

APPLICATION OF GENERATIVE DESIGN AND DIGITAL IMAGE CORRELATION FOR PART OPTIMIZATION AND MECHANICAL TESTING

Nenad Mitrovic¹ Aleksandra Mitrovic² Zaid Alhashmi³

Abstract: Generative design has emerged as a transformative approach in engineering, enabling the creation of highly optimized components with complex geometries that are well-suited for additive manufacturing (AM). This study examines the integration of generative design, AM and digital image correlation (DIC) for iterative part optimization and mechanical performance validation. By leveraging generative design algorithms, parts can be optimized for weight reduction, material efficiency, and structural performance. The rapid prototyping capabilities of AM facilitate swift fabrication of both original and redesigned components, allowing for direct comparison through experimental testing. DIC, as a noncontact full-field measurement technique, plays a pivotal role in validating numerical models by capturing detailed strain distributions under various load conditions. This paper presents a comprehensive framework that highlights the interdependence of these technologies, reviews challenges and advances, and outlines future directions for refining the mechanical design cycle through enhanced data-driven workflows.

Keywords: Generative Design, Additive Manufacturing, Digital Image Correlation, Part Optimization, Mechanical Testing.

1. INTRODUCTION

Modern engineering demands lightweight and high-performance components, especially in sectors such as aerospace, automotive, and biomedical engineering. With increasing expectations for efficiency, sustainability, and innovation, engineers often encounter the limitations of traditional design methods, which can lead to suboptimal solutions due to restrictive constraints and inherent limitations of human intuition. These constraints can include difficulties in exploring nonintuitive geometries, limited manual optimization capabilities, and reliance on time-consuming iterative prototyping processes. Additionally, the use of traditional materials and production methods may not always align with new performance demands. These multifaceted challenges highlight the need for a paradigm shift toward a more holistic and data-driven approach that combines computational tools, advanced manufacturing, and precise experimental validation to bridge the gap between design theory and real-world performance [1].

Generative design represents a transformative tool to overcome these limitations by automating the exploration of potential solutions based on performance criteria. By iterating through a wide range of possibilities, it identifies optimal configurations that meet engineering goals and considers parameters such as material usage, weight, and load constraints. This process enables the discovery of novel structures that surpass conventional designs in efficiency and performance. The generative design process can be compared to a highly sophisticated brainstorming session performed by software, where thousands of potential solutions are evaluated and refined. It enables engineers to explore complex, non-intuitive designs that were previously unattainable due to the limitations of manual design approaches. Moreover, the ability to quickly test these iterations through simulation enhances the speed of the design process, allowing the selection of top-performing candidates for further analysis and fabrication[2].

Once a design is chosen, the complexity of its geometry often requires additive manufacturing (AM), commonly known as 3D printing, for production. Unlike conventional manufacturing methods that remove material to shape a part, AM builds components layer by layer, enabling the fabrication of intricate designs that are difficult or impossible to create using subtractive processes. This layer-wise approach supports internal channels, lattice structures, and organic shapes that maximize strength-to-

¹Full professor, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, nmitrovic@mas.bg.ac.rs

²Professor, Academy of Applied Studies Polytechnic, Novi Beograd Section, Blvd. Zorana Djindjića 152 a, 11070 Belgrade, Republic of Serbia, email: amitrovic@politehnika.edu.rs

Associate Professor, University "Union – Nikola Tesla", Belgrade, Republic of Serbia

³PhD student, University "Union – Nikola Tesla", Belgrade, Republic of Serbia, eng.zaid.alhashmi@gmail.com

weight ratios. AM turns theoretical models into tangible components, transforming previously impossible designs into physical realities while also reducing material waste and offering rapid prototyping capabilities. Additionally, AM allows for customization and the efficient creation of parts with minimal lead time. However, printing quality and post-processing challenges still need to be addressed for full-scale adoption [3].

However, verifying the mechanical performance of these intricate designs requires precise and robust testing methodologies, both before and after the application of a generative design. Digital Image Correlation (DIC) is a key technology in this regard, providing a benchmark for initial component behavior and tracking improvements made by optimized designs. DIC provides full-field, noncontact strain measurements, capturing the deformation behavior of parts under load with unparalleled accuracy. During pre-design testing, DIC reveals how stress and strain are distributed across conventionally designed parts, identifying areas of over-engineering or underperformance. On the contrary, post-design DIC testing validates whether the optimized geometries produced through generative design improve load distribution and eliminate weak points. By comparing strain maps before and after optimization, engineers can gain deeper insights into how generative design impacts real-world performance and make data-driven adjustments to further refine the design [4–7].

The integration of generative design, AM, and DIC creates a cohesive system for advanced engineering workflows. This paper presents a theoretical exploration of this integration and illustrates how these technologies can redefine parts optimization, validation, and performance analysis. By interconnecting design generation, fabrication, and experimental validation, this approach promises to improve design efficiency, reduce development cycles, and push the limits of what is mechanically possible.

2. GENERATIVE DESIGN FOR PART OPTIMIZATION

Generative design is an advanced computational approach that employs algorithms to automatically create multiple design solutions based on user-defined criteria, such as:

- Design space and boundary conditions.
- Load cases and mechanical constraints.
- Target objectives, such as weight reduction, strength, and stiffness.

Unlike traditional CAD-based design, where the user manually refines the part geometry, generative design iterates computationally to produce optimized topologies that meet performance targets. This approach is especially beneficial for weight-sensitive applications, where achieving optimal mass-to-strength ratios is critical.

The principles of generative design, such as Iterative Design Exploration, Topological Freedom, and Performance-driven Optimization, demonstrate how computational algorithms can streamline the design process and create innovative solutions. These foundational elements define how generative design reshapes the engineering landscape by automating the search for efficient structures, enabling unconventional geometries, and adhering to strict performance constraints. Below is an overview of these key concepts:

- **Iterative Design Exploration:** Generates thousands of design permutations and narrows down the most efficient solutions based on performance goals and constraints. This approach mirrors an automated brainstorming process where software explores novel configurations that a human designer might not consider. The iterative nature also enables rapid evaluations of trade-offs between competing objectives, such as weight reduction and stiffness.
- **Topological Freedom:** Produces unconventional, organic geometries that often outperform traditional structures. Generative design's ability to create highly optimized topologies—such as lattice structures and voids—improves material distribution while maintaining mechanical strength. These topologies can enhance cooling, reduce vibration, and provide multi-functional components in sectors such as aerospace and medical devices.
- **Performance-driven Optimization:** Ensures that each design iteration adheres to mechanical constraints and performance goals. Unlike manual design adjustments, generative design

integrates constraints such as load paths, safety factors, and fatigue resistance into its computational process. This ensures that the final design balances innovation with reliability, making the generated parts viable for critical applications.

3. ADDITIVE MANUFACTURING FOR RAPID PROTOTYPING

The complexity of generatively designed parts often necessitates the use of advanced additive manufacturing techniques such as selective laser sintering (SLS), stereolithography (SLA), and fused deposition modeling (FDM). This reliance on AM stems from its ability to realize intricate geometries that traditional methods cannot achieve. Additive manufacturing offers several advantages, including:

- **High Geometric Freedom:** Enables the realization of intricate shapes, including internal lattice structures and organic geometries that are impossible to achieve using traditional manufacturing techniques. This allows for more precise control over stress distribution and weight optimization.
- **Part Consolidation:** Facilitates the integration of multiple parts into a single component, reducing assembly time, potential weak points, and overall cost while improving mechanical performance.
- **Material-specific Customization:** Supports printing strategies tailored to specific generative design requirements, including the use of lightweight alloys, reinforced polymers, or advanced composites that improve performance under various load conditions.

These advantages underscore the role of AM as a critical enabler for generative design applications, helping to bring complex designs from concept to reality efficiently and effectively by bridging the gap between digital models and physical components. AM's capability to produce detailed, precise geometries while minimizing material waste and enabling customization significantly enhances the feasibility of generatively designed parts, making it an indispensable part of modern engineering workflows.

However, while AM offers rapid production capabilities that allow both the original part and its generatively designed counterpart to be manufactured quickly for experimental comparison, it also introduces challenges such as anisotropic mechanical properties, residual stresses, and potential defects that must be addressed to ensure reliable performance. This rapid cycle of fabrication and testing highlights limitations of traditional measurement methods, making DIC a crucial tool in providing precise, full-field strain analysis and bridging the gap between experimental validation and design iteration.

4. DIGITAL IMAGE CORRELATION FOR MECHANICAL TESTING

Digital Image Correlation is an advanced optical measurement technique used to track the deformation of a specimen by analyzing changes in a speckle pattern applied to its surface. This method enables precise measurement of how materials respond to mechanical loads and is particularly effective in capturing subtle deformations across complex geometries. The ability to provide non-contact, full-field measurements makes DIC essential for validating both conventional and generatively designed parts. The key benefits of DIC for mechanical testing include:

- **Non-contact Measurement:** DIC does not interfere with the specimen during testing.
- **Full-field Strain Mapping:** Captures strain distribution over the entire surface, revealing localized stress concentrations and deformation modes.
- **High Accuracy and Versatility:** Provides precise measurements of displacement and strain under various loading conditions.

DIC is especially effective for testing generatively designed parts due to their often-irregular geometries, which can be difficult to instrument with traditional strain gauges. For in-plane strain measurements, 2D DIC provides accurate data across flat or planar surfaces, allowing engineers to monitor strain distribution and deformation precisely [8–10]. However, for out-of-plane deformations and more complex, three-dimensional geometries, 3D DIC offers a robust solution, capturing depth-

related displacements and strains in intricate structures [11]. This dual capability makes DIC invaluable for evaluating stress concentrations at weak points identified by computational simulations and provides a comprehensive toolset for validating the mechanical performance of advanced designs.

5. THEORETICAL FRAMEWORK FOR INTEGRATION

The proposed framework for integrating generative design, AM, and DIC centers on optimizing part performance and accelerating mechanical validation. By leveraging the rapid fabrication capabilities of AM, original and redesigned components can be quickly produced and subjected to comparison tests. This approach enables precise evaluation of improvements in load distribution and mechanical behavior. However, traditional measurement methods struggle to capture the full deformation fields needed for such comparisons. Here, DIC plays a crucial role, providing comprehensive strain analysis for both in-plane and out-of-plane measurements. This integration creates an efficient feedback loop that supports iterative design refinement and part optimization through experimental insights. The framework involves the following steps:

1. **Design Generation:** This step involves carefully defining the design space, material properties, and load cases, considering any practical constraints such as maximum allowable stresses and fabrication feasibility. Generative design software is used to explore and create a range of optimized parts, each iteration fine-tuned to achieve optimal performance characteristics based on specific goals such as weight reduction and durability.
2. **Manufacturing:** After selecting the most promising design, the part is fabricated using appropriate AM techniques tailored to the design's complexity. This phase includes considerations for build orientation, layer thickness, and post-processing steps to mitigate defects such as porosity or warping. The rapid nature of AM allows for quick fabrication of both baseline and optimized parts, facilitating faster experimental testing cycles.
3. **Mechanical Testing:** The fabricated part undergoes comprehensive mechanical testing to evaluate its performance under various load conditions, such as tensile, compressive, or fatigue tests. Digital Image Correlation is employed to capture full-field strain and displacement data, providing detailed insights into the mechanical behavior across the entire surface of the part. This step enables precise identification of stress concentrations and deformation patterns, which are crucial for validating the design improvements.
4. **Validation and Iteration:** Compare experimental DIC data with simulated strain results from finite element analysis (FEA). The DIC measurements provide crucial feedback for verifying and refining numerical models, ensuring that the simulations accurately reflect real-world behavior. When discrepancies between expected and observed performance arise, the results inform targeted design adjustments to address weaknesses. This process may involve revisiting earlier steps, refining constraints, or adjusting material properties. Once improvements are made, the design is re-tested, starting a new iteration cycle from the design generation phase to validate changes and further optimize performance.

This iterative process enables the identification of potential failure points by comparing DIC results with FEA simulations and guides targeted improvements to refine designs for enhanced mechanical robustness. By using DIC data to validate the numerical model and inform design modifications, this approach facilitates restarting the workflow from the initial design generation phase, ensuring continuous improvement through successive iterations.

6. FUTURE DIRECTIONS AND CHALLENGES

The integration of generative design, AM, and DIC has unlocked significant potential for part optimization and validation, but further progress requires addressing remaining gaps and leveraging emerging opportunities. Future efforts should focus on enhancing the synergy of these technologies to refine the iterative design process further. Some promising directions include:

- **Digital Twins:** Virtual representations of physical components that integrate real-time data from DIC to update numerical models and simulations continuously. These digital twins can improve predictive accuracy and support more effective design adjustments.
- **Improved Material Models:** Development of more accurate models for AM materials that capture their non-linear and anisotropic behavior, facilitating better predictions during FEA.
- **Automated Design Feedback Loops:** Machine learning algorithms integrated with DIC data could automate error detection and suggest refined designs.
- **Real-time Data Processing:** Enhanced real-time DIC data processing to enable faster analysis and feedback during mechanical testing, reducing iteration times.
- **Multi-material AM Integration:** Expanding capabilities to include hybrid multi-material AM processes for components requiring different mechanical properties within a single part.

Additionally, collaborations aimed at creating open-source DIC software and standardized testing frameworks may encourage broader adoption across different industries. By focusing on these aspects, the integration of generative design, AM, and DIC can be refined to address complex challenges and unlock more effective solutions in the future.

The application of generative design, AM and DIC faces several challenges that must be addressed for widespread adoption. Generative design can produce highly optimized yet complex geometries, but the computational cost and the need for accurate boundary condition definitions can be significant hurdles. Additive manufacturing, while enabling intricate designs, may introduce material anisotropy, residual stresses, and fabrication defects that complicate performance predictions. Meanwhile, DIC, despite its precision, requires careful calibration, high-resolution imaging, and substantial data processing power. The integration of these technologies also poses challenges related to the synchronization of data flows, real-time feedback loops, and the need for cross-disciplinary expertise. Addressing these challenges through improved algorithms, material modeling, and automation will be key to harnessing the full potential of this combined approach.

7. CONCLUSION

The integration of generative design, additive manufacturing, and digital image correlation presents both significant potential and notable challenges for optimizing and validating high-performance mechanical components. While this approach enhances the design process from initial concept to experimental validation, it also requires precise alignment of each step to overcome issues related to computational costs, material behaviors, and data synchronization. By addressing these challenges and leveraging the strengths of each method, engineers can iteratively refine their designs and develop lightweight, efficient, and robust components for diverse applications. This paper emphasizes the need for refined workflows and highlights key advancements that can drive improvements in simulation accuracy, manufacturing precision, and experimental validation.

Future research should focus on addressing current limitations and developing automated, data-driven workflows that seamlessly integrate simulation, fabrication, and testing. By addressing these areas, future research can refine workflows, enhance predictive capabilities, and unlock new opportunities for improving the synergy between generative design, AM, and DIC.

8. REFERENCES

- [1] Thompson, M.K.; Moroni, G.; Vaneker, T.; Fadel, G.; Campbell, R.I.; Gibson, I.; Bernard, A.; Schulz, J.; Graf, P.; Ahuja, B.; et al. Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints. *CIRP Annals* **2016**, *65*, 737–760, doi:<https://doi.org/10.1016/j.cirp.2016.05.004>.
- [2] Pilagatti, A.N.; Atzeni, E.; Salmi, A. Exploiting the Generative Design Potential to Select the Best Conceptual Design of an Aerospace Component to Be Produced by Additive Manufacturing. *The International Journal of Advanced Manufacturing Technology* **2023**, *126*, 5597–5612, doi:[10.1007/s00170-023-11259-7](https://doi.org/10.1007/s00170-023-11259-7).

- [3] Bahnini, I.; Rivette, M.; Rechia, A.; Siadat, A.; Elmesbahi, A. Additive Manufacturing Technology: The Status, Applications, and Prospects. *The International Journal of Advanced Manufacturing Technology* **2018**, 97, 147–161, doi:10.1007/s00170-018-1932-y.
- [4] Sutton, M.A.; Orteu, J.-J.; Hubert W., S. *Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications*; Springer, 2009; ISBN 9788578110796.
- [5] Mitrovic, N.; Petrovic, A.; Milosevic, M. Strain Measurement of Pressure Equipment Components Using 3D Digital Image Correlation Method. In *Proceedings of the Procedia Structural Integrity*; Elsevier B.V., 2018; Vol. 13, pp. 1605–1608.
- [6] Tanasić, I.; Šarac, D.; Mitrović, N.; Tihaček-Šojić, Lj.; Mišković, Ž.; Milić-Lemić, A.; Milošević, M.; Mišković, Milić-Lemić, A.; Milošević, M. Digital Image Correlation Analysis of Vertically Loaded Cylindrical Ti-Implants With Straight and Angled Abutments. *Exp Tech* **2016**, 40, 1227–1233, doi:10.1111/ext.12156.
- [7] Tanasic, I.; Milic-Lemic, A.; Tihacek-Sojic, L.; Stancic, I.; Mitrovic, N. Analysis of the Compressive Strain below the Removable and Fixed Prosthesis in the Posterior Mandible Using a Digital Image Correlation Method. *Biomech Model Mechanobiol* **2012**, 11, 751–758, doi:10.1007/s10237-011-0348-5.
- [8] Mitrovic, N.; Mitrovic, A.; Reljic, M. Strain Measurement of Medical Textile Using 2d Digital Image Correlation Method. In *Lecture Notes in Networks and Systems*; 2021; Vol. 153, pp. 447–464.
- [9] Mitrović, N.; Mitrović, A.; Travica, M. Tensile Testing of Flat Thin Specimens Using the Two-Dimensional Digital Image Correlation Method. *Structural Integrity and Life* **2023**, 23, 9–13.
- [10] Mitrović, N.; Golubović, Z.; Mitrović, A.; Travica, M.; Trajković, I.; Milošević, M.; Petrović, A. Influence of Aging on the Flexural Strength of PLA and PLA-X 3D-Printed Materials. *Micromachines (Basel)* **2024**, 15, doi:10.3390/mi15030395.
- [11] Popovic, D.; Mitrovic, N.; Petrovic, A.; Milosevic, M.; Momcilovic, N. Sustainable Development of Pressure Equipment Using 3D Digital Image Correlation Method. *Chemical Industry and Chemical Engineering Quarterly* **2020**, 26, doi:10.2298/CICEQ190124006P.