constraints.

The novelty of this study lies not in the use of generative design alone, but in the formalization of a constraint-driven methodology that integrates actuator-defined geometry, decentralized AM limitations, and modular interface requirements as first-order inputs to the generative synthesis process. Rather than treating manufacturability and actuator integration as post-hoc considerations, these factors are directly encoded into the generative problem formulation.

This study formalizes a constraint-driven generative design framework that integrates actuator-defined geometry, modular interface preservation, and decentralized AM constraints directly into the structural synthesis process. Rather than presenting generative design as an autonomous form discovery mechanism, the proposed methodology encodes engineering intent as explicit geometric and mechanical priors, ensuring functional compatibility by construction. The following sections define the methodological structure and mathematical formulation of this framework, establishing a generalizable approach for the actuator-integrated robotic component design.

CONSTRAINT-DRIVEN GENERATIVE DESIGN FRAMEWORK

This section formalizes the proposed constraint-driven generative design framework. The methodology is structured as a sequential process comprising baseline definition, constraint formulation, bounded generative refinement, and manufacturing-aware validation. Rather than presenting a case-specific implementation, the following sections define the generalizable procedural logic underlying actuator-integrated component synthesis under decentralized AM constraints.

The baseline component within this framework is defined as a fully specified reference geometry that satisfies kinematic compatibility, actuator integration, and manufacturability requirements before generative refinement. The purpose of this baseline definition is not to achieve structural optimality but to establish a constraint-carrying scaffold that encodes engineering intent and functional interfaces before automated material redistribution.

The AM constraint mode in modern generative design tools incorporates build-direction-aware structural modeling and biases material placement along orientations that improve structural continuity under layer-based fabrication. Although the solver does not explicitly model the full orthotropic material behavior, it accounts for the AM logic by aligning load-bearing members with the specified build direction, thereby improving the structural reliability under anisotropic fabrication conditions.

To bridge the conceptual framework of decentralized manufacturing with robotic component synthesis, a systematic workflow was defined. This methodology, illustrated in Figure 1, abstracts the design process into a modular sequence that prioritizes the preservation of the interface and fabrication constraints. By formalizing these steps—ranging from initial kinematic mapping to generative synthesis and orientation-aware validation—the approach ensures that organic geometries generated by optimization tools remain compatible with the inherent limitations of FDM-based decentralized production. The following subsections detail the methodological structure of this workflow as applied to actuator-integrated structural links.

The diagram outlines the hierarchical stages of the design process, highlighting the integration of structural requirements, manufacturing constraints (e.g., fused deposition modeling (FDM) anisotropy), and generative optimization to achieve high-performance modular components.

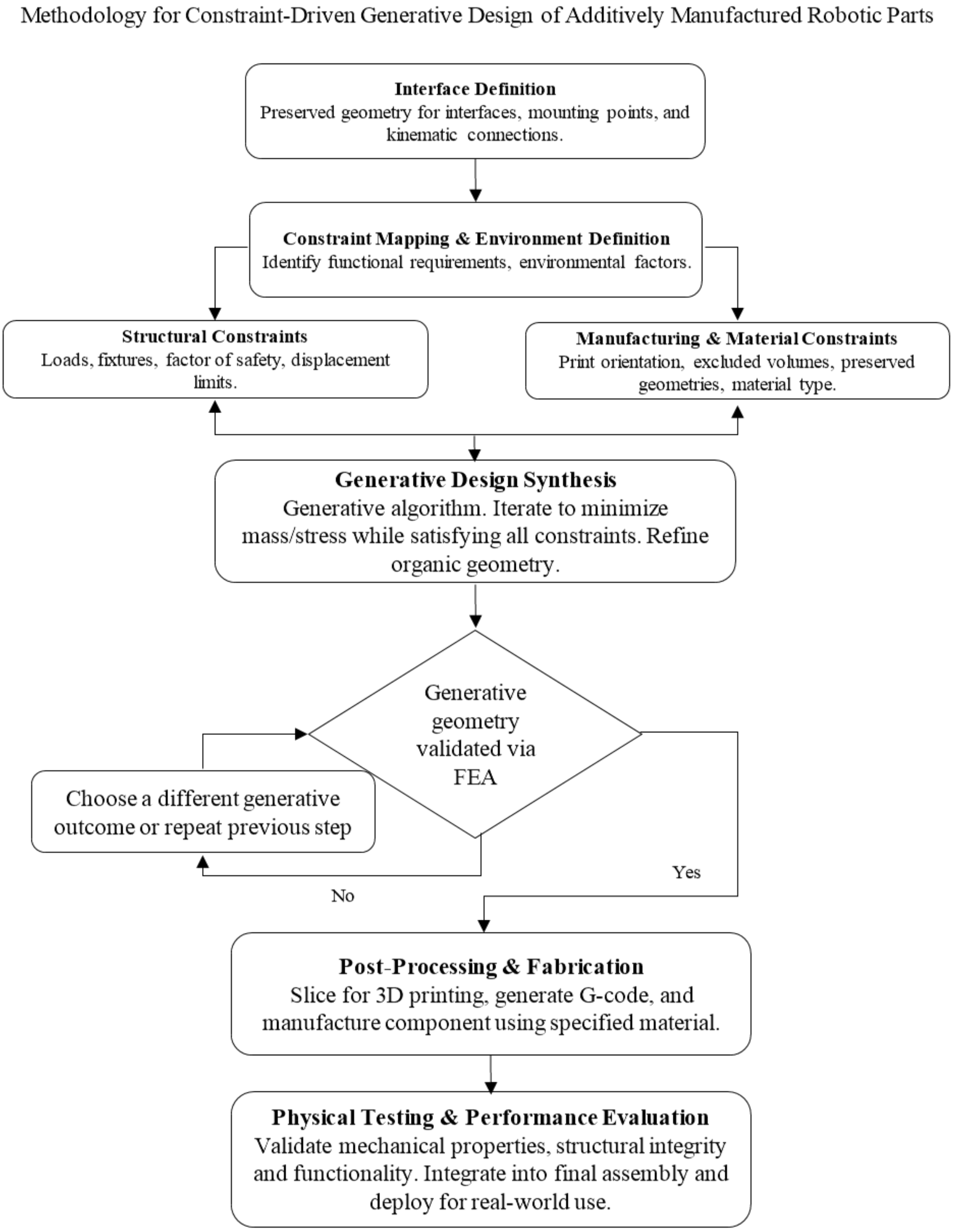

Figure 1. Proposed methodological flowchart for constraint-driven design.

Component Selection and Baseline Modeling

The representative component considered in this methodological formulation corresponds to an actuator-integrated structural link that is typical of legged robotic systems. This abstraction is used to illustrate the constraint formalization without restricting the framework to a specific robot implementation.

The selected component integrates a rotary actuator at one end and a standardized mechanical interface at the opposite end. This configuration captures the essential characteristics of load-bearing links in legged robots: the transmission of bending and torsional loads between joints, precise alignment of actuation axes, and geometric compatibility with modular assemblies. By focusing on this intermediate link archetype, the study targets a class of components known to strongly influence the stiffness distribution, mass placement, and joint loading in multi-legged systems while avoiding dependence on a specific robot architecture or application scenario.

Baseline geometry modeling was conducted prior to any generative or optimization-based operations and served as a reference design for all subsequent stages. The baseline model was constructed as a fully defined manufacturable solid geometry incorporating actuator mounting features, shaft alignment constraints, and a repeatable distal interface. The dimensions and interface features associated with the actuator were defined directly from the manufacturer specifications to ensure realistic mounting conditions and prevent geometric freedom in regions where deviation would compromise kinematic fidelity or assembly feasibility.

Four primary functional requirements guided the definition of baseline geometry. First, precise actuator integration is considered a non-negotiable constraint. The actuator housing region was modeled to ensure coaxial alignment between the actuator output shaft and the intended joint rotation axis. This region included fixed mounting surfaces, fastener locations, and alignment features, and was explicitly excluded from the later geometric modification. This decision reflects the sensitivity of polymer-based actuator housings to misalignment, particularly under cyclic loading conditions, which are typical of legged locomotion.

Second, the baseline component was required to sustain the combined bending and torsional loads transmitted between the joints during the quasi-static stance phases. To accommodate this requirement at the modeling stage, the baseline geometry was defined with continuous material connectivity between the actuator and distal interface regions, avoiding abrupt section transitions or localized thinning. While no structural optimization was applied at this stage, the baseline envelope was shaped to permit clear load transfer paths and avoid geometric features that would artificially bias later generative outcomes.

Third, modularity and interface standardization are explicitly encoded in the baseline definition. The distal interface geometry was modeled as a repeatable mechanical connection independent of any specific downstream component. This interface was designed to support attachment to alternative modules without modification, thereby enabling reconfiguration, replacement, or extension. By decoupling the interface definition from the downstream geometry, the baseline model establishes a modular boundary that can be preserved across multiple design iterations and generative refinements.

Fourth, manufacturability under decentralized FDM conditions was directly embedded into the baseline modeling process. The geometry was constrained to fit within the build volumes typical of consumer-grade FDM printers and was designed assuming common thermoplastic materials with anisotropic mechanical properties. Features known to complicate fabrication, such as fully enclosed cavities, unsupported internal overhangs, and tight tolerance fits, were intentionally avoided. This ensured that the baseline geometry represented a fabrication-ready scaffold rather than an idealized or abstract one.

The resulting baseline component can be described as a prismatic structural envelope with localized volumetric reinforcement around the actuator integration and interface regions. Importantly, this geometry was not intended to be structurally efficient or optimized. Its role within the methodology is to function as a constraint carrier: a fully specified, kinematically valid, and manufacturable reference that encodes the engineering intent prior to the application of generative design tools.

To support the subsequent structural refinement, representative boundary conditions and loading scenarios were associated with the baseline geometry at this stage. The actuator mounting face was designated as a fixed boundary, reflecting attachment to an upstream structure, whereas the resultant forces and torsional moments were defined at the distal interface to approximate the worst-case quasi-static loading during stance. These loading abstractions were selected to inform the relative stress distribution and load-path development in the later stages, rather than to serve as definitive predictors of failure.

Within the overall workflow, the baseline component establishes a methodological foundation for constraint-driven generative refinement. By fully specifying actuator integration, modular interfaces, structural continuity, and manufacturability constraints before introducing automated geometry synthesis, this approach ensures that subsequent design exploration remains grounded in realistic engineering conditions. This separation between baseline definition and generative refinement is central to the methodology, positioning generative tools as a secondary refinement mechanism rather than a primary driver of component architecture.

Constraint Definition and Design Space Formulation

Following the definition of the baseline component geometry described in Section 2.1, the next methodological step consisted of formally translating the functional, structural, and manufacturing requirements into explicit design constraints suitable for generative refinement. The purpose of this stage was to bound the design problem in a manner that preserves actuator integration, modular compatibility, and decentralized manufacturability while still allowing meaningful structural exploration within the remaining free geometry.

The constraint definition was treated as a primary design activity rather than a secondary filtering step. Instead of allowing generative tools to freely explore geometry and subsequently discard infeasible results, constraints are embedded directly into the design space formulation. This approach ensures that all generated outcomes remain compatible with the assembly, actuation, and fabrication requirements intrinsic to the target application.

Preserved Geometry Definition

The first class of constraints concerns the preserved geometry regions. These regions correspond to volumes whose shape, position, and orientation are dictated by kinematic alignment, mechanical interfacing, or assembly requirements; therefore, they cannot be altered without compromising system functionality.

The preserved regions included the actuator housing volume, shaft alignment features, fastener interfaces, and distal modular connection interface. These regions were explicitly defined and excluded from any material removal or redistribution operations during the generative refinement. Their preservation ensured coaxial alignment between the actuator output shaft and the intended joint rotation axis, as well as repeatable mechanical compatibility with downstream modules.

From a methodological perspective, treating these regions as immutable reflects the non-negotiable nature of actuator integration in polymer-based robotic components. Deviations in these zones are known to induce misalignment, increased backlash, and premature wear, particularly when fabricated via FDM. Accordingly, preserved geometry was parameterized directly from manufacturer specifications and standardized interface definitions, and its integrity was maintained throughout the generative process.

Design Space Envelope Construction

A design space envelope was defined to delimit the maximum allowable volume in which material redistribution could occur surrounding the preserved regions. This envelope represents a conservative upper bound on the external geometry of the component, constrained by kinematic clearance, assembly accessibility, and fabrication feasibility.

The envelope was intentionally defined to exceed the minimum material volume required for the load transmission. This choice enables the generative process to explore alternative internal load paths and branching structures while preventing encroachment into forbidden regions, such as actuator clearance zones or interface boundaries. By explicitly bounding the design space, the method avoids the common failure modes of unconstrained generative design, such as the emergence of geometries that are structurally efficient but incompatible with real-world assembly or use.

Importantly, the envelope was not optimized for compactness or mass efficiency at this stage of the study. Its role is methodological rather than performance-driven: to define a safe and functionally admissible region within which generative refinement can operate without violating the mechanical or manufacturing constraints.

Structural Loading Abstractions

The generative design solver was configured using explicitly defined loading and constraint conditions derived from conservative estimates of the leg loading of the robot.

Representative quasi-static loading abstractions were defined at the distal interface, and the actuator mounting interface was treated as a fully constrained boundary. The material properties and safety factors were selected according to the intended thermoplastic material and application-specific reliability requirements. The generative solver enforces equilibrium and stress constraints consistent with these parameters, thereby ensuring structural feasibility within the bounded design domain.

Methodologically, the use of these parameters serves two purposes: First, it reduces the computational complexity, enabling iterative exploration without prohibitive simulation costs. Second, it focuses the generative process on dominant load paths and stress distributions that are most relevant for the early-stage structural synthesis of polymer components. Dynamic effects and transient loading were intentionally excluded at this stage and were treated as downstream validation concerns rather than design drivers.

Manufacturing Constraint Integration

Manufacturing constraints associated with decentralized FDM were directly embedded into the design space definition. These constraints include minimum feature thickness, limits on unsupported overhangs, and exclusion of fully enclosed cavities that would trap support material or compromise print reliability.

Rather than applying these constraints as post-processing filters, they were enforced during the design space formulation to bias the generative process toward fabrication-ready outcomes. This strategy reflects the realities of consumer-grade AM, where excessive support structures, thin unsupported features, or inaccessible internal volumes can negate the accessibility and reproducibility advantages of decentralized fabrication.

The constraint definitions were aligned with conservative DfAM guidelines for mechanically loaded thermoplastic components, prioritizing print success and repeatability over aggressive geometric optimizations.

This study defines a 'decentralized manufacturing context' as any environment utilizing consumer-grade AM hardware (e.g., FDM printers with build volumes typically below 300 × 300 × 300 mm) and widely available thermoplastic filaments such as polyethylene terephthalate glycol-modified (PETG) or polylactic acid (PLA+). By 2026, these tools will have reached a plateau of reliability that allows for highly reliable unattended manufacturing in nonindustrial settings. The methodology assumes no access to post-processing heat treatment or industrial sintering, making the structural plausibility of the design entirely dependent on the optimized geometry and print-parameter synchronization.

Orientation-Aware Constraint Strategy

The material anisotropy inherent to layer-based fabrication was addressed using an orientation-aware constraint strategy. The intended print orientation was selected based on the alignment between the primary load paths and the in-plane filament deposition directions. The design space envelopes and preserved geometry were defined relative to this orientation, ensuring that the critical load-bearing features aligned favorably with the strongest material directions.

This approach avoids the need for detailed anisotropic material modeling while mitigating the most significant effects of interlayer weakness. By treating print orientation as a design parameter rather than a downstream fabrication decision, this method integrates structural and manufacturing considerations within a unified constraint framework.

To account for the inherent material anisotropy of FDM/FFF printing, the generative setup utilized specialized manufacturing constraints within the software (Autodesk Fusion) that accounted for the additive stress planes. The AM constraint mode biases geometric synthesis toward load paths that align with the specified build orientations. Although this does not explicitly model orthotropic material properties, it promotes structural configurations that reduce dependence on interlayer adhesion strength, thereby improving structural robustness under layer-based fabrication conditions. This ensures that the resulting organic geometry is not only optimized for volume but is inherently 'aware' of the weakened interlaminar shear strengths that are typical of 3D-printed thermoplastics.

Methodological Role of Constraint Definition

Collectively, the constraint formulation transforms the generative refinement task from an unconstrained form discovery into a bounded geometry synthesis problem. Material redistribution is permitted only in regions where it does not compromise the kinematic alignment, modular interoperability, or fabrication feasibility.

From a methodological standpoint, this stage is critical because it encodes the engineering intent in a form that generative tools can operate on without eroding the functional requirements. The explicit definition of preserved regions, envelopes, loading abstractions, and manufacturing limits ensures that all generated geometries remain mechanically plausible and fabrication-ready by construction rather than by subsequent selection or correction.

MATHEMATICAL FORMULATION OF CONSTRAINT-DRIVEN GENERATIVE DESIGN

The constraint-driven generative design methodology described in Section 2 can be formally expressed as a constrained structural synthesis problem, as follows: This mathematical formulation abstracts the procedural workflow into a generalized optimization framework independent of any specific implementation or software environment.

The constraint-driven generative refinement procedure can be formally expressed as a constrained structural optimization problem defined over the material domain Ω. Within this framework, the objective is to minimize the structural mass while satisfying the mechanical equilibrium, stress safety, geometric preservation, and manufacturability constraints.

The mass minimization objective is defined as:

$$\min_{\Omega} M(\Omega) \tag{1}$$

Where, $M(\Omega)$ represents the total structural mass as a function of the material distribution in domain Ω.

To ensure structural safety, the maximum equivalent stress must remain below the allowable stress defined by the material yield strength and the prescribed factor of safety (FoS):

$$\sigma_{\max}(\Omega) \leq \frac{\sigma_{\text{yield}}}{\text{FoS}} \tag{2}$$

This constraint ensures that the resulting geometry remains within the elastic operating regime for the applied loading conditions.

Geometric preservation constraints are imposed to maintain the integrity of the actuator interfaces and modular connection regions as follows:

$$\Omega_{\text{preserved}} \subseteq \Omega \quad (3)$$

Where, $\Omega_{\text{preserved}}$ represents the subset of the domain corresponding to the actuator mounting features, alignment interfaces, and standardized modular connection geometry. These regions were excluded from the material redistribution during the generative refinement.

Manufacturing feasibility is enforced through a manufacturability constraint:

$$\Omega \in \Omega_{\text{manufacturable}} \quad (4)$$

Where, $\Omega_{\text{manufacturable}}$ represents the set of geometries compatible with the FDM fabrication constraints, including the minimum feature thickness, allowable overhang angles, and orientation-dependent fabrication limitations.

Structural equilibrium under applied loading is enforced through the governing finite element equilibrium equation:

$$K(\Omega)\mathrm{u} = \mathrm{F} \quad (5)$$

Where, $K(\Omega)$ is the global stiffness matrix dependent on the material distribution, u is the displacement vector, and F is the applied load vector.

In this formulation:

Ω represents the structural material domain

$M(\Omega)$ represents the total mass of the structure

$\sigma_{\max}(\Omega)$ represents the maximum equivalent stress

σ_{yield} represents the material yield strength

FoS represents the Factor of Safety

$\Omega_{\text{preserved}}$ represents preserved geometric regions

$\Omega_{\text{manufacturable}}$ represents the manufacturable design space

$K(\Omega)$ represents the stiffness matrix

u represents the nodal displacement vector

F represents the applied force vector

Collectively, Equations (1)–(5) define a constrained structural synthesis problem in which material redistribution is permitted only within a bounded, physically admissible design space. This formulation ensures that generative refinement produces geometries that simultaneously satisfy the structural safety requirements, actuator integration constraints, and decentralized AM limitations.

DISCUSSION

Impact on Designer Cognitive Load and Iteration Efficiency

A primary advantage of this constraint-driven approach is the significant reduction in the 'trial-and-error' loop typically associated with generative design. In unconstrained optimization, designers often receive high-performance geometries that are fundamentally unprintable or incompatible with existing hardware, necessitating manual 'post-hoc' remodeling that erodes the time-saving benefits of automation. By encoding functional non-negotiables, such as actuator housing and interface clearances, directly into the initial design scaffold, the methodology shifts the designer's effort from fixing broken geometry to evaluating structurally sound alternatives.

This preservation of engineering intent ensures that the generative tool serves as a high-fidelity assistant rather than an autonomous but impractical form generator, a distinction that is critical for rapid development in decentralized manufacturing environments.

Design Guidelines Derived from the Study

Based on the structural behavior implied by the constraint-driven formulation and bounded generative synthesis strategy, a set of transferable design guidelines can be distilled for actuator-integrated modular robotic components fabricated under decentralized AM conditions.

These guidelines are not intended as prescriptive rules but rather as transferable design principles grounded in the structural implications of the proposed constraint-driven formulation.

First, actuator integration regions should be treated as non-negotiable preserved geometries from the earliest stages of the design process. This formulation demonstrates that enforcing the strict preservation of actuator housings, shaft alignment features, and mounting interfaces prevents the propagation of misalignment and stress amplification, which commonly arise when these regions are included within unconstrained optimization domains. For polymer-based components fabricated via FDM, this preservation is particularly critical, as minor geometric deviations can result in disproportionate losses in joint reliability and service life.

Second, modular interfaces should be defined independently of the downstream geometry and maintained unchanged throughout the generative refinement. The study shows that when the interface geometry is treated as a fixed prior, structural variation can occur within the connecting body of the component without compromising interoperability. This enables iterative structural improvement while preserving compatibility across modules, supporting long-term system evolution, reconfiguration, and repair, which are key requirements in modular robotic architectures.

Third, generative design spaces should be bounded by conservative envelopes that encode kinematic clearance, assembly access, and fabrication limits rather than being defined solely by minimum material requirements. The observed generative outcomes indicate that envelope-based formulations encourage the emergence of continuous and interpretable load paths while preventing the formation of geometries that are structurally efficient but practically unusable. This approach shifts the role of generative tools from unrestricted optimization to guided structural refinement aligned with engineering intent.

Fourth, representative quasi-static loading envelopes are sufficient for the early-stage structural synthesis of actuator-integrated polymer components. The stress distributions obtained under simplified stance-phase loading were effective in identifying the dominant load paths and reducing stress localization without the computational overhead of a full dynamic simulation. In decentralized and rapid-iteration contexts, this tradeoff provides a pragmatic balance between physical fidelity and design efficiency.

Fifth, manufacturability constraints must be embedded directly into the design space, rather than applied as a post-hoc filter. This ensures that the generated geometries remain fabrication-ready by construction and prevents the emergence of structurally efficient but physically unrealizable configurations.

Sixth, the intended print orientation should be treated as a structural design parameter, not merely a fabrication decision. Aligning the design space with the primary load paths mitigates the effects of material anisotropy inherent to layer-based fabrication and improves structural reliability without increasing design complexity. The results suggest that even without advanced anisotropic material modeling, orientation-aware constraint definitions yield tangible improvements in load distribution and stress management.

Finally, generative refinement should be evaluated not only on numerical performance metrics, such as mass reduction or peak stress, but also on structural interpretability and fabrication robustness. The selected outcome demonstrates that clearly legible load paths and conservative feature dimensions provide a more reliable basis for real-world deployment than marginal gains in the optimization objectives. This criterion is particularly relevant in distributed manufacturing environments, where reproducibility and tolerance to variability often outweigh absolute-performance optimization.

These guidelines articulate a design philosophy in which generative tools augment, rather than replace, engineering judgment. By foregrounding constraints derived from actuation, modularity, and fabrication realities, designers can leverage generative refinement to produce mechanically credible, interoperable, and fabrication-ready components suitable for decentralized robotic systems. As such, the guidelines provide a practical foundation for extending the presented workflow to other actuator-integrated modules and robotic platforms operating under similar constraints.

CONCLUSIONS

This study formalized a constraint-driven generative design framework for actuator-integrated robotic components fabricated under decentralized AM constraints. By defining preserved geometric regions, bounded design envelopes, structural loading abstractions, and manufacturability domains prior to geometry synthesis, the methodology reframes generative design as a bounded structural refinement process, guided by explicit engineering intent.

The mathematical formulation presented herein expresses the design task as a constrained structural synthesis problem in a physically admissible material domain. This formalization ensures that actuator integration, modular interface fidelity, and fabrication feasibility are preserved throughout the automated material redistribution, eliminating the need for post-hoc geometric correction.

Although motivated by actuator-integrated components relevant to legged robotic systems, the framework is architecture-agnostic and can be extended to manipulators, underwater robotic modules, aerial robotic structures, and other actuator-constrained mechanical subsystems. By embedding functional non-negotiables directly into the generative problem definition, the proposed methodology establishes a reproducible and transferable foundation for manufacturing-aware robotic component design in distributed and resource-limited production environments.

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Data Availability Statement

No further data is provided for this paper.

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AI-assisted tools were exclusively used for minor grammatical and stylistic refinement. All technical content, methodology, design work, simulations, fabrication, and analysis were performed and verified by the author, who assumes full responsibility for the scientific content of this study.

Conflicts of Interest

The author declares no conflicts of interest.

Abbreviations

FDM	Fused deposition modeling
AM	Additive manufacturing
DfMA	Design-for-additive-manufacturing
FoS	Factor of safety

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