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Sensor Driven Topology-Optimization for Additively Manufactured Humanoid Robotic Parts

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Technical Aspects of Multimodal Systems

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Outline

Outline

1. Motivation
2. Fundamentals
3. Capturing Data
4. Optimization Process
5. Results
6. Conclusion

Outline (cont.)

7. Next Steps

Current design

Bitbots' Wolves robot

- Design consists mostly of simple geometric shapes
  - Rectangular feet
  - Optimized for balance
- Legs and feet mainly made from aluminum and carbon parts
- All in all not ideal

Feet of the robot made out of aluminum and carbon

Motivation

Improving the design

- AM already used to produce parts of the robot
- Why not use AM for feet and legs as well?
- Optimize the shape of the parts
  - Less material → less weight
  - Less material → faster printing
  - Faster printing → higher availability
  - Organic structure → nice to have

Topology Optimization

- Reveals optimal structure for given loads
  - Over-think space usage
  - cable management or motor placements
- Requires load constraints
  - Forces have to be measured
  - Useful for walking algorithms

Outline

Outline (cont.)

Available printers

- **Fused Deposition Modeling (FDM)**
  - Prints using PLA or ABS filament
  - Extrudes filament while moving a print head
  - Heated print bed and chamber (ABS)
  - builds from bottom to top
- **Stereolithography Apparatus (SLA)**
  - Prints using polymer resin
  - uses UV light-source below a transparent build platform
  - builds from top to bottom
- **Multijet/Polyjet**
  - Basically an inkjet printer
  - Prints using photo-active polymers
  - Cures using UV light-source
  - Can use multiple materials in one print job
  - builds from bottom to top

FDM Printer

+ easy to fix and easy to extend
+ large enough print bed (20cm by 20cm)
o moderate print time
– moderate accuracy

SLA Printer

- \+ Very high resolution
- – More expensive than FDM
- – Setup is quite sophisticated
- – Longer print times than FDM

Multijet/Polyjet

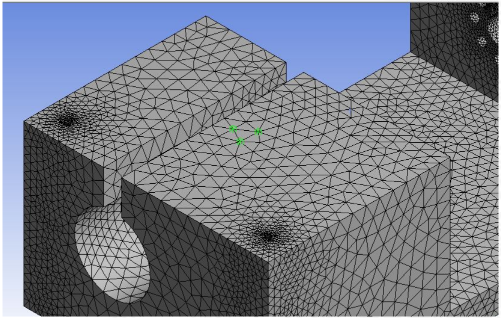
- \+ Very high resolution
- \+ Support material can be added seamlessly
- – Long print times
- – Material is very pricey

Finite Element Method or Analysis

- Numerical approach for solving physics problems
- Divide a complex problem into smaller simpler problems
- Also used for fluid dynamics, heat transfer etc.

Terminology

- Node
- Element
- Mesh
- Degree of Freedom (DOF)
- Nodal displacement vector $\{d\}$ $\{D\}$
- Nodal load vector $\{f\}$ $\{F\}$
- Stiffness matrix $[k]$ $[K]$



Meshed surface with three points of an element highlighted

Terminology

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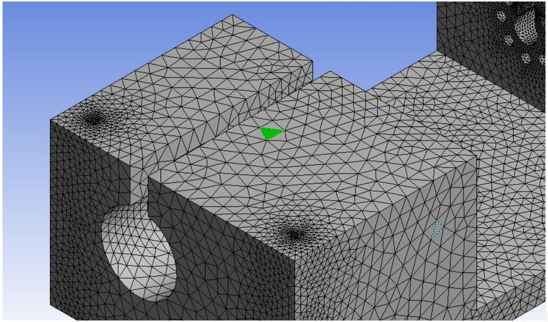

Meshed surface with a highlighted element of the mesh

Terminology

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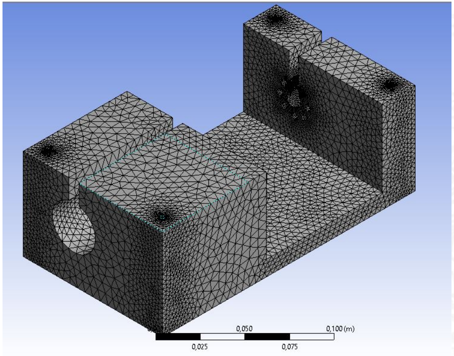

Meshed surface of a 3d-modeled part

Terminology

- Node
- Element
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- Degree of Freedom (DOF)
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Terminology

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FEA Step by Step

1. Define problem
2. Create a simple model
3. Define loads and constraints
4. Meshing
5. Hand over to solver
6. Evaluate results

Solving using FEA

1. Define relation between loads and deformations
   $\{f\}_i = [k]_i\{d\}_i$
2. Link all relations through continuity constraints
   $\{F\} = [K]\{D\}$
3. Define boundary conditions
   $\{F_{BC}\} = [K_{BC}]\{D_{BC}\}$
4. Solve for displacement vector $\{D_{BC}\}$
   $\{D_{BC}\} = [K_{BC}]^{-1}\{F_{BC}\}$

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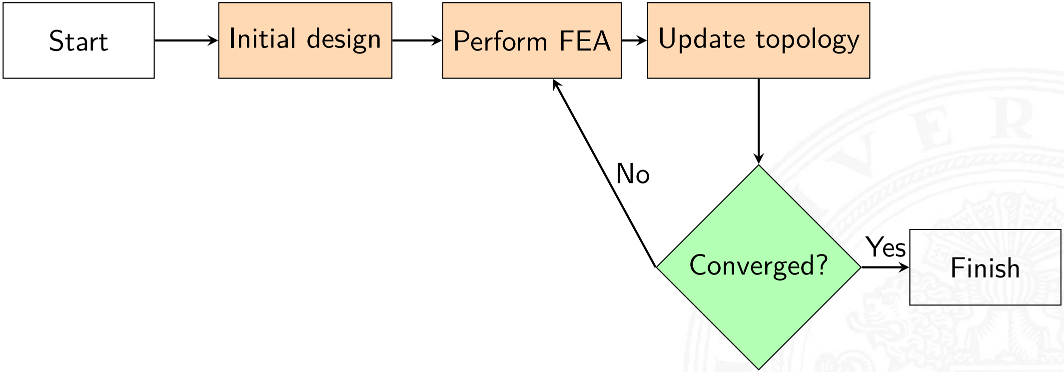
What is topology optimization?

- Optimization task
- Optimizes for minimal compliance/flexibility based on constraints
- Solves material distribution problem
- Iterative process


Start
Initial design
Perform FEA
Update topology
Converged?
No
Yes
Finish

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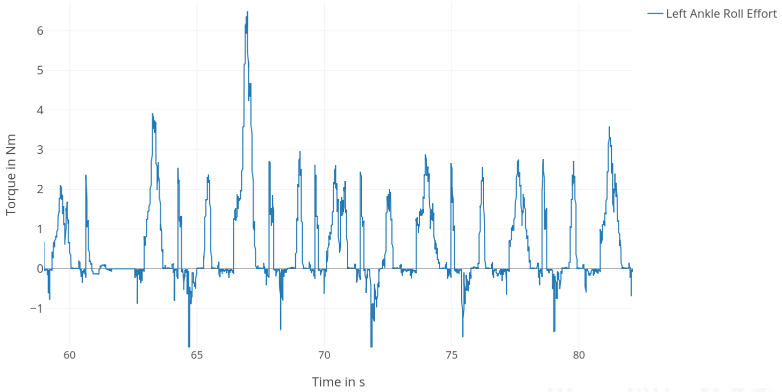
Outline (cont.)

7. Next Steps

Servo efforts

- Effort of the servo motors captured during walking
- Peak effort for ankle roll was at 6.49Nm

Servo efforts

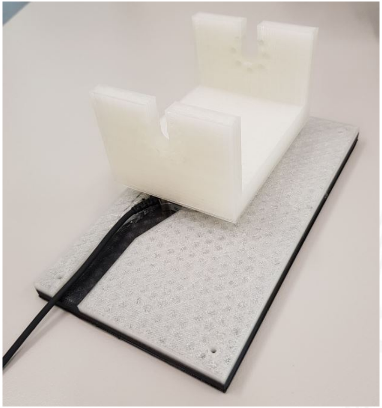


Section of reported torques of the left ankle roll motor

Using a F/T-Sensor

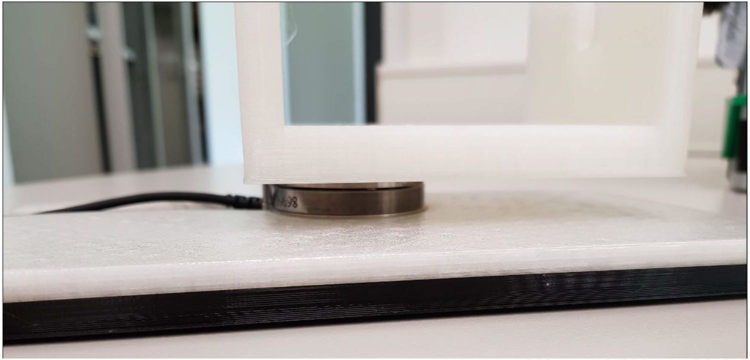
- ATI Mini45 f/t-sensor was used
- Sensor was placed inside the foot and the leg
- Sensor reports forces in x-,y-direction up to 580N
- 1160N in z-direction
- Reports torque in x-,y-,z-direction up to 20Nm

Using a F/T-Sensor



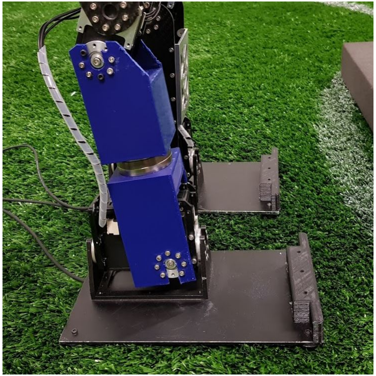
3D-printed foot with an ATI Mini45 f/t-sensor between the top and the bottom part

Using a F/T-Sensor



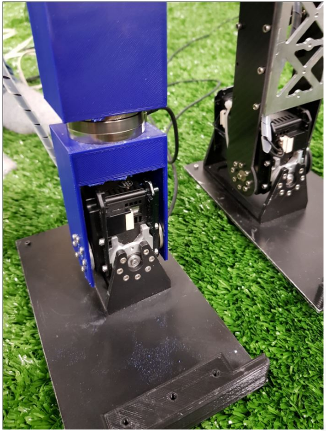
Closer view of the sensor inside the foot

Using a F/T-Sensor



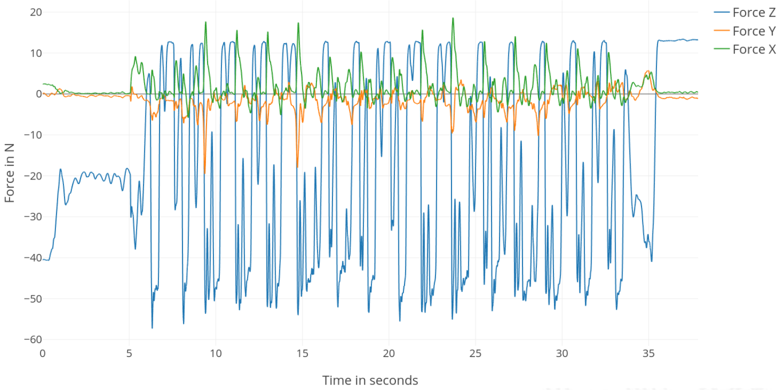
3D-printed leg consisting of two parts with an ATI Mini45 f/t-sensor connecting both parts

Using a F/T-Sensor



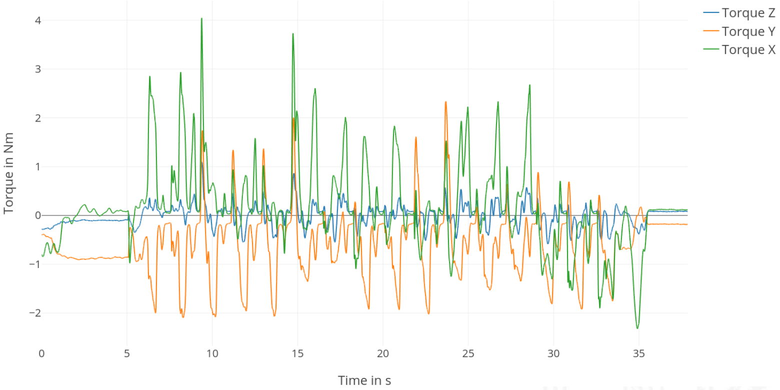
Closer view of the sensor inside the leg

Using a F/T-Sensor



Graph showing forces in x-,y- and z-direction reported by the ATI Mini45 f/t-sensor

Using a F/T-Sensor



Graph showing torques in x-,y- and z-direction reported by the ATI Mini45 f/t-sensor

Outline

Outline (cont.)

Tools Used

- ANSYS Workbench suite
- ROS and Gazebo framework
- FDM printer
- Slic3r for slicing

ANSYS Workbench

- Combines a variety of software solutions
  - CAD tools
  - Mathematical solver
  - Simulation tools
- Solutions are heavily integrated
- Workflow-like control flow

Tools Used: ROS and Gazebo framework

ROS and Gazebo framework

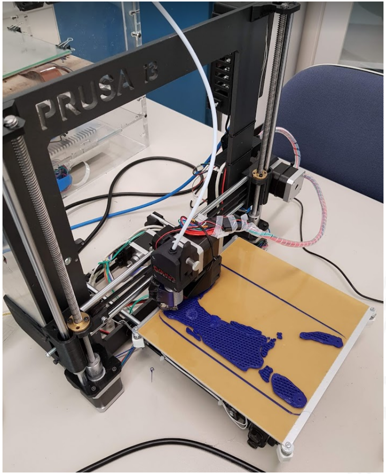
- ROS kinetic
- Simulation of falling, walking and idling
- Collecting data from simulation and motor values

Tools Used

FDM Printer

- Prusa i3
- Printing of optimized parts

Tools Used



Prusa i3 3d-printer printing a topology optimized foot

Steps of the optimzation process

1. Modeling the part
2. Define loads and constraints
3. Run a FEA
4. Define design and exclusion regions
5. Define constraints
6. Run a topology optimization
7. Post process results

Prerequisites

- Define material properties
- Add module to workflow

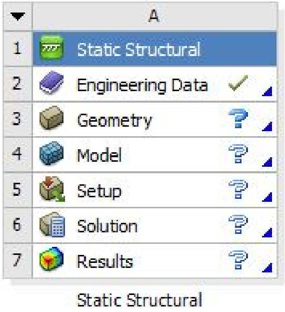
Properties of Outline Row 3: Polylactic acid

	A	B	C
1	Property	Value	Unit
2	Density	1,24	g cm^-3
3	Isotropic Elasticity		
4	Derive from	Young's Modulus and Poisson's Ratio	
5	Young's Modulus	3500	MPa
6	Poisson's Ratio	0,36	
7	Bulk Modulus	4,1667E+09	Pa
8	Shear Modulus	1,2868E+09	Pa
9	Tensile Ultimate Strength	73	MPa

Table showing the defined properties of polylactic acid inside ANSYS Workbench

Prerequisites

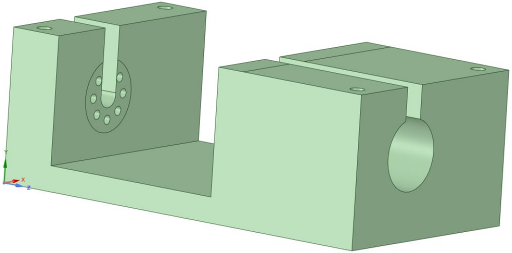
- Define material properties
- Add module to workflow



Static structural module with steps for a FEA inside ANSYS Workbench

Modeling the part

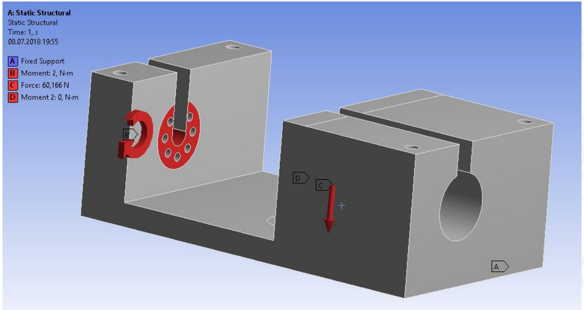
- Define large block of material
- Model in required design elements



3D-Model of a foot for a robot designed to use the maximum amount of space available

Defining loads and constraints

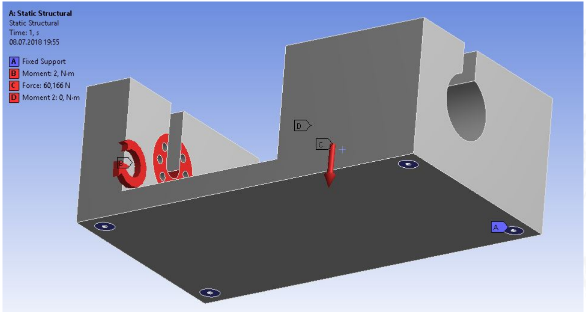
- Fixed support defined for the studs
- Torque and loads act on bearing and mounting face



Model of the foot with torque and forces defined on faces in red

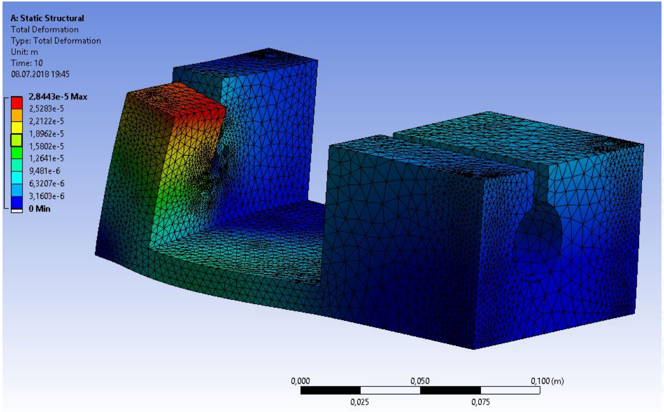
Defining loads and constraints

- Fixed support defined for the studs
- Torque and loads act on bearing and mounting face



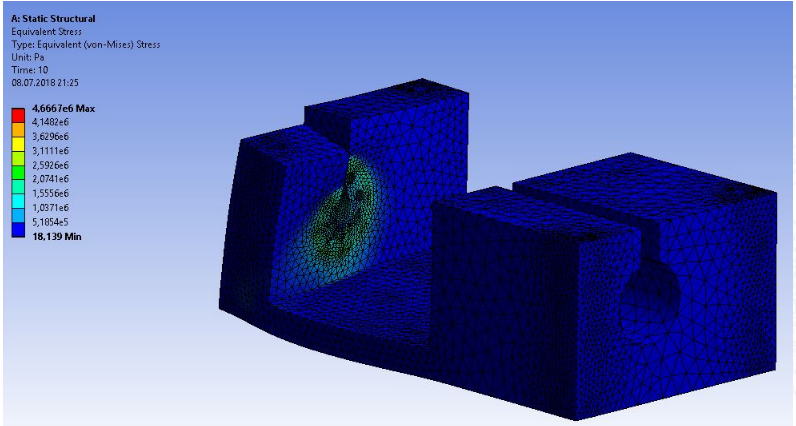
Model of the foot with supported faces in blue

Run the FEA



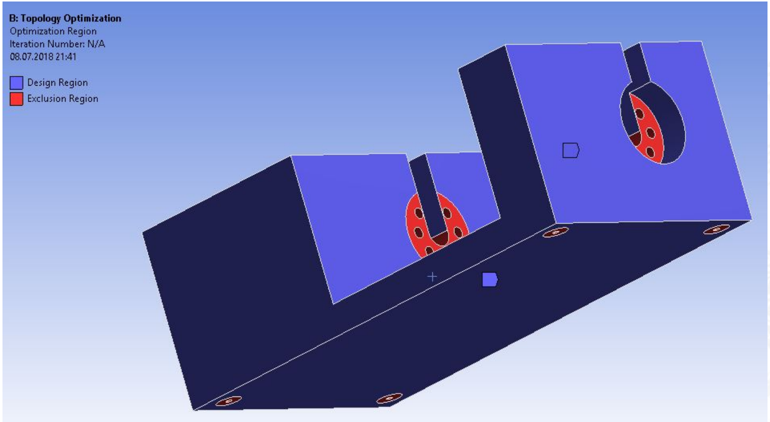
Results of the FEA showing deformation with blue being the least and red the most amount of deformation

Run the FEA



Results of the FEA showing stress with blue being the least and red the most amount of stress

Define the design and exclusion regions



Model of the foot showing areas that will not be touched by the optimization process in red and available area for optimization in blue

Response Constraint

Define the response constraint for topology optimization

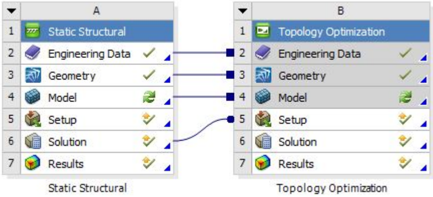
- Volume
- Mass
- Max deformation
- Max stress

Define additional constraints

- Additional response constraints
- Manufacturing constraints
  - Symmetry
  - Extrusion

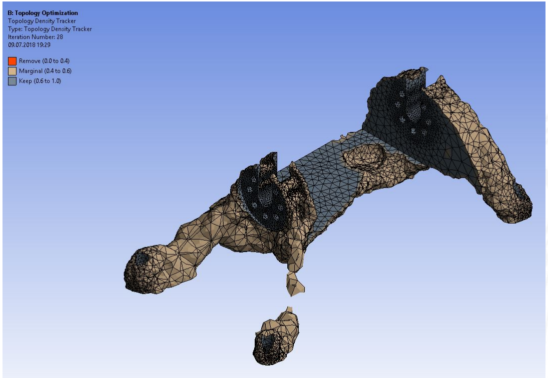
Solve the topology optimization

- Can be computed concurrently
- Current state can be inspected



Modules of an optimization workflow linked together

Solve the topology optimization

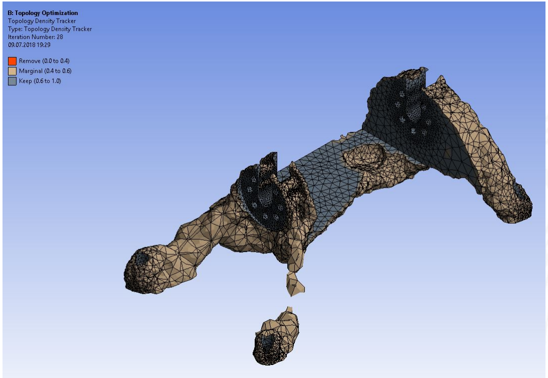


Result of the topology optimization showing a rough faceted body with a disconnected part

From optimized model to printable part

- Optimization returns rough stl-file
- Faceted body needs to be checked for errors and disconnected parts
- Model is then shrink-wrapped
- Model can be smoothed further

From optimized model to printable part



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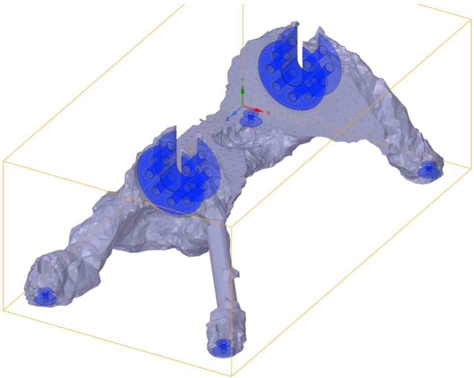

Fixed faceted body with areas with important features highlighted in blue

From optimized model to printable part

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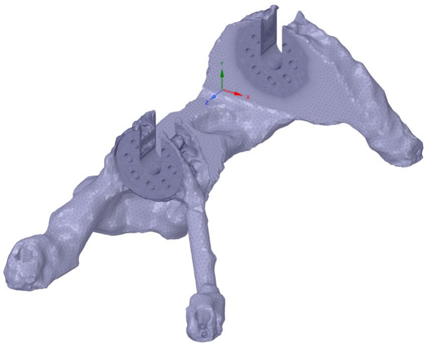
- Faceted body needs to be checked for errors and disconnected parts
- Model is then shrink-wrapped
- Model can be smoothed further

From optimized model to printable part

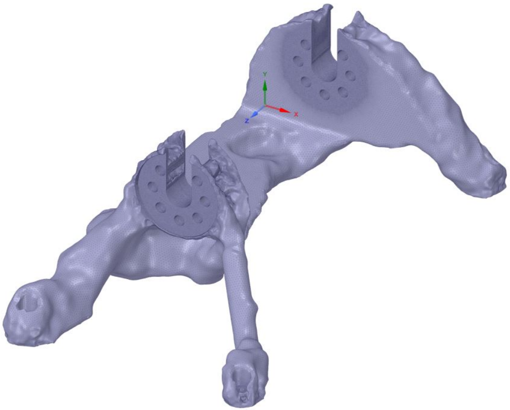


Faceted body with smoothed-over surface

From optimized model to printable part

- Optimization returns rough stl-file
- Faceted body needs to be checked for errors and disconnected parts
- Model is then shrink-wrapped
- Model can be smoothed further

From optimized model to printable part



Faceted body with very high element count after additional smoothing

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Results

- Print time: between 19 and 6 hours
- Filament used: slightly over 4m
- Weight:
  - 270g (original)
  - 148g (optimized)
  - 45% weight reduction
- Passed quick walking test

Original foot on a scale

Optimized foot on a scale

Outline

Outline (cont.)

7. Next Steps

Was it worth it?

- Optimized part is lighter
- Can be printed in approx. 6 hours
- Doesn't break
- Looks less boring

Outline

7. Next Steps

Next Steps

What next?

- Stress test parts
- Printing a part that finally breaks
- Has walking improved?

Thank You

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