GRIPPER
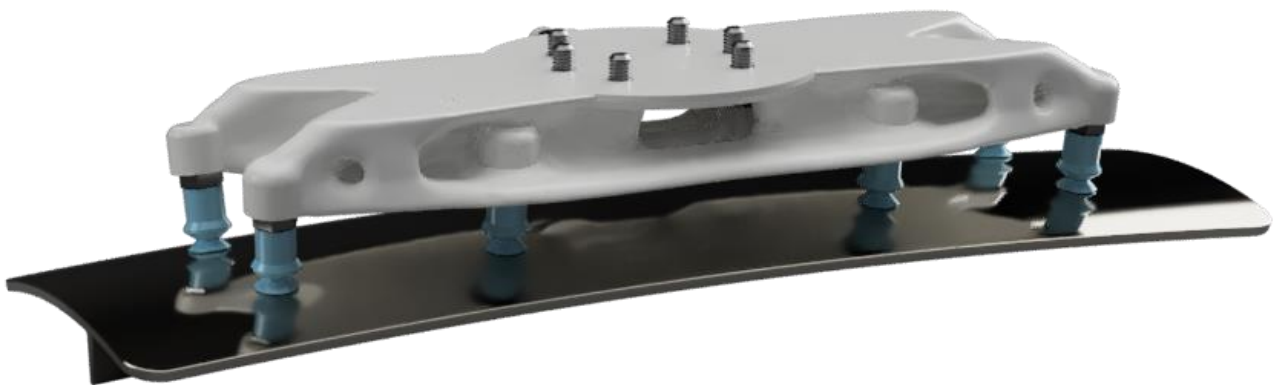
Topology-optimized, additively manufacturable robotic end effector for increased productivity

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Overview

The robot arm can be a valuable tool for automation in the workplace and are made more useful by the end effector deployed in their use. The robot end effector is a device that bolts to the end of the robot arm and is what interacts with the part on the assembly line.

Fig 1 - Kuka robots. Source Wikipedia.

Company A has a robot used in their assembly-line process. This robot picks up a part in one location and places it in a second location. The current end effector used is intricate and bulky. The company believes with a lighter end effector they can reduce the energy needed per pick-and-place cycle and decrease cycle time. Furthermore, a simpler end effector can decrease downtime as there is a potential for fewer parts to be used in the end effector assembly. Company A believes a purpose-driven design 3D printed will fill these goals.

It is our task to design this end effector.

We are supplied CAD (Computer Aided Design) models of the current end effector.

In our design process we take into consideration the important aspects of this specific robotic gripper use case. We consider loads and material selection for our design. We design and analyze using finite element analysis (FEA) in the Autodesk Fusion 360 CAD environment.

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Background

A company uses robotic arm automation in their production. The purpose of this robot is to quickly pick up an object from one location and move that object to a second location. The current end effector for this robot weighs one kilogram and is comprised of eighty individual pieces, of which eighteen are unique components. The company has great interest in reducing the weight to reduce wear and cycle time with the goal of increased productivity. Furthermore, they would like to reduce the number of parts on each gripper and have an extra gripper easily accessible to increase operational reliability.

Goal

Using computer aided design, topology optimization, finite element analysis and additive manufacturing, we will have an end effector design with a reduction of mass and part count over the original design. This should result in increased reliability due to the lower part count and ease of manufacture. Reducing mass of the end effector will allow for quicker cycle time, increasing productivity, and reducing the wear on the robot, minimizing downtime. Using additive manufacturing will allow for the end effector to be quickly reproducible, further reducing downtime by having a spare end effector available on short notice.

Method

Tools

Software

CAD
Autodesk Fusion 360 – version 2.0.10356 - Active Plan: Fusion 360, Student – for design, topology optimization, static stress simulations and converting CAD model to STL file for printing.

Mesh handling
Instant Meshes (wjakob, 2021) for converting triangulated mesh from Fusion 360 into a quad mesh. Fusion requires a quad mesh to work the model more easily in the CAD environment.

Slicer
Ultimaker Cura - Version 4.9.1 (https://ultimaker.com/software/ultimaker-cura) is used to slice the STL for printing a prototype.

Operating System
macOS Big Sur – version 11.4

Hardware

Laptop Computer
MacBook Pro 2018 - 2,3 GHz Quad-Core Intel Core i5 - 16 GB 2133 MHz LPDDR3

3d Printer and Filament
Ultimaker 2+ 2016
Add:north X-PLA – White, 2.85 mm diameter, plant based polymer filament. Approximately 140 grams.

Workflow

Design Rules - Understand the use case

A load of 1.8kg must be picked up by a vacuum suction end effector. The material is Tungsten in the shape of a curved sheet *(fig 2)*. This load must be transported to a second location by movement of an ABB robotic arm and released. The robot runs two shifts and must accomplish 5040 lifts per day. The current cycle time is 10 seconds per lift.

When the part is picked up, a maximum of 0.3 mm deflection is allowed in the extremities of the end effector.
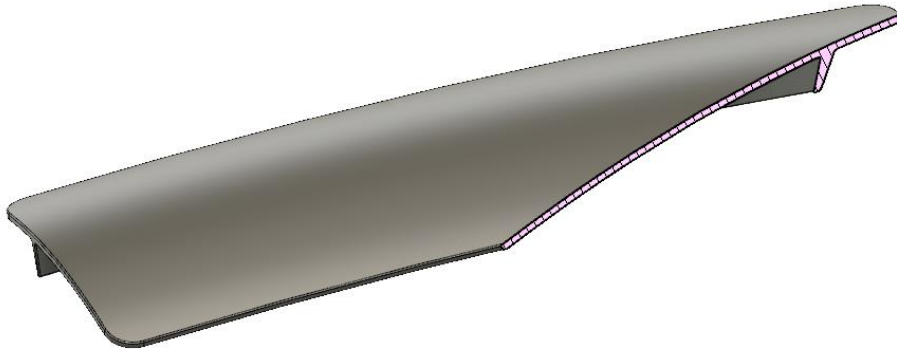
Fig 2 - View of tungsten sheet metal part with section analysis. Screen capture in Fusion 360 design workspace. Own work.

Analyze existing model

By analyzing the existing model, we count approximately 80 - 82 parts of which 18 - 21 are unique components. There is a main mounting plate on which all the components mount. The plate attaches to the robot arm. For the suction nipples to be directed at the part to create a proper seal, they are attached via a swivel. Pipes are shaped to transfer the vacuum between the nipples and the source *(fig 3)*.

Fig 3 - Supplied end effector model for analysis. Counting all the parts involved with this assembly sums to approximately eighty and approximately eighteen of those parts are unique. Screen capture in Fusion 360 design workspace. Own work.

We can see that there is approximately 60 mm between the robot and the workpiece *(fig 4)*.
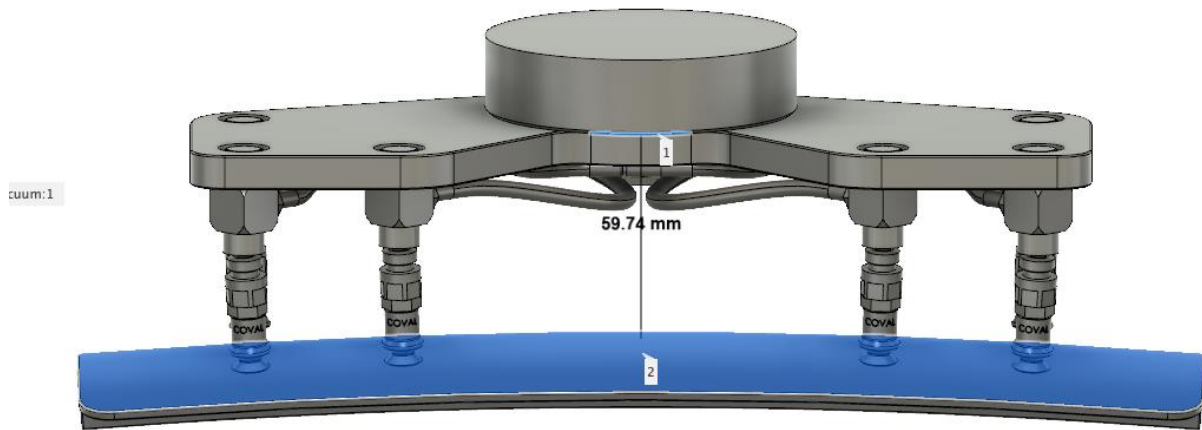
Fig 4 - Distance between robot arm and workpiece. Screen capture in Fusion 360 design workspace. Own work.

Ideate

We let our imagination run wild here and create a rough sketch as to what the new end effector could look like, how we can reduce the part count and what parts might need to remain.

Before I had the details of this project, I whipped up an approximate model with the power of Fusion 360 *(see 'Initial rough sketch' Fusion link)*. This model is a design approach to get a better understanding of working with 3d sketches and t-splines for running preliminary static stress analysis simulations. Running a simulation with typical ABS plastic gives us a rough idea of what is possible.

CAD for topology optimization

Two models are created for topology optimization. The first design is roughly modeled in CAD and is half modelled to save time as the design will be symmetric *(fig 5)*. Attention is paid to the robot mounting point to allow proper fix points. A very rough design space is created in the shape of a cubic rectangle with the dimensions 152 x 100 x 22 mm. Mounting holes of 6 mm and shoulders of 16 mm are modelled on appropriate angles and heights based on the location of the threaded suction fittings. This is achieved by modeling directly from the shoulders of the fittings as placed on the tungsten sheet.
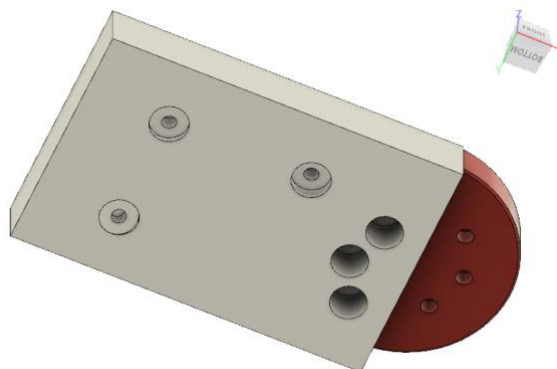

Fig 5 - First CAD design prior to running topology optimization. Screen capture from the design workspace in Fusion 360. Own work.

The second model is the same as the first model but mirrored and combined to the full width. A mounting puck of the same diameter of the robot connection and a depth of 4 mm is created to be a

part of the model that will not be optimized. This area is created as a separate component and the overlapping area is subtracted from the design space by a Boolean operation.

Optimize Topology

The two models listed above are optimized using Fusion 360's simulation workspace and is computed on the cloud. The model is simplified by removing all components from the design except for the puck and design space. Fixed points are added where the bolts attach to the puck. Loads of 4 newtons are added at 90 degrees down from each suction mount. The load to be carried is 1.8 kg or roughly 18 newtons. Four newtons on each suction location equates to 24 newtons, or roughly 2.4 kg. This value is somewhat arbitrarily chosen as a value 33 percent higher than the requirement as an attempt to slightly overbuild the design. The mesh is set to an absolute size of 2 mm. There are preserved regions of 15 mm diameter and 6 mm deep perpendicular to the suction mounting shoulders. The second model was set up the same as the first only symmetrical so there are six fixed points and six loads *(fig 7)*.
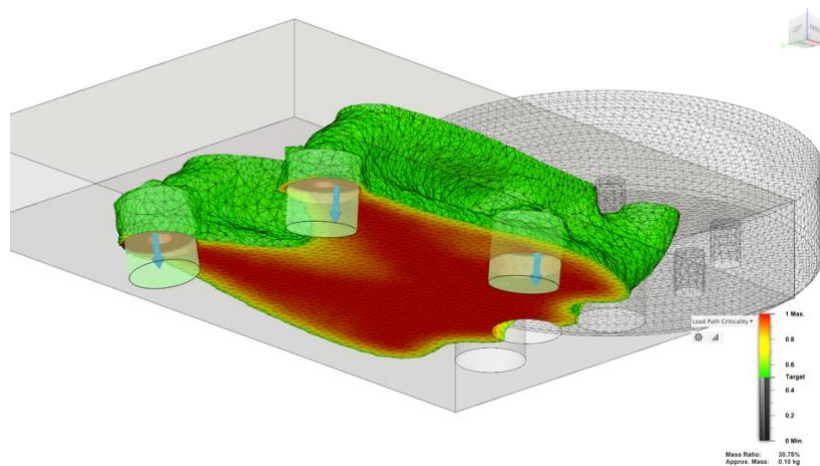
Fig 6 - Results from first topology optimization. Note the two-millimeter mesh size and loads perpendicular to the suction mounting shoulders. Screen capture in Fusion 360 simulation workspace. Own work.
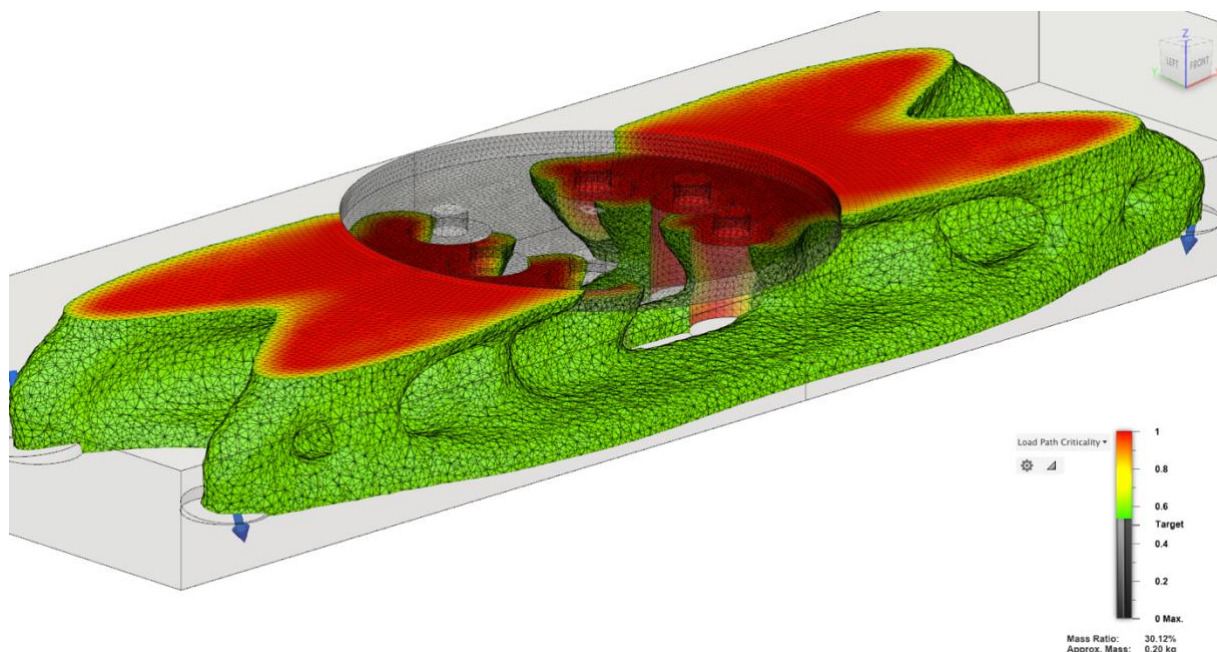
Fig 7 - Topology optimization of the full length for comparison. Note the puck in the top center as a non-optimized space. Screen capture in Fusion 360 simulation workspace. Own work.

CAD model from optimization

Promote to Design Workspace

After the topology optimized mesh is achieved it is promoted to the design workspace. Fusion has trouble handling large meshes converted to solids. We would like to convert the model to a t-spline form for easy tweaking and smoothing. To make this conversion we need a quad mesh.

Convert to Quad Mesh

To quickly build the quad mesh out of the triangular mesh we export the topology optimized mesh as an .obj file and use the open-source software called Instant Mesh. The settings are as in the screenshot *(fig 8)* and the result is saved as an .obj and imported back into Fusion 360.
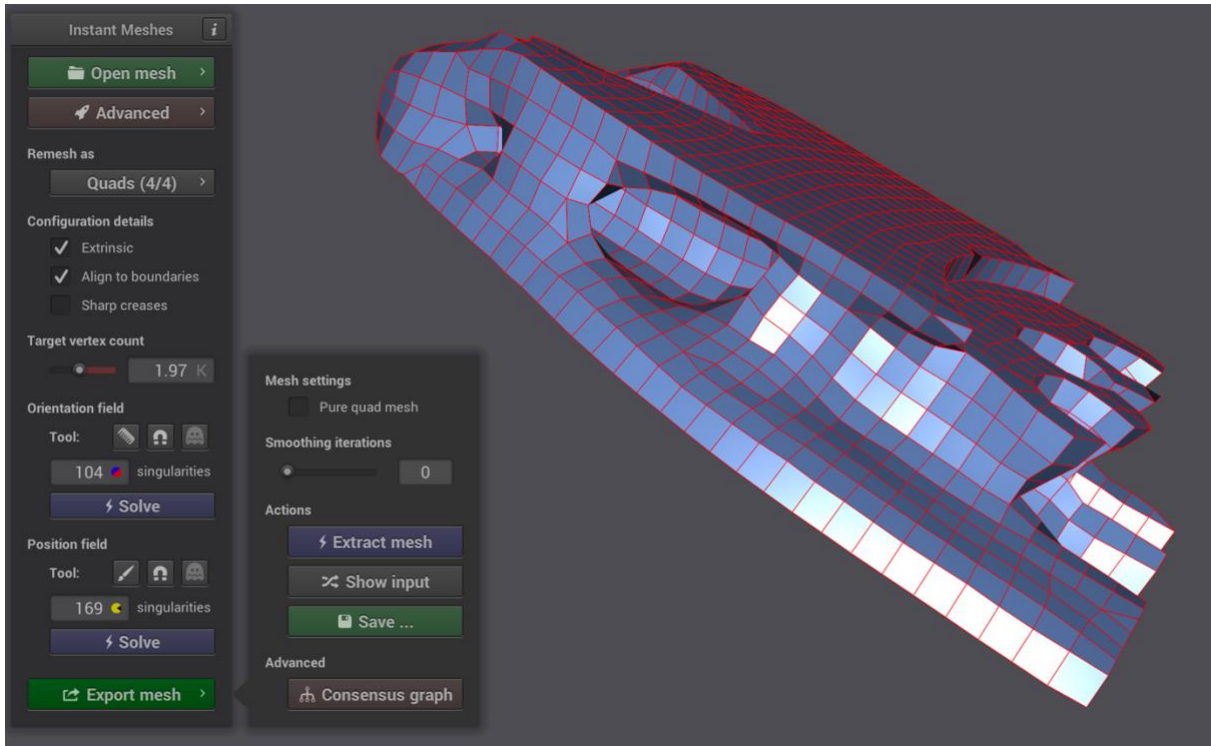
Fig 8 - Instant Mesh open-source software used to convert the triangular mesh to a quad mesh as required to create a t-spline form from mesh in Fusion 360. Screenshot from Instant Mesh program. Own work.

Finish CAD and prepare for simulation

The quad mesh is converted to t-spline body in Fusion 360 by disabling design history, right clicking on the mesh body, and selecting convert. In the form workspace we can repair the body and make any adjustments to the form, then convert it to BRep using the convert tool. We add 15 mm wide by 12 mm tall cylinders to the three suction mounting points, in the same orientation, and combine all the bodies in this component together.

Simulation

We set up a simulation to validate our design falls within acceptable parameters of our goal. In the simulation workspace in Fusion 360, we apply fixed constraints to the area in contact with the YZ plane and the three holes where bolts will be mounted through to the robot arm. A four-newton load in the negative direction is applied perpendicular to each of the three suction mounting faces as in

the topology optimization simulation. The mesh size is set at 2 mm and the simulation is sent to the cloud for computation *(fig 9)*.
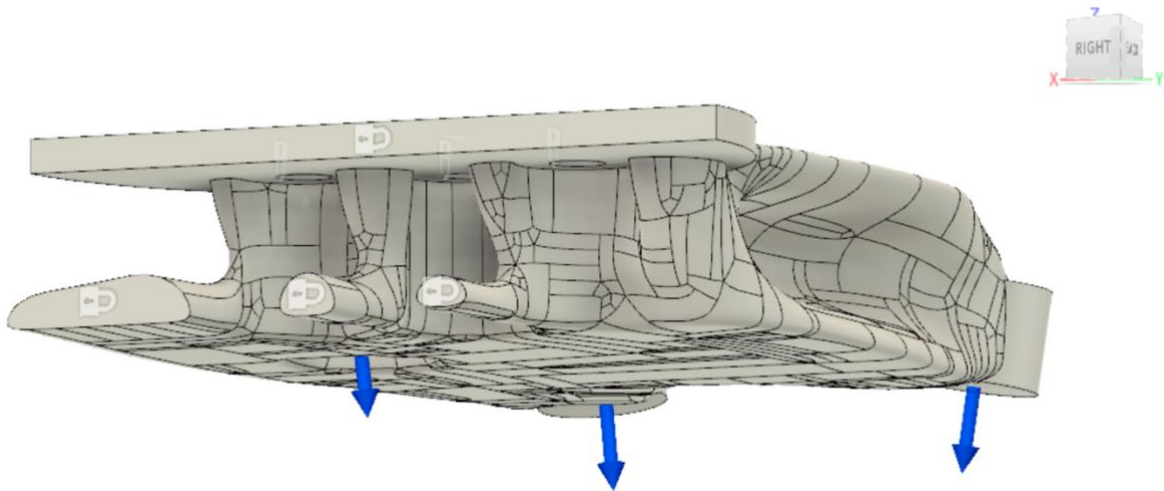
Fig 9 - Simulation setup to validate design. Screen capture in Fusion 360 simulation workspace during finite element analysis static simulation. Own work.

Finalize the CAD Model

Three internal channels of 3 mm are added with a 3d sketch and spline curve connecting all three suction fitting cylinders. Holes and threads for the 8 mm suction fittings are modeled in each cylinder so they can be additively manufactured. Fillets and chamfers are added, and the model is mirrored across the YZ plane. Finally, a mount point is added, and threads modelled for the 8 mm vacuum line attachment, and vacuum channels created between the attachment and the earlier designed channels *(fig 10)*.
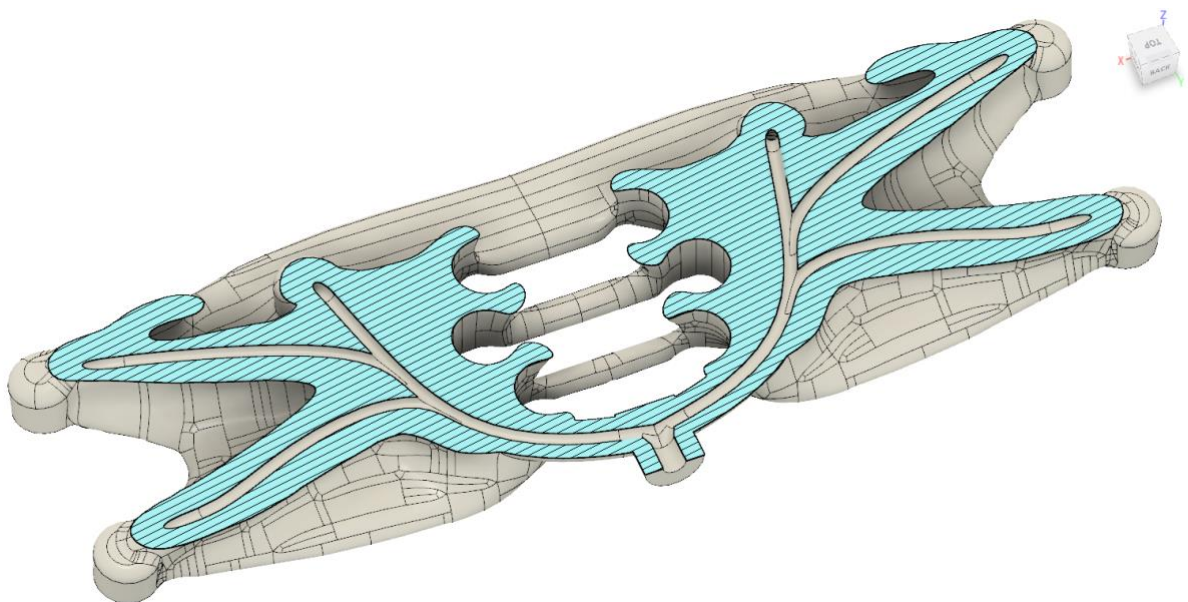
Fig 10 - Section analysis of the mirrored and combined end effector body. Note the three-millimeter vacuum channels converging at a central location where the vacuum line attachment will be fitted. Threads for vacuum line fitting not yet modelled. Screen capture in Fusion 360 design workspace. Own work.

Design Rules

The final design will be printed using selective laser sintering (SLS) additive manufacturing. As 3d printing goes, each form requires us to adhere to special design rules to achieve successful results.

SLS is a form of polymer powder bed fusion, a process which a fine layer of powder is deposited over the build platform, the layer is selectively melted using a laser which fuses the polymer together and the platform is lowered the thickness of the next layer and the process repeats until all layers of the part have been fused (Diegel, Nordin, & Motte, 2020).

When the part is finished printing it is entirely encapsulated in the raw, un-melted, powder. This requires some cleaning and handling post-printing but has the benefit of supporting the part during printing, so no extra support is required to be printed.

We must consider the powder in our design process. The powder must have a means to escape the printed part. The un-sintered powder is extra mass and does not contribute to the structural integrity of the part. We will be printing our part solid for full strength of the topology optimization so no extra powder evacuation holes will be needed. The interior vacuum channels are 3 mm diameter which is sufficient in size for powder evacuation post printing.

The final part after SLS printing is almost isotropic but has slightly less strength between the printed layers (EOS GmbH, 2012). This slight anisotropy can be mitigated by placing the part to be printed in an orientation that builds on the strength in the XY direction. For our end effector, one option is to rotate the part 90 degrees with the vacuum fitting facing down.

SLS prints best with relatively even wall thickness (Diegel, Nordin, & Motte, 2020, p. 111). This is due to the expansion and contraction of the polymer as it is melted. We consider this going forward with our design. If unacceptable warpage occurs in our SLS print, we can easily create a hollow part with a constant wall thickness of under 3 mm and powder evacuation holes. Our part is designed with sufficient strength to allow this shelling.

Other considerations when planning to print with SLS include a minimum wall thickness of 1 mm, hole proximity to wall edge of a minimum of 0.8 mm, minimum diameter of through holes corelating to wall thickness and minimum clearance between moving parts of 0.5 mm (Diegel, Nordin, & Motte, 2020, pp. 111 - 115), all of which are not applicable to our current design.

Material Data

The materials we have available to us are PA2200 Balance 1.0 and PA3200GF (EOS GmbH, 2012). They are both based on polyamide 12 which is a type of nylon (Nylon 12, 2021).

	PA2200 BALANCE 1.0	PA3200GF
DESCRIPTION	EOS brand Polyamide 12 powder for SLS	EOS brand Glass fiber reinforced polyamide 12 powder for SLS
DENSITY	9.3E-04 kg / mm^3	1.22E-06 kg / mm^3
YOUNG'S MODULUS	1650 MPa	3200 MPa
POISSON'S RATIO	0.394	0.35
YIELD STRENGTH	80 MPa	73 MPa
TENSILE STRENGTH	48 MPa	51 MPa

The material data sheets from EOS are somewhat limited so some calculated assumptions are made. According to the Cambridge Engineering handbook, the shear modulus G can be approximated with

the formula $G \approx \frac{3}{8}E$ where E is the elastic modulus. Cambridge handbook further shows a common yield and tensile strength of nylon (PA) to be 50-94.8 and 90-165 MPa respectively (Cambridge University Engineering Department, 2003). With the data, and PA2200 Balance 1.0 tensile strength of 48 MPa, we can assume a Yield strength of approximately 80 MPa.

Prototype

A full-scale prototype is sliced in Ultimaker Cura 4.9.1 and printed using FFF (Fused Filament Fabrication) and PLA on the Ultimaker 2+ 3d printer. Add:north brand white X-PLA, a rigid plant based polymer, and basic settings are used for printing.

Results

The new design is comprised of five unique parts as opposed to 18 on the original design. There are 26 parts in total if we count the six bolts and six washers that connect the end effector to the robot, the six suction cups with six threaded inserts and one vacuum line coupling. This is a reduction of 3.15 times fewer parts than the original 82. This simplifies the construction considerably over the original.

Fusion Links

Final version - https://a360.co/3xOe6IX

Initial rough sketch - https://a360.co/3zQD1h2

Physical properties

Mass of gripper body: 228.3 g (PA2200)

Mass of suction and bolts 2.3g per suction coupling (Al and Si), bolts 4.8 g and washers 1 g (steel). All required components are six of each which combined equals 48.6 g.

Total mass of assembled end effector and bolts to mount to the robot arm: 276.9 g

There is over 72% mass savings when compared to the original end effector design.

PA2200 and PA3200GF comparison

	PA2200 BALANCE 1.0	PA3200GF
MASS	228 g	263 g
VON MISES STRESS - MAX	2 MPa	2.1 MPa
DISPLACEMENT - MAX	0.03 mm	0.02 mm
FACTOR OF SAFETY – PER YIELD	15	15

Topology Optimization

Topology optimization successfully removed over seventy percent of the mass of the crude design space leaving what looks like natural bone growth *(fig 6 and 7)*. Topology optimization is based on load path analysis and is thus removed from load magnitude. See FEA section for quantitative simulation data.

FEA – Finite Element Analysis

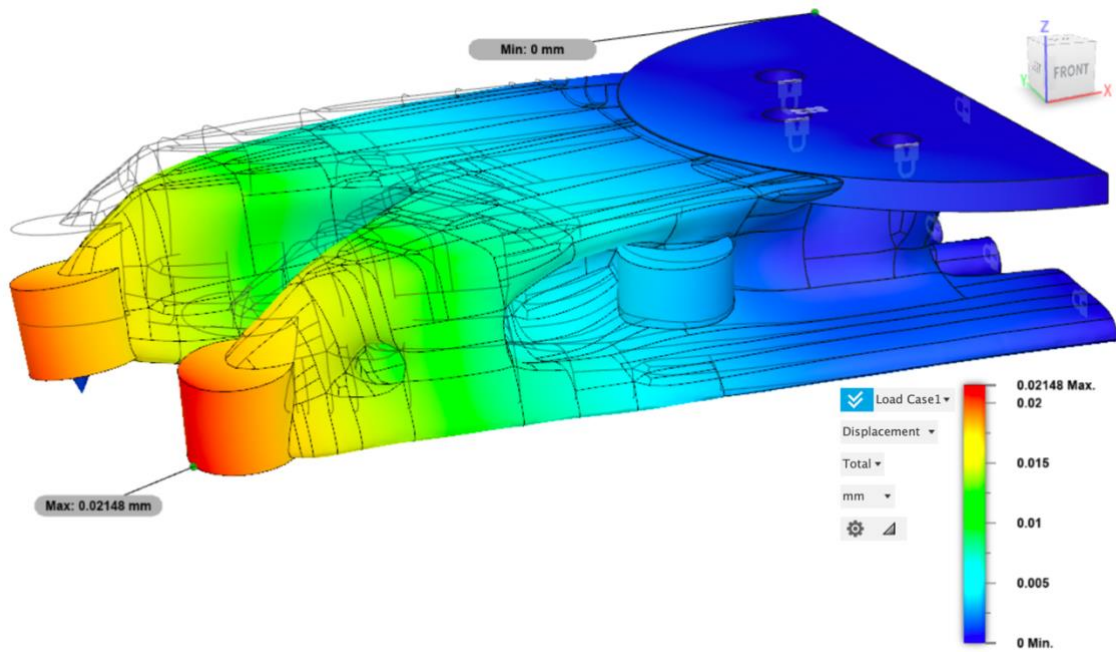FEA has shown the deflection to be a maximum of 0.02 mm *(fig 11)*.

Fig 11 - FEA deflection. Note deflection image exaggerated for illustration. Screen capture in Fusion 360 simulation workspace. Own work.

Printed Prototype

The printed prototype is simply for demonstration of size and real-world feel. It is light, stiff and functional. The holes printed threaded and the inner vacuum passages can hold air pressure above one atmosphere. No formal measured tests were conducted on this prototype.
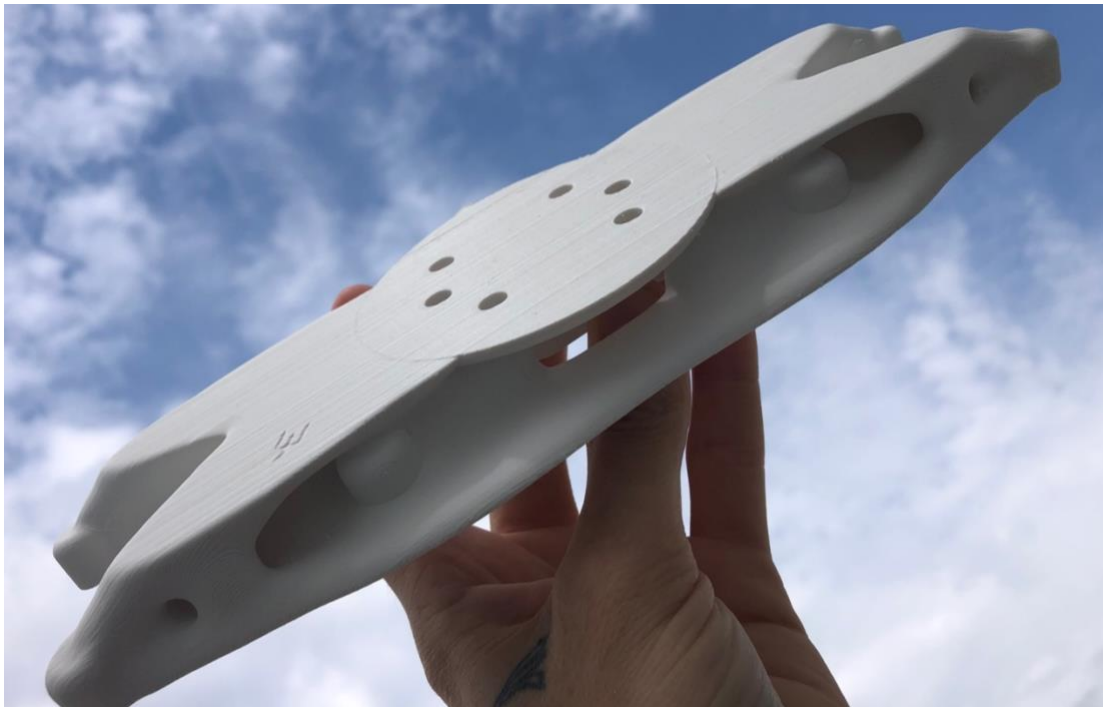

Fig 12 - Printed prototype in PLA. Own work.

Discussion

The results were somewhat unsurprising. Topology optimization does a great job of creating intuitive critical load paths, and when converted to a CAD model, perform well under static stress analysis. In Fusion 360, there is difficulty in converting the mesh data to an editable cad model without third party software.

The design is overbuilt for the loads suggested, however the loads suggested do not consider acceleration rates of the robot arm which could result in larger instantaneous loads on the end effector. The factor of safety is greatly dependent on the yield strength of the material and the value used is somewhat assumed based on other examples and calculations. The end effector use case is an industrial setting and thus has the potential to be subjected to abuse or greater loads than intended. Furthermore, SLS printing is not completely isotropic, being weaker in the Z direction of the print volume. A large factor of safety is one way to account for these situations.

There are pros and cons to the original model. The design assembly is very simple to build out of pre-existing parts, consequently making it easy to understand and replacement parts can be quite common if there is a failure somewhere, for example, in a vacuum line. The negative side of this means that failures are more likely, simply because there are over three times more parts than the new design solution. The consequence of more parts includes a requirement to keep many different unique parts in stock. This design is heavy, and the moment of inertia is greater due to the load being farther away from the robot arm. This can cause extra wear on the robot arm and slower cycle times due to accelerations requiring more energy.

There are pros and cons to the new design. The new design is lighter, and the moment of inertia is closer to the robot arm therefore requiring less energy to accelerate. This should allow for increased productivity by reducing cycle time or reduced energy consumption at lower cycle counts per shift. All the parts as one piece in the central body could be considered a con if there is a simple problem like a vacuum leak, as the entire body might need to be replaced. Oppositely, it is a benefit to have all the pieces combined into one body as a replacement is a digital model and one simply needs to print a new one at relatively low cost and downtime. This has the added benefit of not needing to store many types of parts for repair or replacement. The new design is created as a CAD model, allowing iterative tweaks to the design shape, or placement of suction fittings to be made quickly, and functional prototypes are simple to produce via 3d printing. This has the added potential of increasing productivity by adapting the ideal end effector to the application even as the application changes.

The initial rough sketch design *(see second fusion link)* was made in under three hours. That design is not meant for production as I did not possess the required parameters at the time of design. It turns out to be a decent design type which required less time for me to model if compared to the topology optimized design. Now that I am familiar with how to quickly convert a mesh body to a t-spline using Instant Meshes, the speed at which I create topology models should increase.

Upon double checking my simulation data I noticed some inconsistencies in the material property values. Some of the values appeared to be different than the values I had originally typed into the material properties fields. Further testing and inspection of the Fusion 360 material properties shows that it is important to hit the apply button after changing a single field in the material properties. When originally changing the properties, I changed all the fields at once and then hit apply. It is possible that this is a bug in Fusion 360. Applying custom materials is cumbersome and the user interface is clearly less polished than the rest of the Fusion 360 UI. This requires further care and inspection.

Conclusion

It could be possible to reduce the part count even further by avoiding the threaded part of the suction cup fitting and designing it to be printed. A silicone cup can be slid over the printed fitting eliminating the need for threaded fasteners, saving weight and complexity. It is possible to take the design and optimize further by shelling the structure and creating ribs and lattices if the weight is to be further reduced, however that is a project for the future.

Topology optimization is a powerful tool for analyzing load paths in a CAD model. This allows us to validate our gut feelings on a design's possible strength and is easily developed into a final model or simply used as a reference to design a simple or equivalent parametrized model from scratch. Finite element analysis allows us to take our completed model and run simulations based on our understanding of the loads that will be subjected upon it resulting in a prototype or final working design with few iterative steps and scratched prototypes. We used these tools to achieve our goals of light-weighting and simplifying the robotic end effector design with over three times fewer parts than the original and a quickly reproduceable design.
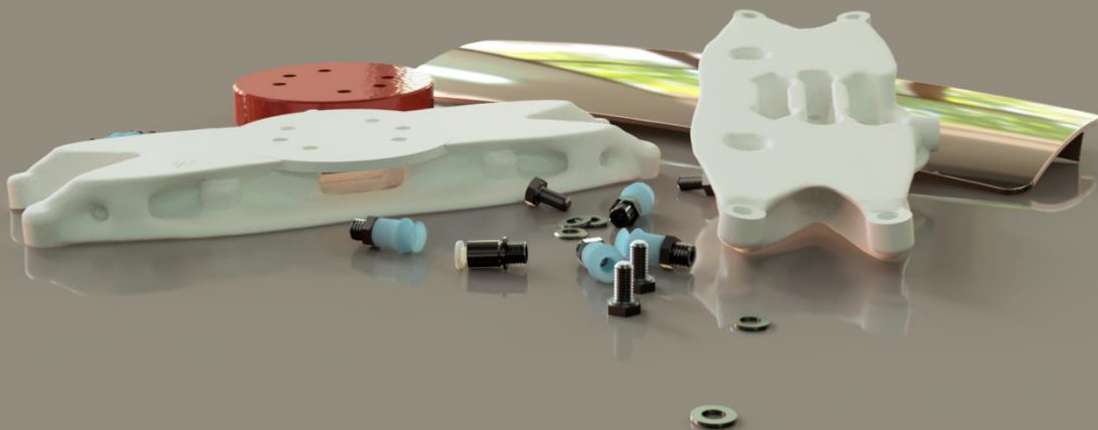
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Cover image: Rendering of final topology optimized and static stress simulated end effector. View from front. Page one image: View from rear. Rendered in Fusion 360. Own work.