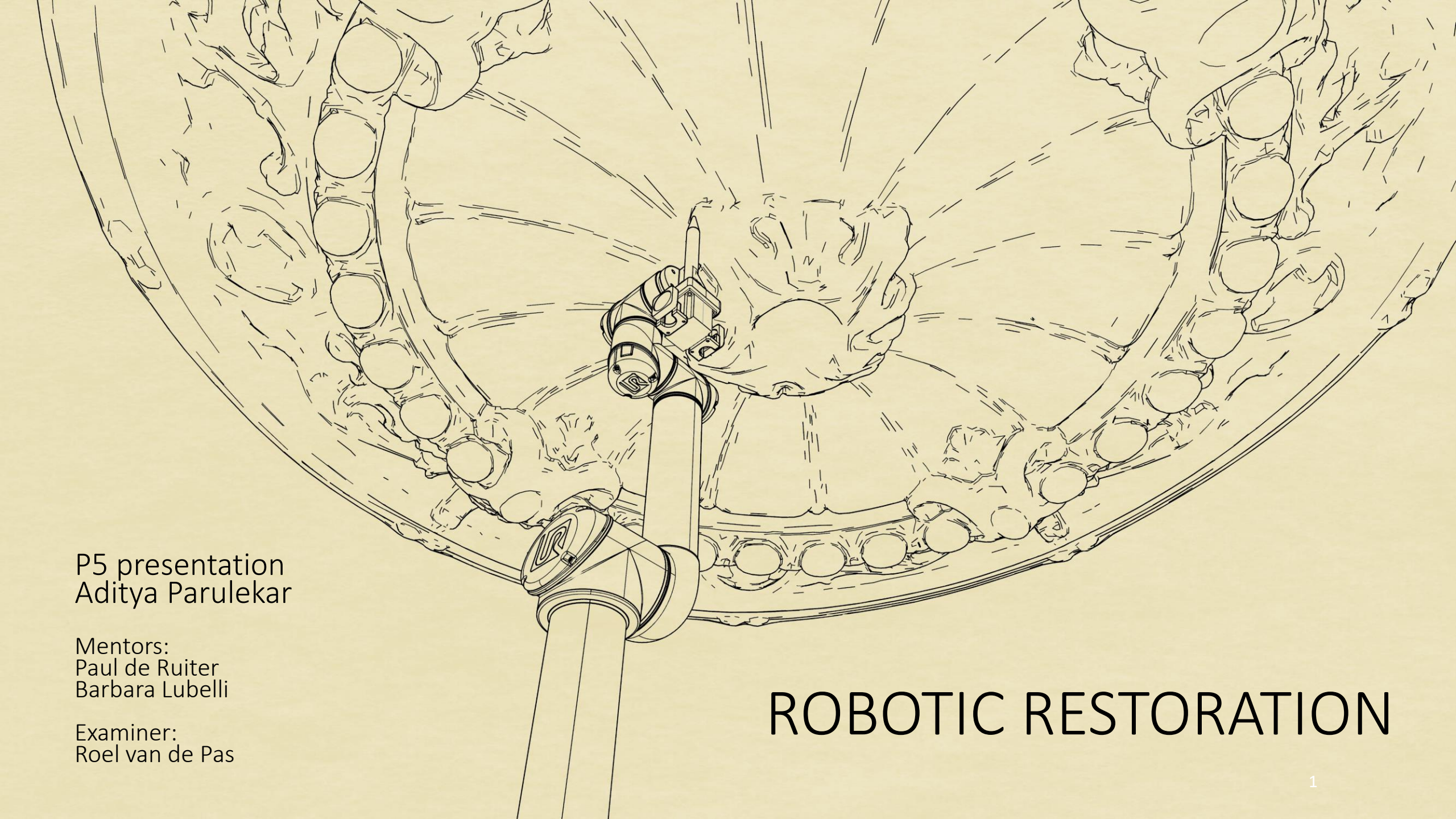


# ROBOTIC RESTORATION

P5 presentation
Aditya Parulekar

Mentors:
Paul de Ruiter
Barbara Lubelli

Examiner:
Roel van de Pas

# Mask of Mayan Sun God

Temple of the Night Sun, 400 AD, Guatamala

- Shark swims every day from East to West through the sky → Sun God

# Sculptures of Hindu gods

Temple of Shiva, 7h century AD, Chennai, India

- Human-like features: relationships, jewellery, war

www.wikkimedia.org

# Ornamented ceilings

Huize Nolet, 1804, Schiedam, Netherlands

- Juniper leaves & ships →

Booming world wide export of Gin from Schiedam from the 18th century onwards

# Ornamentation

Temple of the Night Sun, 400 AD, Guatamala

Temple of Shiva, 7h century AD, Chennai, India

Huize Nolet, 1804, Schiedam, Netherlands

Who were our ancestors?
What did they do?
What did they believe in?
What was important to them?

Heritage

Widely used

# Stucco

Temple of the Night Sun, 400 AD, Guatamala

Temple of Shiva, 7h century AD, Chennai, India

Huize Nolet, 1804, Schiedam, Netherlands

Binder + Aggregates + Water

Lime, gypsum sand, stone powder

# Ornamented stucco ceilings: gypsum

Stucco ceiling, Huize Nolet, NL, 1804

Images: Wikimedia.com, tbafbouw.nl

Heritage

Widely used

# Damage over time → fragile

Heritage

Widely used



Image source: Stuc: Kunst & Techniek

# Traditional restoration

Heritage

Widely used

Image source: Stuc: Kunst & Techniek, RCE 2010

# Traditional restoration

On site restoration

**Anton van Delden**, restoration plasterer, chairman Neerlandsch Stucgilde

Image source: Stuc: Kunst & Techniek, RCE 2010

Heritage

Widely used

# Traditional restoration

(UWV, 2019), (Neerlands Stucgilde,2017)

How can we restore stucco ornaments in the future?

Image source: Stuc: Kunst & Techniek, RCE 2010



Heritage

Widely used

Physically demanding

Complex shapes

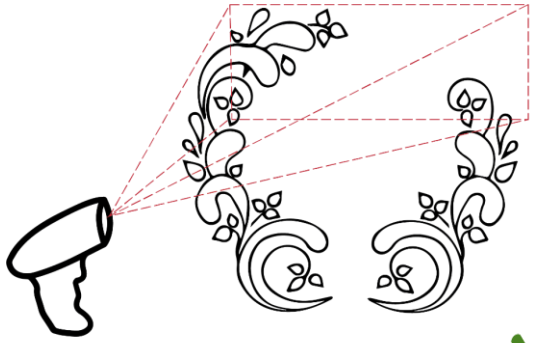
Labour intensive

Expensive

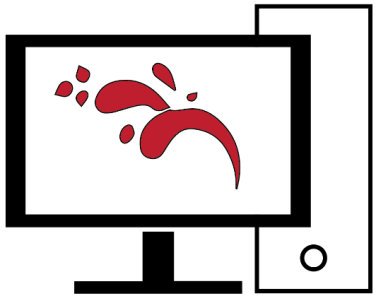
Shortage in personnel

Mismatch supply & demand

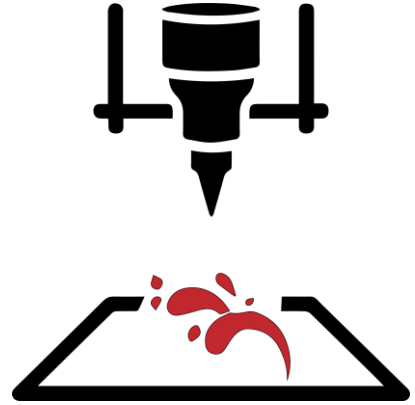
# Digital Fabrication



3D scanning ✓



CAD reconstruction ✓



3D printing

Heritage

Widely used

Physically demanding

Complex shapes

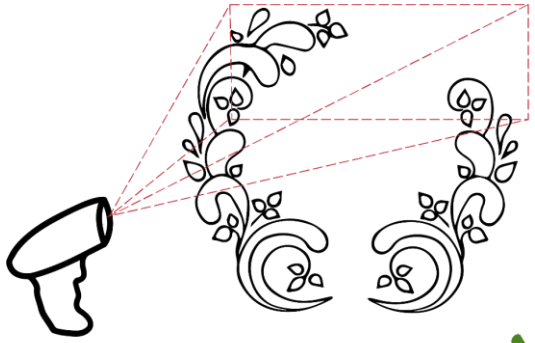
Labour intensive

Expensive

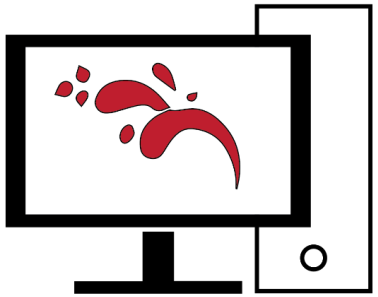
Shortage in personnel

Mismatch supply & demand

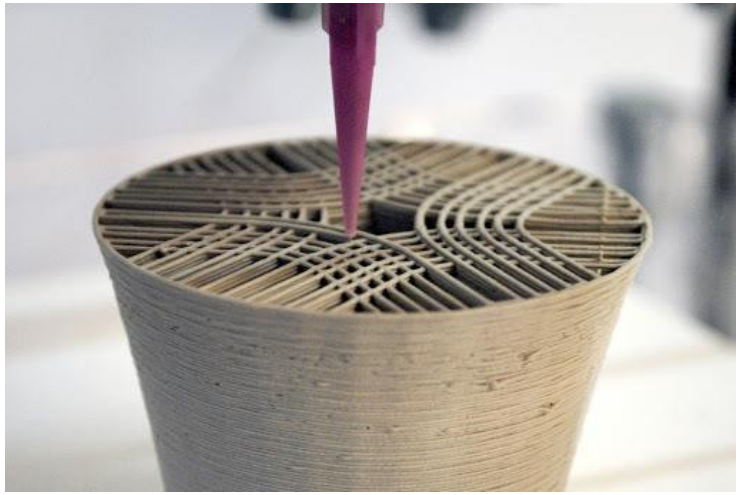
# Digital Fabrication



3D scanning ✓



CAD reconstruction ✓



3D printing: vertically down

Heritage

Widely used

Physically demanding

Complex shapes

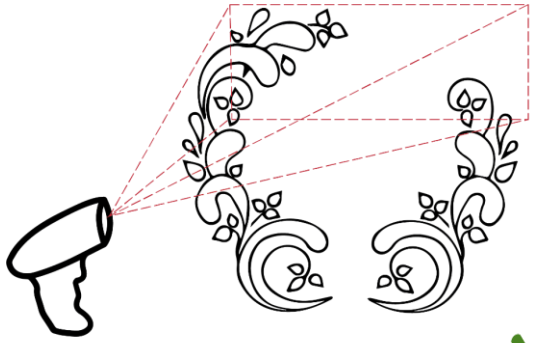
Labour intensive

Expensive

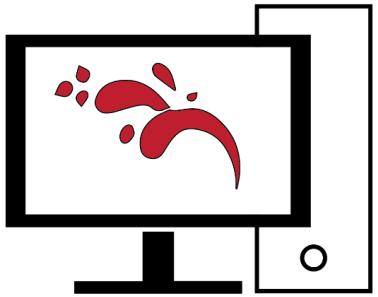
Shortage in personnel

Mismatch supply & demand

# Digital Fabrication



3D scanning ✓



CAD reconstruction ✓

Heritage

Widely used

Physically demanding

Complex shapes

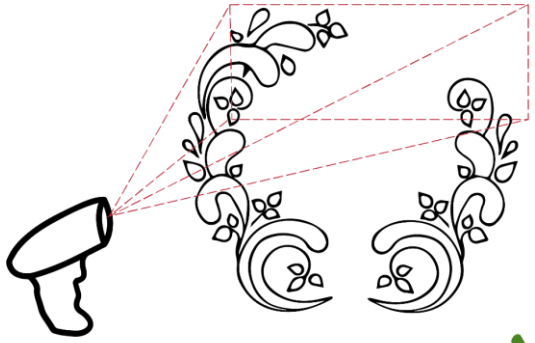
Labour intensive

Expensive

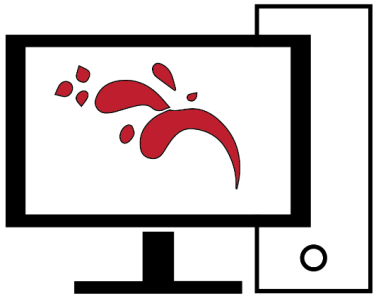
Shortage in personnel

Mismatch supply & demand

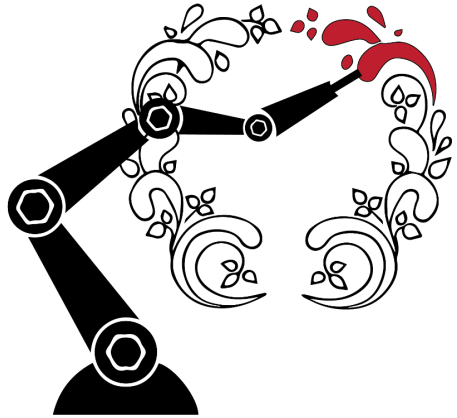
# Digital Fabrication



3D scanning ✓



CAD reconstruction ✓



In-situ 3D printing gypsum with robot ?

Heritage

Widely used

Physically demanding

Complex shapes

Labour intensive

Expensive

Shortage in personnel

Mismatch supply & demand

# Conservation guidelines

**International Charter of Venice:**

Article 10: *"Where **traditional techniques prove inadequate**, the consolidation of a monument can be achieved by the use of any **modern technique for conservation** and construction, the efficacy of which has been shown by **scientific data** and **proved by experience**."*


Heritage


Widely used


Physically demanding


Complex shapes


Labour intensive


Expensive


Shortage in personnel


Mismatch supply & demand

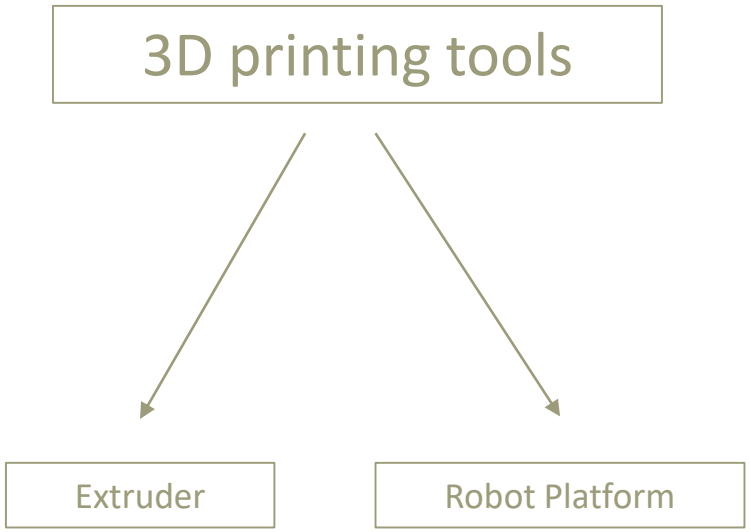
# Objective

3D printing tools

3D printing material

Integration into practise

# Objective

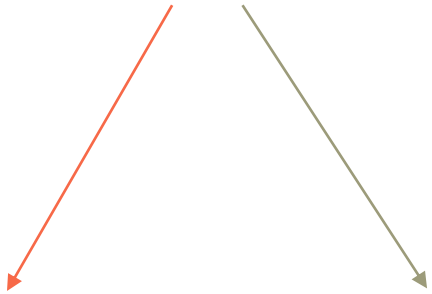



3D printing material

Integration into practise

# Objective

3D printing tools



Extruder

Robot Platform

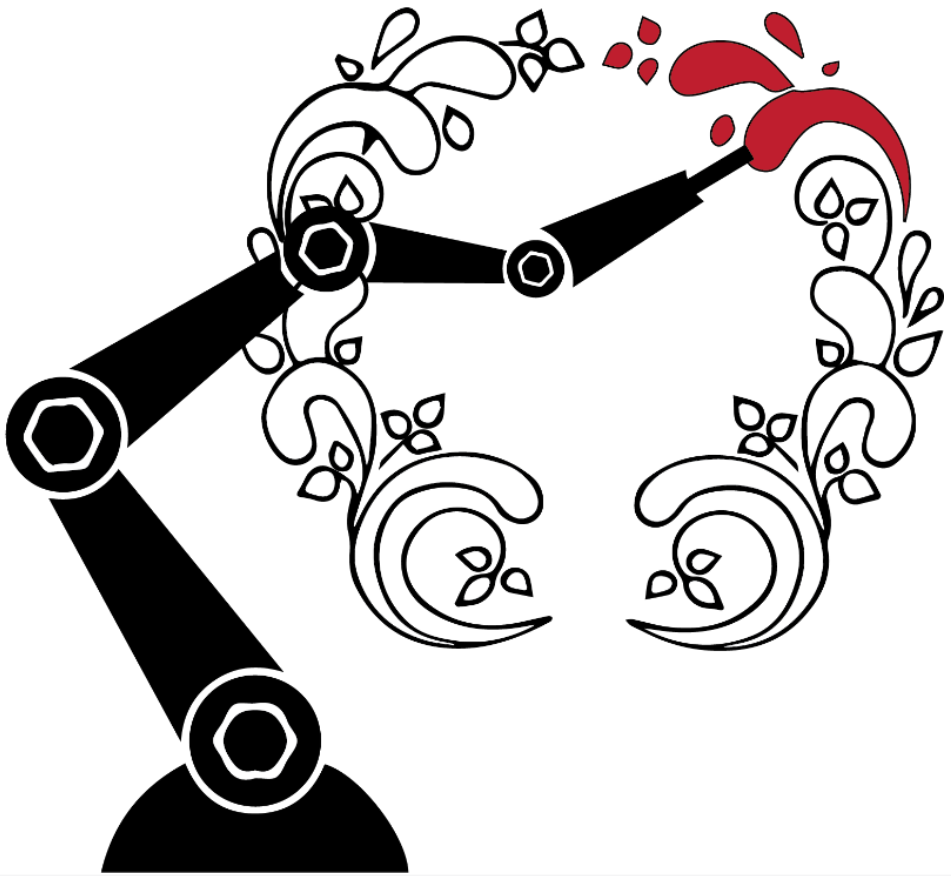
3D printing material

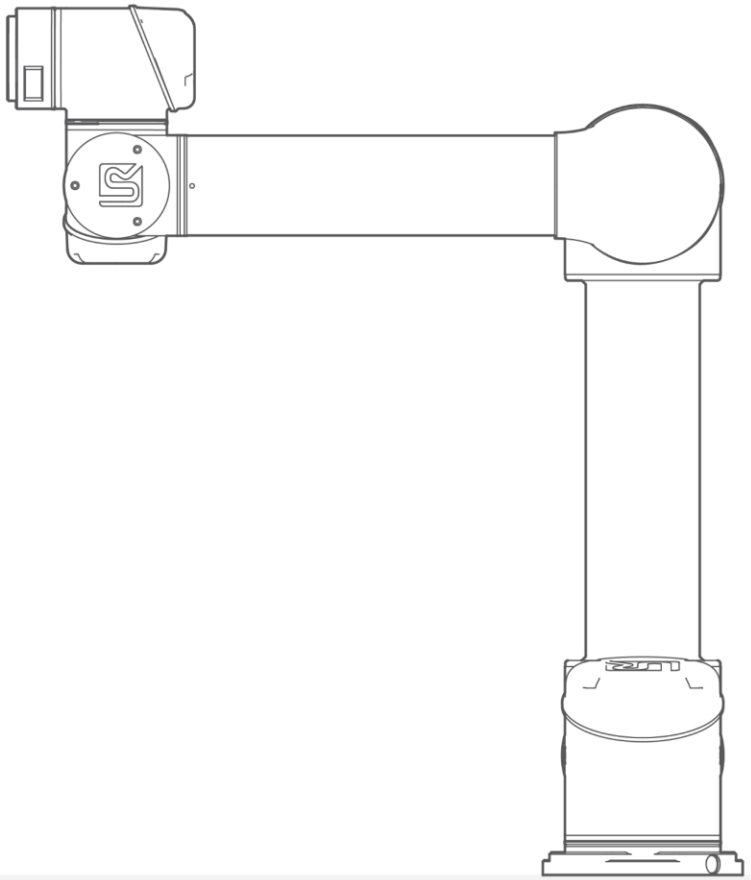
Integration into practise

# 3D printing tools

## Extruder design

# UR5 robot

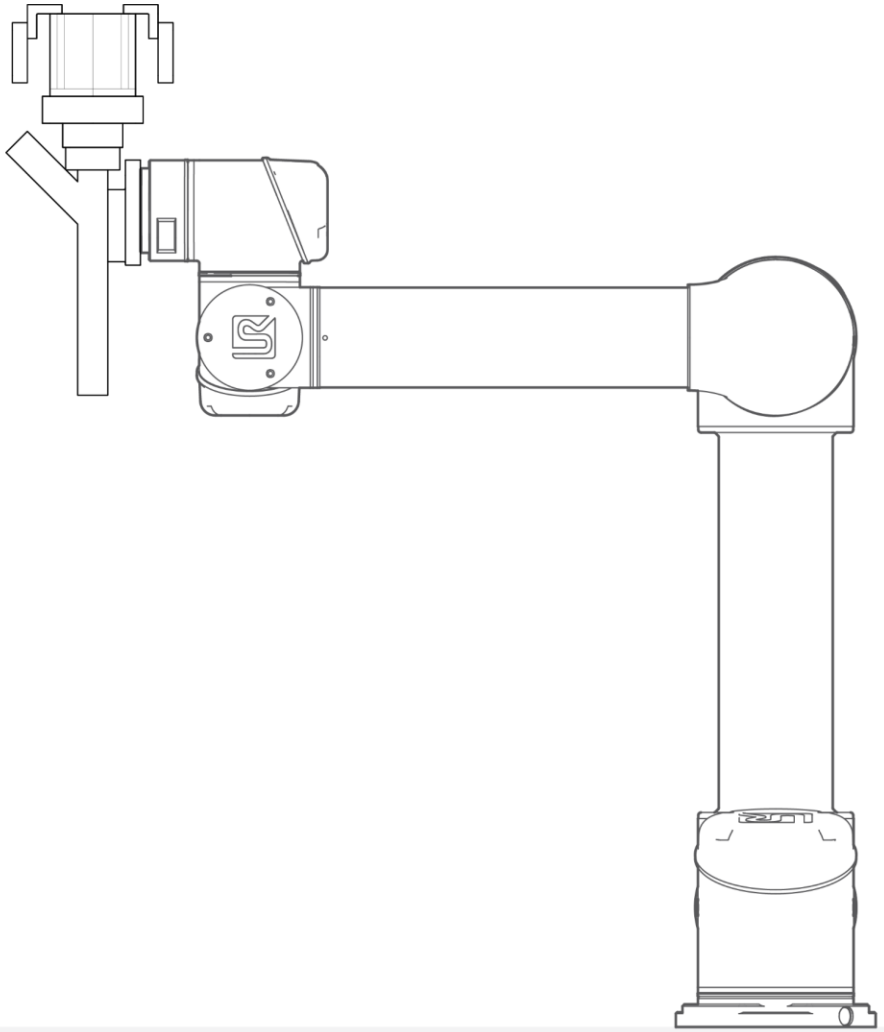




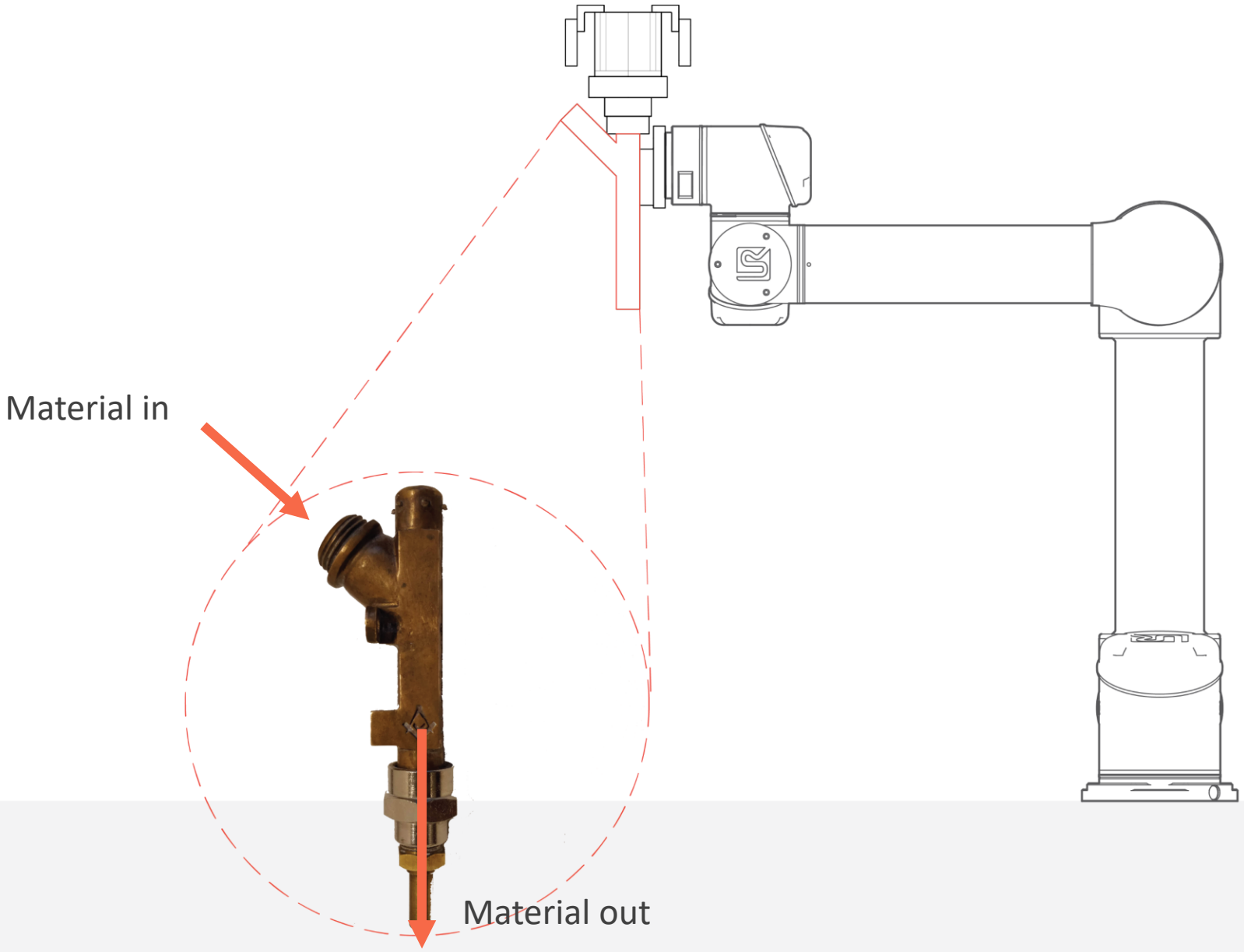
Multi-axis robot

# Extruder

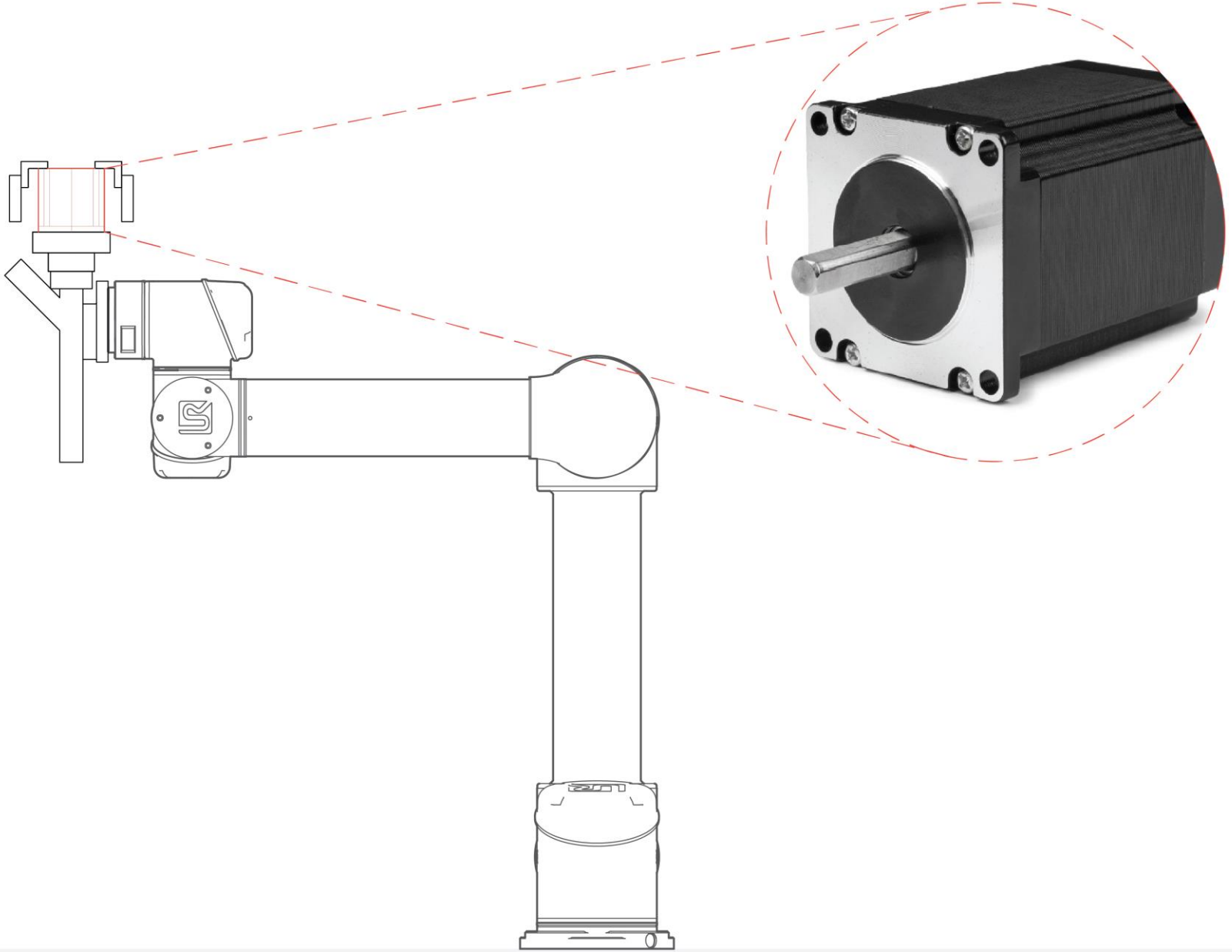

Syringe extruder



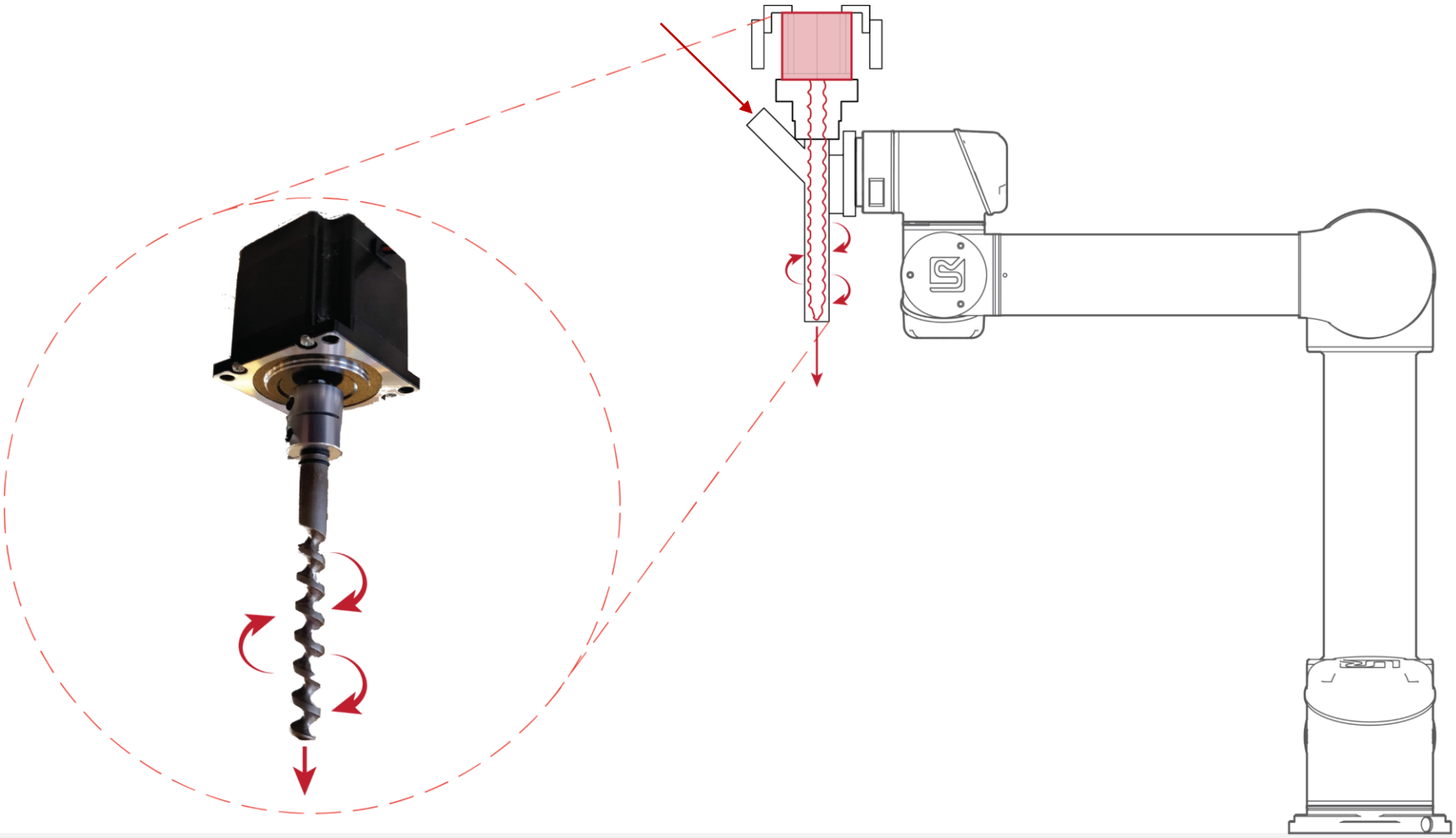
Steel funnel + inlet



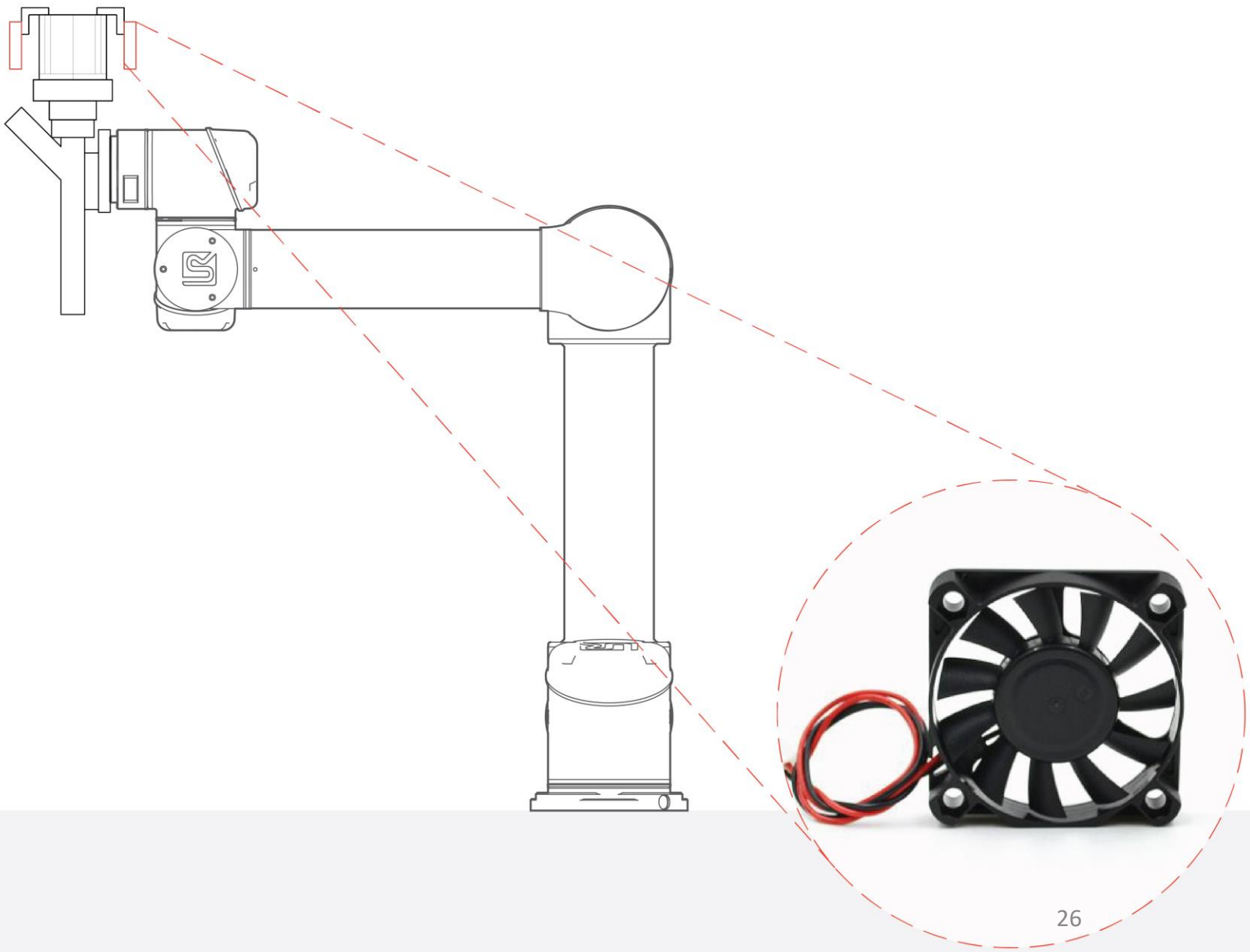
NEMA 23 stepper motor



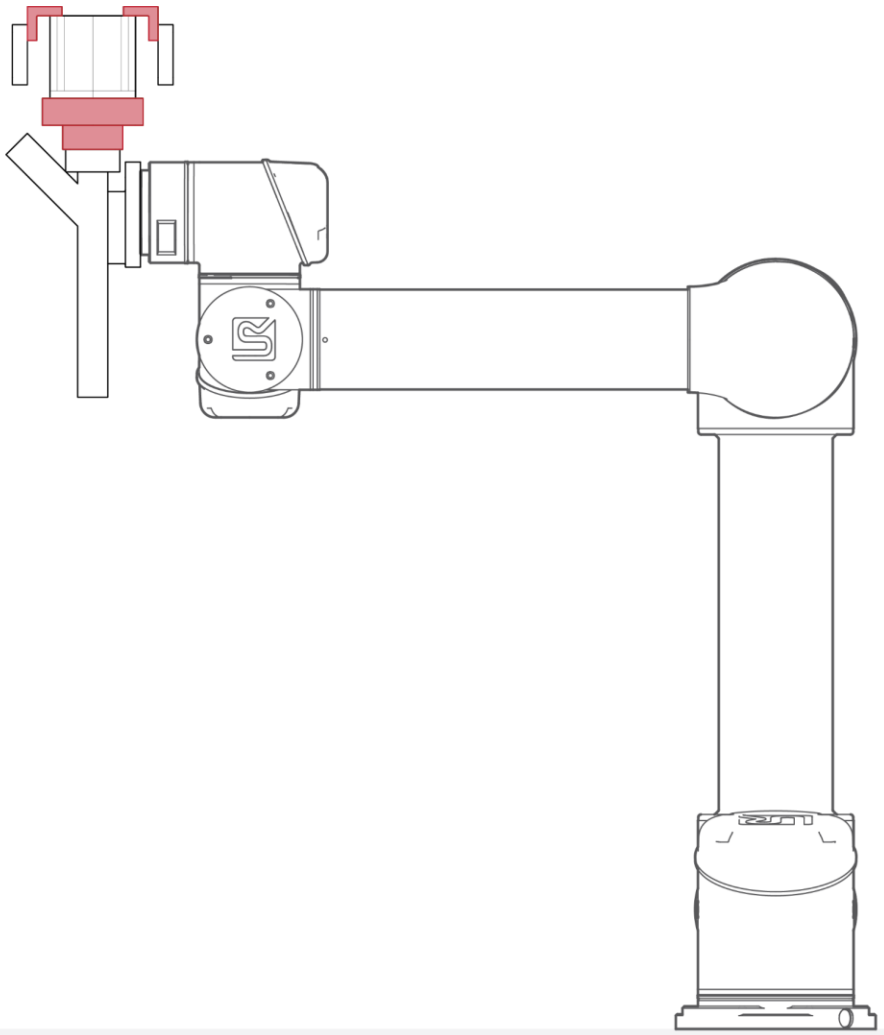
# Extruder mechanism



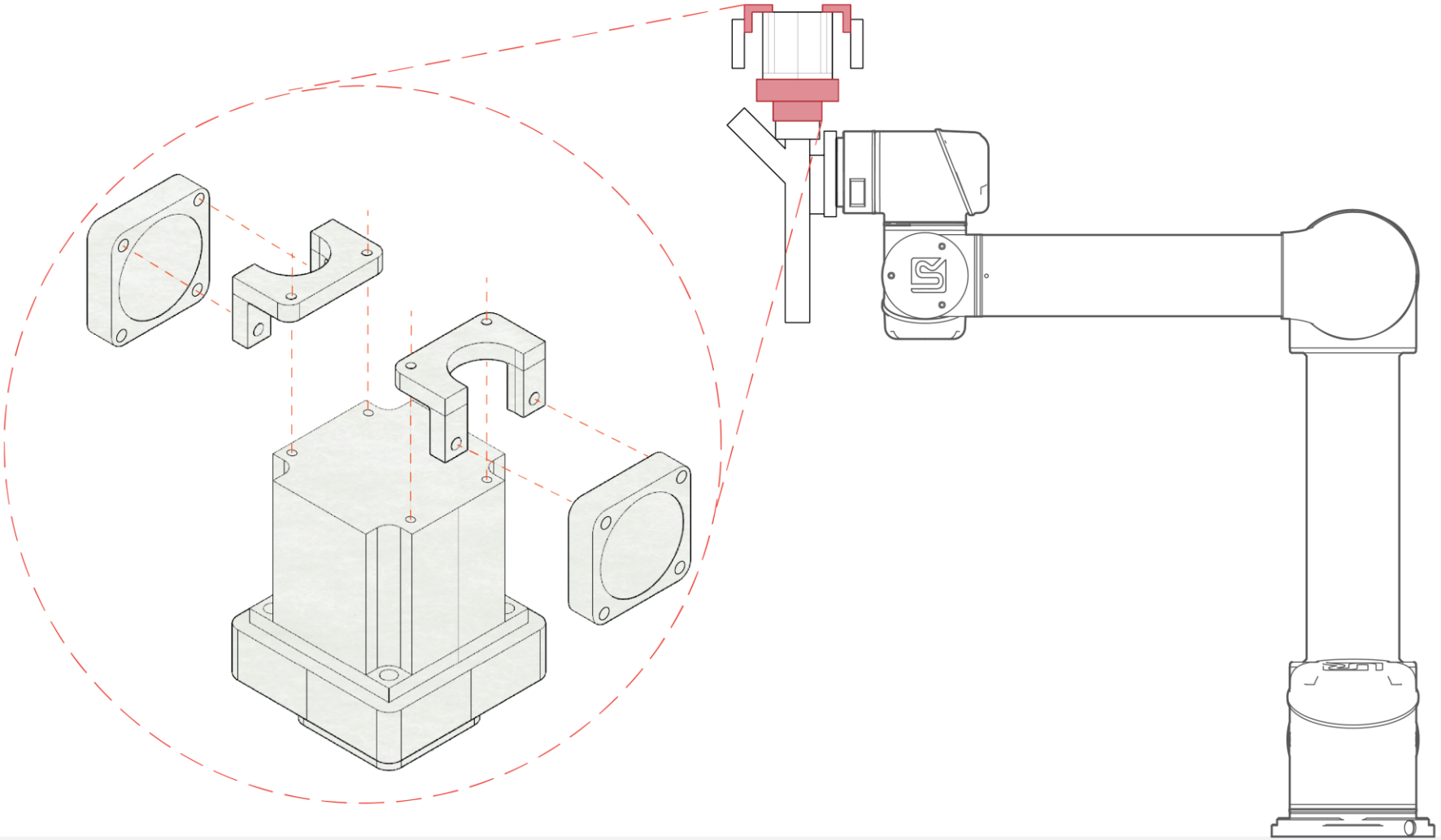
# Cooling fans

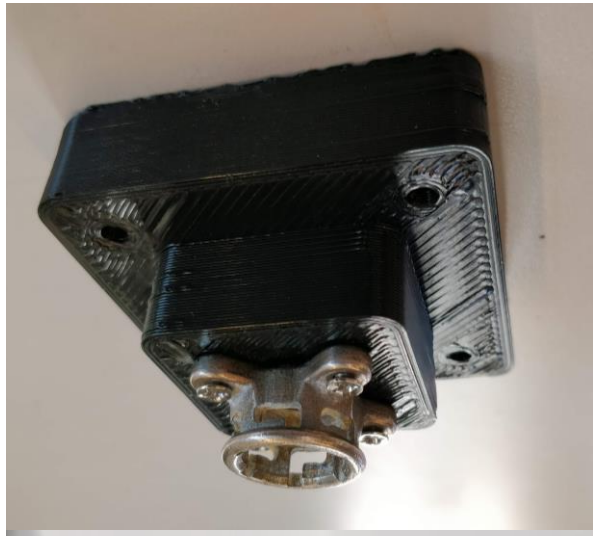


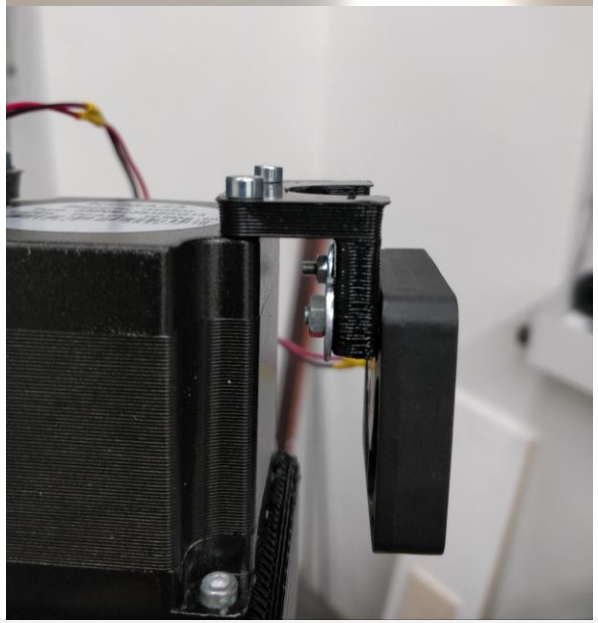
# Connector parts



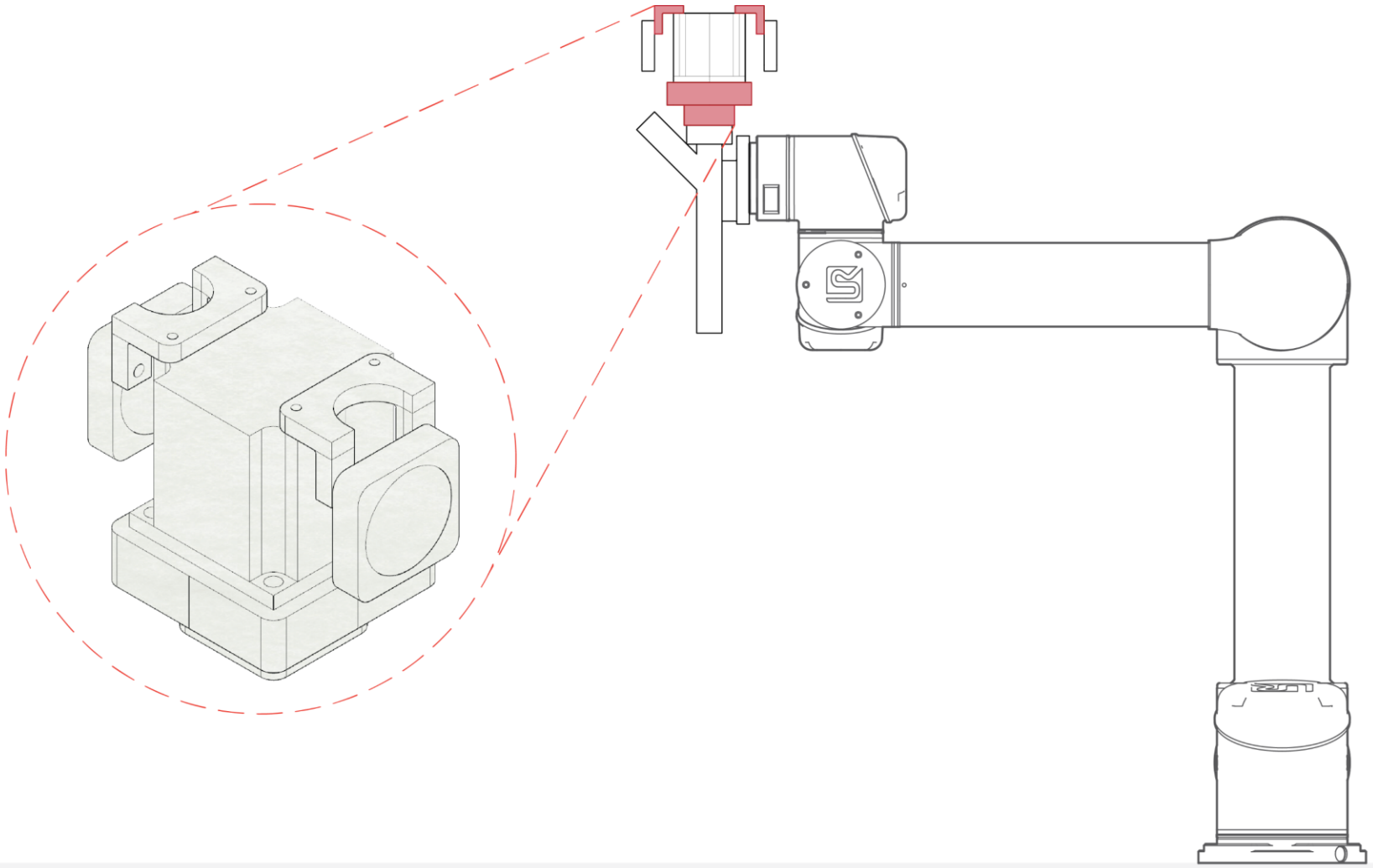
# Assembly with 1 type of bolt



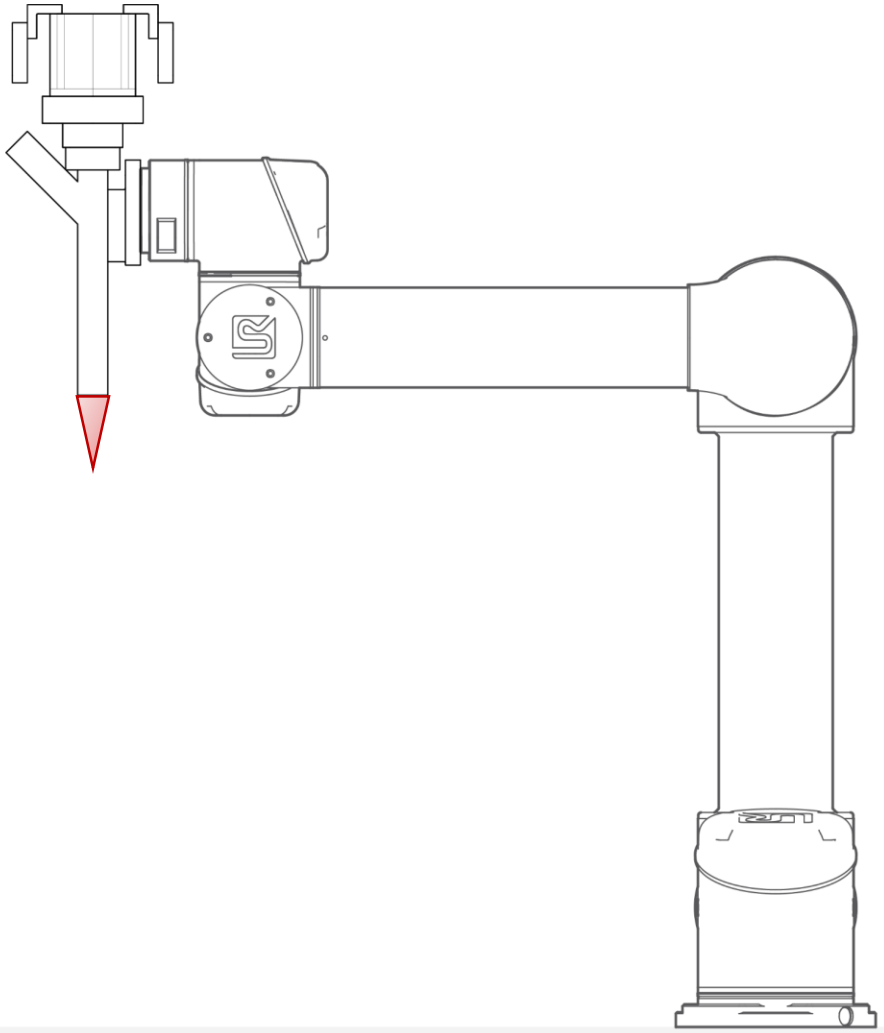


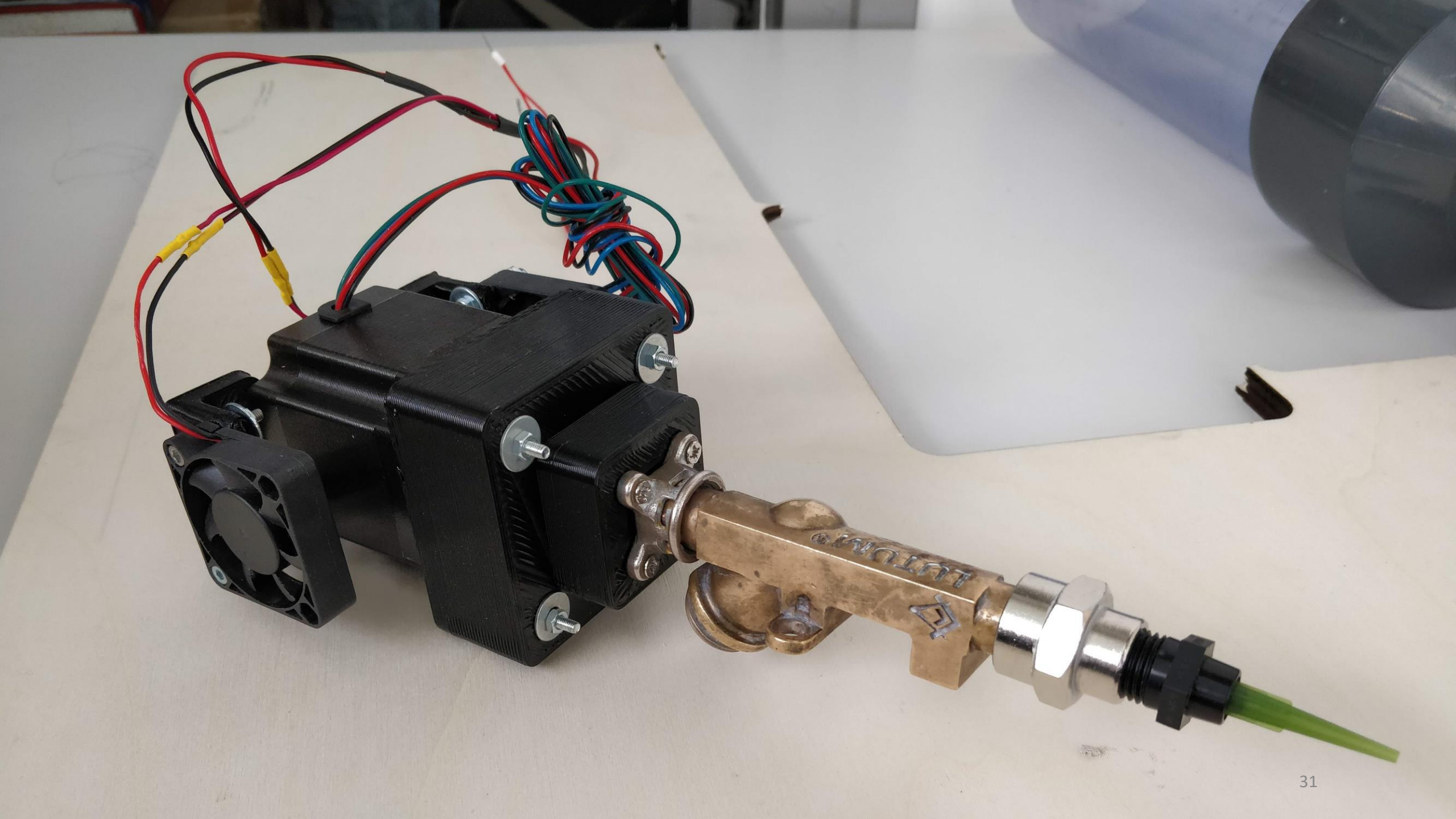


# Assembled elements

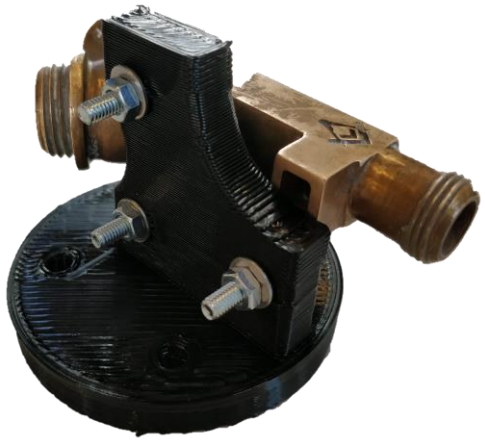


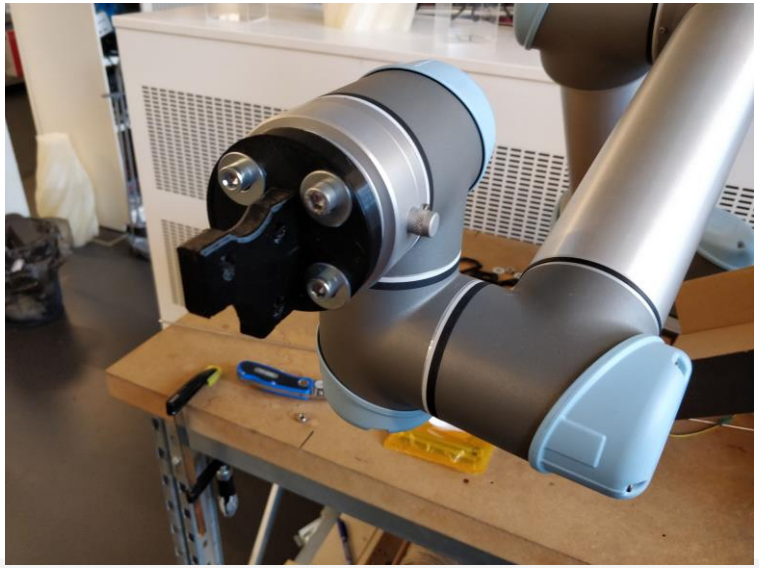
# Nozzle variations

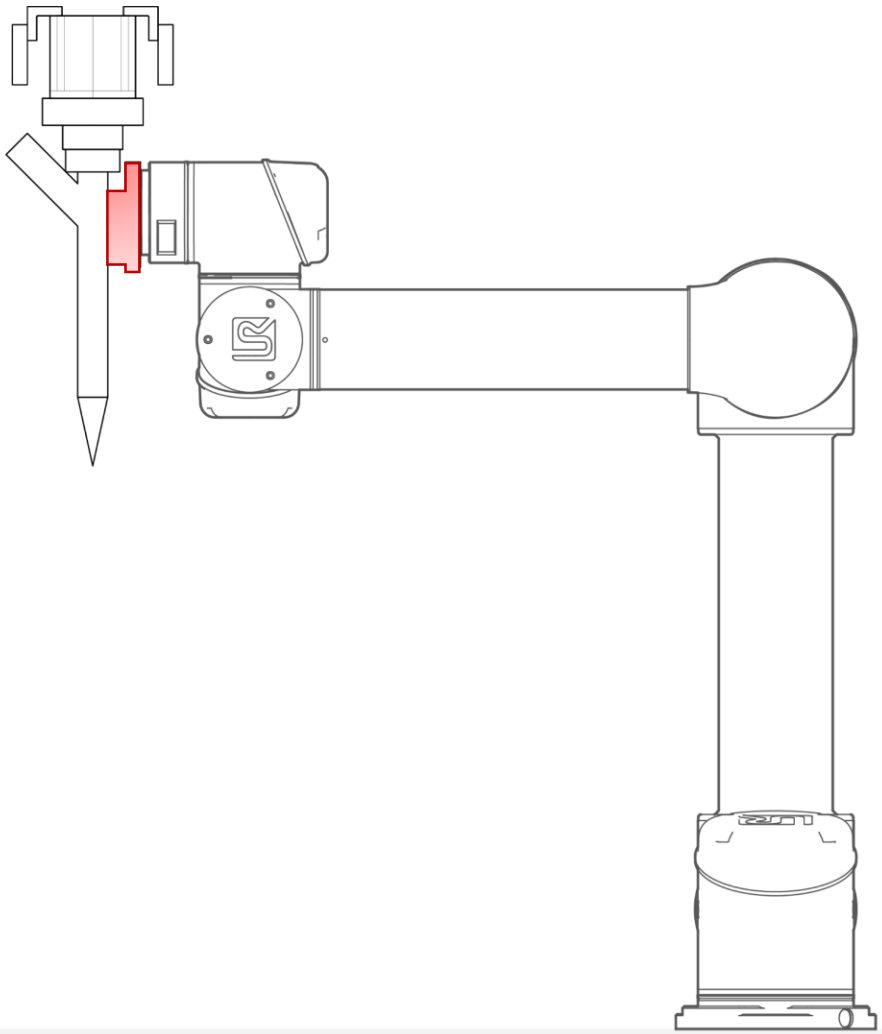




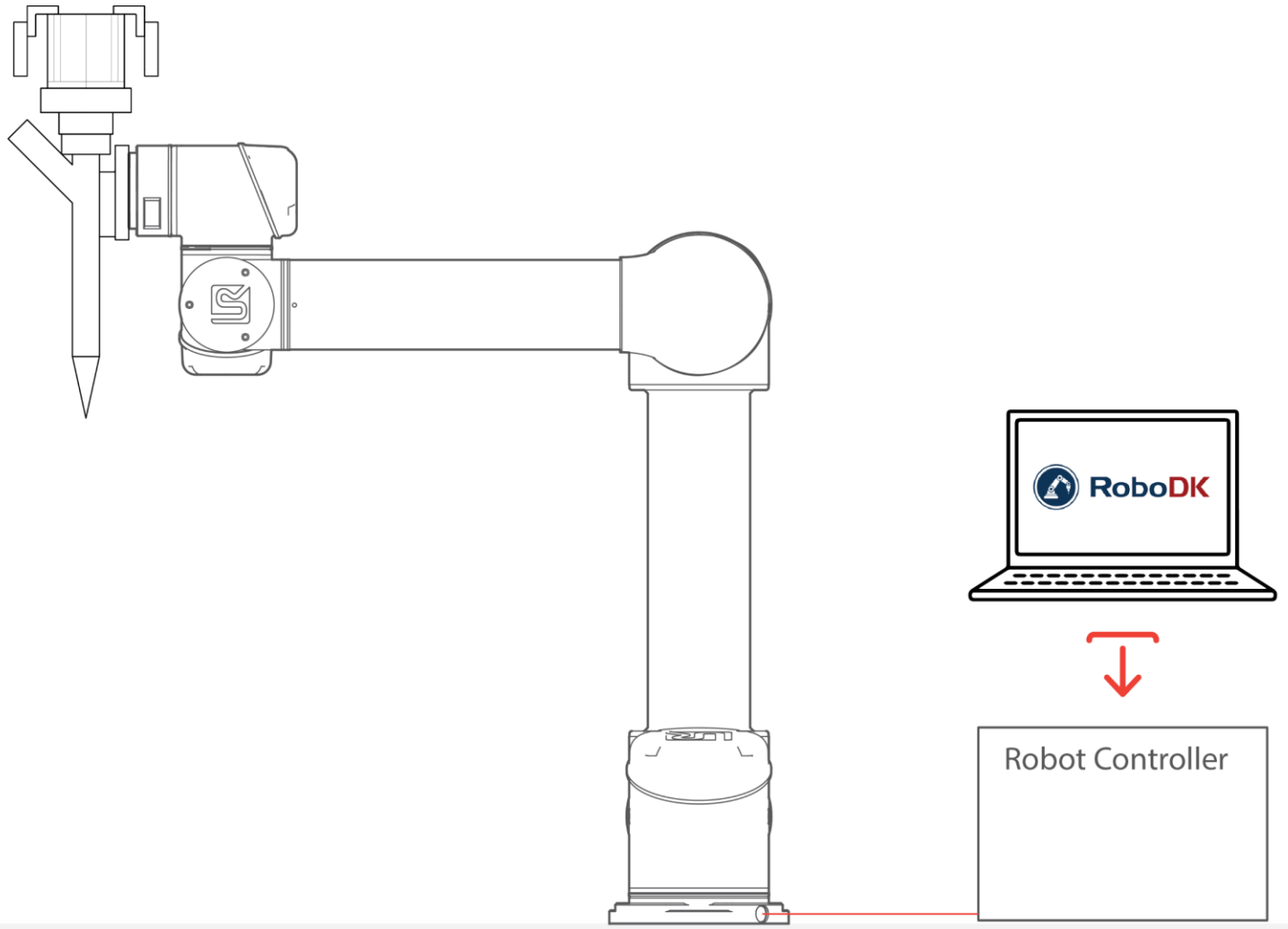
# Extruder



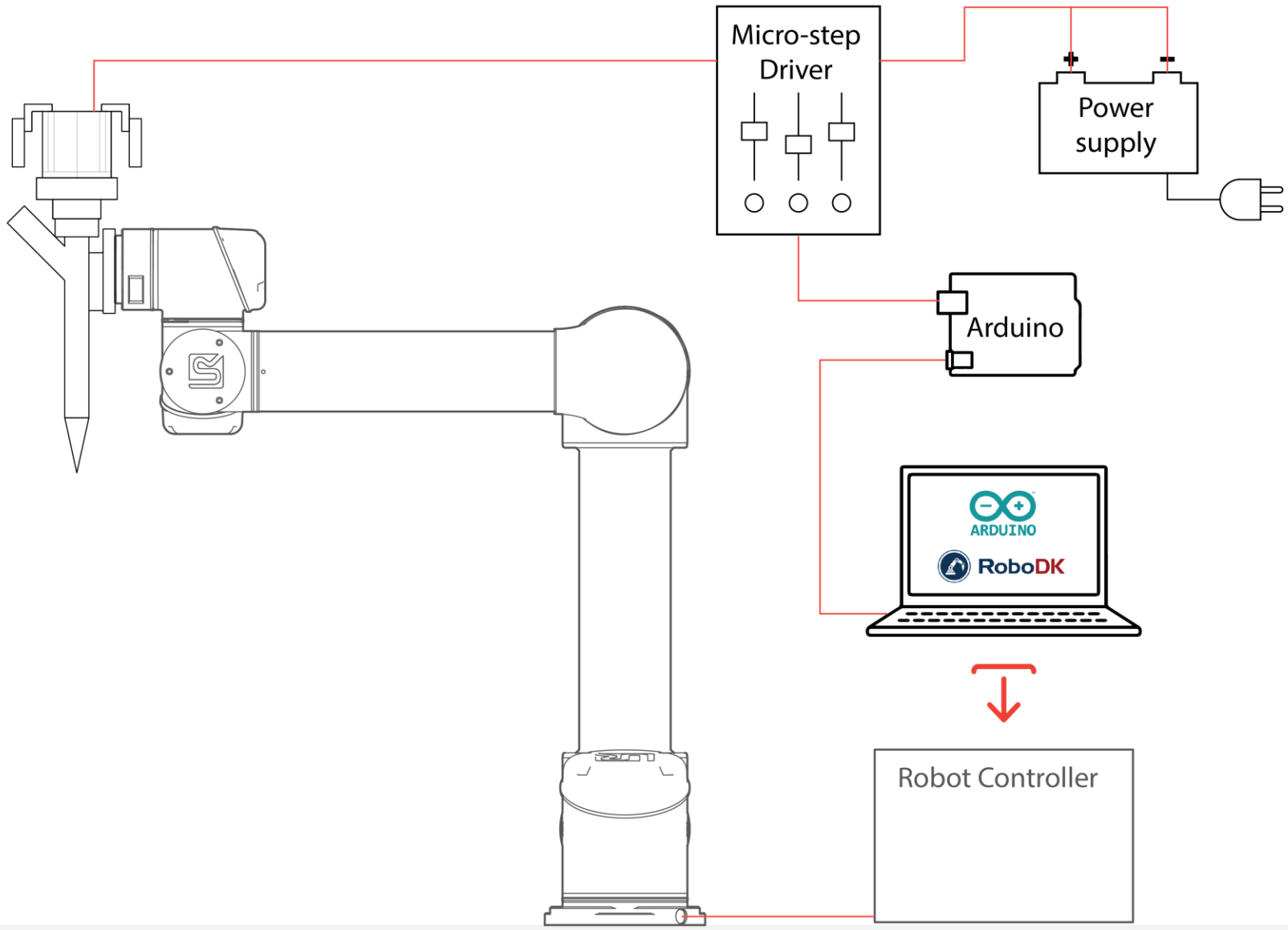




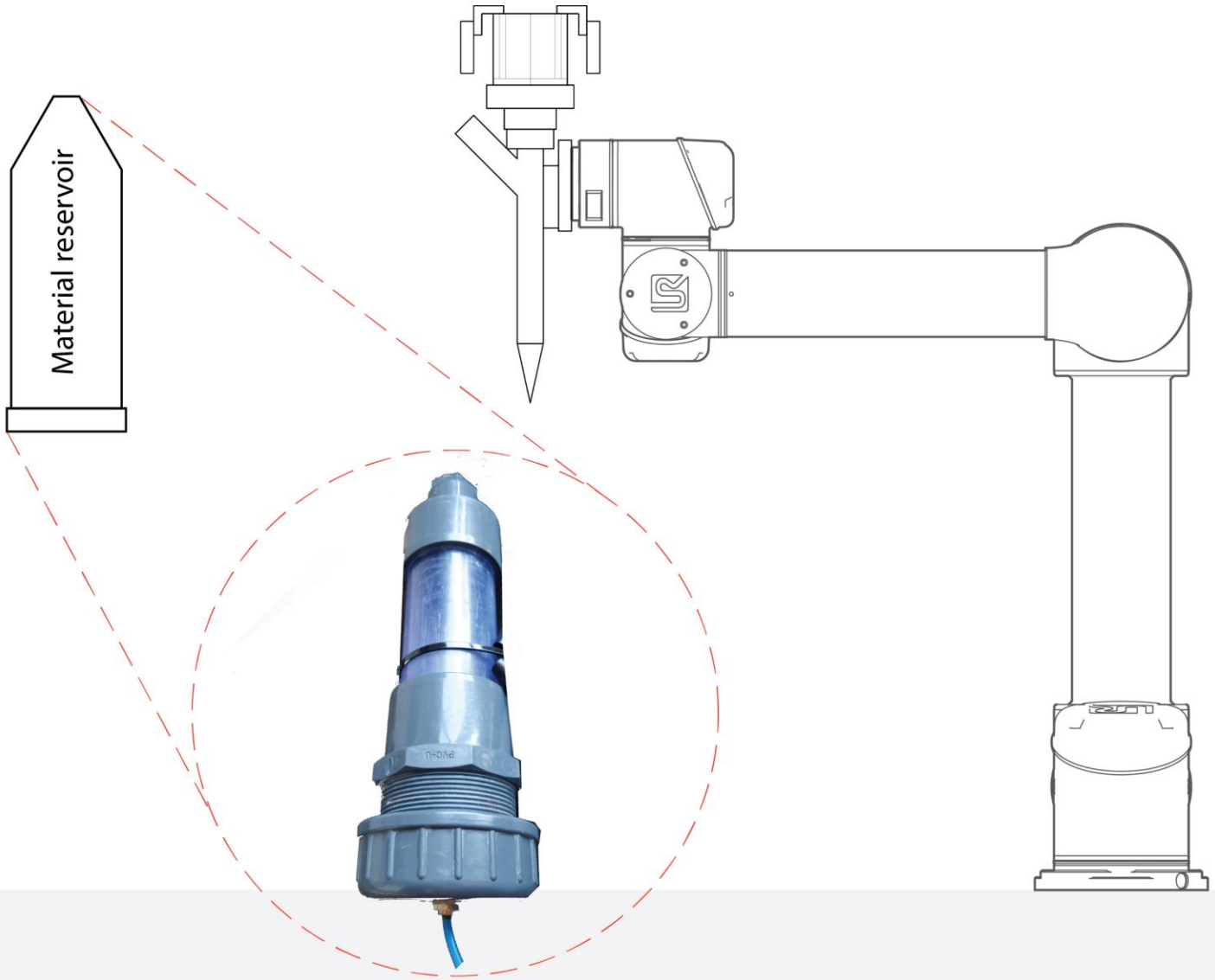
# Robot programming & simulation



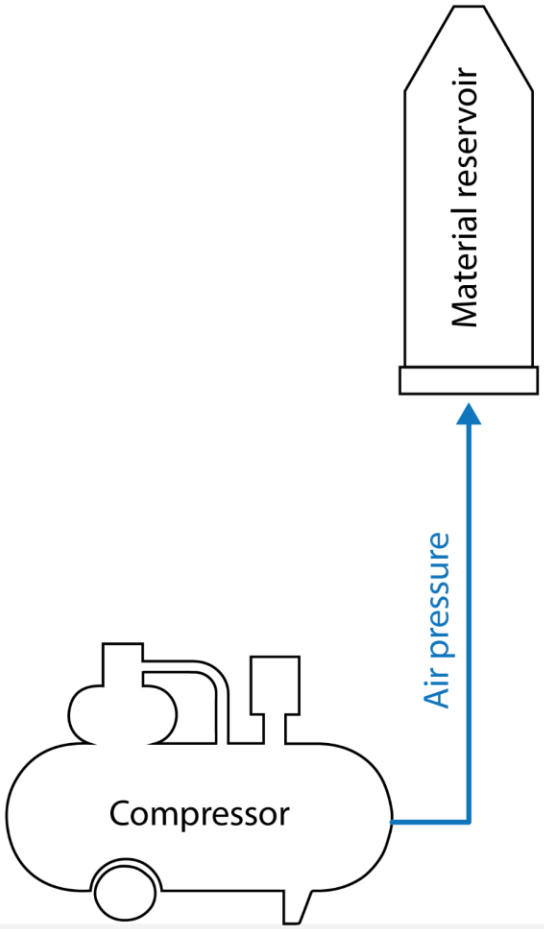
# Robot & extruder control

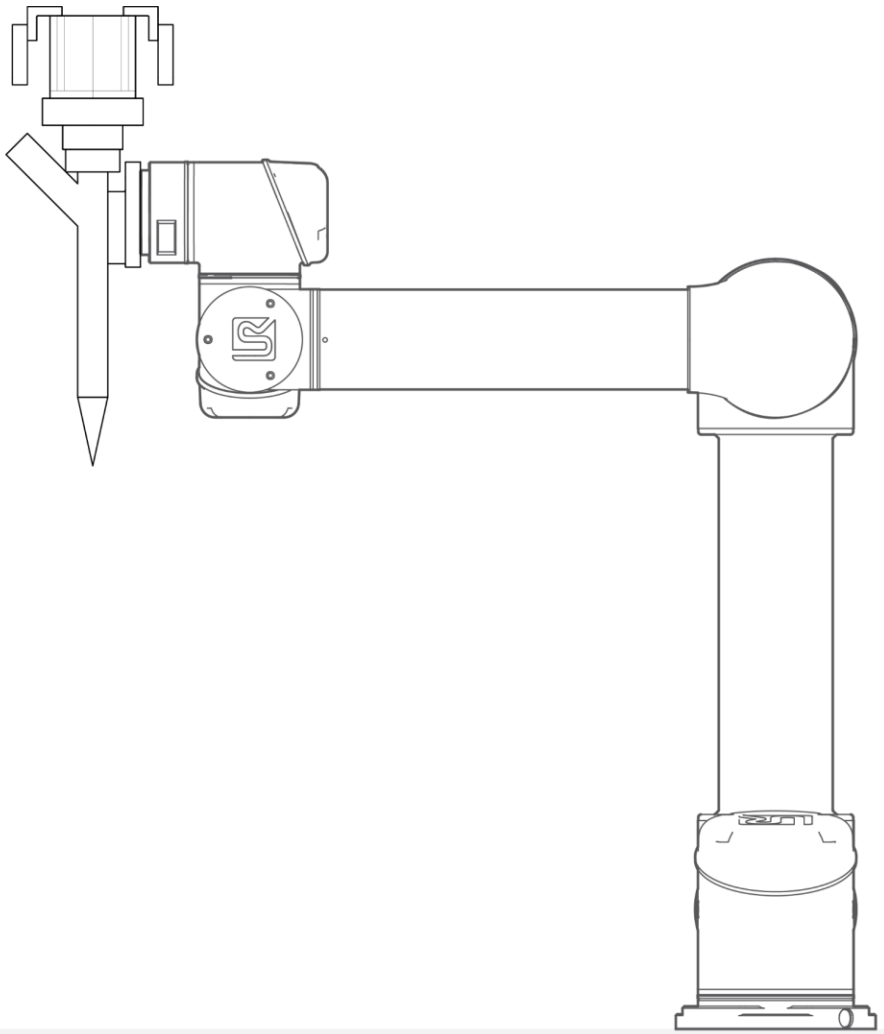


# Material reservoir

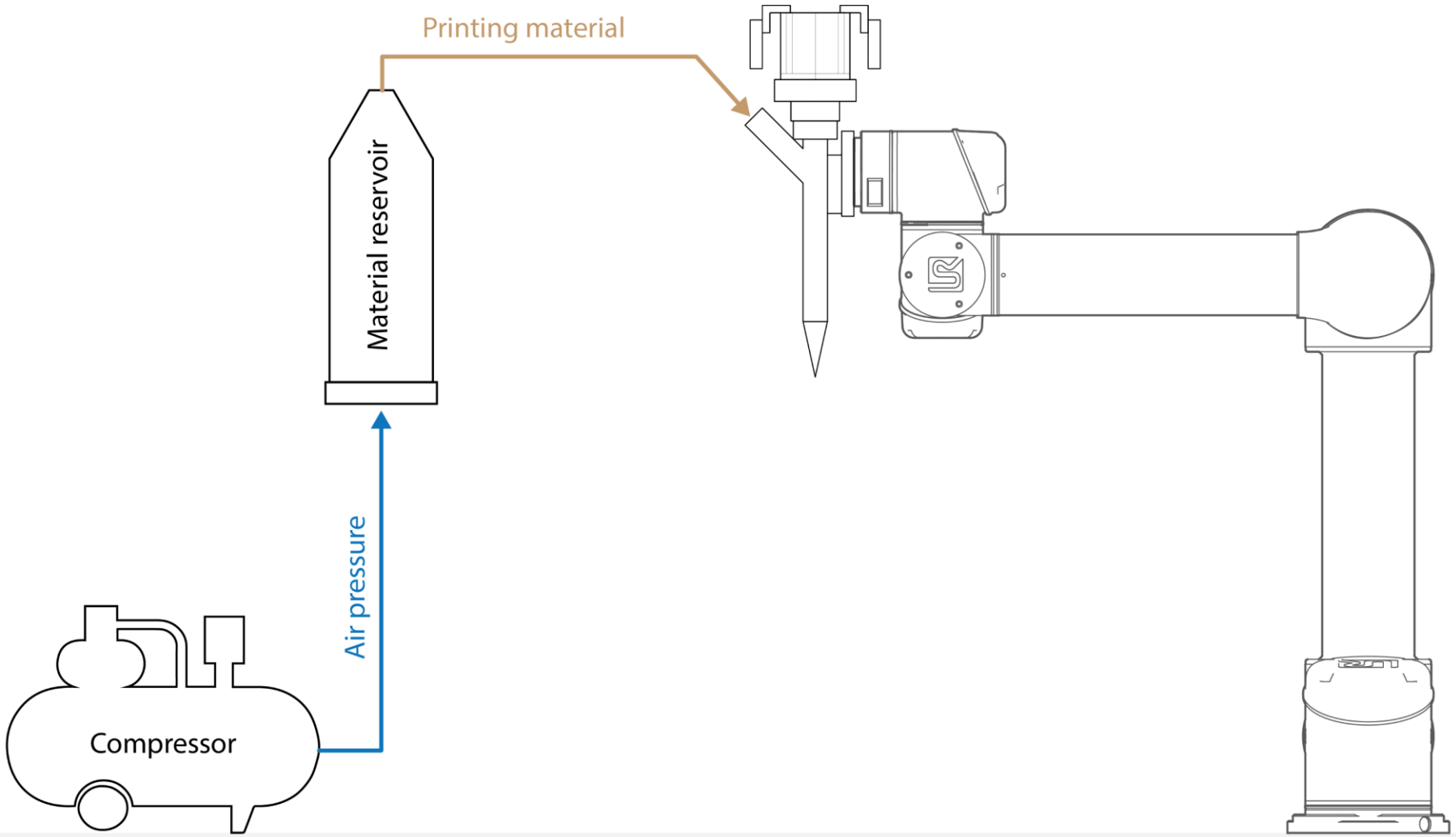


# Compressor

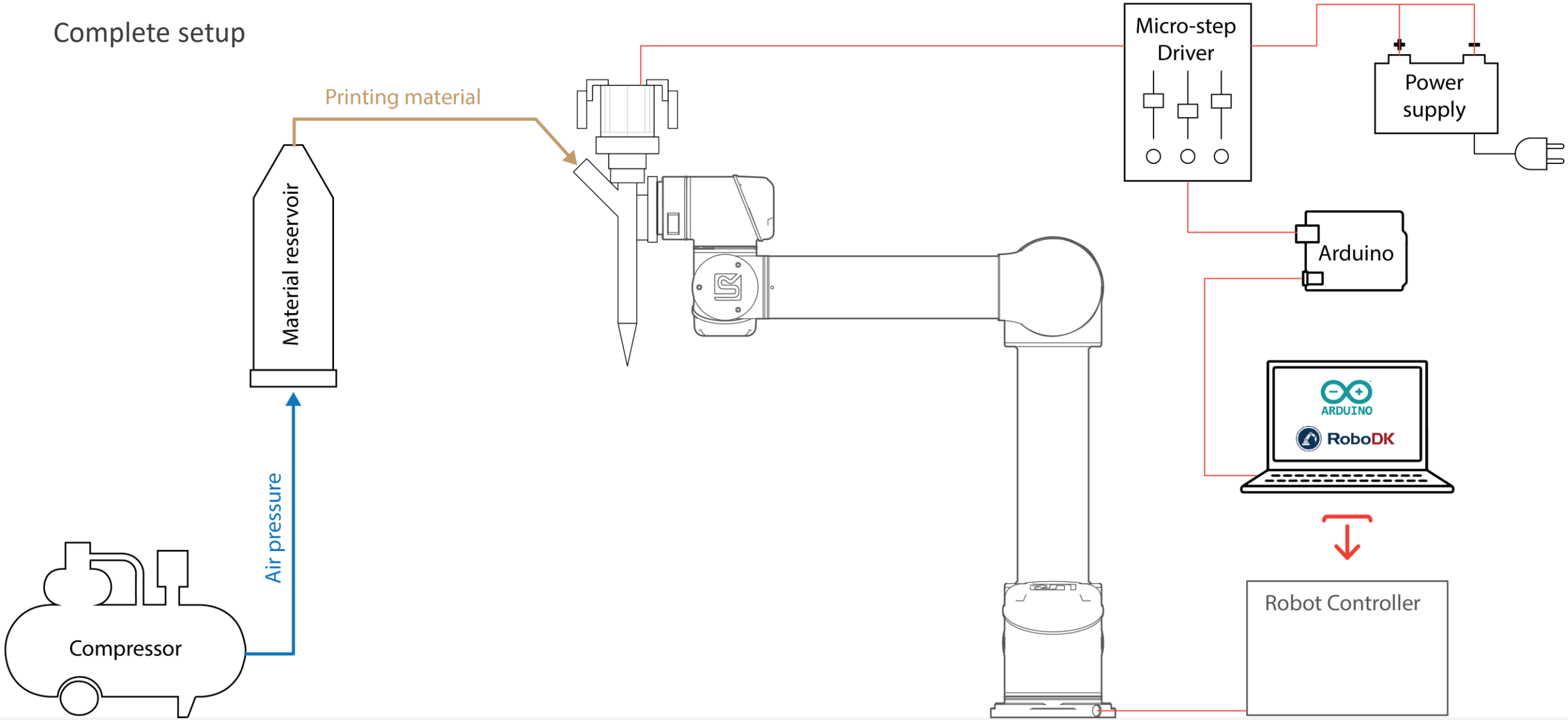


# Material feeding principle



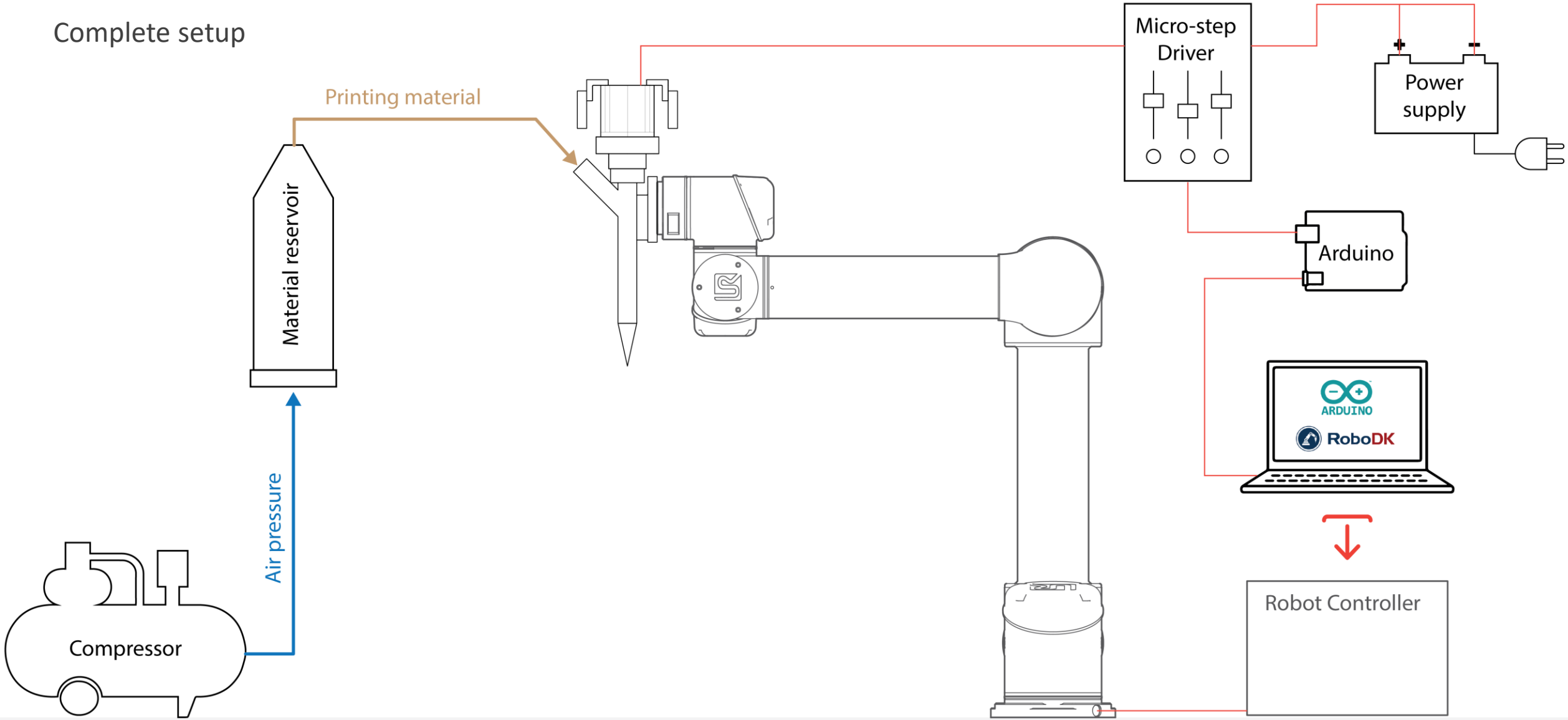
# Complete setup



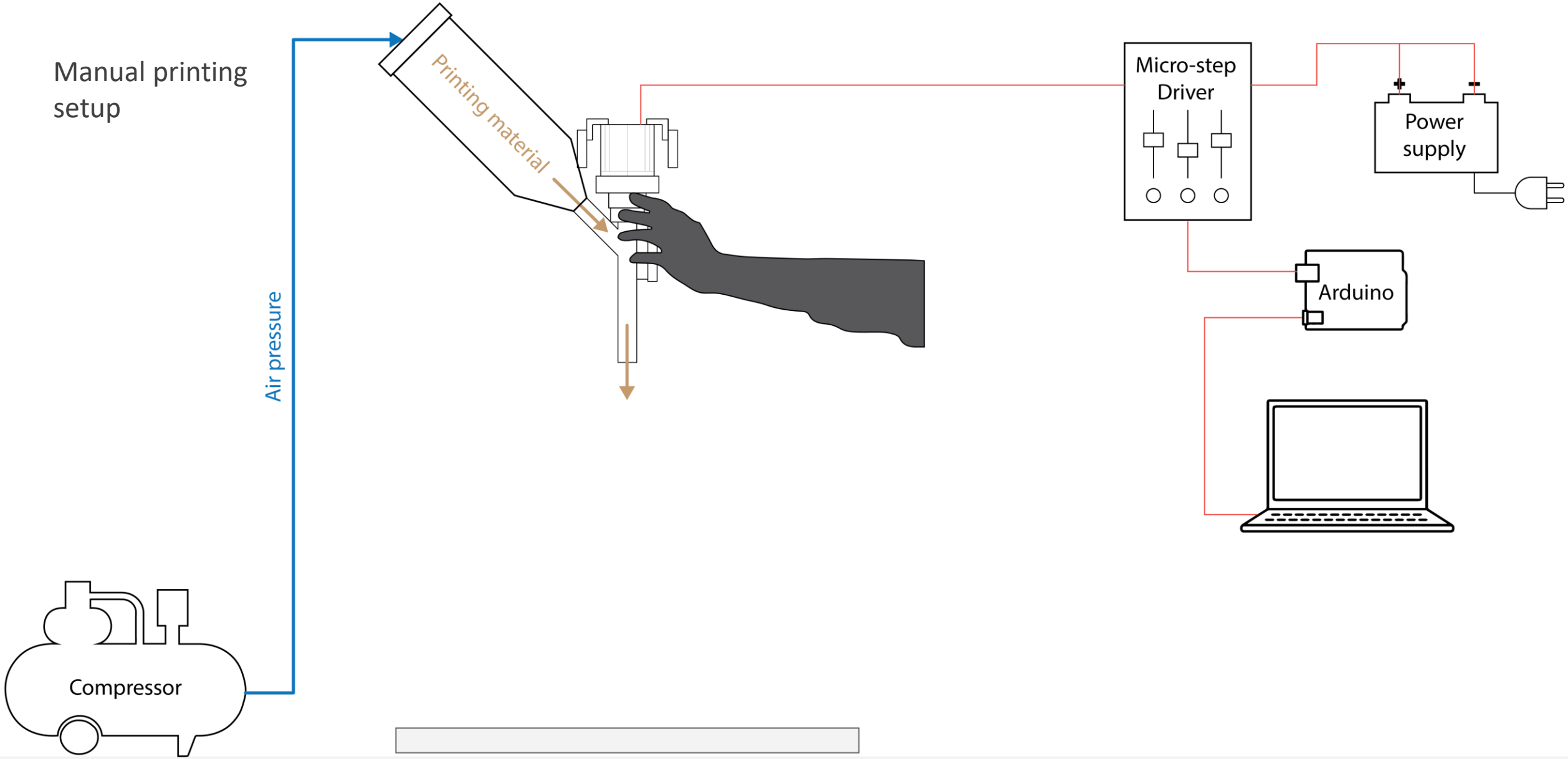
# Corona


# Mini-LAMA home-lab

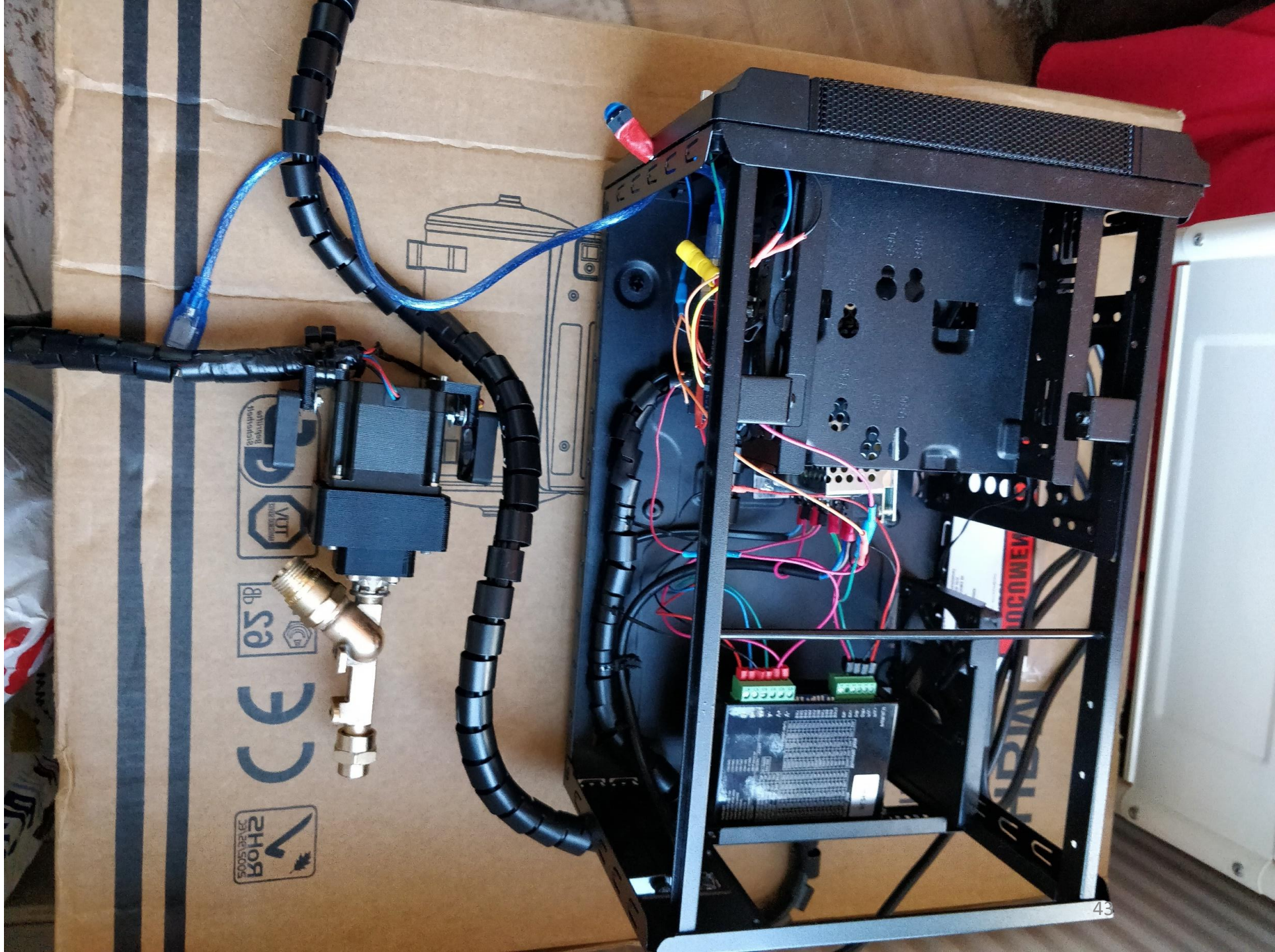
# Complete setup



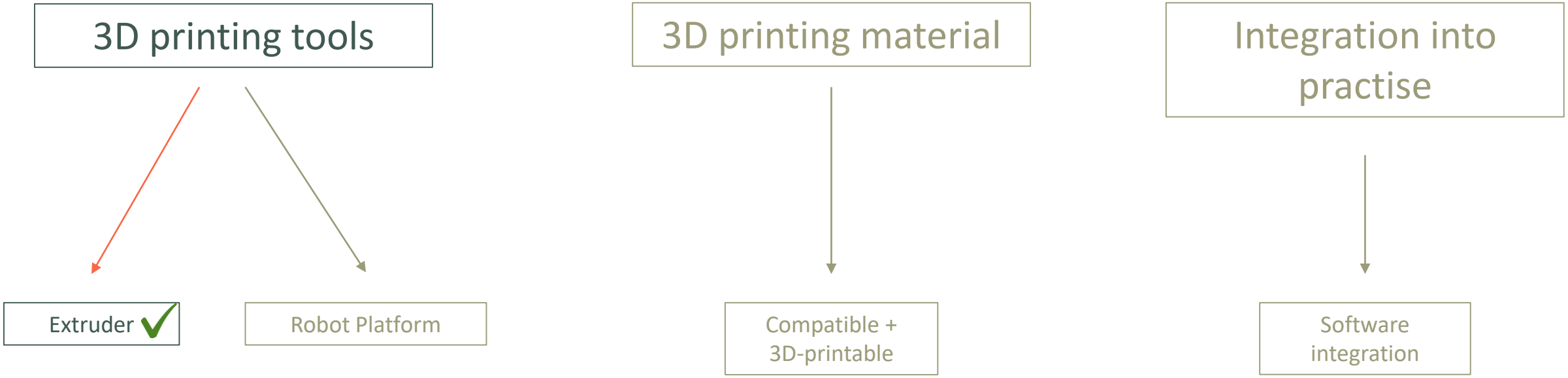
Manual printing setup



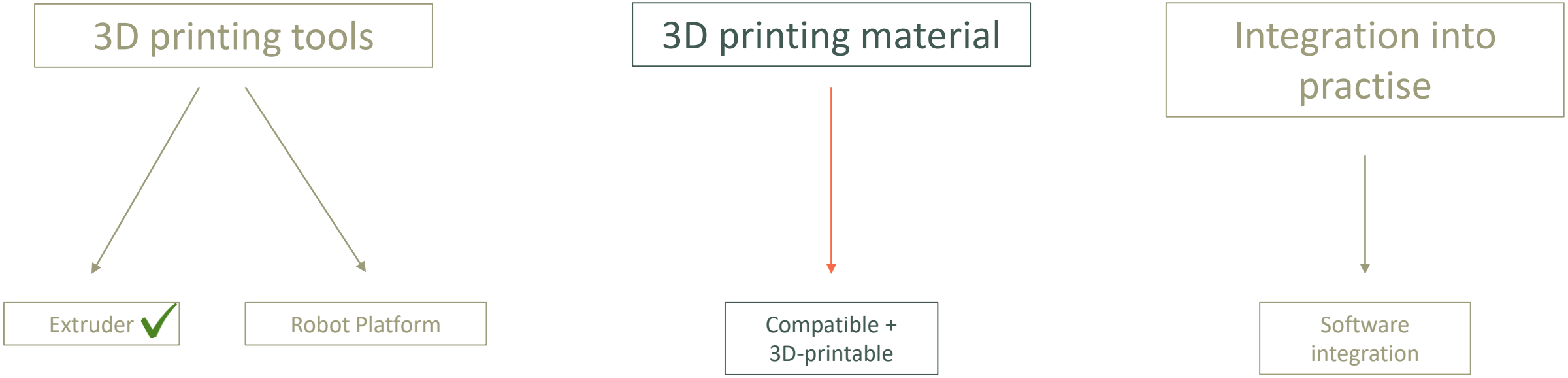
Extruder
Driver
Arduino Uno
Power supply



# Objective


3D printing tools
3D printing material
Integration into practise
Extruder
Robot Platform
Compatible + 3D-printable
Software integration

# Objective


3D printing tools
3D printing material
Integration into practise
Extruder
Robot Platform
Compatible + 3D-printable
Software integration

# Gypsum-based 3D printing material

# Ceiling substrate: gypsum → Compatibility

Restoration material does not lead to accelerated damage to original material.

Stucco ceiling, Huize Nolet, NL, 1804

# Gypsum-based printing mixtures

+

+

**Binder**
Knauf Rotband gypsum

**Aggregates**
Marble powder

**Water**

# Mixed to form a paste

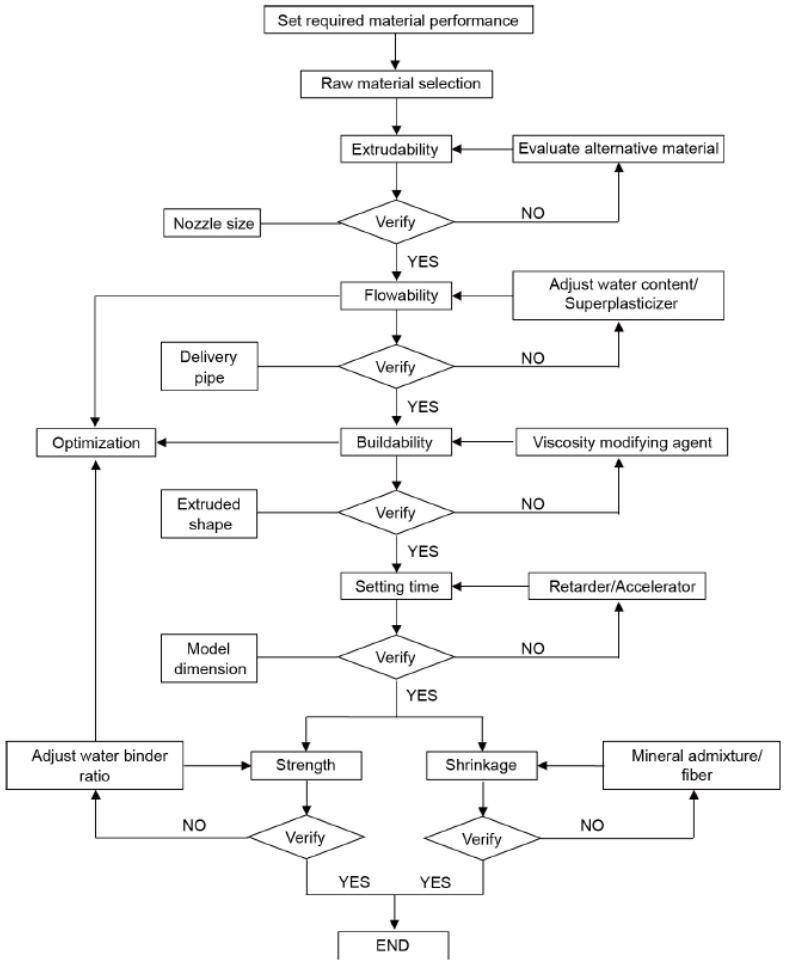
# Optimal ratio for 3D printing

:

:

| Binder | Aggregates | Water |
| --- | --- | --- |
| Knauf Rotband gypsum | Marble powder | |

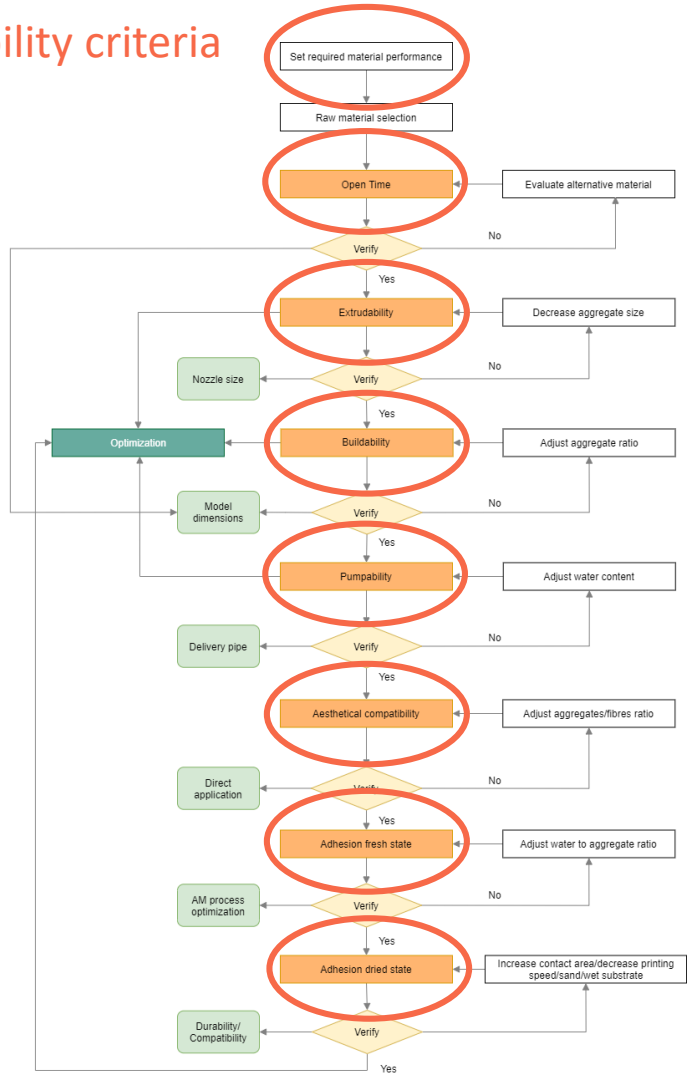
## Framework for concrete 3D printing




Ma et. al, 2018

## Framework for In-situ gypsum 3D printing

Printability criteria



# Printability criteria: gypsum

Pumpability

Extrudability

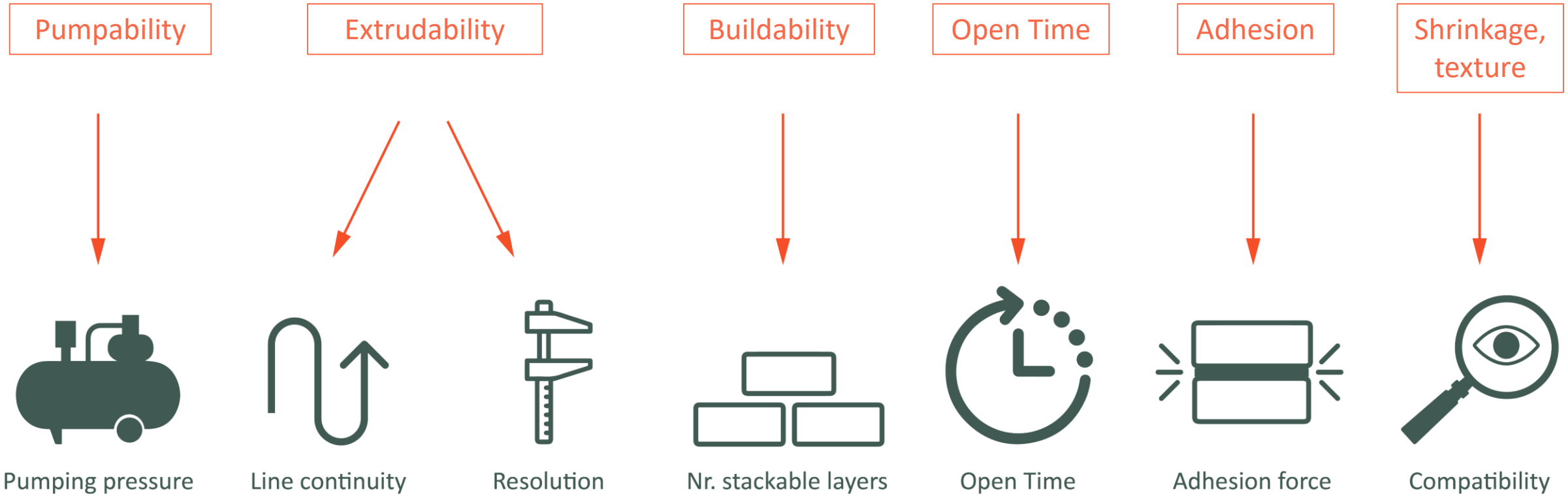
Buildability

Open Time

Adhesion

Shrinkage, texture

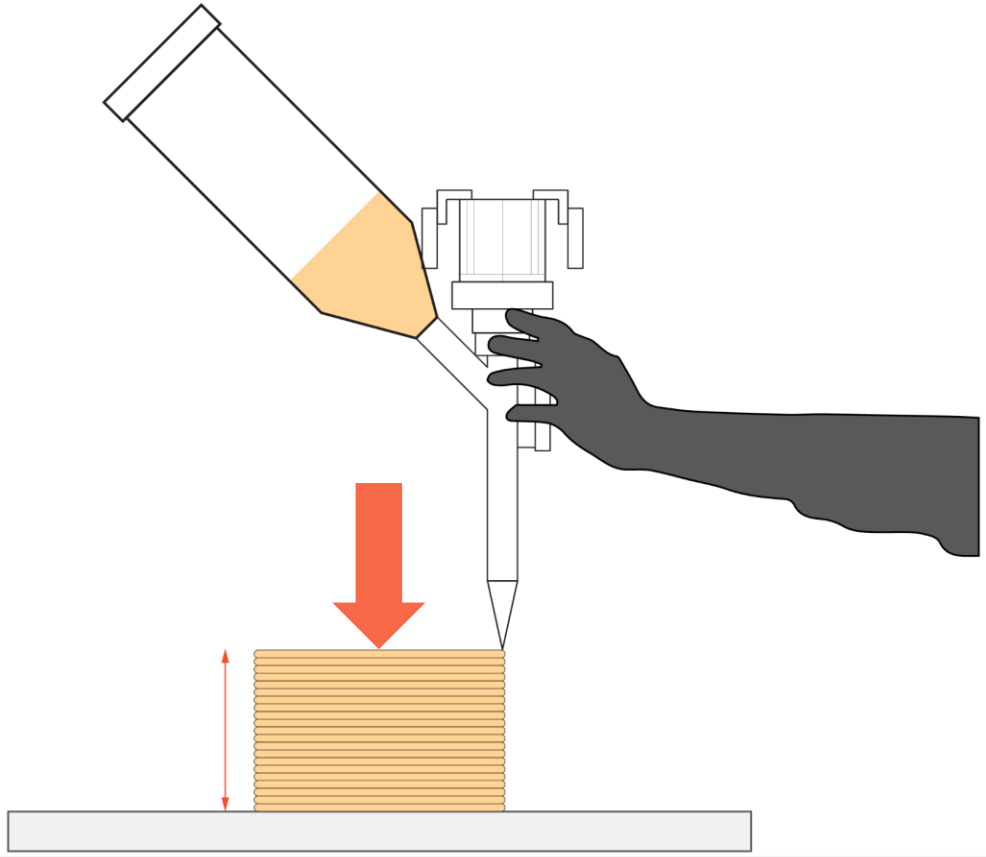
# Measurable parameters



# Mixtures tested

| Sample | Gypsum type | Water (mL) | Marble powder (fine aggregate) (g) | Gypsum (g) | Gypsum/Marble powder ratio(-) |
|---|---|---|---|---|---|
| G0 | Molda 3 Normaal | 500 | 0 | 775 | - |
| G1 | Molda 3 Normaal | 170 | 0 | 300 | - |
| G2 | Molda 3 Normaal | 195 | 150 | 300 | 02:01 |
| G3 | Knauf Rotband | 195 | 0 | 300 | - |
| G4 | Knauf Rotband | 295 | 300 | 330 | 01:01 |
| G5 | Knauf Rotband | 200 | 100 | 300 | 03:01 |
| G6 | Knauf Rotband | 200 | 50 | 300 | 06:01 |
| G7 | Knauf Rotband | 130 | 100 | 200 | 02:01 |
| G8 | Knauf Rotband | 130 | 80 | 200 | 2.5:01 |
| G9 | Knauf Rotband | 130 | 50 | 200 | 04:01 |
| G10 | Knauf Rotband | 82 | 0 | 100 | - |

# Strong – Buildable



Buildability

Pumpability
extrudability

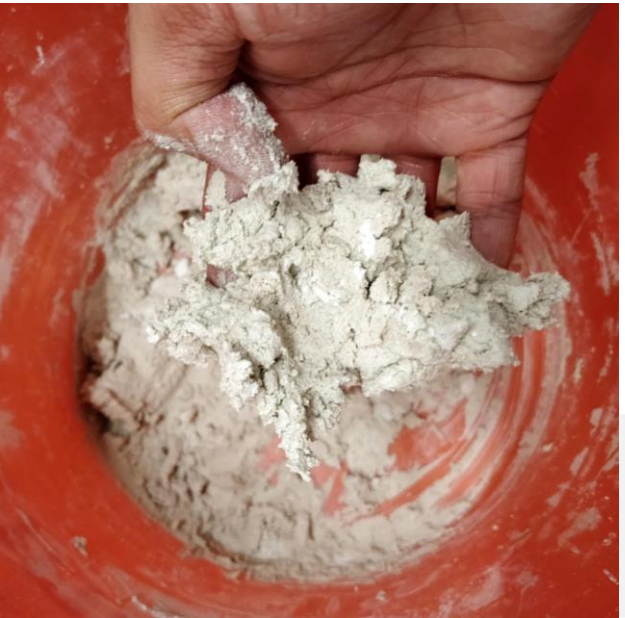
Open Time

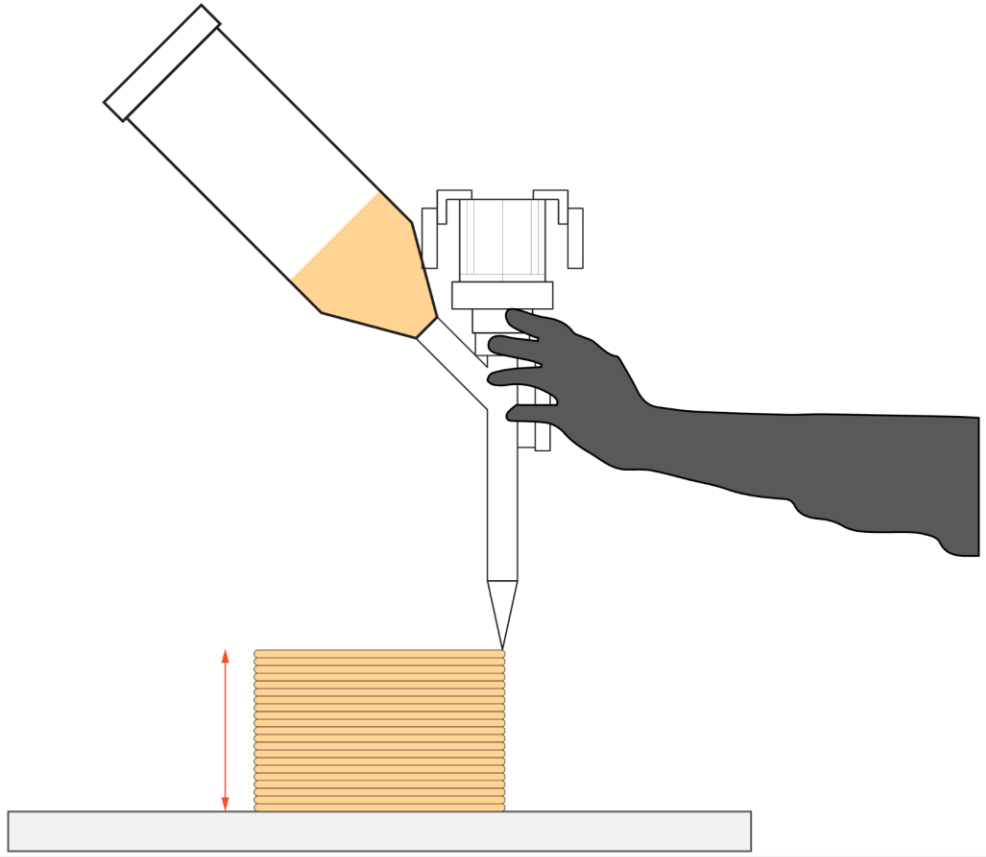
Fresh adhesion

Dry adhesion

Resolution

# Strong – Buildable → thick





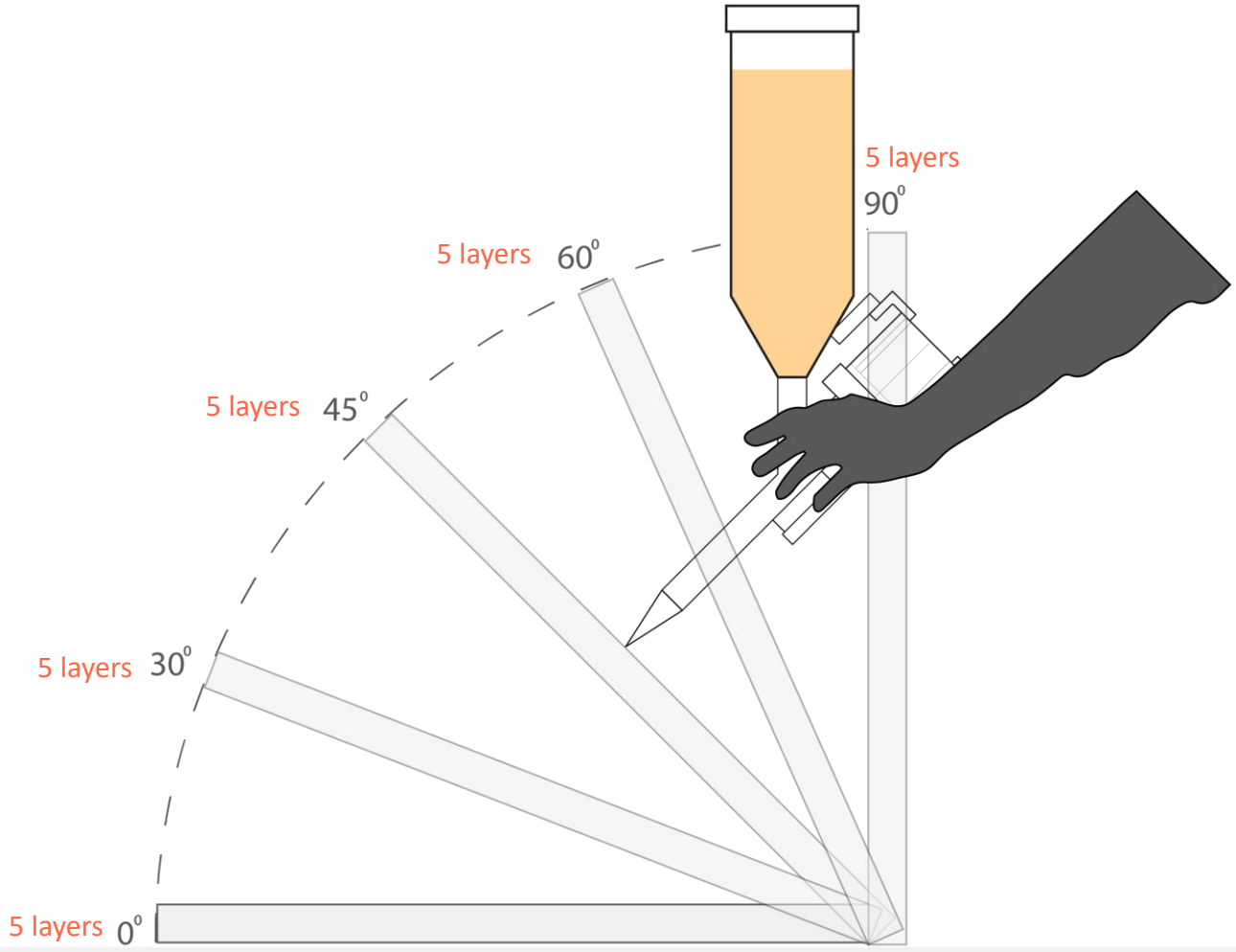
# Flowable/extrudable → liquid

# Setting → slow → print longer/larger

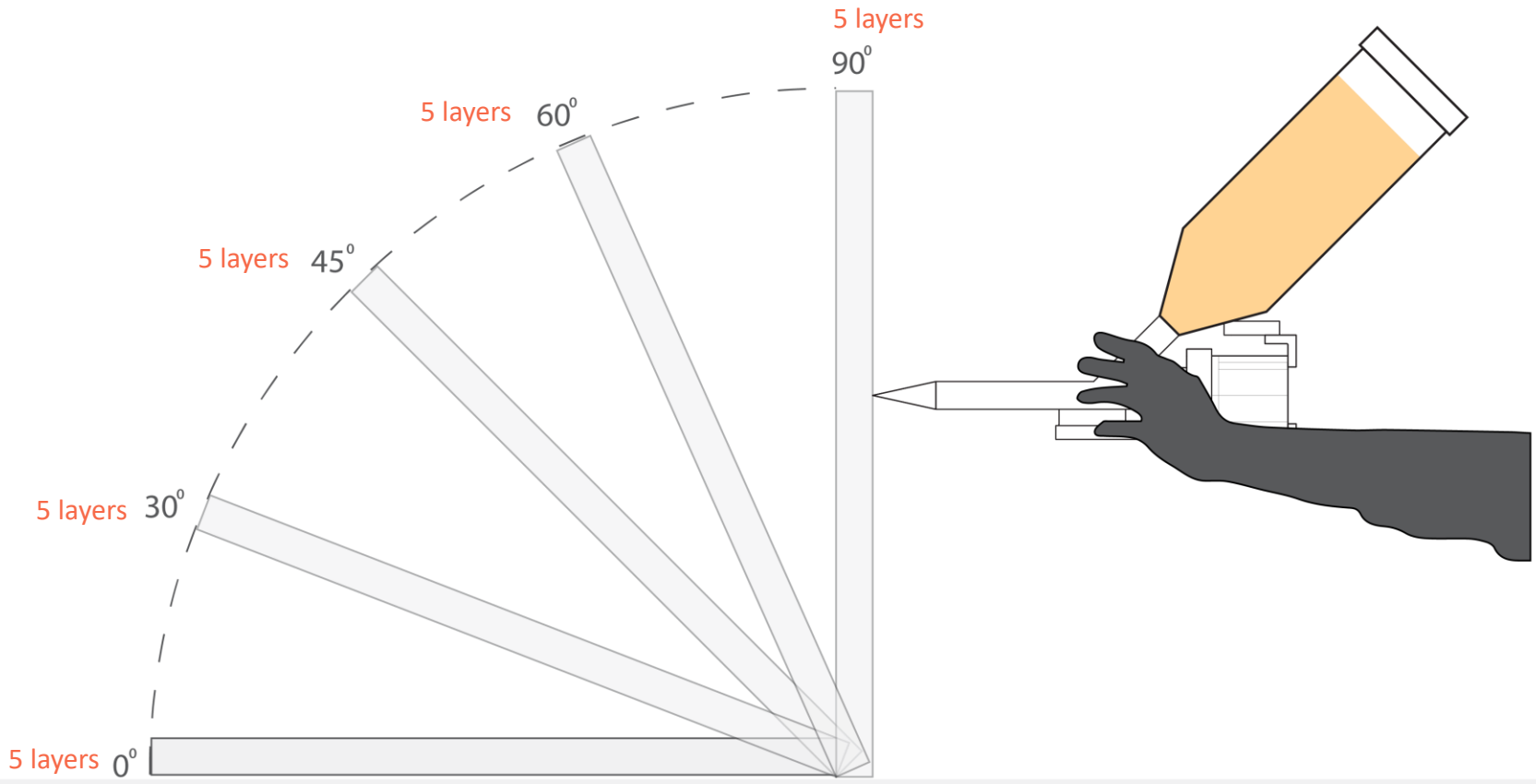
Liquid paste

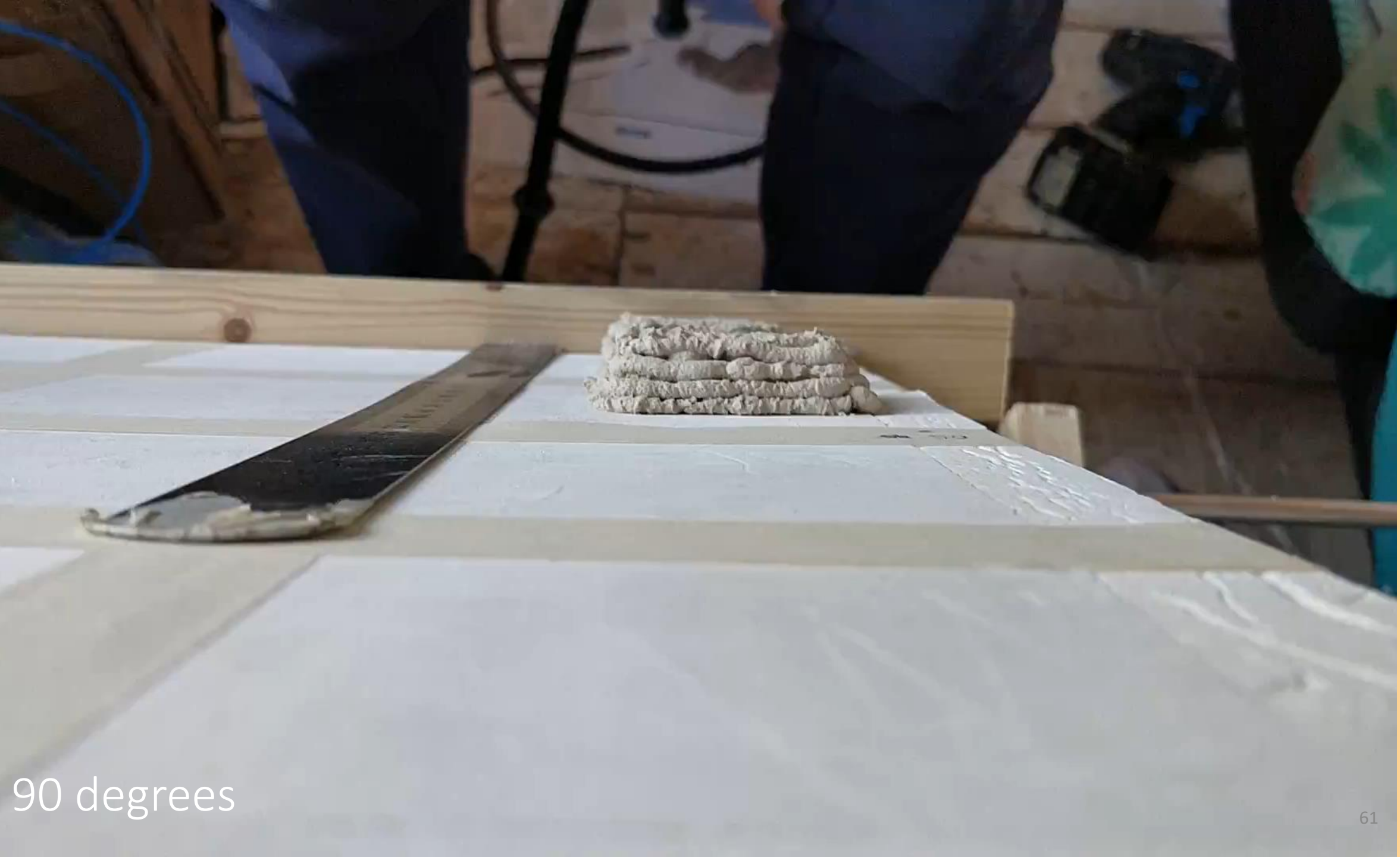
Solid block

# Stick to surface: adhesion in fresh state



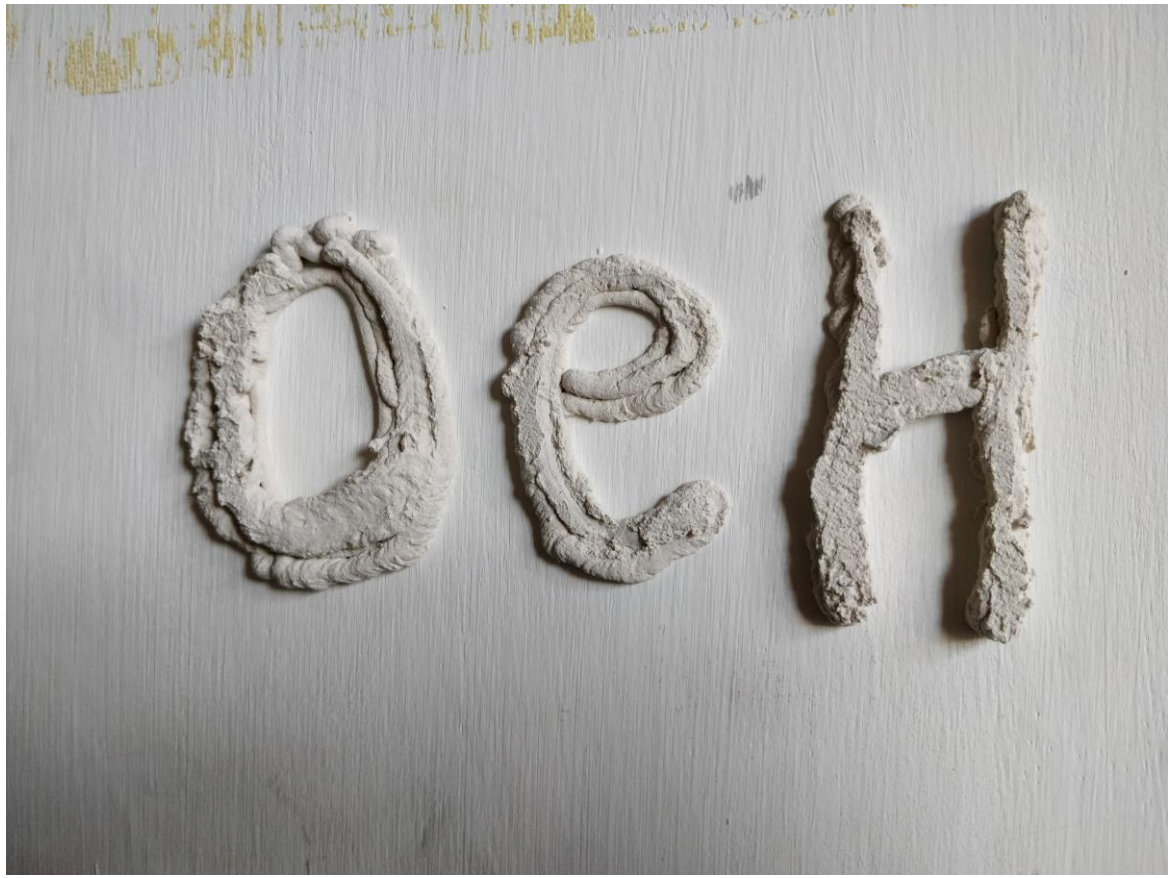
# Stick to surface: adhesion in fresh state

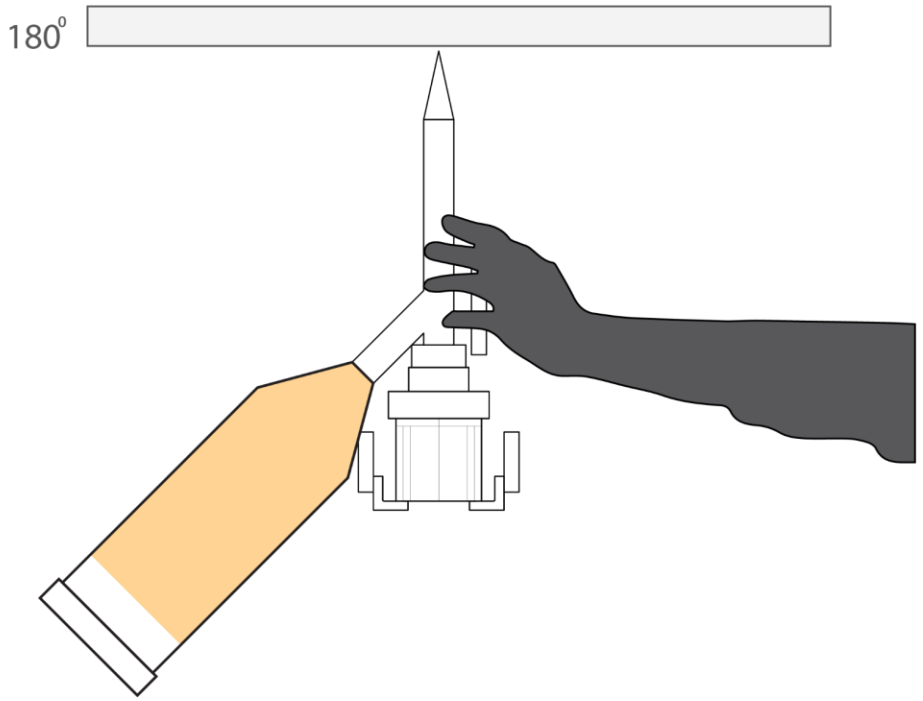




90 degrees

# House decorations




# 3D printing Upside down

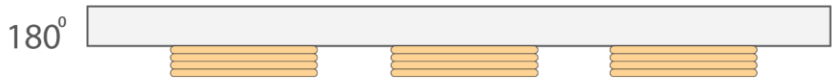
Buildability

Pumpability
extrudability

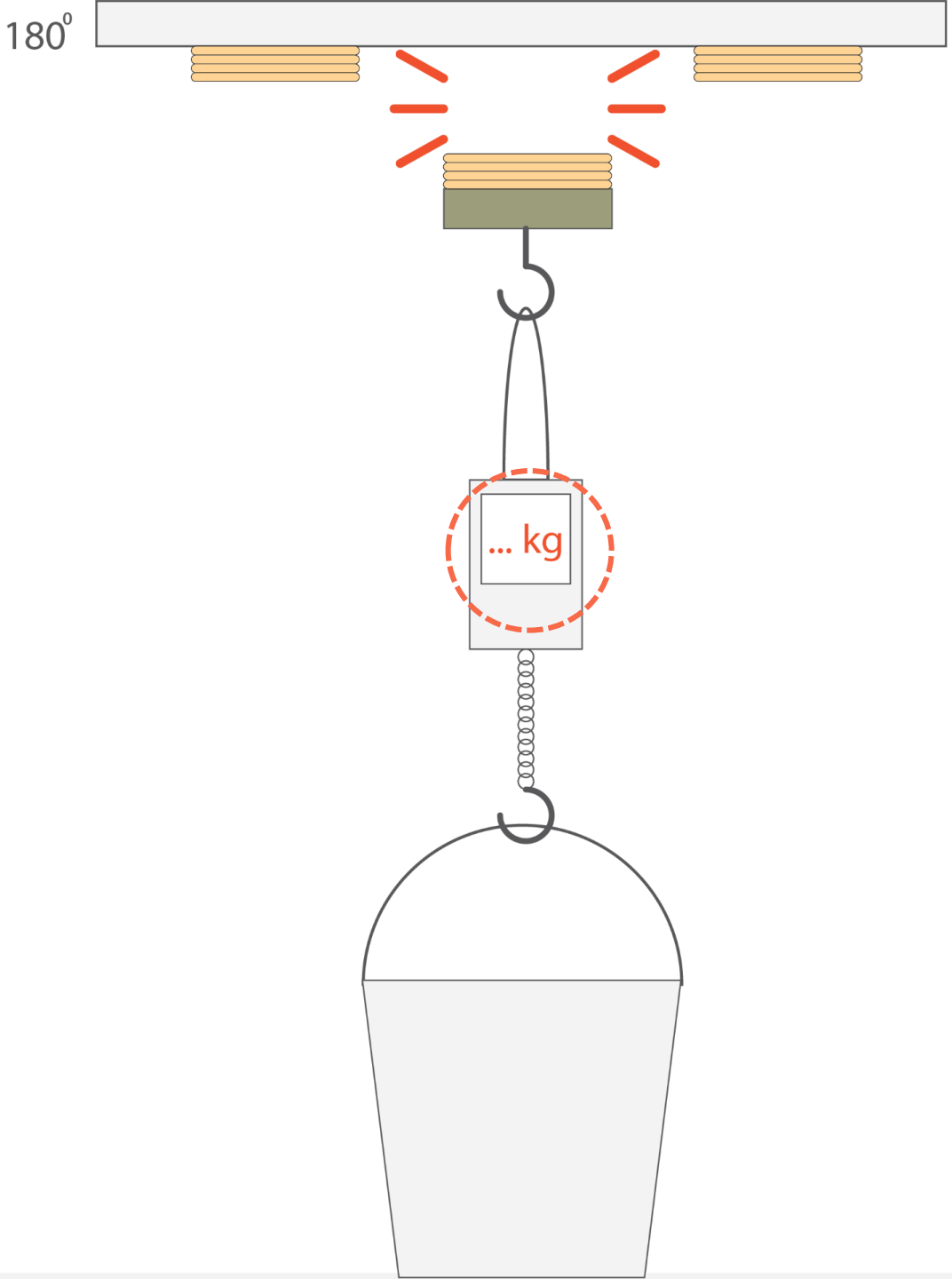
Open Time

Fresh adhesion

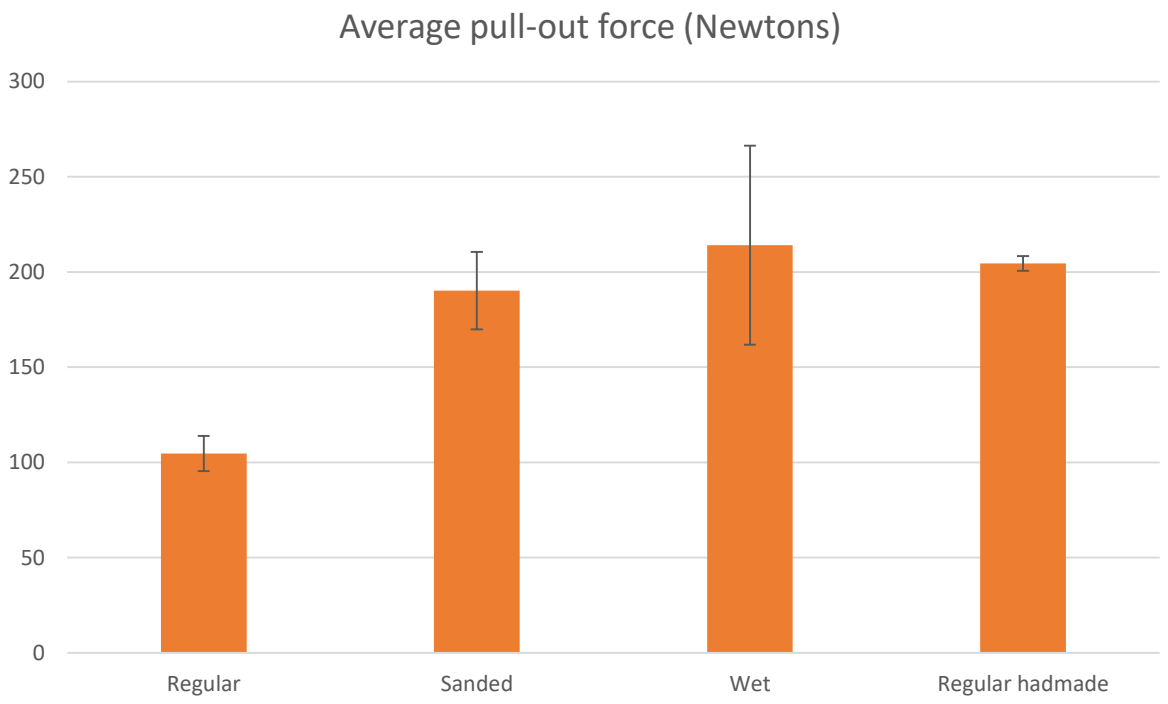
Dry adhesion



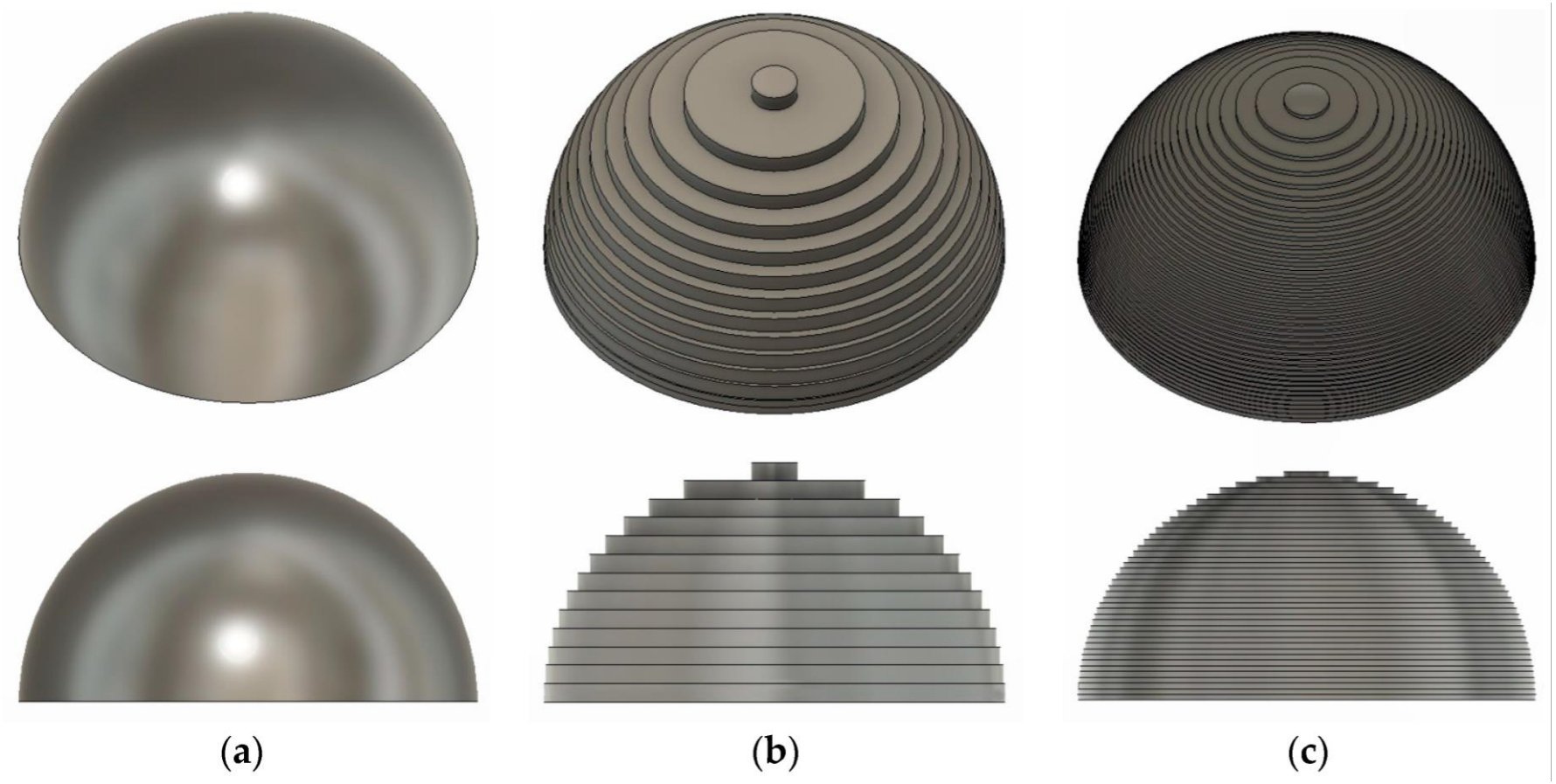

# Sufficiently strong connection? → Adhesion: Dried


180°
... kg

# Adhesion: Dried



# Print resolution




Stucco ornaments: smooth surface

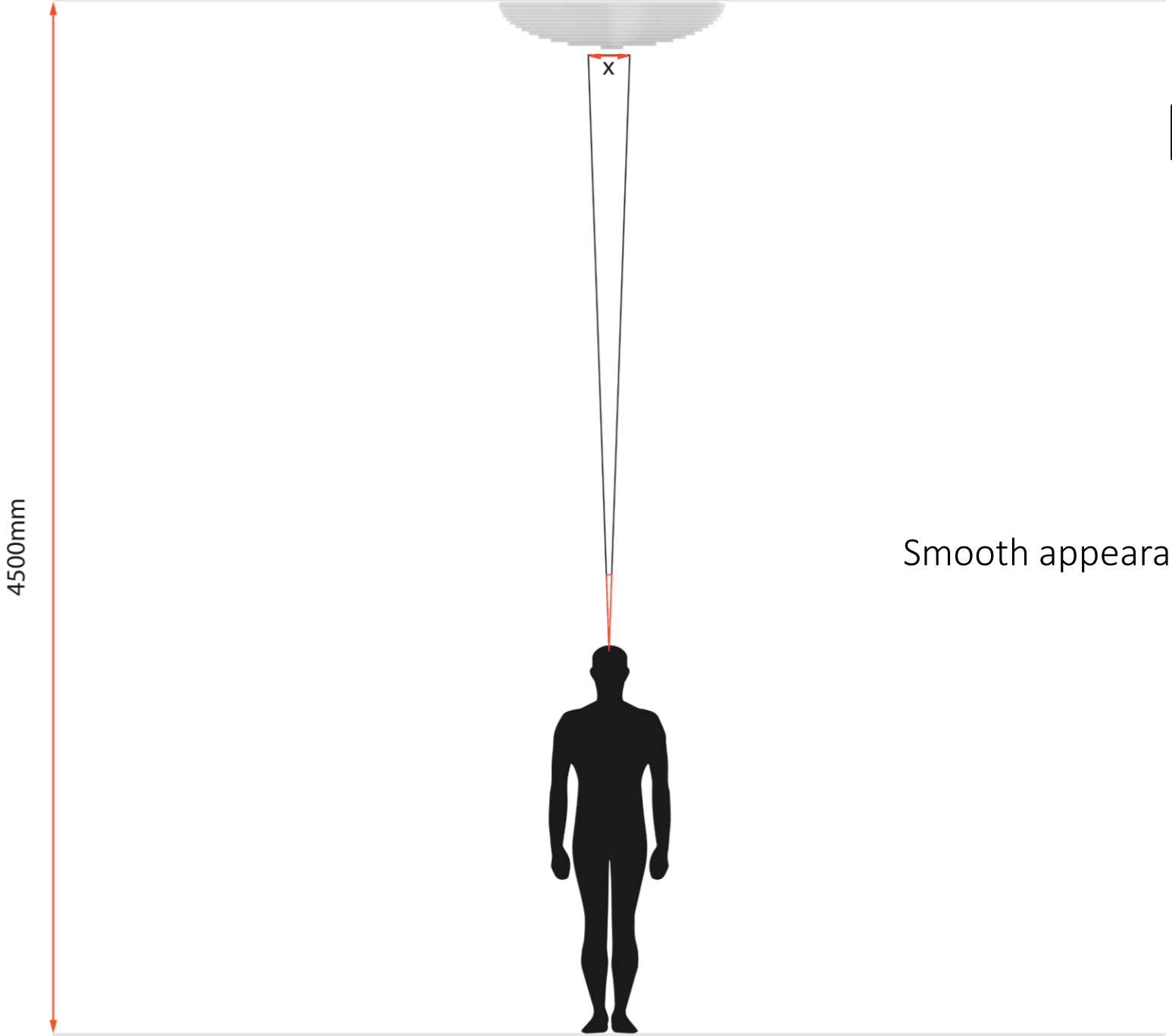
Contour effect: visible layers

Thin layers: look smooth

Natural History Museum, Rotterdam

# Print resolution

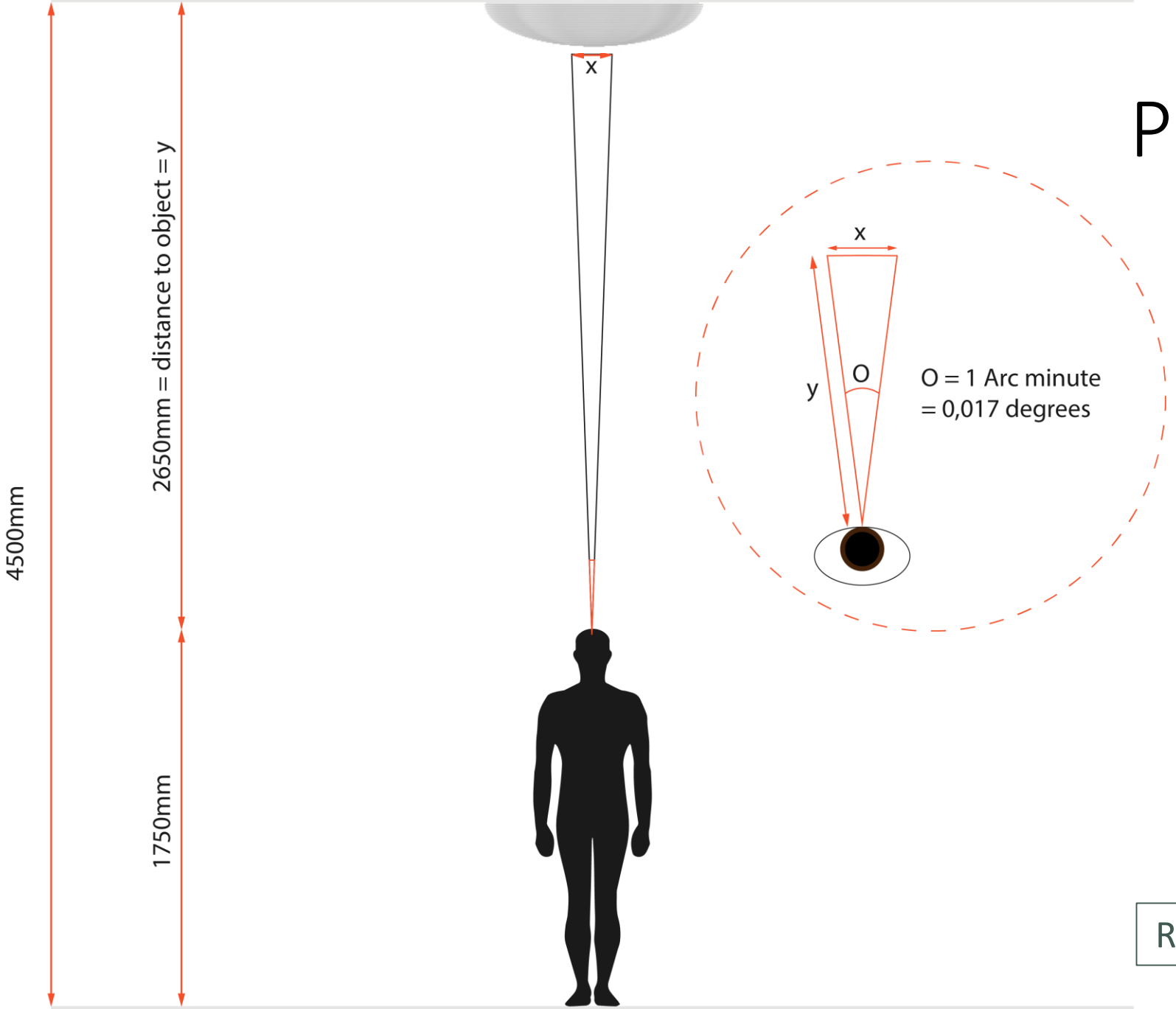
# Print resolution




Natural History Museum, Rotterdam

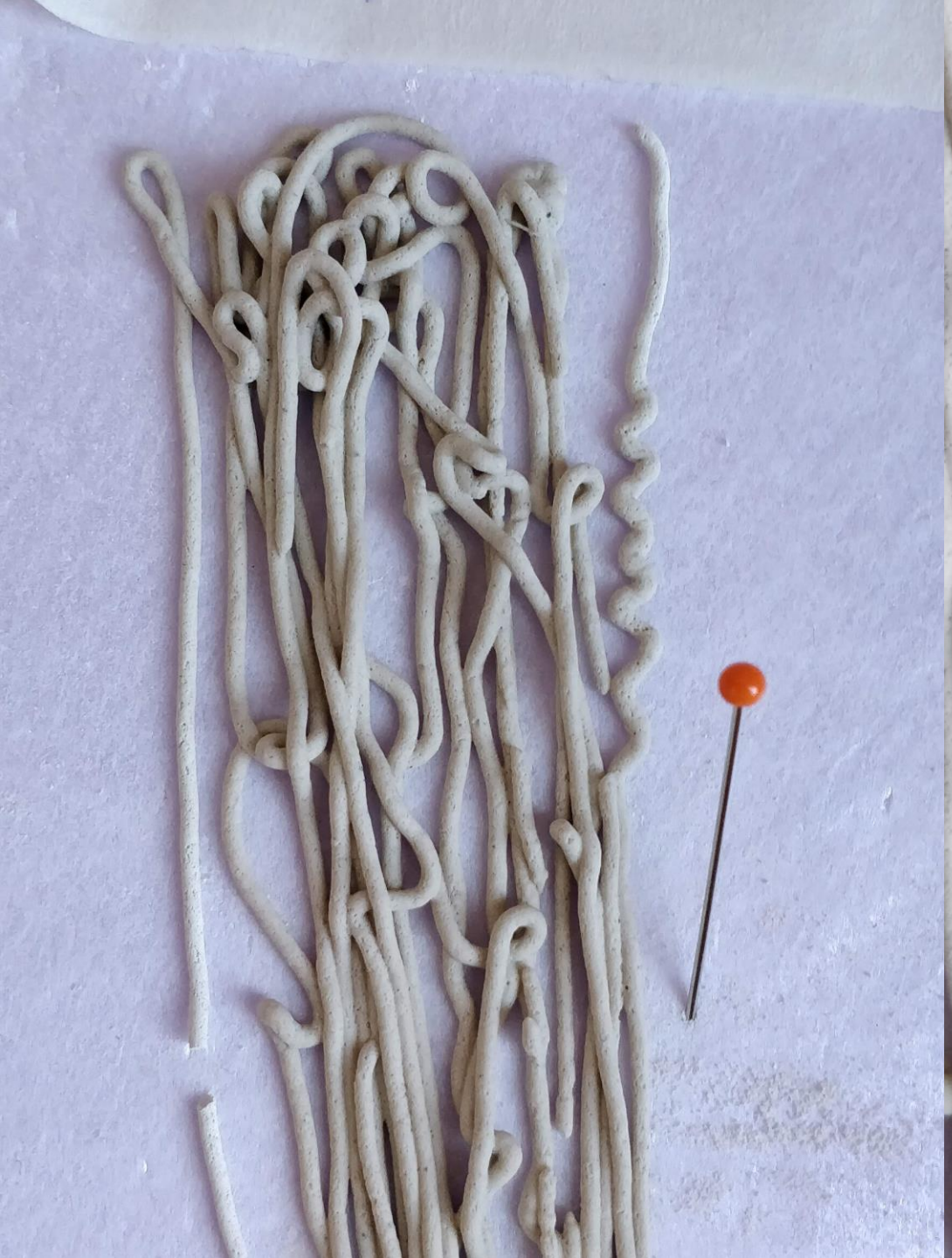
Smooth appearance → how thin must layers be?

# Print resolution




Natural History Museum, Rotterdam

Required resolution: **0,8mm**



- 1 mm wide
- 0.5mm high

Buildability

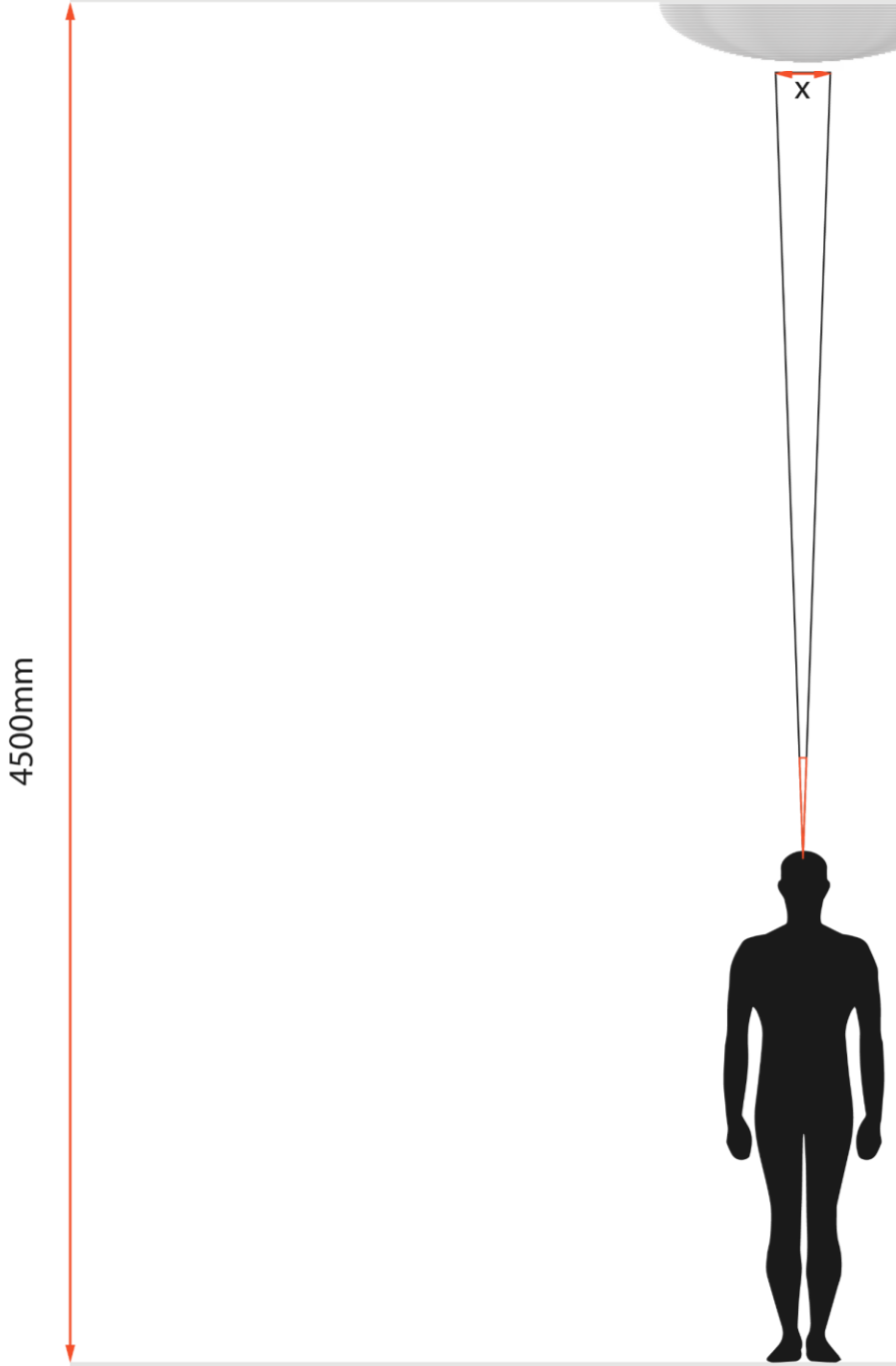
Pumpability
extrudability

Open Time

Fresh adhesion

Dry adhesion

Resolution

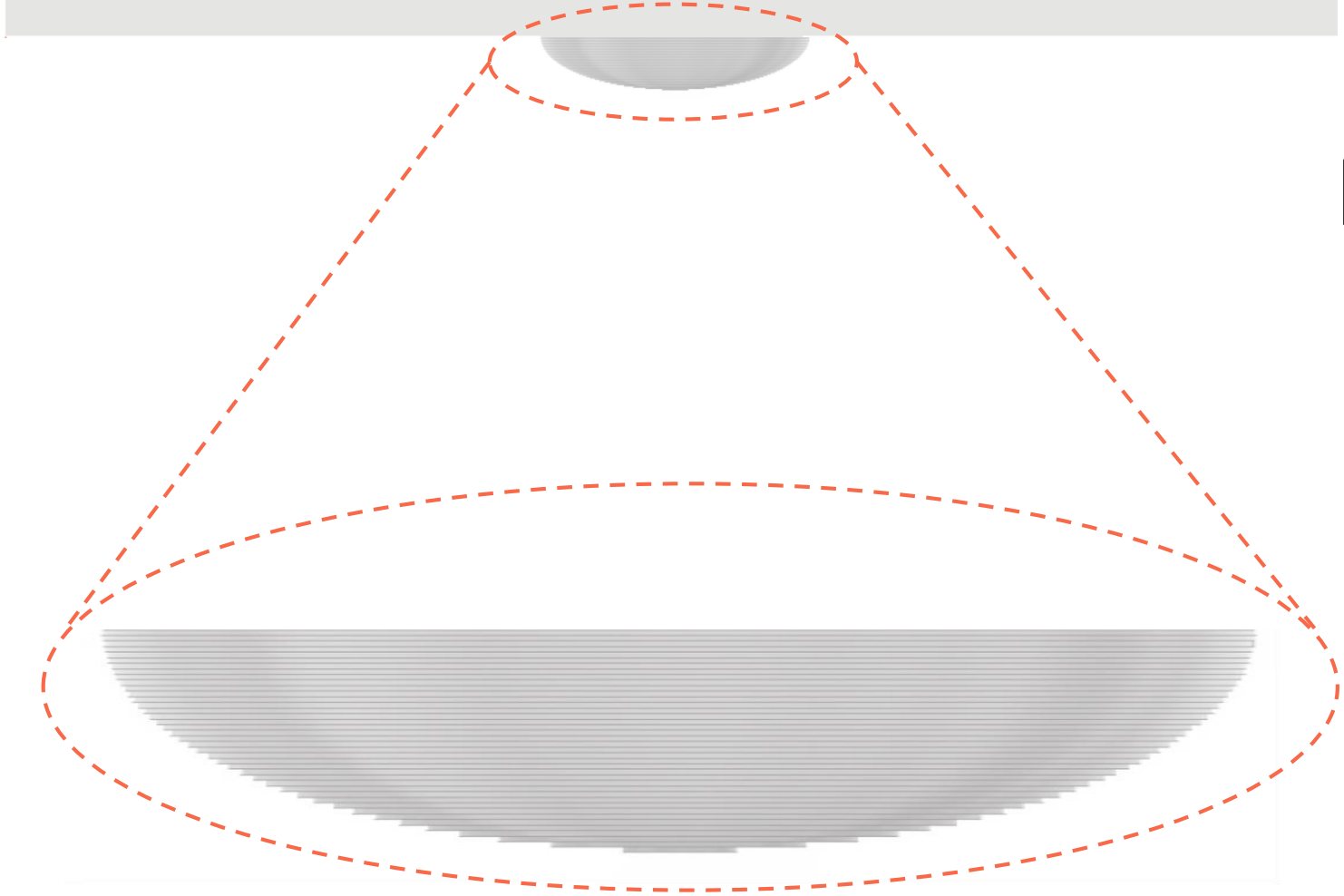



Natural History Museum, Rotterdam

# Print resolution

From **regular viewing distance**: restored parts **appear smooth**

→ Harmoniously integrated with the original work



# Print resolution

Upon **closer** inspection: Restored parts are **clearly distinguishable** → Not **falsify the authenticity** of the work

Natural History Museum, Rotterdam

# Mixtures tested

| Sample | Gypsum/marble powder | Gypsum/water | Printable time (min) | Line continuity (1-5) | Nozzle width (mm) | Extrusion width (mm) | Nr. Of layers without collapse | Shrinkage (%) | Cracking (1-5) |
|---|---|---|---|---|---|---|---|---|---|
| G0 | | 1,55/1 | 4 | 1 | . | . | 1 | - | 1 |
| G1 | | 1,75/1 | 2 | 2 | . | . | 1 | - | 1 |
| G2 | 02:01 | 1,55/1 | 1 | 3 | . | . | 1 | - | 3 |
| G3 | | 1,55/1 | 35 | 4 | 2,25 | 2,5 | 5 | - | 2 |
| G4 | 01:01 | 1,02/1 | 84 | 4 | 4,55 | | 5 | - | . |
| G5 | 03:01 | 1,50/1 | 78 | 5 | 2,25 | 2,5 | 21 | - | 1 |
| G6 | 06:01 | 1,50/1 | 85 | 4 | 4,55 | 5,5 | 11 | - | 2 |
| G7 | 02:01 | 1,50/1 | 40 | 4 | 4,55 | 4,6 | 15 | - | 2 |
| G8 | 2,5:01 | 1,50/1 | 45 | 4 | 4,55 | 4,8 | 9 | - | 3 |
| G9 | 04:01 | 1,50/1 | 45 | 4 | 4,55 | 4,5 | 14 | - | 2 |
| G10 | | 1,22 | | | 1 | 1 | | - | (Sieved) |


Buildability


Pumpability extrudability


Open Time


Fresh adhesion


Dry adhesion


Resolution

# Mixtures tested

| Sample | Gypsum/marble powder | Gypsum/water | Printable time (min) | Line continuity (1-5) | Nozzle width (mm) | Extrusion width (mm) | Nr. Of layers without collapse | Shrinkage (%) | Cracking (1-5) |
|---|---|---|---|---|---|---|---|---|---|
| G0 | | 1,55/1 | 4 | 1 | . | . | 1 | - | 1 |
| G1 | | 1,75/1 | 2 | 2 | . | . | 1 | - | 1 |
| G2 | 02:01 | 1,55/1 | 1 | 3 | . | . | 1 | - | 3 |
| G3 | | 1,55/1 | 35 | 4 | 2,25 | 2,5 | 5 | - | 2 |
| G4 | 01:01 | 1,02/1 | 84 | 4 | 4,55 | | 5 | - | . |
| **G5** | **03:01** | **1,50/1** | **78** | **5** | **2,25** | **2,5** | **21** | **-** | **1** |
| G6 | 06:01 | 1,50/1 | 85 | 4 | 4,55 | 5,5 | 11 | - | 2 |
| G7 | 02:01 | 1,50/1 | 40 | 4 | 4,55 | 4,6 | 15 | - | 2 |
| G8 | 2,5:01 | 1,50/1 | 45 | 4 | 4,55 | 4,8 | 9 | - | 3 |
| G9 | 04:01 | 1,50/1 | 45 | 4 | 4,55 | 4,5 | 14 | - | 2 |
| G10 | | 1,22 | | | 1 | 1 | | - | (Sieved) |



Buildability

Pumpability extrudability

Open Time

Fresh adhesion

Dry adhesion

Resolution

# G5 material recipe

| 3 | : | 1 | : | 1.54 |
|---|---|---|---|---|

| Binder<br>Knauf Rotband gypsum | Aggregates<br>Marble powder | Water |
|---|---|---|

# G5 performance → Suitable for application

Buildability

**21 layers**

Pumpability
extrudability

**4 bar**

Open Time

**1.5 hours**

Fresh adhesion

**360°**

Dry adhesion

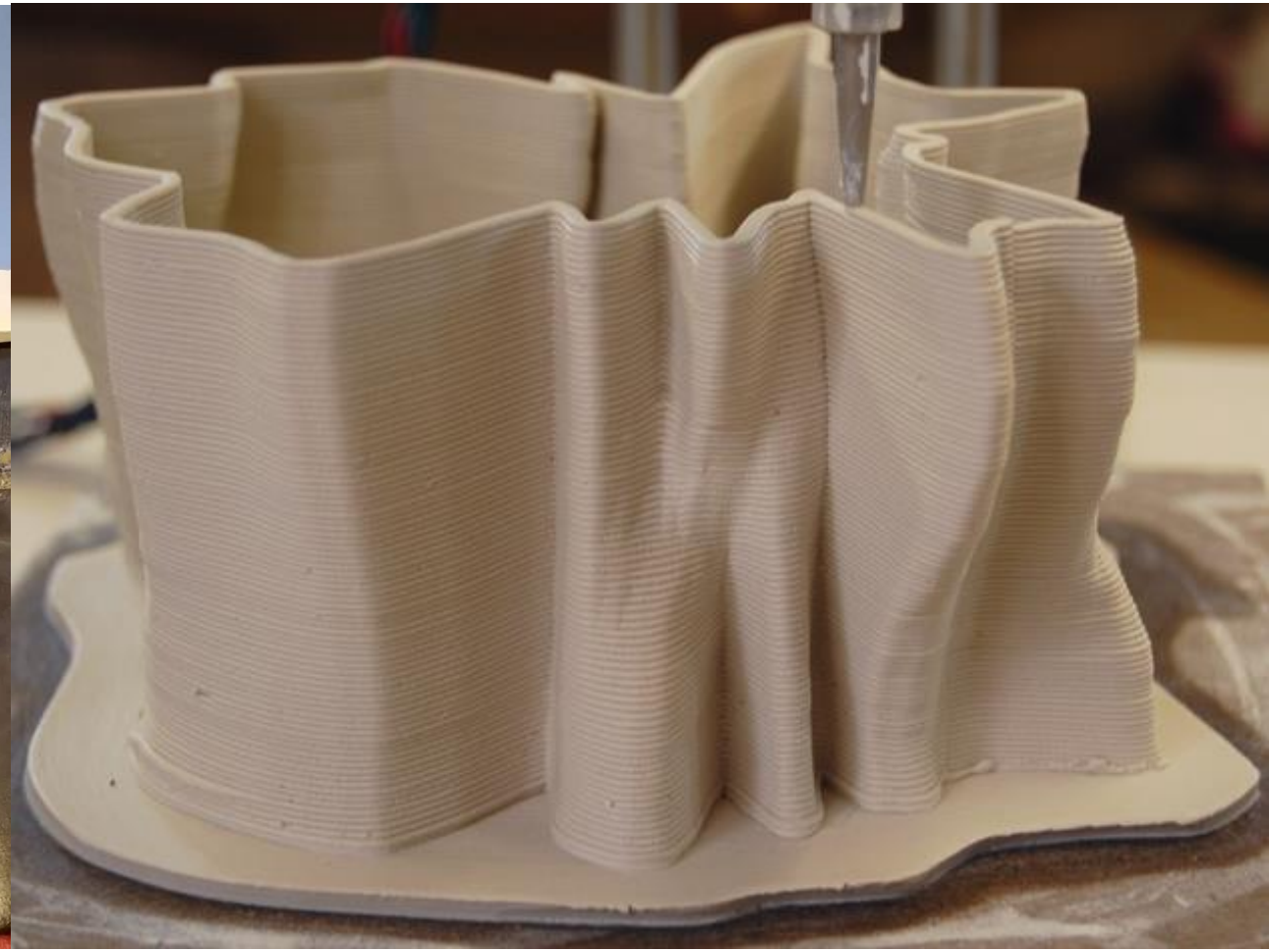
**24kg**

Resolution

**0.5mm**

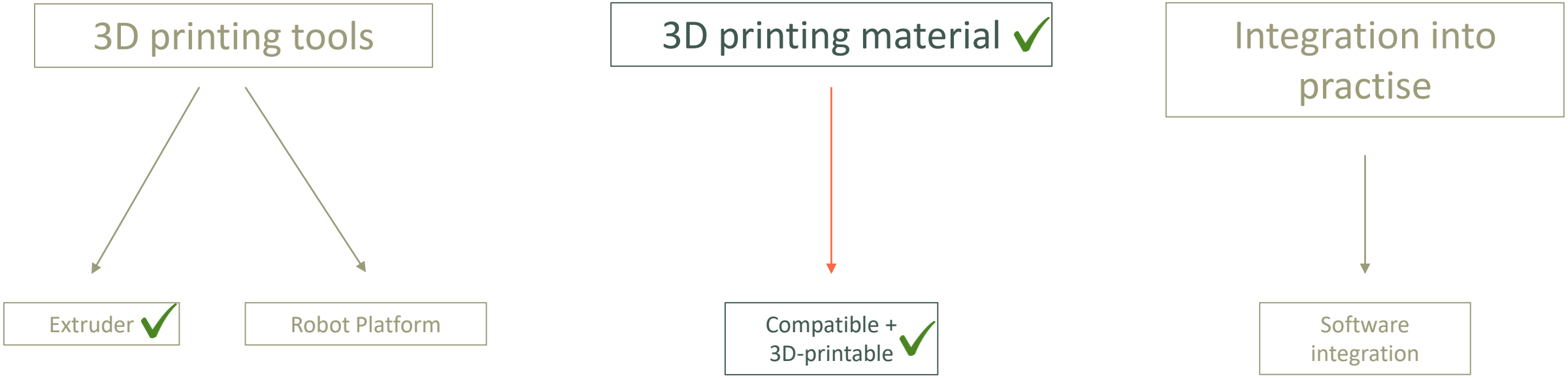
# Material design: manual vs robotic

Gypsum 3D prints by hand

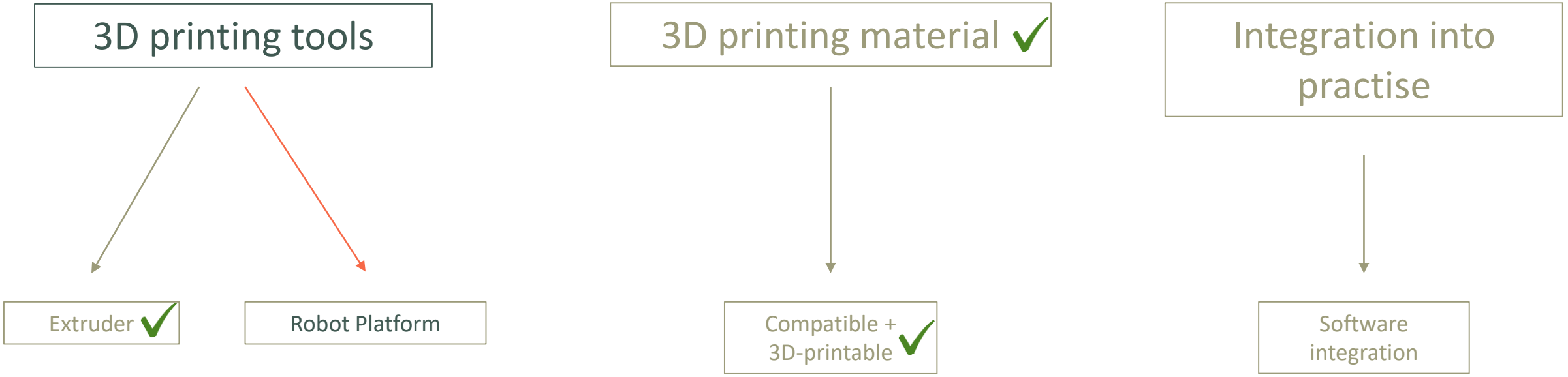


Clay 3D print with robot

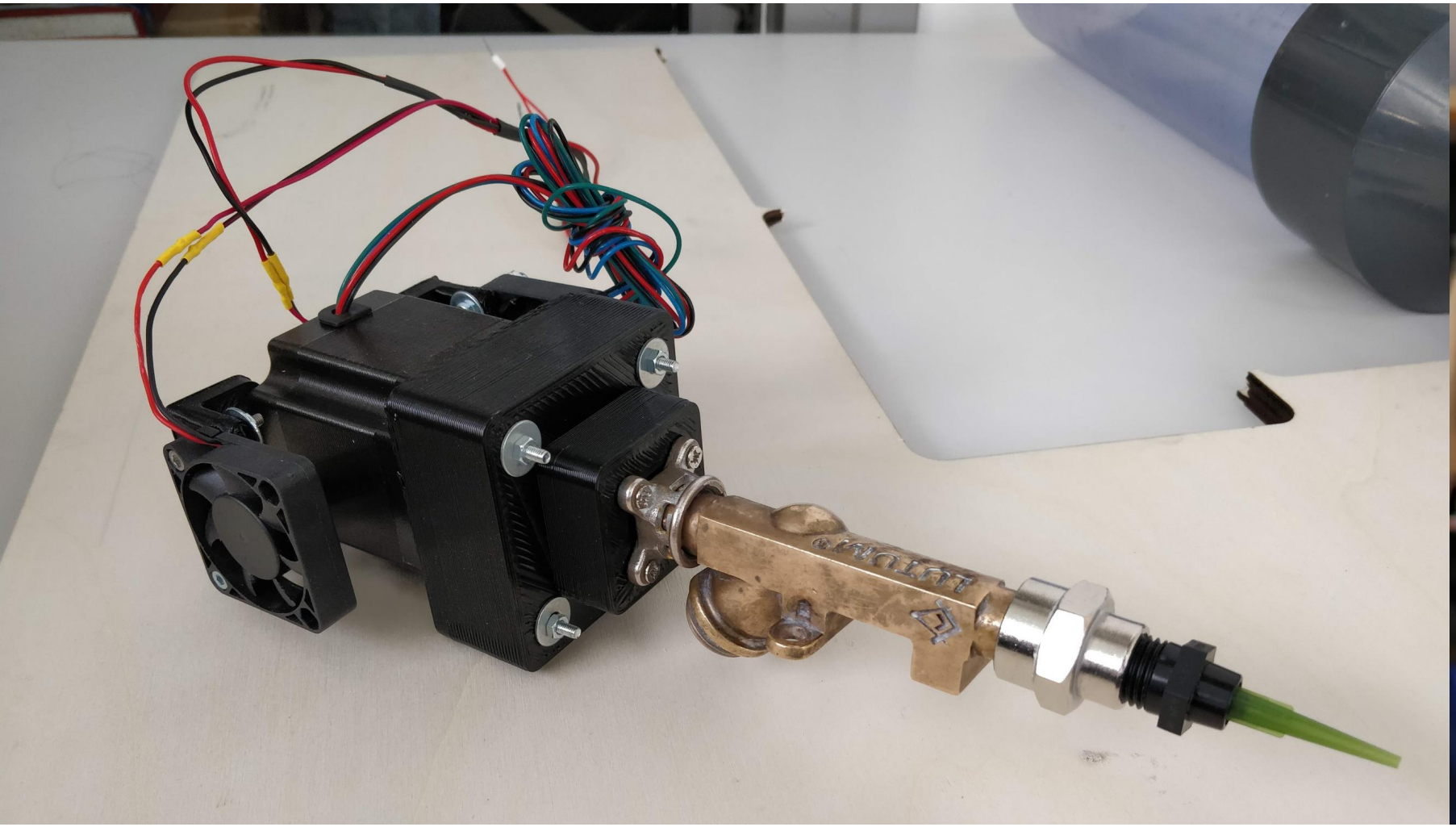
# Objective


3D printing tools
3D printing material
Integration into practise
Extruder
Robot Platform
Compatible + 3D-printable
Software integration

# Objective


3D printing tools
3D printing material ✓
Integration into practise
Extruder ✓
Robot Platform
Compatible + 3D-printable ✓
Software integration

# Extruder + printing material + ?



# 3D printing tools

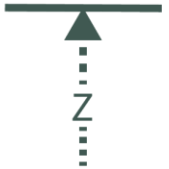
Restoration Robot Platform (RRP)

# RRP: Requirements

Size

Weight

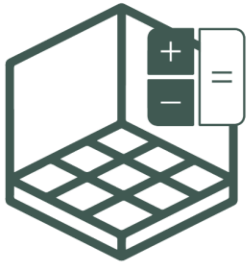
Mobility




Reach

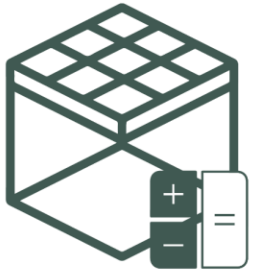
# RRP: Requirements


Building codes



Floor load


Arbo-laws



Ceiling height

Size

Weight

Mobility

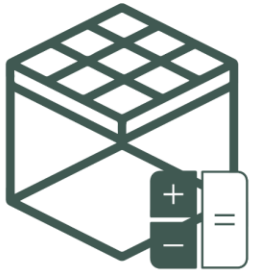

Reach

# RRP: Requirements

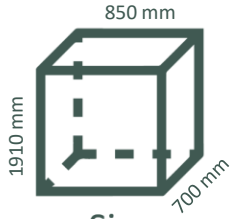

Building codes

Floor load


Arbo-laws



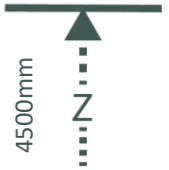
Ceiling height




Size


Weight

Mobility




Reach

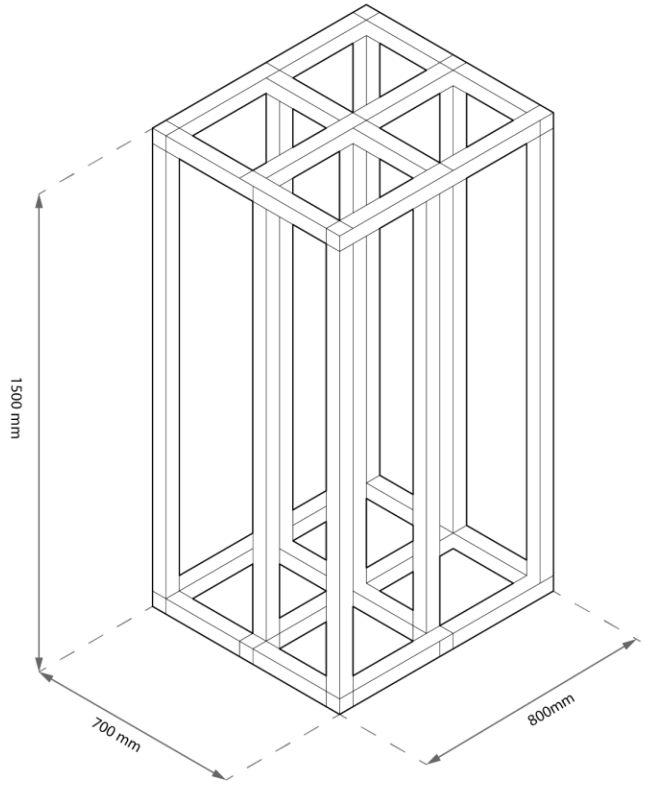
Fit through doors

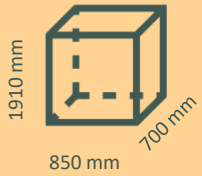
Supportable by old wooden floors

1 person, stairs

Reach 4,5m tall ceilings

# Aluminium frame: fits through doors



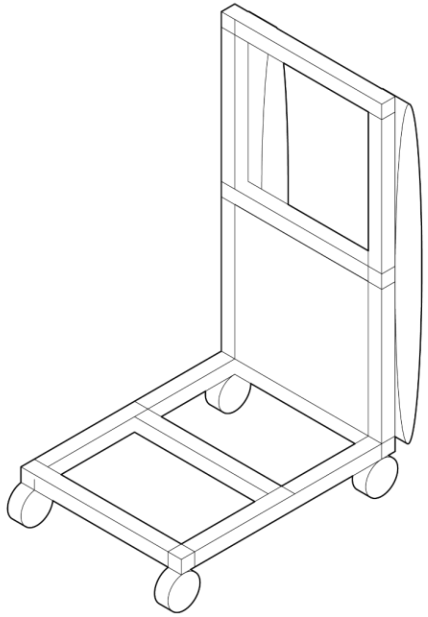


< 155kg

Stairs

4500mm

# Mobility: can climb stairs



Electric stair climbing trolley
Weight: 30kg
Payload: 310kg
Feature: Powered mobility

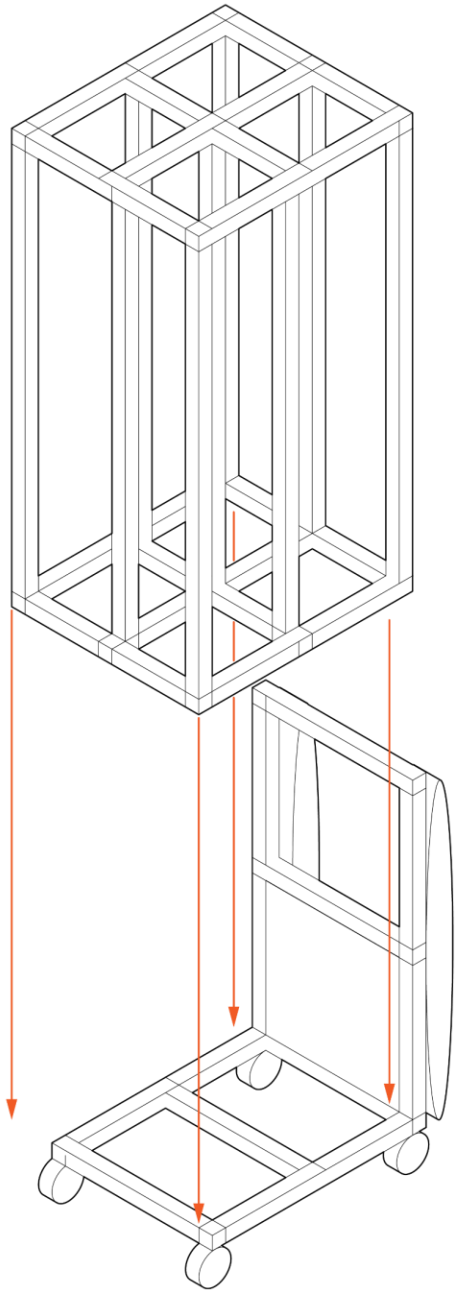
1910 mm
700 mm
850 mm

40 kg
< 155kg

Stairs

4500mm

# Mobility



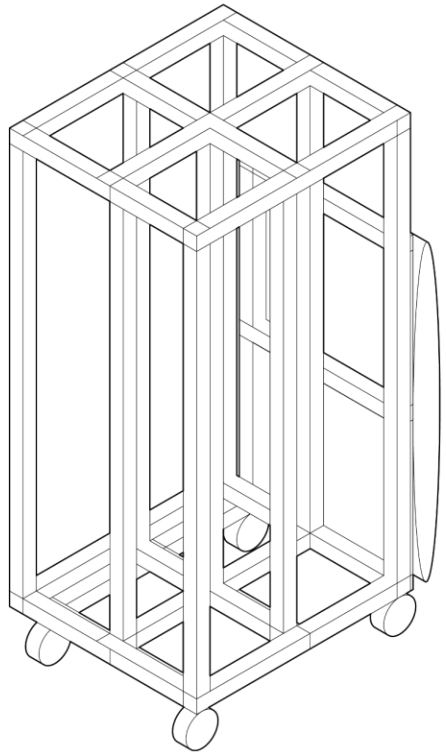
1910 mm
700 mm
850 mm

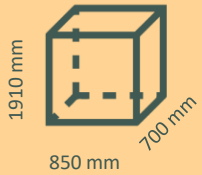
40 kg
< 155kg

Stairs

4500mm

# Mobility







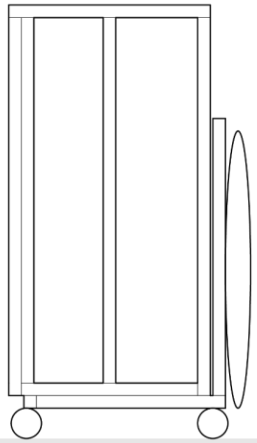
< 155kg

Stairs

4500mm

# Vertical reach: can reach tall ceilings

45000mm



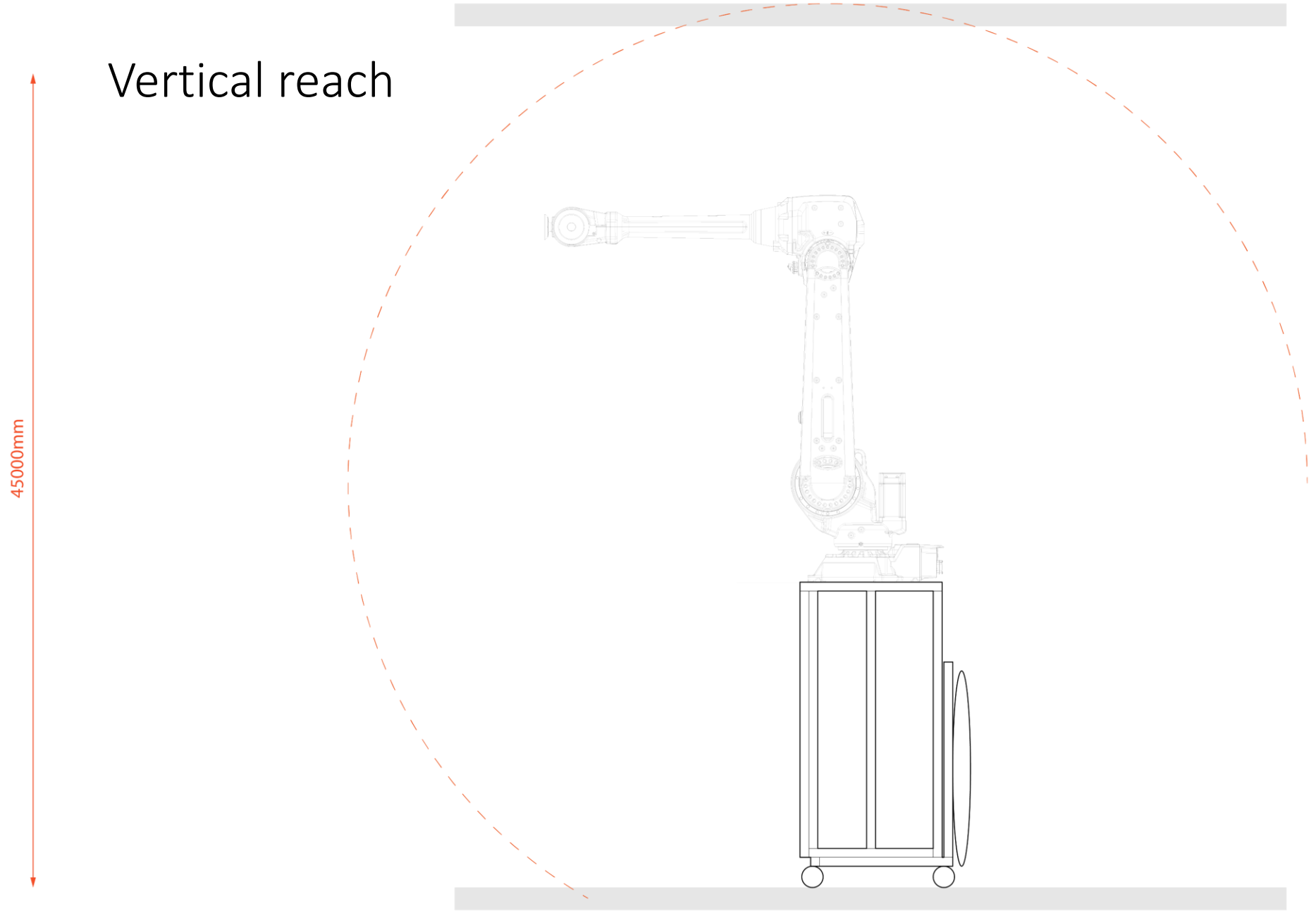
1910 mm
700 mm
850 mm

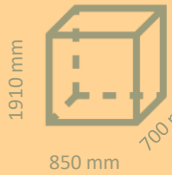
40 kg
< 155kg

Stairs

4500mm

# Vertical reach




480 kg

< 155kg

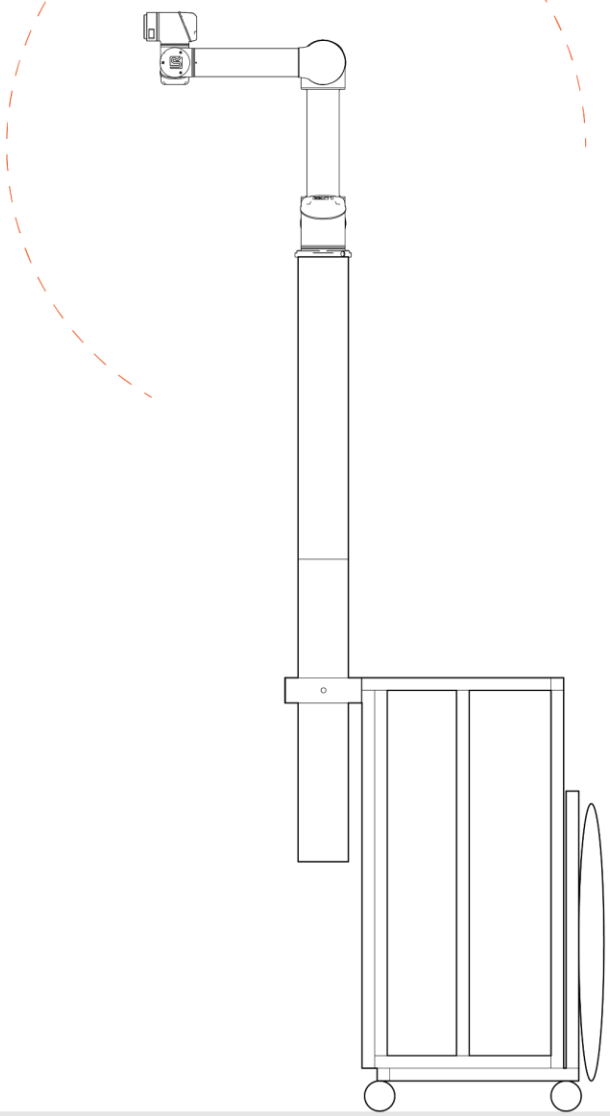
Stairs


4500mm

# Vertical reach

45000mm

Video camera crane



1910 mm

700 mm

850 mm

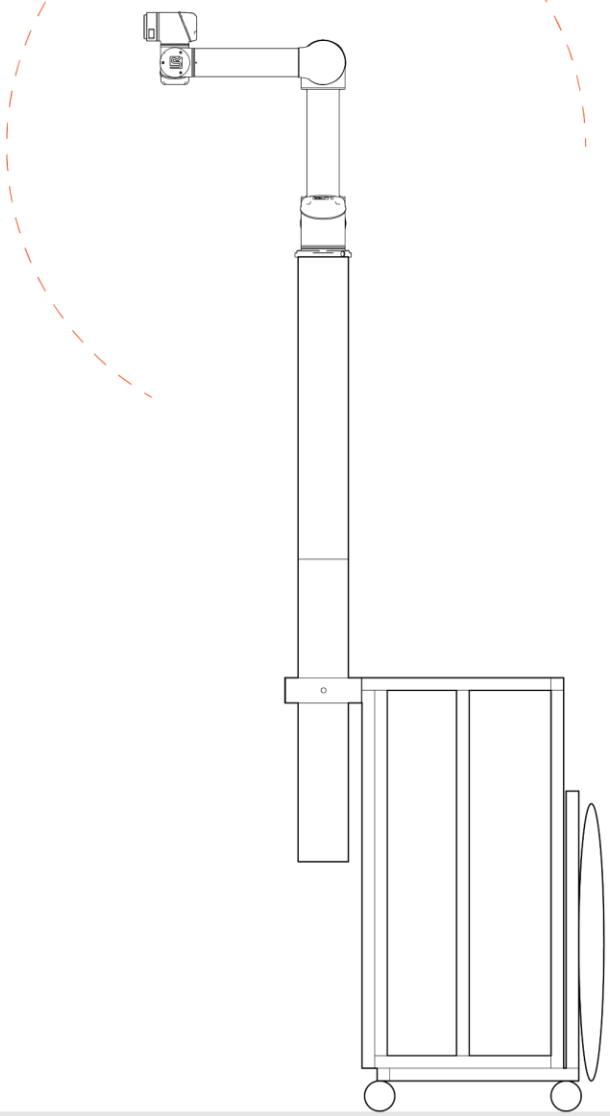
+40 kg

< 155kg

Stairs

4500mm

# Vertical reach

Video camera crane
Model: Kite-11
Feature: Gyroscopic stabilizing
Weight: 24kg
Payload: 25kg

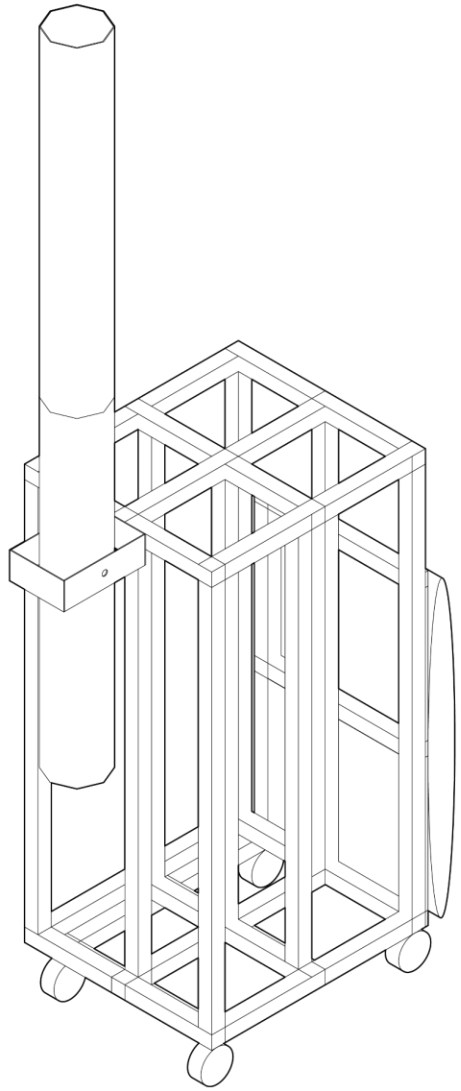
1910 mm
700 mm
850 mm

+64 kg
< 155kg

Stairs

4500mm

# Crane mounted



1910 mm
700 mm
850 mm

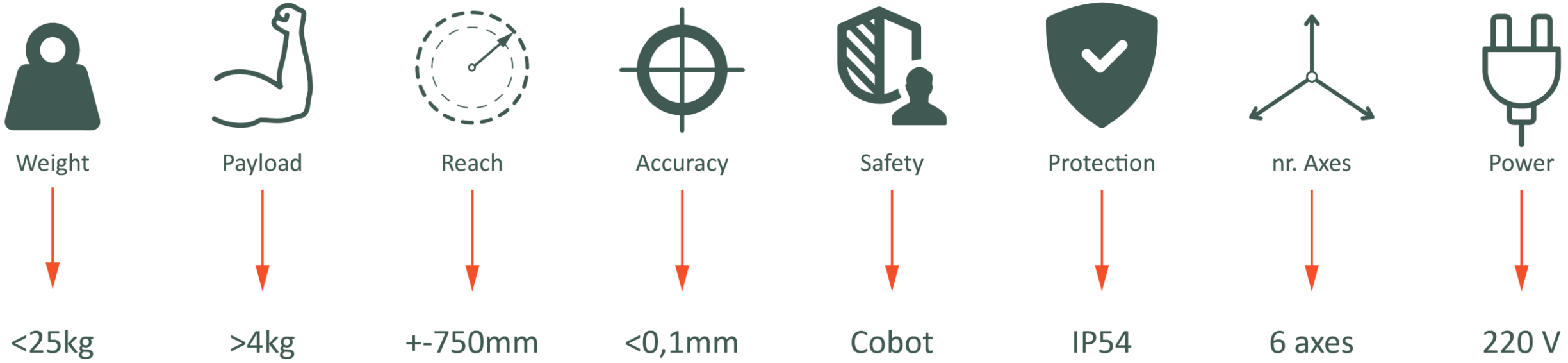
+65 kg
< 155kg

Stairs

4500mm

# Robot selection: criteria

# Robot selection: constraints



# Robot selection

| Name | Manufacturer |
|---|---|
| UR5 | Universal Robotics |
| UR10 | Universal Robotics |
| HC10 | Yasakawa |
| HCR-5 | Hanwha Techwin |
| HCR-12 | Hanwha Techwin |
| I-5 | AUBO |
| I-7 | AUBO |
| I-10 | AUBO |
| KR1205 | Kassow Robots |
| KR1805 | Kassow Robots |

I-5

HCR-5

KR1205

UR5



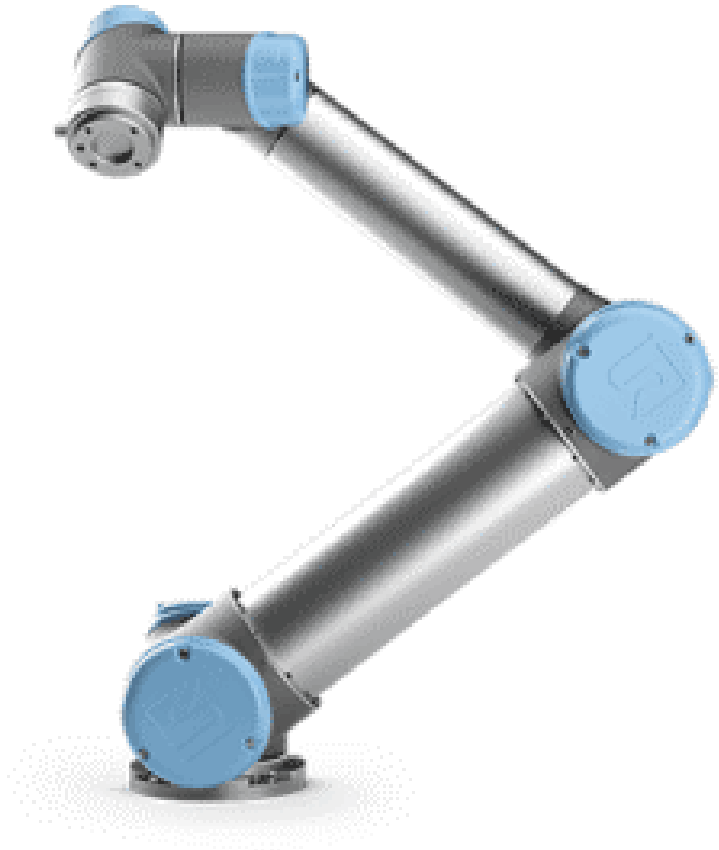







# Robot selection: UR5

| Name | UR5 |
|---|---|
| Manufacturer | Universal Robotics |
| Robot weight | 20,6 |
| Controller weight | 15,2 |
| Total weight | 35,8 |
| Payload | 5 |
| Reach | 850 |
| Repeatibility | 0,03 |
| Type | **Collaborative** |
| Protection | IP154 |
| Nr. Of axis | 6 |
| Power supply | 220 V |

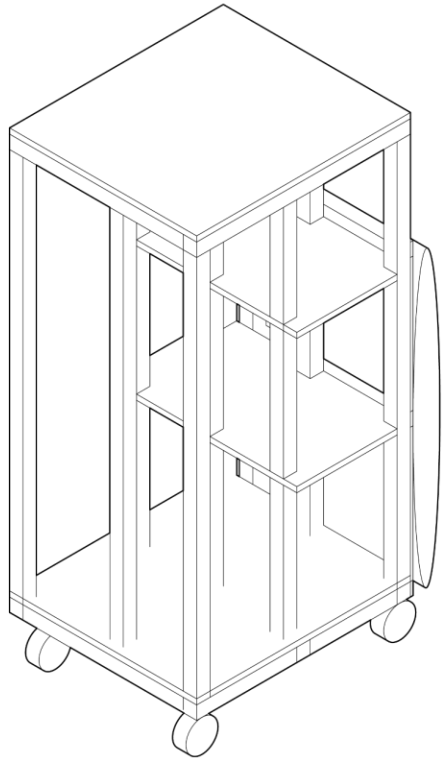









# Shelves & top



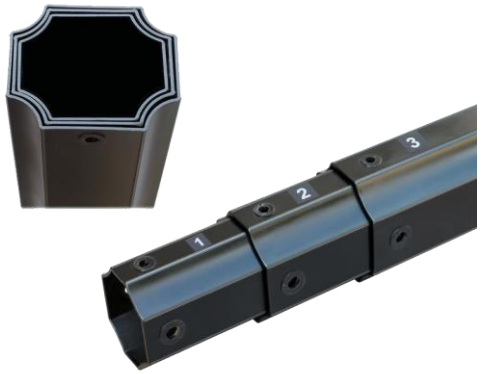
1910 mm
700 mm
850 mm

+66 kg
< 155kg

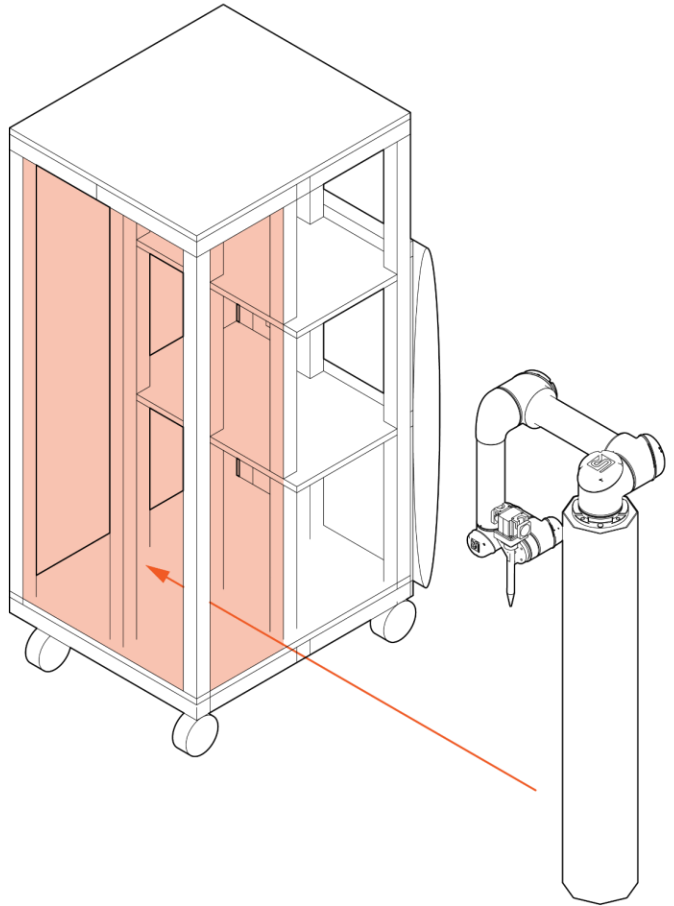
Stairs

Z
4500mm

# Stow crane + robot + extruder




Telescopic segments
Reach: 0 – 5,1m



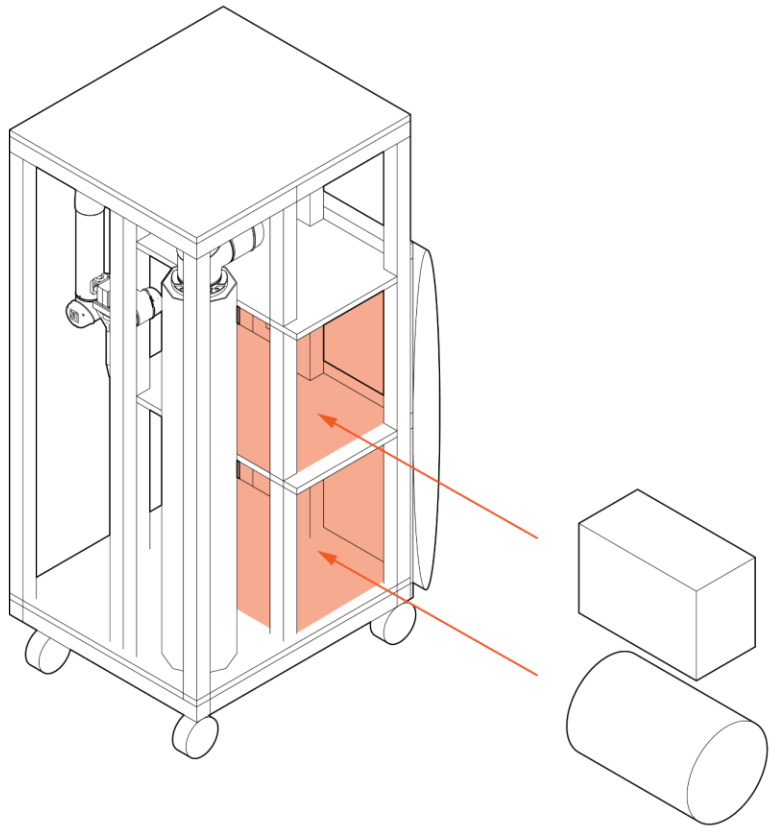
1910 mm
700 mm
850 mm

+87 kg
< 155kg

Stairs

4500mm

# Stow robot controller & compressor



1910 mm
700 mm
850 mm

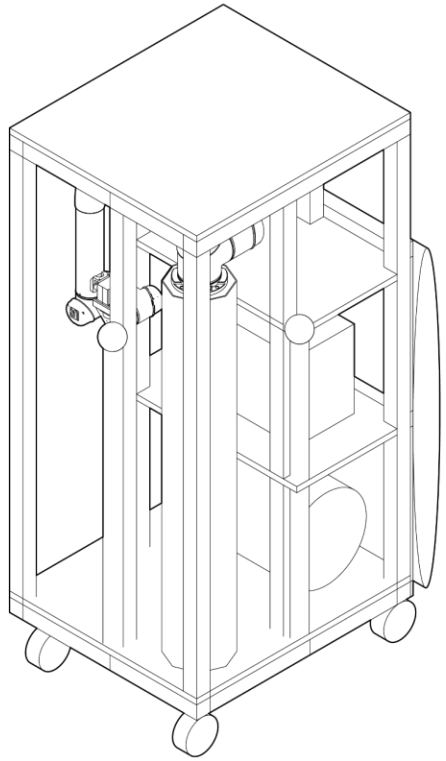
+107 kg
< 155kg

Stairs

4500mm

# Legs for stability

Stabilizing legs



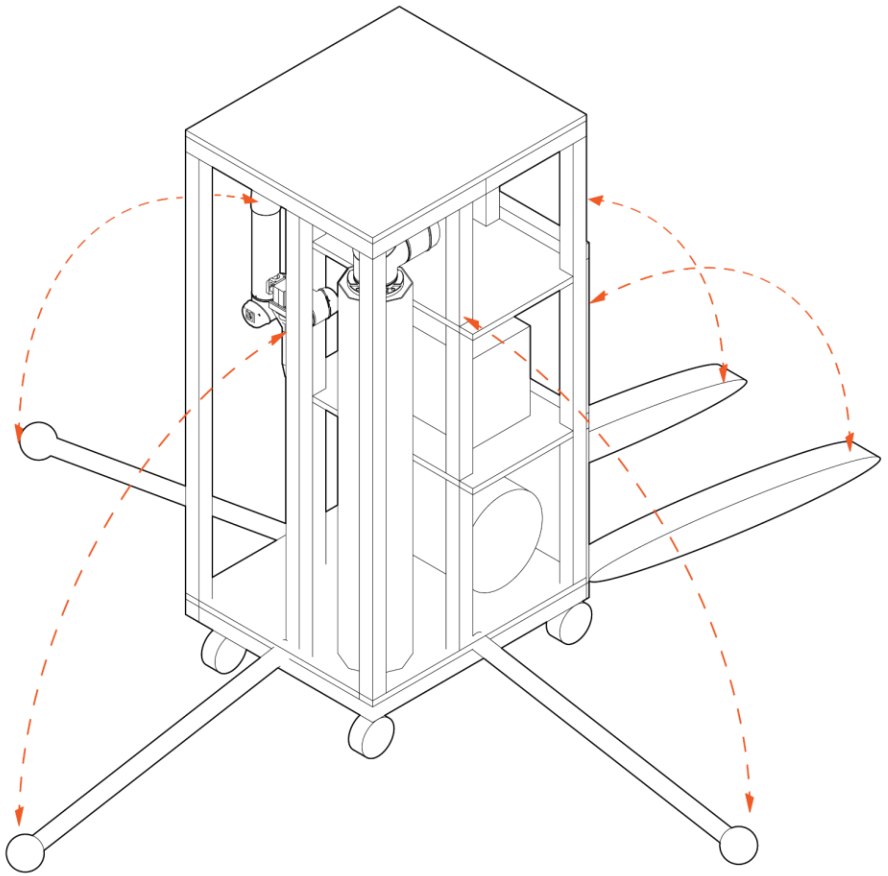
1910 mm
700 mm
850 mm

+113 kg
< 155kg

Stairs

Z
4500mm

# Stability legs out during 3D printing



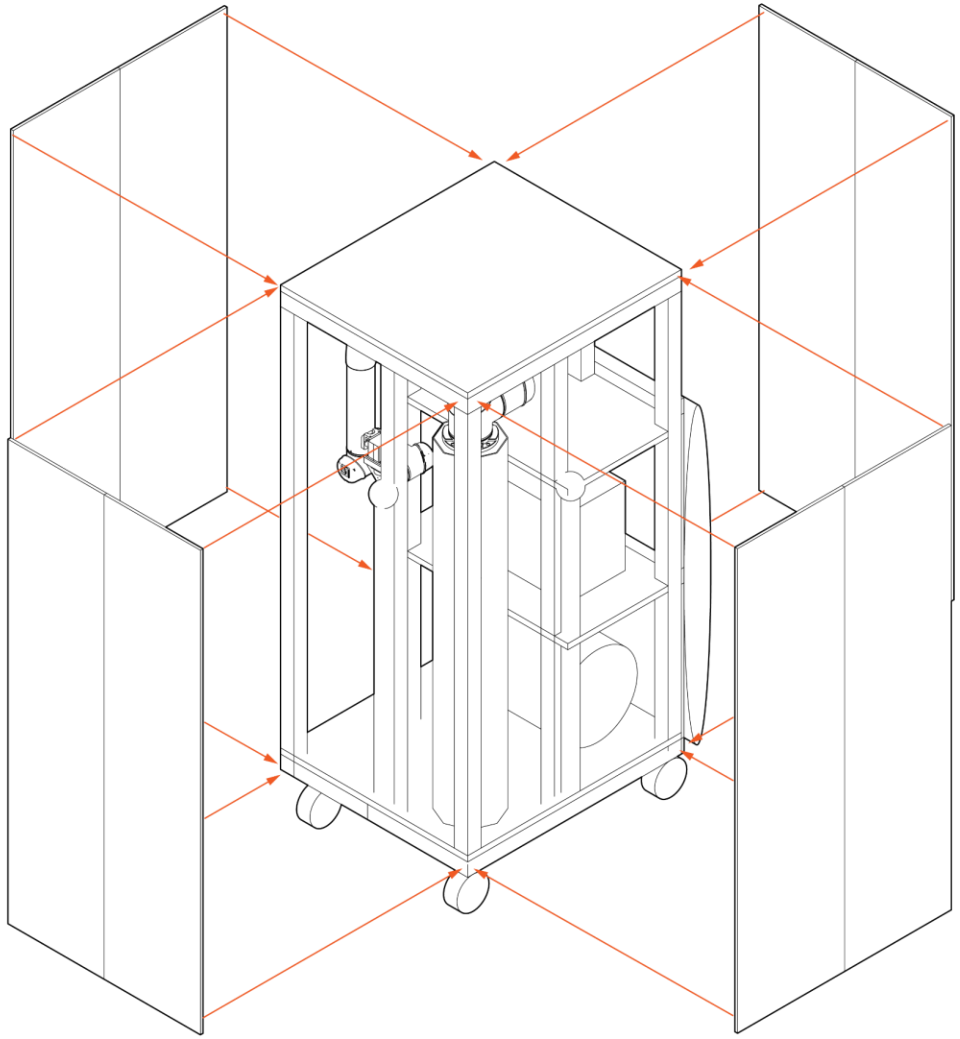
1910 mm
700 mm
850 mm

+113 kg
< 155kg

Stairs

Z
4500mm

# Protective doors



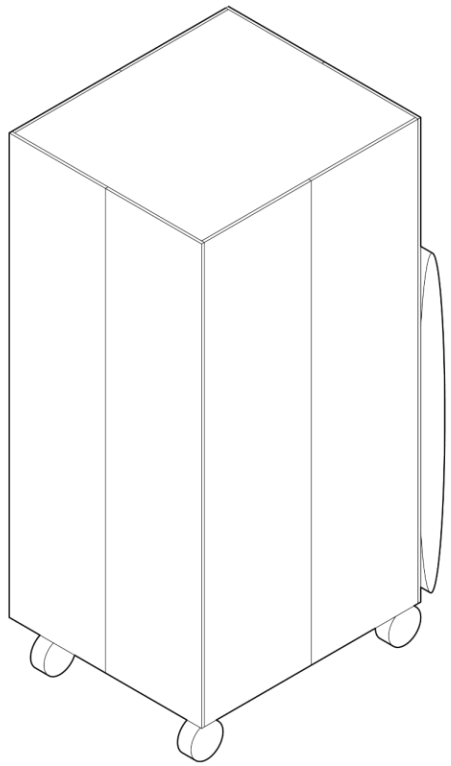
1910 mm
700 mm
850 mm

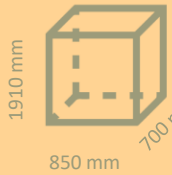
121 kg
< 155kg

Stairs

4500mm

# Final prototype design: Transportation mode





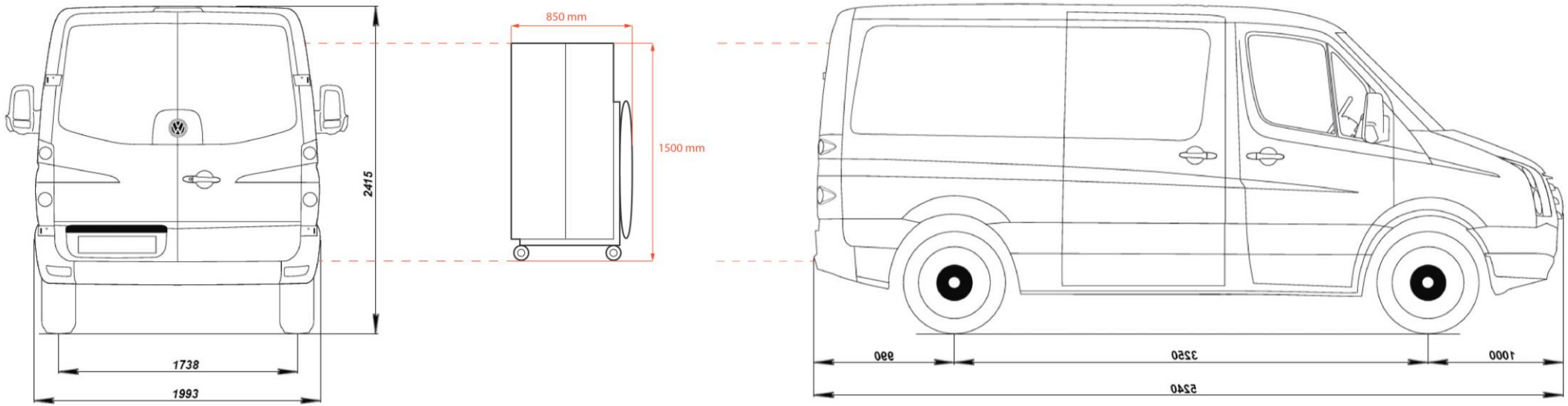


< 155kg

Stairs


4500mm

# Transport to site




1910 mm
700 mm
850 mm

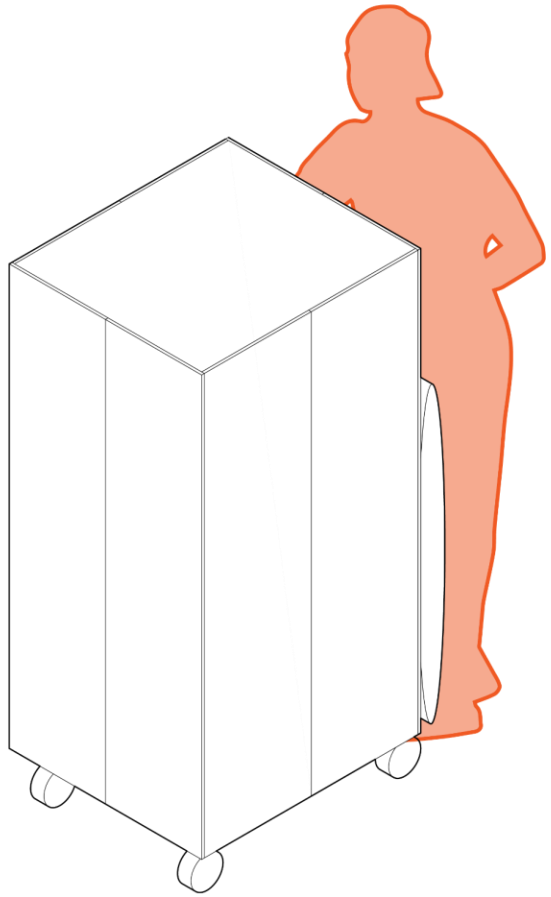
121 kg
< 155kg

Stairs

4500mm

Volkswagen Crafter

# Movable by 1 person



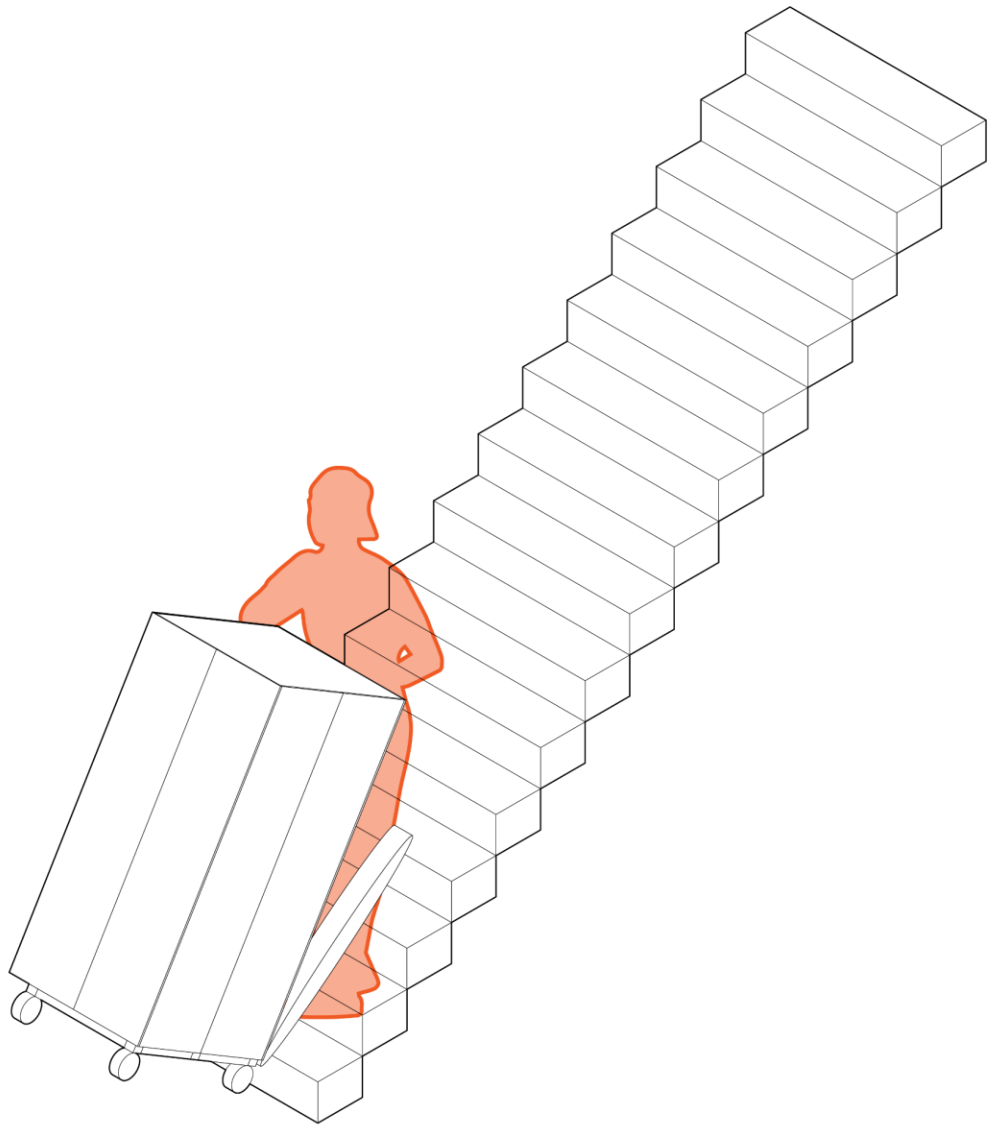
1910 mm
700 mm
850 mm

121 kg
< 155kg

Stairs

4500mm

# Stair-proof



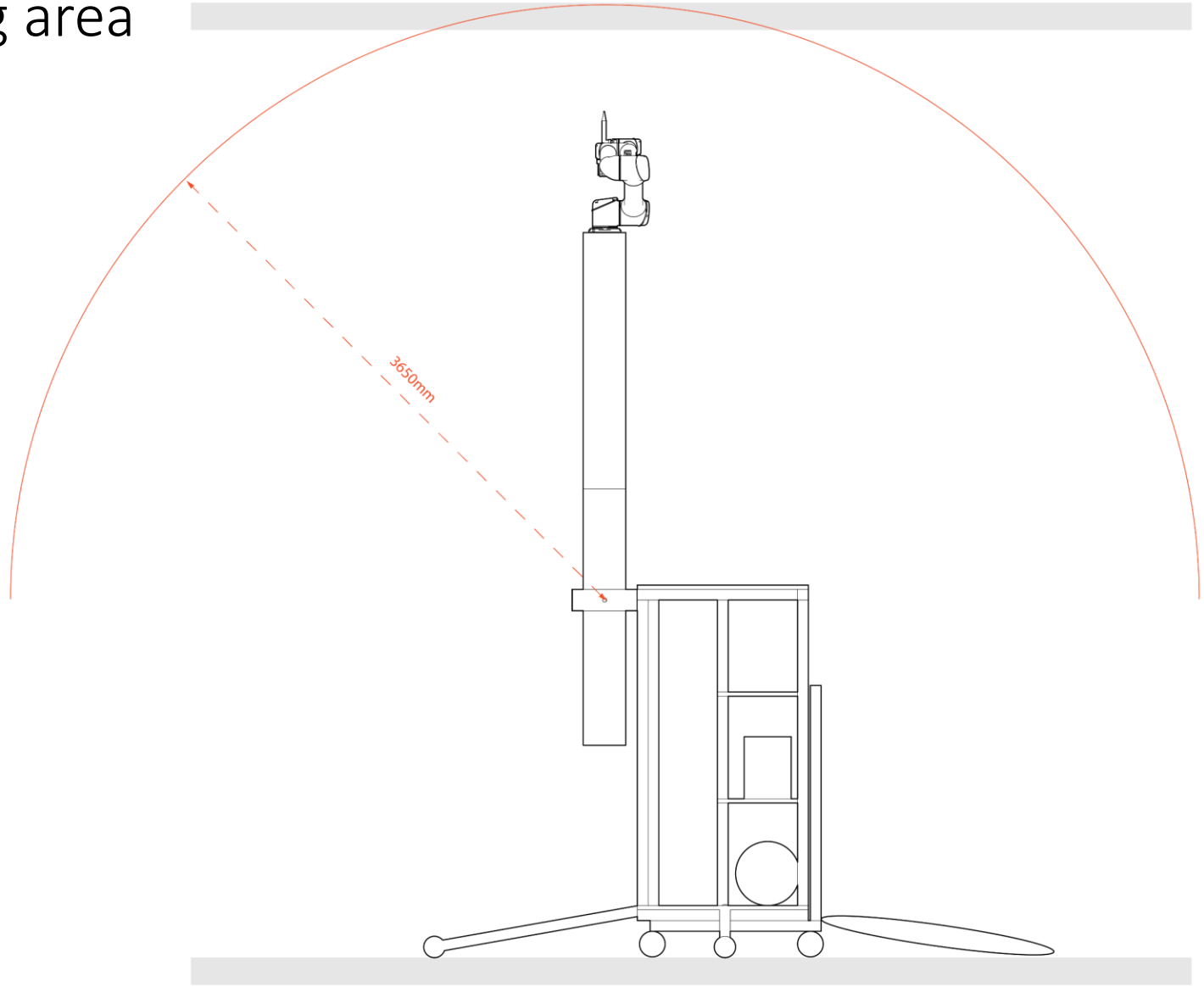
1910 mm
700 mm
850 mm

121 kg
< 155kg

Stairs

4500mm

# Working area



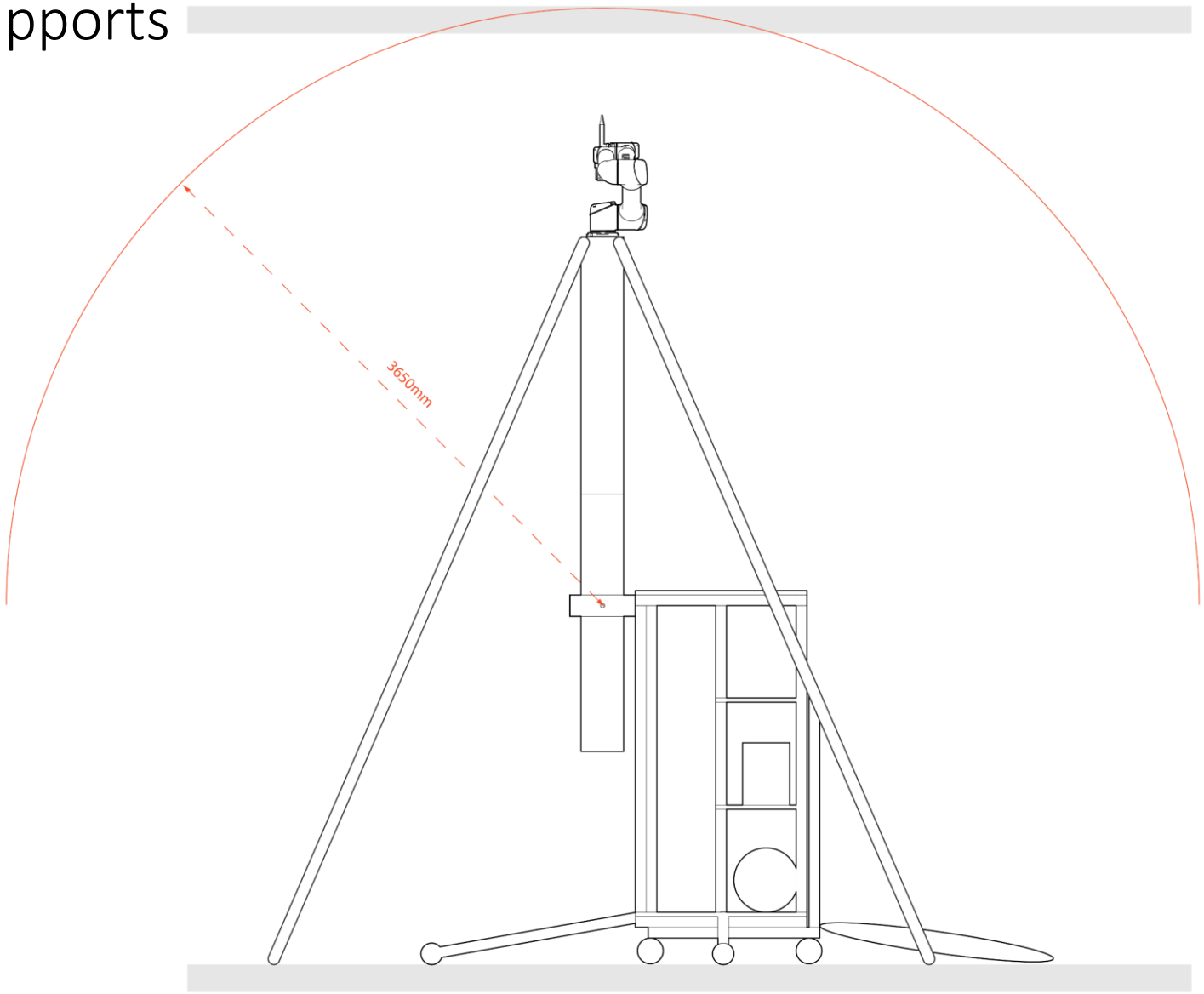

1910 mm
700 mm
850 mm

121 kg
< 155kg

Stairs

Z
4500mm

# Tripod supports



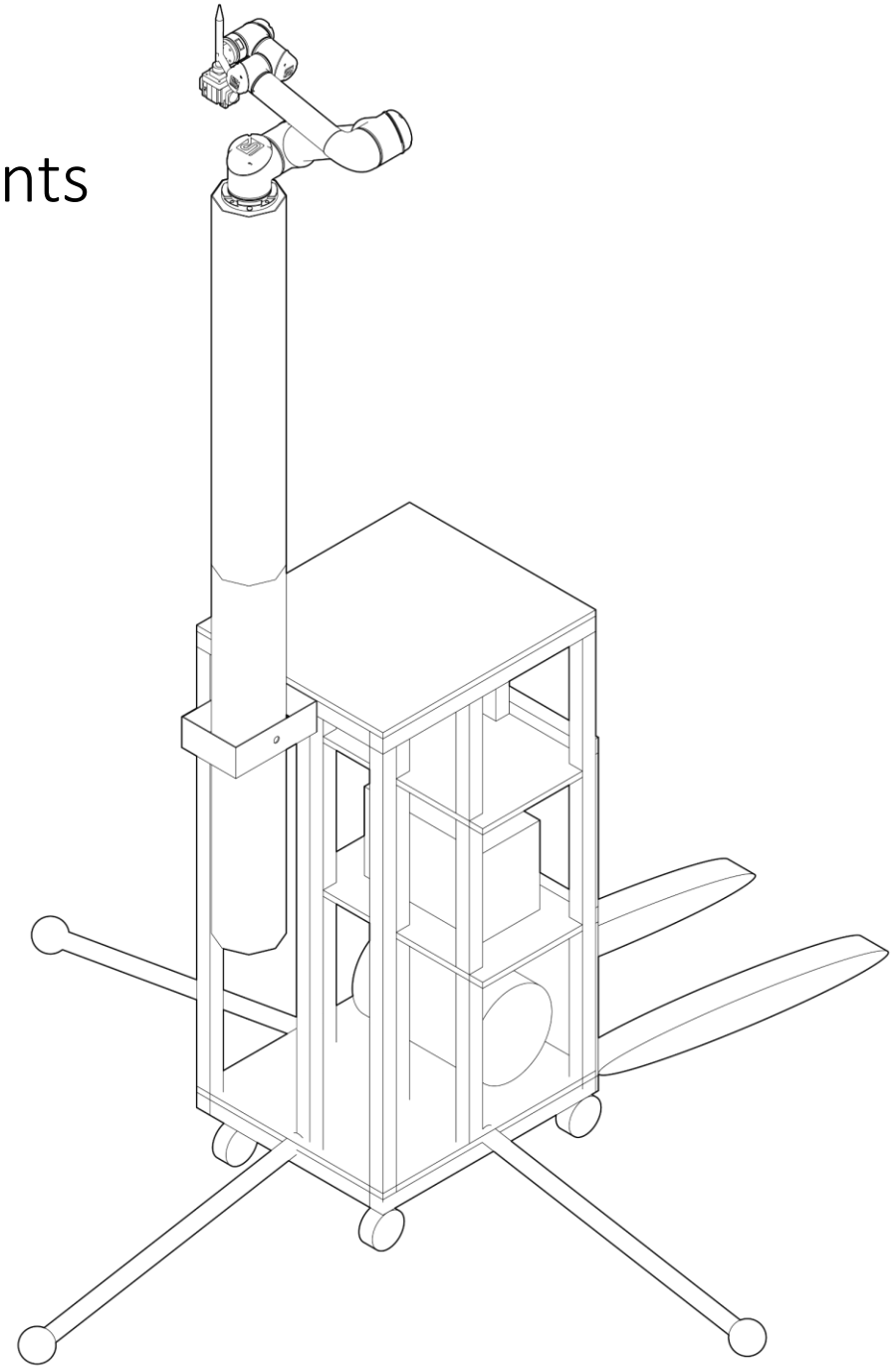

1910 mm
700 mm
850 mm

121 kg
< 155kg

Stairs

Z
4500mm

# Off the shelf components



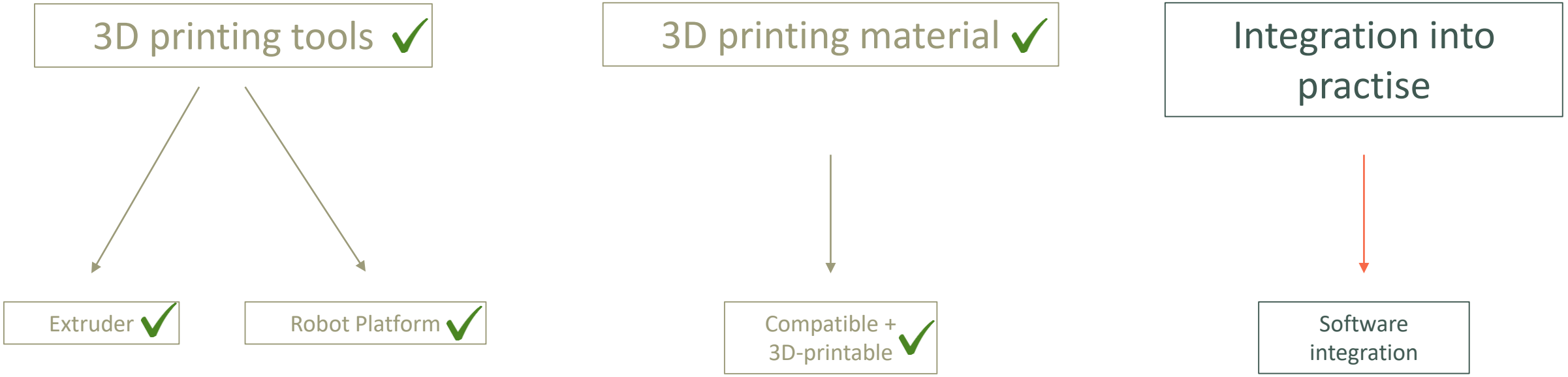
1910 mm
700 mm
850 mm

121 kg
< 155kg

Stairs

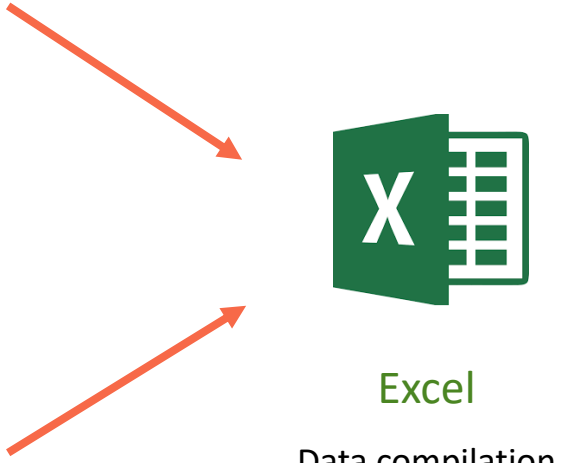
4500mm

# Objective


3D printing tools
3D printing material
Integration into practise
Extruder
Robot Platform
Compatible + 3D-printable
Software integration

# Software plug-in: Robotic Restoration

Tool specifications



Material properties

Excel

Data compilation

## Printer settings input

| Quality | | Note |
|---|---|---|
| Nozzle width (mm) | 2,25 | |
| Layer height (mm) | 1 | Extr. Speed |
| Initial layer height (mm) | 1 | |
| Outer wall line width (mm) | | |
| Inner line width (mm) | | |
| Top line width (mm) | | Top of a sub-part |
| Bottom line width (mm) | | Bottom of a sub-part |
| Infill line width (mm) | 1 | First layers |
| Initial layer line width (mm) | | First layers |
| Finish layer line width (mm) | | Visible layer |

| Shell | | Note |
|---|---|---|
| Wall thickness (mm) | 2 | >1,3 |
| Wall line count | 1 | |
| Top thickness (mm) | 2 | >1,3 |
| Top layers | 1 | |
| Bottom thickness (mm) | 2 | >1,3 |
| Bottom layers | 1 | |
| | | |

| Infill | | Note |
|---|---|---|
| Initial fill density (%) | 100 | Better adhesion |
| Infill density (%) | 30 | |
| Infill pattern... | Zig-zag | |
| Infill layer height (mm) | 2 | |
| Infill line width (mm) | 2 | |

| Travel | | Note |
|---|---|---|
| Avoid collision with print | TRUE | RoboDK setting |
| Avoid collision with substrate | TRUE | RoboDK setting |
| Collision avoidance margin (mm) | 50 | |
| Z Hop | TRUE | Slicer setting |
| Z Hop height (mm) | 350 | Bounding box Z + 50 |

| Speed | | Note |
|---|---|---|
| Perimeter wall speed (mm/s) | | Lower |
| Infill wall speed (mm/s) | | Higher |
| Initial layer speed (mm/s) | | Lower |
| Final layer speed(mm/s) | | Lower |
| Average printing speed (mm/s) | 40 | |
| Extrusion speed (mm/s) | | Motor speed (NEMA23) |
| Compressor pressure (bar) | 4 | |

## Printer settings output

| Settings output | | Note |
|---|---|---|
| Printing time (min) | 41,66666667 | TRUE |
| Layer count | 300 | FALSE |
| Print sections required | 14,28571429 | |
| Bounding box X | TRUE | |
| Bounding box Y | TRUE | |
| Bounding box Z | TRUE | |
| Robot stationing coordinates | (x,y,z) | Middle |
| Length of toolpath (mm) | 100000 | |

## CAD file

| Print geometry | | Note |
|---|---|---|
| Volume (m^3) | 0,006 | |
| Mass (kg) | 6 | TRUE |
| Bounding box X (mm) | 500 | TRUE |
| Bounding box Y (mm) | 400 | TRUE |
| Bounding box Z (mm) | 300 | TRUE |
| XY plane area (m^2) | 0,2 | |
| | | |

## Robot specification

| Robot specs | | Note |
|---|---|---|
| UR5 | | |
| Max payload (kg) | 5 | |
| Reach X (mm) | 750 | |
| Reach Y (mm) | 750 | |
| Reach Z (mm) | 750 | |

## Nozzles

| Name | Width (mm) | Note |
|---|---|---|
| N1 | 3,25 | |
| N2 | 4,7 | |
| N3 | 5,5 | |
| N4 | 2,95 | |
| N5 | 1,75 | |
| N6 | 1 | |

## Material specifications

| Material specs | | Note |
|---|---|---|
| Bulk density (kg/m^3) | 1000 | |
| Shrinkage (%) | | |
| Buildable layers | 21 | |
| Min extrusion width (mm) | 1 | |
| Pumping pressure (bar) | 4 | |
| Open time (min) | 78 | |
| Adhesion fresh (1-5) | 5 | Excellent |
| Adhesion dry (kg) | 27 | TRUE |

## Crane

| Kite-11 specs | Value |
|---|---|
| Reach (mm) | 3320 |
| Weight (kg) | 24 |
| Payload (kg) | 25 |
| PWR (-) | 1,041666667 |
| DOF (-) | 3 |

## Nozzles

| Nozzle name | N1 | N2 | N3 | N4 | N5 |
|---|---|---|---|---|---|
| Diameter (mm) | 1,4 | 2,3 | 5,4 | 7 | 10 |
| Length (mm) | 45 | 82 | 36 | 37 | 85 |

## Extruder

| Printer specs | Value |
|---|---|
| Motor | NEMA23 |
| Power (A) | 4 |
| AC/DC | DC |
| Torque (kg/cm) | 12,85 |
| DEG | 1,85 |

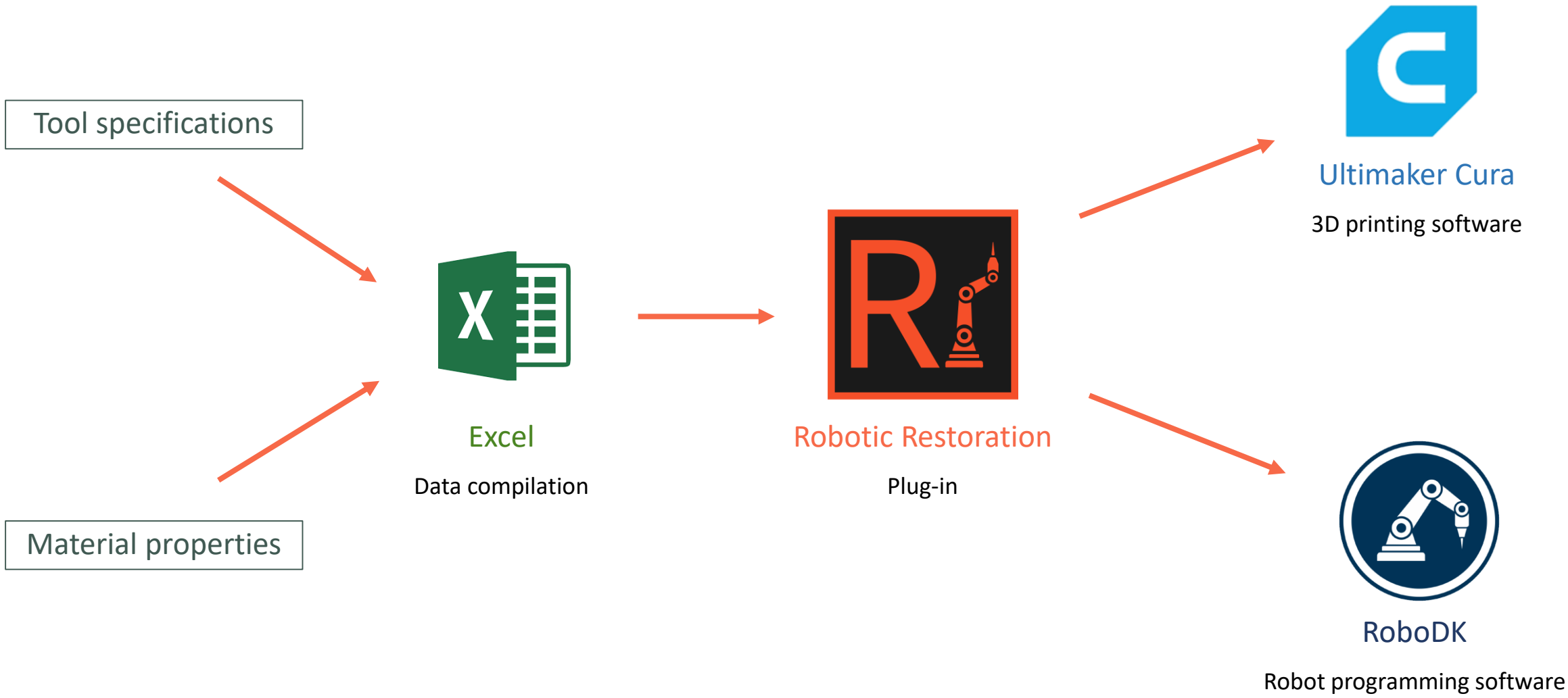
## Compressor

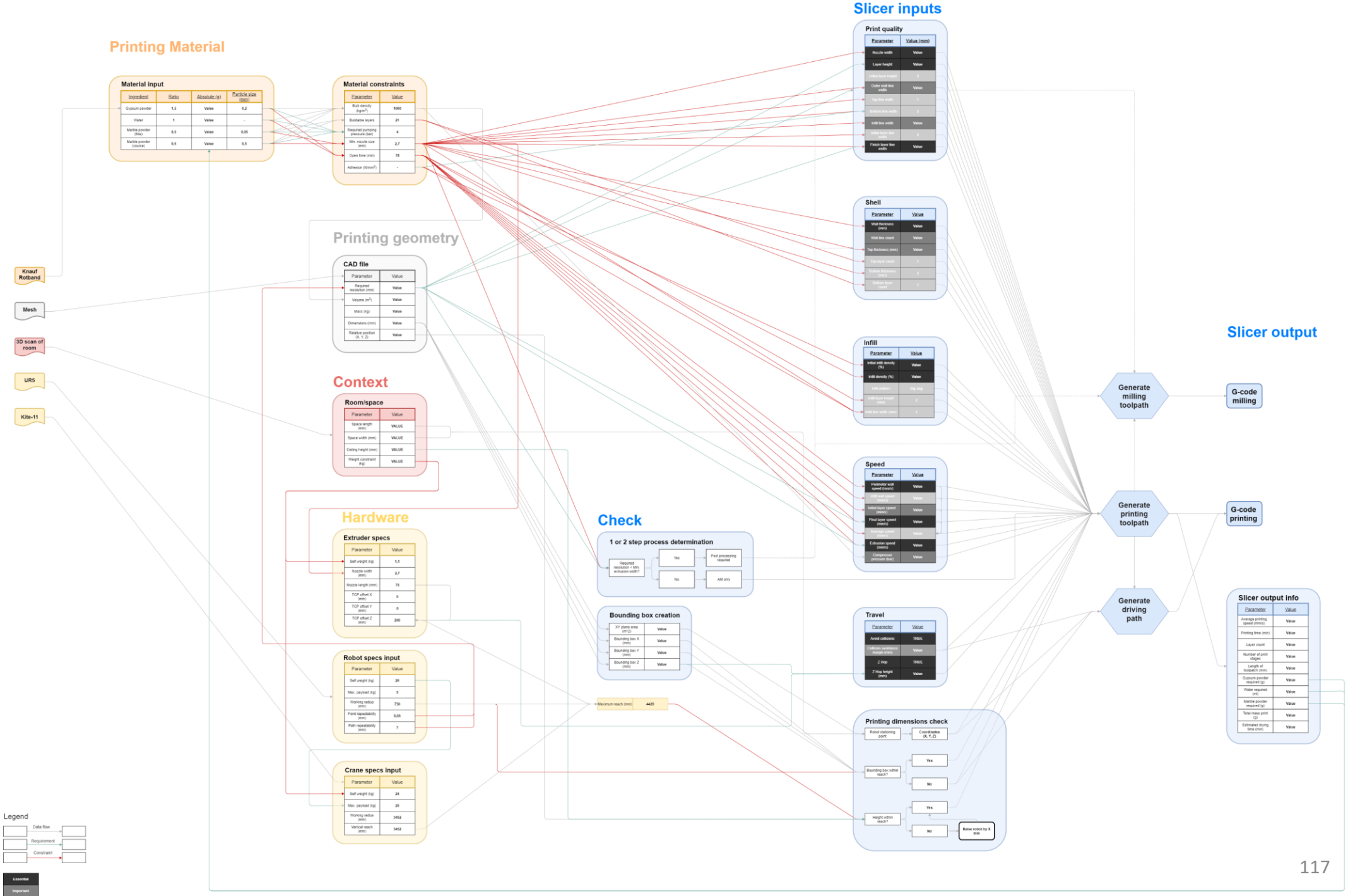
| Compressor specs | Value |
|---|---|
| Air output (L/min) | 45 |
| Power (PK) | 0,75 |
| Max pressure | 8 |
| Voltage (V) | 230 |
| Capacity (L) | 20 |
| Weight (kg) | 23 |

## Robot specification

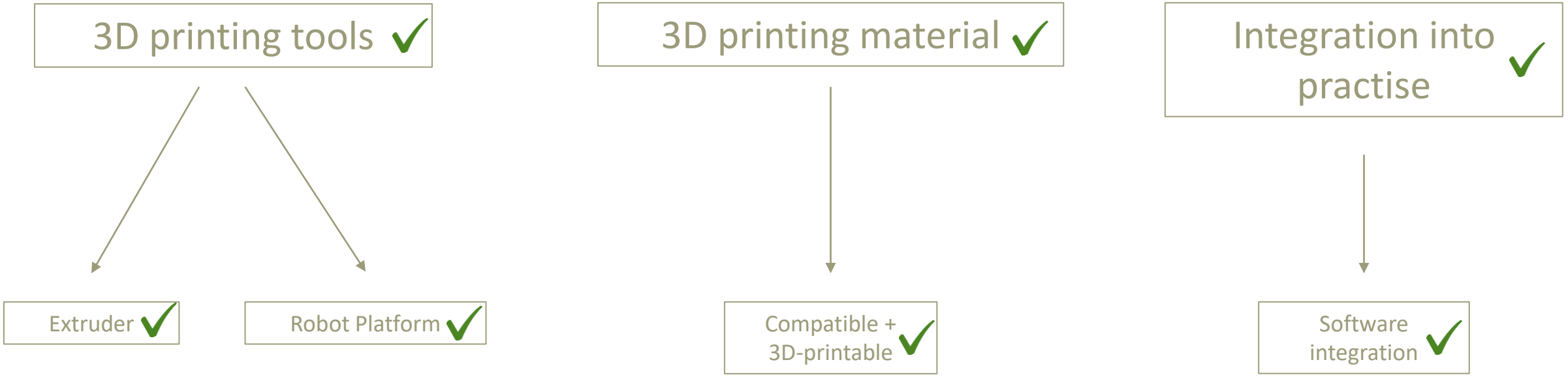
| UR5 specs | Value | Note |
|---|---|---|
| Brand | Universal Robots | |
| Type | 6 DOF | |
| Axes | 6 | |
| Weight | 20 | |
| Payload (kg) | 5 | |
| PWR (-) | 0,25 | |
| Reach Z (mm) | 750 | |
| Repeatability (mm) | 0,1 | |

# Software plug-in: Robotic Restoration

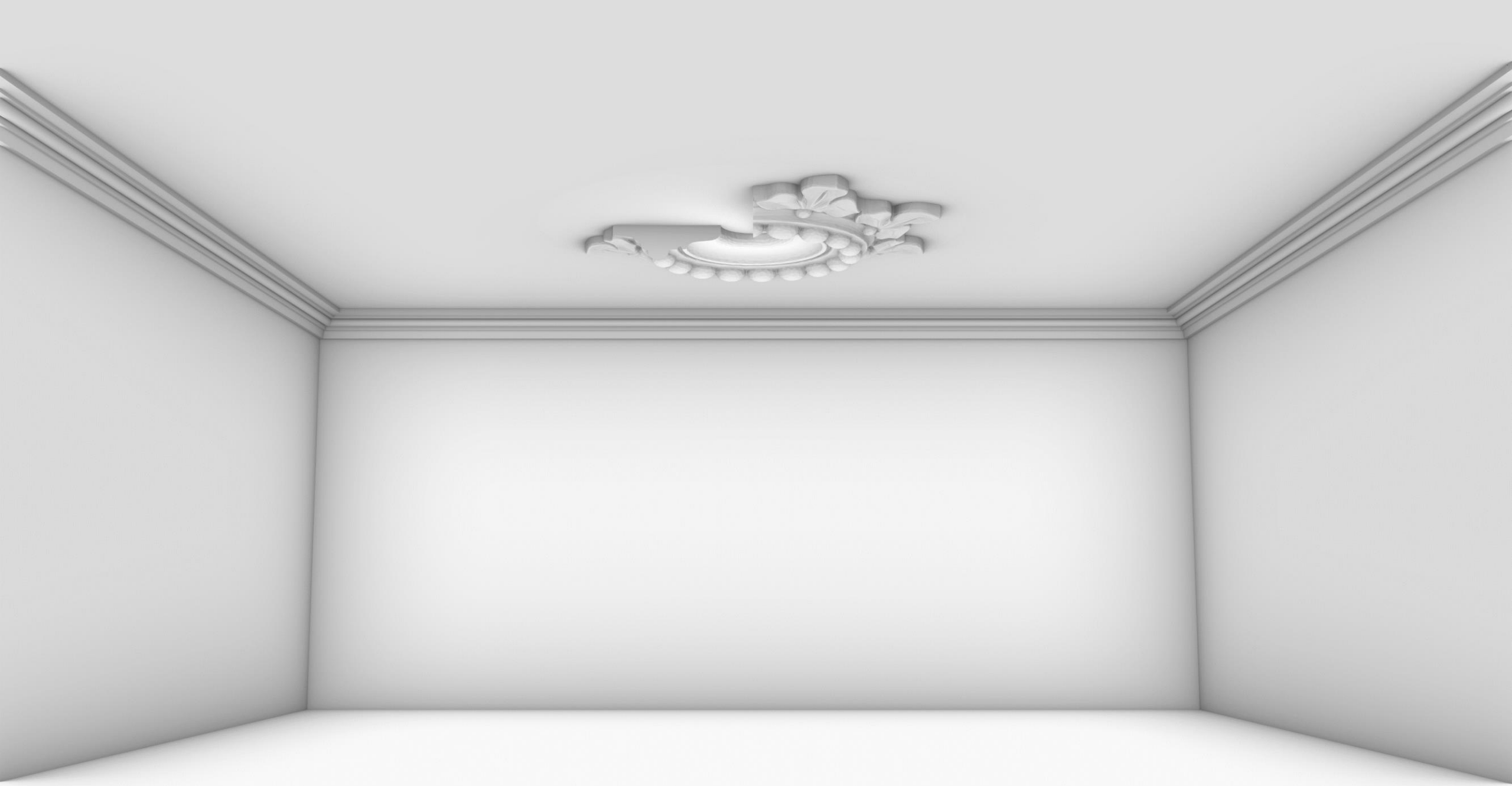



Printing Material
Material input
Material constraints
Printing geometry
CAD file
Knauf Rotband
Mesh
3D scan of room
UR5
Kite-11
Context
Room/space
Hardware
Extruder specs
Robot specs input
Crane specs input
Check
1 or 2 step process determination
Bounding box creation
Slicer inputs
Print quality
Shell
Infill
Speed
Travel
Printing dimensions check
Generate milling toolpath
Generate printing toolpath
Generate driving path
Slicer output
G-code milling
G-code printing
Slicer output info
Legend
Data flow
Requirement
Constraint
Essential
Important
Optional

# Objective


3D printing tools
3D printing material
Integration into practise
Extruder
Robot Platform
Compatible + 3D-printable
Software integration

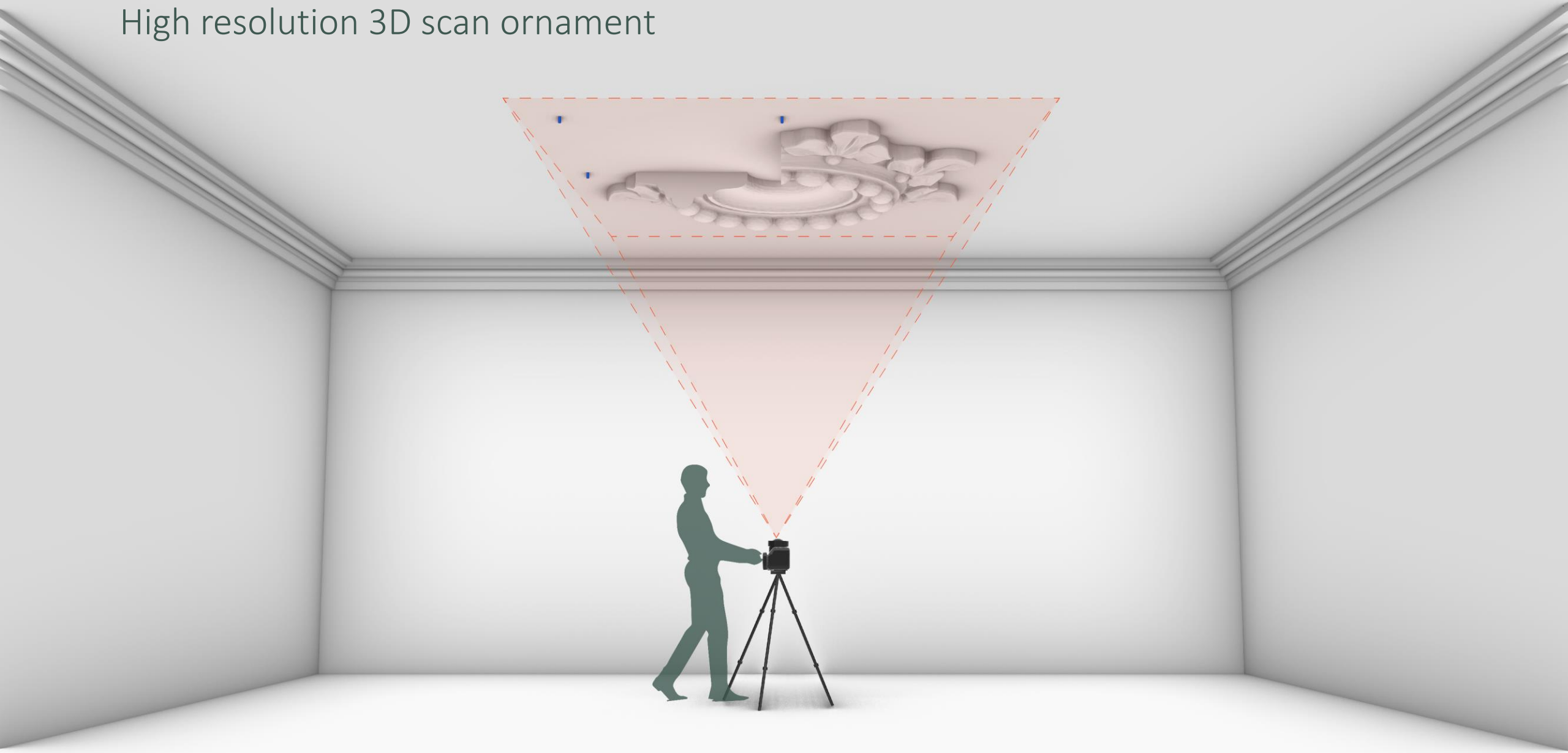
# Proposed New Restoration Method



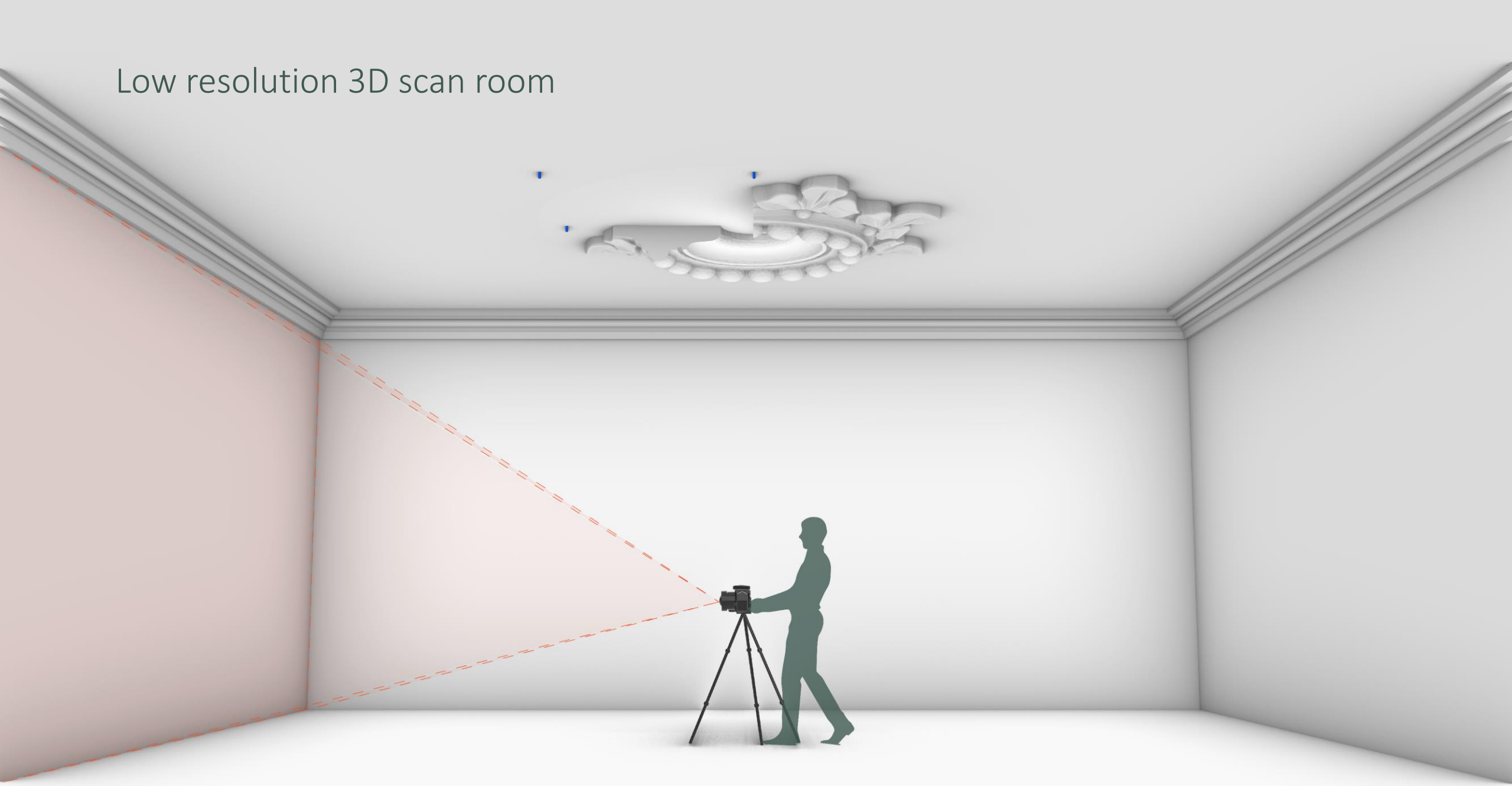
# Inspect damaged area

# Place reference markers

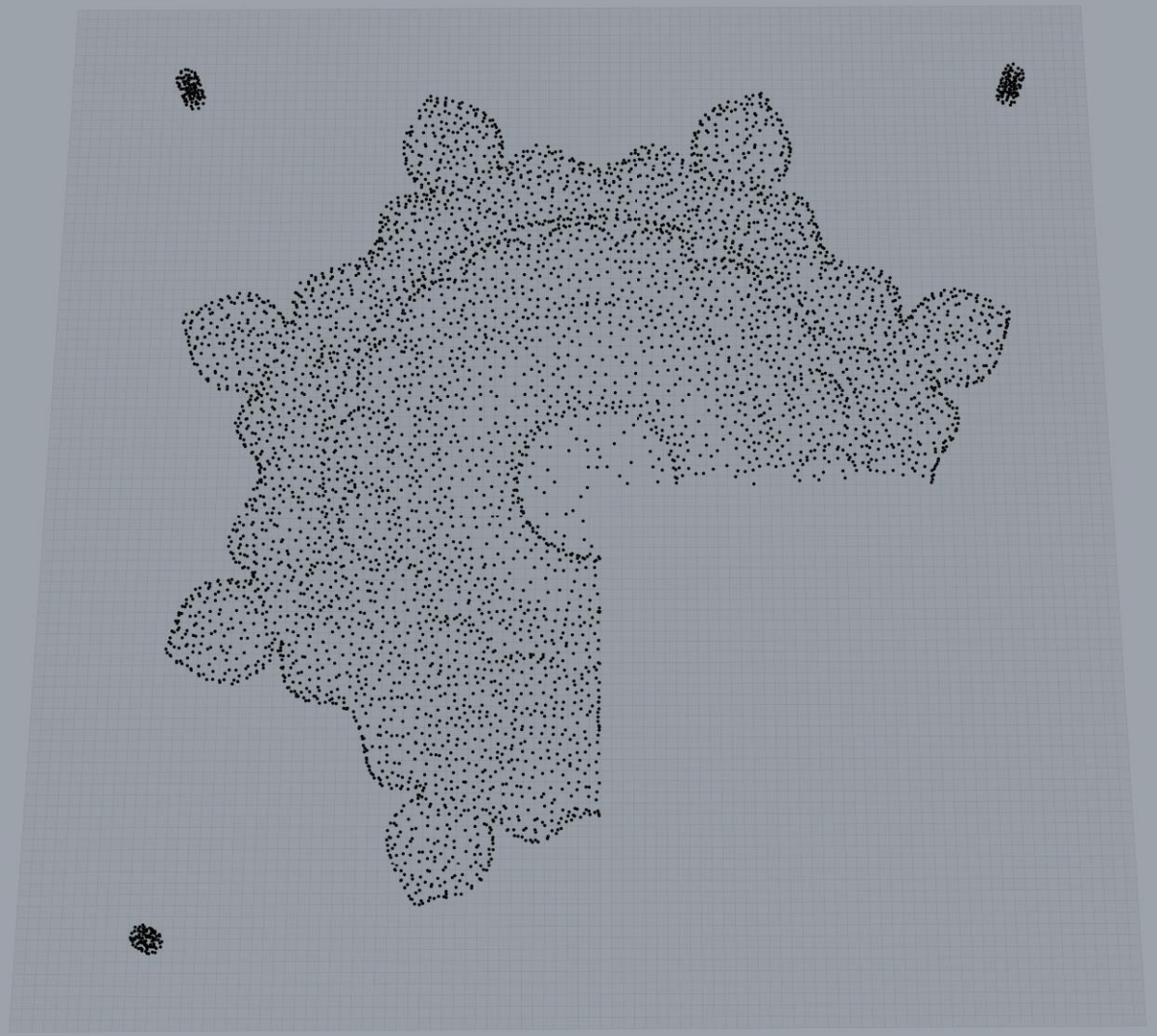
# High resolution 3D scan ornament



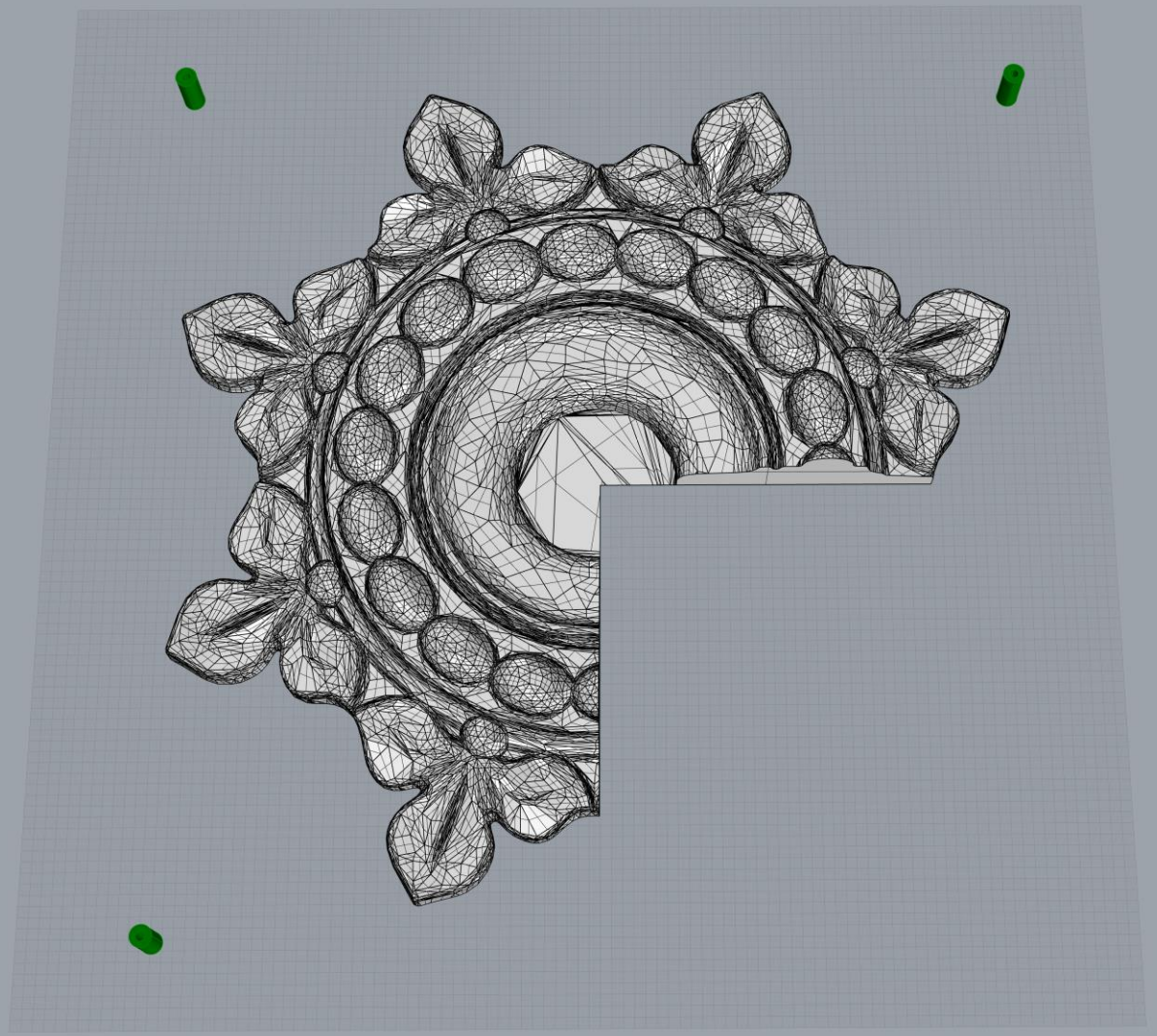
# Low resolution 3D scan room



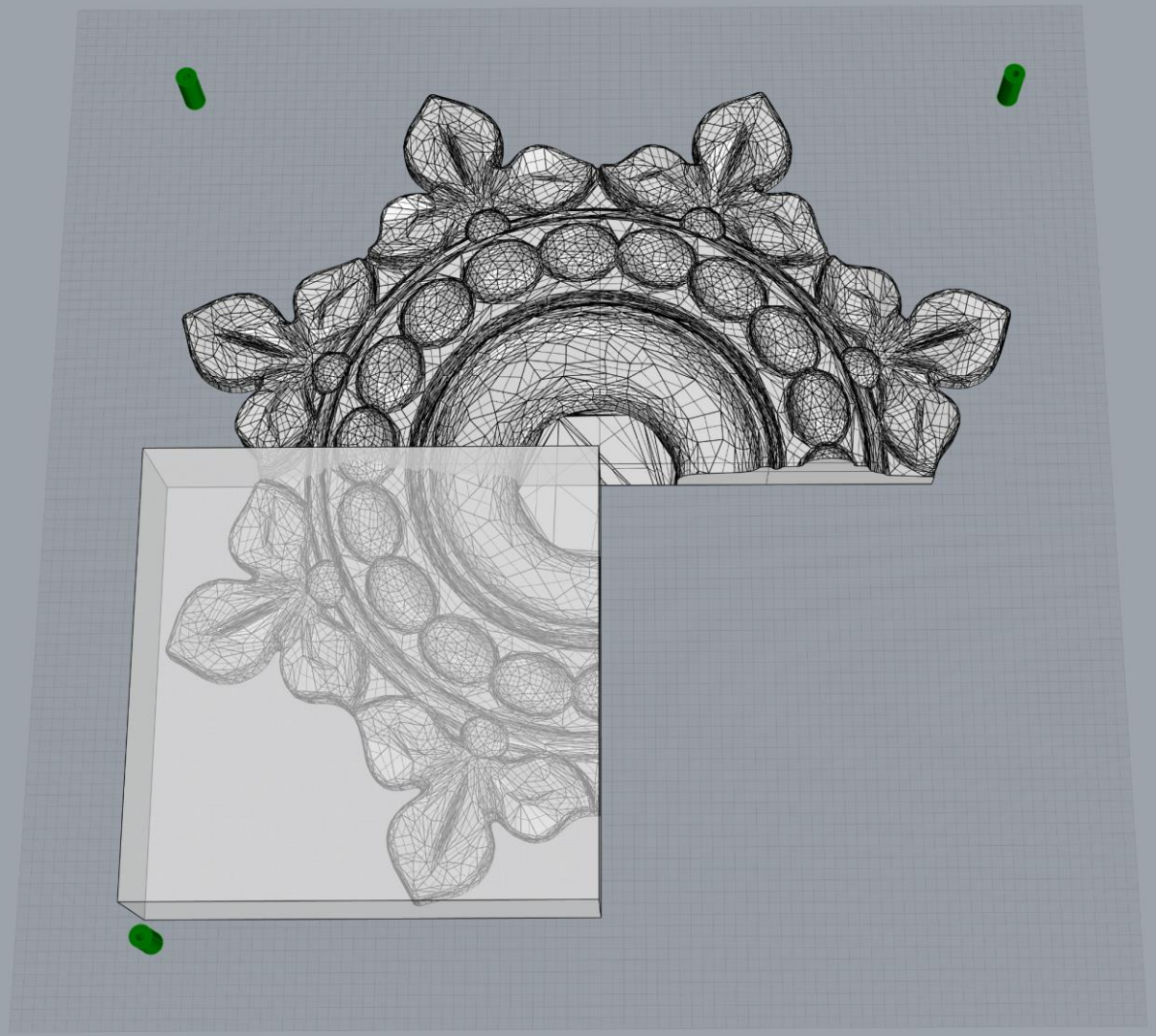
# Point cloud from 3D scan



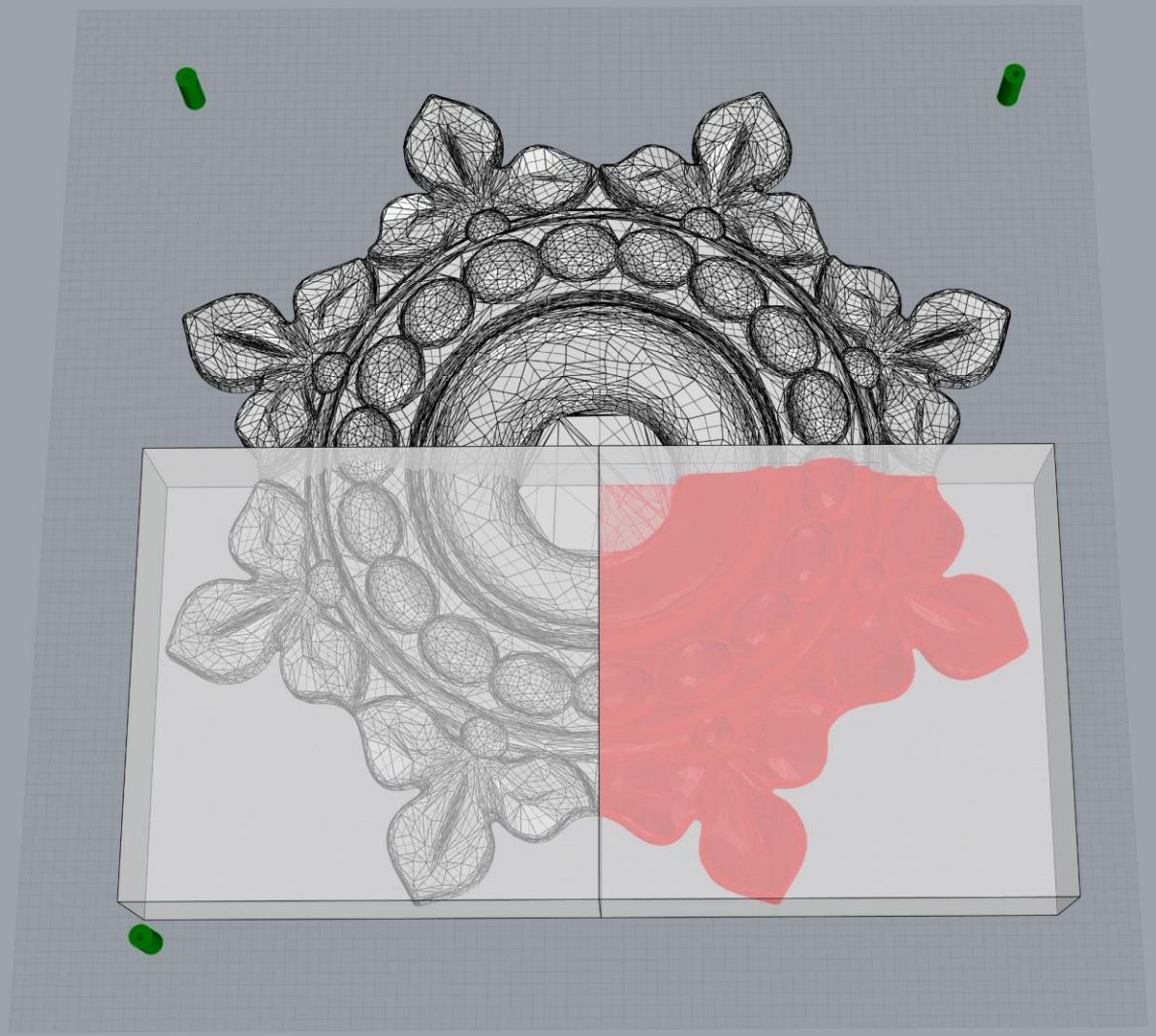
# Convert point cloud to mesh



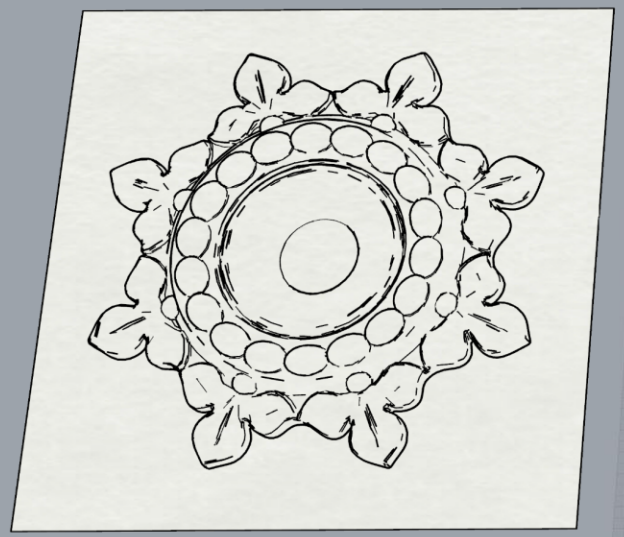
# Identify repeating elements

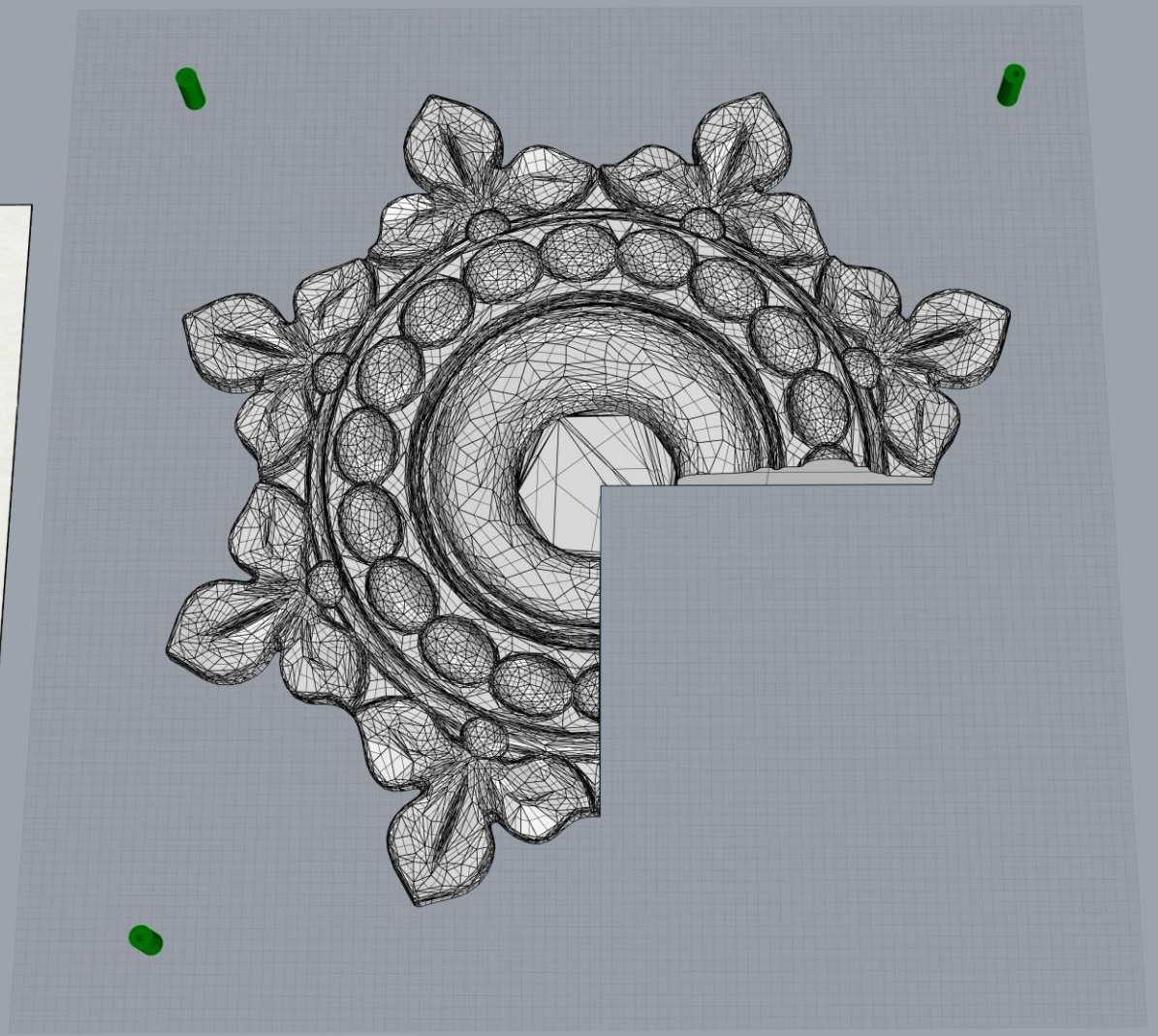


# Interpolate geometry

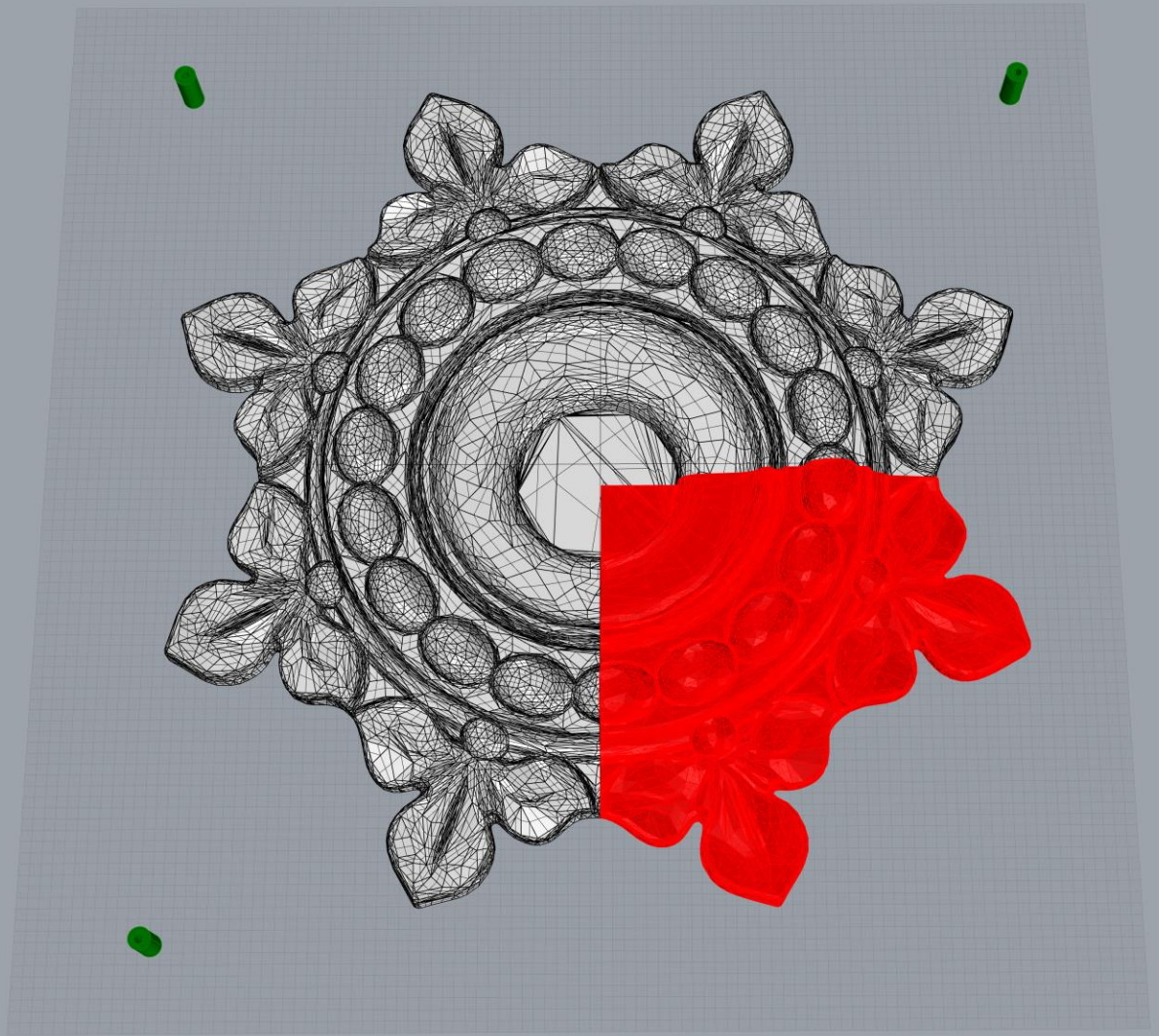


# Model using historic documentation

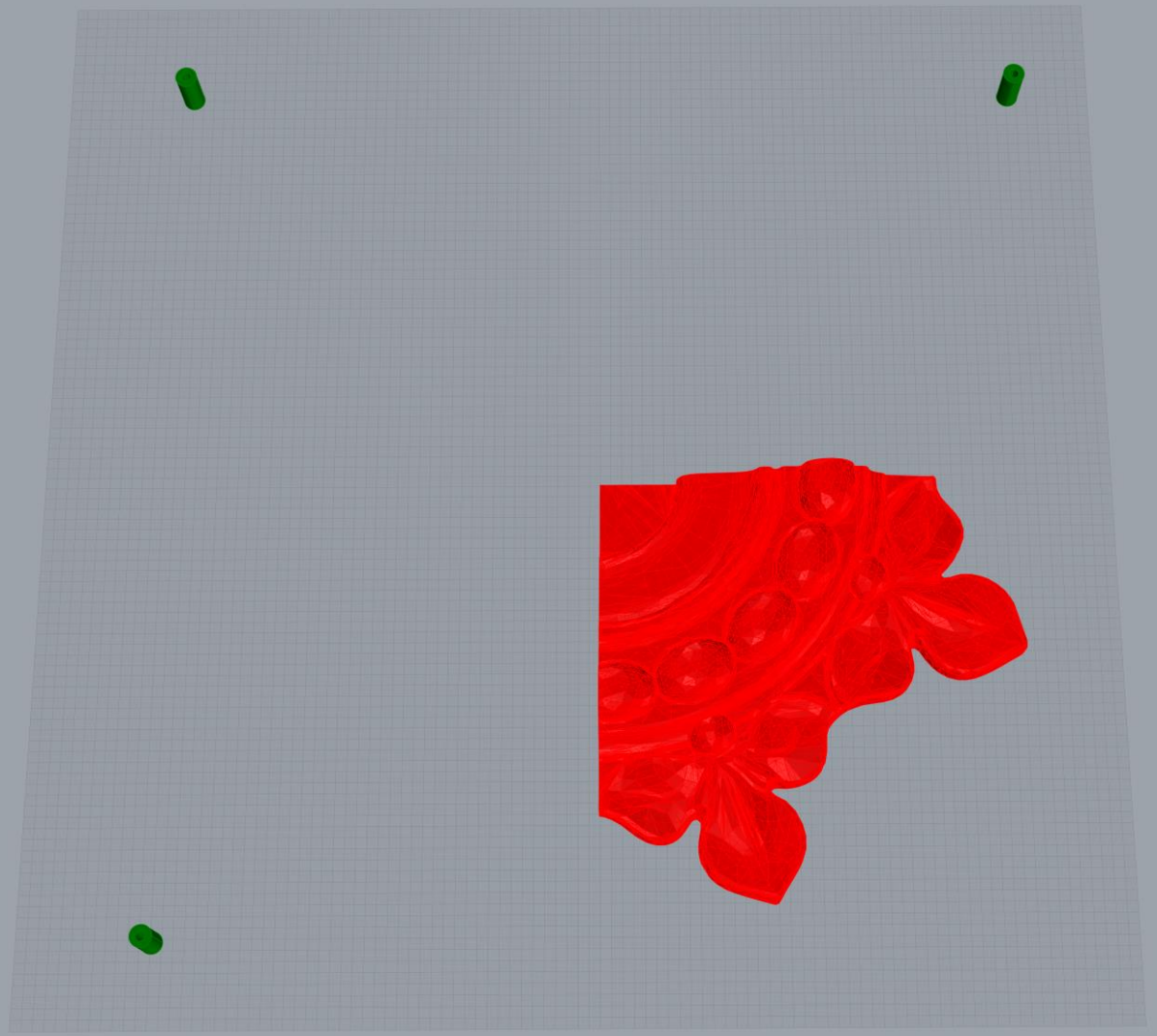




# Modelled missing geometry



# Convert CAD geometry to STL format



# Export STL-file to 3D printing software


**Rhinoceros**
3D modelling software

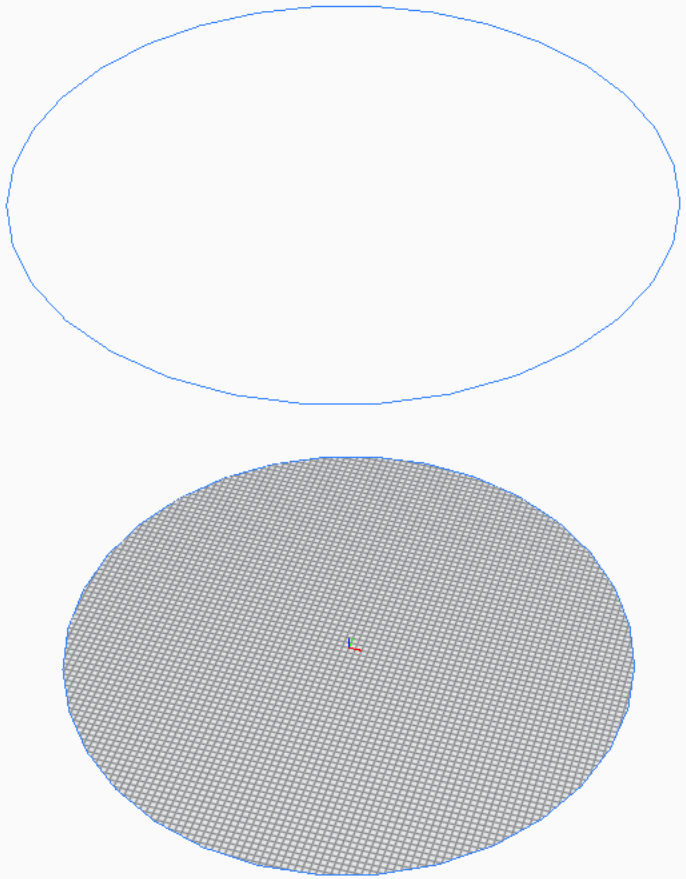
**Ultimaker Cura slicer**
3D printing software

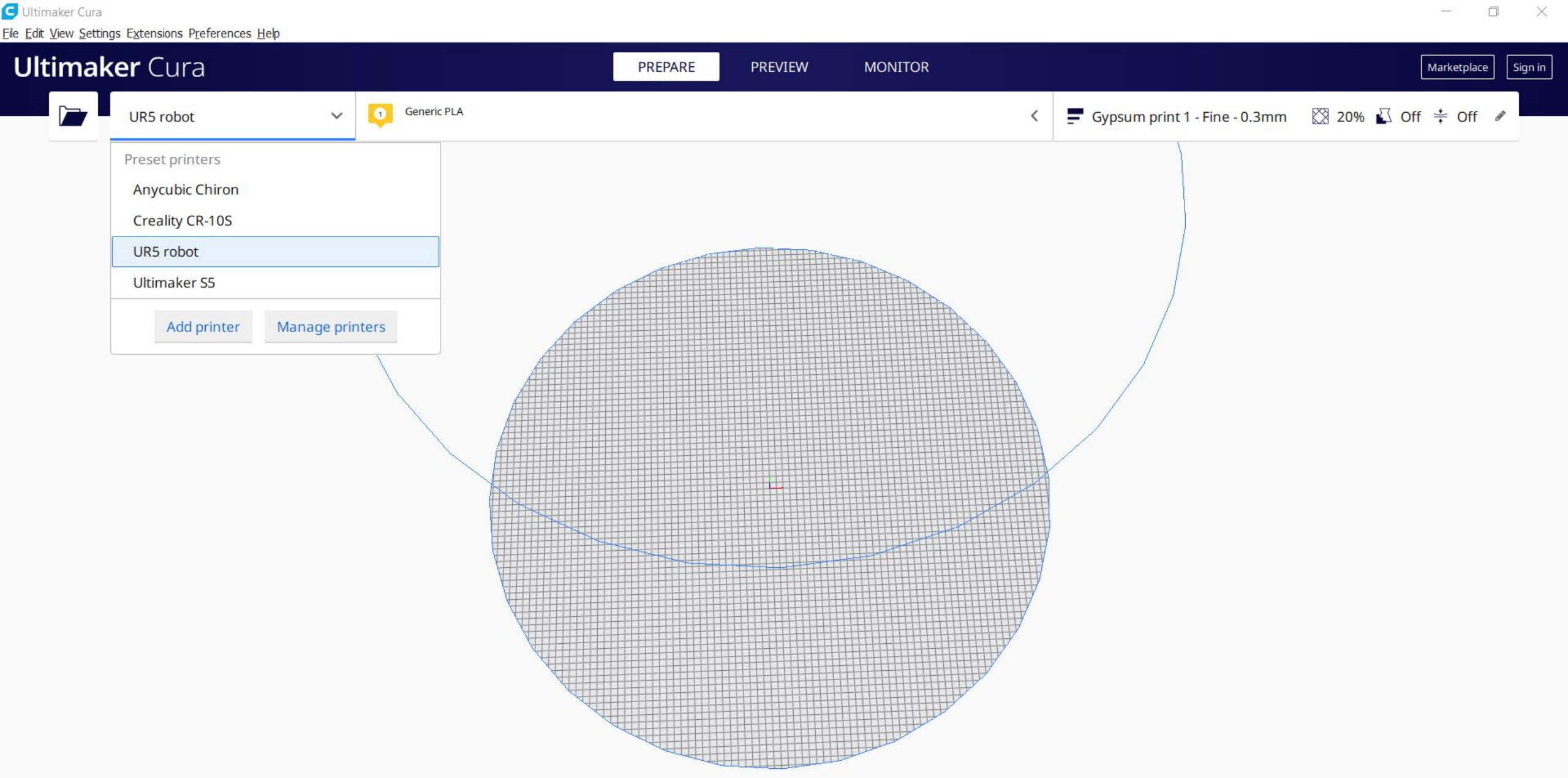
Ultimaker Cura

File Edit View Settings Extensions Preferences Help

Ultimaker Cura PREPARE PREVIEW MONITOR Marketplace Sign in

UR5 robot | Generic ABS | Gypsum print 1 - Fine - 0.5mm | 20% | Off | Off




Ultimaker Cura
File Edit View Settings Extensions Preferences Help
Ultimaker Cura
PREPARE
PREVIEW
MONITOR
Marketplace
Sign in
UR5 robot
Generic PLA
Gypsum print 1 - Fine - 0.3mm
20%
Off
Off
Preset printers
Anycubic Chiron
Creality CR-10S
UR5 robot
Ultimaker S5
Add printer
Manage printers

Ultimaker Cura

File Edit View Settings Extensions Preferences Help

Ultimaker Cura

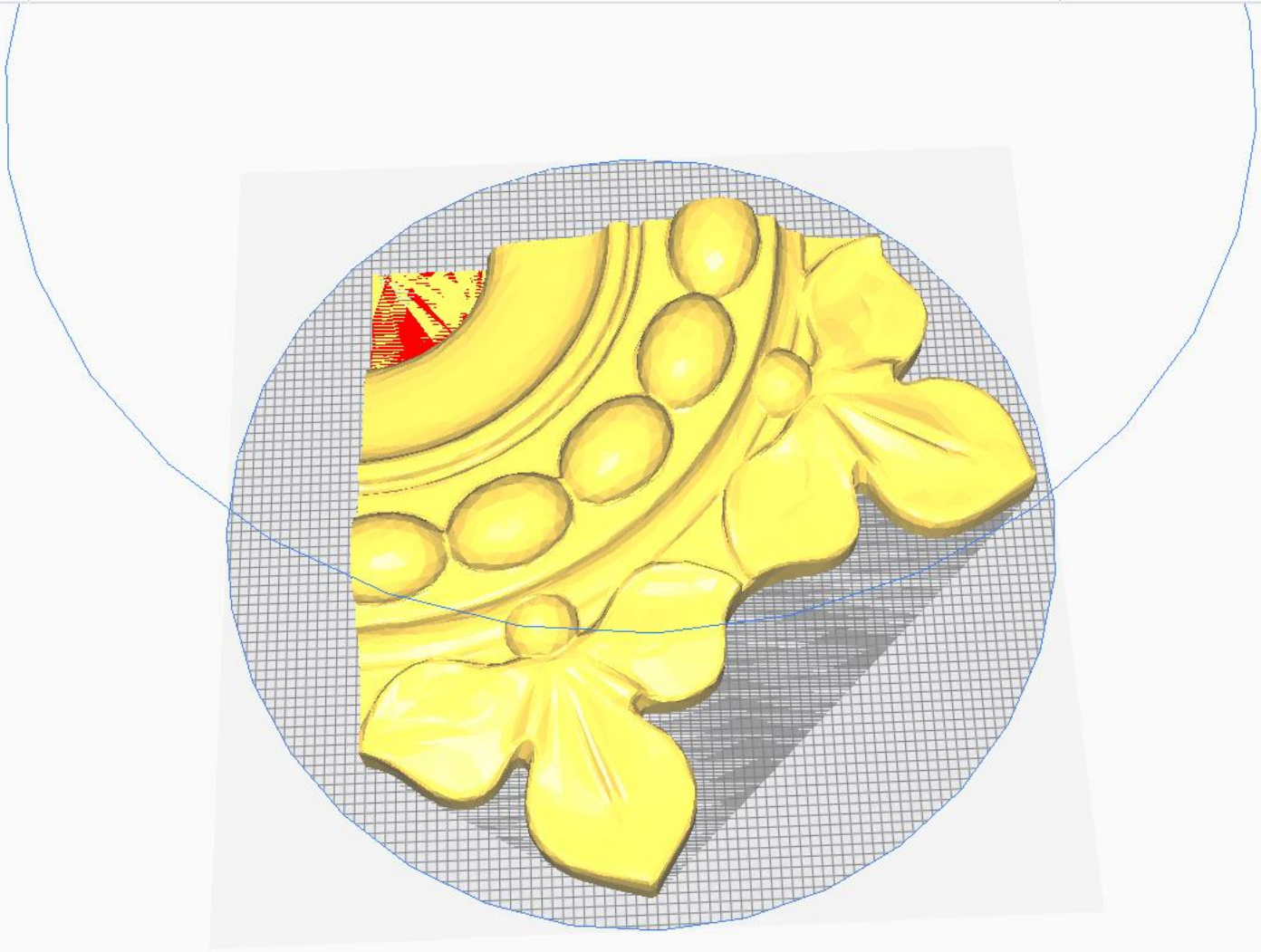
PREPARE PREVIEW MONITOR

Marketplace Sign in

UR5 robot

Generic PLA

Gypsum print 1 - Fine - 0.3mm 20% Off Off



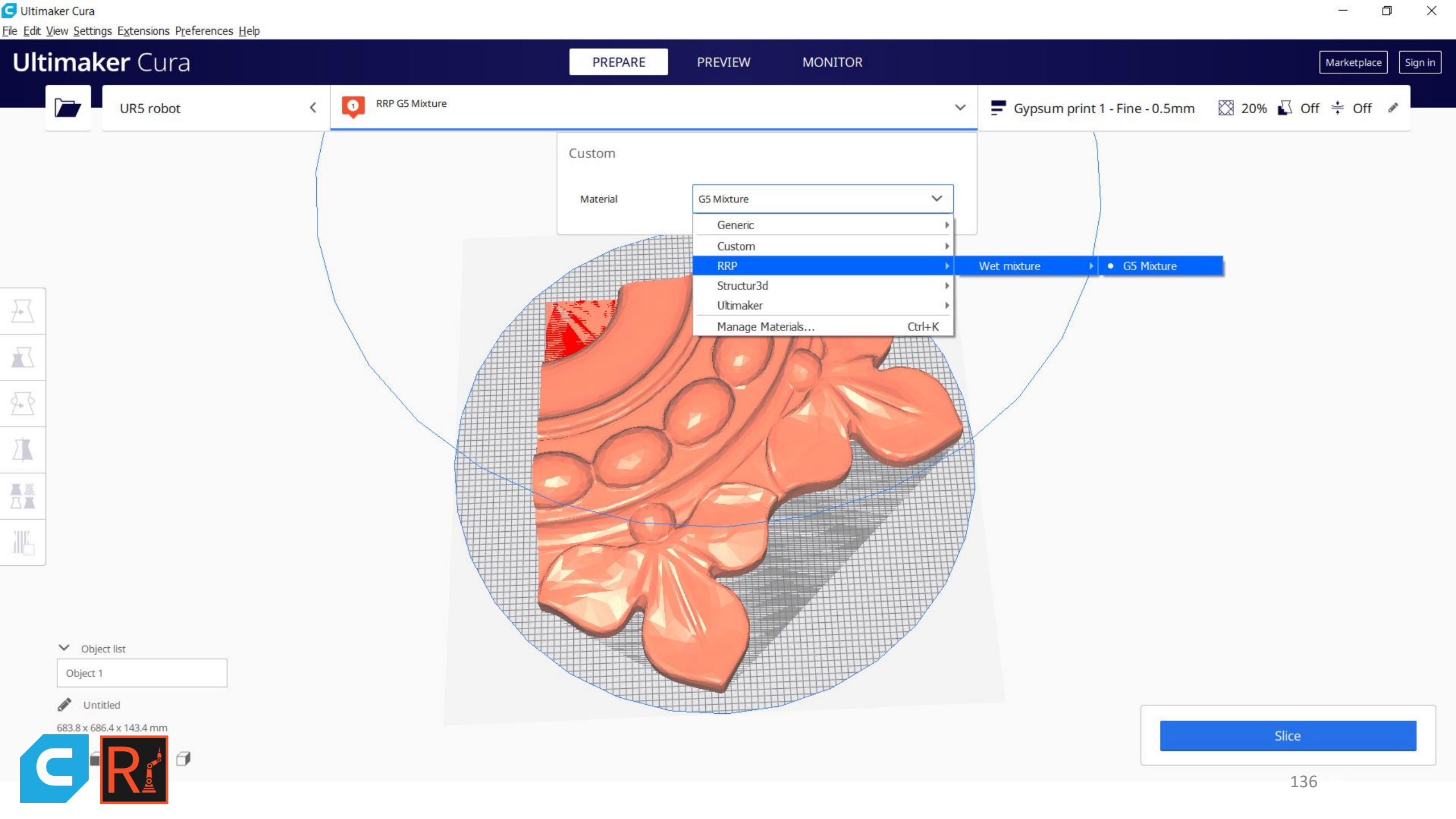
Object list

Object 1

Untitled

683.8 x 686.4 x 143.4 mm

Slice


Ultimaker Cura
File Edit View Settings Extensions Preferences Help
Ultimaker Cura
PREPARE
PREVIEW
MONITOR
Marketplace
Sign in
UR5 robot
RRP G5 Mixture
Gypsum print 1 - Fine - 0.5mm
20%
Off
Off
Custom
Material
G5 Mixture
Generic
Custom
RRP
Structur3d
Ultimaker
Manage Materials... Ctrl+K
Wet mixture
G5 Mixture
Object list
Object 1
Untitled
683.8 x 686.4 x 143.4 mm
Slice

Ultimaker Cura

File Edit View Settings Extensions Preferences Help

Ultimaker Cura

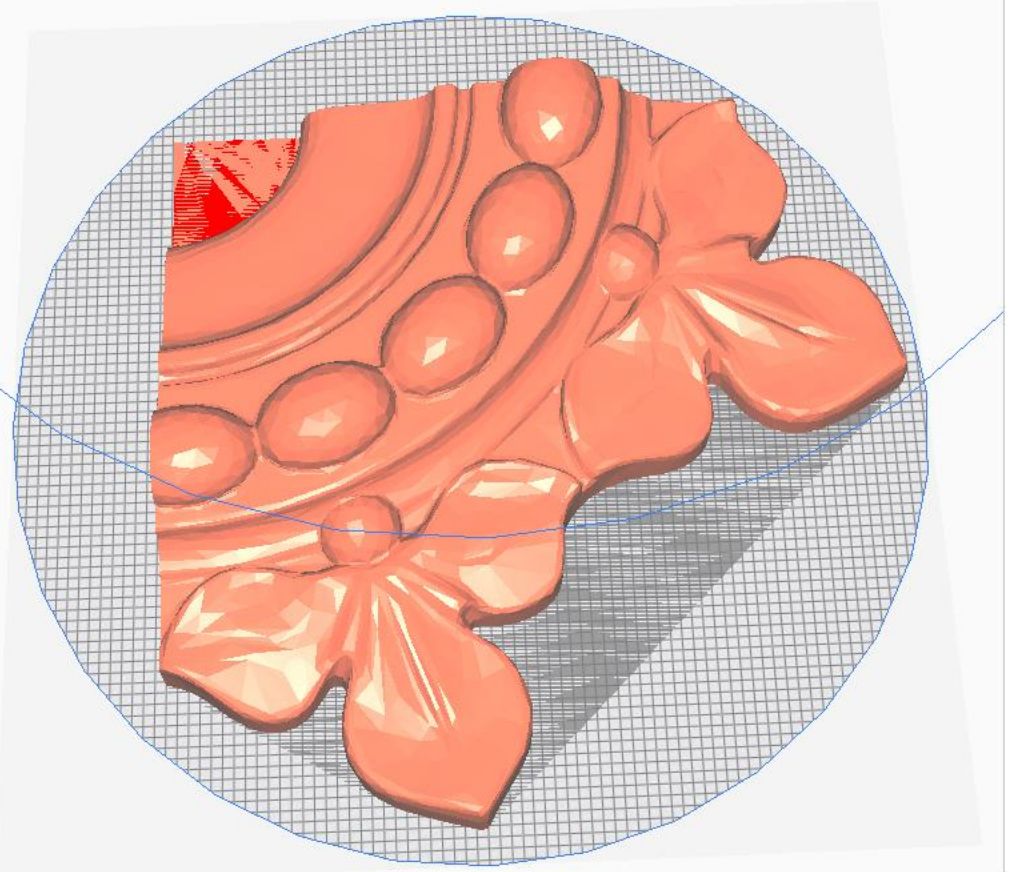
PREPARE PREVIEW MONITOR

Marketplace Sign in

UR5 robot

RRP G5 Mixture

Gypsum print 1 - Fine - 0.5mm 20% Off Off



Print settings

Profile: Gypsum print 1 - Fine - 0.3mm

Search settings

Quality

| | | |
|---|---|---|
| Layer Height | 0.5 | mm |
| Initial Layer Height | 0.5 | mm |
| Line Width | 1 | mm |
| Wall Line Width | 1 | mm |
| Outer Wall Line Width | 1 | mm |
| Inner Wall(s) Line Width | 1 | mm |

Shell

Infill

Material

Speed

Travel

Cooling

Support

Build Plate Adhesion

Dual Extrusion

Recommended

Object list

Object 1

Untitled

683.8 x 686.4 x 143.4 mm

Ultimaker Cura

File Edit View Settings Extensions Preferences Help

Ultimaker Cura

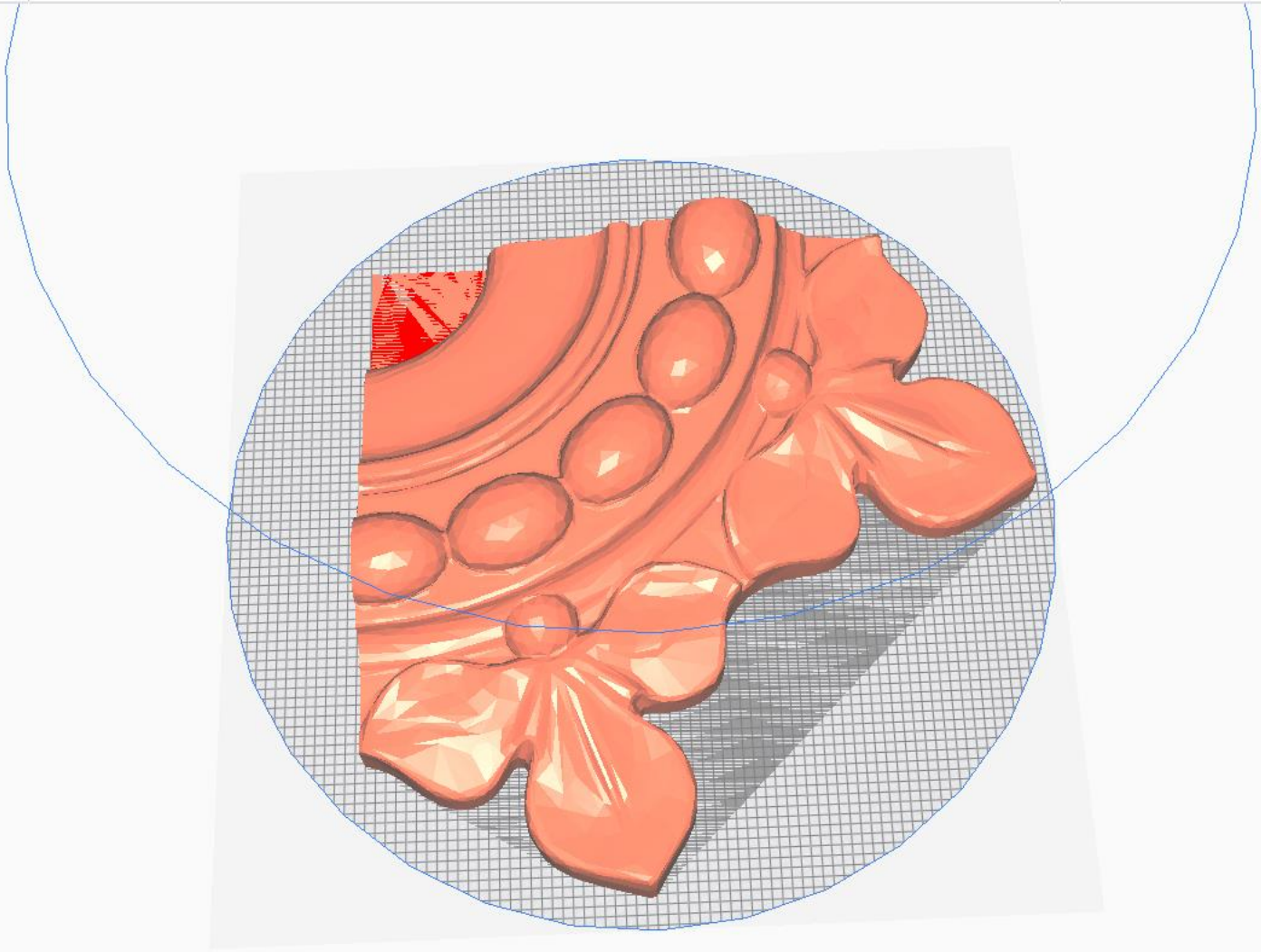
PREPARE PREVIEW MONITOR

Marketplace Sign in

UR5 robot

RRP G5 Mixture

Gypsum print 1 - Fine - 0.5mm 20% Off Off



Object list

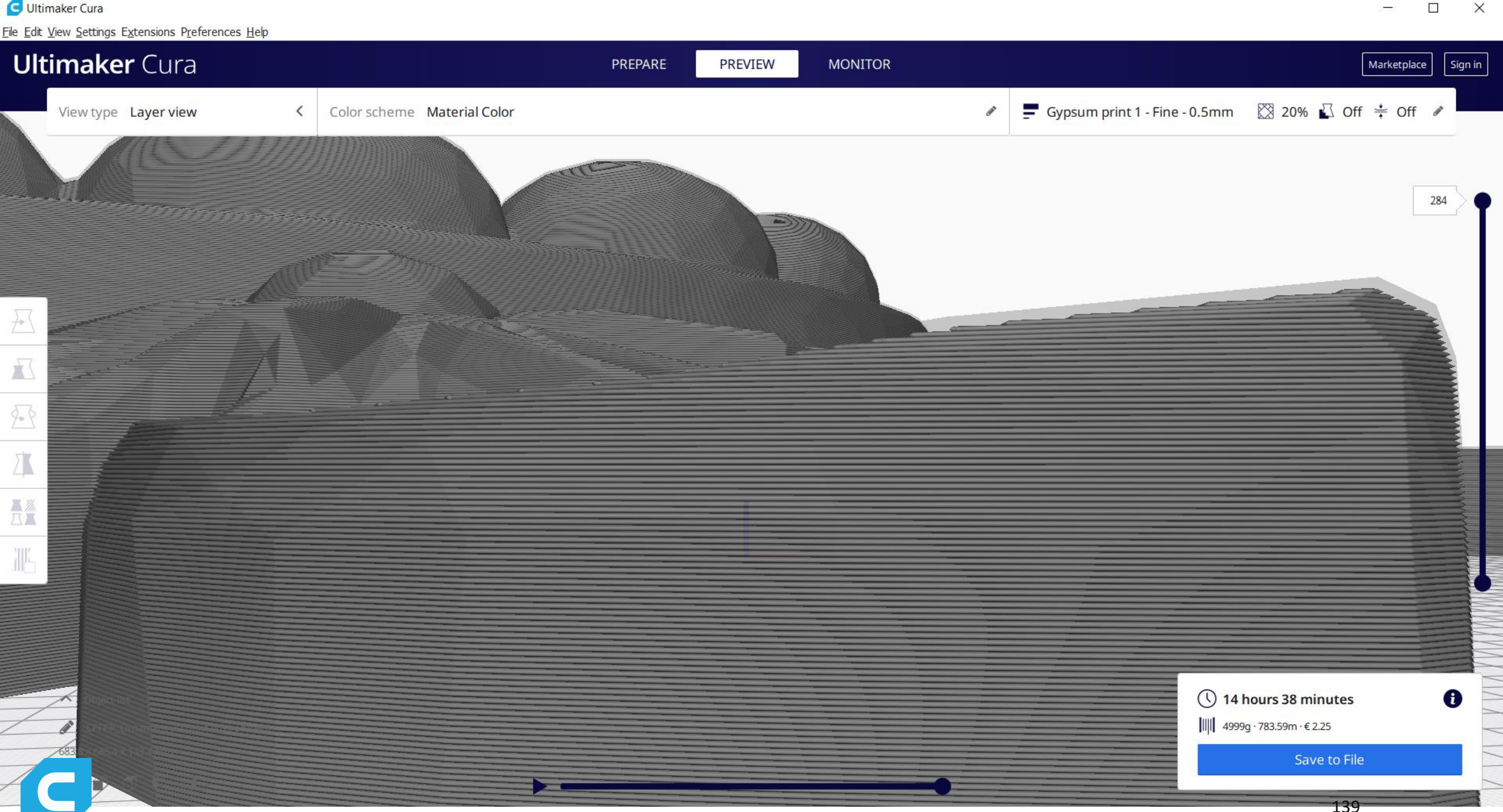
Object 1

Untitled

683.8 x 686.4 x 143.4 mm

Slicing...

Cancel


Ultimaker Cura
File Edit View Settings Extensions Preferences Help
Ultimaker Cura
PREPARE
PREVIEW
MONITOR
Marketplace
Sign in
View type Layer view
Color scheme Material Color
Gypsum print 1 - Fine - 0.5mm
20%
Off
Off
284
14 hours 38 minutes
4999g · 783.59m · € 2.25
Save to File

Ultimaker Cura

File Edit View Settings Extensions Preferences Help

Ultimaker Cura

PREPARE | PREVIEW | MONITOR

Marketplace | Sign in

View type Layer view | Color scheme Material Color | Gypsum print 1 - Fine - 0.5mm | 20% | Off | Off

284

Object list

Object 1

Untitled

683.8 x 686.4 x 143.4 mm

14 hours 38 minutes

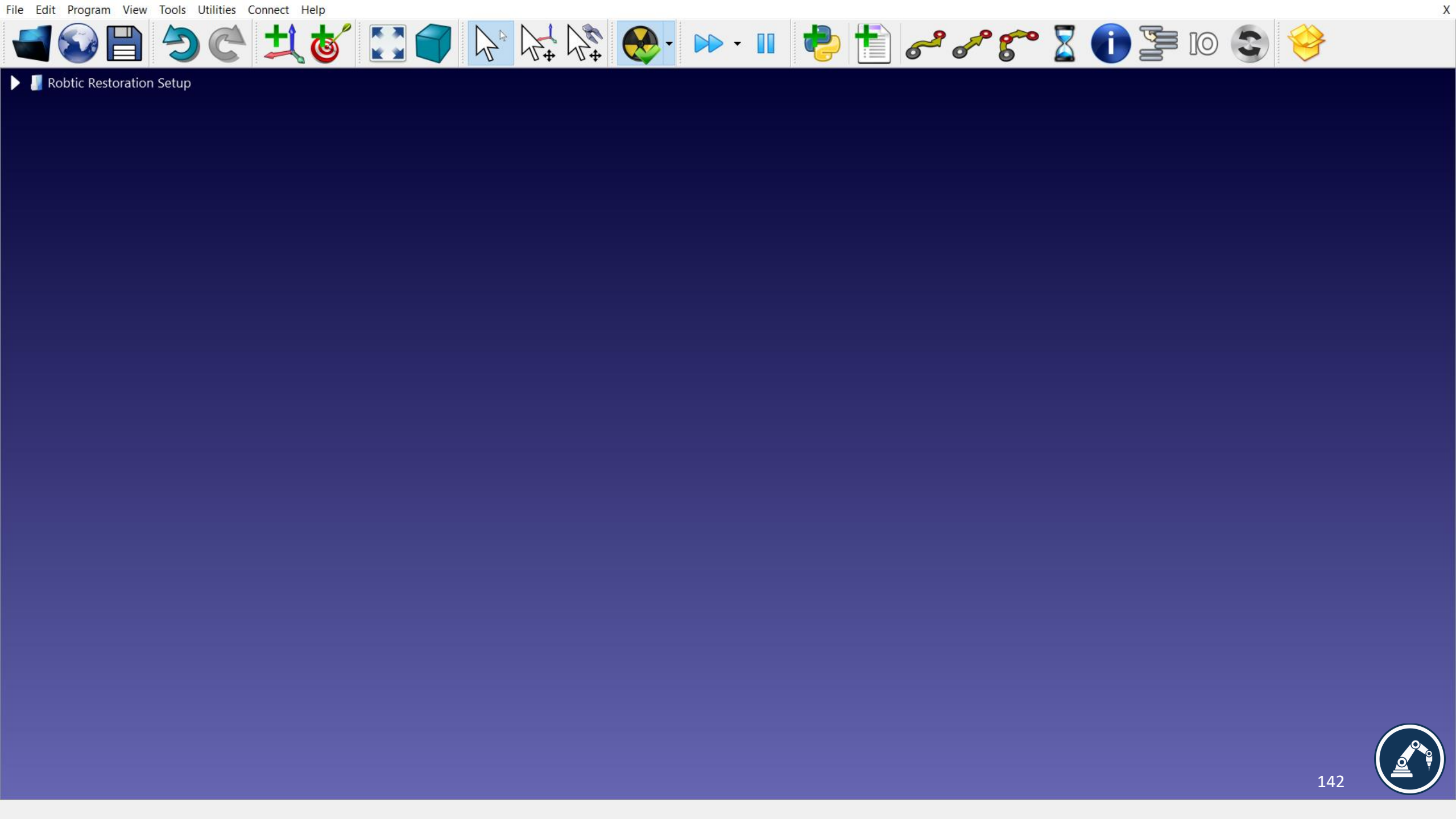
5000g · 783.73m · € 2.25

Save to File

# Export 3D printing instructions (G-code) to Robot programming software

**Ultimaker Cura slicer**
3D printing software

**RoboDK**
Robot programming & simulation software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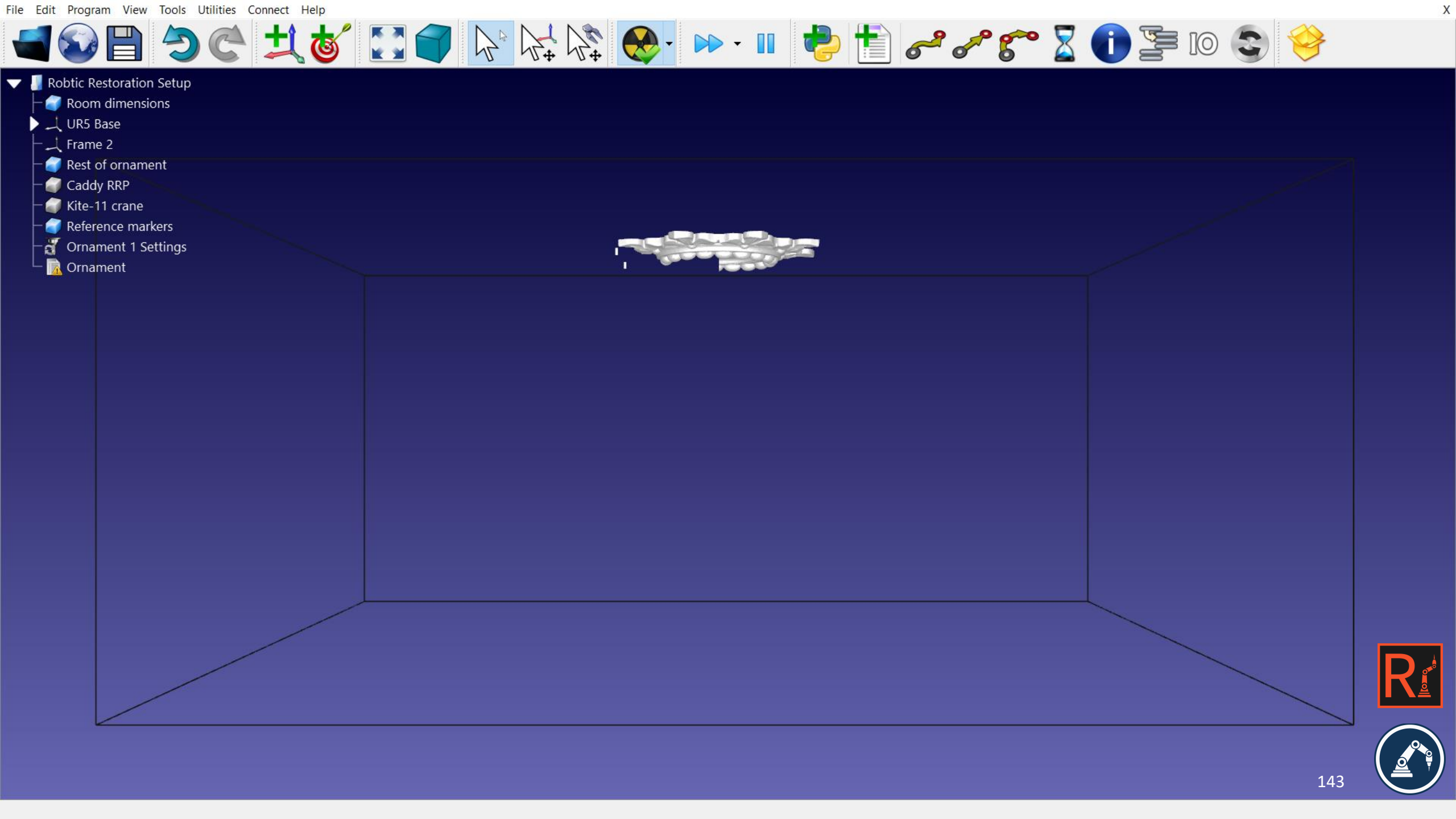
X
Robtic Restoration Setup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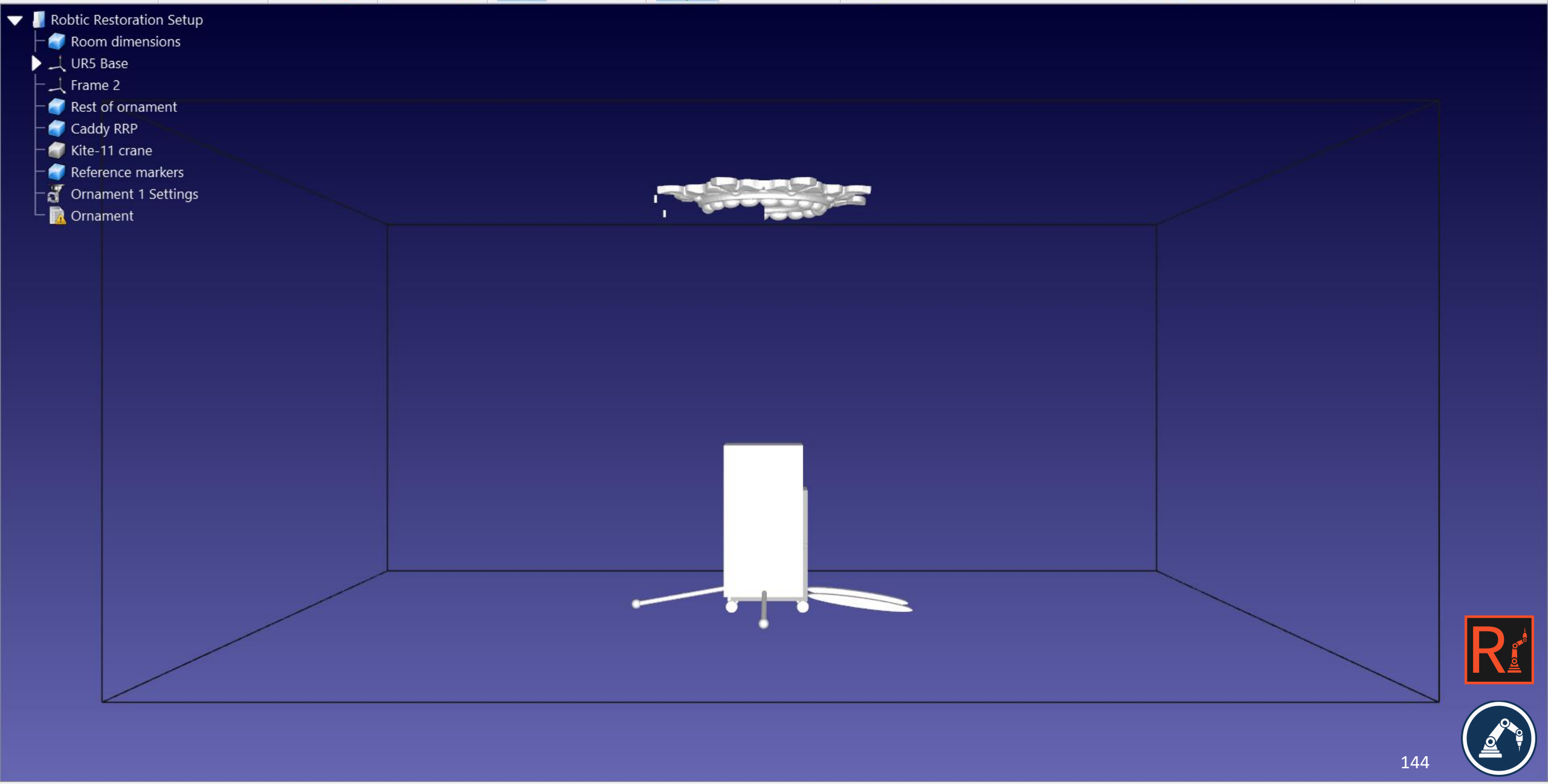
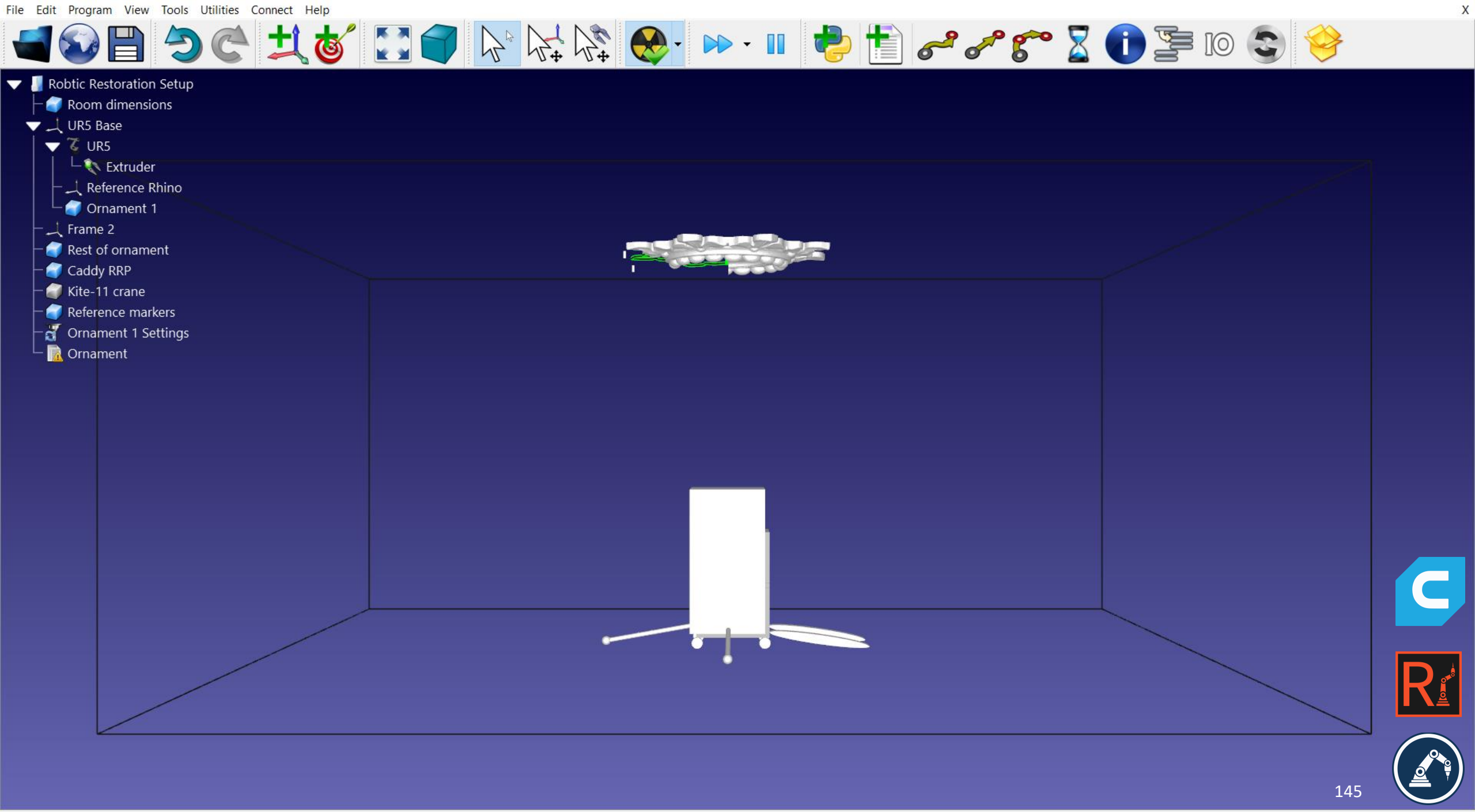
X
Robtic Restoration Setup
Room dimensions
UR5 Base
Frame 2
Rest of ornament
Caddy RRP
Kite-11 crane
Reference markers
Ornament 1 Settings
Ornament

File Edit Program View Tools Utilities Connect Help X




File Edit Program View Tools Utilities Connect Help
X
Robtic Restoration Setup
Room dimensions
UR5 Base
UR5
Extruder
Reference Rhino
Ornament 1
Frame 2
Rest of ornament
Caddy RRP
Kite-11 crane
Reference markers
Ornament 1 Settings
Ornament

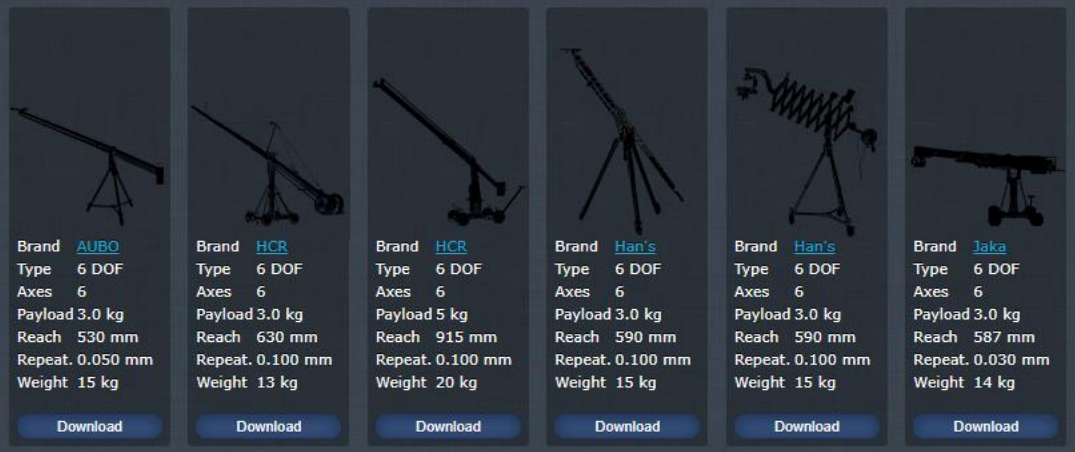
File Edit Program View Tools Utilities Connect Help

Online Library

# Crane library

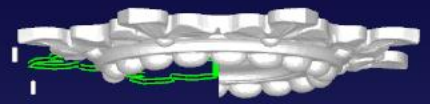
Brand ▾ ➤Type ▾ ➤Axes ▾ ➤Payload ▾ ➤Reach ▾ ➤Weight ▾

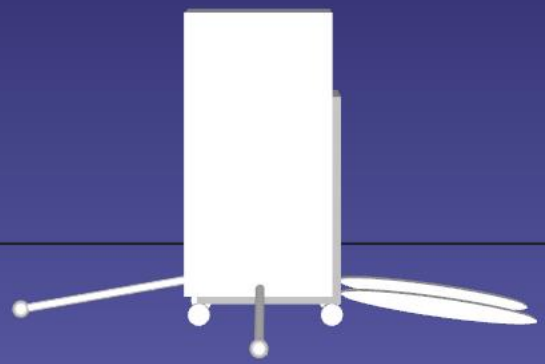
Reset filter



| Brand | AUBO | HCR | HCR | Han's | Han's | Jaka |
|---|---|---|---|---|---|---|
| Type | 6 DOF | 6 DOF | 6 DOF | 6 DOF | 6 DOF | 6 DOF |
| Axes | 6 | 6 | 6 | 6 | 6 | 6 |
| Payload | 3.0 kg | 3.0 kg | 5 kg | 3.0 kg | 3.0 kg | 3.0 kg |
| Reach | 530 mm | 630 mm | 915 mm | 590 mm | 590 mm | 587 mm |
| Repeat. | 0.050 mm | 0.100 mm | 0.100 mm | 0.100 mm | 0.100 mm | 0.030 mm |
| Weight | 15 kg | 13 kg | 20 kg | 15 kg | 15 kg | 14 kg |
| | Download | Download | Download | Download | Download | Download |

- Robtic Restoration Setup
  - Room dimensions
  - UR5 Base
    - UR5
      - Extruder
    - Reference Rhino
    - Ornament 1
  - Frame 2
  - Rest of ornament
  - Caddy RRP
  - Kite-11 crane
  - Reference markers
  - Ornament 1 Settings
  - Ornament





File Edit Program View Tools Utilities Connect Help

Online Library

Repeat. 0.050 mm
Weight 15 kg
Download

Repeat. 0.020 mm
Weight 15 kg
Download

Repeat. 0.100 mm
Weight 13 kg
Download

Repeat. 0.100 mm
Weight 20 kg
Download

Repeat. 0.100 mm
Weight 15 kg
Download

Repeat. 0.100 mm
Weight 15 kg
Download

**Jaka Zu3**

Brand Jaka
Type 6 DOF
Axes 6
Payload 3.0 kg
Reach 587 mm
Repeat. 0.030 mm
Weight 14 kg
Download

**Kawasaki FS03N**

Brand Kawasaki
Type 6 DOF
Axes 6
Payload 3.0 kg
Reach 620 mm
Repeat. 0.050 mm
Weight 20 kg
Download

**Kawasaki RS03N**

Brand Kawasaki
Type 6 DOF
Axes 6
Payload 3.0 kg
Reach 620 mm
Repeat. 0.020 mm
Weight 20 kg
Download

**Mitsubishi RV-2AJ**

Brand Mitsubishi
Type 6 DOF
Axes 6
Payload 2.0 kg
Reach 410 mm
Repeat. 0.020 mm
Weight 17 kg
Download

**Toshiba TV800**

Brand other
Type 6 DOF
Axes 6
Payload 3.0 kg
Reach 892 mm
Repeat. 0.020 mm
Weight 20 kg
Download

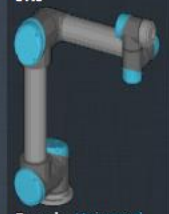
**UR3**

Brand Universal Robots
Type 6 DOF
Axes 6
Payload 3.0 kg
Reach 500 mm
Repeat. 0.100 mm
Weight 11 kg
Download

**UR3e**

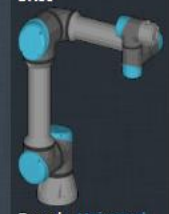
Brand Universal Robots
Type 6 DOF
Axes 6
Payload 3.0 kg
Reach 500 mm
Repeat. 0.030 mm
Weight 11 kg
Download

**UR5**



Brand Universal Robots
Type 6 DOF
Axes 6
Payload 5 kg
Reach 850 mm
Repeat. 0.100 mm
Weight 18 kg
Download

**UR5e**



Brand Universal Robots
Type 6 DOF
Axes 6
Payload 5 kg
Reach 850 mm
Repeat. 0.030 mm
Weight 18 kg
Download

- Robtic Restoration Setup
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    - UR5
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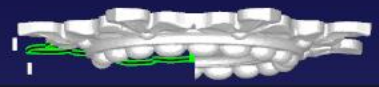

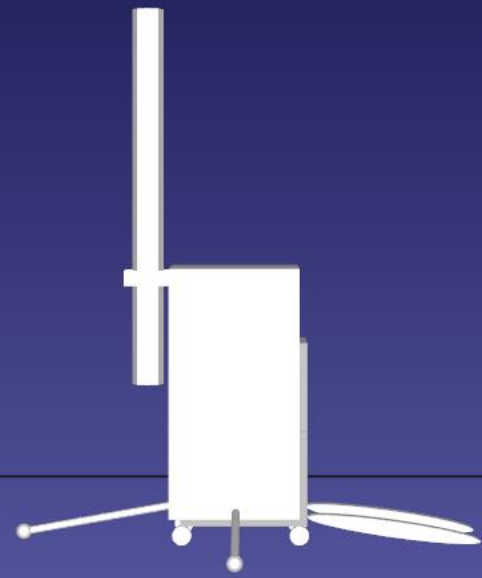

File Edit Program View Tools Utilities Connect Help X

- Robtic Restoration Setup
  - Room dimensions
  - UR5 Base
    - UR5
      - Extruder
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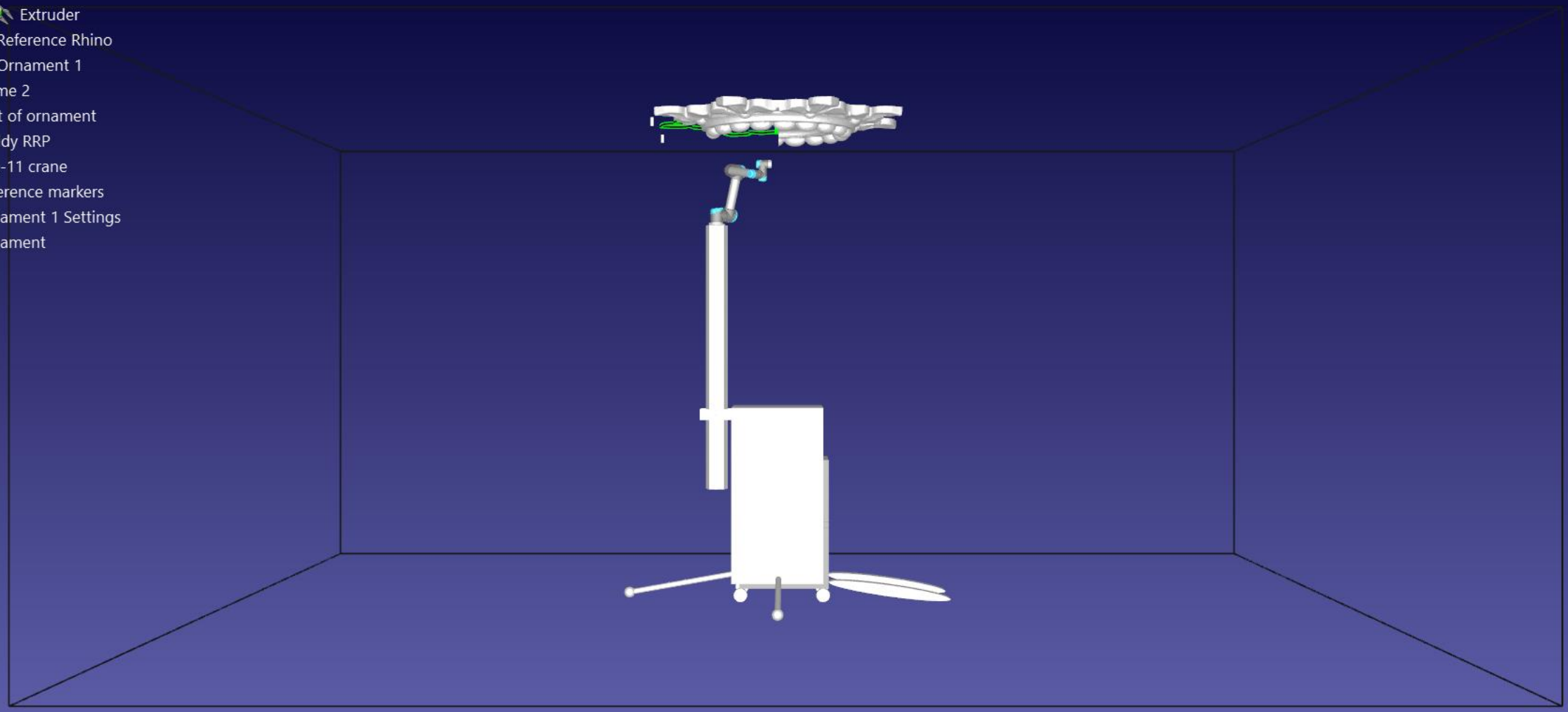

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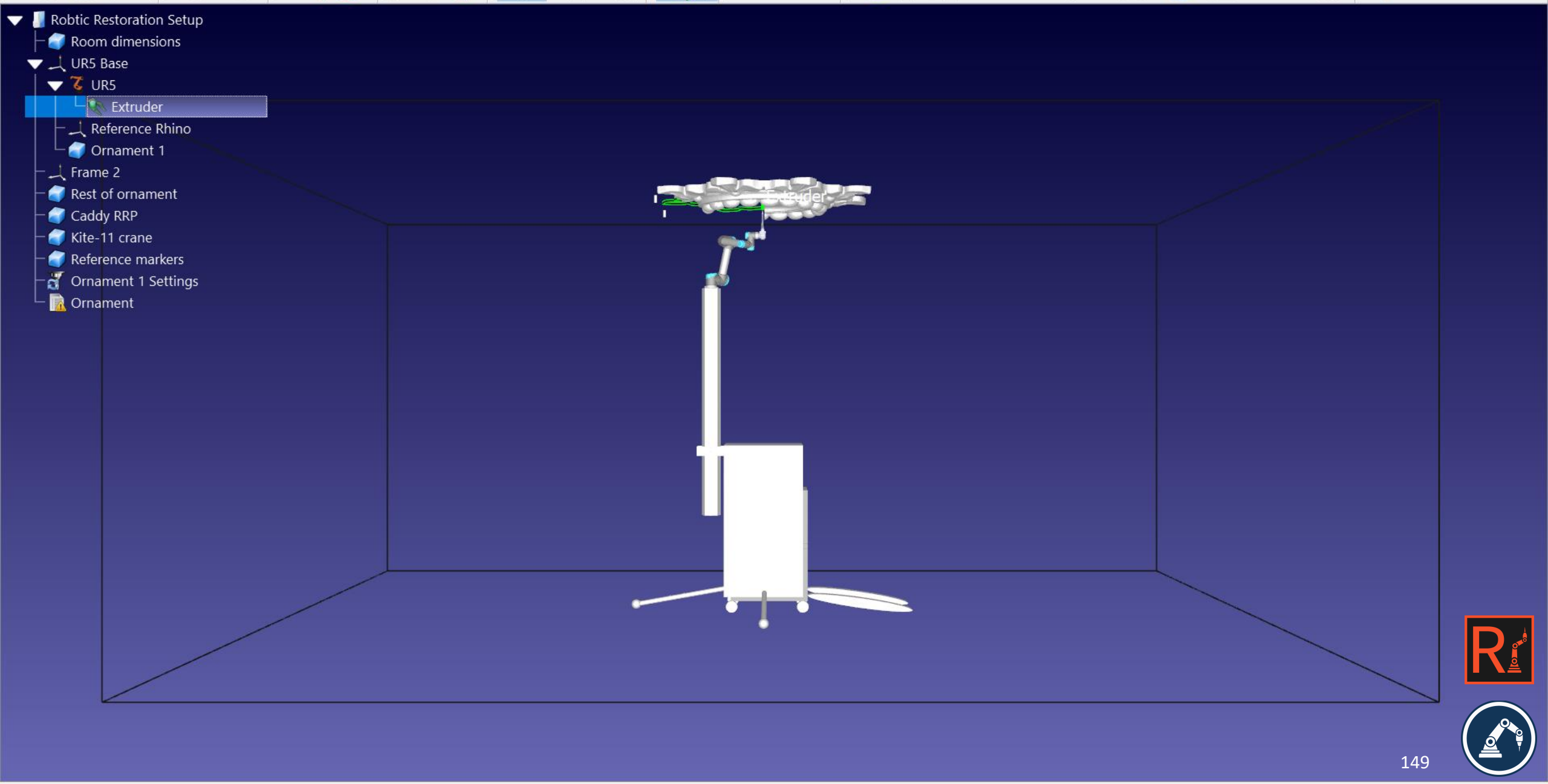
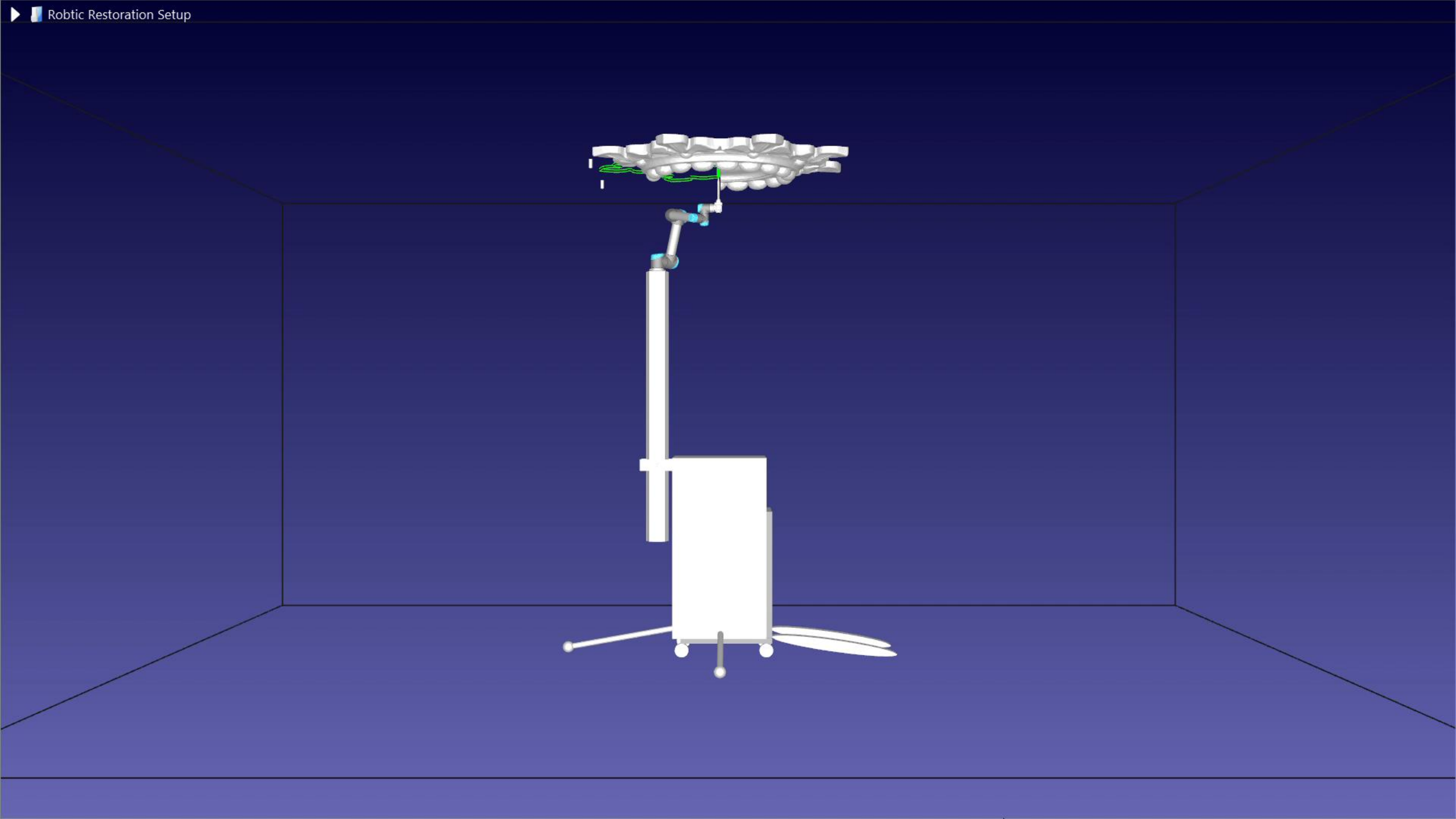
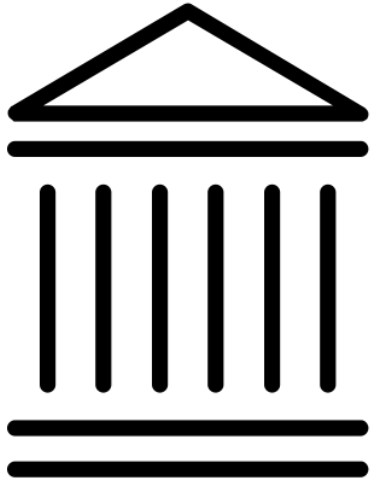



Robtic Restoration Setup

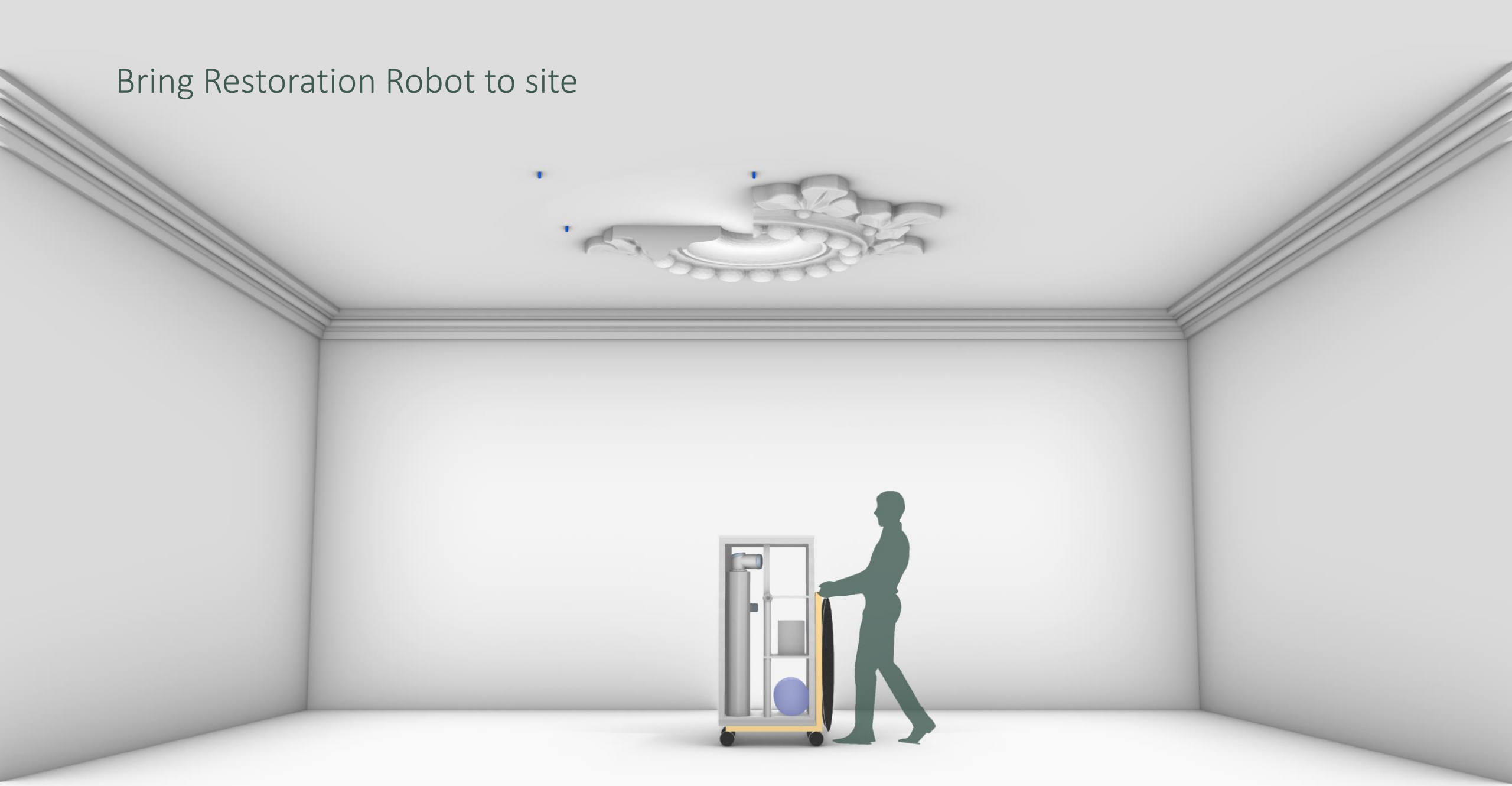
# Save robot instructions (Toolpath)

**RoboDK**
Robot programming & simulation software

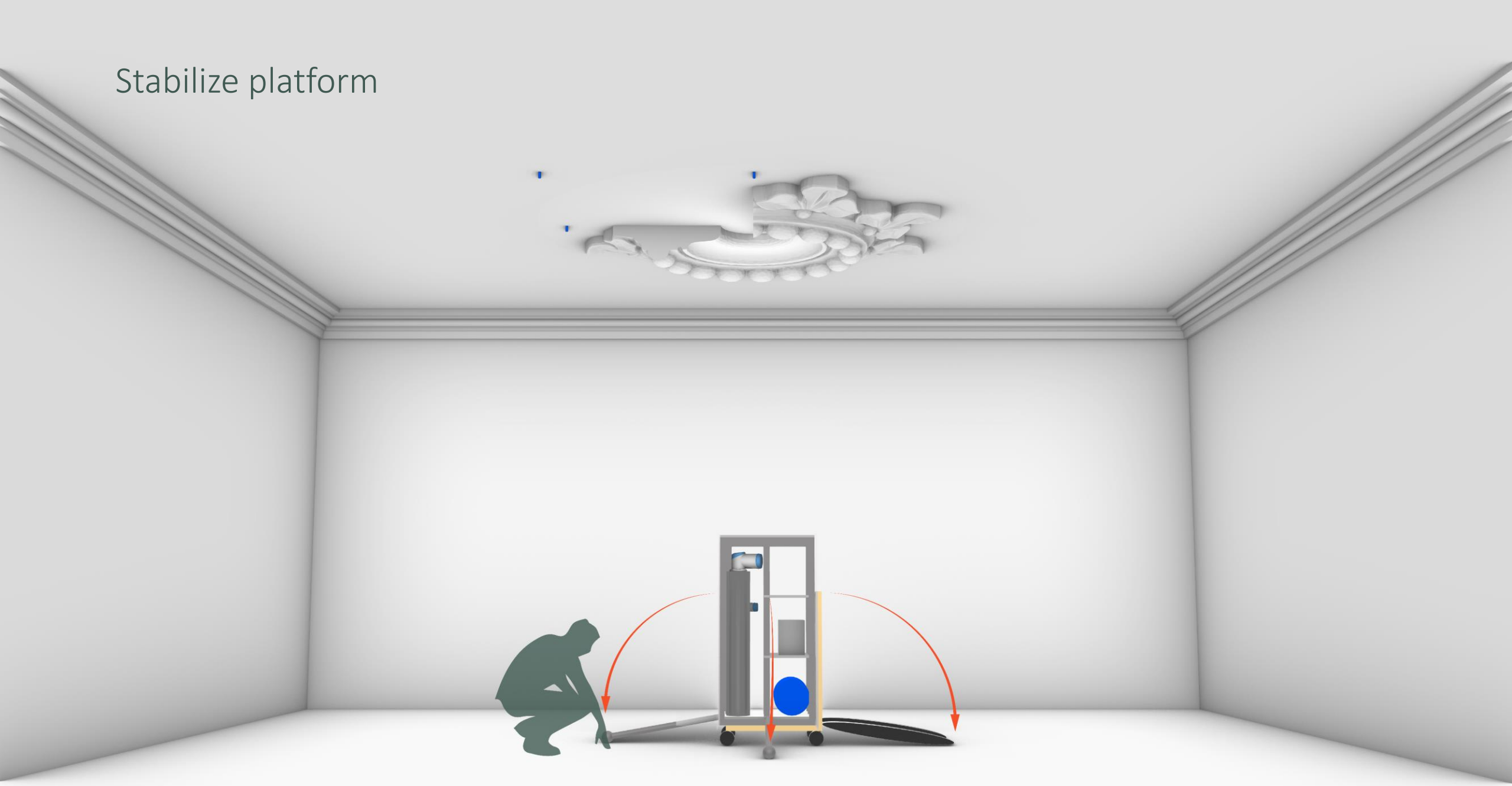


**Restoration site**

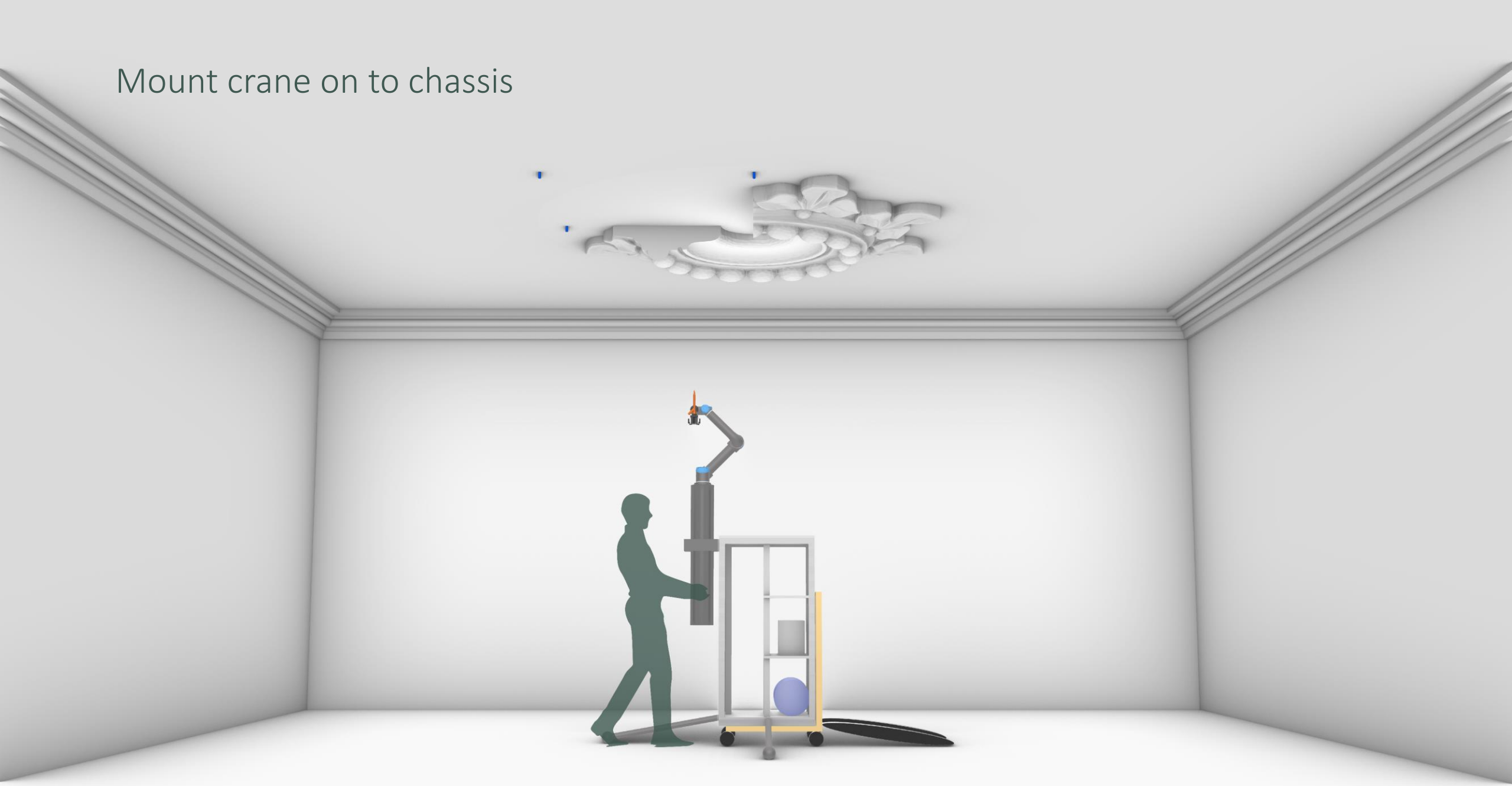
# Bring Restoration Robot to site



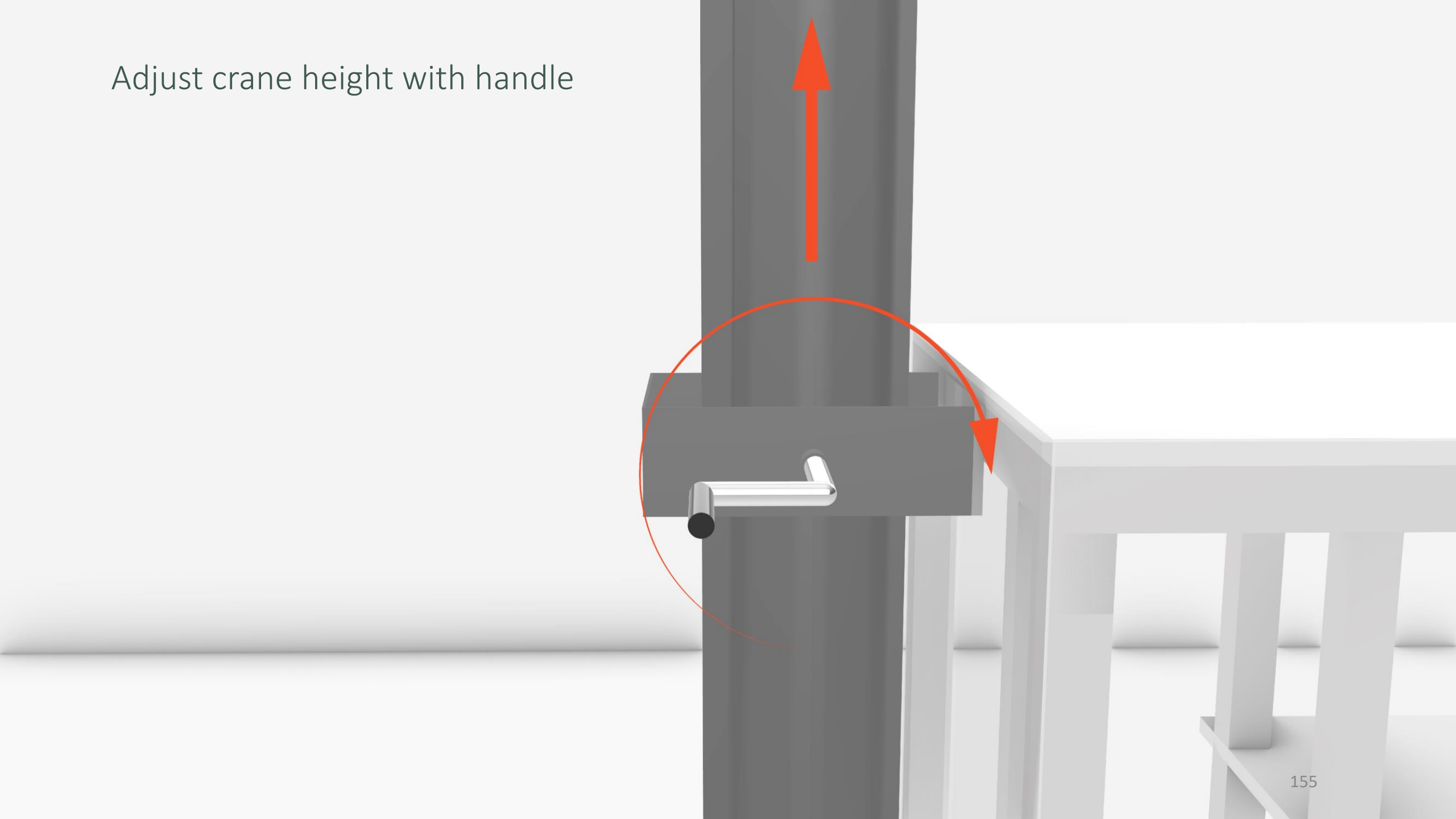
# Stabilize platform



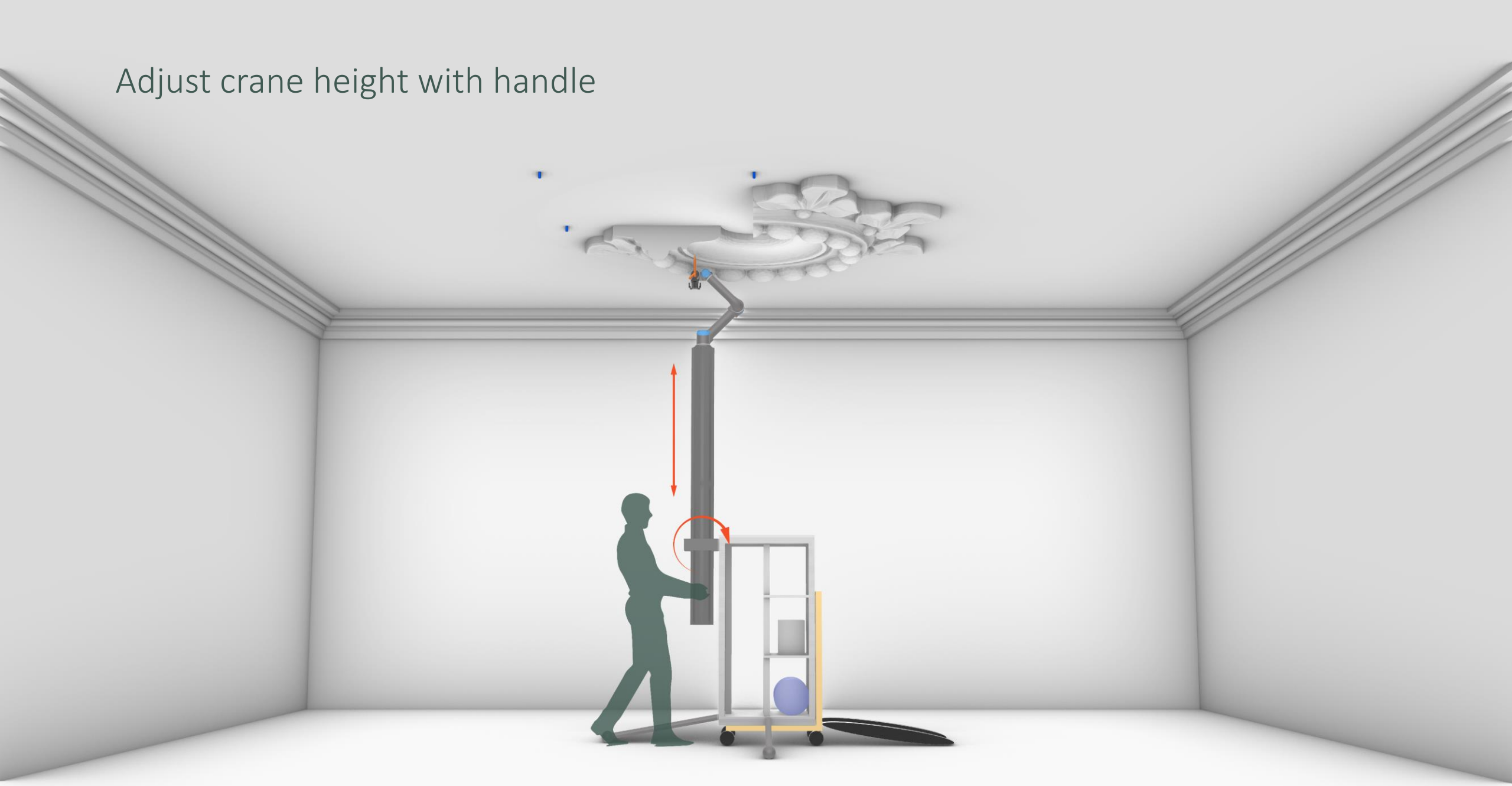
# Mount crane on to chassis



# Adjust crane height with handle

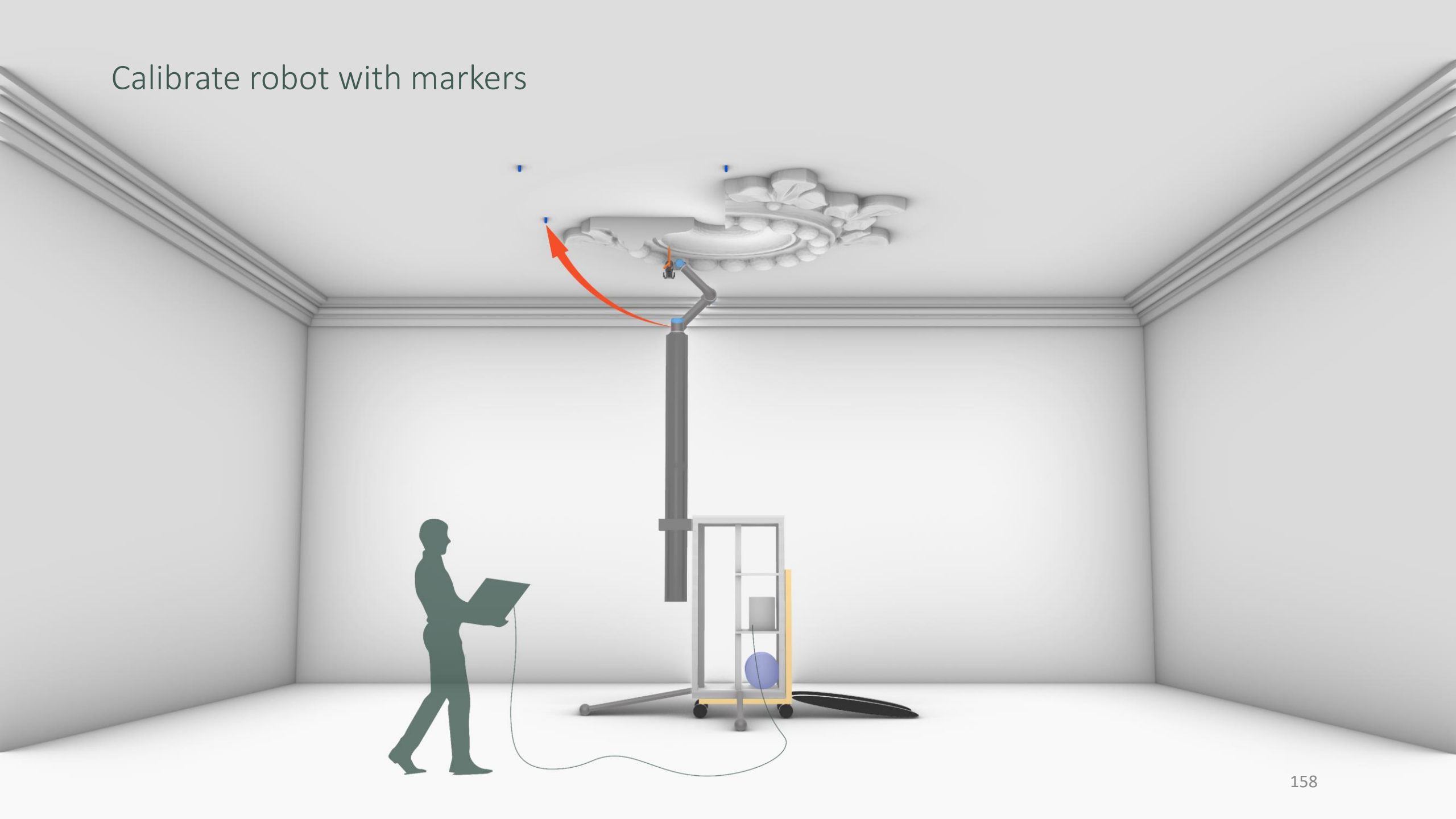


# Adjust crane height with handle

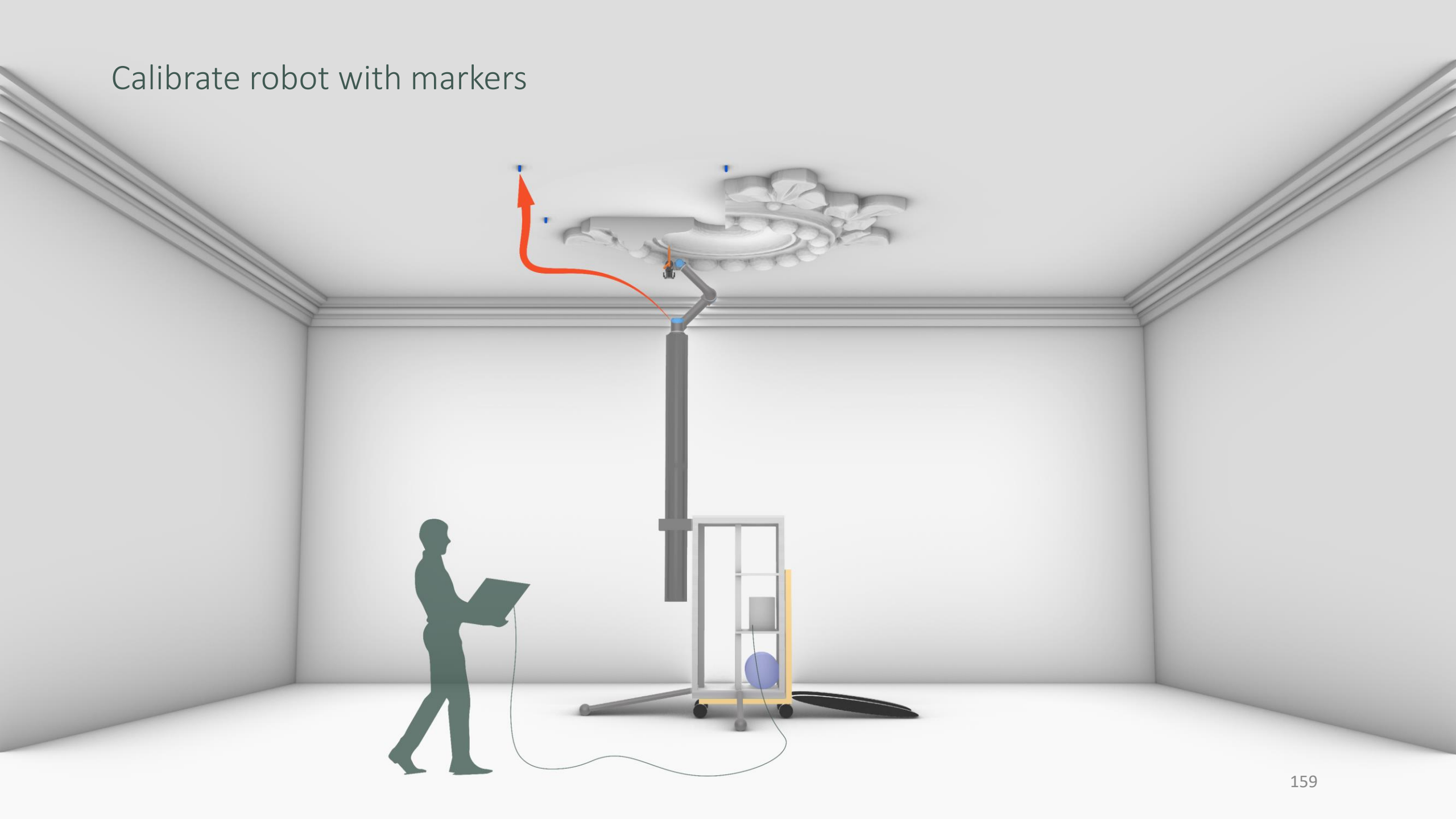


# Calibrate robot with markers

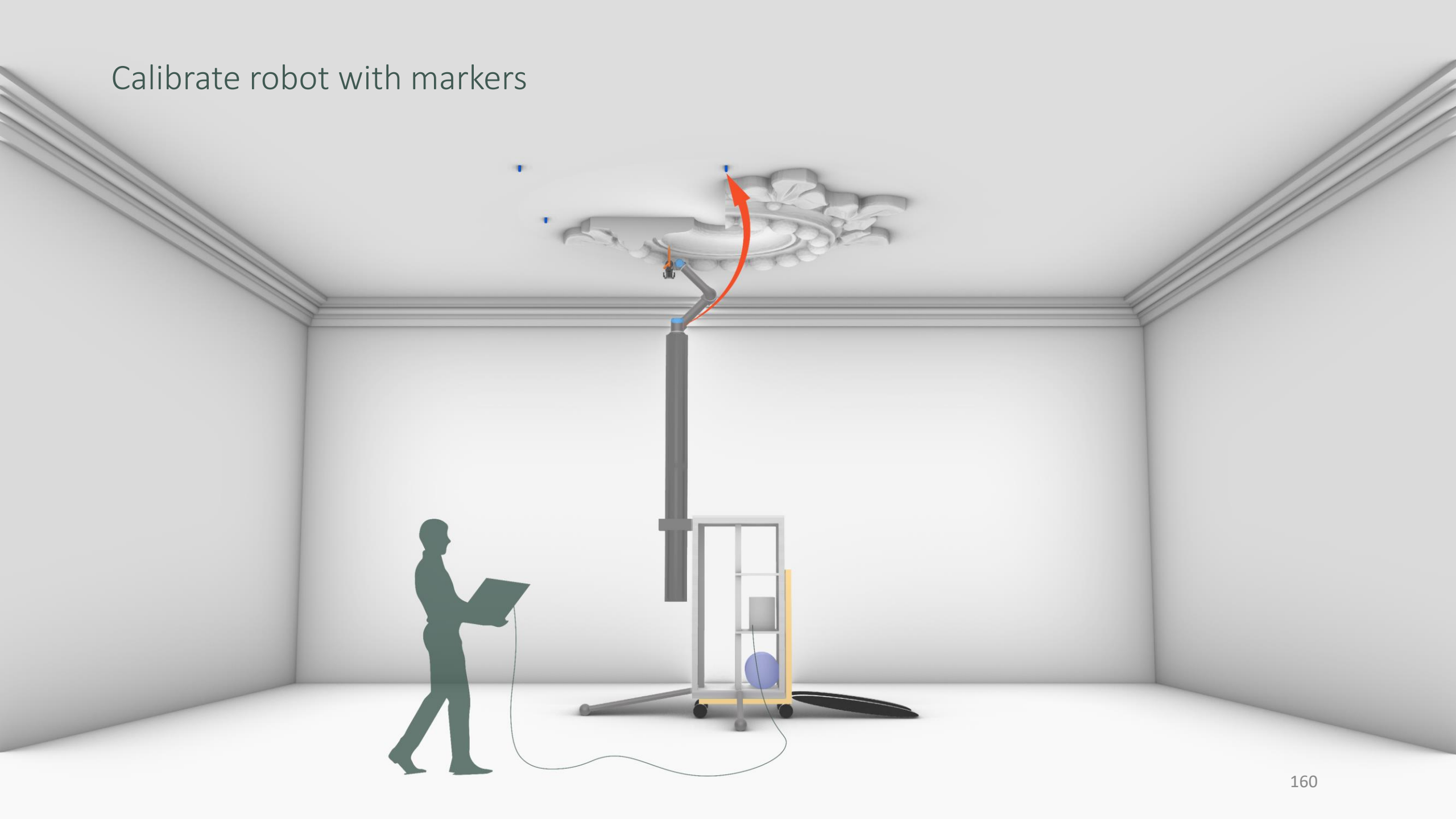
# Calibrate robot with markers



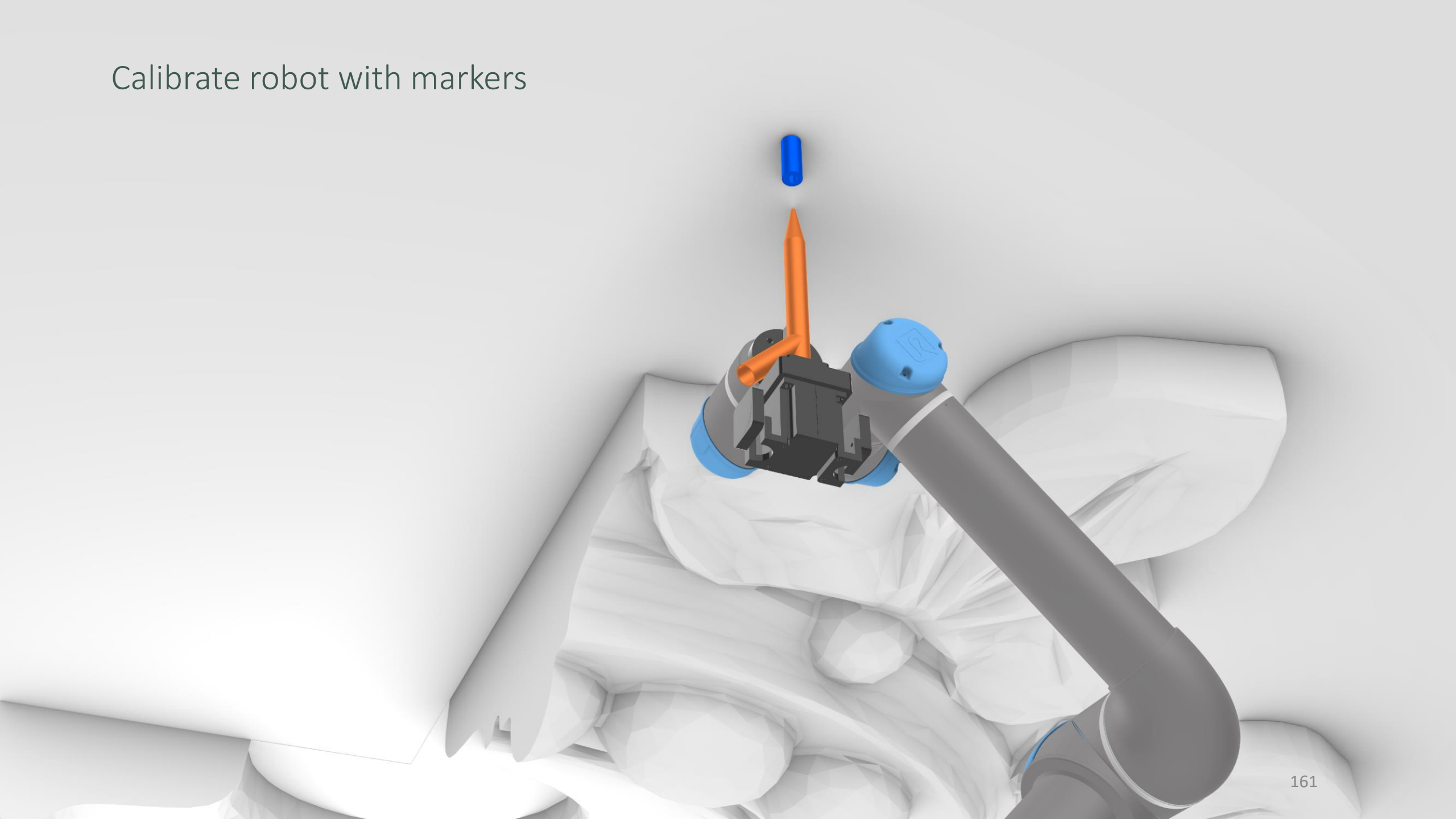
# Calibrate robot with markers



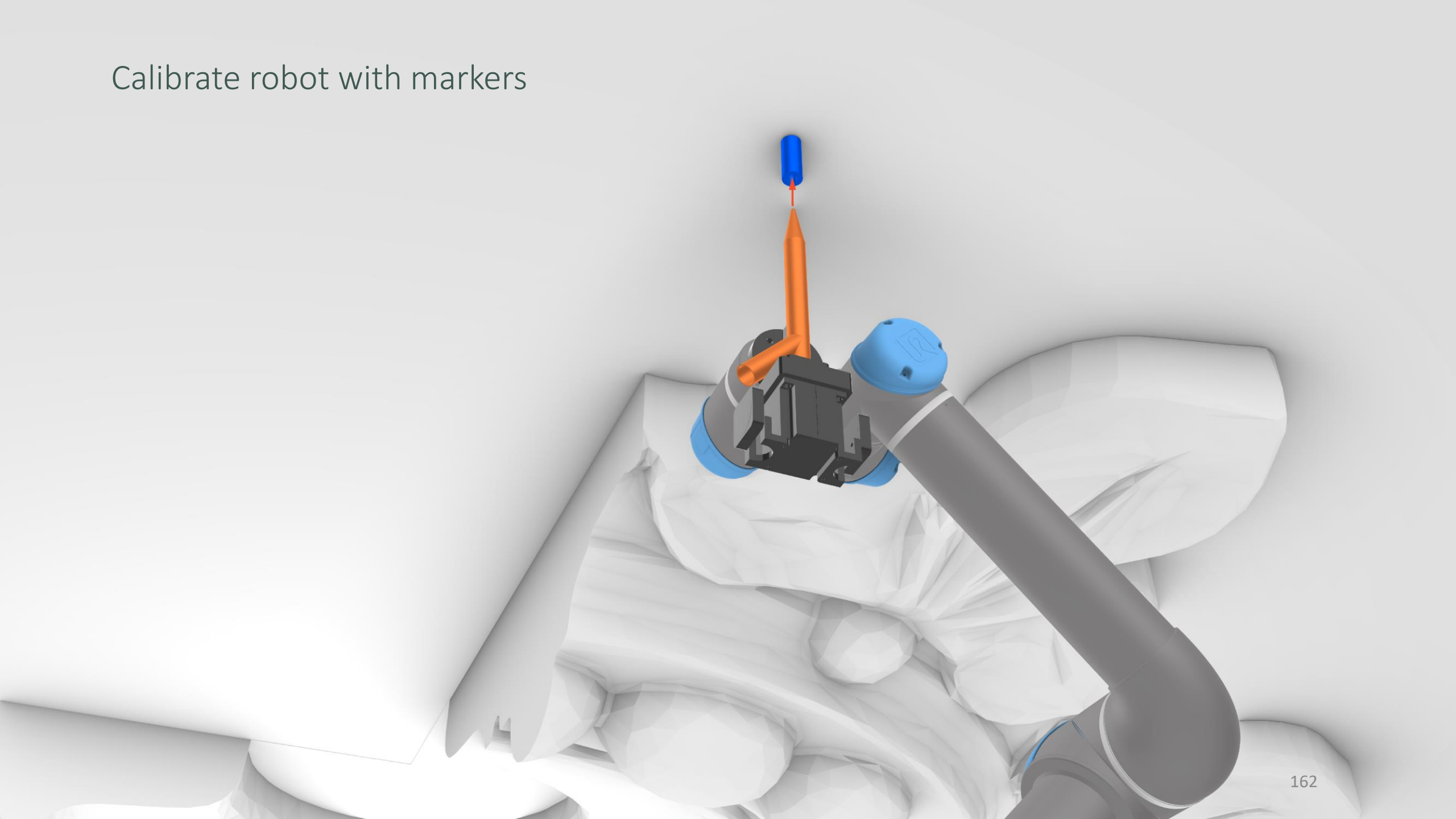
# Calibrate robot with markers



# Calibrate robot with markers



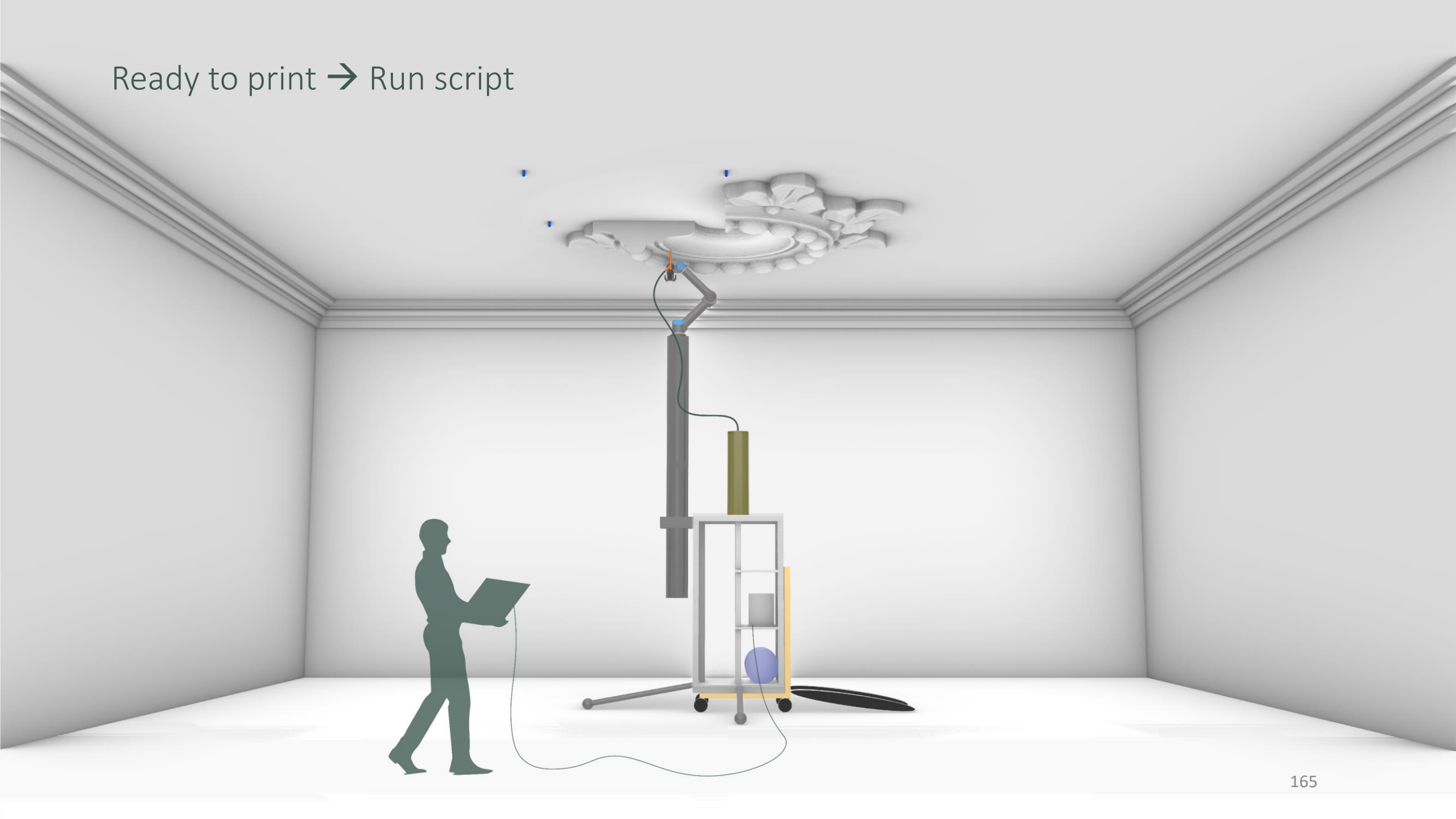
# Calibrate robot with markers



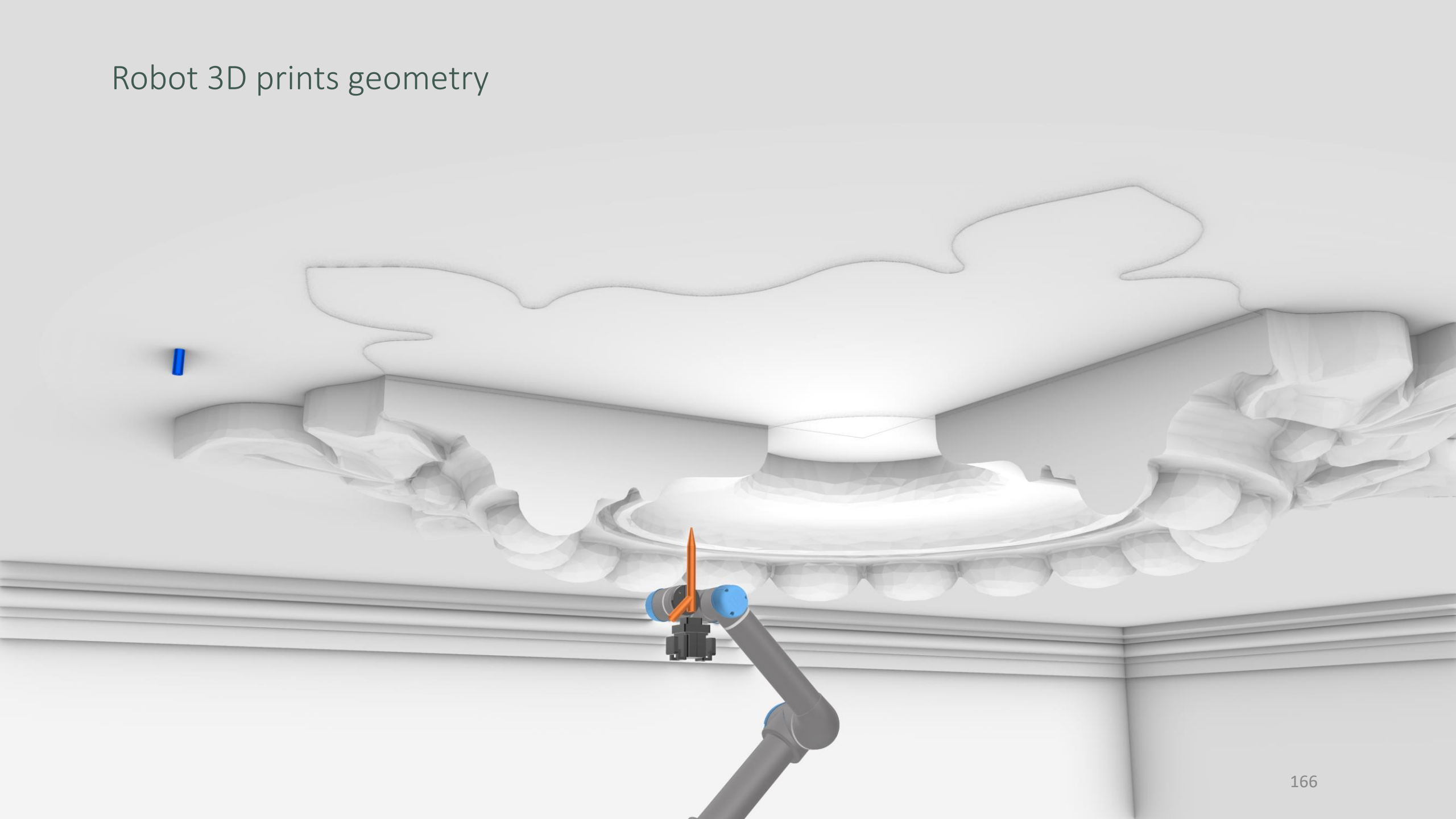
# Make (G5) printing mixture

# Fill reservoir with mixture

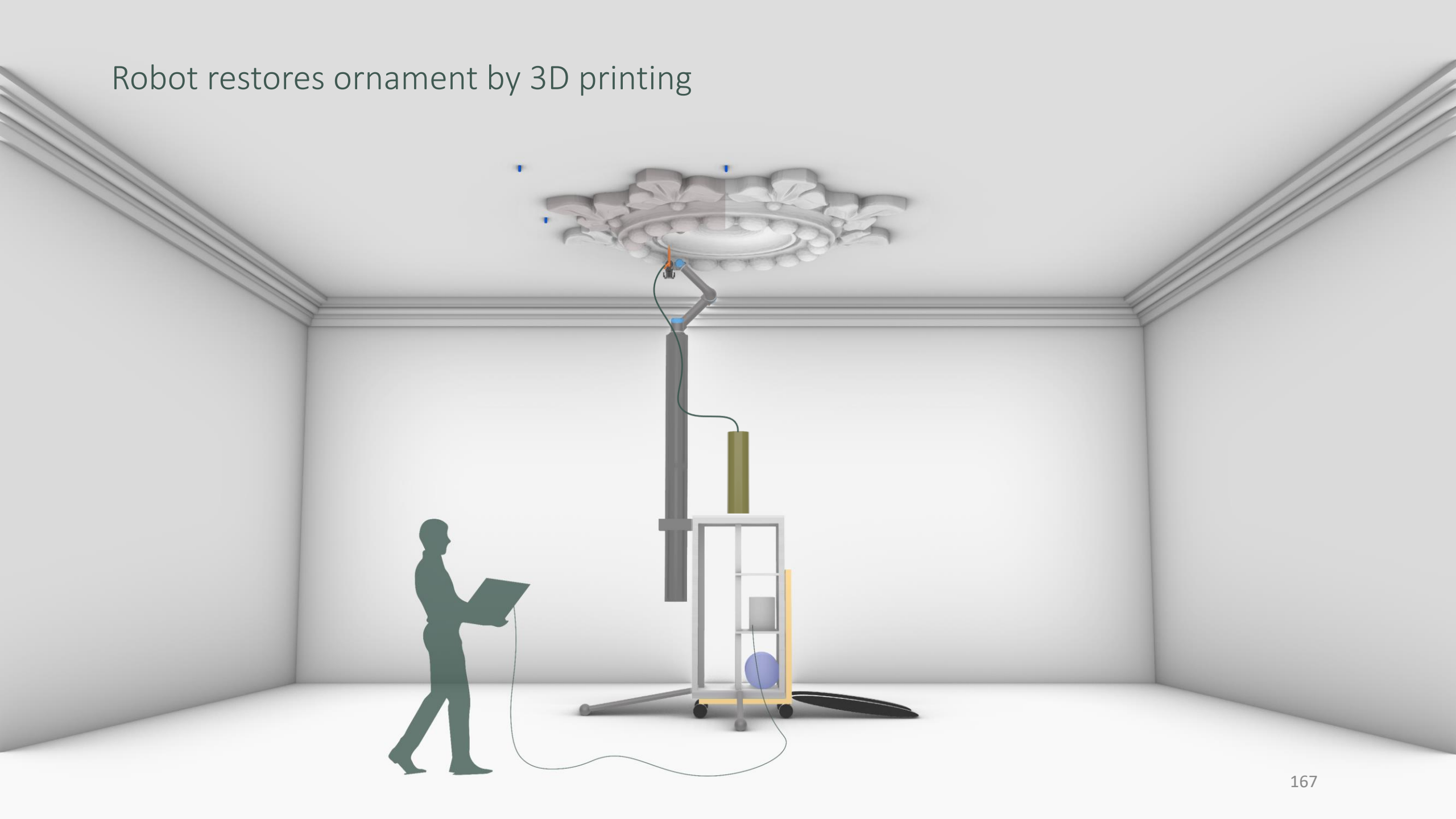
# Ready to print → Run script



# Robot 3D prints geometry

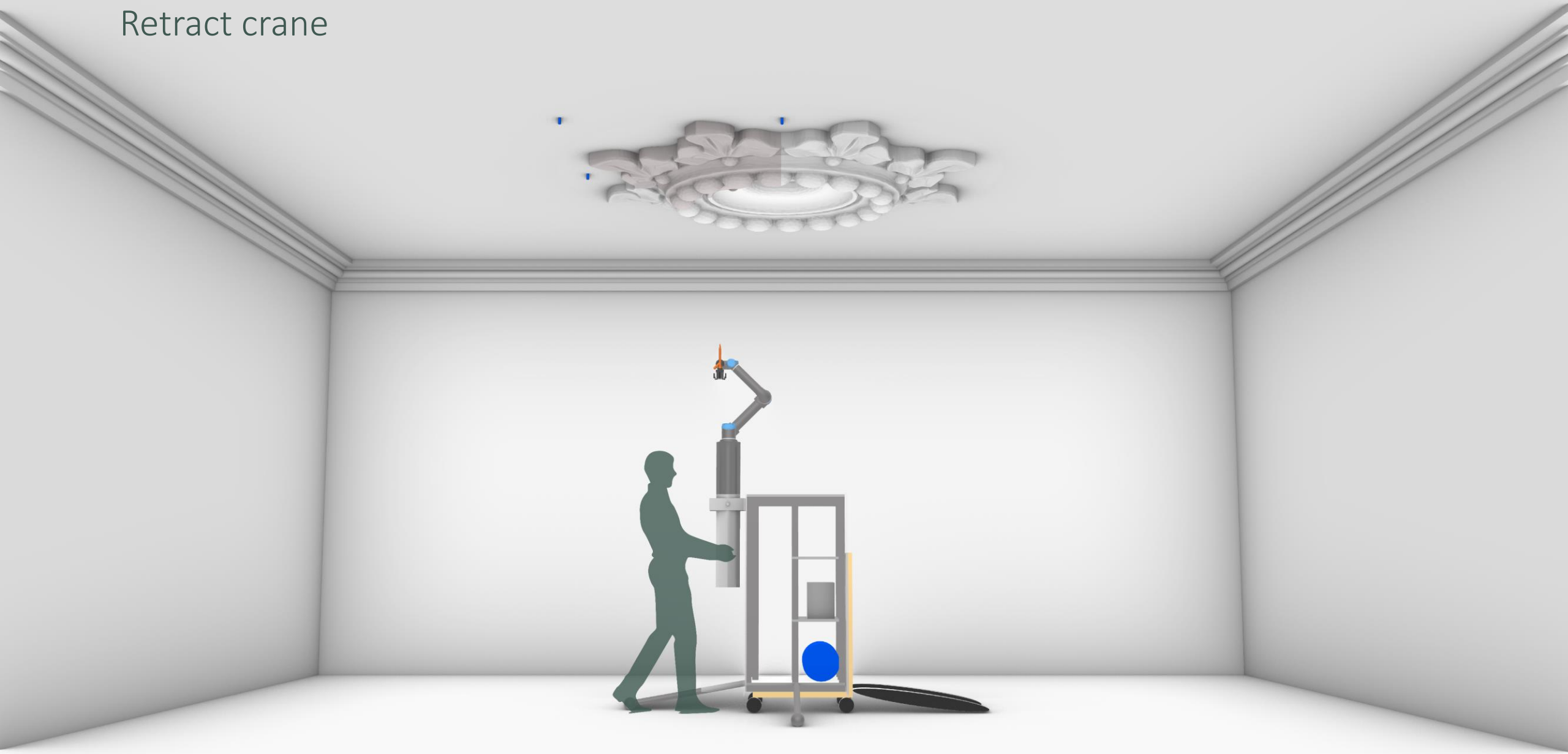


# Robot restores ornament by 3D printing

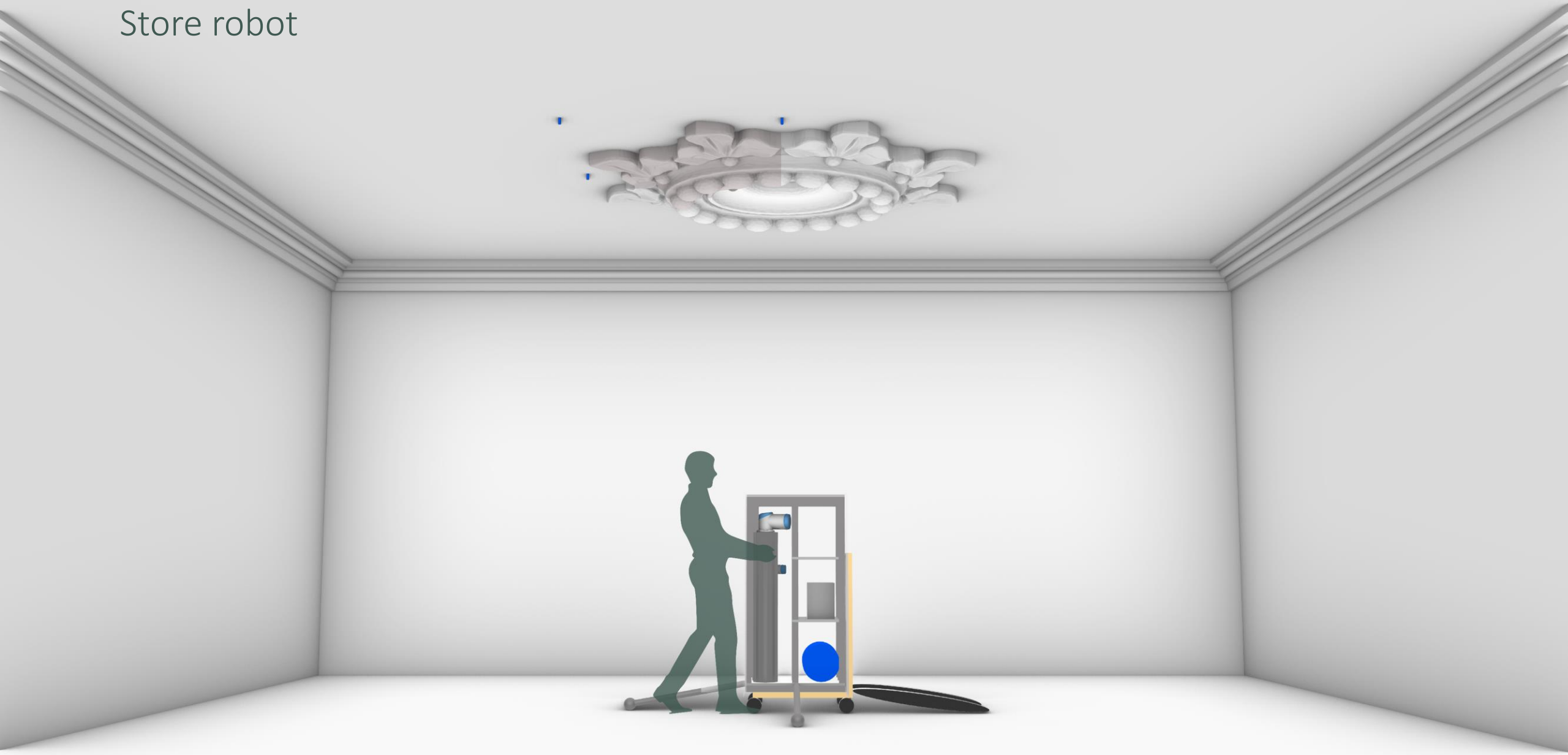


# Inspect work

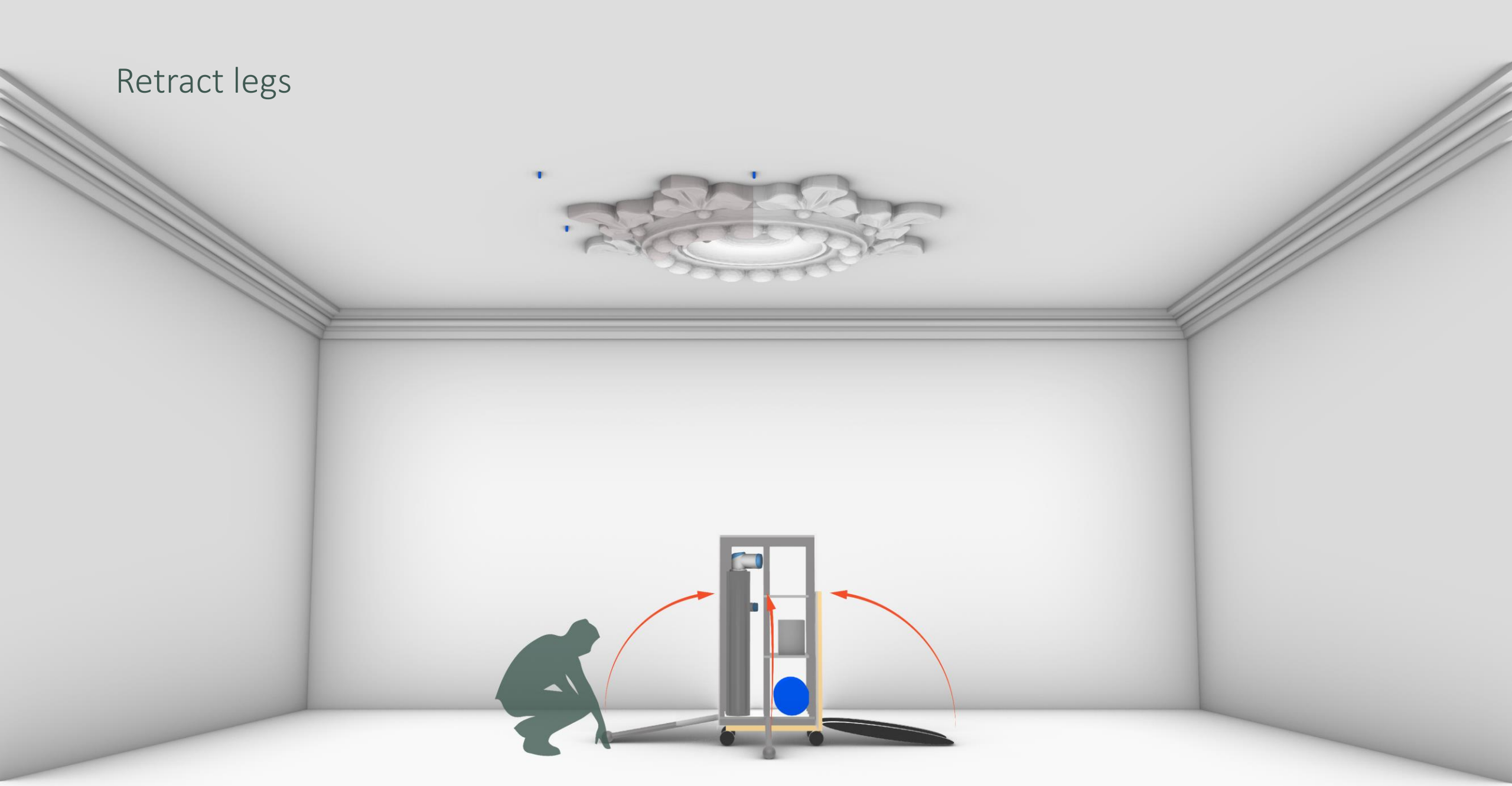
# Retract crane



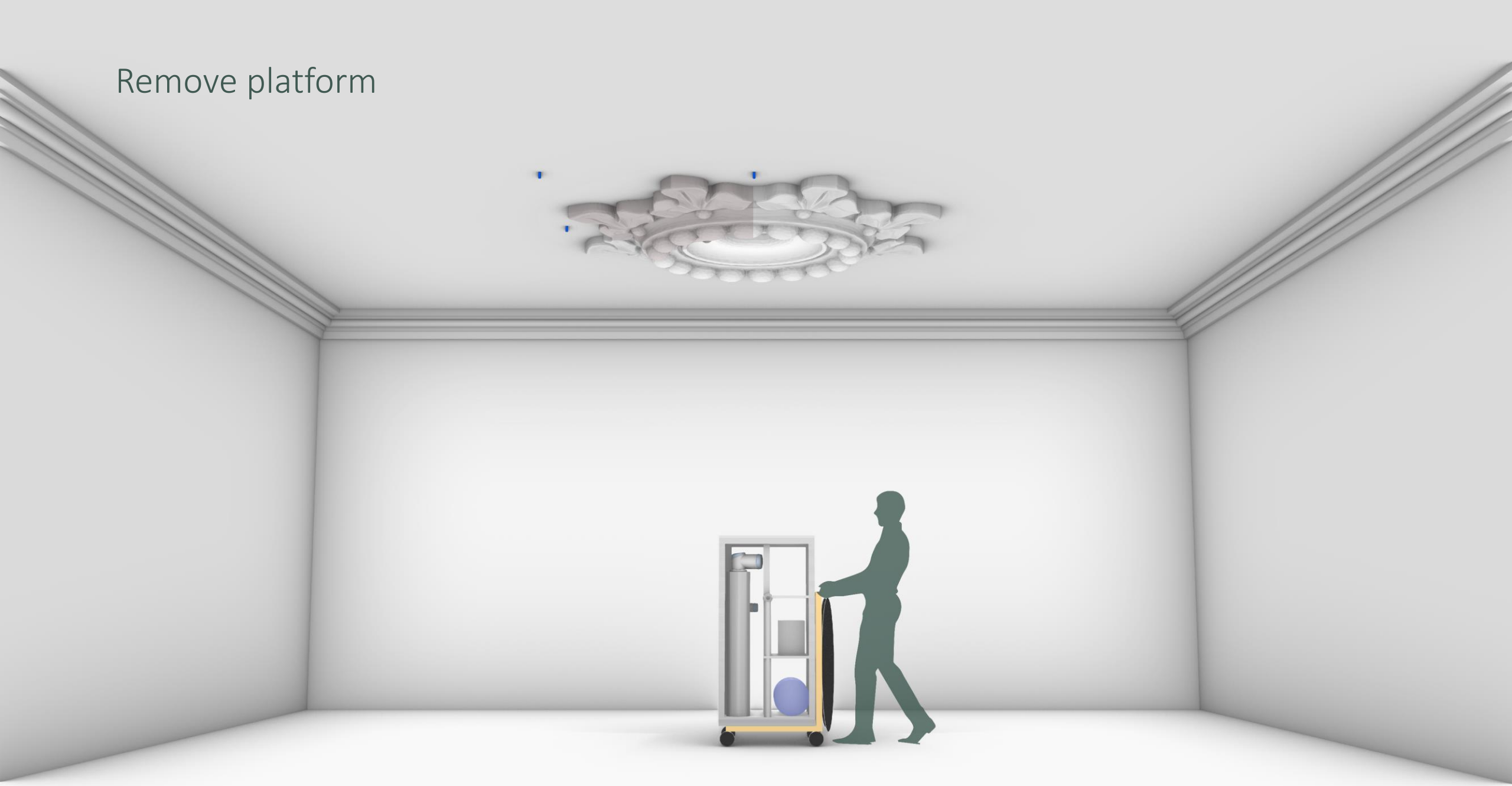
# Store robot



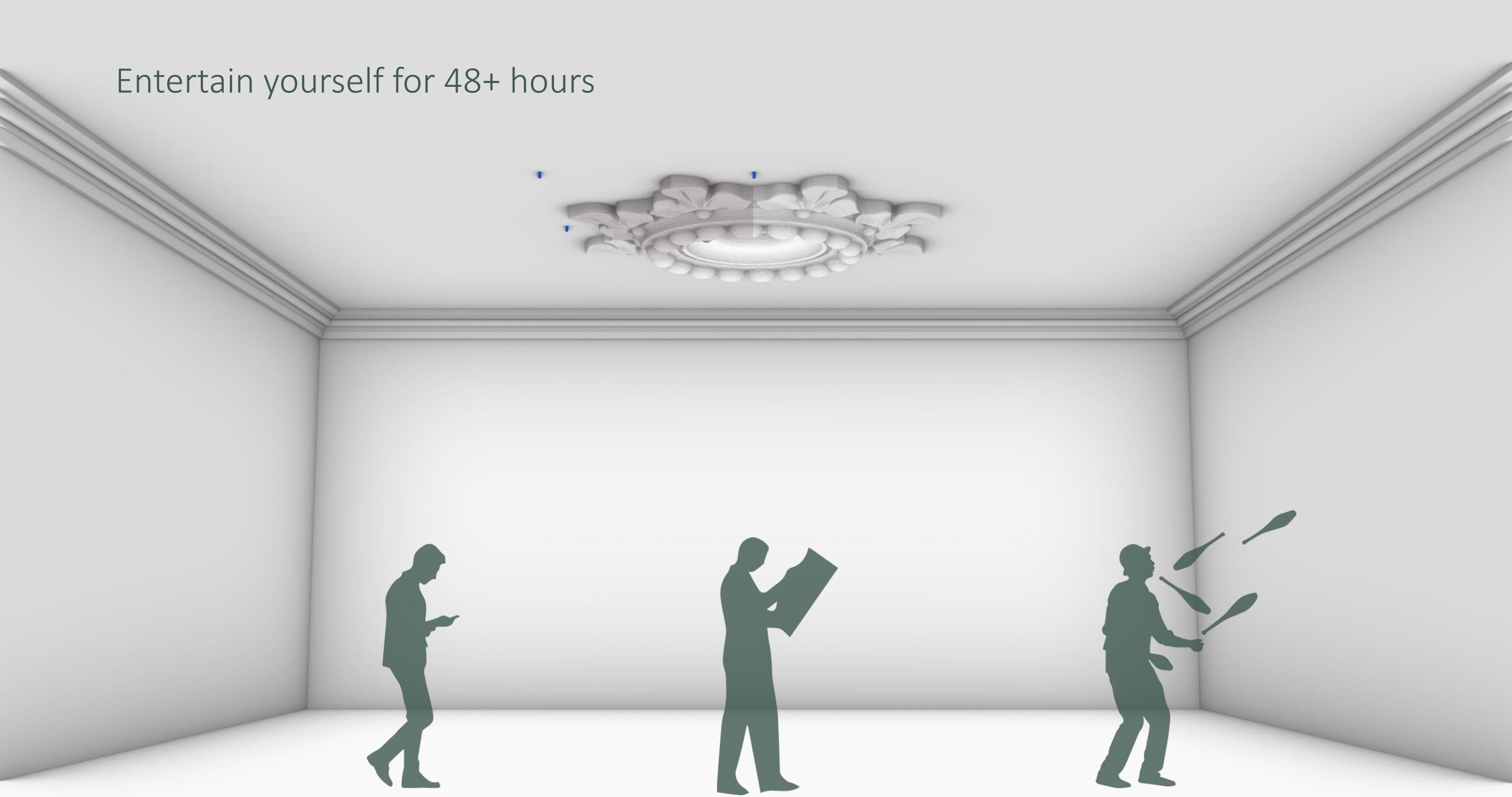
# Retract legs

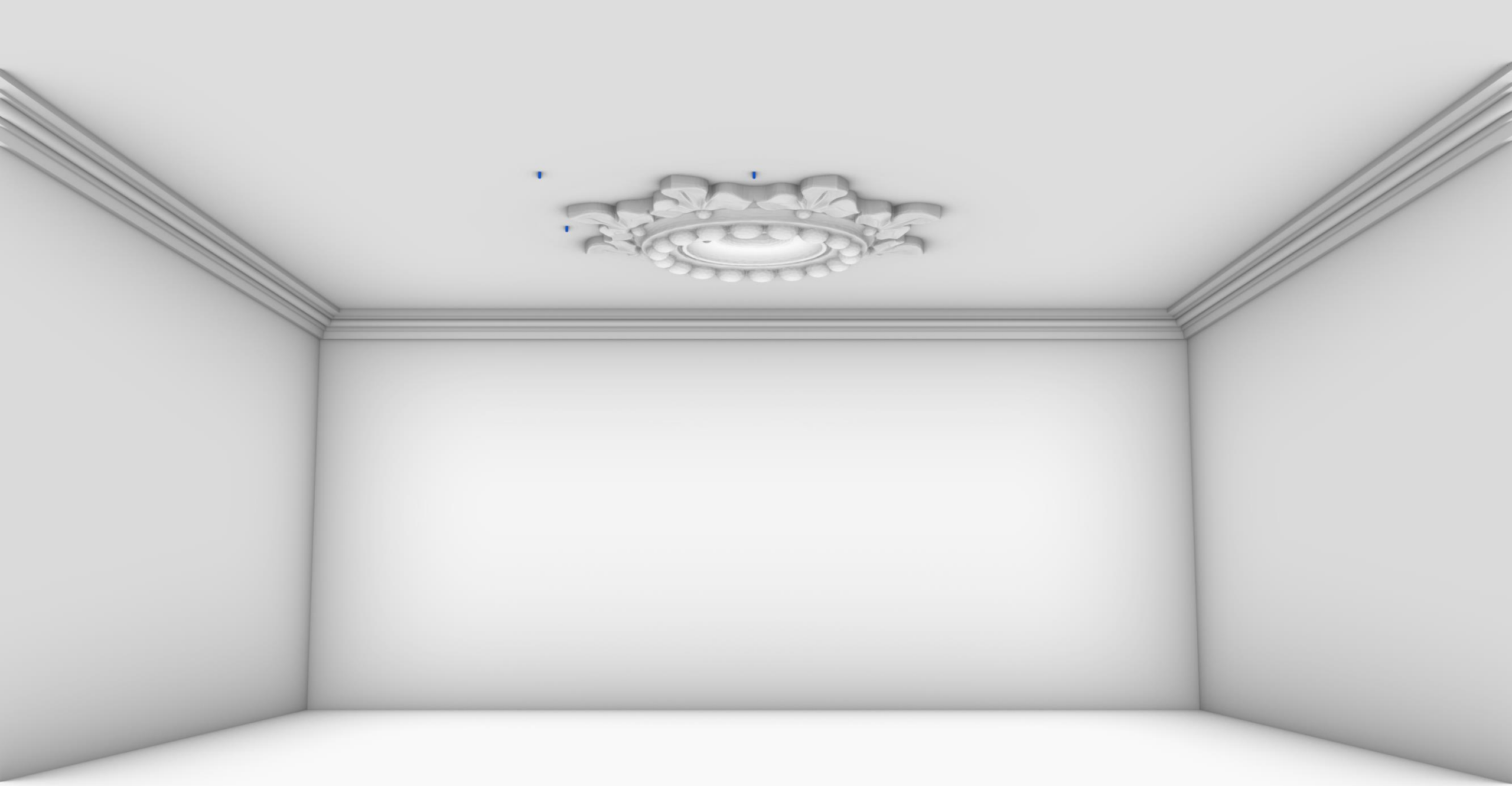


# Remove platform



# Entertain yourself for 48+ hours



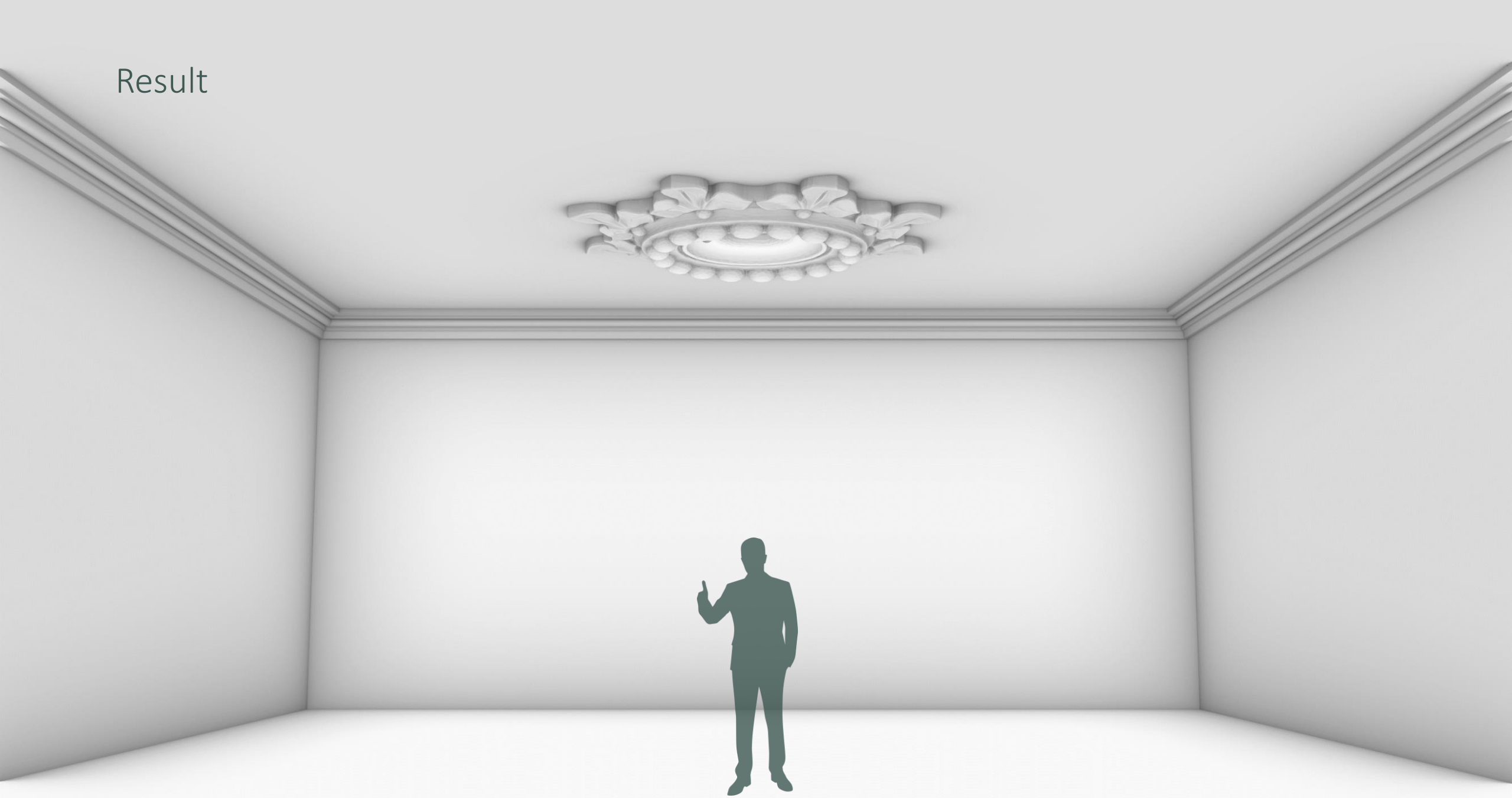


# Final inspection

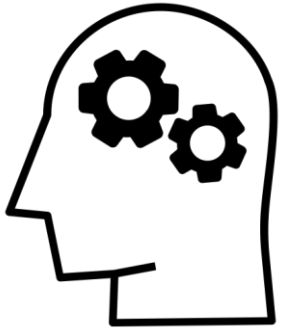
# Remove reference markers

# Remove reference markers

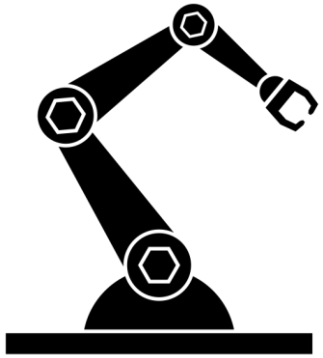
# Result



# Digital Fabrication method



Human knowledge



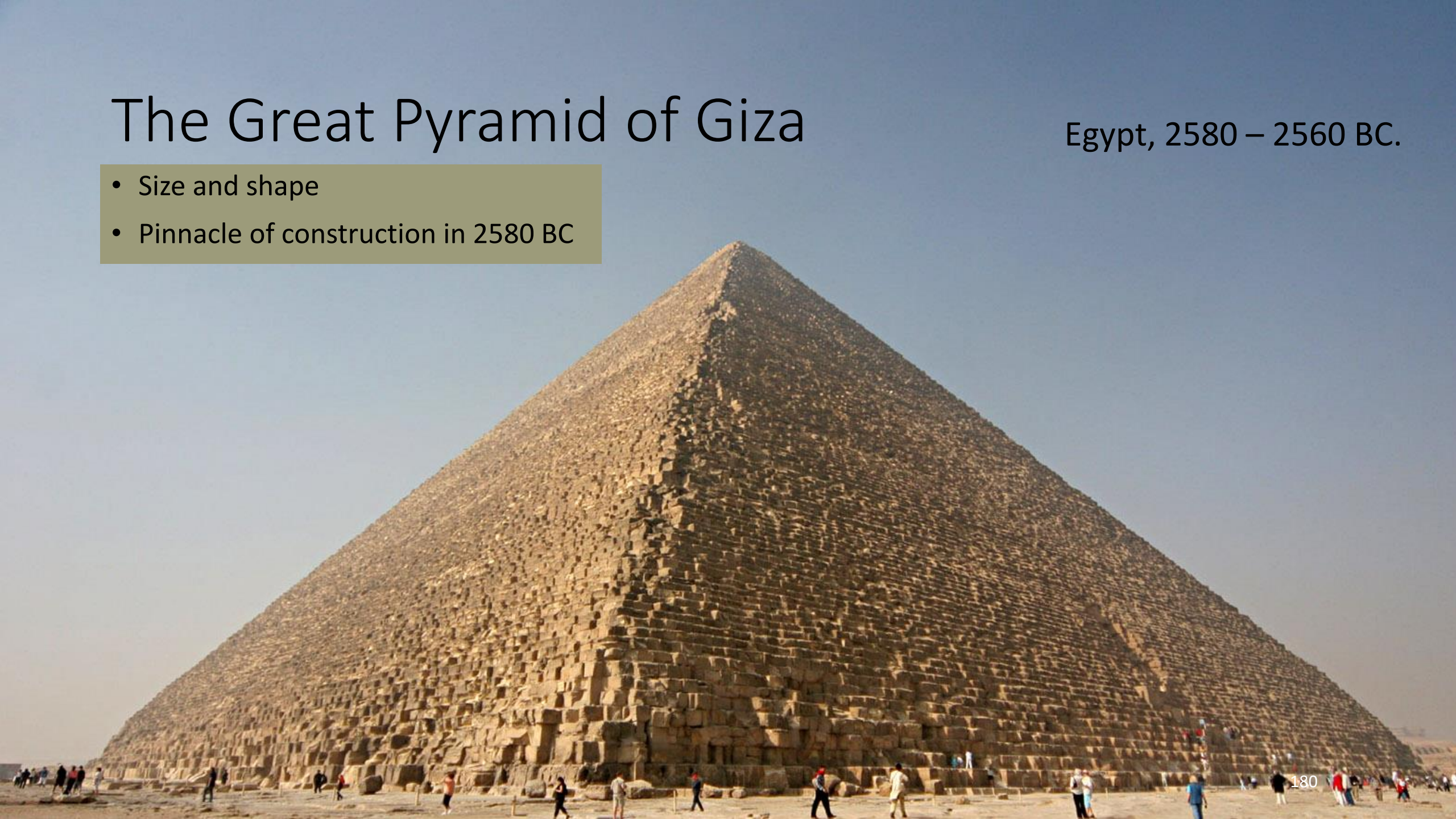
Machine labour

- Restoration
- Construction

# The Great Pyramid of Giza

Egypt, 2580 – 2560 BC.

- Size and shape
- Pinnacle of construction in 2580 BC



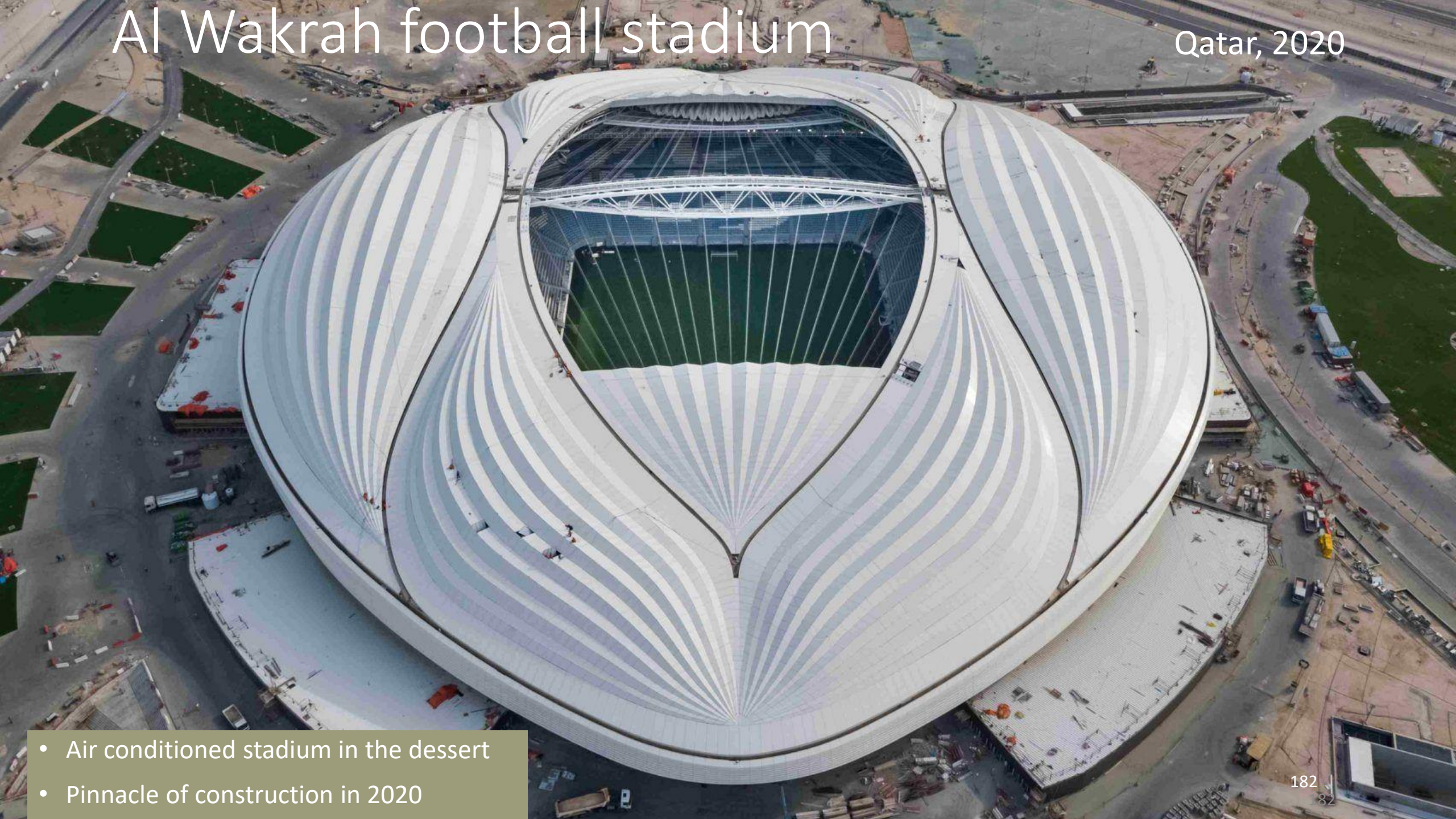
# The Great Pyramid of Giza

Egypt, 2580 – 2560 BC.

Construction method is unsustainable for workers

# Al Wakrah football stadium

Qatar, 2020



- Air conditioned stadium in the dessert
- Pinnacle of construction in 2020

# Al Wakrah stadium

Qatar, 2020

Het morele besef van de voetbalwereld

Voetbalclubs zijn oprecht verontwaardigd over racisme, maar gaan wél naar Qatar, waar moderne slaven stadions bouwen.

Maarten de Gruyter · 3 dec 2019 om 07:00 uur

Arbeiders werken aan het Al-Wakrah-stadion in een buitenwijk van de Qatarese hoofdstad Doha. Foto: ANP

www.hetgoedeleven.nl

Migrant workers suffer from coronavirus-safe conditions in Qatar

Pressure to complete the construction project for the 2022 World Cup exacerbates the situation

Atalayar

AFP/MARWAN NAAMANI - Foreign workers at the construction site of Al-Wakrah Football Stadium, one of the stadiums for the 2022 World Cup in Qatar

www.atalayar.com

Qatar covered up the death of 1200 workers

Rights groups accuse body of whitewashing Qatar's image and politicising rights issues

Published: April 14, 2019 15:38

Gulf News

A construction site in Doha. Rights groups say more than 1,200 migrant workers have died building World Cup facilities.

Image Credit: AFP

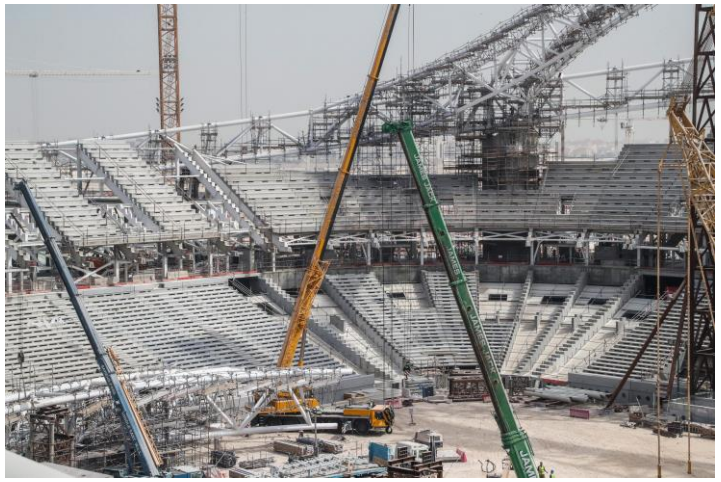
www.gulfnews.com

We are unable to **construct** buildings sustainably and responsibly for our workers?

# How we build

2580 BC — 2020 AD — Future

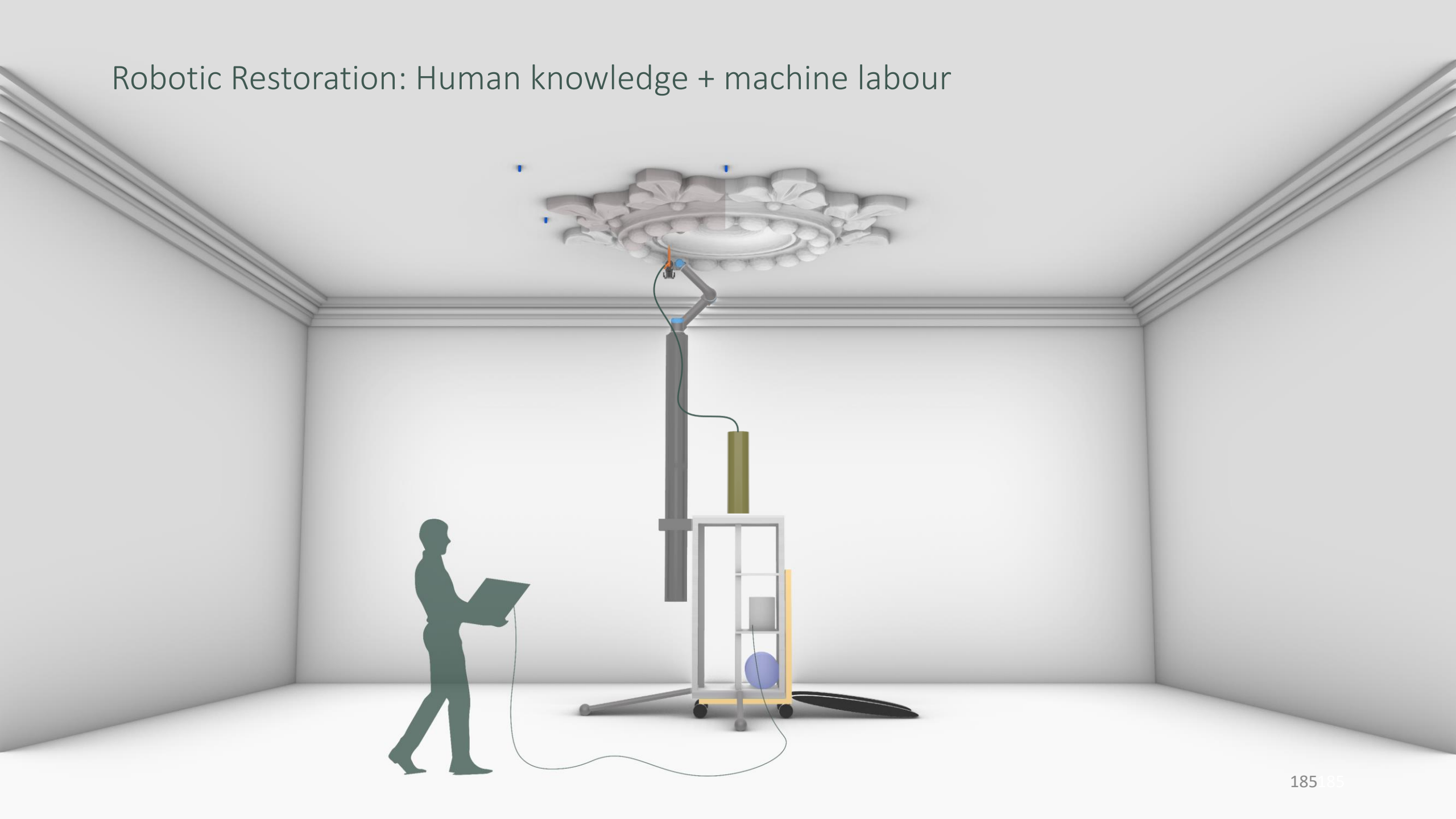
Great Pyramid of Giza, 2580 BC. www.com



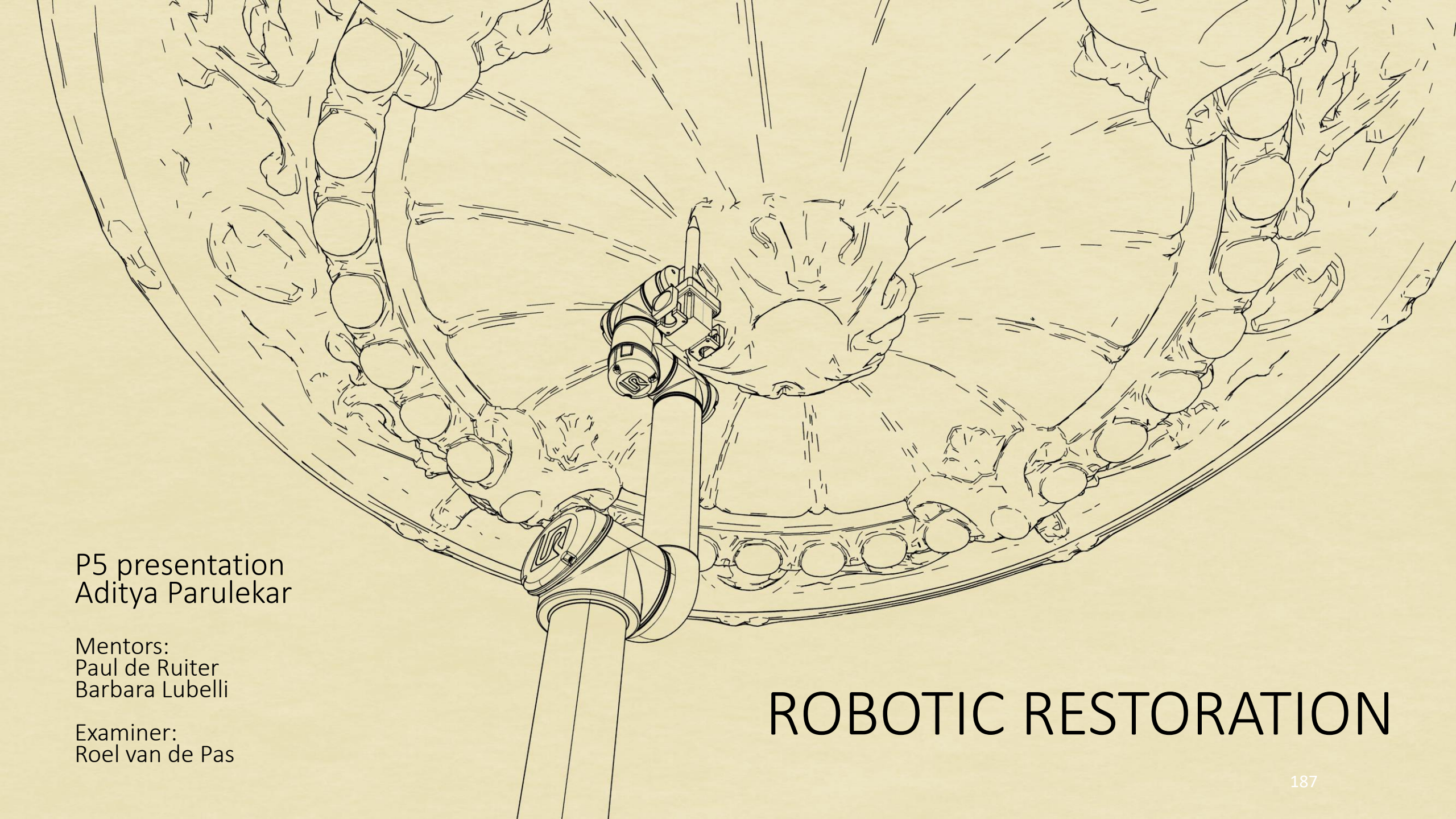
Al Wakrah stadium 2020, www.asiatimes.com

Human labour → Human labour + Machine labour → Human knowledge + Machine labour

# Robotic Restoration: Human knowledge + machine labour



# Preserve our Heritage for future generations



# ROBOTIC RESTORATION

P5 presentation
Aditya Parulekar

Mentors:
Paul de Ruiter
Barbara Lubelli

Examiner:
Roel van de Pas

# APPENDIX

# Research question

*“To what extent can a **Digital Fabrication method** and **3D printable gypsum-based mixtures** be developed for restoration of stucco ornaments by means of in-situ additive manufacturing?”*