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Generative Design for Additive Manufacturing of Satellite Optical Tracker Mount

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Abstract

The organic and intricate nature of machine generated parts is problematic during the manufacturing phase, resulting in high costs and slow production with traditional manufacturing techniques. Additive manufacturing has been explored and approved as the potential solution for fabricating complex geometry and organic lattice structures. With the advances in topology optimization and generative design, design for additive manufacturing (DAM) allows users to generate numerous, high-quality design alternatives that are lighter and stronger than traditionally designed parts. This study addresses the process of designing and load testing a satellite optical instrument mounting bracket using the generative design and simulation capabilities of Autodesk Fusion 360. The workflow pipeline begins with the creation of generative design studies for the instrument bracket in accordance with the design criteria outlined in the optical instrument design challenge, where it is then thermally load tested using finite element analysis (FEA) in Fusion 360 and analyzed for its mechanical behavior.

Keywords: Generative Design, Design for Additive Manufacturing, Satellite Optical Tracker Mount

Introduction

With extreme temperature fluctuations typically spanning hundreds of degrees Celsius, the environment of space is one of the harshest places for machinery to operate. Satellites orbiting the earth will undergo frequent wide temperature swings from -140°C to +140°C when transitioning between the earth's shadow and unfiltered sunlight, resulting in a wide operational temperature range for all components on board [1]. This wide operational temperature range has a dramatic influence on the geometry of every solid component on the satellite due to thermal expansion. Geometric changes are problematic for a variety of reasons; they can cause irregularities in the performance of moving parts, and they can also interfere with the accuracy of finely tuned onboard optics and communications instruments. Thermoelastic geometry changes are unavoidable to a certain extent - all materials have a coefficient of thermal expansion (CTE) that, for a material exposed to a thermal load, will result in some amount of geometric deformation. Previously, engineering teams responsible for the design and manufacture of satellite components attempted to address this problem through improving the thermal properties of component materials in order to reduce thermoelastic deformation as much as possible.

Literature review

1) Prior satellite component manufacturing methods

A ceramic composite material, HB-Cesic, was successfully used by a team of engineers in the design and manufacture of a star tracker assembly bracket on board the Meteosat Third Generation (MTG) weather satellite, operated by the ESA [2]. HB-Cesic was chosen because of its optimal thermoelastic properties, especially in comparison to materials such as Aluminum 6061, Invar, and Zerodur. With a density of 2.9 g/cm^3, a thermal conductivity of 200 W/mK, and a CTE of 2.3 e^{-6}/K, HB-Cesic is an attractive material for the construction of satellite components [3]. Satellite optical system components have also been successfully constructed out of another thermally optimal material, Zerodur, and used on the FOKUS, KALEXUS, and MAIUS-1 rocket missions [4]. Benefits of using these materials include improved thermo-mechanical stability and a reduction in thermoelastic deformation under thermal loads [2, 4]. However, one of the major drawbacks with the usage of components constructed from HB-Cesic or Zerodur is that it relies on traditional manufacturing methods such as CNC machining, trimming, and assembling [2, 4]. Additionally, current design methods are manual in nature and do not use automation in the design process.

2) Automation for design

Automation as a design tool is a relatively new technology in the field of engineering. Traditional design methods typically require conscious and deliberate input from a person, or team, at every step of the design process. While many engineering endeavors still require constant human oversight, certain elements of the design process can now be automated for the first time. Automation allows engineers to explore novel solution possibilities for a great variety of engineering problems while also frequently saving time and potential costs during the design phase. All too often, engineers can become entrenched in particular solution methods that limit their innovative and creative abilities; this has the effect of limiting the conceptual range of possible design solutions for an engineering problem. Automation tools such as generative design and topology optimization can help overcome this issue by providing a wide range of novel solutions for engineering problems that surpass the limits of human imagination. In brief, and with respect to design for manufacturing (DFM), topology optimization can be characterized as a kind of iterative mass subtraction for the purposes of weight reduction and removing unnecessary mass, whereas generative design can be characterized as the iterative rearrangement of mass, and potentially the addition of mass, to optimize a part or component with respect to its design requirements and boundary conditions.

Generative design is quickly being adopted by research teams as a powerful automation tool with a wide range of usage cases. It has been successfully used for the layout and planning of a Swedish residential city block that is optimized for space efficiency and minimizes the environmental impact of construction [5]. It was also used alongside Generative Adversarial Networks (GAN) for image-based design of garments for the fashion industry [6]. Other usage cases include the creation of a series of 6,010 virtual buildings with randomized layouts for the purposes of analyzing the effect of structural geometry on the buildings' energy consumption [7]. There is a growing body of evidence demonstrating that these automation solutions have a broad usage range and a tremendous potential to be used alongside AI-based computing software for mechanical and structural designs. In a recent case study to evaluate the effectiveness of a design methodology for modular spacefaring equipment, an engineering team used topology optimization alongside genetic algorithms to design a satellite antenna [8]. The team was able to construct an algorithm that factored in a number of design and manufacturing criteria including manufacturing cost, design adaptability, and post-processing cost, among others. These criteria, paired with topology optimization, produced a range of unique antenna architectures in which the design of the antenna was optimized for each criterion [8]. Another research team successfully integrated topology optimization into a generative design framework to quickly produce a wide range of structural design outcomes that can be evaluated according to different parameters such as cost, novelty, and compliance [6]. This design methodology pairs elegantly with additive manufacturing techniques, which are quickly becoming one of the dominant forms of manufacturing for space applications [9].

3) Simulation capabilities with generative design

Additive manufacturing is an attractive option for the manufacture of spacefaring components because of its mass-reduction capabilities, as well as its cost-saving potential due to the large amount of material waste associated with traditional subtractive manufacturing techniques [10,11]. It is estimated that additive manufacturing can reduce the cost of a titanium alloy component by as much as 50% due to the reduction in material waste from subtractive manufacturing and machining techniques [12]. Additionally, the 'Buy-to-Fly' ratio of spacefaring components, which is the ratio of purchased material stock mass to final component mass, is typically anywhere from 10:1 to 25:1, and can even be as high as 40:1 [13]. 3D metal printing has been shown to bring this ratio down to 1.5:1, and even as low as 1:1 due to the net shape component geometry produced by additive metal manufacturing [14]. Compared with traditional subtractive manufacturing, additive manufacturing is often faster; this reduction in lead time can reduce the costs of manufacturing satellite components [15]. Additive manufacturing techniques also allow for the mass production of highly intricate, geometrically complex mechanical structures that are difficult to create using subtractive manufacturing [16]. Bugatti was recently able to produce a powerful new brake model for the Chiron by employing selective laser melting (SLM) of a Ti-6AL-4V powder; this brake model was shown to be stronger than prior models with a 40% reduction in mass compared to previous designs [17]. Current industry trends suggest that SLM, as a manufacturing technique, is quickly becoming the dominant component additive manufacturing technique in the aerospace industry; this makes SLM the most likely technique for the manufacture of a satellite mounting bracket like the ones generated in this study [18]. SLM was used to fabricate an aircraft component that was redesigned using topology optimization, with an overall volume reduction of 54% and a weight reduction of 28% between the original aluminum part and final titanium alloy optimized part [19]. Since the geometries produced by generative design for topology optimization are often intricate and organic in nature, it follows that the most efficient way to produce generative design models is through additive manufacturing.

Overview of Project

Purpose

Optical systems are some of the most commonly launched instruments in the space industry. Some prominent examples of optical instruments in space include the Hubble Telescope and the newly launched James Webb Space Telescope, however optical instruments can also be found on Mars rovers and even aboard small CubeSats in low earth orbit. In order for these instruments to capture deep regions of space with any degree of accuracy, optical systems have very strict pointing requirements. Any deviation in the pointing direction of the tracker lens will result in tremendous photographic inaccuracies for deep space photography applications.

Outline of design requirements

The pointing accuracy of an optical system is defined by the 'centerline' of the lens, which can be visualized as a straight line pointing through the central axis of the lens. Since optical instruments are typically mounted on a rigid surface, it is expected that the centerline will not move or shift over time. However, optical instruments on satellites orbiting the earth are subjected to intense thermal loads due to sunlight exposure; this creates large temperature differences in the mounting material between unfiltered sunlight and the full shadow of the earth. As a result, the mounting material will expand and contract due to thermal expansion. This expansion and contraction results in thermoelastic deviation of the central axis of the lens, which reduces the accuracy of the optical system over long distances. It is therefore crucial to design a mounting bracket that expands and contracts in such a way as to minimize the angular deviation of the centerline.

Outline of design constraints

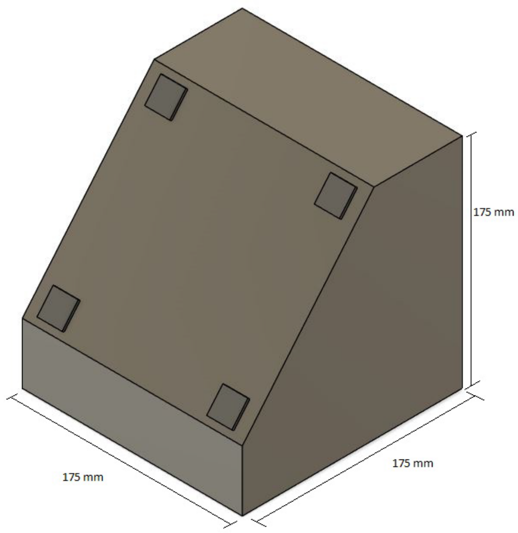
Designing a mounting bracket that deviates as little as possible under thermal load is a current problem faced by engineers in the space industry. This design problem, posed by Dr. Ryan Watkins of JPL, challenges engineers with the task of designing an optical tracker mount that deviates minimally while subjected to thermal loads. The main goal for the tracker design challenge is to produce a mount with a centerline that deviates no more than 0.001° away from its original position. The mount must also have a minimum cross-sectional member size of 1 mm, a fundamental frequency greater than 200 Hz, and a minimum factor of safety of 1.25. The design challenge poses several loading scenarios for the tracker mount, including a force of 2,000 N in the x, y, and z directions, a bulk temperature soak of 85°C, and a steady state heat conduction condition with the tracker at 50°C and the base pads at 10°C. Additionally, all mounting pads along the base are treated as fixed in space. A design space envelope is given as a volumetric reference; the final design must fit within the dimensions of the envelope.

<u>Methodology</u>

1. **Workflow**

To meet these design challenges, our team utilized the generative design capabilities of Autodesk Fusion 360 to construct the mounting bracket. Currently, there are very few commercially available automated design tools that are both effective and user-friendly. Fusion 360 aims to meet this need by providing powerful automation design tools with an intuitive user interface. The goal of this research is to use Fusion 360 generative design to produce a bracket design that thermoelastically deforms in a controlled manner. Previously discussed satellite components, such as those constructed from exotic materials such as HB-Cesic or Zerodur, attempt to address the problem of thermoelastic deformation through the net reduction of deformation by using materials with low CTE values. This research attempts to address the problem of thermoelastic deformation by using automation to create a series of titanium satellite bracket designs that deform in a predictable manner to reduce the angular pointing deviation of a satellite optical system. This method employs comparatively cheaper materials, automation in the design process, and additive manufacturing. These methods combined can potentially reduce material cost, material waste, and production lead time, resulting in globally reduced costs for functionally equivalent satellite components.

The workflow for this project is organized into two sequential steps: generative design and thermal load testing. The generative design phase begins with the design space for the model, which is defined by the dimensions shown in **Figure 1**. The bracket model created during the generative design phase must fit within the volume envelope defined by the design space dimensions. Once the model is completed, it is exported to a 3D format for thermoelastic deformation testing. The model is subjected to a series of thermal loading scenarios, and subsequently analyzed using FEA for its behavior under each loading condition. Models that do not meet the design requirements for thermoelastic deviation are rejected as potential model candidates.



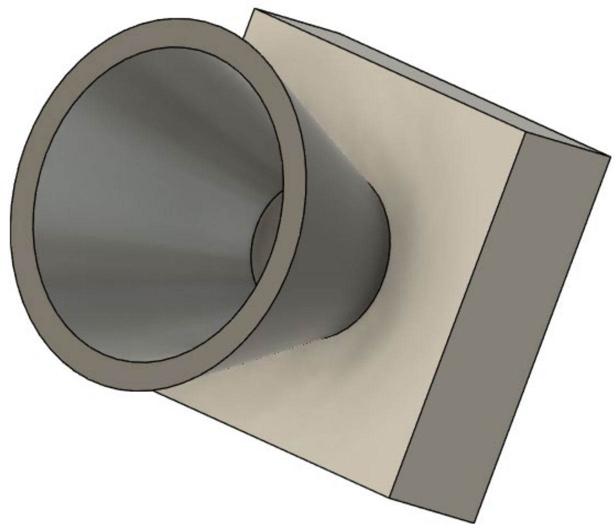


Fig. 1: a) Design space dimensions for the optical tracker mount, **b)** Tracker CAD model

During analysis, it is imperative to keep a static reference point for the optical tracker camera itself. This is shown in **Figure 1 b**, which is a model for the optical tracking instrument. The tracker model is used as a geometric and spatial reference point during thermal FEA, and also serves as a fixture point for the upper mounting pads.

Figure 2 shows the design space as it appears when the tracker model is fixed to the front. Note the instrument mounting pads, shown in green, beneath the optical instrument model. These mounting pads are not valid design spaces because they are an off-the-shelf component and therefore cannot be altered. The yellow pads on the bottom of the design space, however, are free to be altered to produce novel bracket designs. Altering the base mounting pads is one of the first crucial steps in generative design input, which is outlined below.

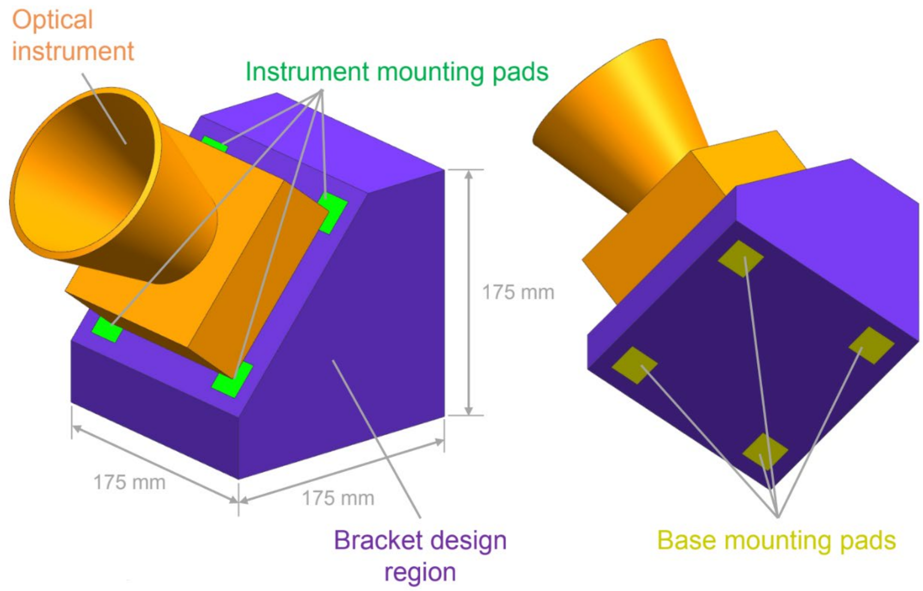


Fig. 2: Optical tracker model placed on design space, shown in violet

2. **Generative design**

Inputs for Fusion 360

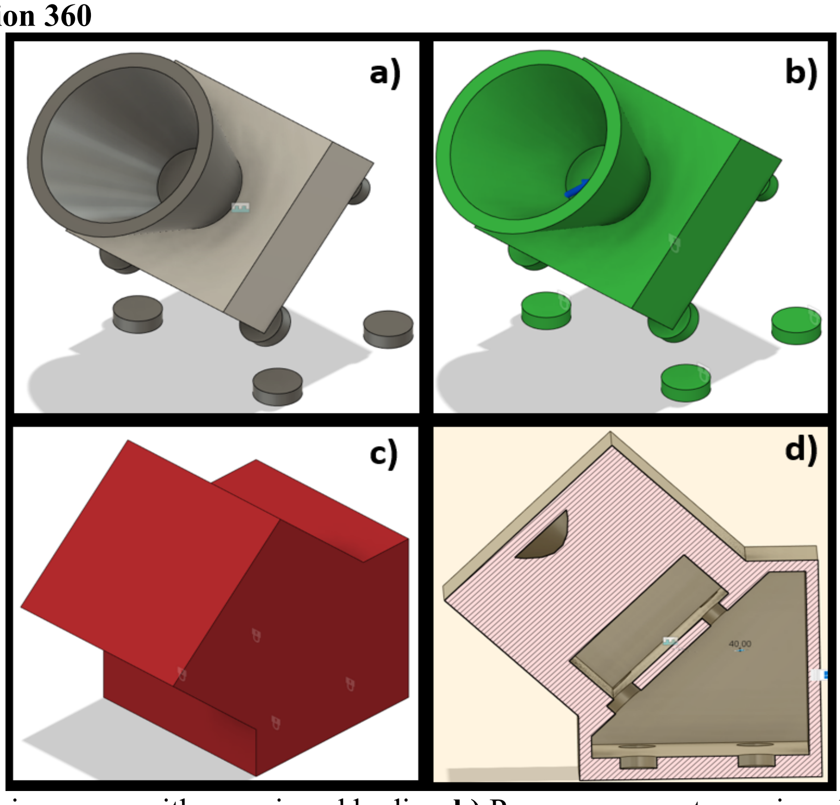


Fig. 3: a) Design space with unassigned bodies, **b)** Preserve geometry assigned to bodies, **c)** Obstacle geometry assigned to shell, **d)** Section view of shell in design space

The first step in utilizing generative design is setting up a design space consisting of bodies to later be defined as preserve and obstacle geometries. An example of this is shown in **Figure 3a)** where the gray bodies were created using the Design workspace within Fusion 360. Unlike conventional part design, generative design only requires bodies that will be used as preserve or obstacle geometrics. Therefore, a body like that shown in **Figure 1** is not required to be made. Not shown here is the shell body that will later serve as the obstacle geometry. Once all bodies are created within the Design workspace, the rest of the setup process will continue in the Generative Design workspace.

Multiple inputs and parameters must be defined in the Generative Design workspace before a study can be successfully conducted. First is assigning the bodies made in the Design workspace as preserve or obstacle geometries. As their name implies, preserve geometries are assigned to bodies to incorporate them in the final shape of the design, while obstacle geometries are assigned to bodies to represent spaces for the design to avoid. These geometries are assigned within the Generative Design workspace once the bodies in the Design workspace are finished. **Figure 3b)** shows preserve geometries assigned to the bodies representing the optical tracker and eight mounting pads. **Figure 3c)** shows the obstacle geometry assigned to the shell body surrounding the optical tracker and mounting pads. A section view of the interior space inside the shell is shown in **Figure 3d)**. This represents the design envelope defined in the problem statement. This ensures that the generative design results do not exceed this defined envelope. Lastly, a symmetrical plane is created through the design space in the XZ plane to produce symmetrical generative design results. This lateral symmetry is beneficial for the thermal analysis and will be further elaborated upon in a later section.

Once all of the preserve and obstacle geometries have been assigned, design conditions including structural constraints and loads are defined. Structural constraints are to apply fixes, pins, or frictionless constraints to a geometry. In **Figure 3b)**, four lock icons can be seen on the bottom four mounting pads, indicating a fixed structural constraint. Structural loads simulate pushing, pulling, and twisting forces. The force identified from the problem statement is applied onto the optical tracker by defining it as X, Y, and Z components of a vector. It is also important to remove the gravity force that is included by default.

Design criteria, such as design objectives, manufacturing method, and materials are also defined. Design objectives allow for the generative design study to prioritize minimizing mass or maximizing stiffness. It also allows for the defining of the factor of safety. As this is an aerospace application, mass reduction is critical and therefore selected. A safety factor of 1.25 is inputted as defined in the problem statement. Next is the manufacturing method, of which the following can be selected: unrestricted, additive, milling, 2-axis cutting, and die-casting. Additive manufacturing is chosen, from which build orientation, overhang angle, and minimum thickness can be selected. All six directions (X+, X-, Y+, Y-, Z+, Z-) were chosen to give the generative design study as much freedom as possible in its results. Overhang angle is left as its default of 45°. Its minimum thickness is entered as 1 mm. Lastly, the material that the results will be printed in is chosen to be titanium 6AI-4V. This will also cause the optical tracker to be made of titanium when it is stated to be made from aluminum 6061-T6 in the problem statement. While the Generative Design workspace allows for multiple materials to be included in the results, this is only valid for separate results; it cannot produce a result consisting of two different materials. Afterwards, the setup is complete, and the generative design study is ready to be converted into a CAD model for further testing.

Fig. 4: A successful converged result in generative design

Figure 4 shows a successfully converged result output from generative design. These result outputs are visually inspected for any material discontinuities and material deposition abnormalities. If the results fail the visual inspection, they are discarded. If the results pass the visual inspection, they are converted into CAD models for further thermal testing. Successful models are explored below in the Results section.

Results

Based on the input parameters and the design space, Fusion 360 can produce multiple results using generative design. This is done in an iterative manner, with each iteration removing more material the software deems unnecessary. This is done until it produces a design that meets the defined parameters but with as little mass as possible. Once finished iterating, two types of results will be generated: converged and completed. Converged results means that the result fulfills all the inputted parameters, while completed results do not. Converged results are the only results that are of interest.

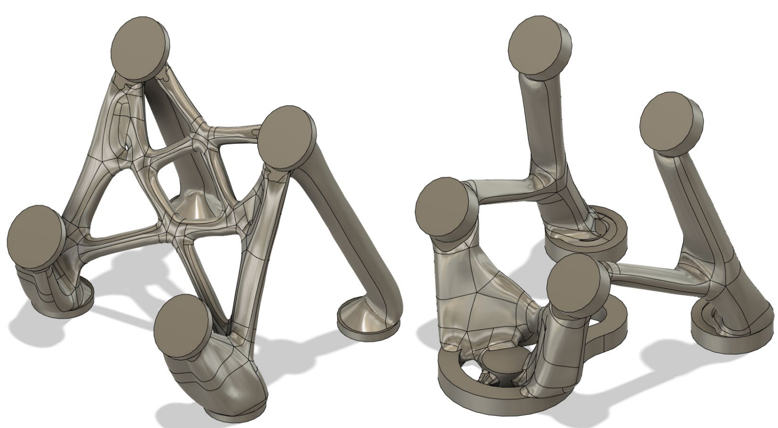


Fig. 5: a) Result from typical mounting pad geometry, **b)** Result from altered base mounting pad geometry

Converged results are then converted into CAD files for further analysis. For instance, **Figure 5a)** shows an example result with "typical" pad geometry. Similarly, **Figure 5b)** shows a result with “atypical” pad geometry because of the creative liberties taken with the lower mounting pad geometry. The ability to experiment with lower mounting pad geometry allows for a tremendous range of design possibilities for further thermal testing.

Thermal analysis

1) Thermal loading scenario inputs

Thermoelastic deviation analysis begins with the application of thermal loads to a completed bracket model from generative design. The thermal loads are referred to as Condition 1 and Condition 2; Condition 1 is defined as a 50°C load applied to the tracker model and a 10°C load applied to the base of the lower mounting pads, and Condition 2 is defined as a 10°C load applied to the tracker model and a 50°C load applied to the base of the lower mounting pads. The lower mounting pads are constrained in space during FEA, since the pads on a physical model would be fixed on a mounting surface. Because the model is expected to function in the vacuum of space, convective cooling is neglected, and the primary means of energy transfer is heat loss due to radiation. The background radiation temperature of space, -270°C, is used as the ambient temperature value. Note that the Autodesk thermal simulation environment uses degrees Celsius instead of Kelvin for radiation inputs. The selected material, Ti-6Al-4V, is applied to the structure, along with its thermal properties. See **Figure 6** for a sample bracket with optical tracker model attached.

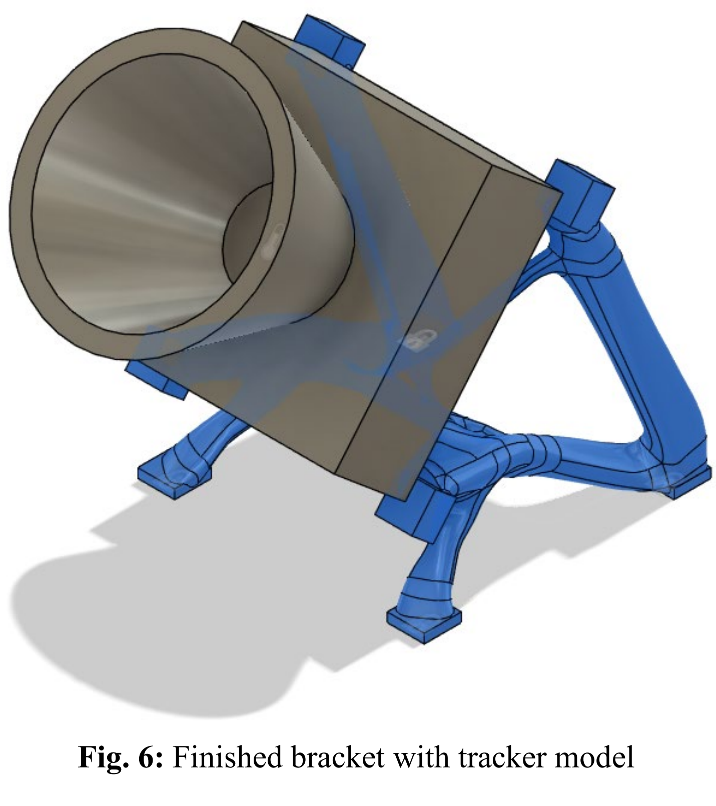


Fig. 6: Finished bracket with tracker model

As stated previously, the tracker model is necessary for subsequent calculations to determine the angular displacement of the centerline axis of the tracker instrument lens. The coordinates of the center of the tracker model are used to draw a vector line in space. This vector line is analyzed before and after thermoelastic deformation, and the total angular distance θ between the undeformed and deformed axis lines is determined.

2) Test case results

The results from each thermal loading case are analyzed inside the Fusion 360 workspace. The model is analyzed for its displacement in the x, y, and z directions with respect to its original position in space. A typical case result is shown below in Figure 7.

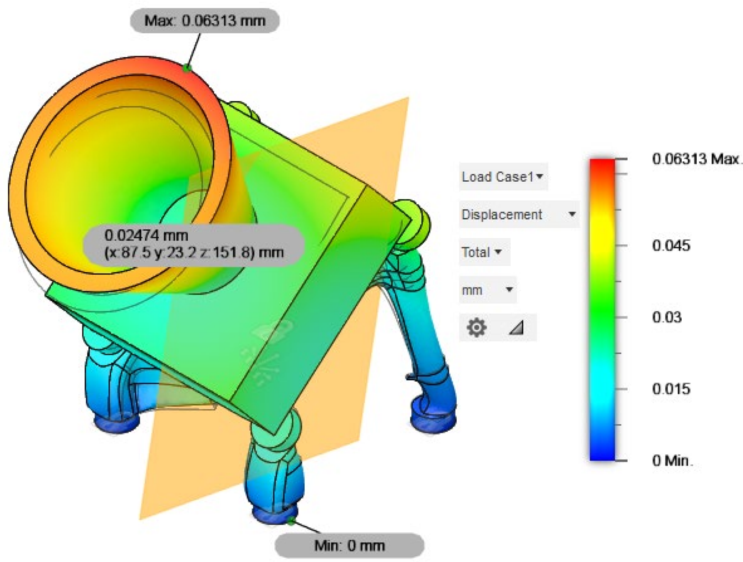


Fig. 7: A typical displacement analysis result with plane of symmetry shown

Due to the lateral symmetry of the bracket model, the bracket does not deform whatsoever in the lateral direction, which dramatically reduces the amount of total thermoelastic deviation under full thermal load. For these models, the lateral direction is defined as the x direction, and the plane of lateral symmetry is defined as the y-z plane. Lateral symmetry is advantageous for reducing thermoelastic deviation because the total amount of deviation in the x direction is mirrored about the plane of symmetry. The internal forces generated by the thermal loads are equal and opposite, resulting in a complete cancellation of any lateral deviation. This results in thermoelastic deviation that is constrained to the y-z plane, and therefore a dramatic reduction in the total amount of thermoelastic deviation in comparison with an asymmetric model. Deviation results are collected for the x, y, and z directions, as well as total linear displacement. Deviation is calculated using the following formula:

$$Cos(\theta) = \frac{A \cdot B}{|A| * |B|}$$

where θ is the angle of deviation, *A* represents the original centerline through the tracker model, and *B* represents the centerline of the tracker after thermoelastic deformation. Vectors A and B are constructed by connecting coordinate points at the geometric center of the tracker model front and rear surfaces before and after deformation. The angle of deviation, θ, is then found and compared with the maximum amount of allowable deviation. If the angle of deviation exceeds that of the design requirement, the design model is rejected as a possible candidate.

3) Optimal Results

A wide range of resulting structures have thus far been generated in Fusion 360. These results have dramatically different geometries and different thermoelastic behavior. While this research endeavor is still currently ongoing, early results are promising. Of the generated bracket design models, the design with the lowest thermoelastic deviation had a total maximum angular deviation of 0.0039°. See **Figure 8** for bracket model. Although this deviation falls outside of the target deviation angle of 0.001°, it is a vast improvement over earlier models which deviated as much as 0.010° or higher from the original centerline position. The performance of this bracket model, as well as the continuous refinement of each subsequent bracket model iteration, demonstrates the potential for this method to be used as a technique for the development of spacefaring structural components.

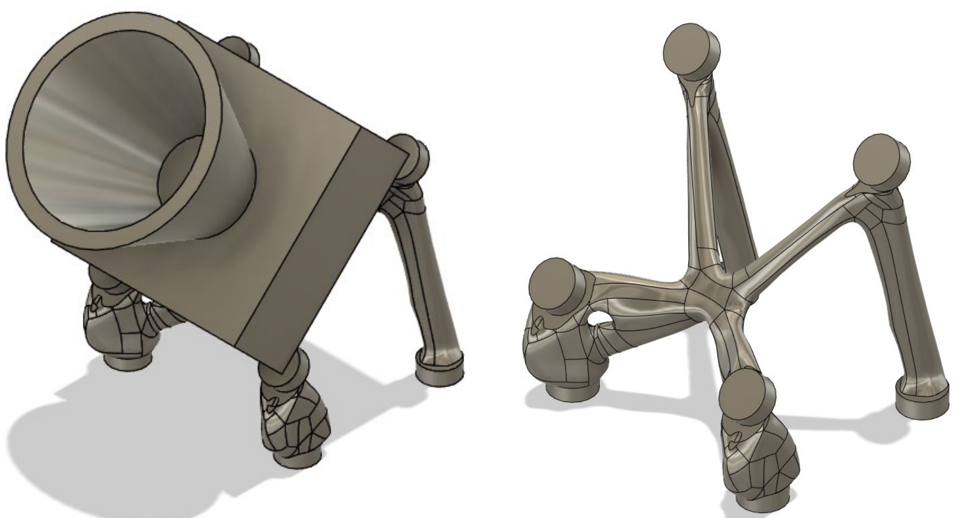


Fig. 8: Best performing bracket model **a)** with tracker, and **b)** without tracker

Discussion

The implications of this research are compelling; it provides an alternative design and manufacturing methodology for the purposes of controlling thermoelastic deformation rather than eliminating it. It also capitalizes on the large number of intricate structural models that can be created quickly through automation, as well as the cost-reducing capabilities of using metal additive manufacturing for component fabrication. An additional benefit of the usage of metal additive manufacturing is the ease with which prototypes of a model can be made. Since the fabrication process with metal additive manufacturing is largely automated, bracket models can be fabricated and tested relatively quickly. The scope of this research involves testing each generated bracket model using the thermal FEA capabilities of Fusion 360. A proposed method to further verify the performance of generative design outcomes is the physical testing of prototypes manufactured using metal additive manufacturing. Testing methods for assessing the pointing accuracy of large earth-based telescope systems, such as the Large Synoptic Survey Telescope (LSST), involve the usage of laser trackers and a series of fixed calibration points [14]. Another optical system verification method proposed by a team at the Johns Hopkins University Applied Physics Laboratory involves the usage of a projected light dome to simulate a starry environment for the testing of optical systems [15]. Even further, an engineering team at the University of Bristol successfully trained an artificial neural network to predict the mechanical properties of generative design structures fabricated with filament deposition modeling (FDM), further strengthening the ties between neural network capabilities, generative design, and additive manufacturing [17]. Similar methods may be employed to test the accuracy and performance of prototype bracket models such as the ones generated in this study.

It should be stated that the design and manufacturing methodology outlined in this paper is not meant to completely replace traditional engineering and manufacturing techniques for space applications; instead, this paper proposes the usage of generative design as one potential option for the design of spacefaring structural components. Previous research has gone into materials engineering for the development of thermally optimal materials to address the problem of thermoelastic deformation in space. This research endeavor merely aims to propose an alternative solution for the problem of thermoelastic deformation by controlling the deformation, instead of reducing it, through automated design. The appropriate design and manufacturing methodology should be chosen carefully after a cost-benefit analysis is performed. For example, the usage of exotic materials such as HB-Cesic may be more appropriate for a spacefaring component, even with traditional manufacturing techniques. However, the usage of generative design with additive metal manufacturing opens the door for a wide variety of novel component designs that may be more suitable for a given application. Specifically, automation as a design tool allows for a tremendous number of highly intricate designs to be created in a very short time frame. A large number of unique designs can be generated fairly quickly, resulting in a reduction in lead times and cost of labor as a result; this reduction in labor cost alone makes automation an attractive option for the space industry. According to the International Futures Program (IFP), the commercial space industry is projected to grow between 18-40% between 2004 and 2030, while entities such as Morgan Stanley estimate that the space industry will have a collective net worth of over $1 trillion by 2040 [13]. These figures suggest that the space industry may need to fully adopt automation as a design tool in order to meet future productivity needs. Generative and parametric design techniques have been shown to be potential solutions to bridge the growing productivity gap between the building industry and the manufacturing industry by facilitating design alternatives, improving information management, and fostering design efficiency [16]. Furthermore, it should be stated that automation will not replace engineers in the design process, but instead augment the abilities and boost the productivity of individual engineers. Engineers are still responsible for the definition of component usage cases and boundary conditions for design components and will still be required to evaluate the results from automation software.

Acknowledgements
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References

1. Goueffon, Y., Aldebert, G., Mabru, C., Arurault, L., Tonon, C. and Guigue, P., 2012. Flaking of black anodic films in space environment: Ageing and numerical simulation. *Mechanics of Materials*, 45, pp.72-82.
2. Matthias Kroedel, Jonathon Komadina, Laurent Perrin, Marc Berill, "MTG star tracker assembly bracket: a successful story of fabrication of light-weighted structures," Proc. SPIE 11101, Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems IV, 1110102 (30 August 2019); https://doi.org/10.1117/12.2526267
3. Matthias Kroedel and Tsuyoshi Ozaki "HB-Cesic composite for space optics and structures", Proc. SPIE 6666, Optical Materials and Structures Technologies III, 66660E (17 September 2007); https://doi.org/10.1117/12.731011
4. Mihm, M., Marburger, J., Wenzlawski, A., Hellmig, O., Anton, O., Döringshoff, K., Krutzik, M., Peters, A., Windpassinger, P. and the MAIUS Team, 2019. ZERODUR® based optical systems for quantum gas experiments in space. *Acta Astronautica*, 159, pp.166-169.Mukkavaara, Jani, and Marcus Sandberg. "Architectural Design Exploration Using Generative Design: Framework Development and Case Study of a Residential Block." *Buildings (Basel)*, vol. 10, no. 11, MDPI AG, 2020, pp. 1–17, https://doi.org/10.3390/buildings10110201
5. Yuan, C. and Moghaddam, M., 2020. Attribute-Aware Generative Design With Generative Adversarial Networks. *IEEE Access*, 8, pp.190710-190721.
6. Oh, S., Jung, Y., Kim, S., Lee, I. and Kang, N., 2019. Deep Generative Design: Integration of Topology Optimization and Generative Models. *Journal of Mechanical Design*, 141(11).
7. Orme, M., Gschweitl, M., Ferrari, M., Vernon, R., Madera, I., Yancey, R. and Mouriaux, F., 2017. Additive Manufacturing of Lightweight, Optimized, Metallic Components Suitable for Space Flight. *Journal of Spacecraft and Rockets*, 54(5), pp.1050-1059.
8. Barriobero-Vila, Pere et al. "Peritectic Titanium Alloys For 3D Printing". *Nature Communications*, vol 9, no. 1, 2018. *Springer Science And Business Media LLC*, https://doi.org/10.1038/s41467-018-05819-9.
9. Borgue, O., Panarotto, M. and Isaksson, O., 2019. Modular product design for additive manufacturing of satellite components: maximising product value using genetic algorithms. *Concurrent Engineering*, 27(4), pp.331-346.
10. Borgue, Müller, Leicht, Panarotto and Isaksson, 2019. Constraint Replacement-Based Design for Additive Manufacturing of Satellite Components: Ensuring Design Manufacturability through Tailored Test Artefacts. *Aerospace*, 6(11), p.124.
11. Rodrigues, Eugénio et al. "An Integrated Energy Performance-Driven Generative Design Methodology To Foster Modular Lightweight Steel Framed Dwellings In Hot Climates". *Energy For Sustainable Development*, vol 44, 2018, pp. 21-36. *Elsevier BV*, https://doi.org/10.1016/j.esd.2018.02.006
12. Whealan George, Kelly. "The Economic Impacts Of The Commercial Space Industry". *Space Policy*, vol 47, 2019, pp. 181-186. *Elsevier BV*, https://doi.org/10.1016/j.spacepol.2018.12.003
13. Mutilba, Unai et al. "3D Measurement Simulation And Relative Pointing Error Verification Of The Telescope Mount Assembly Subsystem For The Large Synoptic Survey Telescope". *Sensors*, vol 18, no. 9, 2018, p. 3023. *MDPI AG*, https://doi.org/10.3390/s18093023

14. B.G. Boone, J.R. Bruzzi, W.F. Dellinger, B.E. Kluga, K.M. Strobehn, “Optical simulator and testbed for spacecraft star tracker development,” Proc. SPIE 5867, Optical Modeling and Performance Predictions II, 586711 (25 August 2005); https://doi.org/10.1117/12.619133
15. Pasetti Monizza, Gabriele et al. "Parametric And Generative Design Techniques In Mass-Production Environments As Effective Enablers Of Industry 4.0 Approaches In The Building Industry". *Automation In Construction*, vol 92, 2018, pp. 270-285. *Elsevier BV*, https://doi.org/10.1016/j.autcon.2018.02.027
16. Goudswaard, Mark et al. "The Creation Of A Neural Network Based Capability Profile To Enable Generative Design And The Manufacture Of Functional FDM Parts". *The International Journal Of Advanced Manufacturing Technology*, vol 113, no. 9-10, 2021, pp. 2951-2968. *Springer Science And Business Media LLC*, https://doi.org/10.1007/s00170-021-06770-8
17. Kazantseva, N. V. et al. "Laser Additive 3D Printing Of Titanium Alloys: Current Status, Problems, Trends". *Physics Of Metals And Metallography*, vol 122, no. 1, 2021, pp. 6-25. *Pleiades Publishing Ltd*, https://doi.org/10.1134/s0031918x21010063
18. Tshephe, Thato Sharon et al. "Additive Manufacturing Of Titanium-Based Alloys- A Review Of Methods, Properties, Challenges, And Prospects". *Heliyon*, vol 8, no. 3, 2022, p. e09041. *Elsevier BV*, https://doi.org/10.1016/j.heliyon.2022.e09041
19. Seabra, Miguel et al. "Selective Laser Melting (SLM) And Topology Optimization For Lighter Aerospace Componentes". *Procedia Structural Integrity*, vol 1, 2016, pp. 289-296. *Elsevier BV*, https://doi.org/10.1016/j.prostr.2016.02.039