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The generative design process for robotic design applications

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Abstract

Additive Manufacturing (AM) has led to the development of more complex geometries and organic components which can be easily manufactured. This has proven to be a crucial milestone for designers with a radical step change in the thought process to fully utilise its potential. As the output geometries and manifolds from part optimization approaches like topology optimization (TO) and generative design (GD) are lighter but too complex to be manufactured by conventional manufacturing methods. Generative Design provides a possibility to optimize the design for specific AM technology and materials. This paper defines the workflow of methodology for the design of an elbow or shoulder rigid link for a serial manipulator. Utilizing GD for a light-payload industrial robotic application results are compared with carbon fibre tubing and conventional aluminium extrusions which are often used in the design and application of both elbow and shoulder rigid links. It was observed that utilising GD provides significant potential benefits for robotics design. For example, light-weighted manipulator structures can reduce cost and energy consumption whilst maintaining overall strength clearly demonstrating the potential benefit of this approach for industrial robotic design.

Keywords: Additive manufacturing, Robotics, Generative design, Computer aided design

1. Introduction

Design approaches for varied manufacturing processes have always been distinct. For instance, a very specific manufacturing process such as 3-axis milling requires thought and consideration in terms of the fabrication process and its constraints [1]. Although design methods have matured and modernised over time with the onset of the digital era and improved Computer Aided Design (CAD) tools, the manufacturing constraints are the basis for any design space boundaries.

Increasing the performance of an industrial robot often requires a more stringent design with high stiffness for lighter articulated robots. Manufacturers address this requirement by increasing the manipulator link cross-section to enhance stiffness, which results in mass augmentation and hence, increased positional errors due to deformation under gravity [2]. Studies specific to design of robots [3,4] show topology optimization as a valid solution for stiffness maximization with mass constraints.

Recent open-source explorations and research in the domain of AM has led to some exemptions from previous manufacturing-based design restrictions and hence much more complex geometries and organic components can be easily manufactured [5]. This has proven to be a crucial milestone for designers as traditional CAD processes [6], pre-established idea fixation [7] constraints the design output from 'unknown' expanse of designs that are otherwise not obvious to human imagination and design skills.

Topology Optimization (TO) [8] and Generative Design (GD) [9,10] are the two, computationally expensive but, convenient automated design solutions that are available to close this gap in design. TO and GD utilize evolutionary algorithms and optimization on various target dimensions. The design is optimized using either 'gradient-based' programming techniques, for example the optimality criteria algorithm and the method of moving asymptotes, or 'non-gradient-based' such as genetic algorithms- solid isotropic material with penalization (SIMP) and the evolutionary structural optimization (ESO) or the bi-directional evolutionary structural optimization (BESO). Structural Optimization can be used to resolve size, shape, and topology. Here, topology optimization is usually referred to as general shape optimization [11]. Most techniques usually optimize either topology or both size and shape [12].

Generative Design however addresses the optimization problem differently [13] and contrary to Topology Optimization no initial design stage is required for the optimised solution. The inputs required are geometric preserves and obstacles, boundary definitions such as loads and constraints, the material to be used for manufacturing, and the manufacturing process used.

With the use of these variables, a portfolio of a large number of compatible design solutions can be identified from which the desirable solutions can be chosen and exported as a boundary representation (BREP) format file for any further appropriate alterations.

Numerous applications from simple optimized chair [9] design to complicated optimized bike [14] and car chassis [16] design have been successfully generated and fabricated for use.

This paper illustrates the methodology for GD process in general and its potential application in light weight manipulator link generation. It serves as a proof of concept to replace conventional aluminium based bulky extrusions with generatively designed and additively manufactured light weight, low cost and robust, elbow and shoulder links for a robot. This paper also examines how the immobile and inert links in a robotic manipulator are generated with their mechanical properties compared against a reinforced carbon fibre tube and aluminium extrusion solutions for low payload applications.

2. Material and methods

Notably the most interesting trait that GD offers is the ability to explore the entire available design space both efficiently and effectively. Autodesk has been at the forefront of generative design development since 2018 with its Fusion 360 CAD package.

In subsection 2.1 the Generative Design Process is discussed specifically in relation to Fusion 360, including the working (algorithm) in general . Subsection 2.2 discusses the general methodology for setting up and running a GD study highlighting the decisive aspects of each step in the process. Subsection 2.3 contains parameters that were used, the results for which are discussed in Section 3. 'Results'.

2.1. Working

An iterative approach is used to generate multiple feasible CAD solutions based on the manufacturing constraints and product performance requirements. Design parameters like material, size, weight, strength, manufacturing methods, and cost constraints are defined by engineers and the software then uses an AI-based algorithm to generate and filter the valid designs among an array of design options. The software explores all the possible permutations of a solution and tests, learns, and evolves from each iteration. The synthesis of design happens with a combination of a convex hull generation followed by topology optimization initialization and iterative evolution.

2.1.1. Gift-Wrapping/ Convex Hull

A Convex Hull (CH) is a polygon (2-dimensional case, Fig. 1) or a polyhedron (3-dimensional case, Fig. 2) or a polytope (for higher dimensions) which encapsulates all the data points in a set. It is the most reserved boundary strictly made with its vertices being some of the points in the input set.

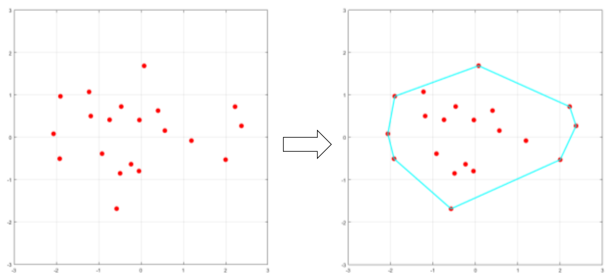

Fig 1. Polygon Convex Hull in 2D data set.

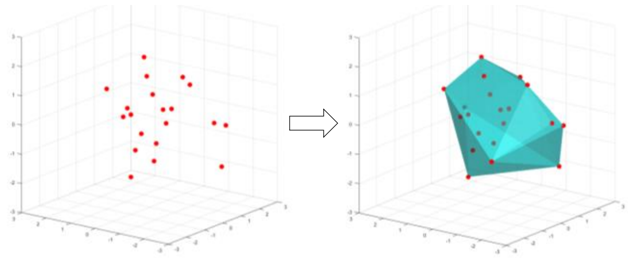

Fig 2. Polyhedron Convex Hull in 3D data set.

In literature, there are many algorithms available for calculating CH for the planar cases for instance Gift Wrapping or Jarvis March $O(nh)$[16], Graham Scan $O(n \log n)$ [17], Quickhull $O(n \log n)$ [18], Divide and Conquer $O(n \log n)$ [19], Chan's Algorithm $O(n \log n)$ [20] etc. For the case of 3 dimensions Divide and Conquer, Quickhull and Chan's algorithm can be adopted, latter being the best suited and efficient. Quickhull is used for computation of convex hulls in higher dimension. Here *'O'* represents the order of time complexity for computation, n is the number of input data points (vertices or nodes) and h is the number of points on the convex hull. Exactly which algorithm runs in the back end of the Fusion 360 GD source code for generating this initial wrapping is not yet published by Autodesk for open access and research.

The appropriate CH generation is paramount to the GD process as it serves as the most reserved volumetric space that is needed for a design solution for preserves' connectivity. Regardless of the algorithm used for CH generation, an input geometry is created to be structurally optimized by considering all the geometric inputs and regions of interest in the CAD, namely preserves, obstacles and starting shape.

a) <u>Preserves</u>: the regions (Fig. 3) that are not to be modified and should be present in the outcome as it is. Usually, these are the bodies/components in the design where the part under optimization interfaces with the rest of the assembly.

b) <u>Obstacles</u>: the region (Fig. 4) where the material is disallowed. Usually, as a design requirement for empty space or either for accompanying components.

c) <u>Starting shape</u>: This is not always required as the shrink wrapping eliminates the need. However, in certain design scenarios where the preserves cannot "see" one another because of an obstacle, a starting shape (Fig. 5) provides for a route for the preserves to be connected. The process follows the simple Boolean operations defined in (1).

$$(Preserve\ Envelope\ +\ Starting\ Shape)\ -\ Obstacles\ =\ Design\ Space\ Envelope \quad (1)$$

2.1.2. Topology Optimization

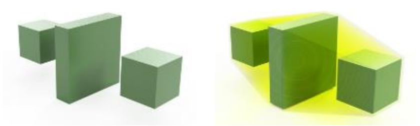

Fig 3. Preserves (green) with the suitable shrink wrap envelope (yellow) [21].

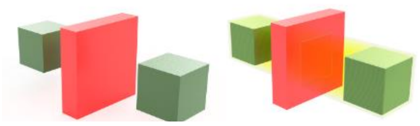

Fig 4. Obstacle (red) with an invalid shrink wrap envelope (yellow) [21].

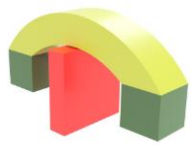

Fig 5. Defined starting shape (yellow) [21].

The topology optimization initialization iteratively creates a lean manifold by carving out volume, from this initial Design Space Envelope not supported by the loads indicated by Final Element Analysis (FEA) at each step. The solver inside Fusion 360 GD is based on linear-static FEA methods. This means that there is no load eccentricity applied. If the part under consideration is set up with pure compression or tension, there is a likelihood of unrealistic results as buckling is not considered. This shortcoming can be overcome by defining orthogonal small loads to the primary load in pure loading condition.

Since the core-mechanism is a level-set approach to topology synthesis, they are highly sensitive to the initial shape's surface area (either created by the solver by Convex hull generation or specified by the user as a starting shape) [22,23].

2.2. Methodology

2.2.1. Pre-requisites

This is an important step as during the setup, user creates the 'bodies' which are going to be interfaced with the rest of the assembly (mountings) and where essentially the loads will be defined for the analysis. Either a blank design or a pre-defined model is well suited for implementing a GD study. Mounting holes and load faces are generated in the 'Fusion 360 Design' workspace excluding any non-essential/peripheral parts like fasteners and pins etc. These parts will essentially be the preserve bodies for the GD process. Another crucial factor in design is the obstacle geometry which covers the space where the user doesn't want the generative design to allow materials to enter. Optionally, Obstacle Offset and Starting Shape can also be defined in further steps.

For the proposed use case of light weight manipulator link design, the preserves were defined as the mounting holes for the actuators. An obstacle component was used for making a hollow link design for the possible passage of pneumatic and electrical pathways. The fasteners and the tool access space were also defined as an obstacle geometry. Additionally, a starting shape was also provided for better control of the output design and allow shrink wrapping [Fig 6].

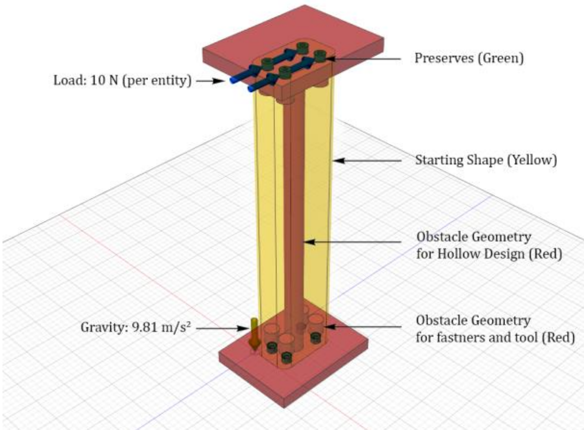

Fig 6. Study Setup.

2.2.2. Study Setup

After switching to the 'Generative Design' workspace in Fusion 360 the following steps were taken:

a) The visibility property for all the components in the robot assembly including actuators, bearings etc. was toggled off. Only visible components were the Preserves, Obstacle, and the Starting shape. Turning the visibility off for all the components apart from the components being used in the GD process as defined above helps to simplifying the process and declutter the workspace.

b) Modifications/additions to the obstacle sub-space were made for generating path for mounting screws and tool access for assembly. Abstracting the model from the existing set of parts by making any required (minor) edits using the 'Edit Model' tool is critical to define clearances efficiently as voids in the final design.

c) The Preserve Geometry, Obstacle Geometry and starting shape geometry (optional) were assigned to the appropriate components in the design. These are the inputs for the initialization of Convex Hull generation and further structural optimization occurs over this computed volume. 'Obstacle Offset' can also be defined if needed which can be used to control geometric tolerances.

f) The next step was to assign the 'Design Conditions' or boundary conditions on the preserves. These are the constraints to movement and any loads that the part will undergo. Several load cases can be made to represent various dynamic scenarios to simulate the real use-case. These are critical as each iteration tries to optimize the flow of stress due to load on each step of material removal or addition.

In the present use case, the end effector payload was set to 200 g (including the end of arm tool weight).Load torque was calculated for each joint actuator and suitable actuators were procured. The 'moment' applied in this GD study was 10 Nm., which was marginally more than the maximum stall torque rating of the actuator selected for the Elbow Joint, i.e., 9.2 N.m. The link length was 250 mm. Therefore, a radial load of 40N was applied to the free end of the link (Fig. 6).

g) Objective and Limits for the GD were specified in the 'Design Criteria' section. A choice between 'Minimize Mass' and 'Maximize Stiffness' was made at this stage and the factor of safety was also defined. This is essentially the weighting between mass and stiffness for design as mentioned in the Introduction section.

'Minimize Mass' was chosen as the design criteria with a Factor of Safety of 2.

h) Both additive and subtractive methods of manufacturing were available as options. AM was selected as the choice of method since, it generates better unrestricted design options and was also specific to the study at hand.

i) The materials defined for the part decide the part's mechanical and thermal properties. For light-weighting constraint, material selection was reserved to polymer-based AM materials. A maximum of 10 materials can be chosen (as options) for a single study.

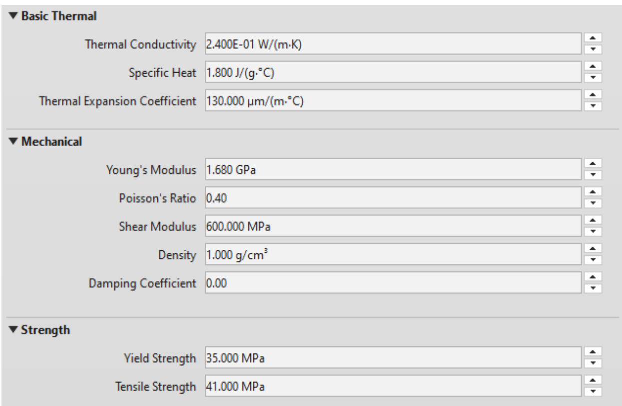

Fig 7. Custom material profile for Polyamide (PA)-12.

A custom PA-12 material profile was created according to the material manufacturer specifications and was used for the study (Fig. 7) since Selective Laser Sintering (SLS) was the preferred and available AM method. SLS was chosen as the parts produced have homogeneous material properties and the fabrication method is free from orientation dependence and hence no use of support structures is required. No restrictions to orientation and overhang angles of 45° were given as input in the corresponding fields for 'Additive'. 45° of overhang angle allows the algorithm to build and explore design solutions in the domain of both orthogonal axes without any bias.

j) Post validation, the solution generation commenced. Due to computational complexity the solver is based on Autodesk cloud-based server for calculation and analysis of every iteration.

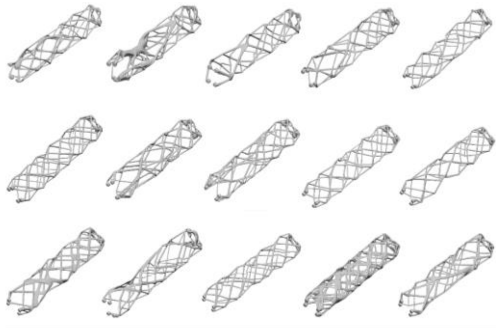

Fig 8. Array of selected Generative Design outcomes from this study.

2.2.3. Generative Results

This section discusses the basis of comparing several design outcomes (Fig. 8) and selecting the most suitable. There are several tools available to determine which solutions are worth further investigation. Fig. 9 illustrates the data for several converged GD outcomes. Global Displacement, Von Mises Stress and Mass values were the critical variables for selecting the suitable design. Filtering and sorting of the results can also be done using several other parameters like cost, factor of safety, volume etc. 'Outcome 10' was chosen as the preferable design as it showcased nominal values (Table 1.) for the variables mentioned above when compared to other designs.

Table 1. Data values for Outcome 10.

Max. Global Displacement	Max. Von Mises Stress	Mass
3.02 mm	12.59 MPa	26.52 g

It was then exported as a BRep/T-spline body into the base model to inspect the context. Also, some modifications were made to this form to remove the self-intersecting surfaces and to make the base of the form closed and connected. Post GD modification of the form made it stiffer with an add-on of 3.27 g of mass. Minor modifications can be performed using the 'Form' tools in the Fusion 360 package to remove any self-intersecting surfaces, if required.

A structural analysis was then performed to compare Outcome 10 (250 mm length) with the Carbon Fibre Reinforced Tubing and standard Aluminium Extrusion Profile of dimensions 35 mm * 1.5 mm * 250 mm (ID * Wall Thickness * Length) and 40 N of force on the top

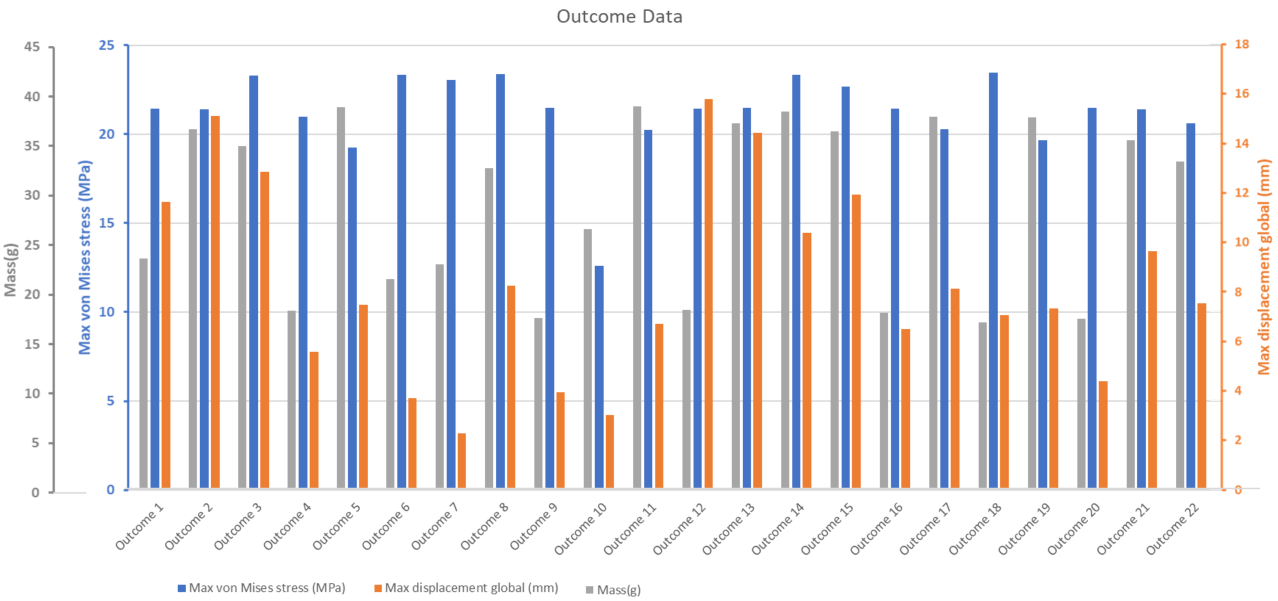

Fig 9. Data visualization of Generative Design Converged Outcomes.

faces with the bases fixed (Fig 10). Simulated Load Torque:

$$40\ N * 0.25\ m = 10\ N.m \quad (2)$$

For meshing of the components 'Adaptive Meshing' with the minimum element dimension of 1 mm was used for the GD form structure. FEA results for this comparison are provided and discussed in the next section.

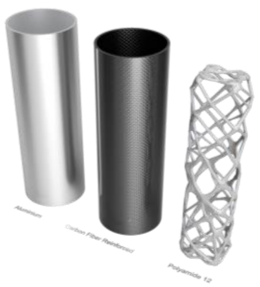

Fig 10. From left to right- Aluminium (AL 6082-T6); Carbon Fibre Reinforced (CF/EPOXYLAM.); GD Outcome 10 (PA-12).

3. Results and discussion

Negligible stress and deformation under given load clearly signifies (Fig. 11) that Aluminium and Carbon Fibre material in profile extrusion form are suitable but is an over specifcation. Using the GD form with PA-12 as the material for fabrication validates in the current structural loading with the maximum deformation of 1.27 mm and a maximum stress of 6.27 MPa. Also, a significant 92.25% and 85.36% reduction in weight is observed in the GD form compared to the Aluminium and Carbon Fibre respectively (Table 2). These results consolidate the use of Generative Design for producing optimally lean but strong parts for robotics applications utilsing 3D printed polymers. Higher tolerances can also be achieved by inculcating hybrid fabrication into the process. 3D printed parts can be drilled/milled or modified to appropriate tolerances by using subtractive post-processing techniques.

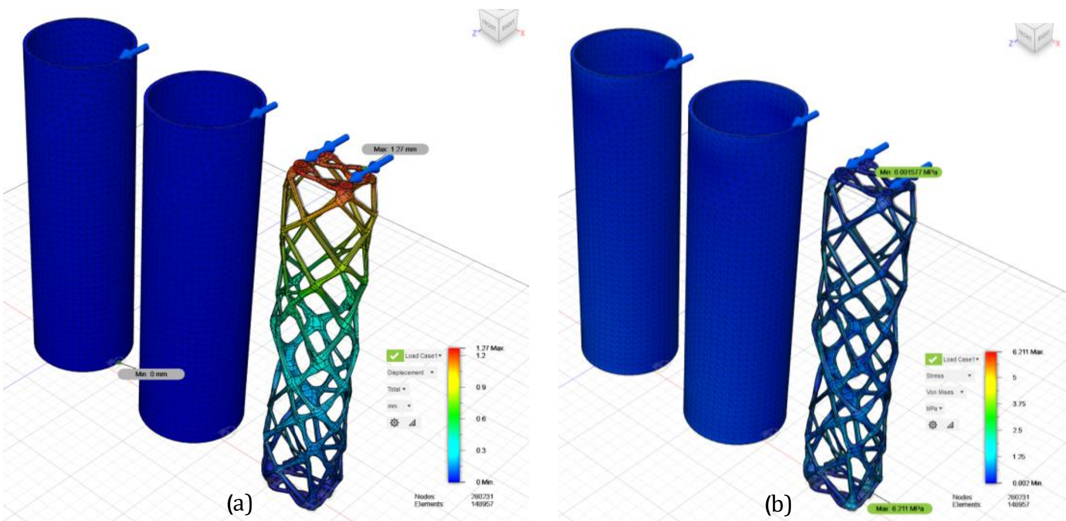

Fig 11. Finite Element Analysis results. (a) Global Deformation (mm); (b) Von Mises Stress.

Table 2. Mass values of the 3 designs under comparison.

Aluminium(AL 6082-T6)	Carbon Fibre Reinforced (CF/EPOXY LAM.)	GD Outcome 10 (PA-12)
384.35 g	203.56 g	29.79 g

4. Conclusion

This innovative approach to design GD has significant potential for robotics as it substantially reduces weight(~85-90%), making the whole system lighter whilst maintaining key strength properties. Lighter robotics will also allow the design of economical actuators due to reduced torque requirements for identical but lighter manipulator configurations with unchanged end effector payloads.

The future scope of this research will exapnd on the use of additional AM materials and methods. Further work will also focus on considering the defects and compensation for numerous variables [24] in the 3D Printing process, including infill homogeneity and anisotropy of the mechanical properties in the additively manufactured parts. These intrinsic and unknown defects in the additively manufactured components make it difficult to model the 3D printing processes and therefore include these variables in the simulation results. Therefore, comparison studies to validate the simulation results with the physical prototypes of the form will also be undertaken. It is anticpiated that these studies will clearly demonstrate and validate the potential benefit of this approach for industrial robotic design and application.

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Author's statement

Conflict of interest: Authors state no conflict of interest. (* For Fig 3, 4 and 5: Content Posted on Autodesk Knowledge Network is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License. https://knowledge.autodesk.com/customer-service/share-the-knowledge)

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