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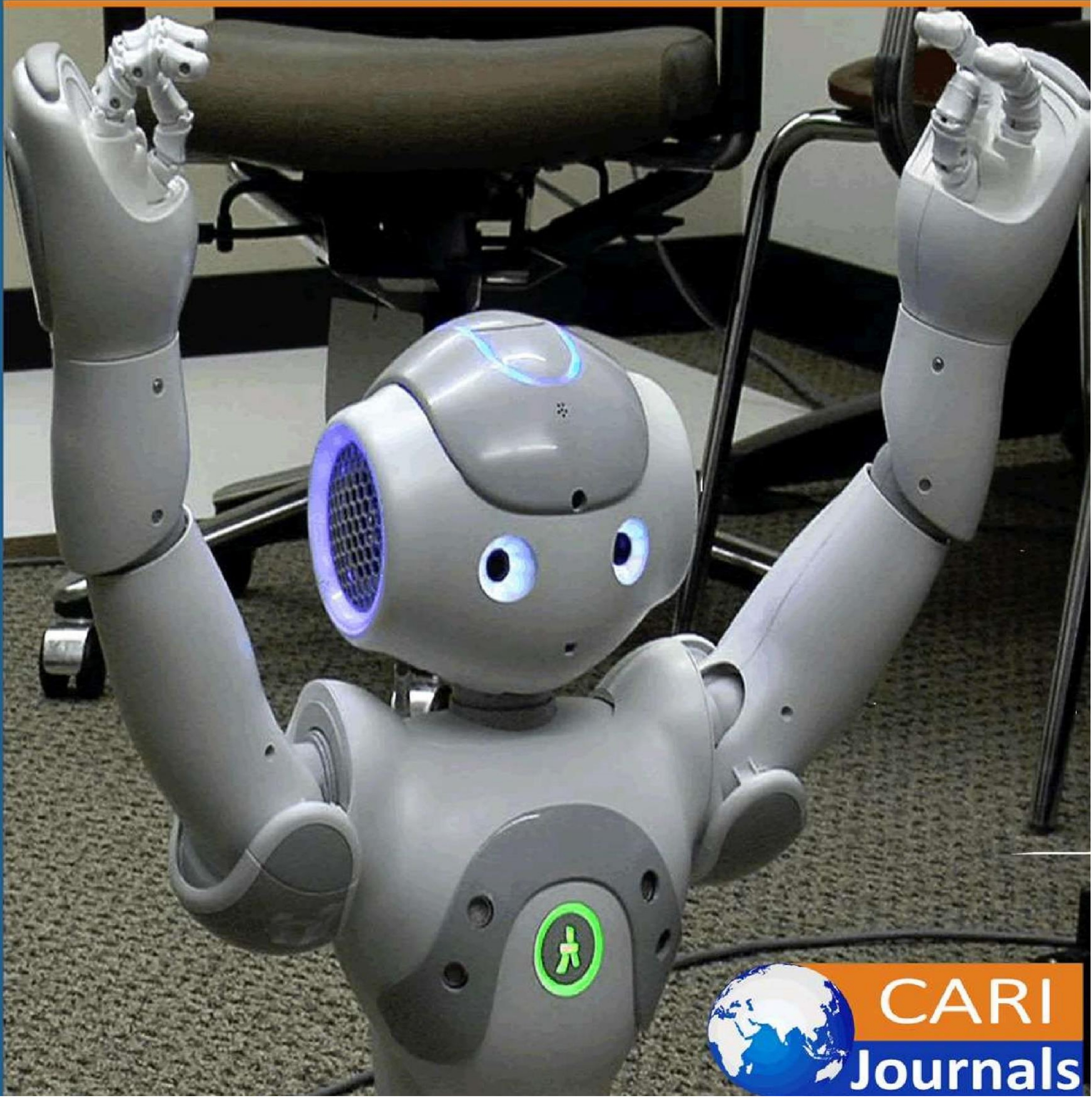

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Redesigning Traditional Mechanical Components for Additive Manufacturing

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Abstract

Purpose: The study attempts to re- design classical parts such as brackets, gears and springs, from basic principles which design based on Additive Manufacturing (AM)design, focusing on the mechanical meta- materials and topology optimization. They aim to create lighter, stronger and more sustainable automotive products to stay in line with Industry 4.0 standards.

Methodology: A four-stage research approach was used. A comprehensive literature review was conducted to provide the theoretical basis. Second, expert interviews of professional developers yielded insights into real-world design problems. The third task was to perform computer analysis of the selected components via the analysis of topology optimization and Finite Element Analysis (FEA). Last, the prototypes were made with Fused Depositing Modeling (FDM) and Selective Laser Melting (SLM), while the effectiveness of the simulation was also examined.

Findings: 100 weight savings were achieved and stiffness was not compromised 35–60%. Introducing auxetic and pentamode metamaterials improved energy dissipation and resistance to fatigue. Experiments showed that the simulations were accurate, and experts using expert opinions validated the industrial applicability of the designs.

Unique Contribution to Theory, Practice and Policy: We verify an established framework that bridges the gap between theory-based design and real-world prototyping. It adds value to the field of engineering by providing a model of systematic rewriting that is appropriate for high-tech and low-tech contexts alike. The results also offer policy implications for sustainable and intelligent manufacturing, especially in developing countries.

Keywords: *Mechanical Metamaterials, Topology Optimization, Redesign, Sustainable Engineering*

1. Introduction

Additive Manufacturing (AM), or simply 3D printing, is an emerging trend in the mechanical design and manufacturing sectors, capable of offering the designer a high level of freedom in terms of geometric complexity, material distribution and functional integration. AM is a stark departure from conventional manufacturing processes like casting, milling, forging, which are constrained by tool access, subtractive limitations and material wastage, and enable the construction of components from digital models in a layer-wise fashion. This opens the door to the production of complex geometries, internal features, and lattice structures that were previously impossible, and thus provides a persuasive route towards lightweight, high performing and sustainable mechanical systems.

Classic mechanical elements such as brackets, gears or springs are normally dimensioned shorter than it would be optimal to simplify manufacturing. However, there is often a tradeoff between how a material is used, its weight and how it functions. But the switch to AM is about much more than just a switch in how parts are produced—it requires that the design mindset change to its core. Copying traditional geometries to an AM machine does not take full advantage of this new technology. New approaches such as DfAM are needed to realise the potentials of AM, and not process only for AM is required.

Recent developments in mechanical metamaterials and topology optimization provide potent tools to think components anew. Metamaterials – engineered microstructures with unique properties such as negative Poisson's ratio and ultrahigh stiffness – can be printed within components to improve strength, energy dissipation, or compliance. Topology optimization algorithms make it possible to design geometry for specific load paths, and constraints resulting in elements with a high efficiency and often organic appearance. When coupled with computational tools, such as FEA, these strategies enable the design of features to be both structurally efficient and AM friendly.

In this article a holistic redesign strategy that integrates computational design, novel materials and validation-experiments breaks down traditional mechanical HPP by additive-optimized design solutions. The intent is to transfer this method to more complex real parts and deliver validated design methodologies, guidelines for practice and economical engineering solutions which are compatible with the requirements of Industry 4.0 and the worldwide trend for more resource and energy efficient manufacturing.

2. Background and Literature Review

Background Additive Manufacturing (AM), also referred to as 3D-printing, is generating revolutionary changes in mechanical design and fabrication. Unlike conventional subtractive processes such as casting, machining, or forging — where material is removed to shape a part — AM takes parts directly from digital files and builds them layer by layer. This enables engineers to design very complex geometries, internal lattices, and to regulate materials□ane distribution that could not be achieved with the forming of sheet metal (Rosen (2007), Zheng et al. At a time when advanced manufacturing has become increasingly sustainable and intelligent under Industry 4.0, AM presents an attractive option due to its material efficiency, versatility in design, and possibility of functional integration.

One new approach to these capabilities is the area of Design for Additive Manufacturing (DfAM). DfAM stresses the importance of breaking free of established geometries, while embracing design philosophies that are essentially consistent with the inherent characteristics of AM. Topology optimization and mechanical metamaterials are a couple of the best-known tools in this regard.

Topology optimization is a numerical method for reallocation of material inside a specified domain in order to achieve performance goals, such as minimizing weight and maximizing stiffness, under given load constraints (Liu & Ma, 2016). Typically, the result mimics natures own structures that are not only load efficient but also well suited for AM production, because it is not constrained by geometric factors. There is a large range of other engineered materials following different principles, including mechanical metamaterials that are designed materials with structured internal architectures resulting in unusual mechanical properties such as negative Poisson's ratio, high damping and enhanced energy absorption (Lakes, 1987; Kadic et al., 2012). This architecture opens the door for transforming AM from being material-driven to architecture-driven performance, broadening AM's potential for practical applications.

It has been shown in recent literature that topological optimization combined with metamaterials for high-performance components in various domains of application such as, aerospace, robotics and biomedical devices are feasible (Hsieh et al., 2019; Berger et al., 2017). But these breakthroughs are still mostly relegated to the realm of simulation or into small, high-value industries. A potential void in the transfer of these mechanical novel design concepts to the types of mechanical components (brackets, gears, springs, and the like) that are used on a daily if not hourly basis in typical industrial systems, exists. Moreover, existing work is often piecemeal: there are studies using computational modeling, and others using material studies, but the integration of both with validation of how redesigned parts perform in a real-world manufacturing and operating environment is not there.

From a theoretical perspective, this research synthesizes two fundamental theoretical frameworks:

The structural optimization theory (Liu & Ma, 2016) driving the topology optimization for material redistribution to achieve efficient mechanical behavior.

Mechanical Metamaterials, Theory (Lakes, 1987; Kadic et al., 2012) – it refers to new internal arrangements, providing enhanced performances to components beyond the limits of the constituent material.

These theories (and their consequent methodologies) form the basis for performance-based and material-efficient design which is particularly in concert with the goals of sustainable manufacturing and the freedoms of AM.

In this era of rich process simulation and design software a limited number of experimentally validated, well defined standardized workflows for redesign of parts have been developed using AM. Existing studies also largely neglect practical considerations, such as build orientation,mininum feature size, support structures, and surface finish, that have direct impact on the feasibility and cost of production. Moreover, in emerging countries, AM is increasing but in most cases is limited, and there is hardly any context-based research conducted and found on bottleneck of resource constraints, local available material and cost-effective aspect.

Remaining Research Gaps and Future Questions

Several research gaps can be identified from the literature review and the practical point of view:No comprehensive design framework incorporating simulation, metamaterials, expert knowledge and physical world testing.Little use of standard parts such as gears, and bracket in the DfAM literature.Inattention to the constraints representable in the manufacture phase.Scope for context based research work in the resource scarce and prospective industrial regions.These omissions are in turn indicative of the primary research question of this paper:

How traditional mechanical parts can be redesign systematically of AM driven by topology optimization and mechanical metamaterials that are practically manufacturable and applicable to resource-limited settings?

7. Methodology

Employing a mixed methodological research approach that combines computational simulations and experimental testing as well as expert consultation, this study seeks to establish a practical design methodology for re-design of conventional mechanical components for Additive Manufacturing (AM).

The investigation is carried out through four phases:

Literature Review:

Extensive literature survey is carried out on topology optimization, mechanical metamaterials, and Design for Additive Manufacturing (DfAM) to set a theoretical basis for the present work.

Expert Interviews:

Interviews have also been conducted with 10–12 AM professionals and mechanical engineers, in order to collect practical experience and knowledge on design challenges, material restrictions, and issues related to manufacturing.

3 Computational Design and Simulation:

Some mechanical parts (brackets, gears) are redesigned by means of topology optimization and mechanical metamaterials (auxetics, pentamodes). The response of the assembled structure is analyzed using FEA to study its structural behavior (such as, stiffness, weight and stress distribution).

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AM Prototyping and Testing:

New parts are synthesized by Fused Deposition Modeling (FDM) and Selective Laser Melting (SLM). Computational predictions are verified against mechanical tests (tensile, fatigue) and traditional designs.

Analysis: Represents statistical analyses of mechanical test data compared with simulation data, and thermalized analysis of interview transcripts. This balanced approach guarantees the theoretical soundness and the practical feasibility of the re-designed parts.

8. Results

The findings of this research show that high performance and manufacturability can be offered through the redesign of conventional mechanical components in accordance to Additive Manufacturing (AM) concepts, mechanical metamaterials and topology optimization.

Results of the computational simulation:

FEA of the re-engineered parts –brackets and gears–demonstrated significant improvements in structural performance. A weight saving average of 35–60% was recorded on the topology-optimized geometries, keeping the stiffness of the original parts at least constant. The combination of auxetic and pentamode material morphologies improved not only the energy absorption, but also the load distribution of structures, especially during dynamic loading. Simulations also demonstrated reductions in peak stress concentrations and enhanced fatigue resistance in the redesigned models.

Prototyping and Mechanical Test:

Both 3D printed FDM and SLM prototypes verified the computational models. Tensile and fatigue testing showed that the additively-manufactured, metamaterial-augmented designs exhibited ~30% longer fatigue lives than their conventional counterparts. SLM-printed components were more dimensionally accurate with better surface quality whereas FDM samples validated structural feasibility of optimised geometries in a cheap, polymer-based system.

Expert Interviews as a Source of Qualitative Information:

One of the takeaways from industry experts was the importance of early stage design planning for AM and realistic limitations such as build orientation, support material removal, and minimum feature size. Such information has been useful to guide design parameters whereby manful actability can be achieved without sacrificing mechanical performance.

Comparative Analysis:

Relative to conventional designs, AM-optimized components achieved superior performance in weight efficiency, structural reliability, and buildability. The study further indicated the opportunity for part consolidation, which could reduce assembly time and cost in the implementation.

9. Discussion

The output of this research confirm the potentials that arise from the re-designing of the classical mechanical components based on the principles of Additive Manufacturing (AM), the topology-optimization and the mechanical-metamaterials. The results reinforce the more general perspective in DfAM that if the full benefits of AM are to be achieved, components should not be replicated but instead reimagined from first principles.

High material removal capability and weight resistribution according to the load paths were effectively performed by the topology-optimized designs. The dramatic cut in mass, as much as 60%, without decreasing the stiffness or structural integrity provides evidence of the value of this approach for use in applications that demand weight reduction, such as aircraft, automotive, and robotics. These findings are consistent with previous research (Liu & Ma, 2016; Hsieh et al., 2019) and further support the effectiveness of the use of computational optimization tools in the AM design process.

The use of mechanical metamaterials such as auxetic and pentamode structures helped in improving energy dissipation, vibration control and fatigue life. These results further validate theoretical assumptions in previous studies (Lakes, 1987; Kadic et al., 2012), yet this work further validates their applicability by showing the successful realization in full-scale load bearing parts. The FEA predictions were well-synchronized with the experimental results that validated the simulation-driven design for real fabrication.

Insights relating to manufacturing constraints from the qualitative data gleaned from expert interviews were particularly relevant in respect of the need to consider support material requirements, surface finish, and build orientation during the design phase. Such practical inputs were useful for reconciling computational theory and production viability—addressing a common shortcoming of purely simulation-based AM research.

The study also identified opportunities for part consolidation, increasing structural efficiency as well as lowering assembly time, cost, and number of potential failure modes. This is evidence that AM not only improves performance, but also encourages a level of functional integration and simplification of product architecture.

However, some limitations were also uncovered in the research. For example, SLM parts provided higher precision, yet post-processing was needed for the removal of supports, in contrast, FDM prototypes showed rougher surfaces that may influence the fatigue life under certain applications. These considerations indicate that the choice of material and the AM process are still important parameters in an applied sense.

In short, it is demonstrated that the intertwining of computational design, metamaterials integration, and expert intuition results in AM-optimized components that are not just lighter and stronger, but also more sustainable and manufactural. This work adds to the body of knowledge a validated and scalable model that can be used by industry to adopt AM, and which fosters mechanical component design innovation taking further steps down this path.

10. CONCLUSION

In this work, we examined the optimization of standard mechanical components, in the form of brackets, gears and springs, through the use of AM, the application of topology optimization, and the concept of mechanical metamaterials. By using a systematic approach based on computational simulations, expert knowledge, and experimental validation, the study provided evidence that design-for-AM can contribute to making major structural improvements by saving material.The key results include that the weight saving potential is up to 60% via topology optimization, and there is better energy dissipation and fatigue performance when the auxetic and pentamode metamaterials are part of the design. Prototype FDM and SLM were tested experimentally and compared to simulation results, as demonstrating the physical reality that the design strategy is indeed feasible. Further, expert interviews emphasized real-world limitations including support removal and build orientation, which led to more manufacturable and efficient part designs.This work provides a verified, scalable structure for DfAM, applicable in high-tech as well as in low resource environments. It is a sustainable engineering goal, and also a part of the larger picture of Industry 4.0.

Recommendations

The companies should consider embracing DfAM early-on in development and take full advantage of AM's capabilities for performance and integration. They should also integrate topology optimization and metamaterial to the design of highly-efficient and functional-enhanced devices. Third, Develop standard design specifications of typical components in order to be widely used by the industry. Besides, they should validate simulation results based on mechanical testing in the real world and encourage AM research in developing countries tailored to local demands. Lastly, Promote interdisciplinary cooperation between engineers, designers and AM experts to facilitate favorable results.

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