Generative Design and Digital Manufacturing: Using AI and robots to build lightweight instruments

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ABSTRACT

Digital Engineering technologies are transforming long-stagnant development processes by applying the tremendous advancements in Information Technology (IT) to classical engineering tasks such as design, analysis, and fabrication of space-flight instrument structures. Generative Design leverages developments in Artificial Intelligence (AI) and Cloud computing to enable a paradigm shift in the design process, allowing the engineer to focus on defining the requirements and objectives of the design while AI generates optimized designs which comply with the input requirements. Digital Manufacturing allows these complex lightweight designs to be efficiently manufactured by directly fabricating from the resulting 3D models. The development of these two Digital Engineering technologies realizes significant mass savings while simultaneously reducing structure development time from months to days. This paper describes the development of the Evolved Structures process applying these technologies to spaceflight optical instrument structures including an example demonstrating greater than 10x reduction in development time/cost and greater than 3x improvement in structural performance.

Keywords: Generative Design, Digital Manufacturing, Topology Optimization, Evolved Structures, AI

1. INTRODUCTION

Development of spaceflight missions, especially instruments, is extremely expensive. The International Space Station total cost is ~$150B and the total mass is 444,600kg, yielding a cost/mass ratio of $337K/kg [1]. For the James Webb Space Telescope (JWST) this cost/mass ratio is $1.7M/kg [2]. Developing larger and more powerful instruments within relatively fixed budgets requires radical reduction in development cost. To further this goal for spaceflight structures, the Evolved Structures process has been developed at NASA GSFC. This process has three primary steps:

1. Digitally encode structure requirements into software
2. Use Generative Design AI to evolve optimal designs
3. Fabricate parts directly from CAD models using Digital Manufacturing processes (software + robotics)

As demonstrated by the examples below, this process has realized a greater than 10x reduction in development time/cost while simultaneously improving structural performance (mass/stiffness/strength) by greater than 3x. This radical improvement is enabled by the tremendous advancements in Information Technology (IT) and leverages Commercial off-the-shelf (COTS) software and industrially developed fabrication processes.

1.1 Generative Design

Generative Design is an iterative design process that generates multiple design outputs based on input constraints. OpenAI's Dall-e is an example of Generative Design for images (see Figure 1) [3]. Generative AIs have been applied to the fields of art, music, architecture, and structures. For structures, all leading CAD vendors are developing Generative Design products due to the power and relative maturity of the underlying algorithms. The examples in this paper were designed using Autodesk Fusion 360 Generative Design Extension which has the following capabilities:

- Allows the use of gravity-loaded remote masses to represent mounted components. Using this method allows for a simplified and conservative zero-stiffness representation of the mounted components, which are often of unspecified or changing structural design.
- Directly creates fully manufacturable and editable Boundary Representation (B-Rep) CAD geometry as opposed to tessellated geometry, which is less precise and more difficult to modify.
- Allows direct editing of the organic shapes generated via T-spline manipulation.
- Has design constraints for 2.5 axis, 3 axis, and 5 axis CNC machining in addition to Additive Manufacturing (AM) constraints. This allows mature and low-risk aerospace materials and processes to be used for fabrication.

Figure 1. OpenAI's Dall-e generates multiple images based on the input requirements, in this case, a text prompt describing the desired image. The AI generates several options for the desired armchair including novel concepts such as using the avocado's seed as a pillow.

For Generative Design of structures, the requirements digitally encoded into the design study may include (1) desired mass (2) minimum factor of safety (3) interfaces with other components (4) keep-out zones (5) structural loads (6) minimum natural frequency (7) materials and (8) manufacturing processes.

Generative Design is not a replacement for CAD or Finite Element Analysis (FEA), but rather an abstraction layer on top of these previous technologies as illustrated in Figure 2. One key underlying technology, itself an abstraction layer on top of FEA, is Topology Optimization. Topology Optimization effectively eliminates low stressed elements from a Finite Element Model (FEM) by iteratively running static stress analysis. The two leading Topology Optimization techniques are Solid Isotropic Material with Penalization method (SIMP) and Level Set [4], with Level Set being the newer method generally yielding superior results in terms of both performance and manufacturability.

1.2 Digital Manufacturing

Digital Manufacturing processes fabricate parts directly from CAD models, with minimal human direction. For subtractive manufacturing, such as Computer Numerically Controlled (CNC) milling, Computer Aided Manufacturing (CAM) software ingests the CAD model and outputs a program instructing the milling robot how to move, often in the industry-standard gcode language. The milling robot (CNC machine) then executes the gcode, sometimes requiring intermediate changes in fixturing depending on the part complexity. CNC technology is very mature and simulations of the machining process validate the gcode with high reliability.

Similarly, for Additive Manufacturing (AM, also called 3D printing) CAD models are ingested into software, usually called a slicer due to the layered nature of AM, and a machine program is output, often using the same gcode language developed for CNC. The AM robot then executes the program to create the part. While the generating gcode for AM is often faster and more automatic than for CNC, the validation technology is still developing. It is common to iterate on AM fabrication due to unexpected failures during printing. Metal AM is generally a less mature technology with more manufacturing parameters than CNC. See Section 3 for additional comparison between CNC and AM.

1.3 NASA GSFC's Evolved Structures process

Through Internal Research and Development (IRAD) funding, GSFC has developed a process for digitally encoding requirements, including NASA standards, into Generative Design studies, resulting in ready-to-fabricate optimized parts being developed in as little as 2 hours. The process addresses common GSFC instrument application needs including light path avoidance, thermal isolation, development of quasi-static load cases, bonded joints, and bolted joints. A comparison between a typical development process for instrument structures, and the Evolved Structures process is shown in Figure 3.

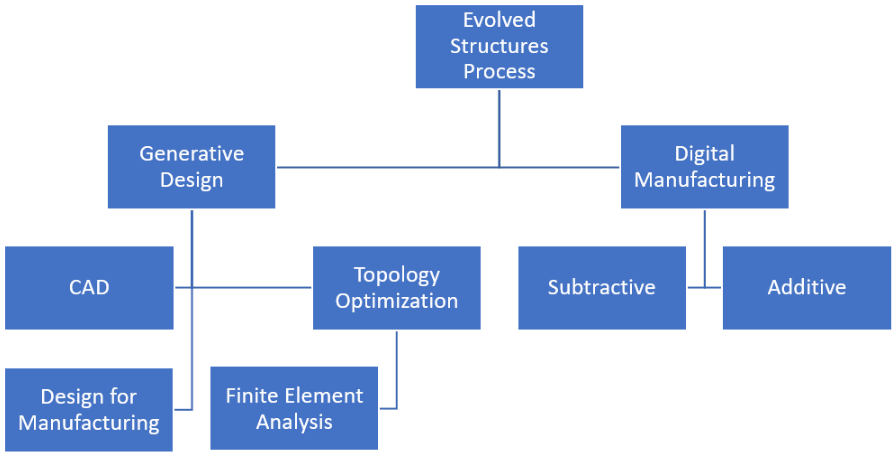


Figure 2. Hierarchy of structural design technologies.

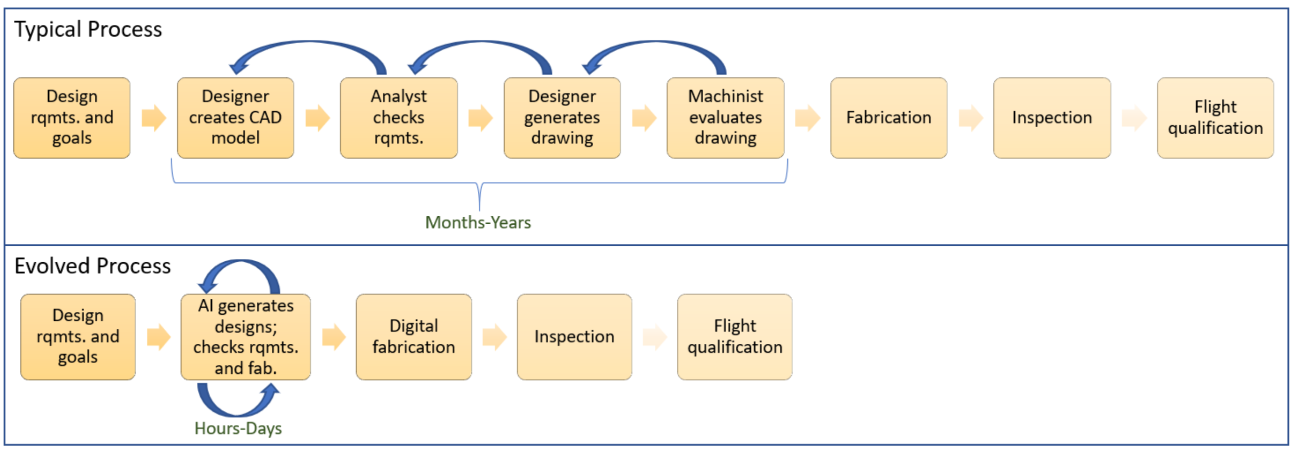


Figure 3. Comparison of a typical development process for instrument structures, and the Evolved Structures process. Iterations between multiple people/organizations are automated into a single process, yielding optimal designs faster.

2. EVOLVED STRUCTURES EXAMPLE: EXCITE TIP/TILT BRACKET

An early application of the Evolved Structures process at NASA GSFC was the Tip/Tilt Bracket from the EXCITE balloon mission, which performs spectroscopy of exoplanets [5]. This section describes the application requirements, compares human and AI designs, and gives results from vibration and static load testing.

2.1 Application description

The EXCITE Tip/Tilt bracket is an example of a common structure needed for instruments. The Tip/Tilt assembly redirects light from the telescope into the dichroic, where it is split to enter the fine guidance star camera and cryostat/science detector. It must be mounted to the back of the telescope with the following requirements.

1. Interface to Tip/Tilt assembly bolt pattern (4x ¼ -20 bolts)
2. Interface to back of telescope (3x ¼-20 bolts)
3. Avoid interfering with Tip/Tilt assembly or associated light paths
4. Survive chute-shock maximum loads; 10g vertical (x), 3g lateral (y and z) applied to 1.35 kg Tip/Tilt assembly.
5. First mode >100 Hz to avoid cryo-cooler excitation
6. Bracket mass target 0.2 kg

2.2 Human vs AI design comparison

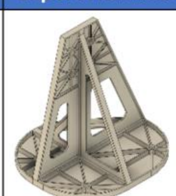
The design problem was completed by expert human engineers; a design engineer and structural analyst iterated together to both develop the CAD model and check requirements compliance with FEA. Design for Manufacturing (DfM) was checked by uploading the geometry to online tools including Xometry and Protolabs. It is common at GSFC for design, analysis, and manufacturing to be performed by separate internal or external organizations.

The resulting design consists of two flat plates in the mounting planes joined by ribs to stiffen the structure. As shown in Table 1, the first iteration was too heavy, so pockets were added to lightweight the design. In the third iteration, the pockets were tuned to increase stiffness. The fourth iteration is a radically different design which meets requirements, but is not readily manufacturable by either CNC or AM.

The inputs using the Evolved Structures process with Fusion 360 are illustrated in Figure 4. The interface requirements are represented with the green Preserve geometry (which must be kept in the final design) and the red Obstacle geometry (which must be avoided). Room for the bolts is specifically reserved with the cylindrical red Obstacles. Constraints and loads are applied similar to a typical FEA. Not shown are the goal function (maximize stiffness at 0.2 kg) and the manufacturing constraints (CNC machining or AM from aluminum).

As shown in Table 1, the AI designs are superior to the expert human designs in every respect. Only the first iteration of the human designs was readily manufacturable, though the second and third iterations could be made manufacturable by adjusting the pocket designs. The AI designs were both readily fabricated; see Figure 5 for photos of the hardware under test. Excluding the unmanufacturable fourth human iteration, the stiffness/mass ratio of the AI designs is >3x better (240 Hz/kg for the third human iteration vs. 740 Hz/kg for the AI-CNC design and 885 Hz/kg for the AI-AM design). The maximum stress of the AI designs is also reduced by 7x for the AI-CNC design and 9x reduced for the AI-AM design. Performance improvements of these magnitudes are rarely seen in the field of mechanical design. Most impactful however is the speed with which the designs were completed. The human designs took two days of effort by two engineers. The AI design took about 30 minutes of effort from one engineer to encode the requirements and about 1 hour of effort from the Generative Design AI, demonstrating an order-of-magnitude improvement in development time/cost.

Table 1. Expert human vs. AI designs of the EXCITE Tip/Tilt Bracket. The human designs were developed over two days by two expert humans (designer and analyst). Both AI designs were completed in about 1 hr. The AI designs are stiffer, stronger, and easier to manufacture.

Designer	Expert Humans	Expert Humans	Expert Humans	Expert Humans	AI	AI
Design						
Iterations	1	2	3	4	31	31
Mass (kg)	0.59	0.18	0.27	0.18	0.2	0.2
1st Mode (Hz)	137	37	65	108	147	177
Max Stress (MPa)	26.3	189	103	60.7	14.8	11.2
Manufacturing	CNC $1700, 3 weeks	CNC No quotes	CNC No quotes	CNC/AM No quotes	CNC $1000, 3 days	AM $2000, 3 weeks

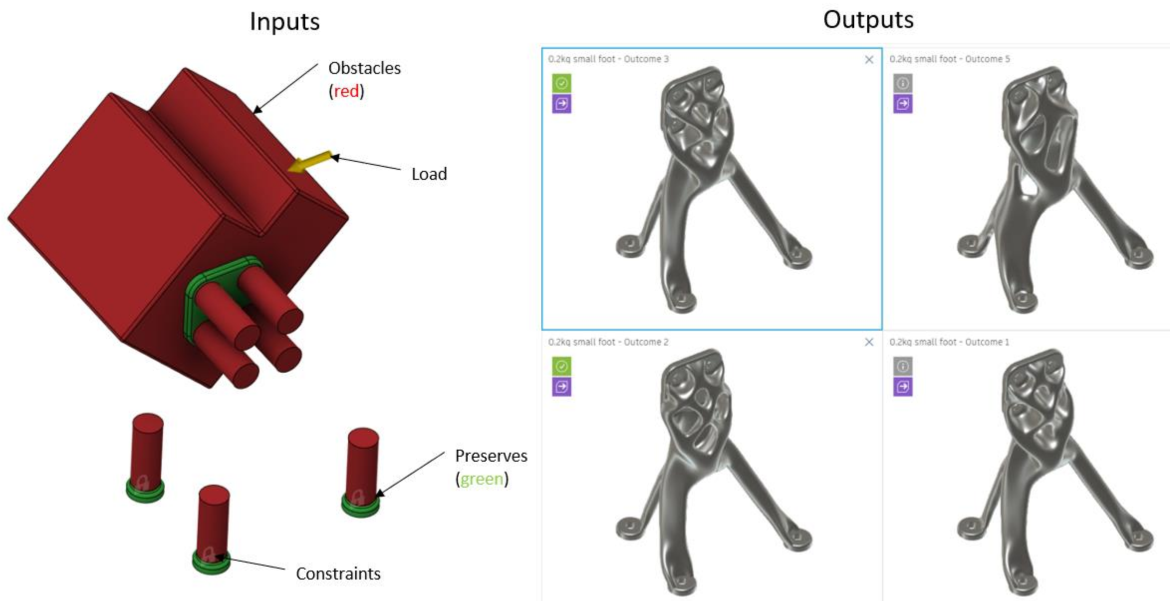


Figure 4. Left: inputs to Generative Design include interfaces, loads, design objectives, and manufacturing constraints. Right: Multiple manufacturable designs meeting requirements are autonomously generated.

2.3 Test results

Four variations of the EXCITE Tip/Tilt bracket were fabricated and selectively tested as shown in Figure 5 and Table 2. Both 5-axis and 3-axis CNC machined versions were made from Aluminum 6061-T651 and the two AM versions (of the same design) were made from AlSi10Mg and A6061-RAM2.

For the three brackets vibration tested, the first mode was within 3% of FEA predictions, which is generally considered good correlation at GSFC. As predicted, the AM part was significantly stiffer due to the more optimal geometry enabled by the greater design freedom of AM. Failure loads however were much higher than predicted, generally over 200% higher (e.g. Yield load predicted vs Yield load actual in Table 2). This discrepancy is likely due to the conservative approach to finding maximum stress on an individual node in FEA. In Evolved Structures, the maximum stress is usually highly localized around the interface locations, while the rest of the part has relatively low stress, as a result of topology optimization. To better correlate the failure load to FEA predictions, average stress over a larger number of elements is required. Detailed correlation of FEA with test results is beyond the scope of this paper. The key result is the parts are stronger than predicted. Another obvious trend in the load test data is that the CNC part tested is significantly stronger than the AM parts, despite predictions to the contrary. This may be due to more accurate material properties being available for 6061-T651 material vs. the AM materials which can have process dependence and were taken from manufacturer data sheets. The A6061-RAM2 part is slightly stronger than the AlSi10Mg part of identical design, but not as much as predicted.

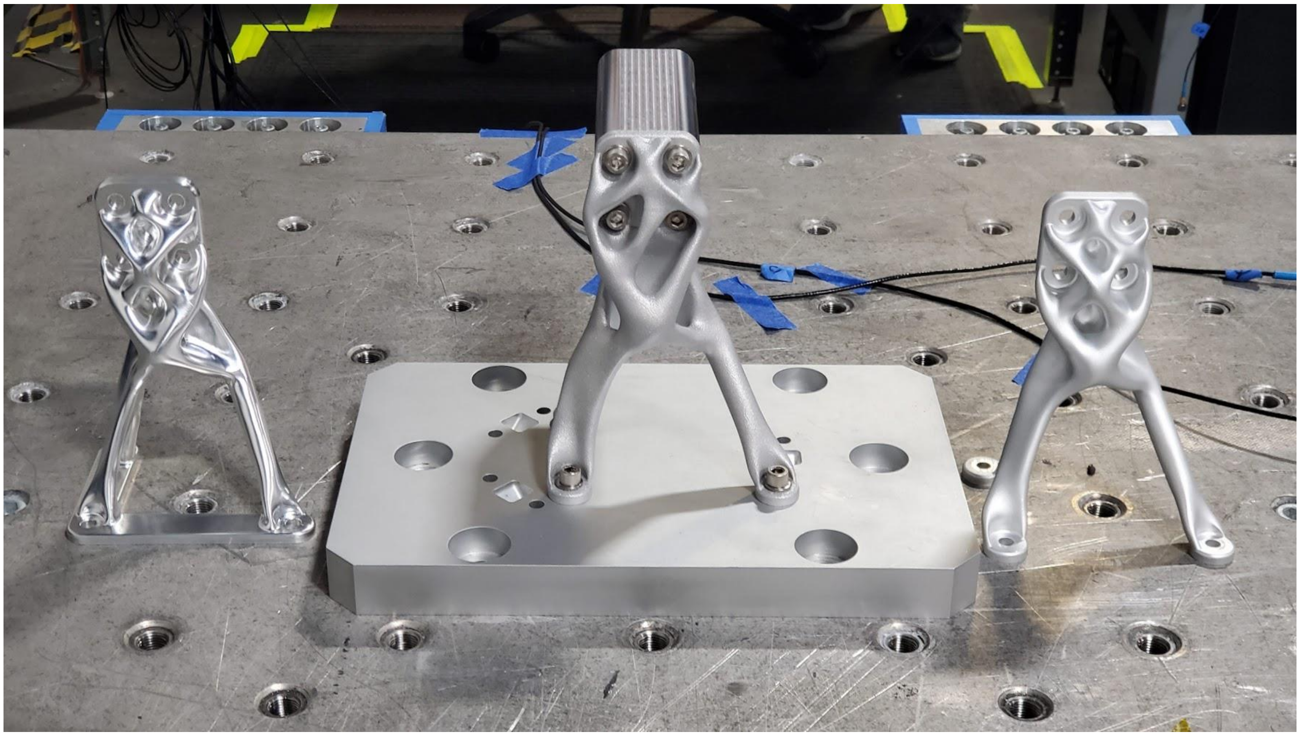


Figure 5. Three designs of the EXCITE Tip/Tilt bracket were vibration tested. A 5-axis CNC version with a flat base was manufactured by Zero Hour Parts (left), an AM version was manufactured by 3D Systems (center), and a 3-axis CNC version was fabricated by Protolabs (right). Test performance matched linear static FEA predictions.

Table 2. Four versions of the EXCITE Tip/Tilt bracket were fabricated and tested. First mode predictions were within 3% of actuals. While the AM versions of the design were stiffer, the CNC version was stronger.

Version Name	CNC-5axis	CNC-3axis	AM-AlSi10Mg	AM-A6061
Material	Al 6061-T651	Al 6061-T651	AlSi10Mg Stress relieved	A6061-RAM2 Stress relieved
Manufacturing process	5-axis CNC	3-axis automated CNC	Laser Powder Bed Fusion (L-PBF)	Laser Powder Bed Fusion (L-PBF)
Manufacturer	Zero Hour Parts	Protolabs	3D Systems	3D Systems
Manufacturing time	3 weeks	3 days	3 weeks	3 weeks
Inspection	CMM + 3D scanning	CMM + 3D scanning	CT + 3D scanning	CT + 3D scanning
Mass (kg)	0.2	0.2	0.2	0.2
1^{st} Mode predicted (Hz)	133	147	177	183
1^{st} Mode actual (Hz)	137	152	178	NA
Yield load predicted (N)	NA	2564	1744	3454
Yield load actual (N)	NA	7424	5823	6139

3. OTHER APPLICATION EXAMPLES

The Evolved Structures process was applied to 20 other applications on a variety of GSFC instrument, a selection of which are shown in Figure 6. Development time/cost and performance improvements realized were similar to those demonstrated by the EXCITE Tip/Tilt bracket example. Recent applications were more complex, such as the ALICE optical bench, which consolidated 7 parts into one. Vibration tests of additional applications also yielded similar results; vibration modes were accurately predicted by FEA and parts survived the required loads without failure.

Figure 6. Other applications of the Evolved Structures process include the EXCITE radiator bracket (top left), the EXCITE cryostat mount (top center), the ALICE Optical Bench (top right), the STAR-X detector mount (bottom left), the CCRS diode bracket (bottom center), and the NGXO mirror mount (bottom right).

Surprisingly, the organic shapes that result from Generative Design were readily CNC machined. In only one application, the EXCITE cryostat mount, did AM prove critically advantageous. CNC machining a large monolithic titanium part (~600x400x200mm) was prohibitively expensive due to the large billet and extensive machining time required. Currently, AM suffers the following disadvantages vs. CNC machining.

- Limited choice of AM vendors due to developing marketplace and technologies
- Material properties can be process dependent, i.e. the same part/material from multiple vendors may have different strengths depending on the AM machine/software used
- Tolerances are poor compared to CNC, frequently resulting in the need for post-printing CNC machining which adds to cost and schedule
- Surface finish is generally rougher than CNC machining.
- Removal of supports requires manual finishing, leading to variable surface quality
- Heat treatment is usually required which adds to cost and schedule
- Additional testing and inspection is required to qualify parts for space-flight per NASA-STD-6030, adding to cost and schedule
- Inability to accurately simulate manufacturing frequently requires re-printing parts due to failures, adding to cost and schedule

AM for Evolved Structures has the following advantages, which need more development to be fully realized:

- Manufacturing impossible-to-machine hollow bone-like structures with superior stiffness/mass performance
- Manufacturing large monolithic structures that are impossible or impractical to machine but greatly simplify assemblies and reduce labor by combining many parts into one

4. TECHNOLOGY READINESS LEVEL (TRL) AND RISK

Owing to their unusual shapes, Evolves Structures can be perceived as increasing risk to aerospace projects. However, the Evolve Structures process is just a new way of developing designs, which adds no additional risk or even decreases risk due to:

- Higher stress margins vs. human designs leading to stronger parts
- Parts are designed using known and predictable algorithms and are less dependent on operator experience and skill.
- Fewer mistakes are made in development due to removal of human/organizational interfaces between design, analysis, and manufacturing functions per Figure 3.
- Organizational standards and requirements can be digitally encoded into Generative Design studies reducing errors and ensuring quality (e.g. bolt edge distance, tool clearance, factor of safety, loads and modes).
- Current organizational structure validation techniques can be used e.g. standard FEA software, inspection, and testing.
- Rapid development of optimized structures encourages early prototyping to reduce system risk.

5. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In conclusion, the Evolved Structures process leverages advances in IT to enable game-changing reduction in the development time/cost of instrument structures while simultaneously improving structural performance. The two key underlying technologies, Generative Design and Digital Manufacturing, are rapidly evolving in industry due to these advantages. Example applications demonstrated greater than 10x reduction in development time and greater than 3x improvement in performance is readily achievable. Test results indicate structural performance is accurately predicted by standard FEA methods, though strength is significantly greater than predicted. At the current state of development, no additional risk to aerospace projects has been found in the use of Evolved structures; however there are areas where risk is reduced.

Thus far, small to mid-sized metallic structures have been demonstrated (0.6 m maximum dimension). Future research will focus on applying the Evolved Structures process to larger structures such as truss structures for large instruments (greater than 1.0 m maximum dimension).

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REFERENCES

[1] "International Space Station." Wikipedia, Wikimedia Foundation, 10 August 2022, https://en.wikipedia.org/wiki/International_Space_Station

[2] "James Webb Space Telescope." Wikipedia, Wikimedia Foundation, 10 August 2022, https://en.wikipedia.org/wiki/James_Webb_Space_Telescope

[3] Ramesh, A., et al. "Zero-Shot Text-to-Image Generation," arXiv:2102.12092, 24 Feb., 2021

[4] Abbey, T., "Topology Optimization Methods." Digital Engineering 247, 1 September 2017, https://www.digitalengineering247.com/article/topology-optimization-methods/

[5] Gregory S. Tucker, et al., "The Exoplanet Climate Infrared TElescope (EXCITE)", Proc. SPIE 10702, Ground-based and Airborne Instrumentation for Astronomy VII, 107025G (29 July 2018); https://doi.org/10.1117/12.2314225