Return to Menu

Targeted Structural Optimization With Additive Manufacturing of Metals

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Sponsoring Program(s)

Space Technology Mission Directorate
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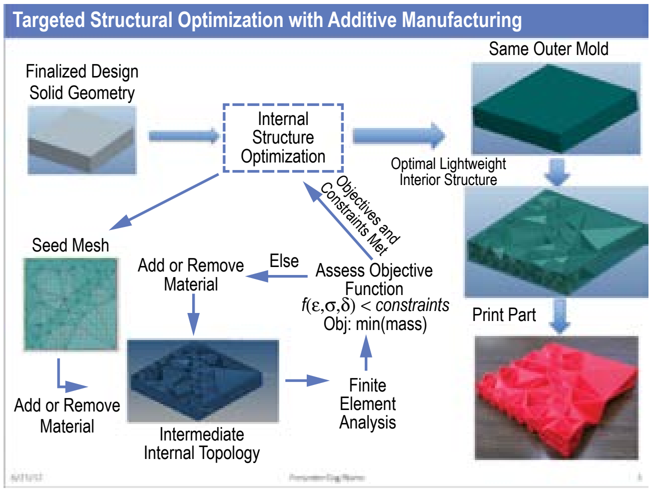
Project Description

The recent advances in additive manufacturing (AM) of metals have now improved the state-of-the-art such that traditionally nonproducible parts can be readily produced in a cost-effective way. Because of these advances in manufacturing technology, structural optimization techniques are well positioned to supplement and advance this new technology. The goal of this project is to develop a structural design, analysis, and optimization framework combined with AM to significantly lightweight the interior of metallic structures while maintaining the selected structural properties of the original solid. This is a new state-of-the-art capability to significantly reduce mass, while maintaining the structural integrity of the original design, something that can only be done with AM.

In addition, this framework will couple the design, analysis, and fabrication process, meaning that what has been designed directly represents the produced part, thus closing the loop on the design cycle and removing human iteration between design and fabrication. This fundamental concept has applications from lightweighting launch vehicle components to in situ resource fabrication.

This design automation and optimization framework is akin to a field of research known as topology optimization combined with a variation of shape optimization. Topology optimization is often used to minimize the mass required by a part while maintaining the overall stiffness required for the structure by removing unloaded material. This area has seen a plethora of attention in the literature and academia and has been implemented in many commercial applications in the general sense. The research activity proposed here effectively combines topology with AM, resulting in minimal mass hardware, and furthers this area by using adaptive mesh refinement with shape optimization, which is a relatively new area of research.

The process is simple in thought; typically structural analysis utilizes the finite element method. This process discretizes continuum structures into discrete solid elements to perform an analysis that will determine the overall strength of the structure. The core of the idea is this. What if, using these solid elements, the solid fill could be removed, but the defining faces of that solid remain as shells? The part will now be lighter, with a similar overall strength and stiffness. This is essentially the core concept behind grid-stiffened structures; this time the outer profile remains intact to maintain form, fit, and function. In traditional manufacturing, this concept is impossible to implement without joining panels, adding complexity and cost, but AM can easily achieve this.



Automation and optimization framework.

The process begins with a part that has already been designed to meet form, fit, and function and is considered to be mature in the design cycle, meaning all applicable requirements (loads, environments, etc.)

have been estimated. The first step in the optimization is to produce a 3D finite element model using tetrahedral elements and run an analysis to determine where material is not being fully utilized. From there, the optimization will begin removing material by converting tetrahedral elements to 2D shell elements with a minimal thickness, thus hollowing the element and removing inefficiently utilized mass. The newly formed shell model is then rerun in the analysis and assessed and ranked based upon an objective function. This loop is repeated until convergence is met. A 3D computer-aided design model of the optimized internal topology is then generated automatically. The outer mold and new internal topology are passed to the AM process to be produced. This concept stands on the shoulders of two well-grounded areas of research, structural optimization and stiffened structures. There is much literature and technical work to draw upon in these disciplines. The goal of this project is not to reinvent either concept, but to utilize all research available in these areas and fine-tune its application through a novel combination with AM.

Anticipated Benefits

Investment in this research will result in developing an enabling technology for AM. Breaking the boundaries here will position NASA Marshall Space Flight Center (MSFC) to continue being a leader in this community and make strides toward being able to produce flight parts or structures entirely by AM.

In addition to this, successful completion of the work outlined in the project will lead directly to follow-on work. Called out in this project is to specifically focus on structural strength aspects of this process, but once this concept is proven, extensions can be made to other areas such as thermal and dynamic design problems. Once this Center Innovation Fund is completed, more attention can be given to structural strength considerations and what problems remained to be solved to make this process acceptable for the production of flight hardware.

Potential Applications

This project will develop a supporting technology that will aid in the structural design process. By extension, the results have a broad scope of application that aligns with many Center strategic priorities. Several key areas of high impact have been identified. Lightweighting metallic structures on International Space Station (ISS) payloads can dramatically reduce up-mass and therefore decrease costs of payloads being delivered to the ISS and allow cargo vehicles to carry more: (1) Advanced manufacturing within in situ fabrication repair —This process would help on-orbit manufacturing by reducing the amount of material needed to build a component and therefore help to limit the amount of raw material needed; (2) Rapid, innovative affordable manufacturing of propulsion components—AM has already been used successfully in a hot-fire of a rocket engine at MSFC. Increasing capabilities of AM would be beneficial to this effort; (3) Affordable and innovative technologies for sample return—A key aspect to sample return is maximizing structural efficiency so as to minimize the amount of propellant needed to be carried on the mission. This technology will support that goal; and (4) Small Spacecraft Enabling Technologies—The ability to both lightweight spacecraft as well as tailor structural properties could be highly useful in the design of spacecraft. Ultimately, this sort of technology could be used to produce small spacecraft chassis entirely by AM.

Notable Accomplishments

The framework for the optimization process was laid out. Several algorithms were developed that allowed creation of a design space that would be suitable for use with a genetic algorithm. The optimization routine is being tuned for the specific problem and manufacturing constraints are in the process of being incorporated into the optimization routine.

References

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