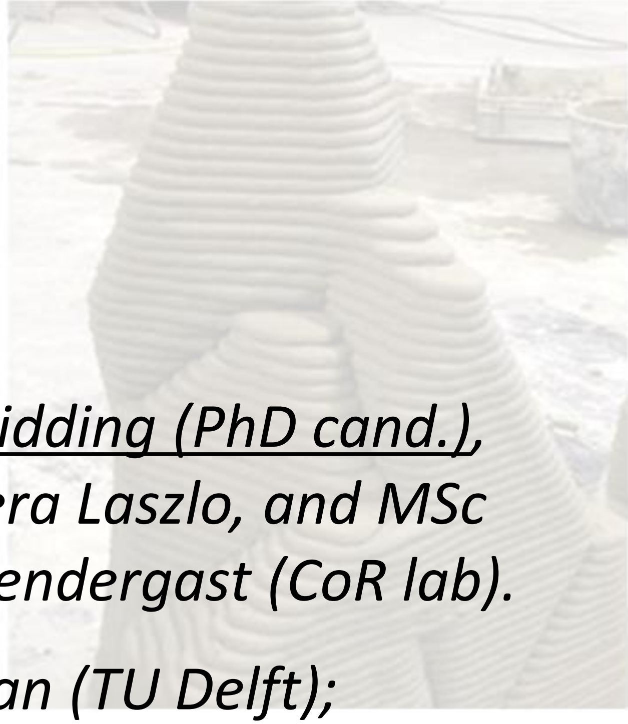




Rhizome 1.0 >2.0

Team: Henriette Bier (project leader), Arwin Hidding (PhD cand.), Giuseppe Calabrese, Atousa Aslaminezhad, Vera Laszlo, and MSc students (RB lab); Luka Peternel and Micah Prendergast (CoR lab).

Supervisors/ Collaborators/ Partners: Kees Kaan (TU Delft); Advenit Makaya (ESA) and Volker Ruitinga (Vertico); Rene Rietmeijer (Dutch Growth Factory), Anna Metke (Exolith), and Jessica Cobb (Mission Control).

Overview

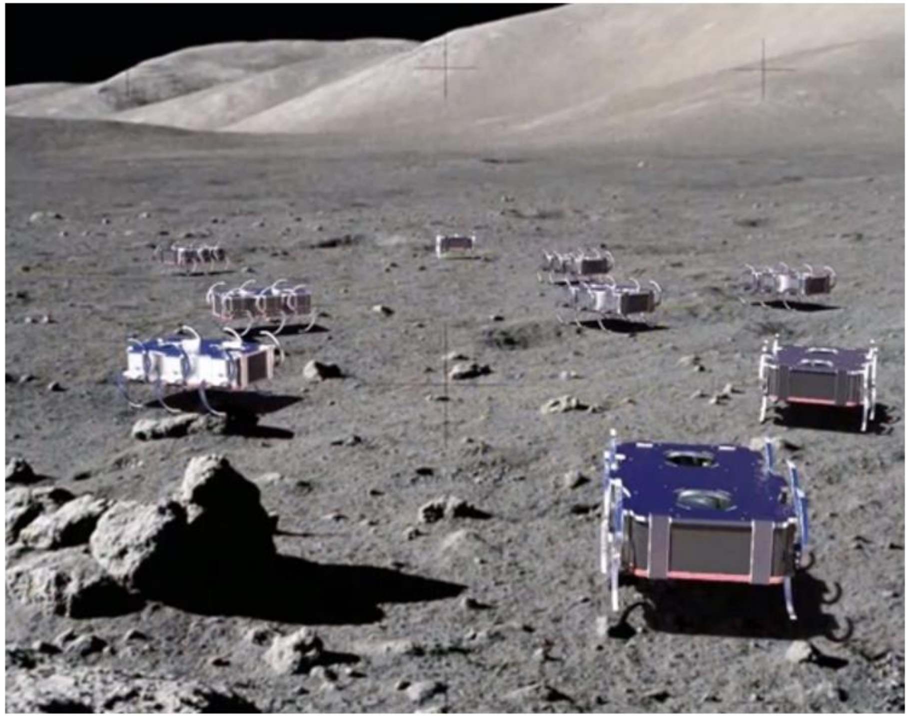
+ *Research background*
+ *State-of-the-art, research gap & research questions*
+ *Requirements habitat*
+ *Methodology*
+ *Publications*
+ *Next steps, GS courses, data management, planning*



Research Background

+ *Rhizome 1.0: ESA & Vertico funded project: proof of concept development*

+ *Rhizome 2.0: ESA & Vertico funded project: scale up capability of Rhizome 1.0*

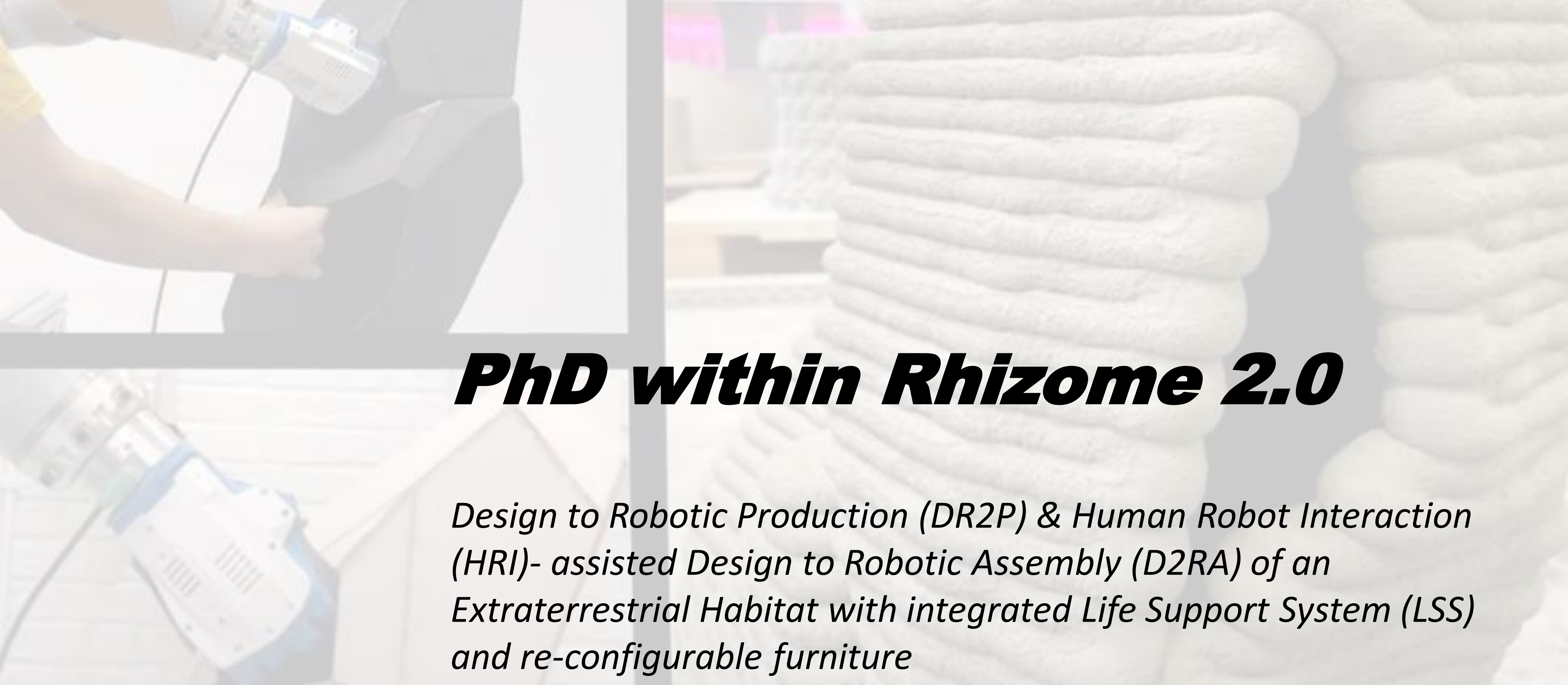


Background: Rhizome 1.0

3D-printing with aggregate replacement by regolith simulant

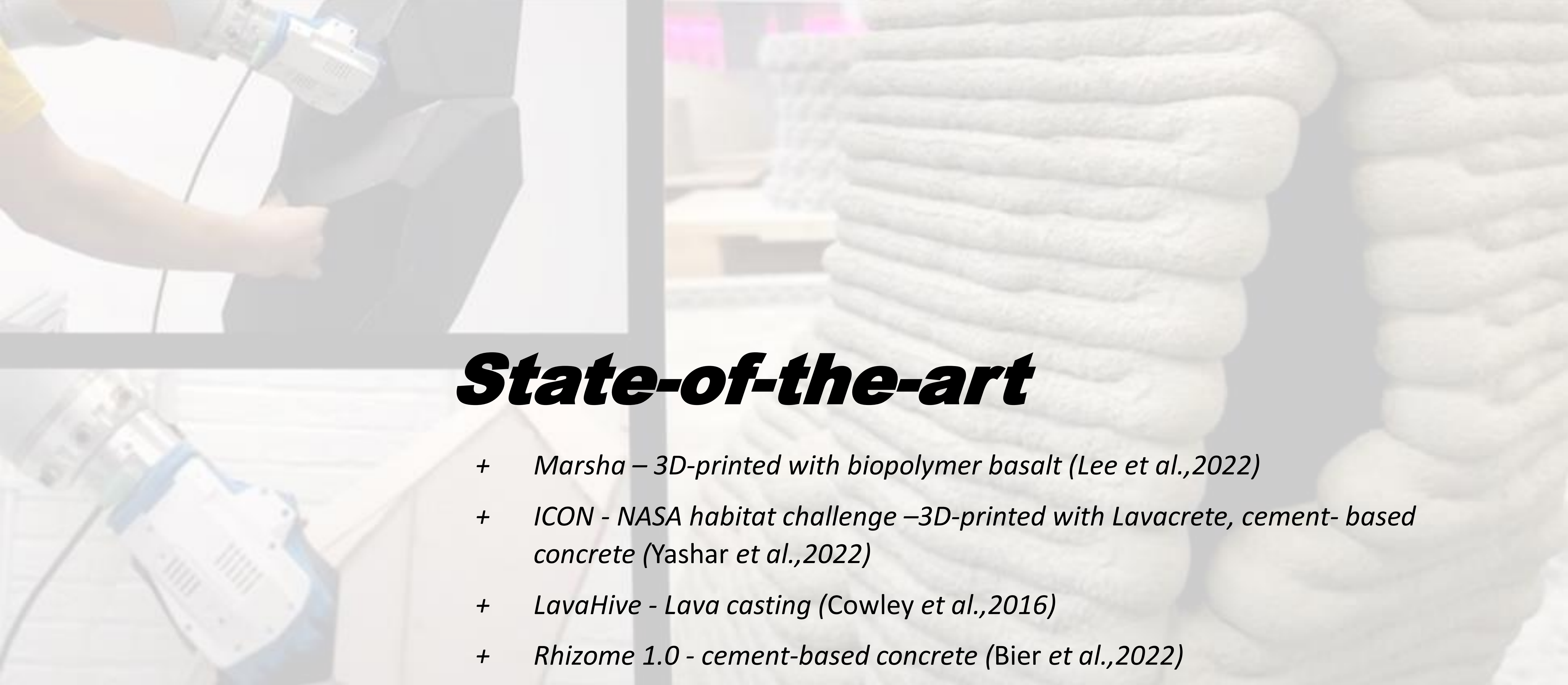
HRI supported assembly of 3D-printed component mock-up

Rhizome 2.0



PhD within Rhizome 2.0

Design to Robotic Production (DR2P) & Human Robot Interaction (HRI)- assisted Design to Robotic Assembly (D2RA) of an Extraterrestrial Habitat with integrated Life Support System (LSS) and re-configurable furniture



State-of-the-art

- + *Marsha – 3D-printed with biopolymer basalt (Lee et al.,2022)*
- + *ICON - NASA habitat challenge –3D-printed with Lavacrete, cement- based concrete (*Yashar *et al.,2022)*
- + *LavaHive - Lava casting (*Cowley *et al.,2016)*
- + *Rhizome 1.0 - cement-based concrete (*Bier *et al.,2022)*
- + *Mars Ice House – water ice (Morris et al.,2022)*

Research gaps

D2RP

+ Integration of LSS, furniture, indoor garden

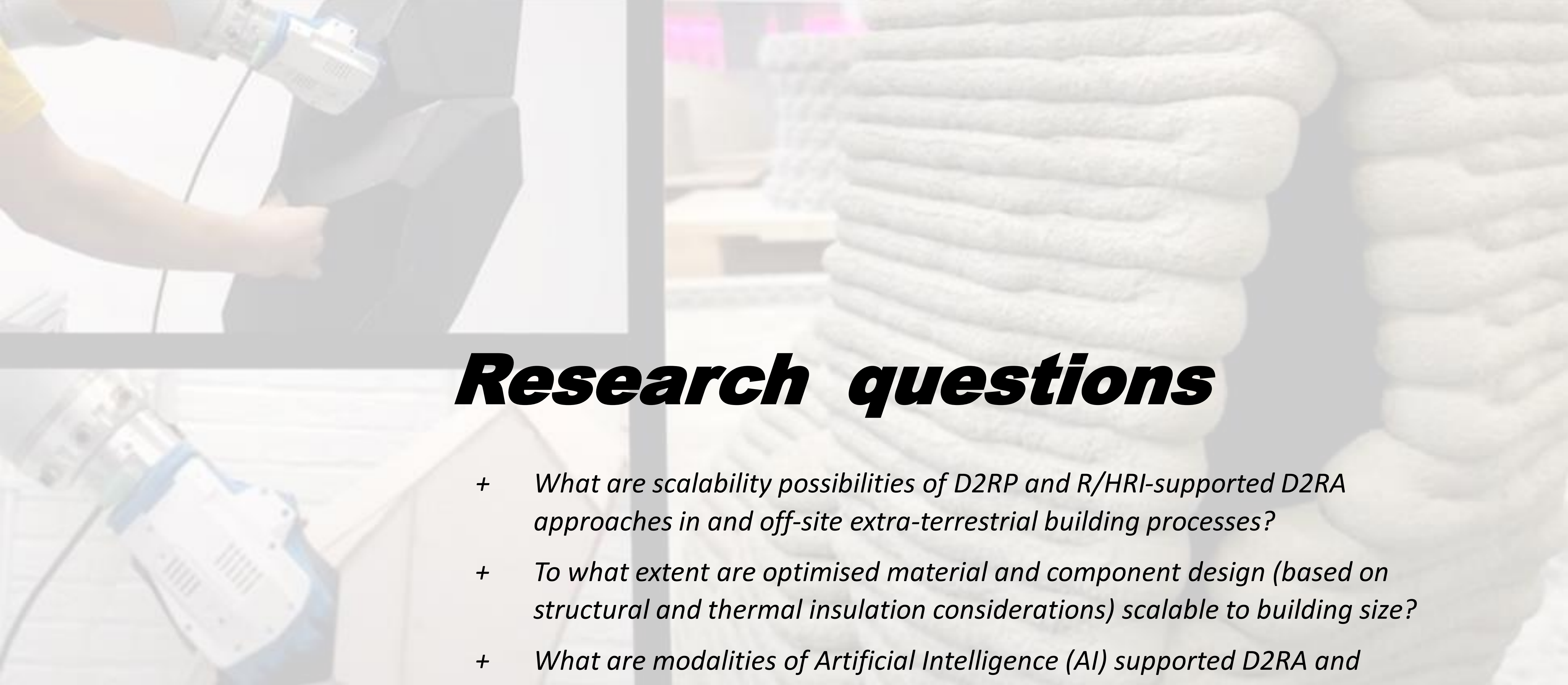
+ 3D printing with geopolymers

D2RA

+ Scaling up HRI–assisted robotic assembly

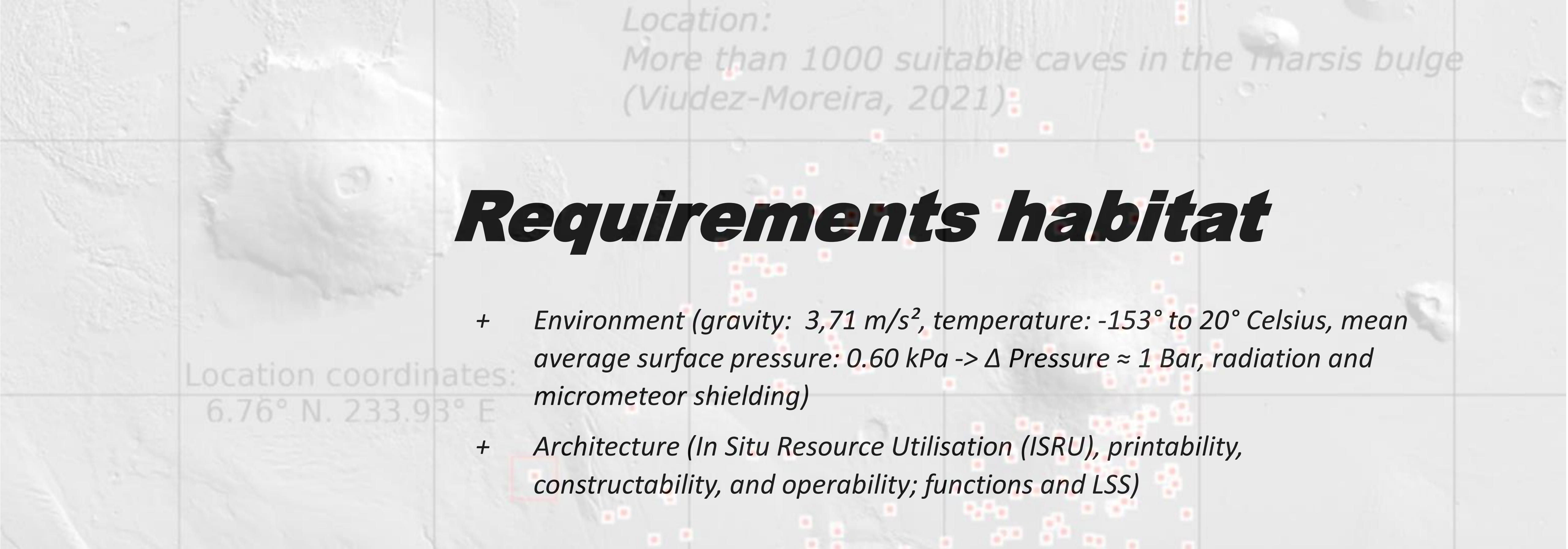
D2RO

+ LSS and indoor garden



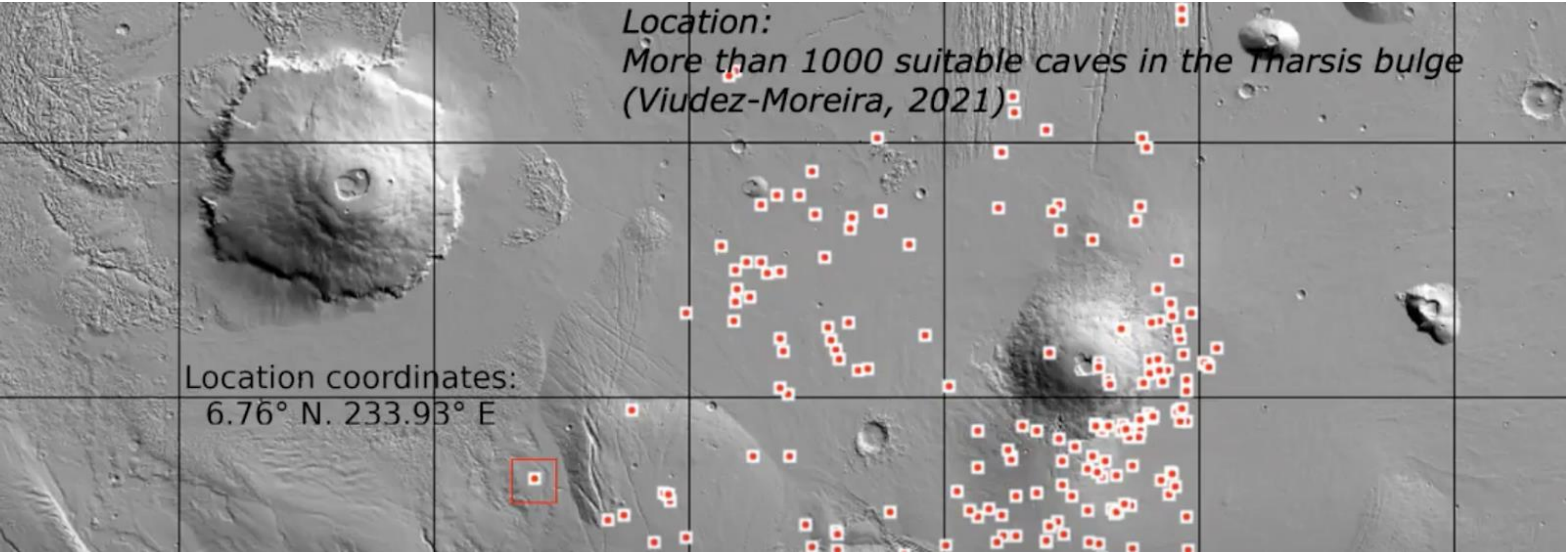
Research questions

- + *What are scalability possibilities of D2RP and R/HRI-supported D2RA approaches in and off-site extra-terrestrial building processes?*
- + *To what extent are optimised material and component design (based on structural and thermal insulation considerations) scalable to building size?*
- + *What are modalities of Artificial Intelligence (AI) supported D2RA and Design to Robotic Operation (D2RO) methods to improve R/HRI-supported assembly and environmental control (i.e., LSS), respectively?*



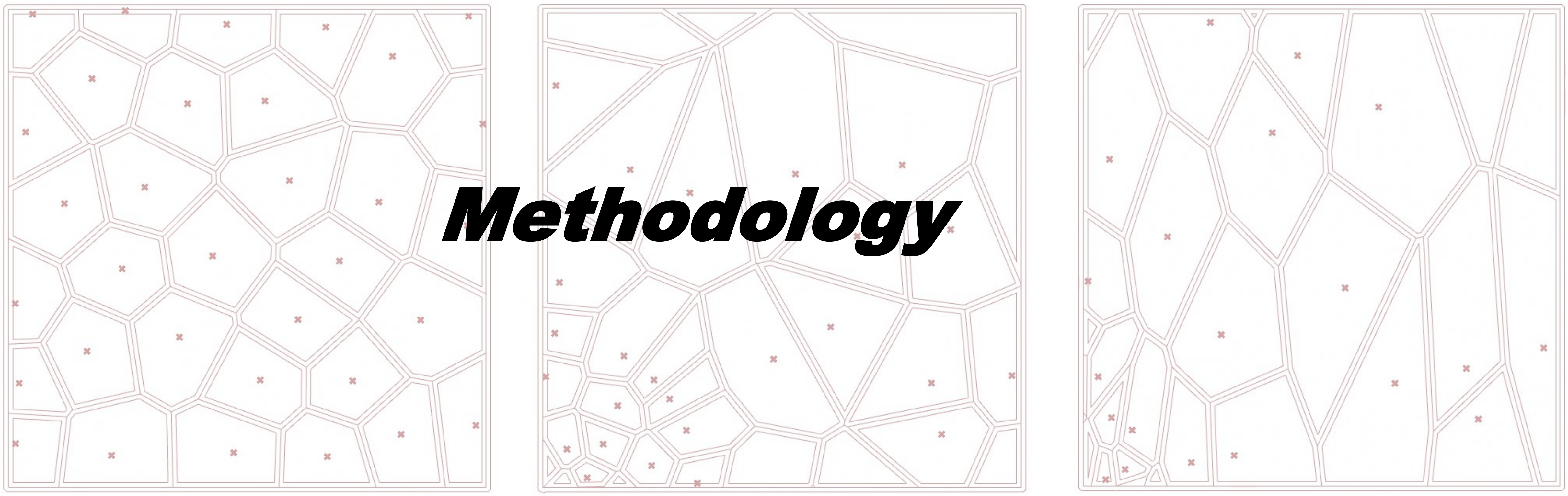
Requirements habitat

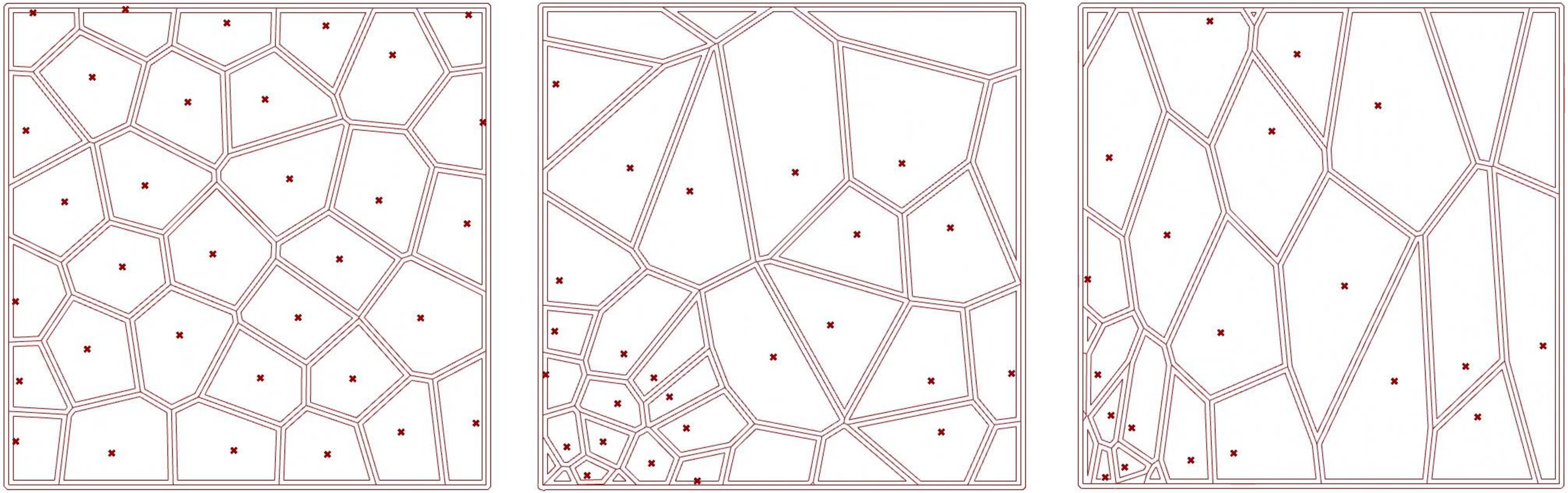
- *Environment (gravity: 3,71 m/s², temperature: -153° to 20° Celsius, mean average surface pressure: 0.60 kPa -> Δ Pressure ≈ 1 Bar, radiation and micrometeor shielding)*
- *Architecture (In Situ Resource Utilisation (ISRU), printability, constructability, and operability; functions and LSS)*



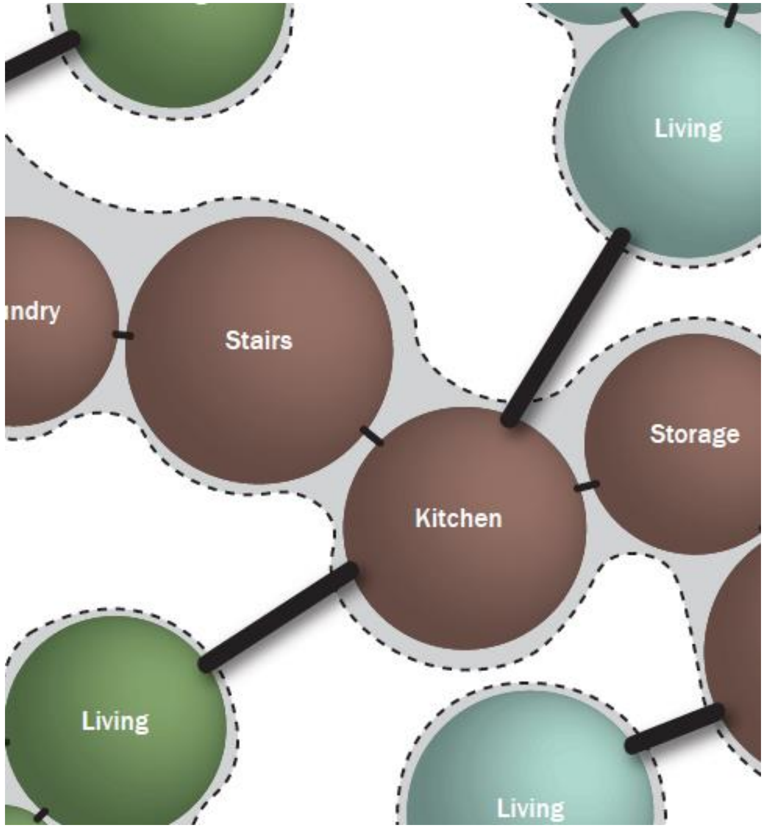
Lava tube location

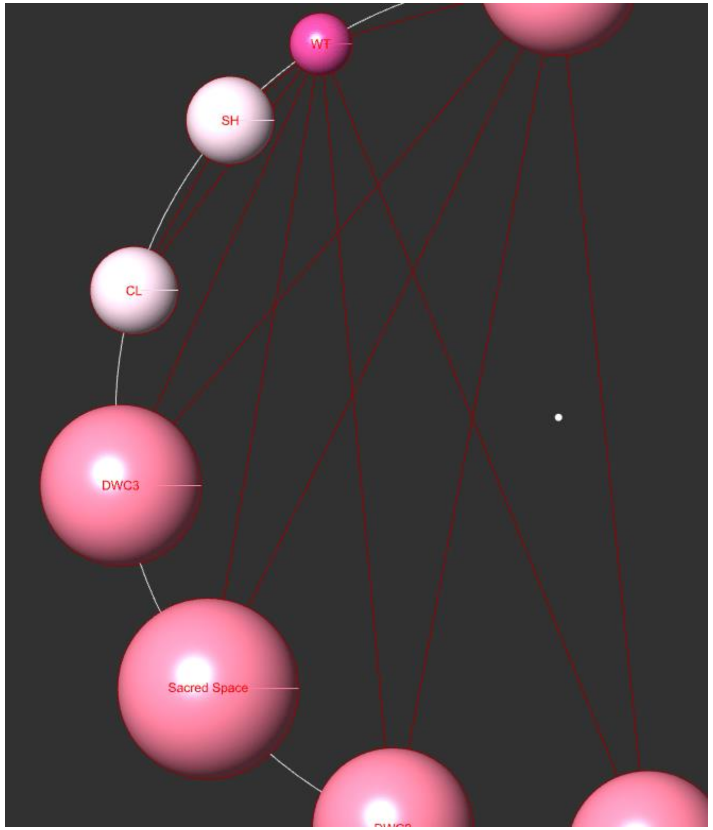
Methodology

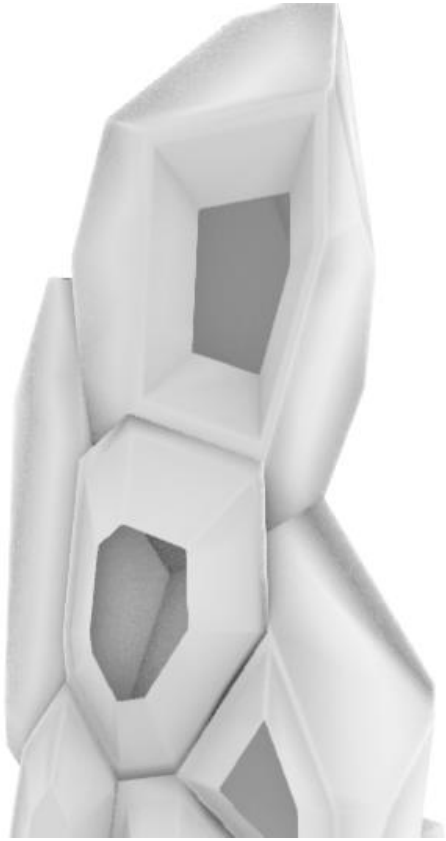




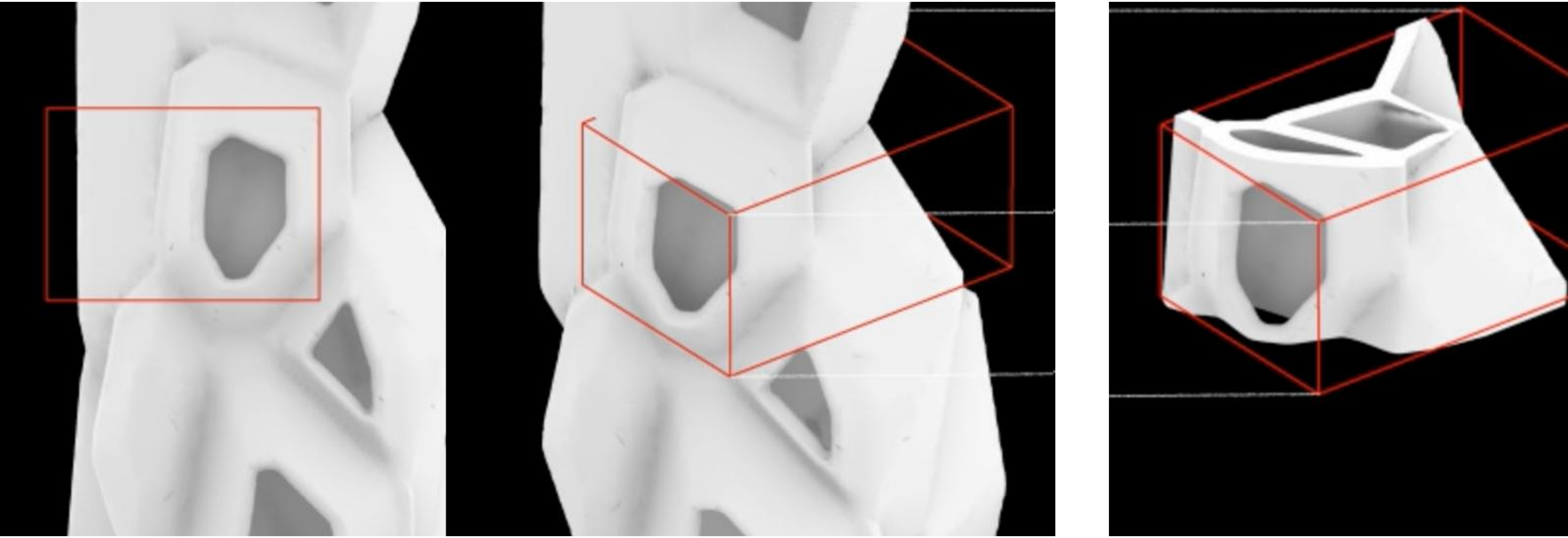
Why Voronoi?



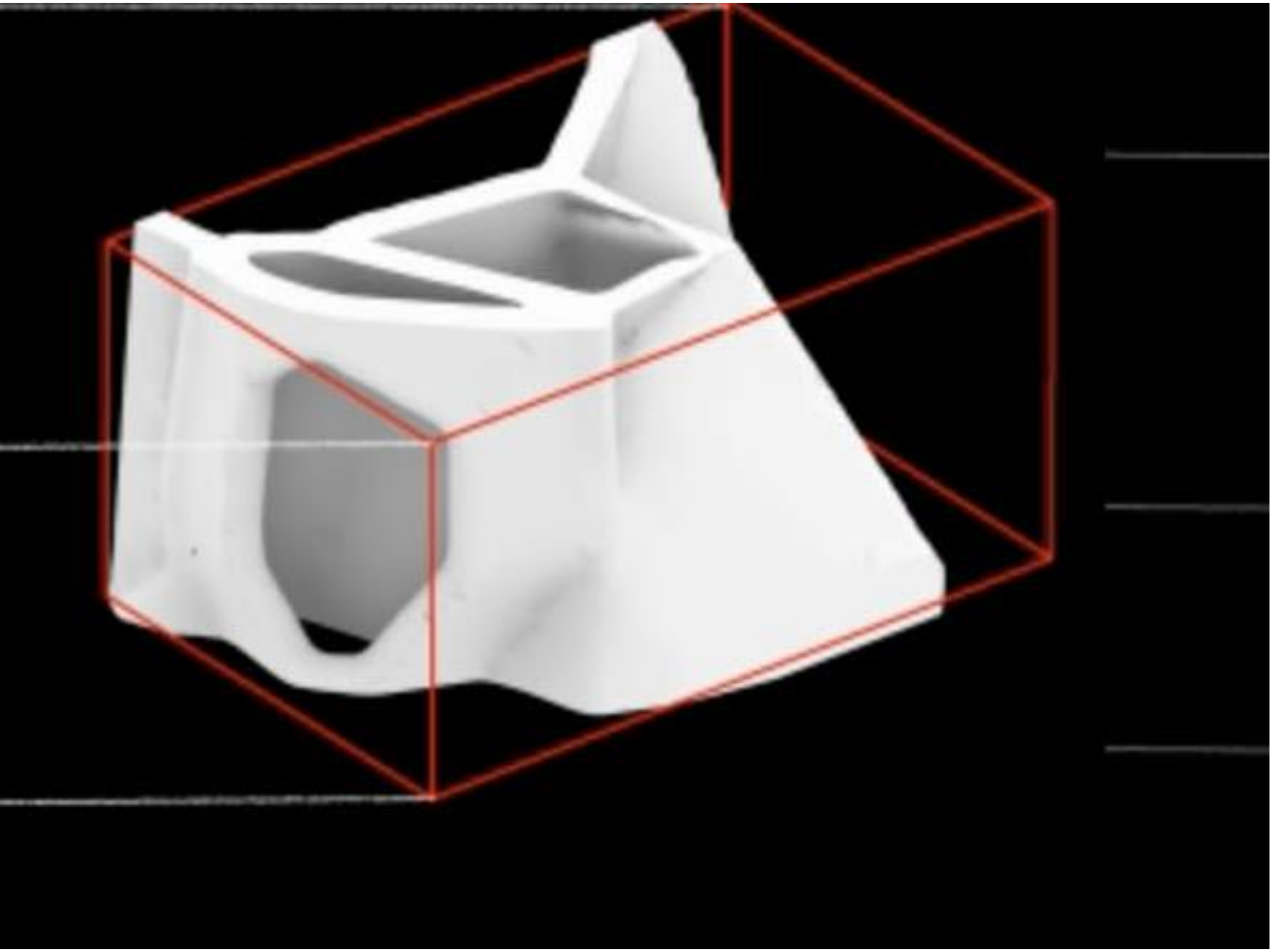


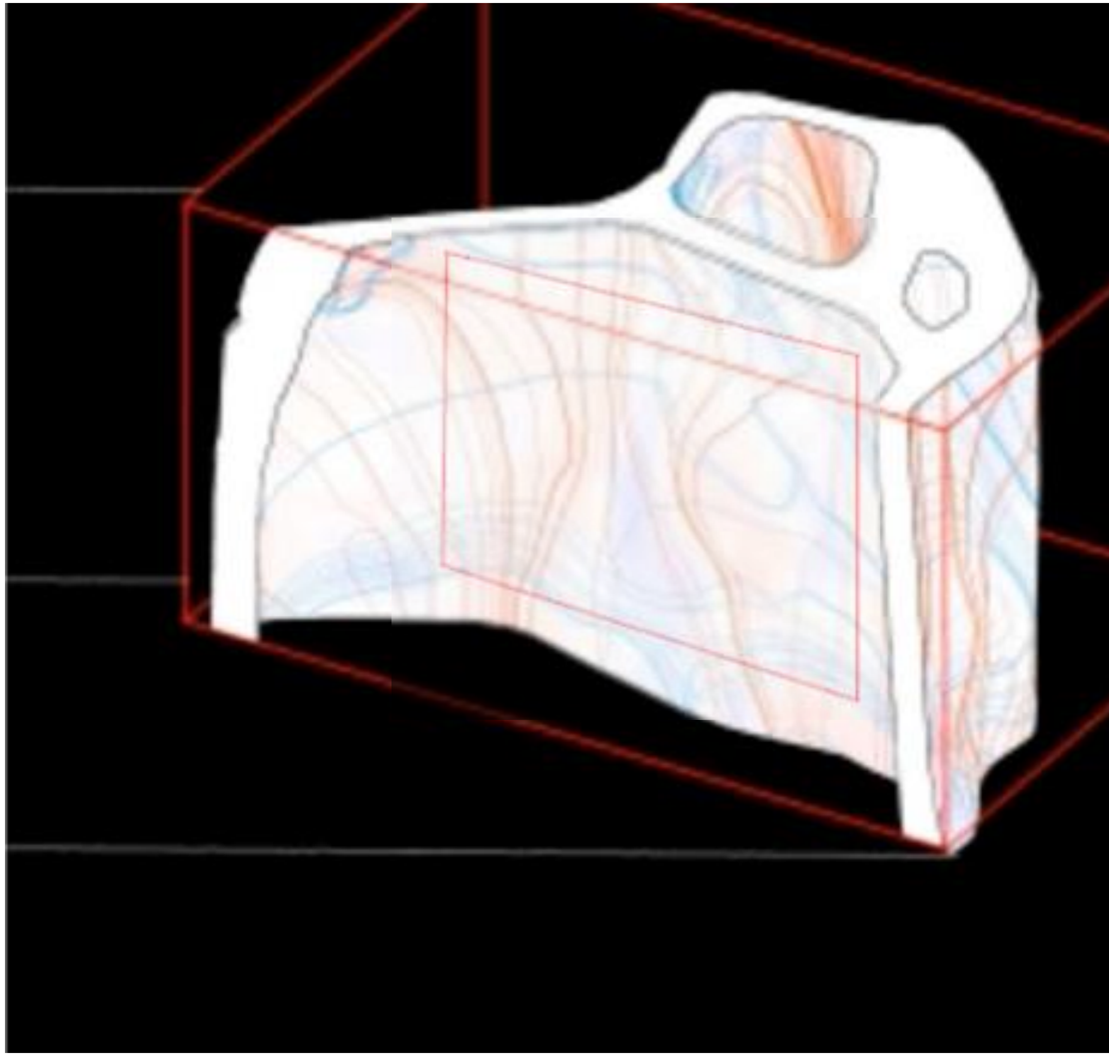


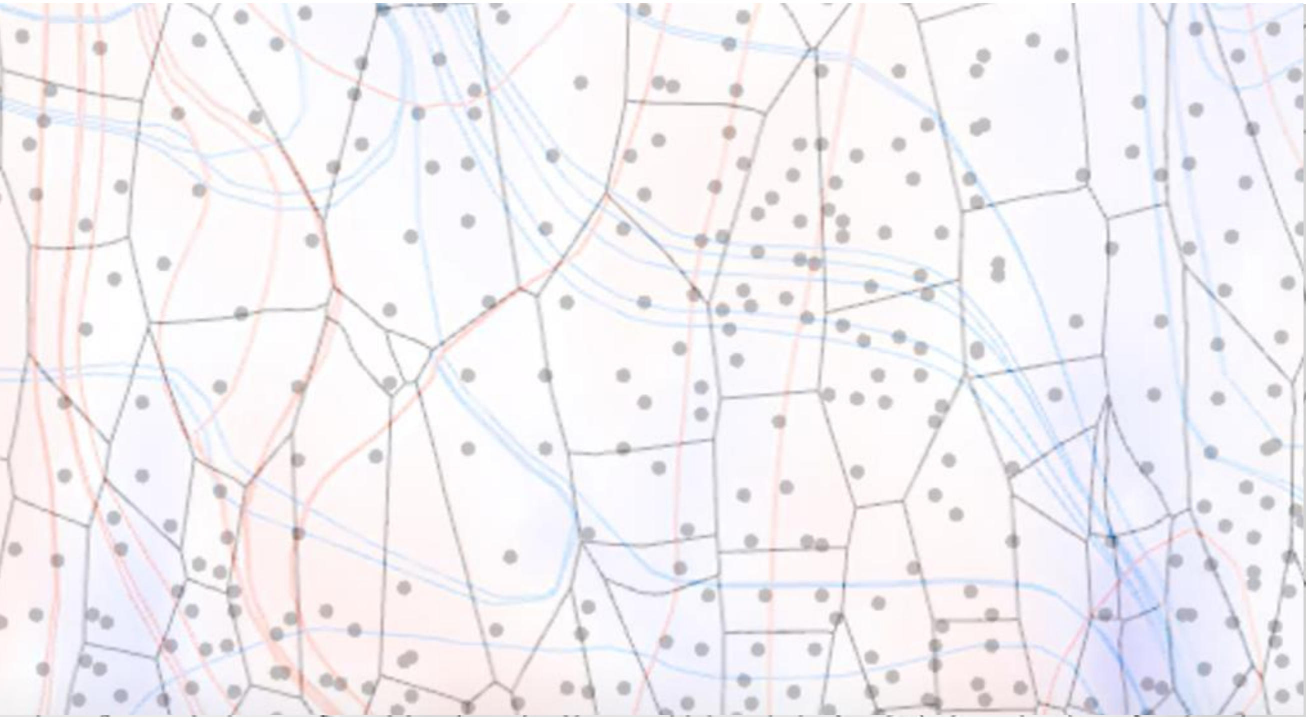
From spatial requirements to building

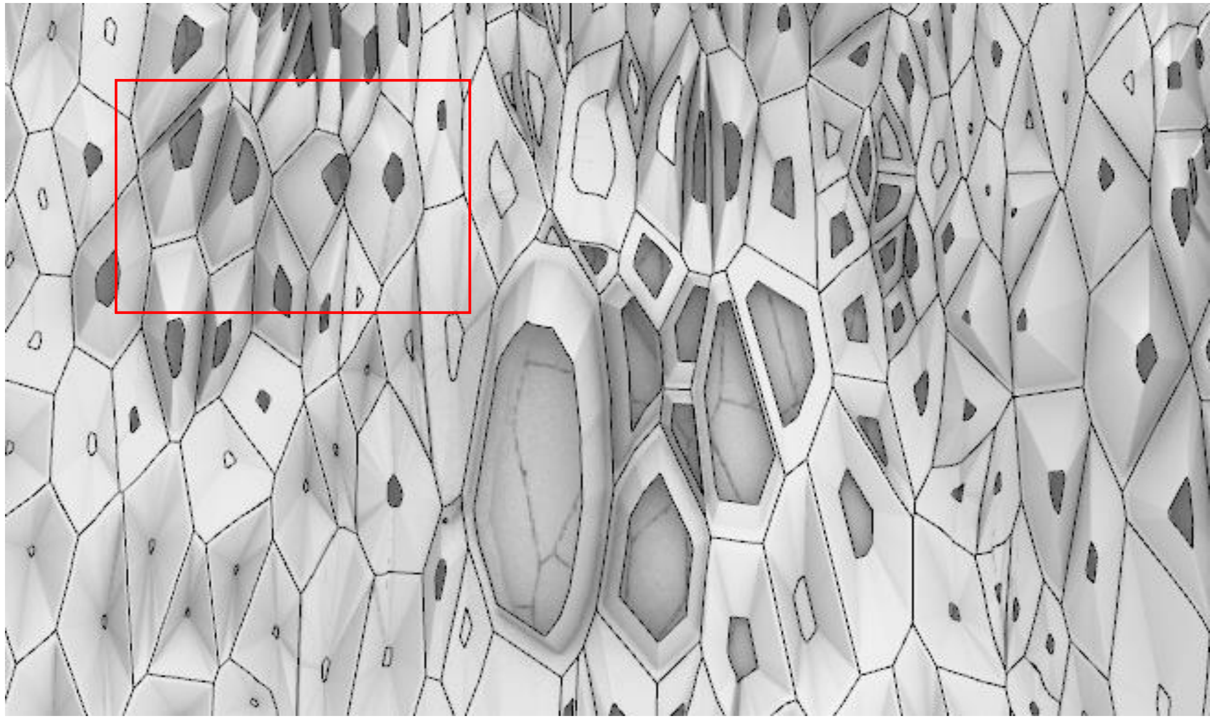


Fragment selection

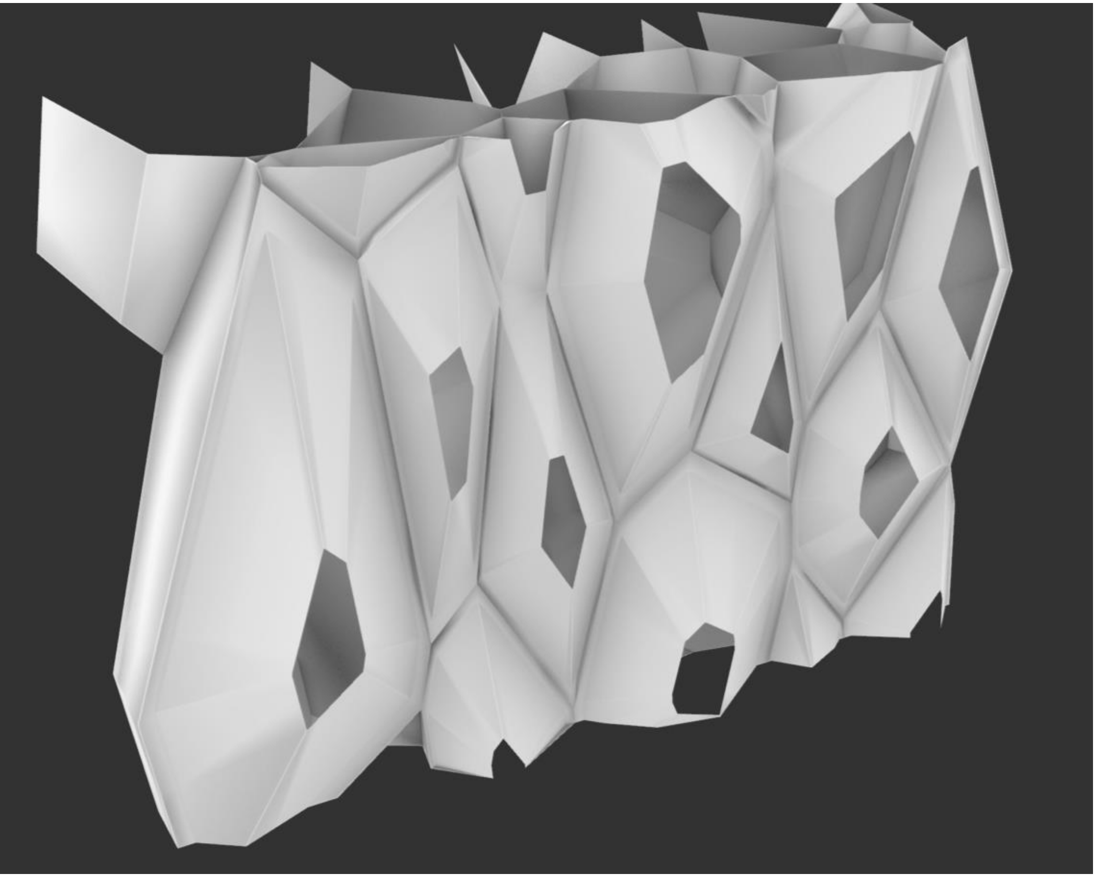


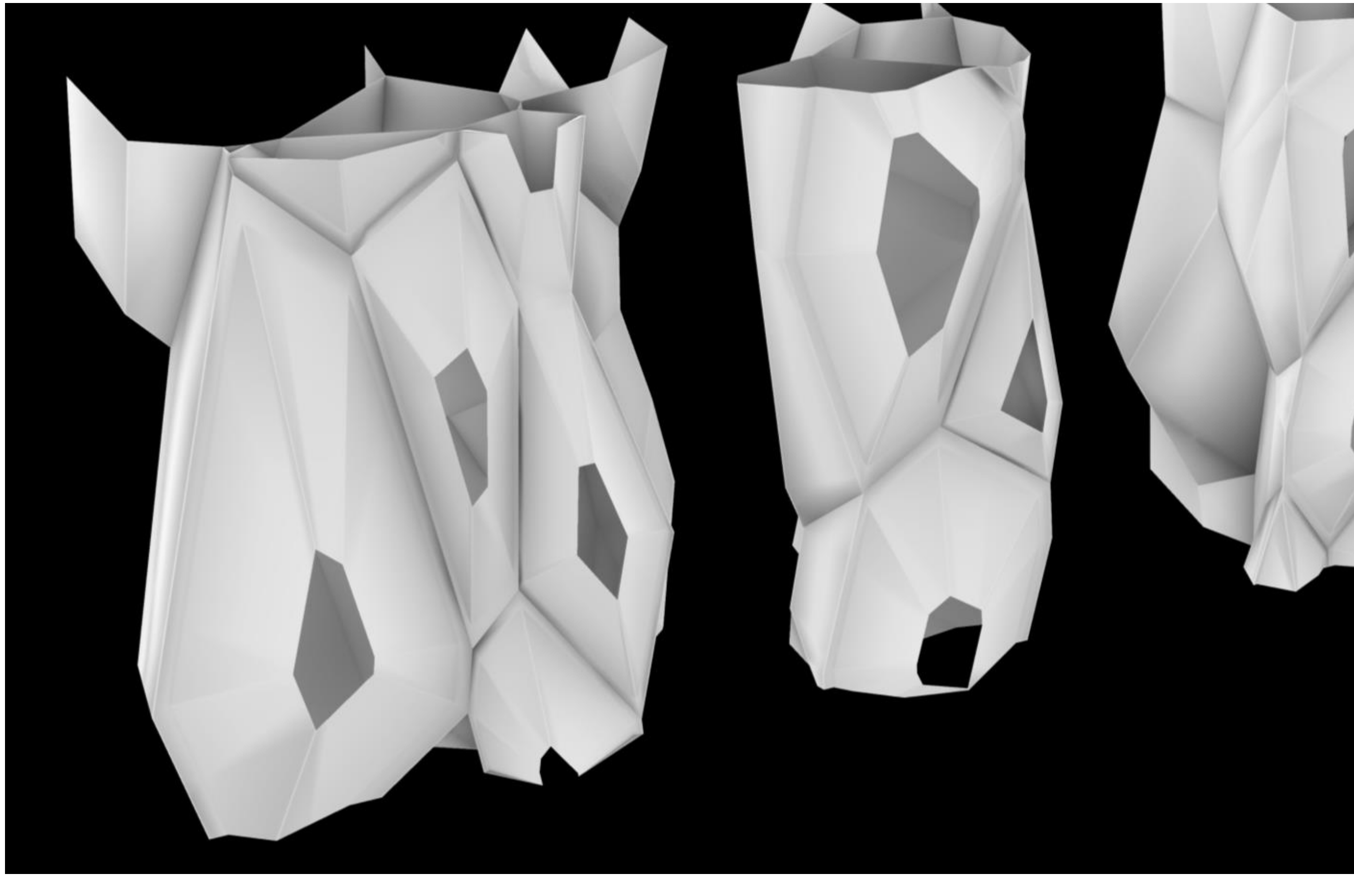




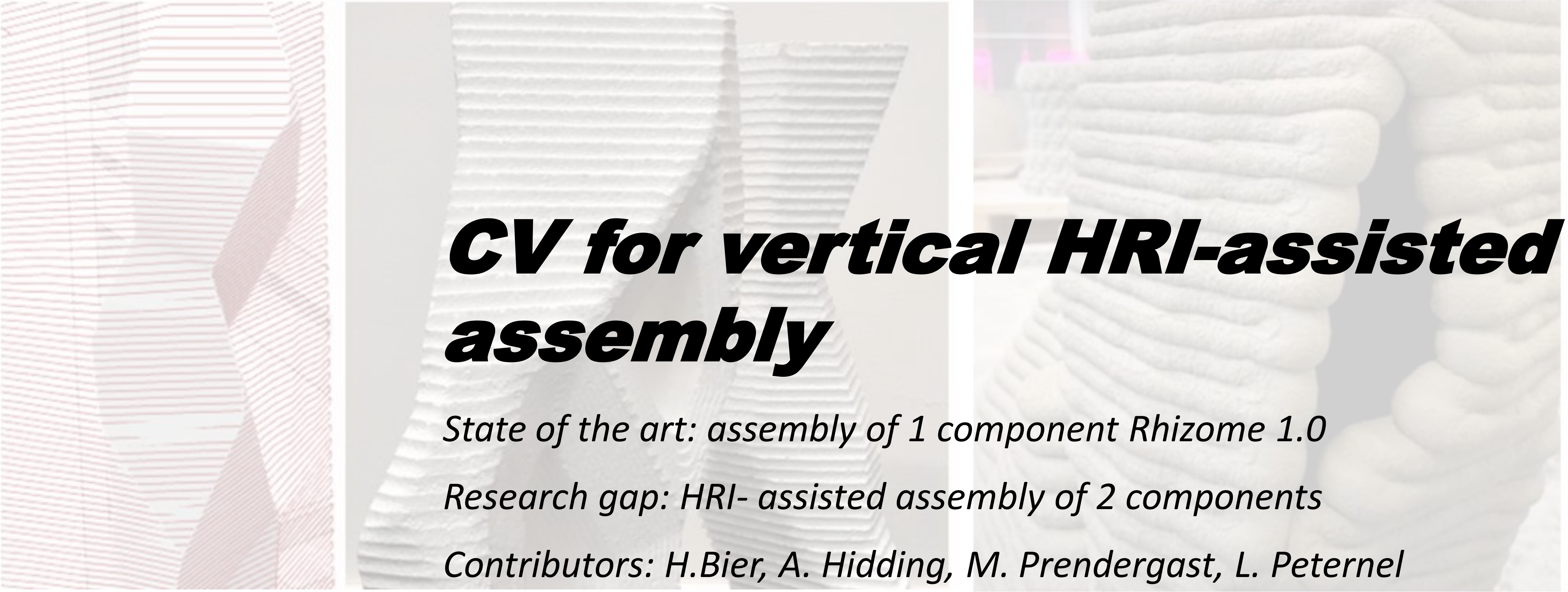


<u>Adaptive Voronoi</u> distribution based on structural and functional optimisation





Componential logic based on <u>assembly</u> requirements



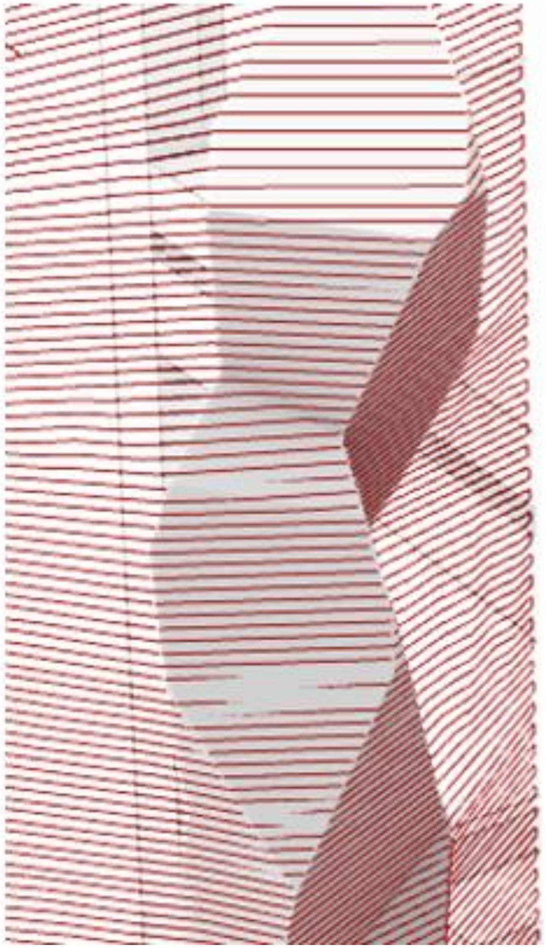
CV for vertical HRI-assisted assembly

State of the art: assembly of 1 component Rhizome 1.0

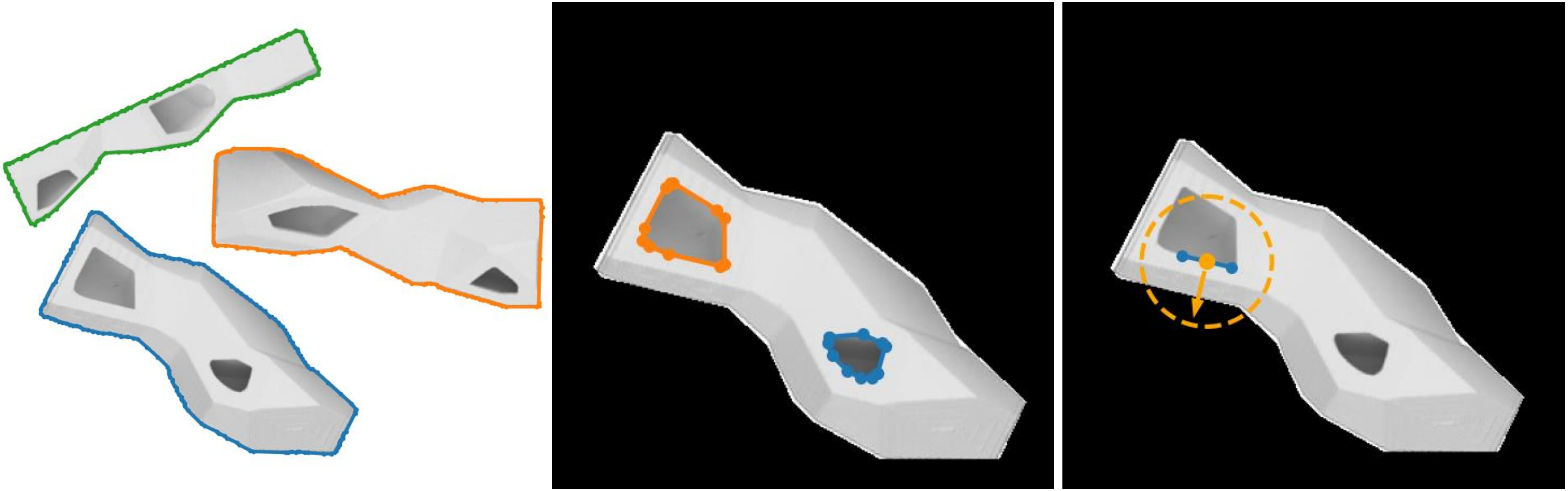
Research gap: HRI- assisted assembly of 2 components

Contributors: H.Bier, A. Hidding, M. Prendergast, L. Peternel

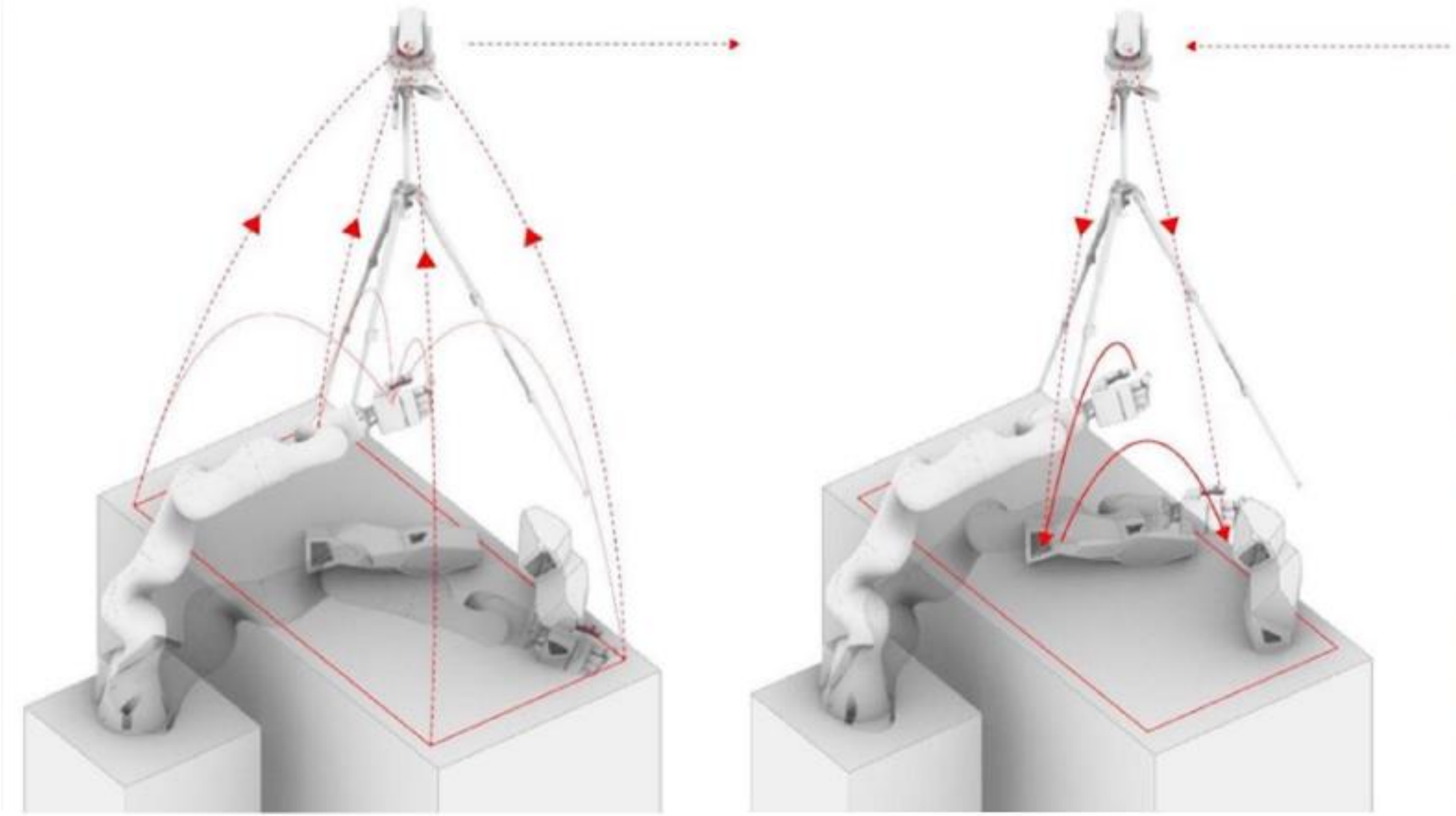
Contribution: supervision of students, D2RP of the mock-ups, HRI session data collection



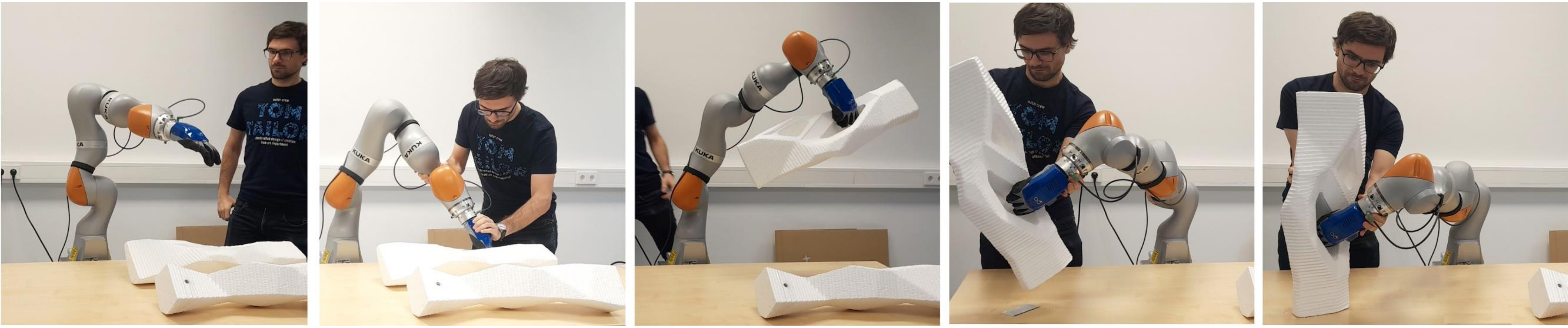
MSc2 workshop: mock-up @RB lab



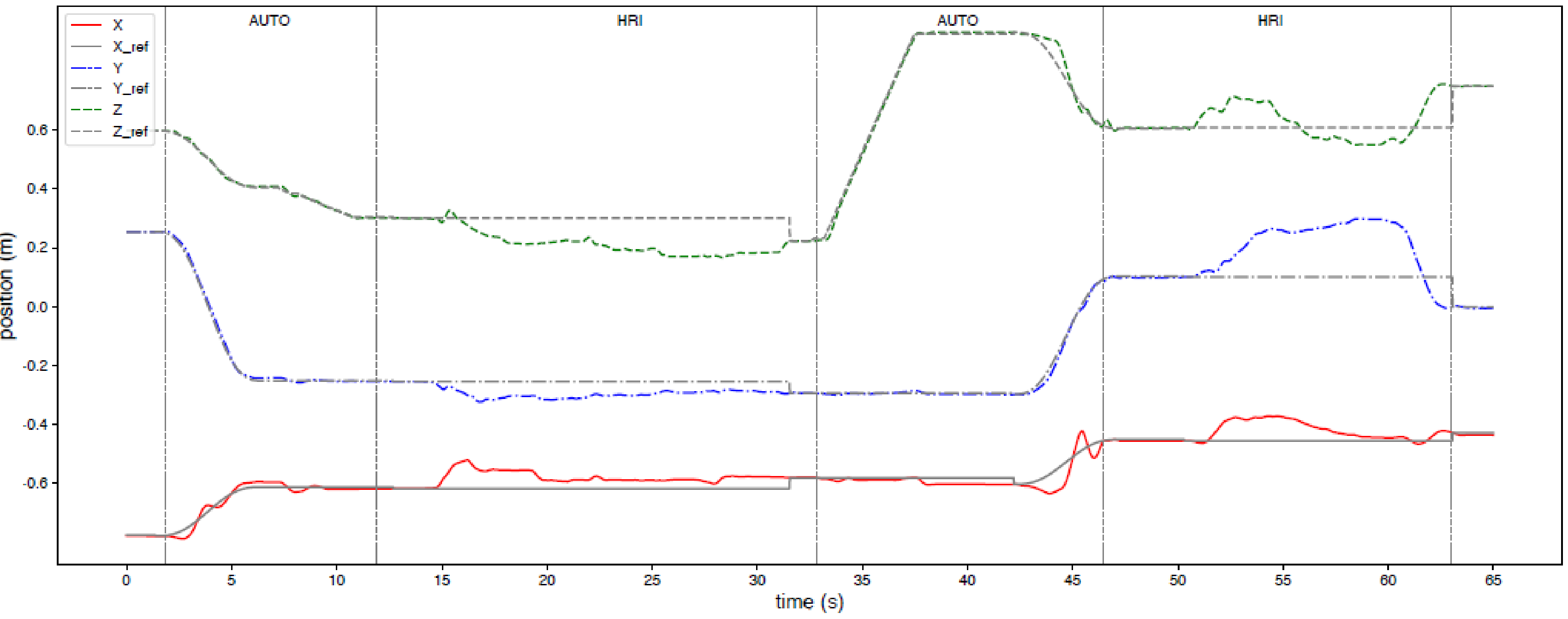
CV for HRI @AiDAPT lab

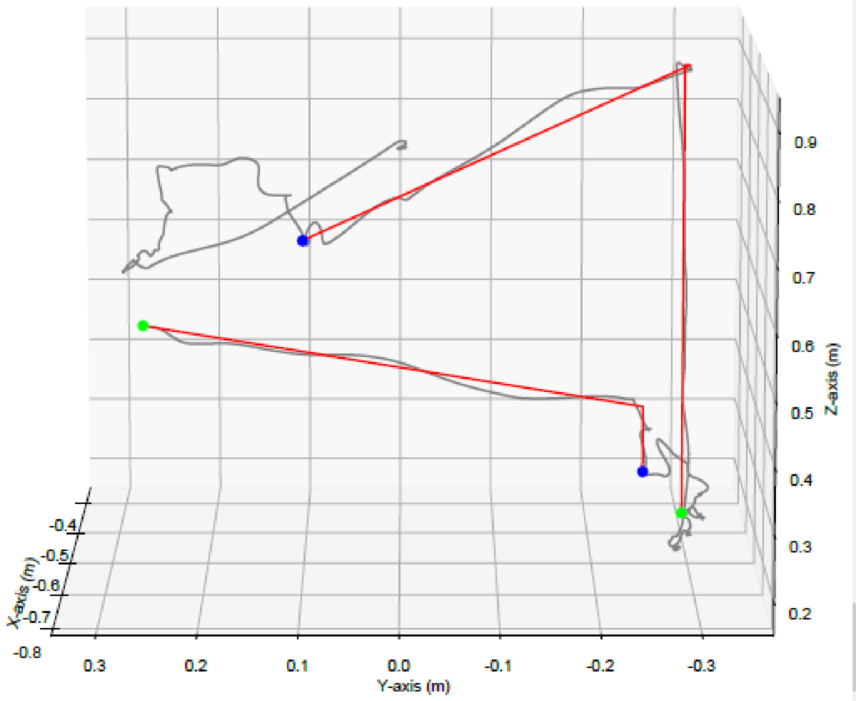


Path planning @CoR lab
@iSpaRo2024

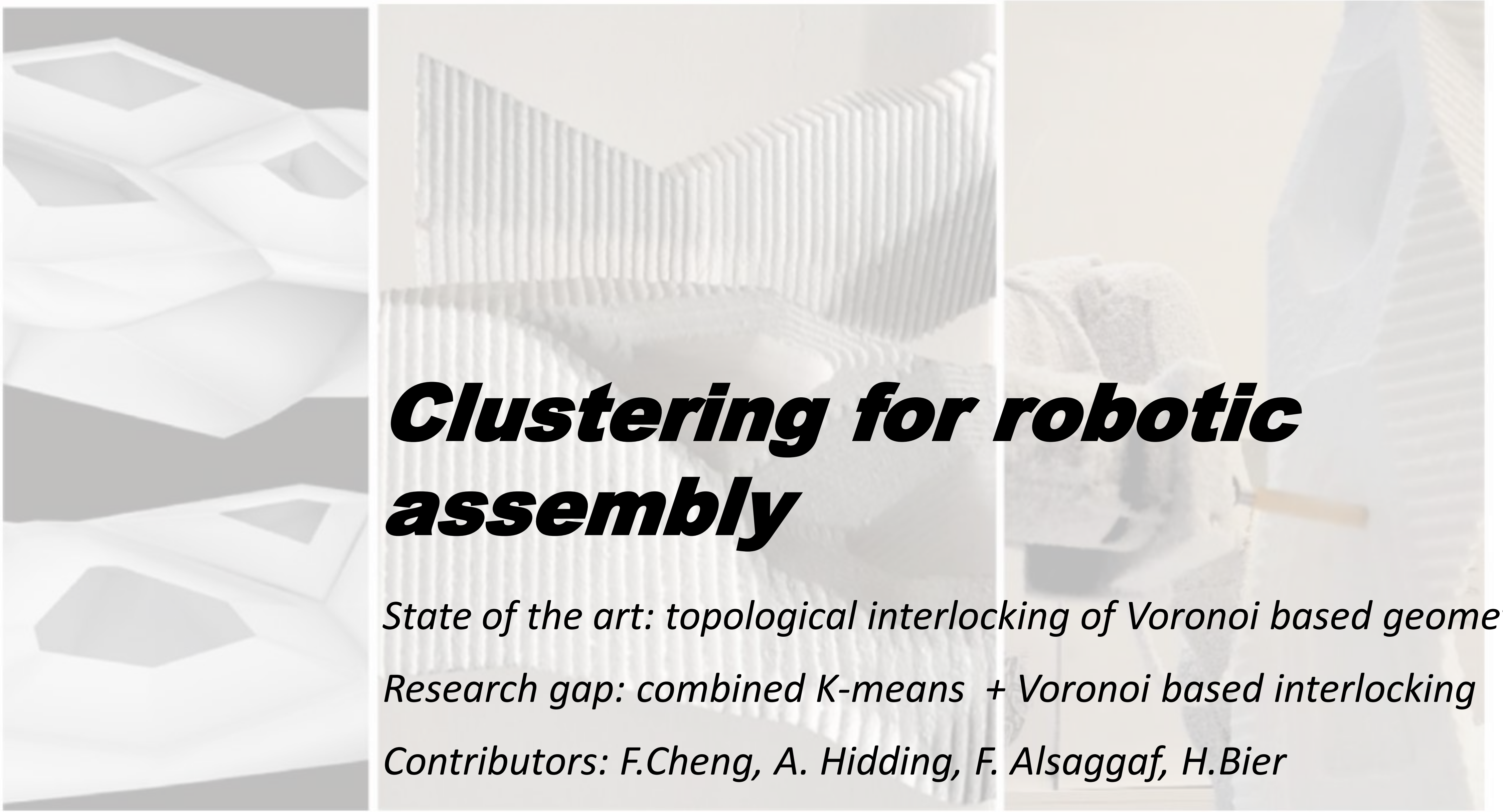


HRI –supported D2RA @CoR lab





Recorded HRI path data @CoR lab



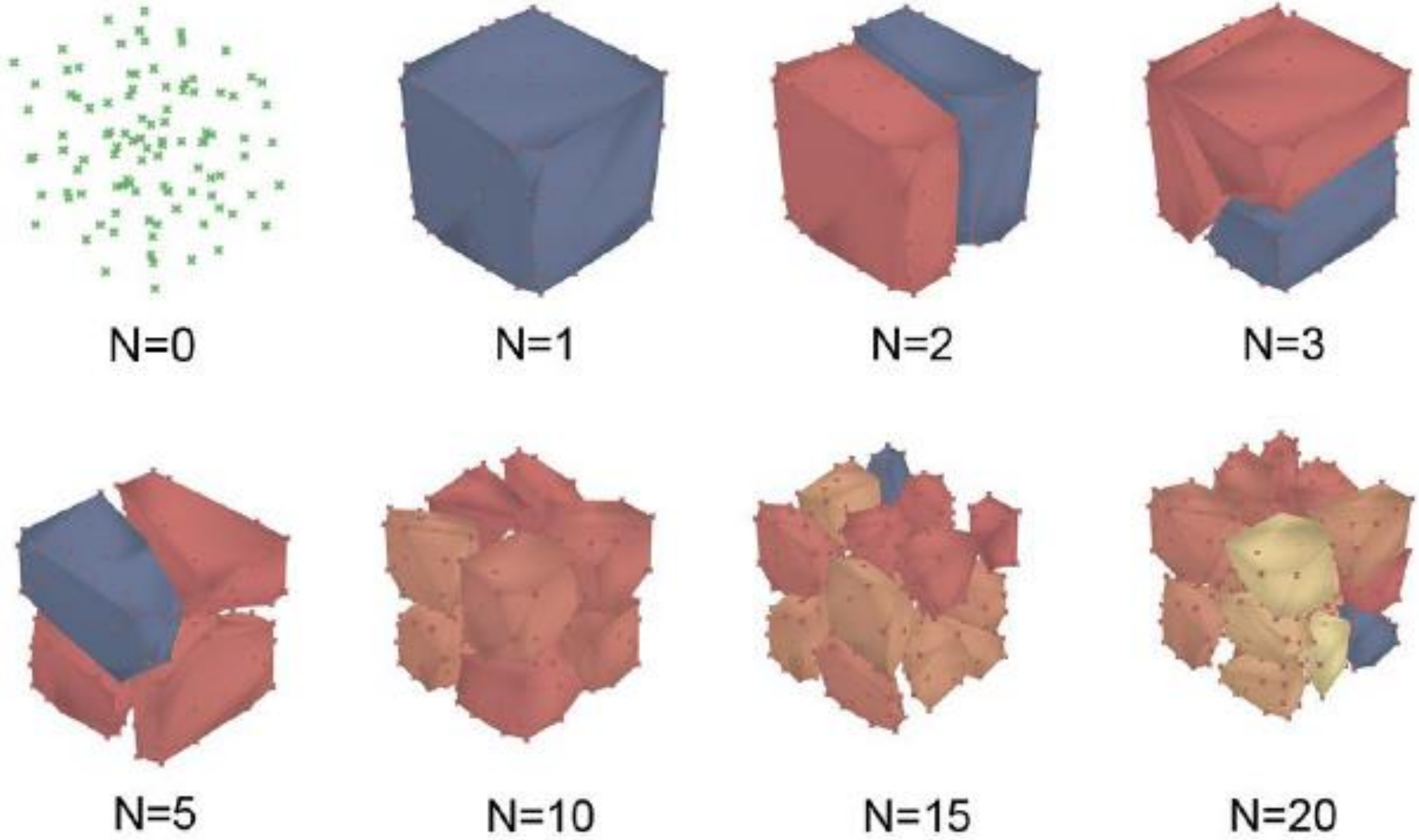
Clustering for robotic assembly

State of the art: topological interlocking of Voronoi based geometry

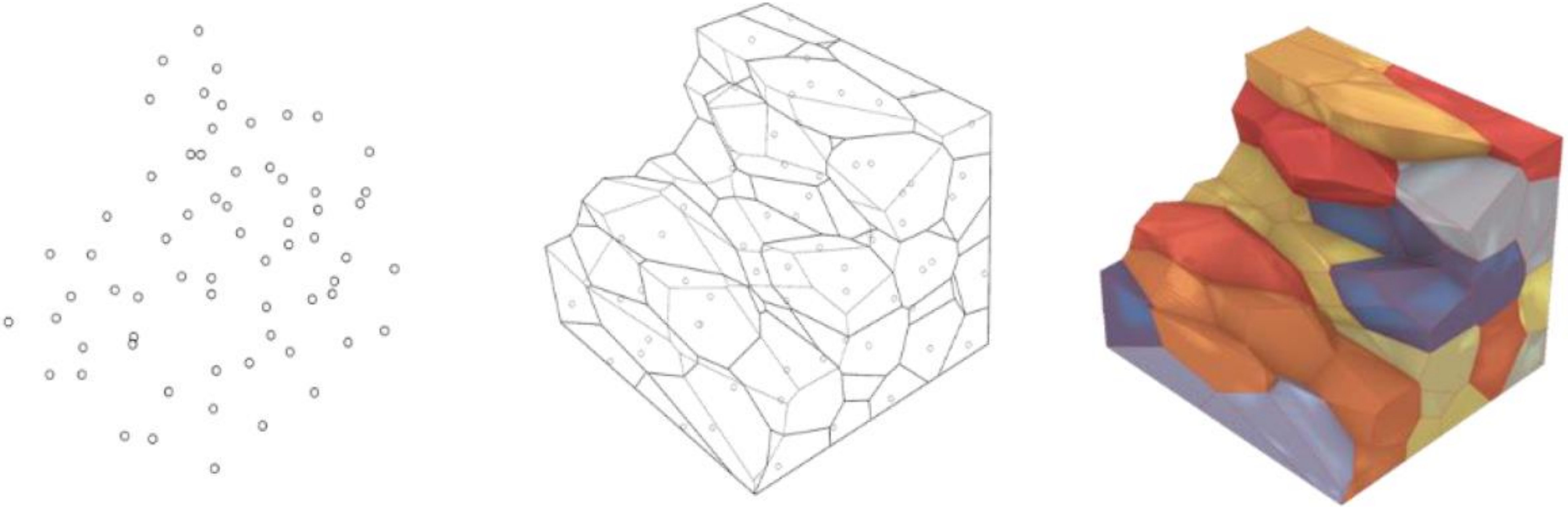
Research gap: combined K-means + Voronoi based interlocking

Contributors: F.Cheng, A. Hidding, F. Alsaggaf, H.Bier

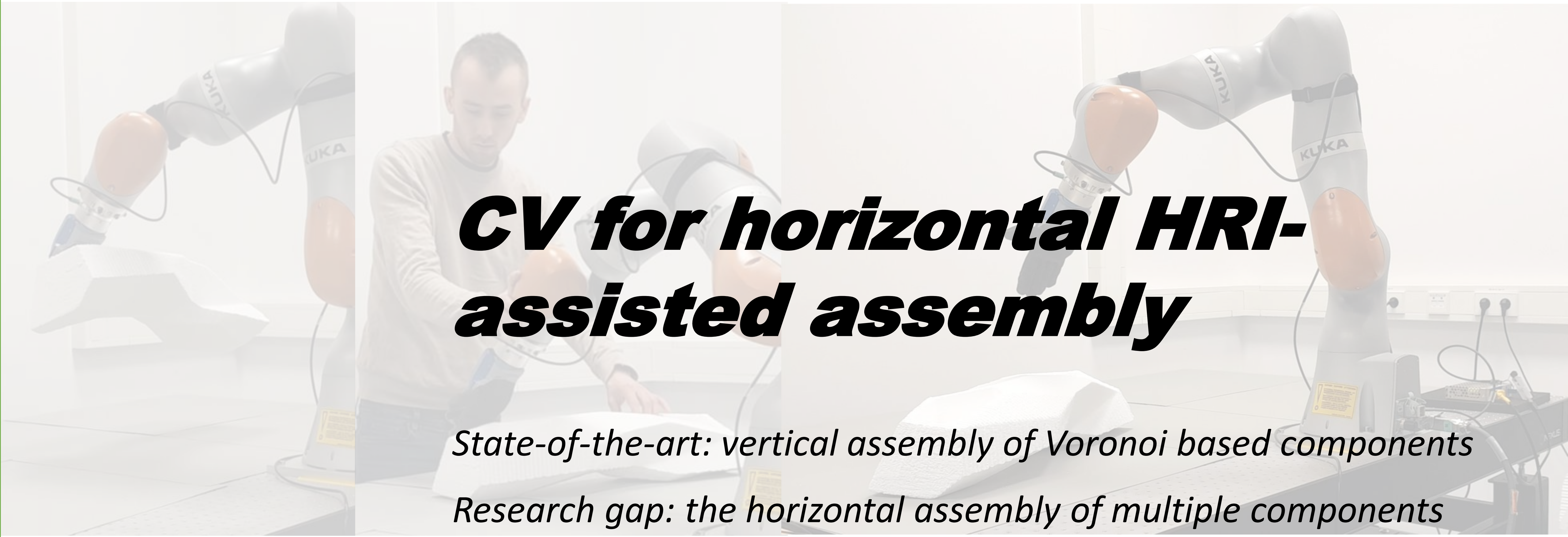
Contribution: D2RP of components, 3D models of Voronoi based components and building skin



Point cloud to K-means clustering



Point cloud to Voronoi cell clustering & component interlocking



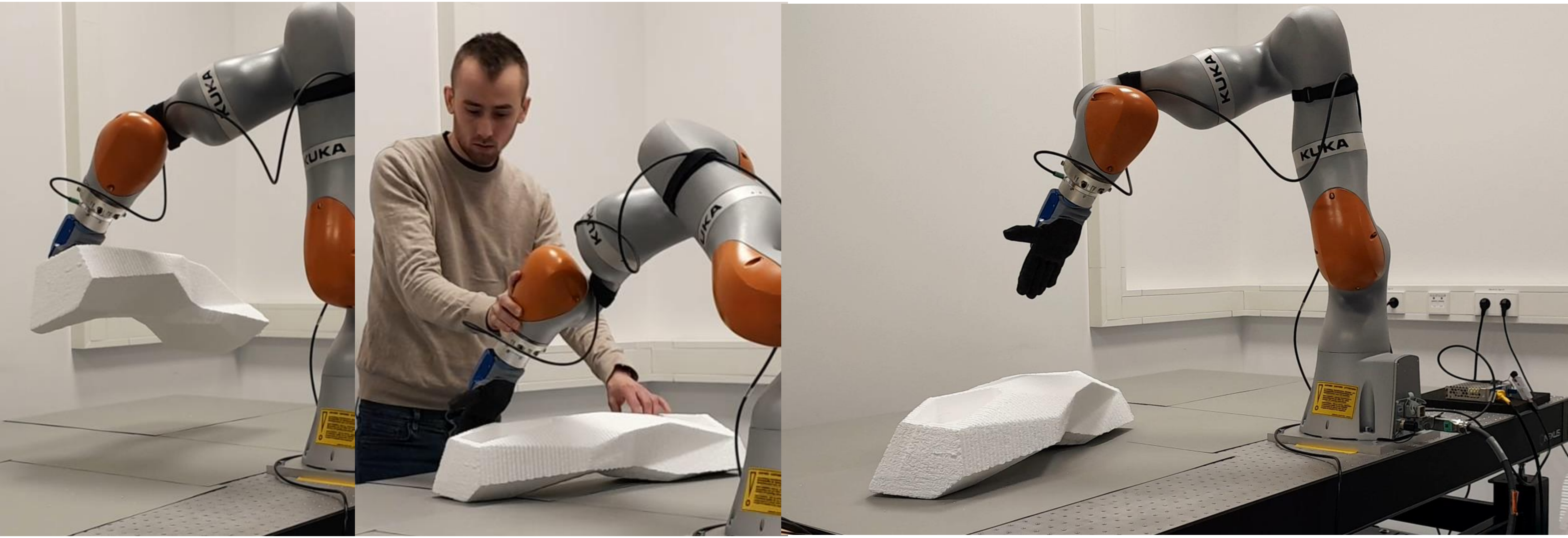
CV for horizontal HRI-assisted assembly

State-of-the-art: vertical assembly of Voronoi based components

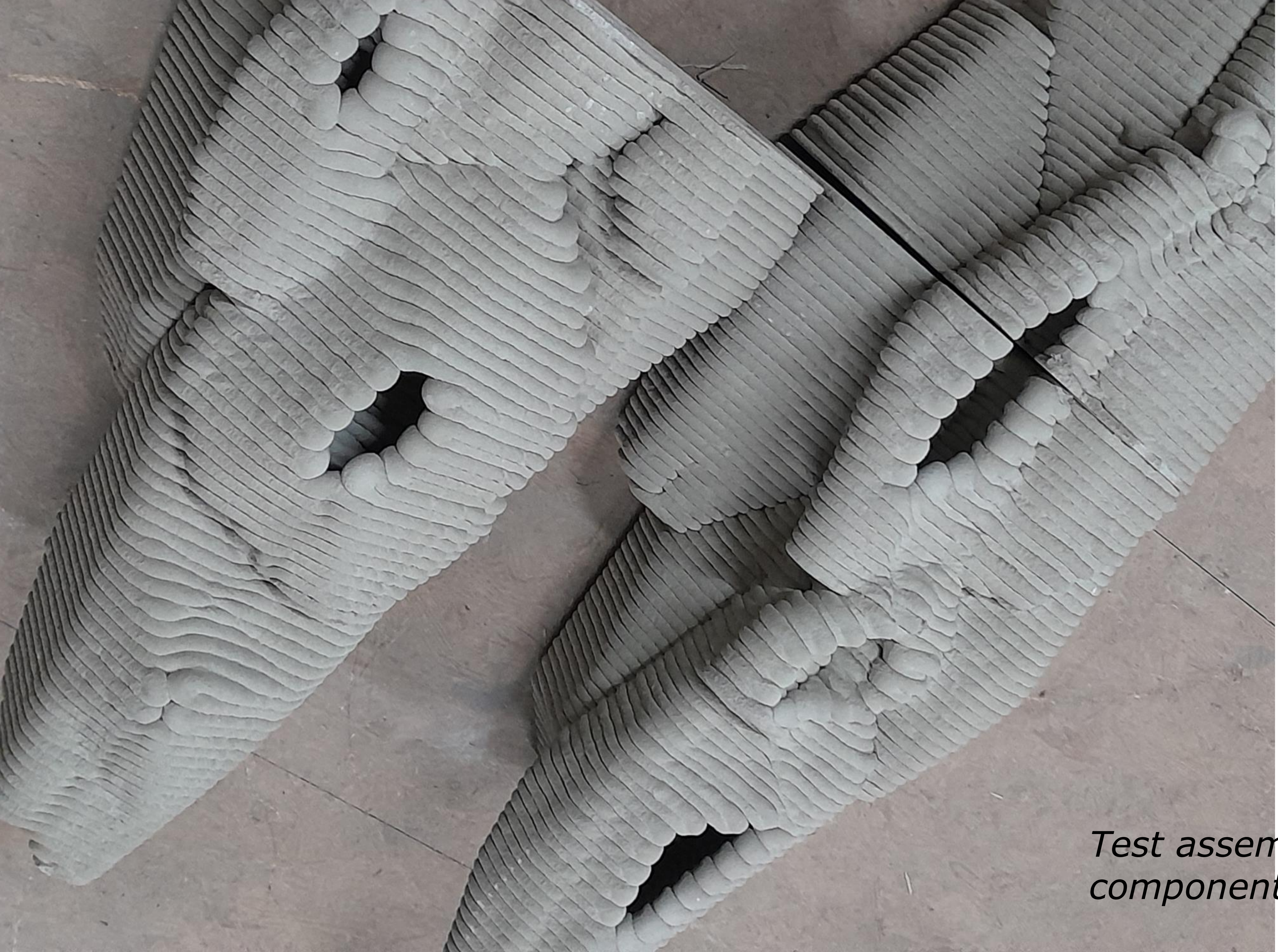
Research gap: the horizontal assembly of multiple components

Contributors: A. Hidding, H.Bier, L. Peternel, M. Prendergast

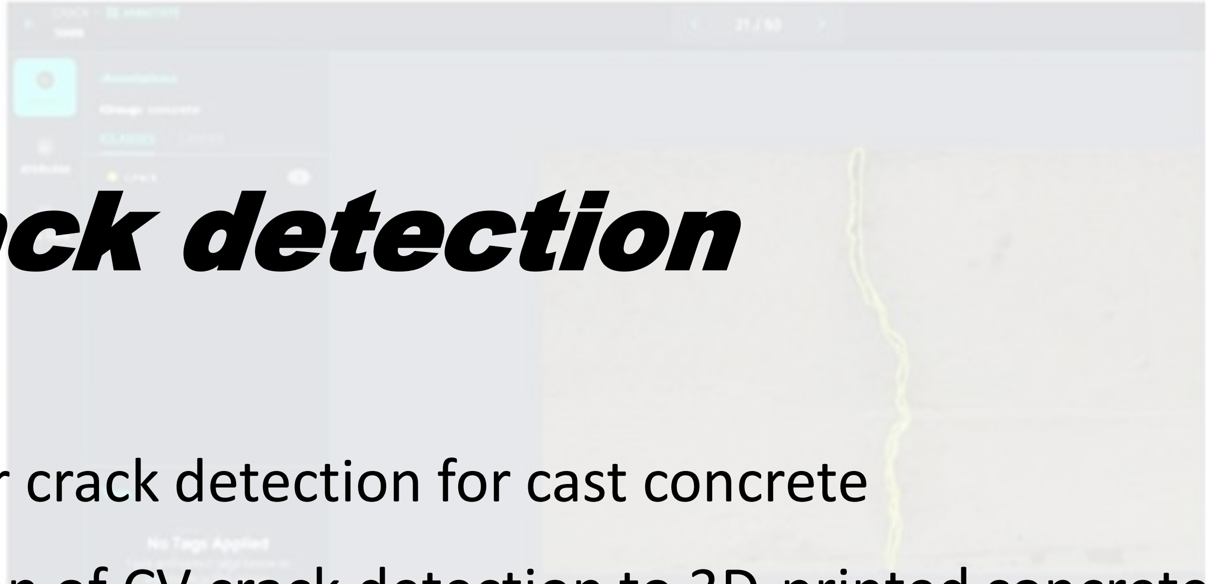
Contribution: D2RP of components, CV detection script, HRI script



Horizontal assembly @CoR lab



Test assembly of 3D printed components



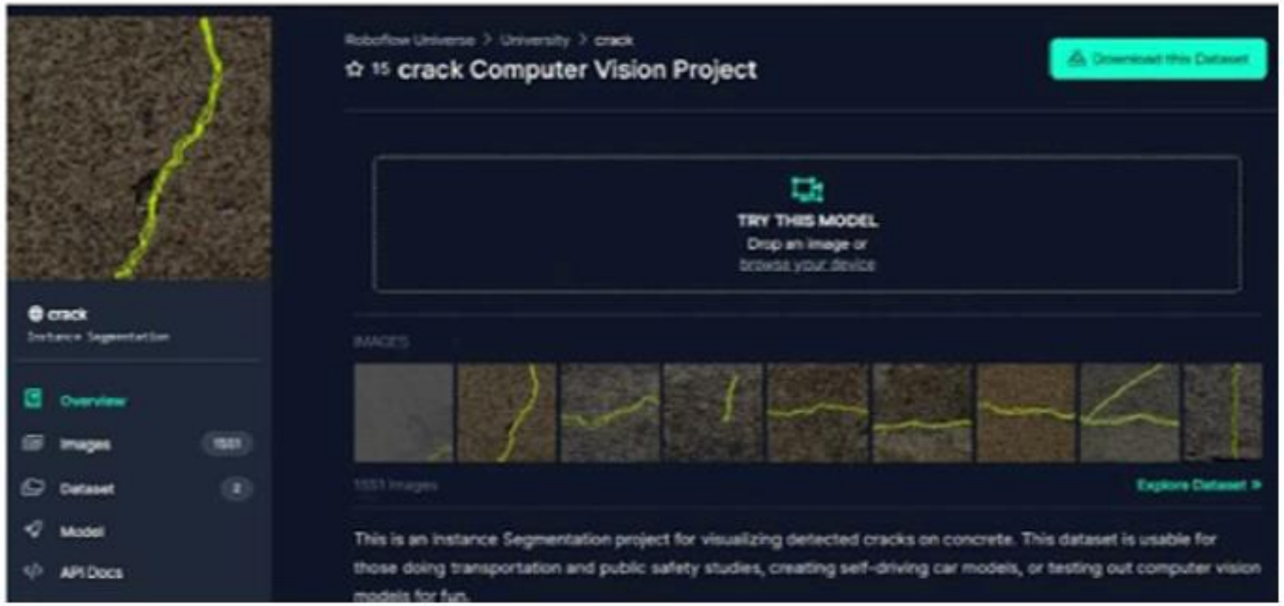
CV for crack detection

State-of-the-art: CV for crack detection for cast concrete

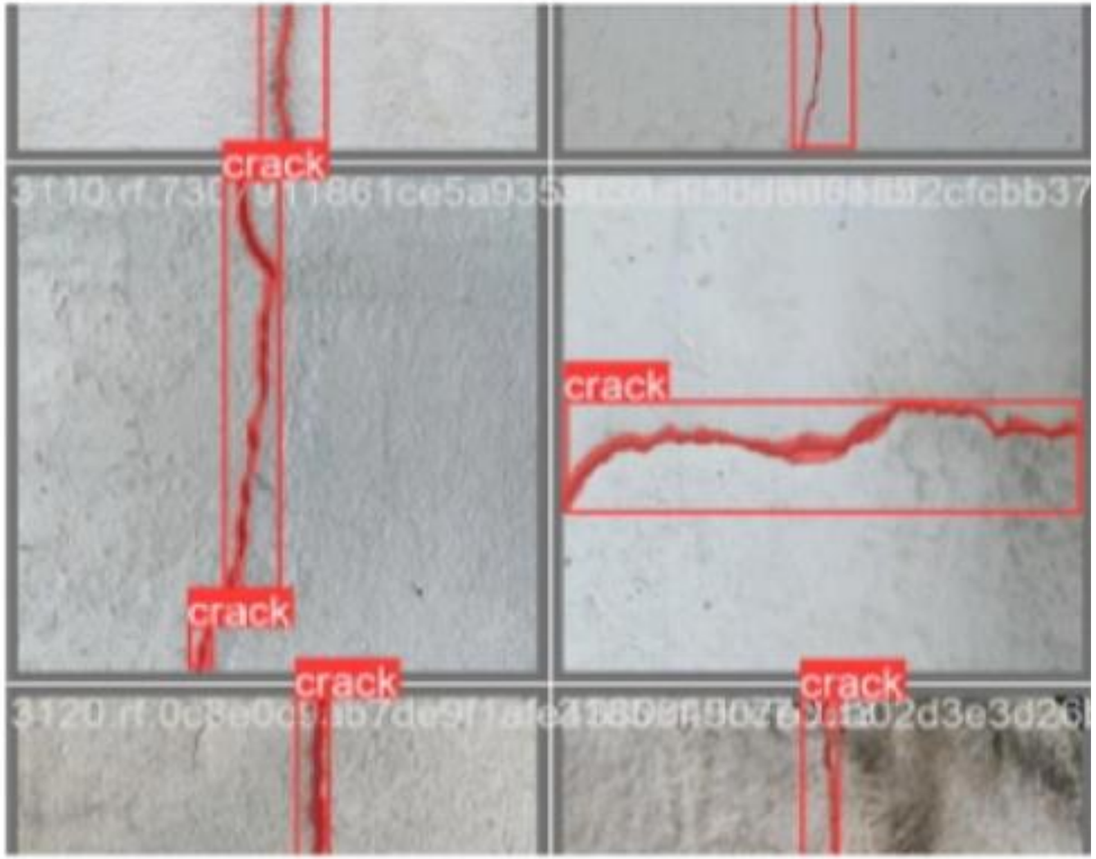
Research gap: extension of CV crack detection to 3D-printed concrete

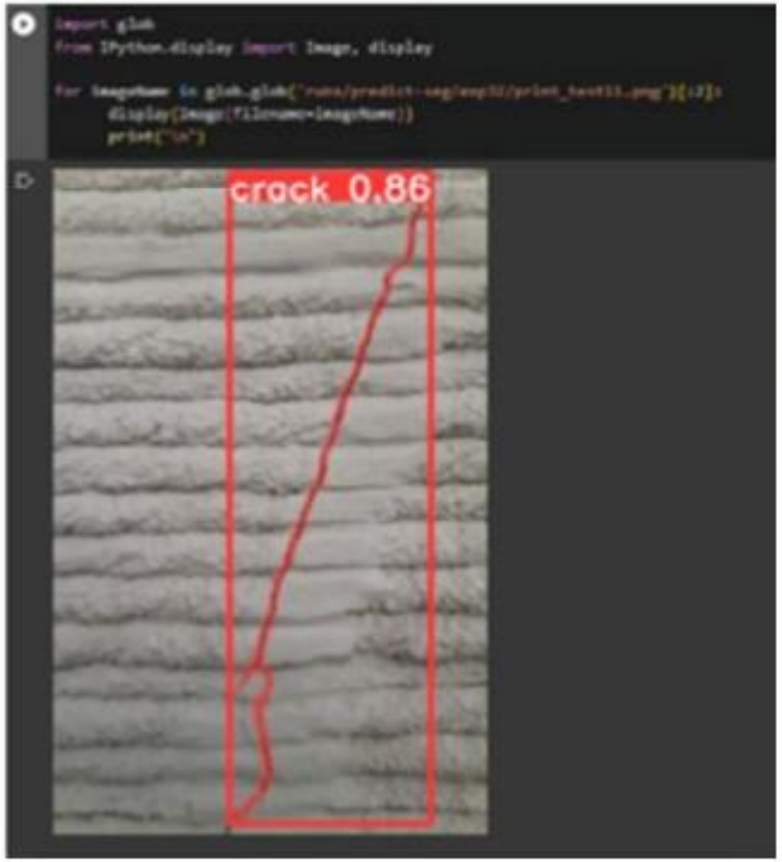
Contributors: H. Bier, A. Hidding, J. Lewandowska, and G.Calabrese

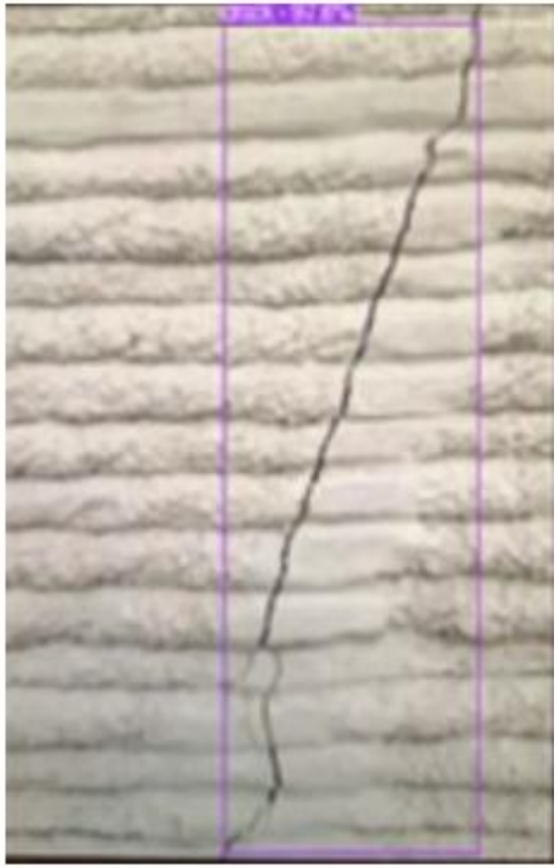
Contribution: Supervision of the MSc 2 students



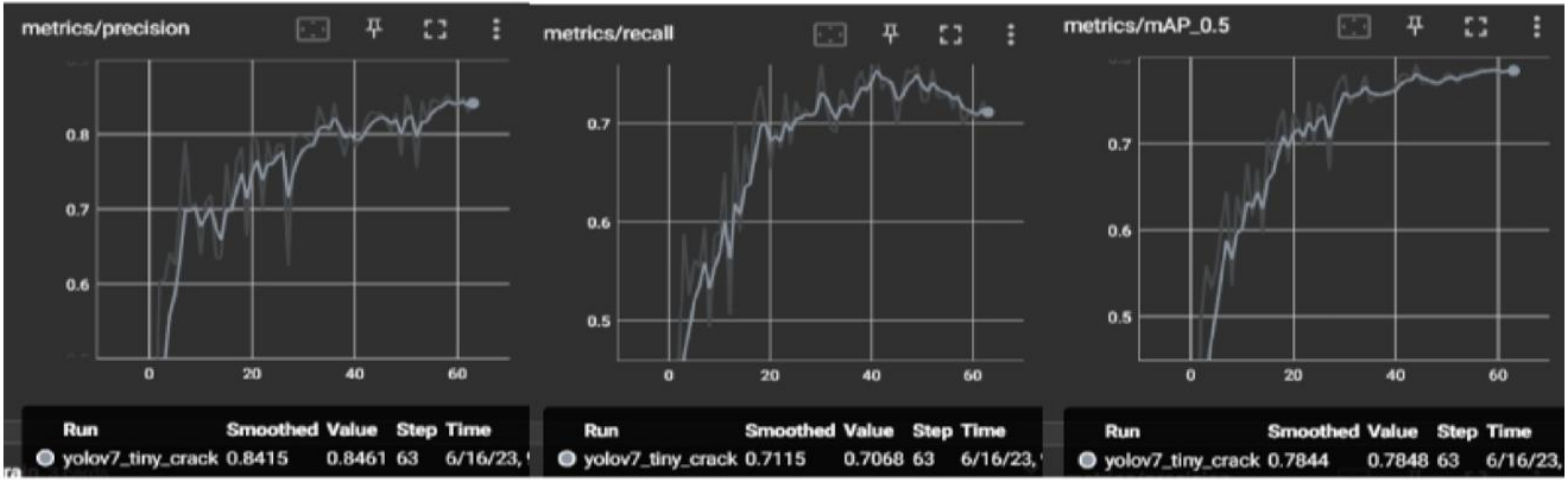
Dataset for crack detection
@Digital Concrete 2024



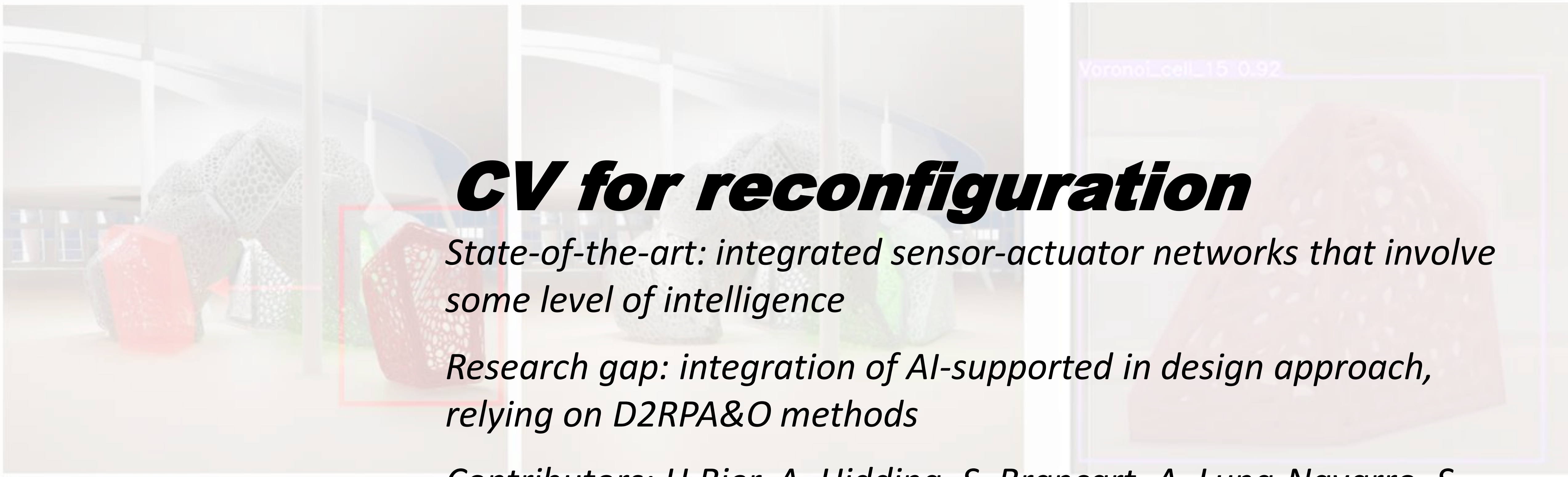




Data for 3D-printed concrete
@Digital Concrete 2024



Results for CV crack detection @Digital Concrete 2024



CV for reconfiguration

State-of-the-art: integrated sensor-actuator networks that involve some level of intelligence

Research gap: integration of AI-supported in design approach, relying on D2RPA&O methods

Contributors: H.Bier, A. Hidding, S. Brancart, A. Luna-Navarro, S. Khademi and C. van Engelenburg

Contribution: Supervision of MSc2 students and D2RP of varibable stiffness cushions

CV for HRI-assisted planting

State-of-the-art: robotic planting, limited HRI

Research gap: increase collaboration between human and robot

Contributors: H.Bier, A. Hidding, M. Prendergast, (…)

Contribution: Software pipeline, CV implementation, HRI script and demo robot operator

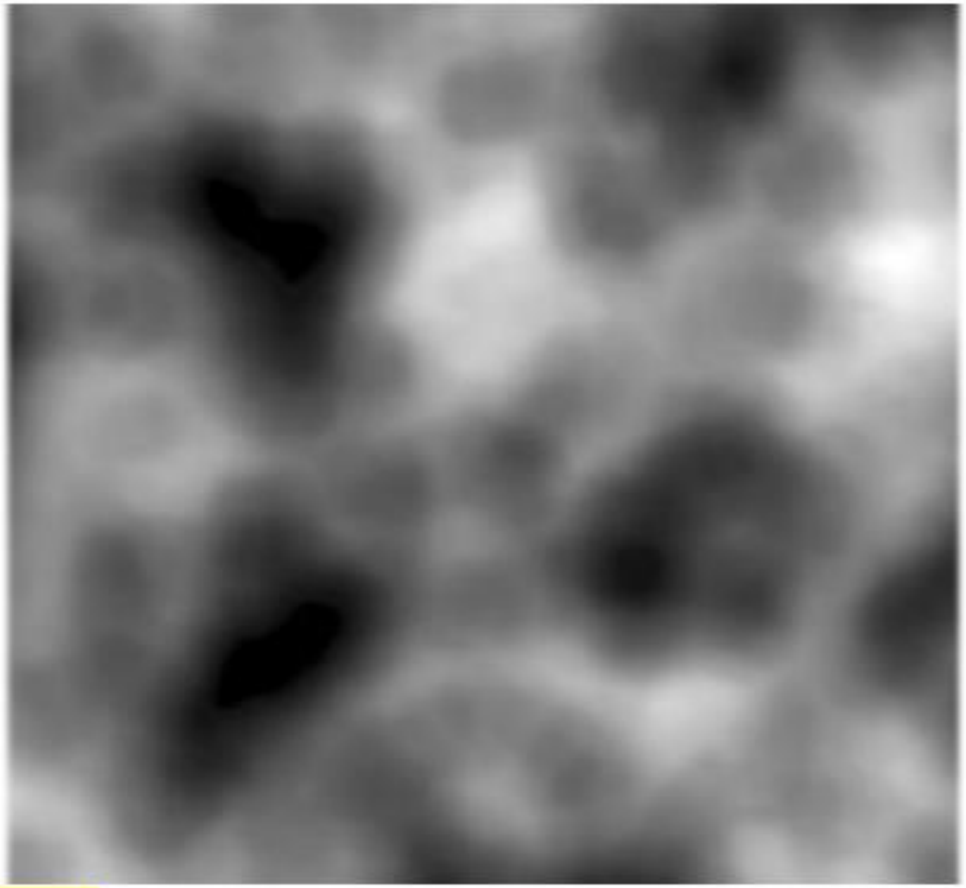
CV for terrain mapping

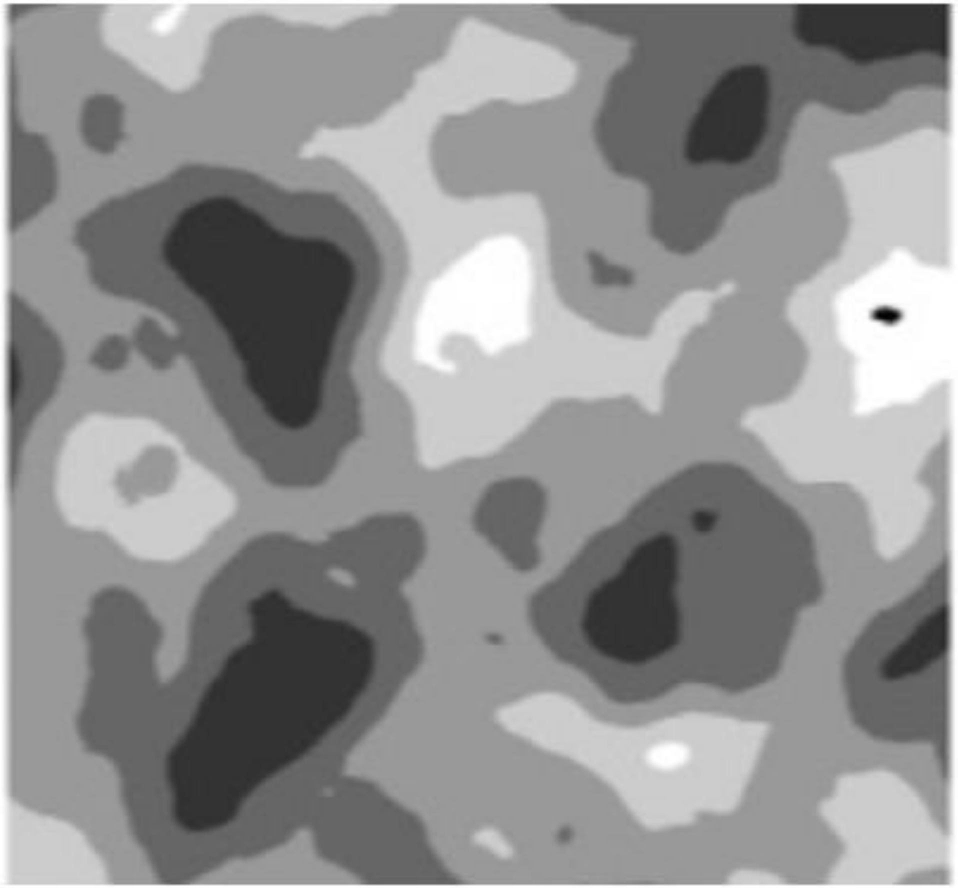
State of the Art: LIDAR / CV and ML appraoches for space exploration and construction.

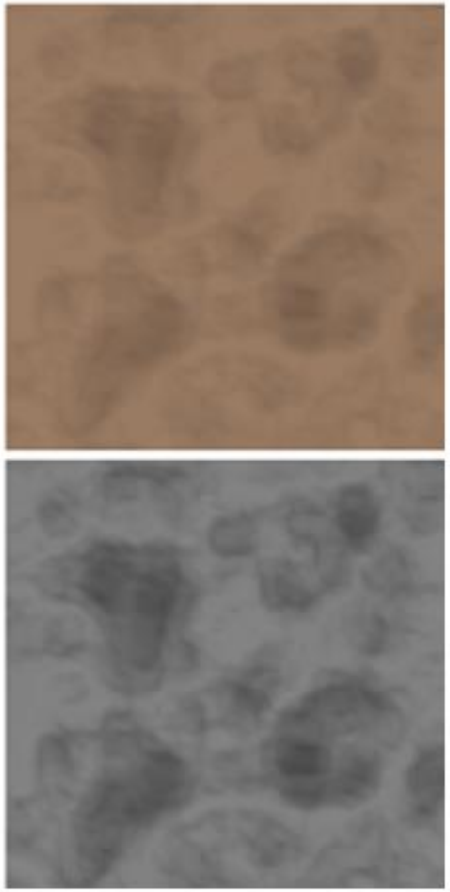
Research Gap: Present research uniquely focuses on the fusion of CV and 3D printing technology in Lava Tube environments

Contributors: G. Calabrese, A. Hidding, H. Bier, C. Engelenburg, S. Kahdemi

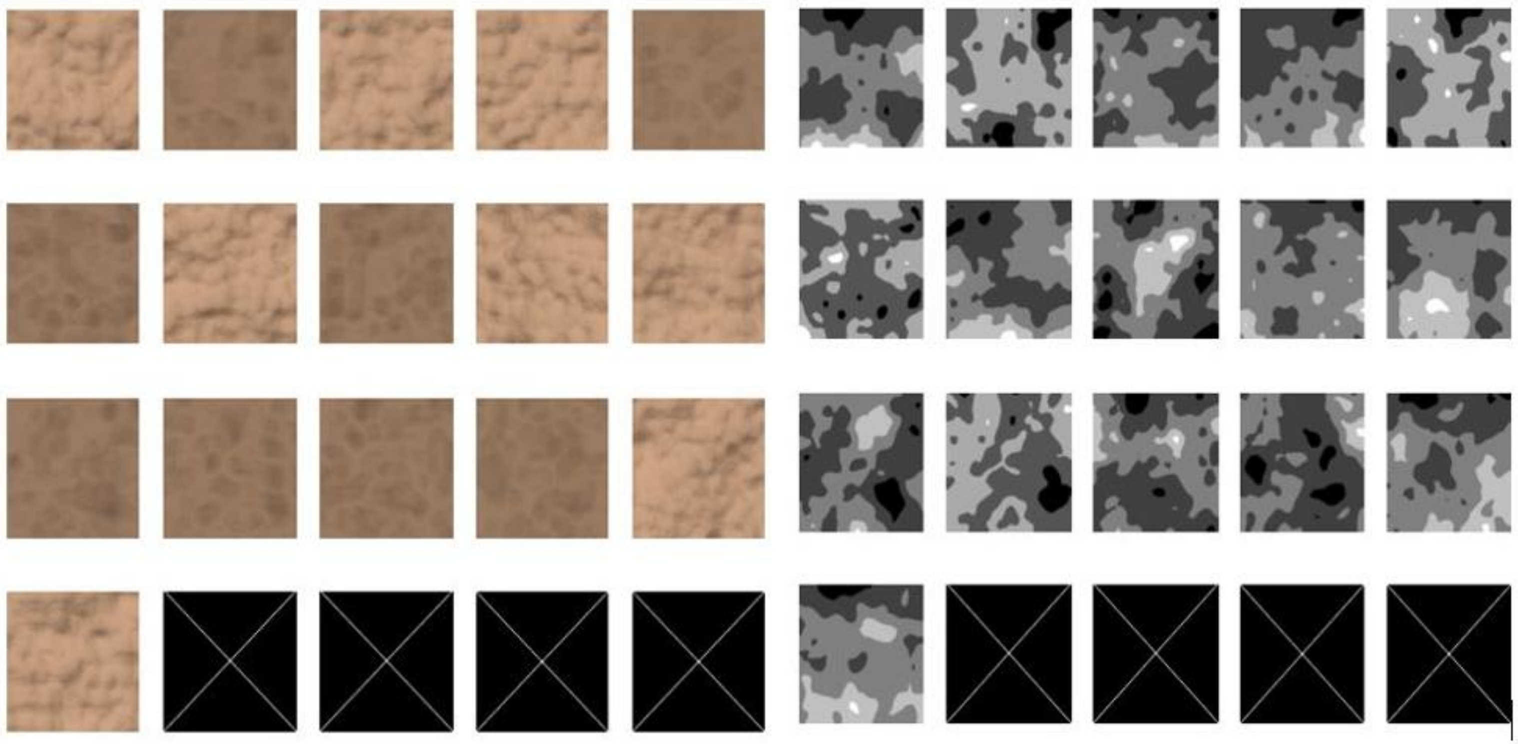
Contribution: Perlin Noise syntetic dataset – parametric generator script







Synthetic dataset for ML
@AiDAPT lab > <u>fieldtrip</u>



```python
from torchvision.models.segmentation import deeplabv3_mobilenet_v3_large, DeepLabV3_MobileNet_V3_Large_Weights
import torch.nn as nn  # Import nn module from PyTorch

weights = DeepLabV3_MobileNet_V3_Large_Weights.DEFAULT
model = deeplabv3_mobilenet_v3_large(weights=weights)

# Change final classification layer to have the correct amount of classes
NCLASSES = 6  # Replace with the number of classes you have
model.classifier[4] = nn.Conv2d(in_channels=256, out_channels=NCLASSES, kernel_size=1, stride=1)

# Check model architecture
print(model)
```

```
Downloading: "https://download.pytorch.org/models/deeplabv3_mobilenet_v3_large-fc3c493d.pth" to /root/.cache/torch,
100%|██████████| 42.3M/42.3M [00:00<00:00, 162MB/s]
DeepLabV3(
  (backbone): IntermediateLayerGetter(
    (0): Conv2dNormActivation(
      (0): Conv2d(3, 16, kernel_size=(3, 3), stride=(2, 2), padding=(1, 1), bias=False)
      (1): BatchNorm2d(16, eps=0.001, momentum=0.01, affine=True, track_running_stats=True)
      (2): Hardswish()
    )
    (1): InvertedResidual(
      (block): Sequential(
        (0): Conv2dNormActivation(
          (0): Conv2d(16, 16, kernel_size=(3, 3), stride=(1, 1), padding=(1, 1), groups=16, bias=False)
          (1): BatchNorm2d(16, eps=0.001, momentum=0.01, affine=True, track_running_stats=True)
          (2): ReLU(inplace=True)
```

CV-supported terrain mapping @AiDAPT lab > fieldtrip

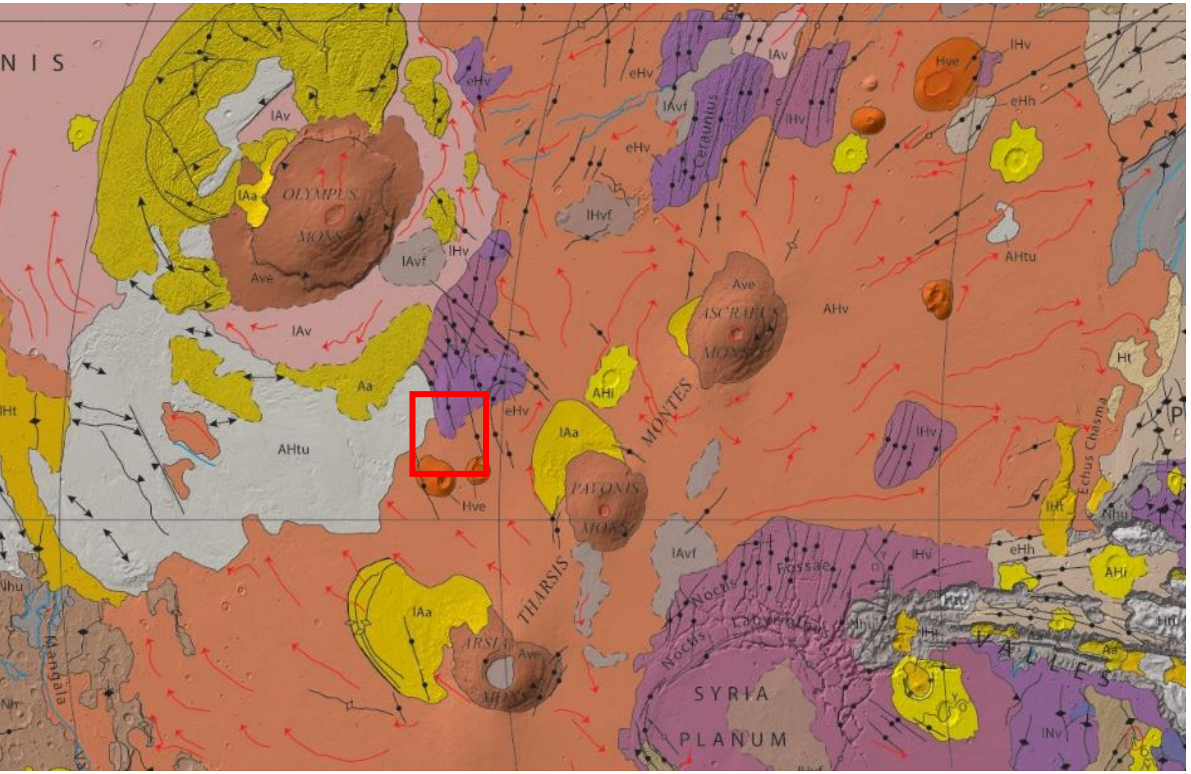
Geopolymer material developement

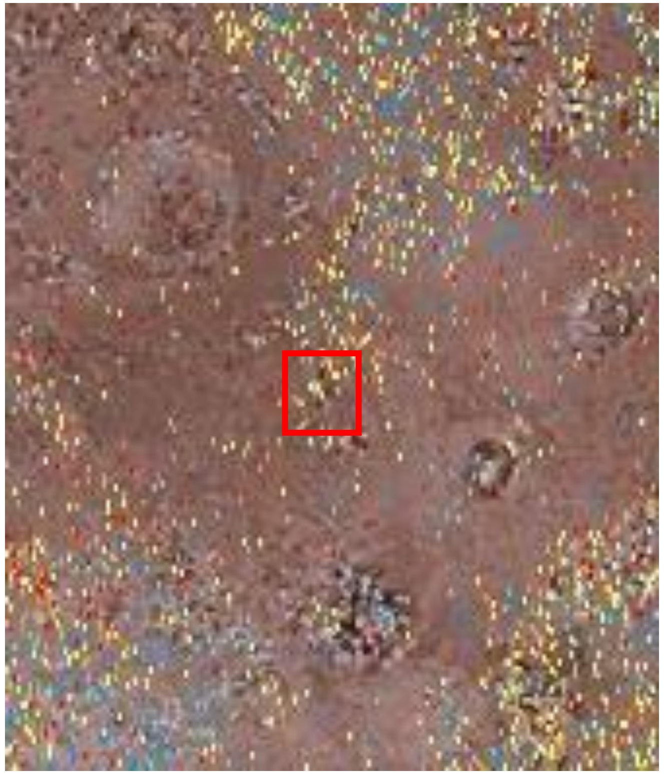
State-of-the-art: Phosphate + Martian simulant geopolymer

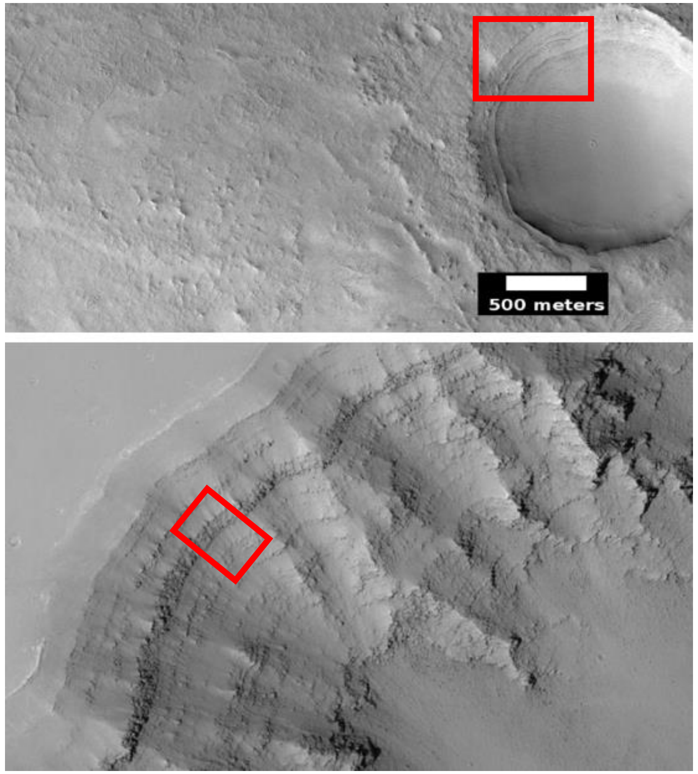
Research gap: Phosphate + Martian simulant based on volcanic ash

Contributors: H.Bier, A. Hidding, G. Calabrese, E. Chen

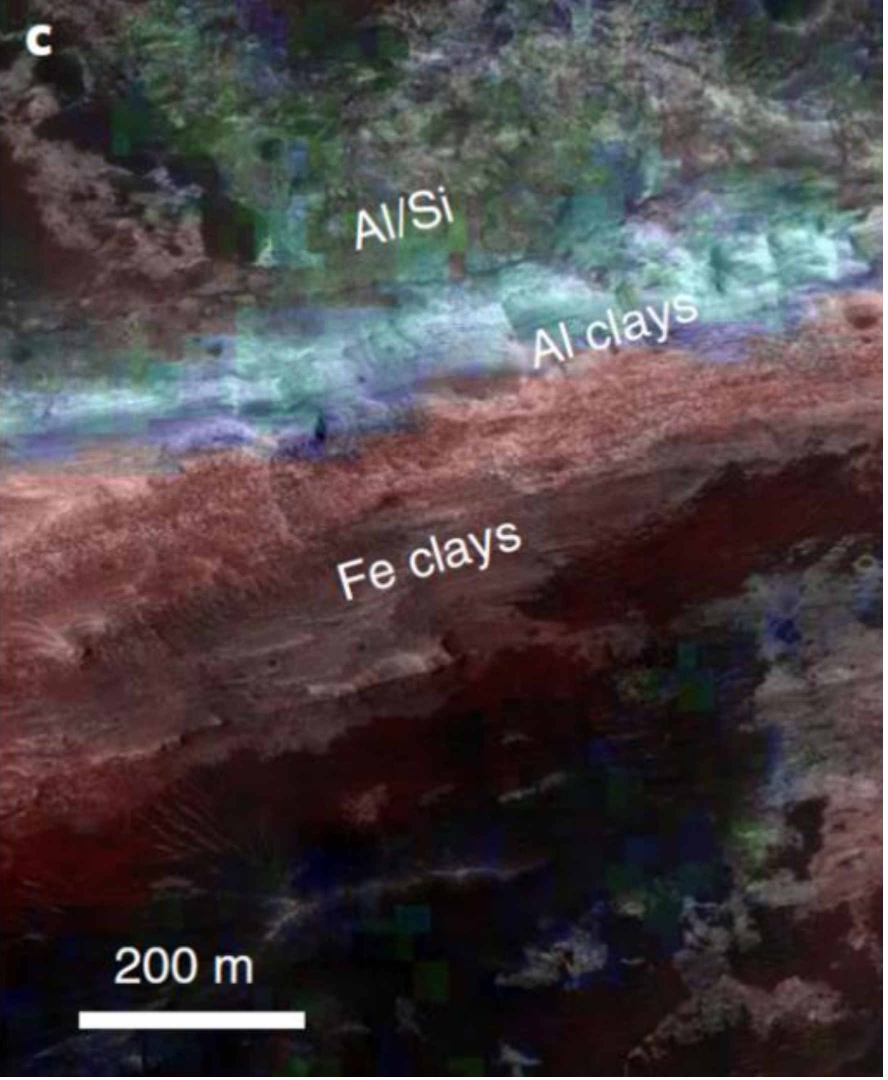
Contribution: Literature review, material experiments, HMP student supervision

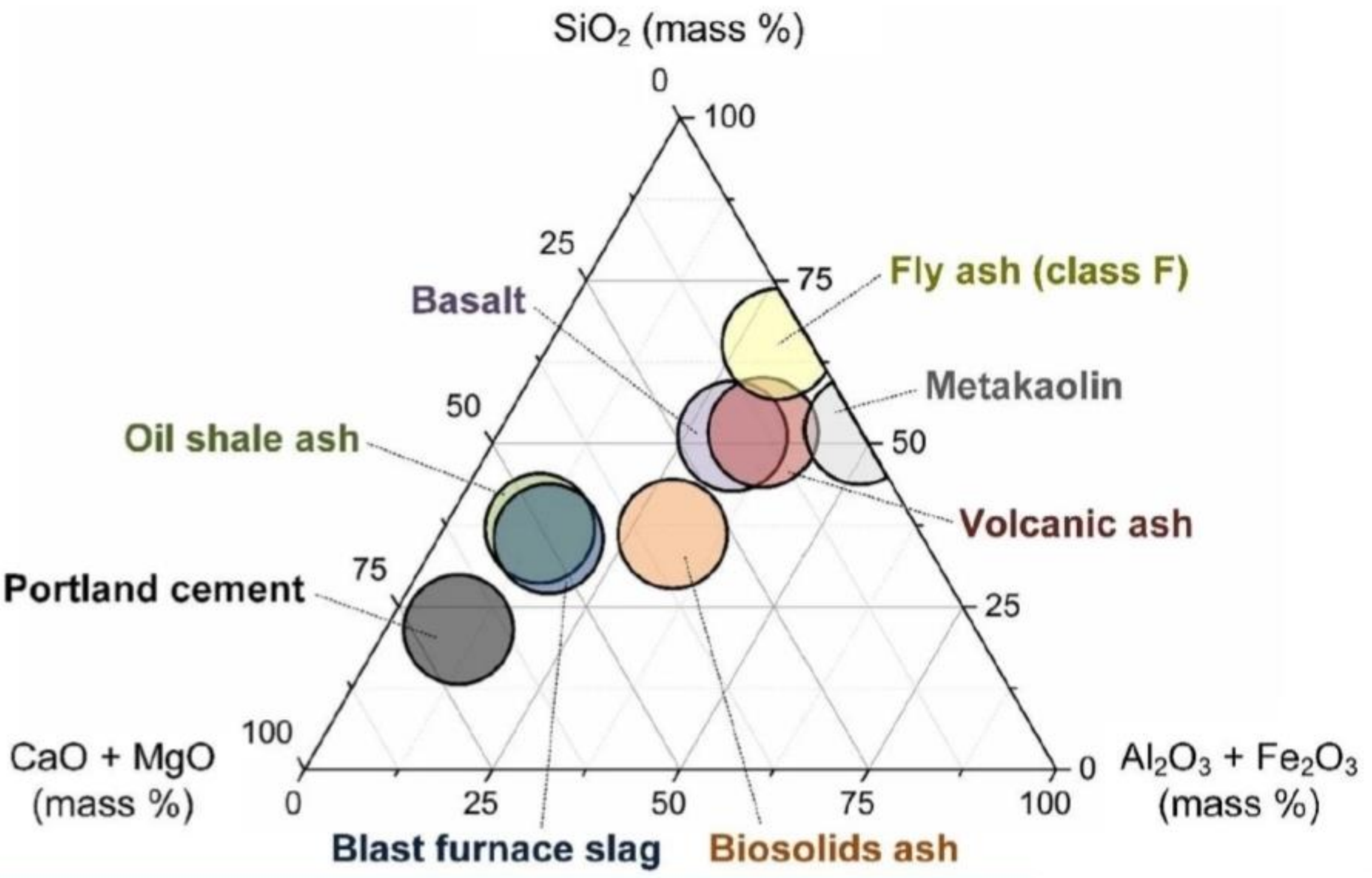




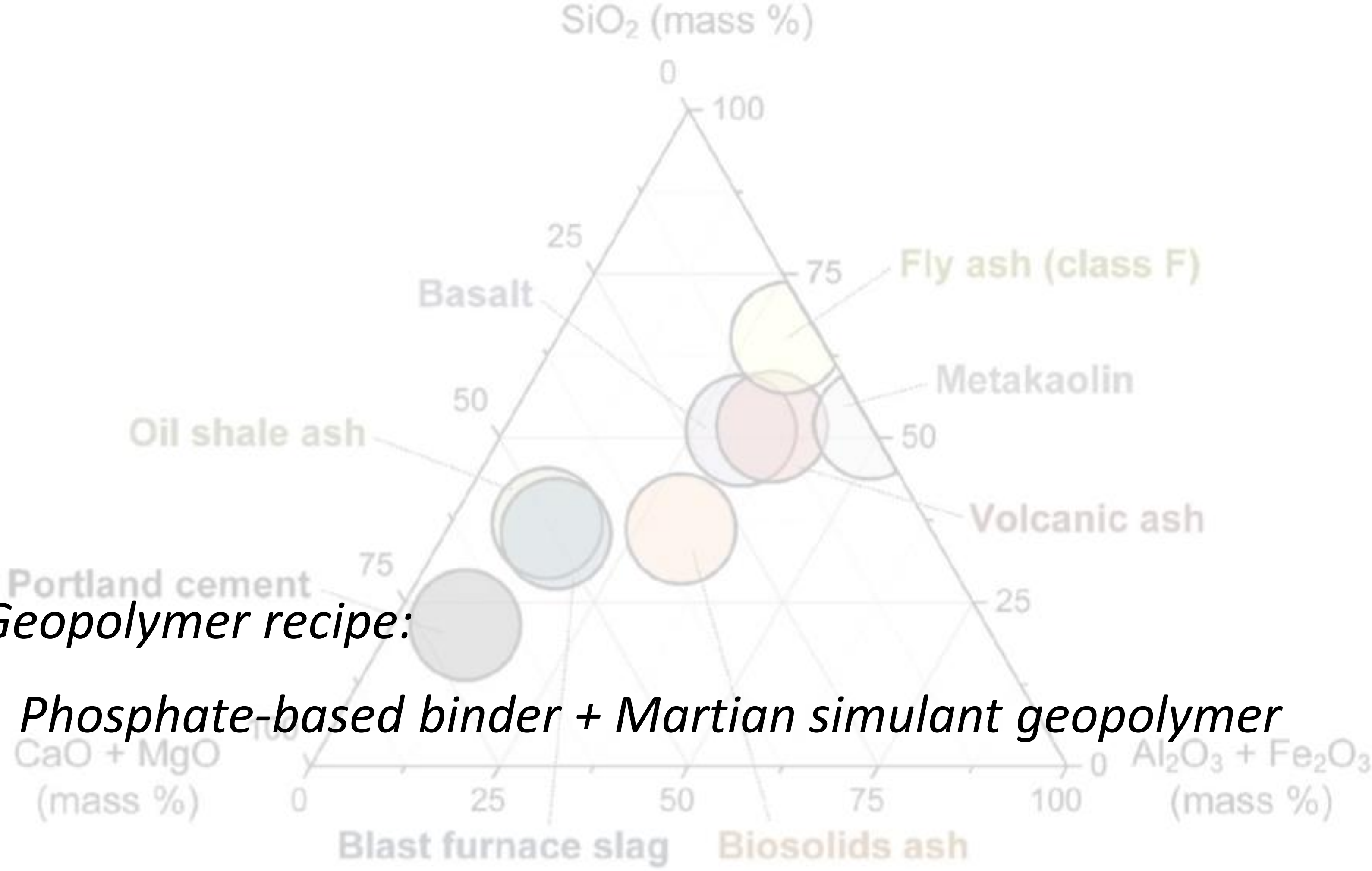


Regolith map (Hauber et al.,2019), meteor impacts (Bandeira et al.,2014) & crater (Secosky, 2017,2018)





ISRU material & chemical composition (Bishop et al., 2018) (Deventer et al., 2020)



Geopolymer recipe:

- *Phosphate-based binder + Martian simulant geopolymer*

Geopolymer recipe (Buchner et al., 2017)

	JSC Mars-1		Martian Surface Fines C-1
Oxide	Wt.%*	Wt.%**	Wt.%***
SiO_2	34.5	43.7	43
Al_2O_3	18.5	23.4	7.5
TiO_2	3.0	3.8	0.65
FeO	2.8	3.5	n.d.
Fe_2O_3	9.3	11.8	17.6
MnO	0.2	0.3	n.a.
CaO	4.9	6.2	6
MgO	2.7	3.4	6
K_2O	0.5	0.6	0
Na_2O	1.9	2.4	n.a.
P_2O_5	0.7	0.9	n.a.
SO_3	n.a.	n.a.	7
Cl	n.a.	n.a.	0.7

- SiO2 (silicium) 44%
- Al2O3 (aluminium) 13,9 %
- Na2O (natrium) 3,1%
- MgO (magnesium) 9,0%
- P2O5 (fosfor) 0,5%
- CaO (calcium) 11%
- K2O (kalium) 3,5%
- Fe2O3 (ijzer) 11%
- TiO2 (titanium) 2,7%

JSC Mars-1 simulant (left) (Carlton et al., 1997), ground Lava (right) (Praxis, 2024)

<u>Next steps (2024-25)</u>

+ Componential interlocking logic for complex building envelope

+ Geopolymer characterization (with HPM students)

+ Moonshot+ Lunar Architecture and Infrastructure inter-faculties graduation pilot

+ CV-supported lava tube mapping in Sicily (with U Palermo and U Padova)

+ AI-supported design of complex building envelope and HRI-supported assembly (with MSc 2-4 students)

+ Vertico: robotic milling of 3D printed concrete for interlocking / informed surfaces

+ Vertico: concrete cracking, shrinkage and environmental control investigation

<u>11 Co-authored Publications (2023-24)</u>

+ The role of AI in architecture (work in progress)

+ AI-supported approach for Human-Building Interaction

+ Advancing Design-to-Robotic-Production and -Assembly of Underground Habitats on Mars

+ Review of Cementless Materials for 3D Printing of off- and on-Earth Habitats

+ Developing a Computer Vision Application for Crack Detection

+ Computer Vision for Terrain Mapping and 3D Printing In-situ of Extra/-terrestrial Habitats

+ Exploring Aspects of In-Situ vs. Prefab 3D Printing for CO2-free Pop-up Architecture

+ Computer Vision- and Human-Robot Interaction-supported Assembly for Collaborative off-earth Habitat Construction

+ Artificial Intelligence Supported Site Mapping for Building Pop-up Habitats

+ Clustering and Topological Interlocking for Robotic Assembly

+ Developing a CV- and HRI-supported Approach for Robotic Planting Designed for Integrated Greenhouses

GS courses (7 GS completed)

+ PhD Start-up Module A-I and II: Introduction to the Graduate School and Navigating the PhD Life (1 GS credits)

+ RO47002: Machine Learning for Robotics (5 GS credits)

+ PhD Start-up Module A-III: Conquering Challenges (0.5 GS credits)

+ PhD Start-up Module B: Scientific Integrity (0.5 GS credits)

+ Robotics / HRI (start 2nd September)

+ FAIR course (ongoing)

Co-tutoring students

+ 18 RB lab MSc 2 students 5 ECTS: Moon station

+ 6 RB lab HMP students 20 ECTS: shallow foundations, geopolymers, integration of LSS, etc.

+ 1 CoR lab MSc 3-4 student 45 ECTS: HRI for assembly

Chapters Thesis (±25% complete)

+ Introduction

+ Computational Voronoi-based Habitat Design with Integrated Life Support System

+ Robotic Production of 3D-Printed Components from Cementless Concrete

+ HRI-supported Assembly of Voronoi-based Interlocking Components

+ Conclusions; References; Appendix

Data management

Depending on the level of development data is shared and archived on http://cpa.roboticbuilding.eu/, https://research.tudelft.nl/, https://repository.tudelft.nl/, and/ or https://data.4tu.nl/.

Conferences:

+ Computer Vision- and Human-Robot Interaction-supported Assembly for Collaborative off-Earth Habitat Construction @ FICTA-2024, London (online), 7th of June 2024

+ Developing a CV- and HRI-supported Approach for Robotic Planting Designed for Integrated Greenhouses @ UPADSD, Florence, 22nd – 24th, Oct 2024

+ Developing a Computer Vision Application for Crack Detection @ Digital concrete 2024, Munich, Germany, 4th -6th September 2024

Planning

Year 1:

1.1 Literature review, 1.2 Material research, 1.3 Printing studies, 1.4 Archiving and publication

Year 2:

2.1 Development of computational model, 2.2 Simulation and testing, assembly, 2.3 Archiving and publication

Year 3:

3.1 Large-scale prototyping, 3.2 Material characterization and testing, 3.3 Simulation and testing of coating, 3.4 Simulation and testing of sensor-actuator system, 3.5 Archiving and publication

Year 4:

4.1 Dissertation, archiving, and publication