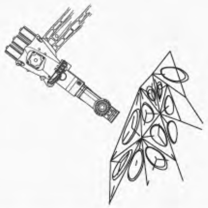
COMPUTATIONAL DESIGN
ROBOTIC FABRICATION

DAR LAB

DIGITAL ARCHITECTURE ROBOTICS

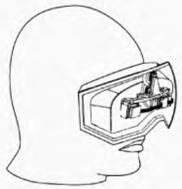
DIGITAL DESIGN

Stimulating the communication of ideas and information by digital media, working on visual perception, context, form and interactive design.



COMPUTATIONAL DESIGN

Discovering creative architectural expressions and solutions, combining traditional principles with new computing design technology.



SIMULATION

Developing skills for the creation of virtual spaces. Drastically altering process and design methods, predicting outputs and performances.

ROBOTIC FABRICATION

Towards a futuristic art of making. Robots break the barriers of traditional design, enabling freedom in expressing impossible forms.

scm group KUKA QD The robotics solution hiteco CIM system


KUKA
hiteco
KUKA

Robotic Fabrication WILL Change the Way We Build and Design Buildings

Federico Rossi – DAR|LAB / London South Bank University

London South Bank University

we focus on new challenges in industrial automation

highly flexible simulation, programming and real-time control solution for industrial machinery

accessible automation robotics for everyone

>> intuitive training: platform for industrial machinery with embedded documentation
>>user-centred: responsive environment, compatible with both academic & industrial contexts
>>improved safety: virtual controller for realistic simulation and error prediction
>>plug-in distribution: brings robotics in existing software products

we focus on new challenges in industrial automation

highly flexible simulation, programming and real-time control solution for industrial machinery

advanced automation extensive robotics toolset

- scalable, cross-platform, vendor-independent robotics development environment
- generic communication protocol for structured data exchange between machines
- full support of machine scripting languages with no semantic shift
- compatible with ROS, vendor-specific APIs, scriptable with 30+ languages

generic communication for CNC machines and robots

- protocol for structured data exchange between machines
- real-time communication over TCP
- fully integrated communication requiring no extra equipment

sensor fusion and natural human-machine interfaces

- automated calibration procedures
- real-time trajectory compensation
- teleoperation
- collaborative robotics

new applications of robotics for construction and creative industries

- bespoke programming, simulation, control and monitoring interfaces
- real-time trajectory compensation
- teleoperation
- collaborative robotics

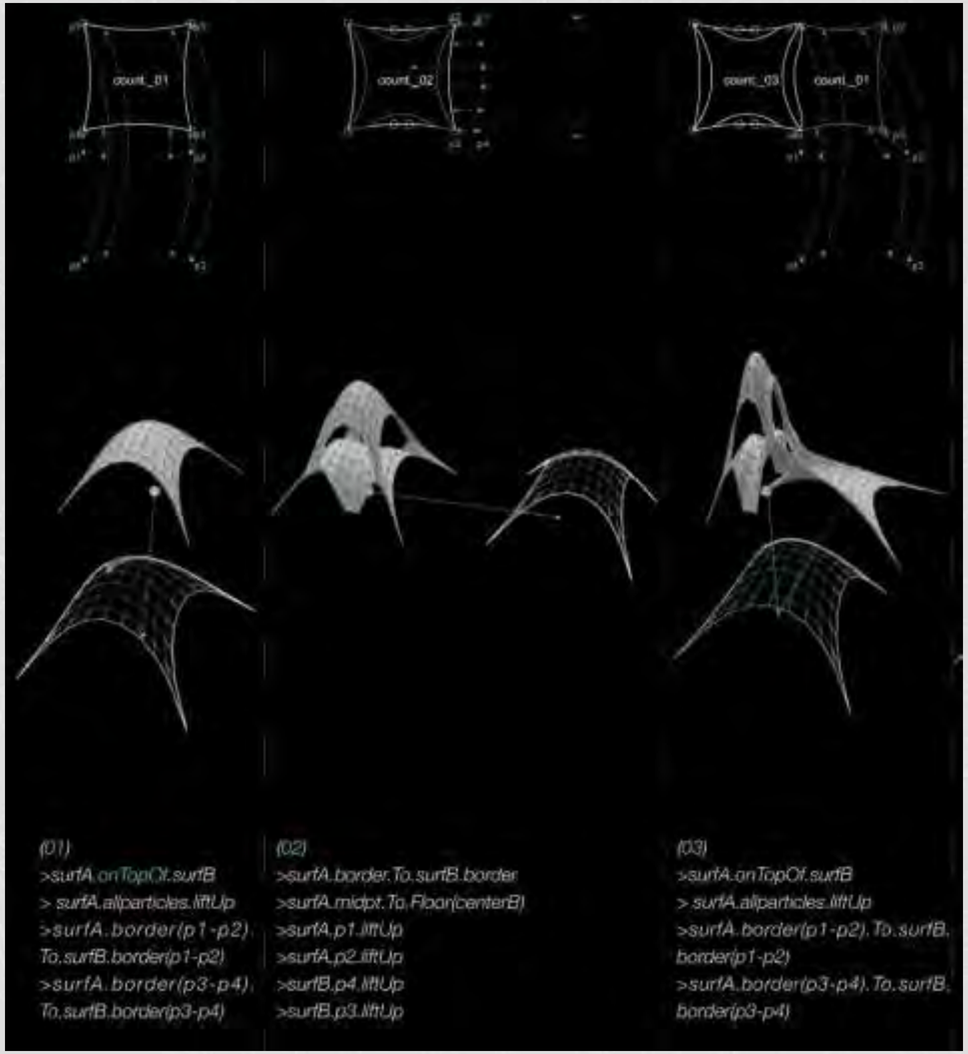
Digital

vs

Physical

Digital vs Physical - Creation

Design Tools



Digital Plaster, Manuel Jimenez Garcia / [m(a)dM], London

Construction Techniques

Bricktopia, Map13, Barcelona

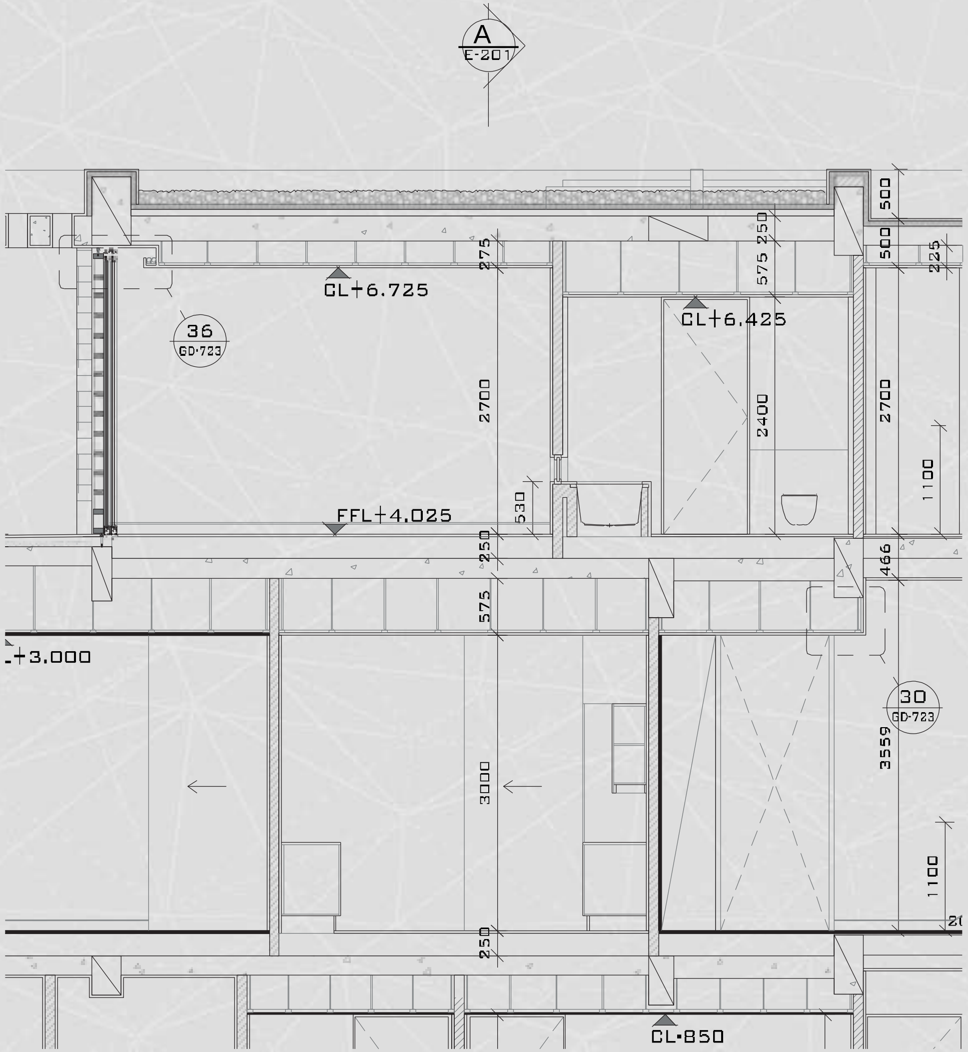
Digital vs Physical - Presentation

Augmented Reality

AR for Architecture, Gulnaz Aksenova, Sochi

AR Viewer, Dan Boghean, Psudigitalbeehive

Plans



Villa Epsilon, S.A. / Andraos Associates, Cyprus

Digital vs Physical - Literacy

Code

```
# ************************************************************************************
# INITIALIZATION FOR THIS PASS
# ************************************************************************************

                COUNT*      $$/F2DPS

        GUILDRET  CAF   ZERO
                TS      RODCOUNT

# Page 802
 +2             EXTEND
                DCA     TPIP
                DXCH    TPIPOLD

                TC      FASTCHNG

                EXTEND DCA
                        PIPTIME1
                DXCH    TPIP

                EXTEND DCA
                        TTF/8
                DXCH    TTF/8TMP

                CCS     FLPASS0
                TCF     TTFINCR

BRSPOT1                 INDEX TCF   WCHPHASE
                        NEWPHASE

# ************************************************************************
# ROUTINES TO START NEW PHASES
# ************************************************************************

P65START        TC      NEWMODEX
                DEC     65
                CS      TWO
                TS      WCHVERT
                TC      DOWNFLAG# PERMIT X-AXIS OVERRIDE
                ADRES           XOVINFLG
                TCF     TTFINCR
```

LUNAR_LANDING_GUIDANCE_EQUATIONS, NASA, The Moon

Specifications

342 Partition studs
- Source: Contractor's choice.
- Type: Softwood.
- Certification: Forestry Stewardship Council (FSC) chain of custody.
- Size: 47 x 72 mm.

348 Timber herringbone struts
- Source: Contractor's choice.
- Type: Softwood.
- Size: 38 x 38 mm (minimum).

356 Framing anchors
- Manufacturer: Contractor's choice.
- Product range or reference: Contractor's choice.
- Material: Galvanized steel.
- Type: To suit connection.

374 Fasteners
- Material: Stainless steel or galvanized or sherardized low carbon steel.
- Nails to timber substrate:
- Standards: To BS 1202-1 orto BS EN 10230-1.
- Length (into supporting structure): 40 mm, or full depth if less than 40 mm.
- Shank diameter (minimum): 3 mm.
- Screws:
- Standard: To BS 1210.
- Length (into suppo ing structure):
To timber suppo s: 30 mm, or full depth if less than 30 mm.
To supporting masonry (minimum): 40 mm.
- Shank diameter:
Wood screws (minimum): 8 s.g. (4.17 mm).
- Plugs for masonry fixings using wood screws: Size to match screws.

344 Blocking
- Source: Offcuts from structural timbers.
- Type: Softwood.
- Size: As adjacent structural timbers.

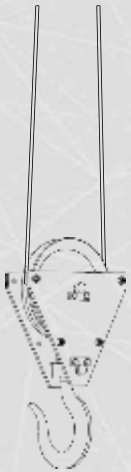
346 Noggins
- Source: Contractor's choice.
- Type: Softwood.
- Size: 50 x 50 mm.

The Drive Specification, S.A./ALL Design, Esher

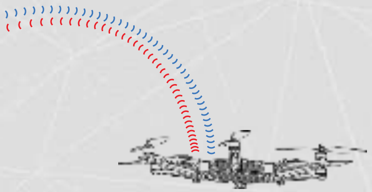
Bridging
the
Gap

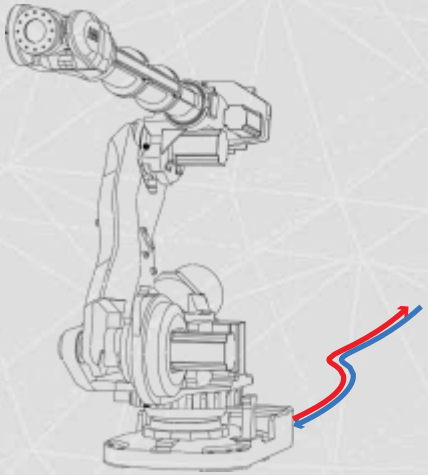
Bridging the Gap - Robotics

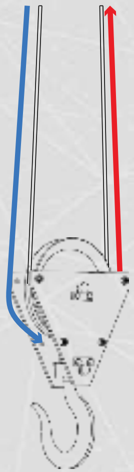
Bridging the Gap - Robotics



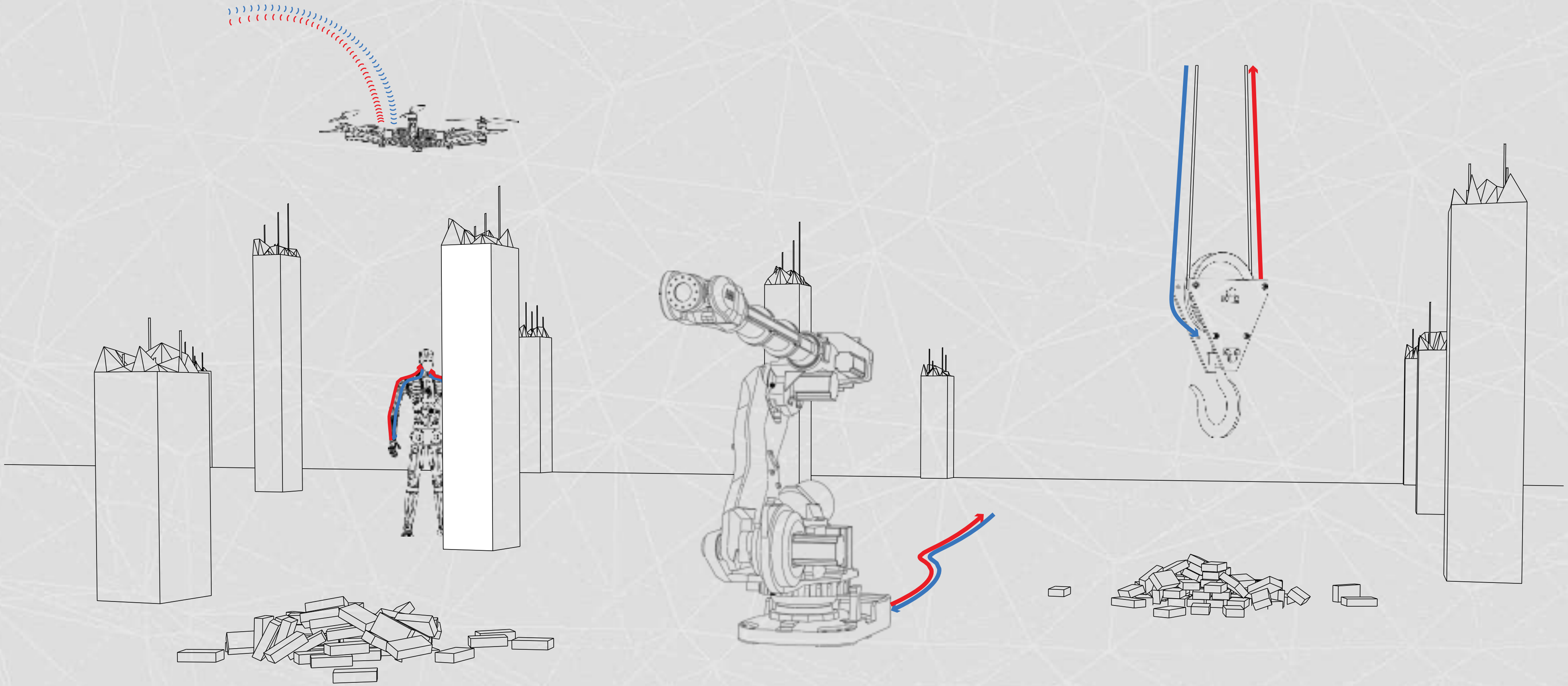
Bridging the Gap - Robotics







Bridging the Gap - Robotics



Bridging the Gap - Non-Issues

Economics

Robots assemble Tesla Model S cars at Tesla factory in California. ©AP via Gizmodo

Safety

Angela Merkel testing ABB's YuMi at Hannover Messe 2015 ©ABB

Bridging the Gap - Issues

Adaptability

Relatively organised brick pile. ©1500Sq.ft

Stratifications, Gramazio Kohler Research, Fabricate, London, 2011

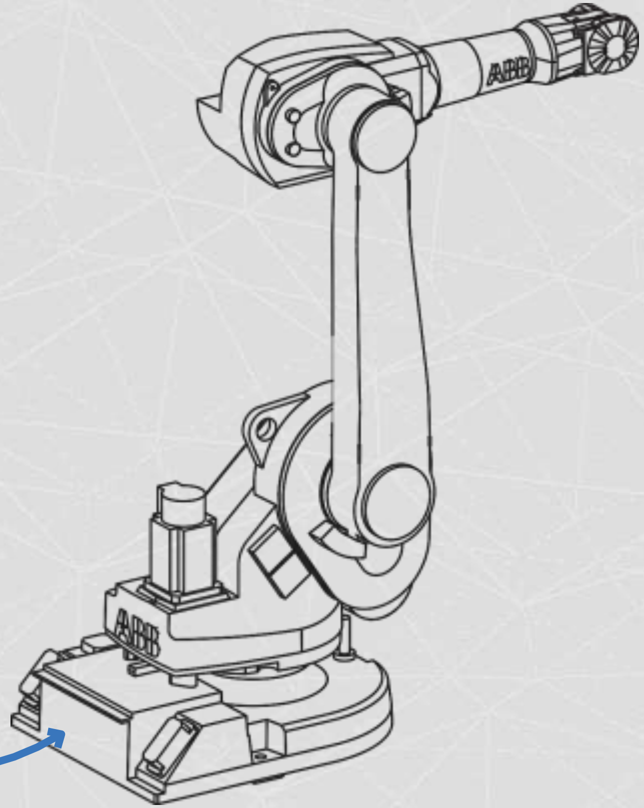
Bridging the Gap - Issues

Communication

Foreman communicating with labourers. ©Gekko Images

```
PARTNO / APT-1
NOPOST
CUTTER / 10.0
$$GEOMETRY DEFINITION
SETPT = POINT / 0.0, 0.0, 0.0
STRTPT = POINT / 70,70,0
P1 = POINT / 50, 50, 0
P2 = POINT / 20, -20, 0
C1 = CIRCLE / CENTER, P2, RADIUS, 30
P4 = POINT / 50, -20, 0
L2 = LINE / P3, PERPTO, L1
PLAN1 = PLANE / P1, P2, P3
PLAN2 = PLANE / PARLEL, PLAN1, ZSMALL, 16
$$MOTION COMMANDS
SPINDL / 3000, CW
FEDRAT / 100, 0
FROM / STRTPT
GO/TO, L1, TO, PLAN2, TO, L4
TLLFT, GOFWD / L1, TANTO, C1
GOFWD / C2, TANTO, L4
GOFWD / L4, PAST, L1
NOPS
GOTO / STRTPT
FINI
```

```
0010010101010100101010101010101011001101
0010110100101010101010101010101010101001
0101010101010101011010101100100101010100
1010101010101010010100101010101010101010
1010101010011010010100101001010101001 0
0101001010010101010010101010110101011001
```



Typical robot communication flow.

Bridging the Gap - Issues

Correctional Guidance

A helping hand. ©Deposit Photos

For an inverse Jacobian controller with an imperfect Jacobian, the commanded change in joint angles, $\Delta\theta_c \in \mathbb{R}^n$ where n is the degrees of freedom for the robot, is calculated as

$$\Delta\theta_c = k\hat{J}^{-1}(x_d - x) = k\hat{J}^{-1}\Delta x_d, \quad (1)$$

where $x \in \mathbb{R}^3$ is the current Cartesian position, $x_d \in \mathbb{R}^3$ is the desired Cartesian position, $\Delta x_d \in \mathbb{R}^3$ is the desired motion in Cartesian space, $\hat{J}$ is an estimate of J, the true system Jacobian, and k is a motion scaling gain. For infinitesimal steps and an ideal quasi-static system, the resulting motion is

$$\Delta x = J\Delta\theta_c = kJ\hat{J}^{-1}\Delta x_d. \quad (2)$$

Therefore the new position after completing the motion is

$$x_{new} = \Delta x + x = kJ\hat{J}^{-1}\Delta x_d + x, \quad (3)$$

and the error after completing the motion is

$$\Delta x_{new} = x_d - x_{new} = x_d - x - kJ\hat{J}^{-1}\Delta x_d. \quad (4)$$

A mapping, $G(\theta, k)$, is derived from Δx_d to Δx_{new}.

$$\Delta x_{new} = G(\theta, k)\Delta x_d = \left(I - kJ\hat{J}^{-1}\right)\Delta x_d. \quad (5)$$

To analyze convergence, the induced Euclidean norm of $G(\theta, k)$ can be defined in the standard way.

$$\left\|G(\theta, k)\right\|_2 = \max_{\Delta x_d \neq 0} \frac{\left\|G\Delta x_d\right\|_2}{\left\|\Delta x_d\right\|_2} = \bar{\sigma}(G), \quad (6)$$

where $\bar{\sigma}(G)$ denotes the maximum singular value of G. If $\left\|G(\theta, k)\right\|_2 < 1, \forall\theta$, the Cartesian error length is always smaller after a step than before the step. Therefore, the Cartesian error length monotonically decreases to zero with subsequent steps, making the controller monotonically and asymptotically convergent. Let v_σ be the right singular vector that corresponds to the maximum singular value, $\bar{\sigma}(G)$. Note that v_σ is the desired direction that results in the largest $\left\|\Delta x_{new}\right\|$. Also note, neither $\left\|G(\theta, k)\right\|_2$ nor v_σ have any application to the orientation of the robot.

While $\left\|G(\theta, k)\right\|_2$ is useful, a potentially more important measure is the angle, ϕ, between the desired motion, Δx_d, and the actual motion, Δx (Fig. 2). If $|\phi|$ is small for all possible motions across the workspace, then for a teleoperated system the slave robot will accurately follow the motions of the master. Let $\left|\phi_{max}(\theta)\right|$ be the maximum absolute value of ϕ over all desired motions, for a specific joint configuration, θ. From linear algebra,

$$Gv_i = \sigma_i u_i, \quad (7)$$

where v_i are the right singular vectors of G, u_i are the left singular vectors of G, and σ_i are the corresponding singular values. So pairs of input and output vectors can be defined where the input vectors, $\bar{v}$, are unit length,

$$\left(\bar{v} = \sum_{i=1}^{m} \alpha_i v_i,\ \sum_{i=1}^{m} \alpha_i^2 = 1\right) \underset{G}{\Rightarrow} \left(\bar{u} = \sum_{i=1}^{m} \sigma_i \alpha_i u_i\right), \quad (8)$$

where $m = \dim(x)$. Then

$$\left|\phi_{max}(\theta)\right| = \max_{\bar{v}} \left\{\cos^{-1}\left(\frac{\bar{v}^T(\bar{v} - \bar{u})}{\left\|\bar{v} - \bar{u}\right\|_2}\right)\right\}. \quad (9)$$

Equation (9) calculates the exact value of $\left|\phi_{max}(\theta)\right|$, but requires searching over a sphere of radius 1, invoking computational requirements tolerable for offline calculations but that may be too great for real-time use. Instead, an upper bound on $\left|\phi_{max}(\theta)\right|$ can be determined geometrically from $\left\|G(\theta, k)\right\|_2$ (Fig. 2). Note that x_{new} must lie within a sphere of radius $\left\|G(\theta, k)\right\|_2 \left\|\Delta x_d\right\|$ from x_d. The conservative estimate, $\hat{\phi}_{max}(\theta, k)$, of $\left|\phi_{max}(\theta)\right|$ is constructed by assuming the actual motion has the largest possible $|\phi|$. Then the actual motion is tangential to the surface of the sphere about x_d, putting a right angle between the actual motion and the radius of the sphere. The resulting right triangle has the desired motion as its hypotenuse. An upper bound on $\phi_{max}(\theta)$ is therefore

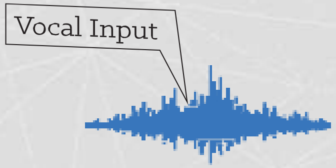
$$\begin{aligned} \hat{\phi}_{max}(\theta, k) &= \sin^{-1}\left(\frac{\left\|G(\theta, k)\right\|_2 \left\|\Delta x_d\right\|}{\left\|\Delta x_d\right\|}\right) \\ &= \begin{cases} \sin^{-1}\left(\bar{\sigma}(G)\right) & , \bar{\sigma}(G) \leq 1 \\ \pi & , \bar{\sigma}(G) > 1. \end{cases} \end{aligned} \quad (10)$$

Let p_ϕ be the direction of desired motion that results in $\left|\phi_{max}\right|$. Note that there is no simple relationship between p_ϕ and v_σ. v_σ is derived from $\left\|G(\theta, k)\right\|_2$, a measure of the maximum length of positional error, unlike $\left|\phi_{max}\right|$, which directly measures the angular error.

Kinematic Error Correction for Minimally Invasive Surgical Robots, Beasley, Howe & Dupont, IEEE 2004 p.358-364

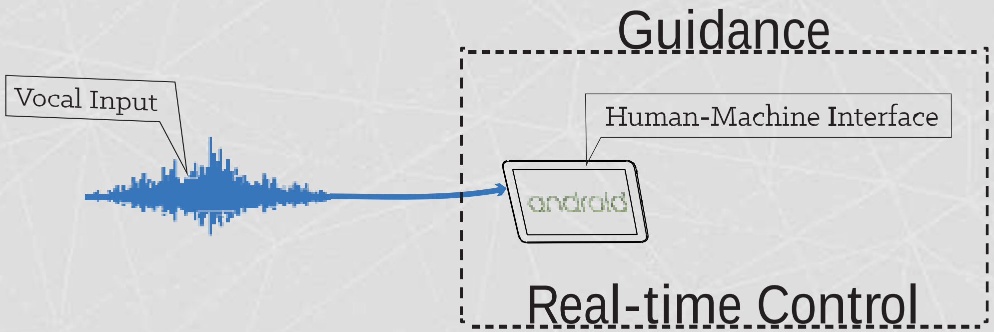
Bridging the Gap - Solutions

Communication

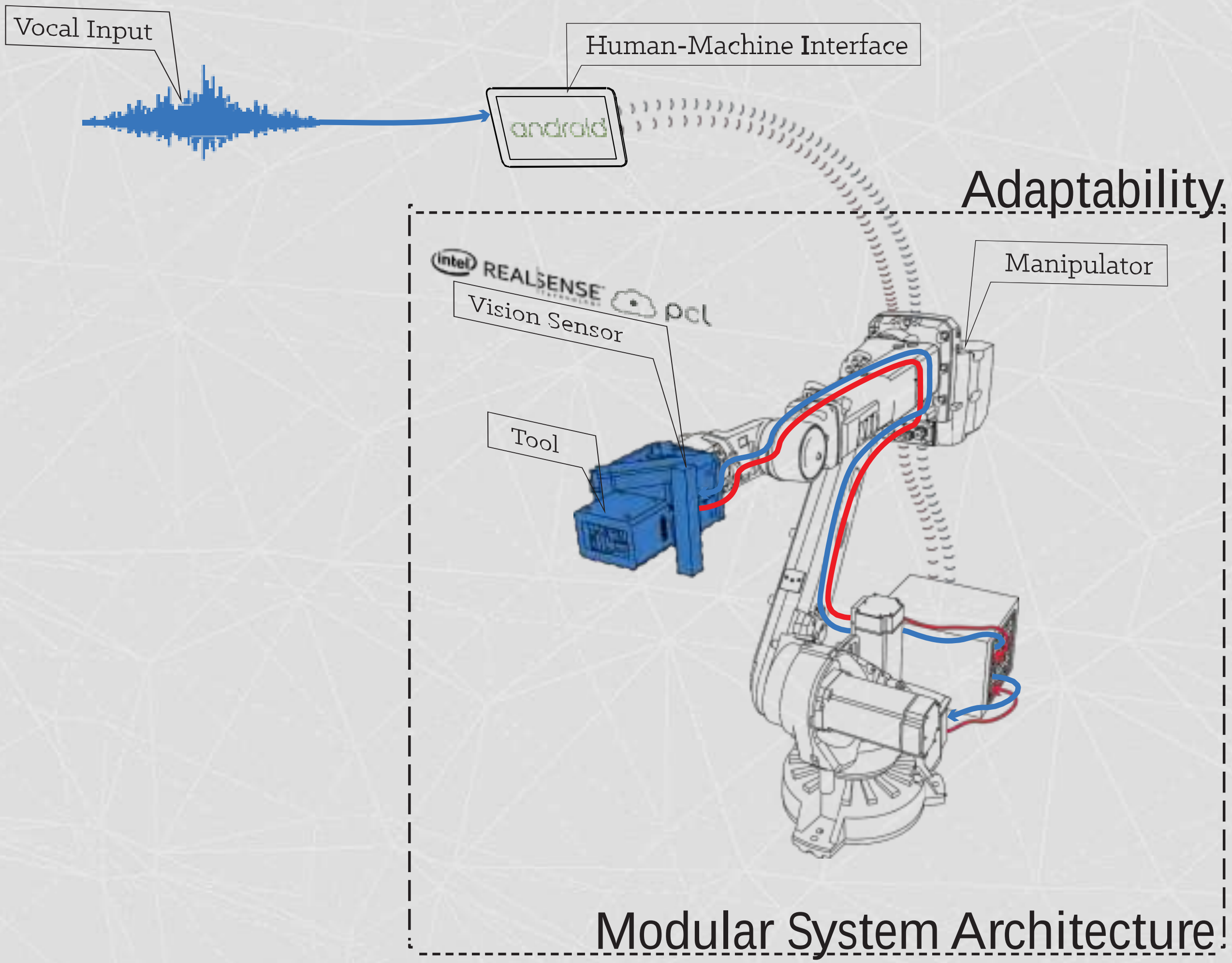


Semantic Input

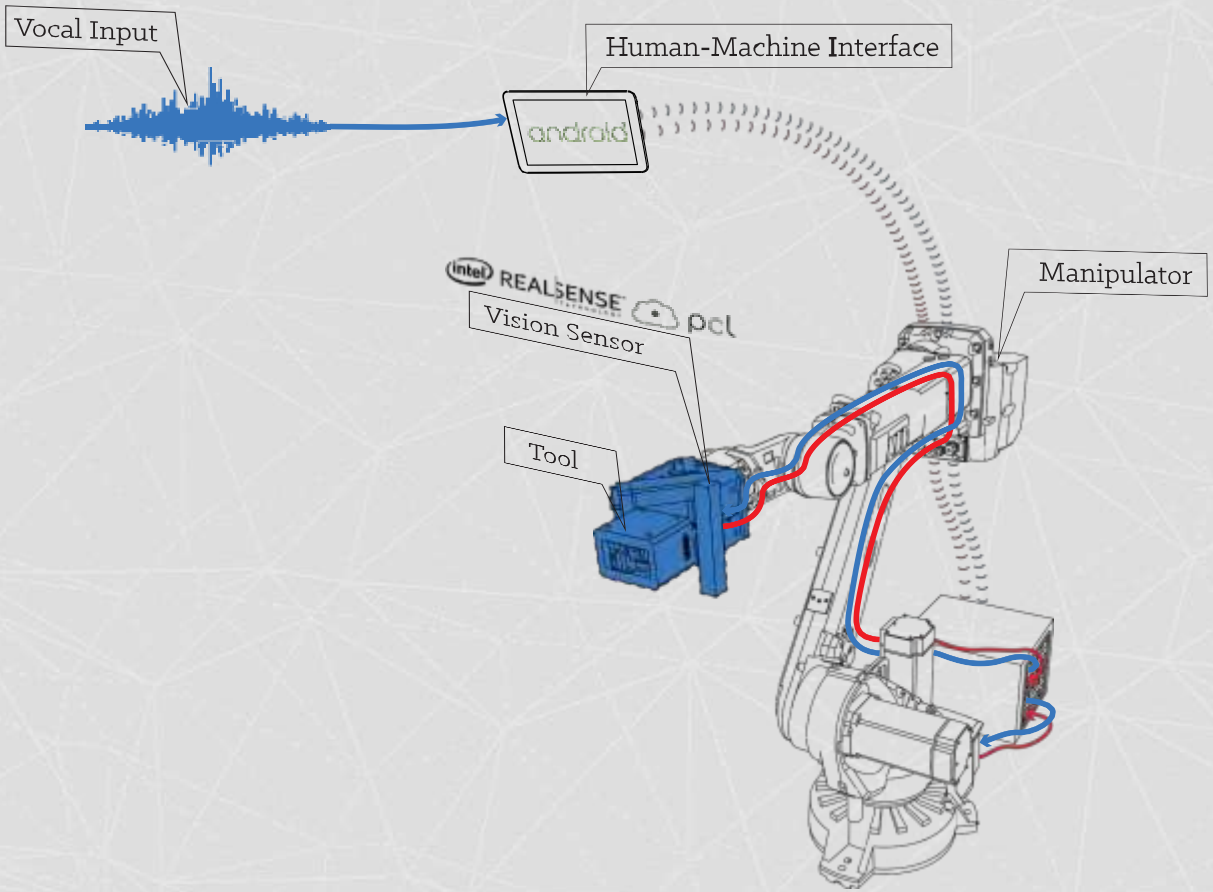
Bridging the Gap - Solutions



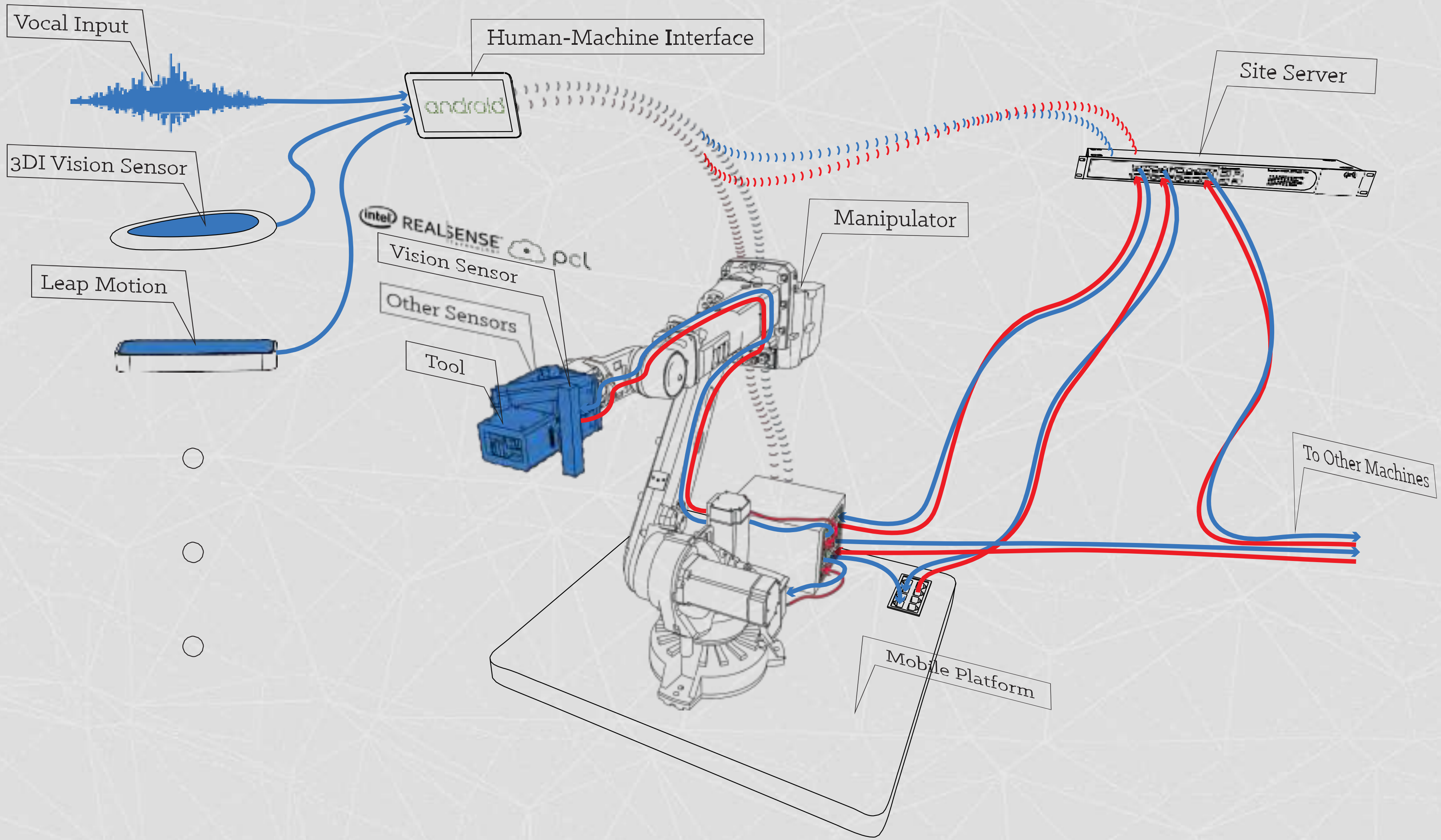
Bridging the Gap - Solutions



Bridging the Gap – System Architecture



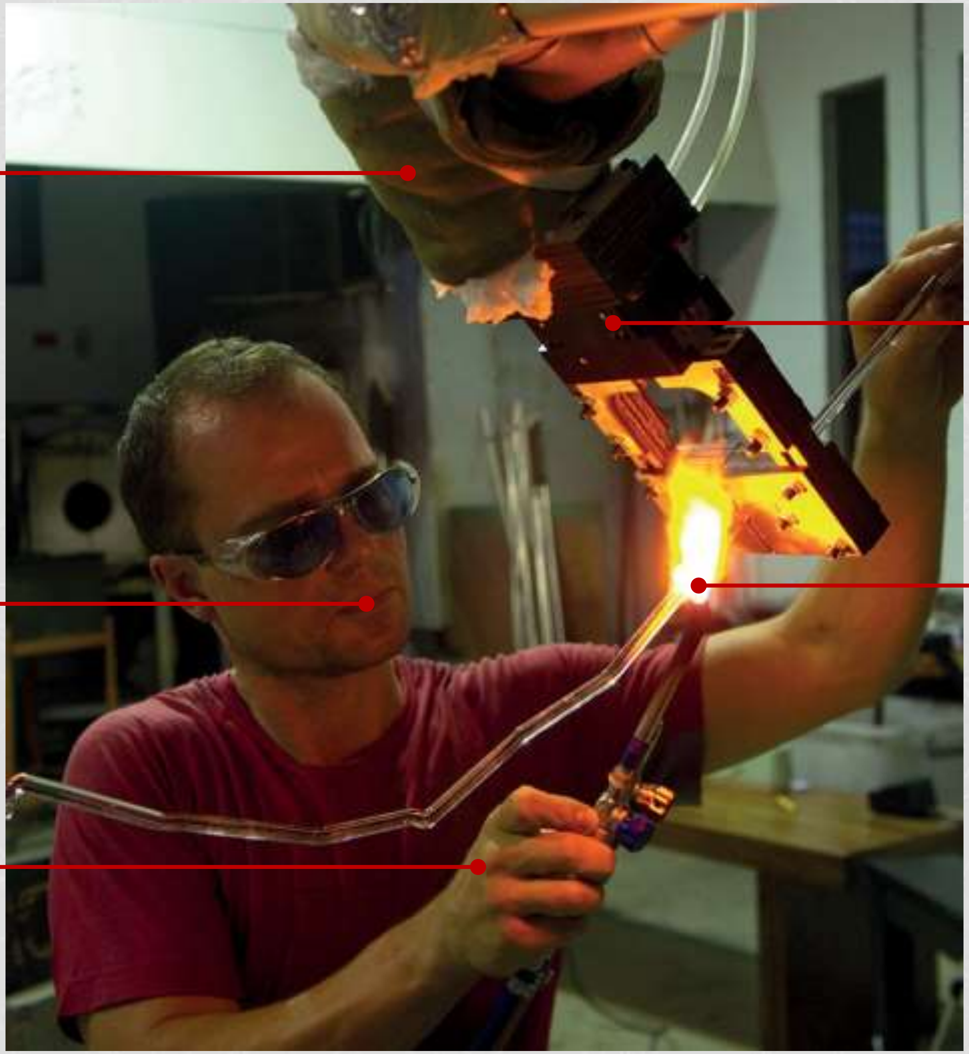
Bridging the Gap – System Architecture



S.A. Towards on-site collaborative robotics: Voice control, co-speech gesture & context-specific object recognition via ad-hoc communication, Schwartz, Andraos & Arnold, 2015 (Springer, RobArch2016)

Goal

Artisanal Scale



AA Visiting School, Taipei, 2014, Jochen Holz & Thibault Schwartz, HAL Robotics

Goal

Construction Scale

Marble Quarrying in Italy. Still from Il Capo, Yuri Ancarani

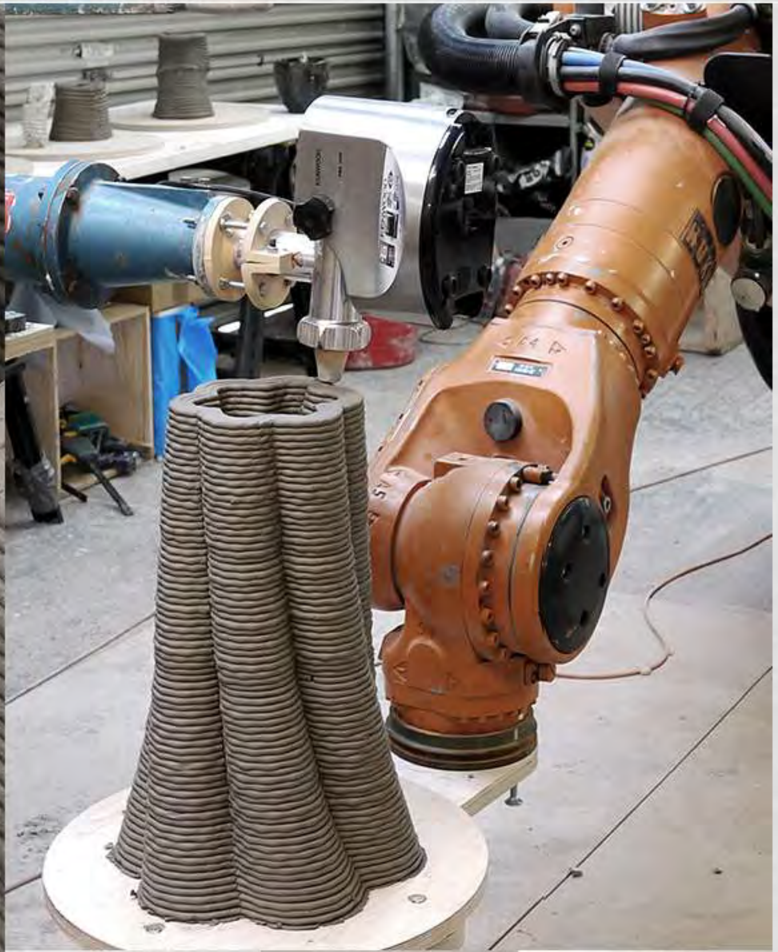
WE USE ROBOTS TO:

MILL / EXTRUDE / HOT WIRE CUT / PICK & PLACE

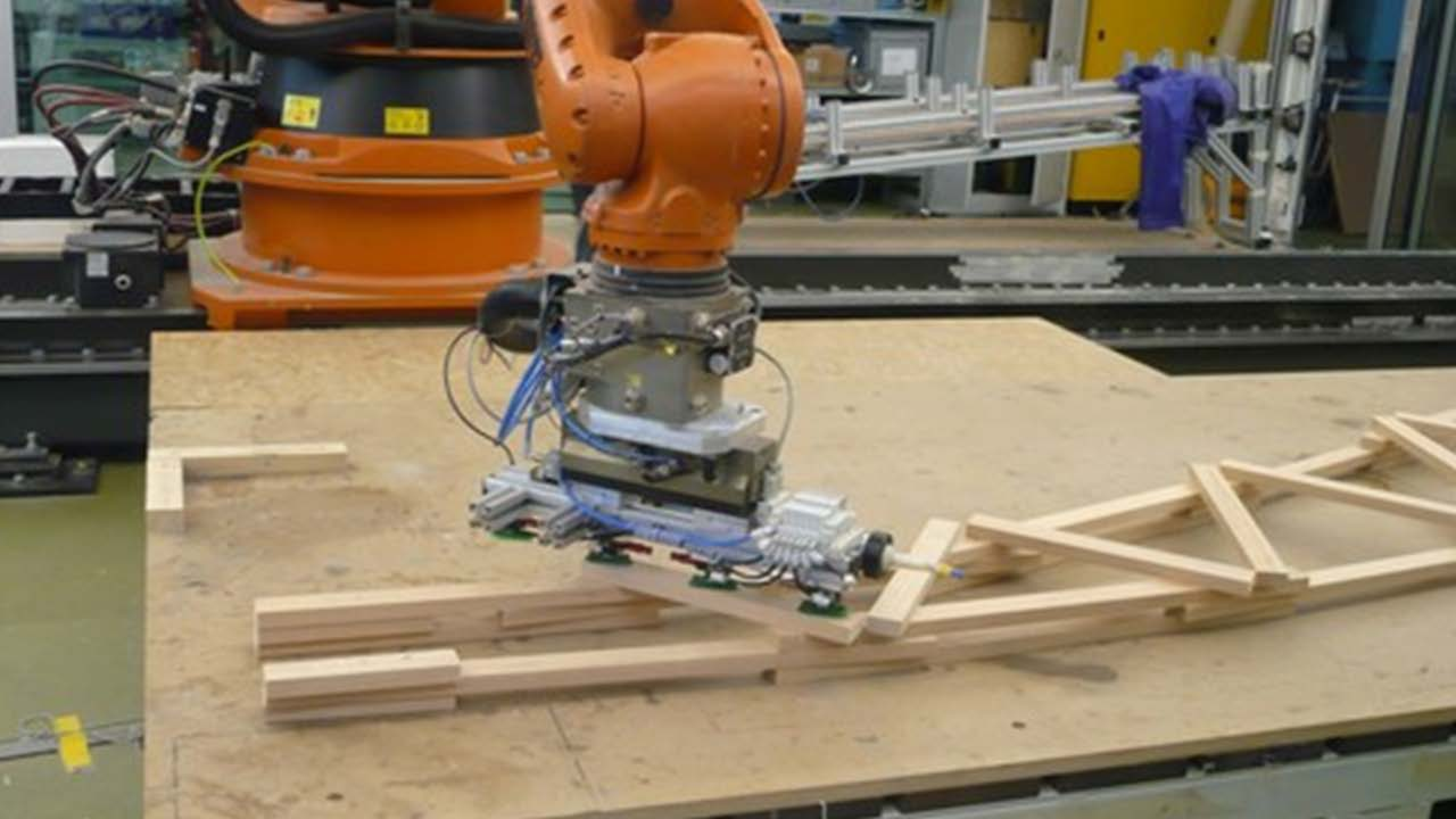

KUKA
KUKA

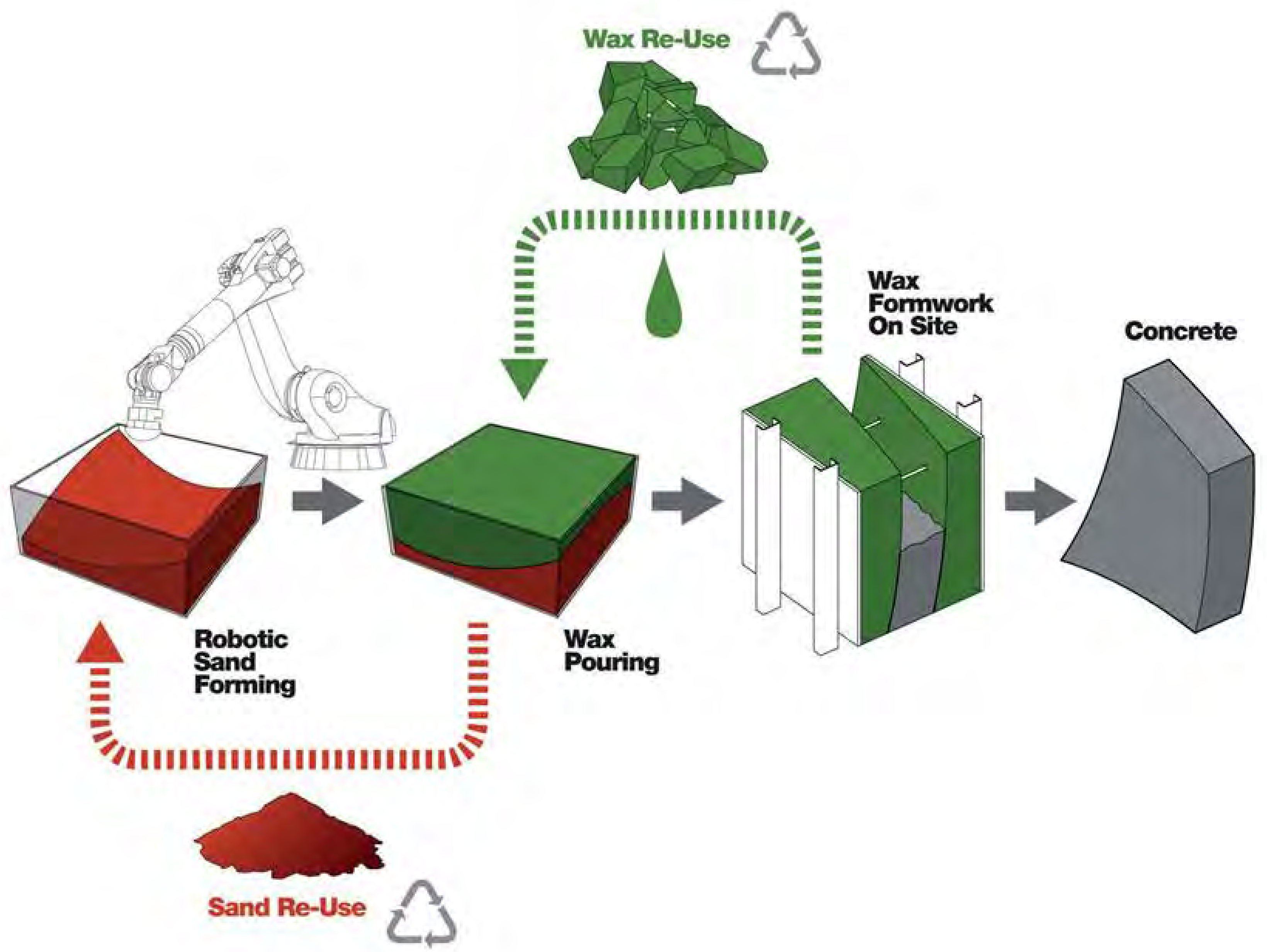
Large scale Robot 3D printing

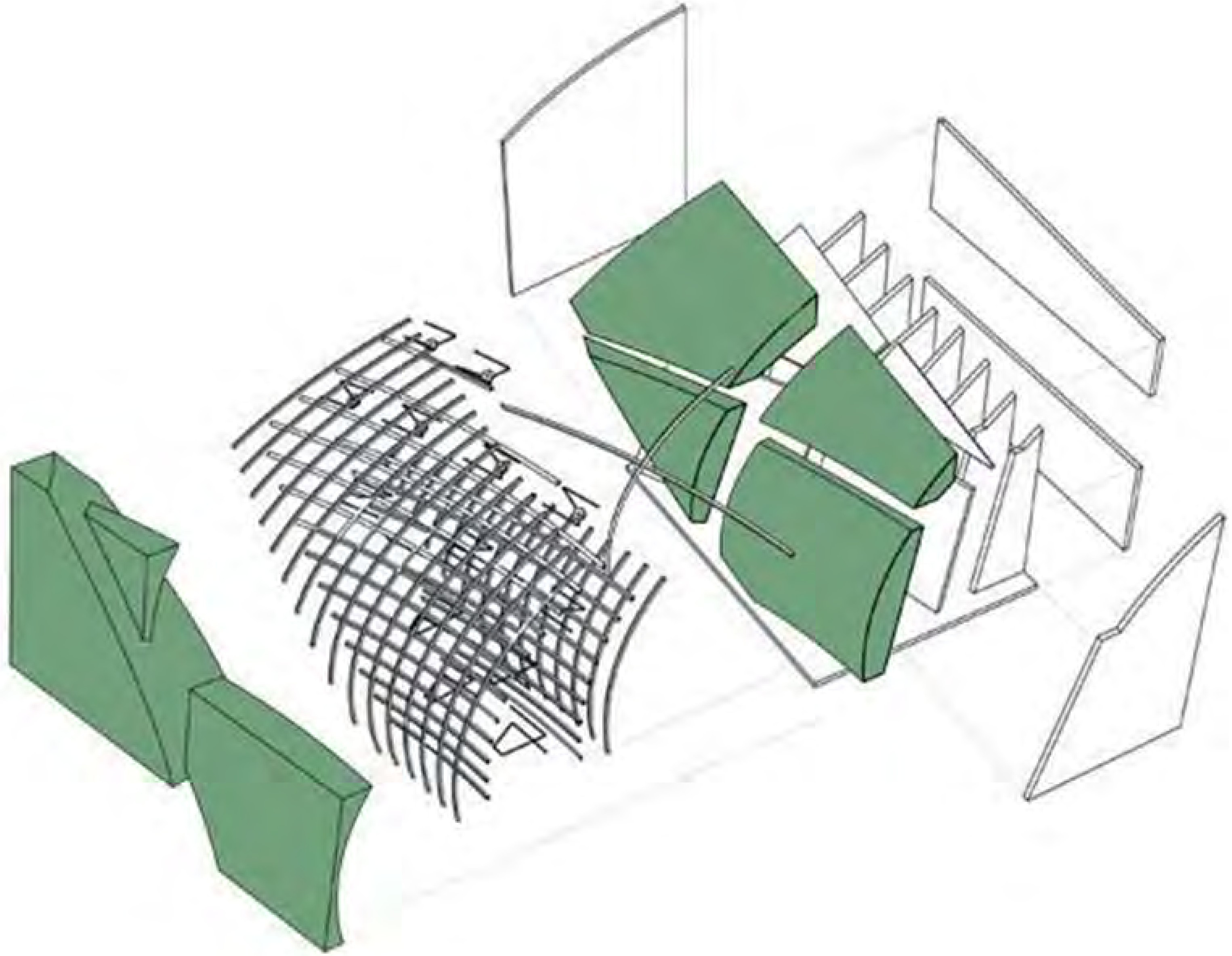


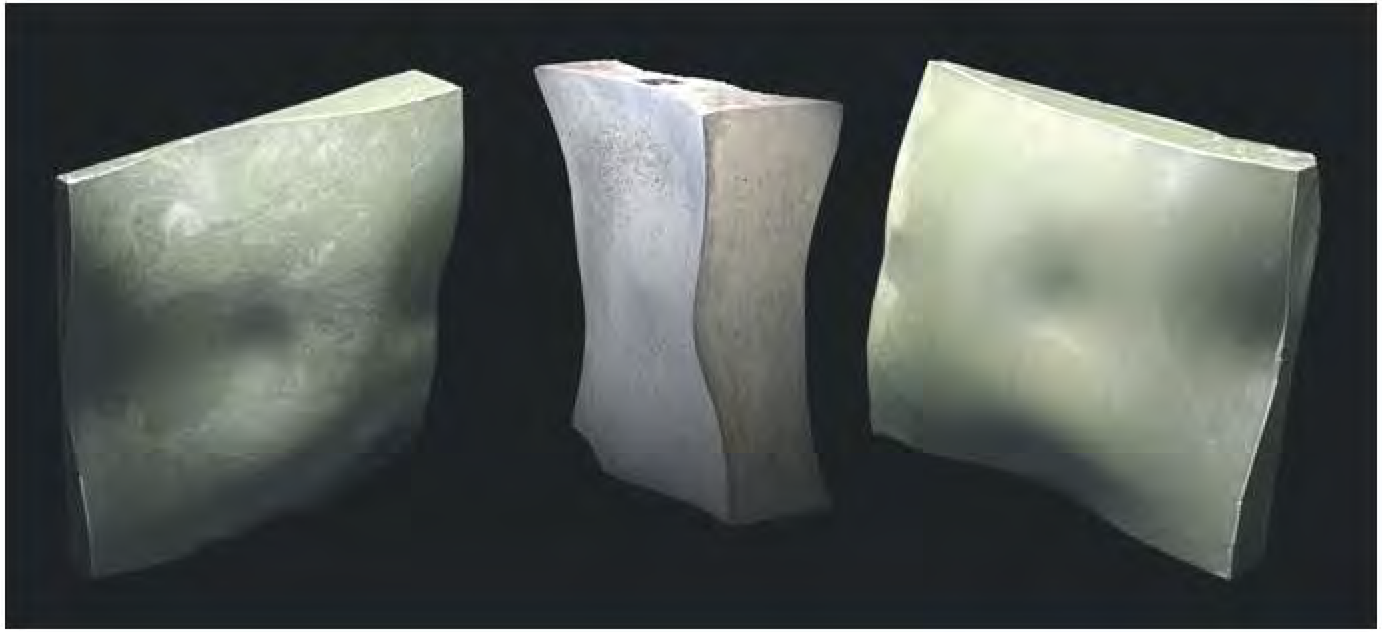





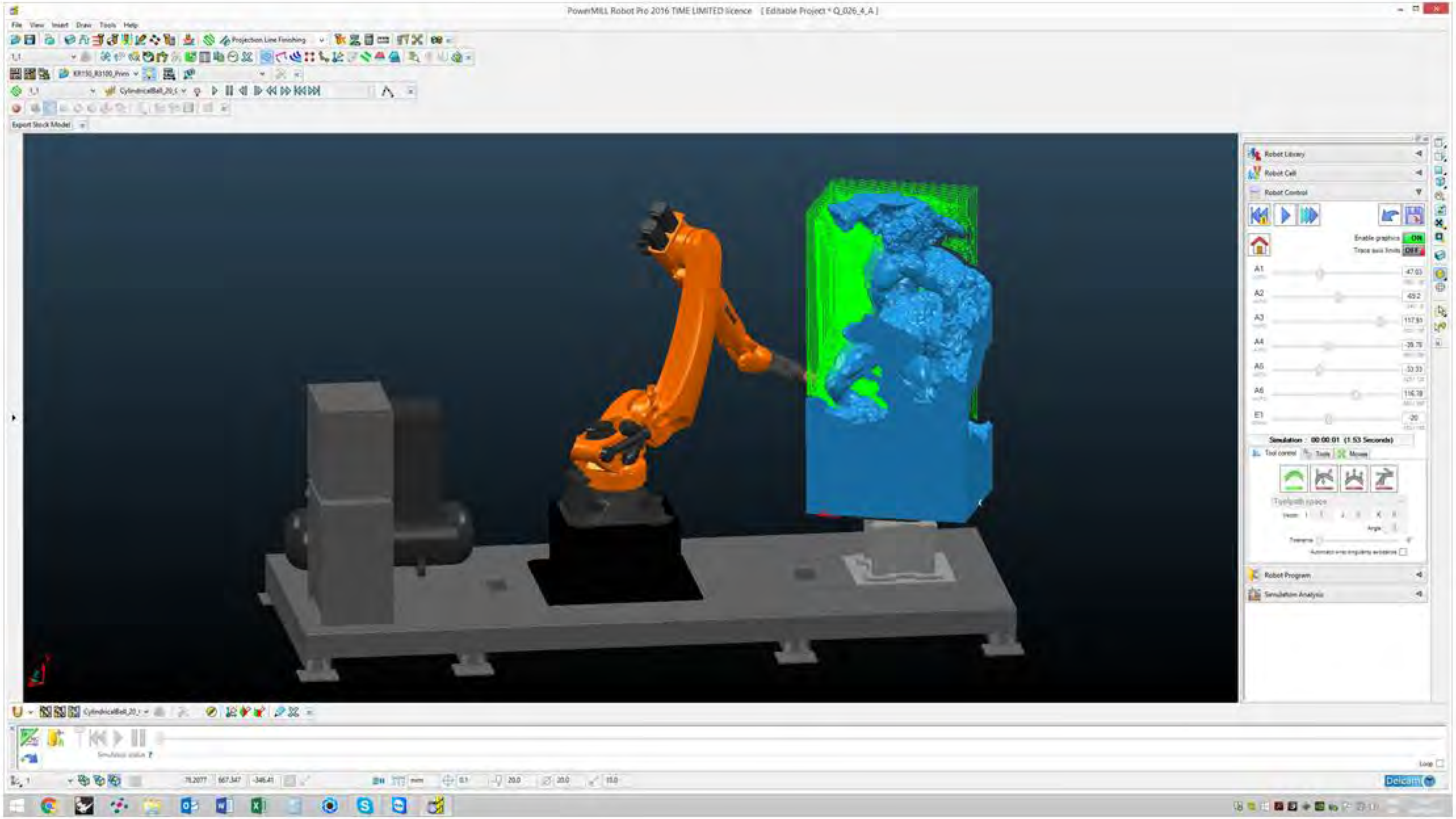


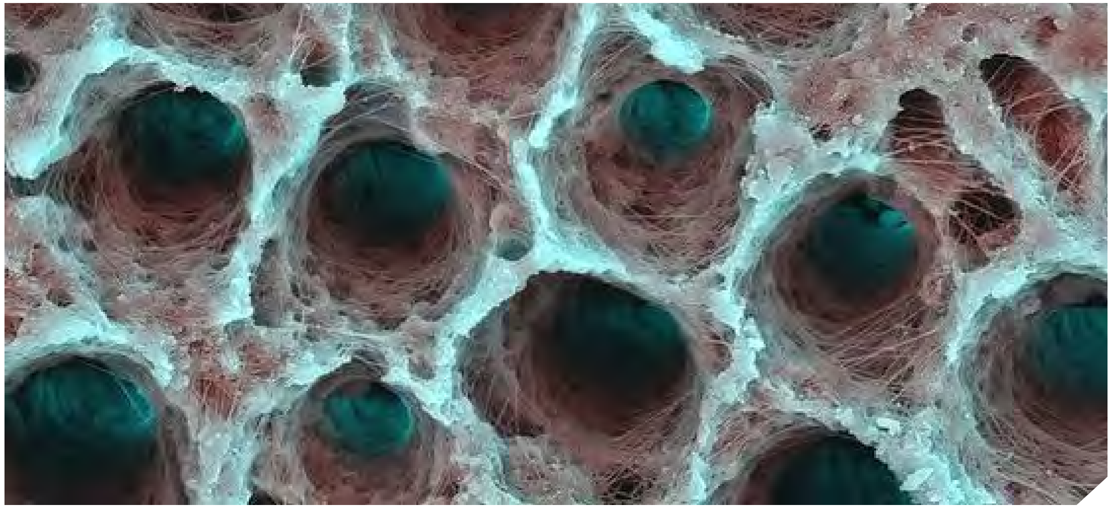

Wax Re-Use
Wax Formwork On Site
Concrete
Robotic Sand Forming
Wax Pouring
Sand Re-Use

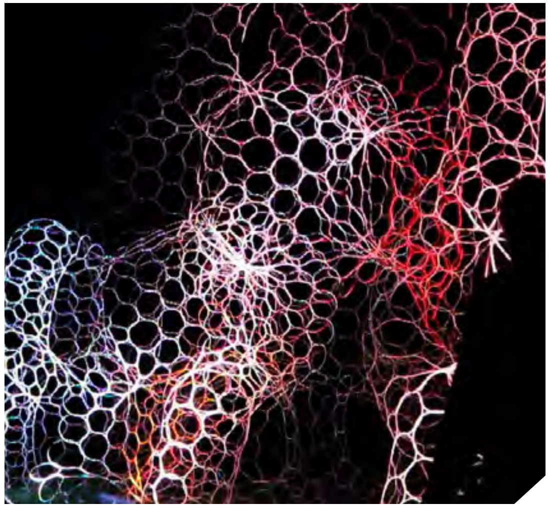


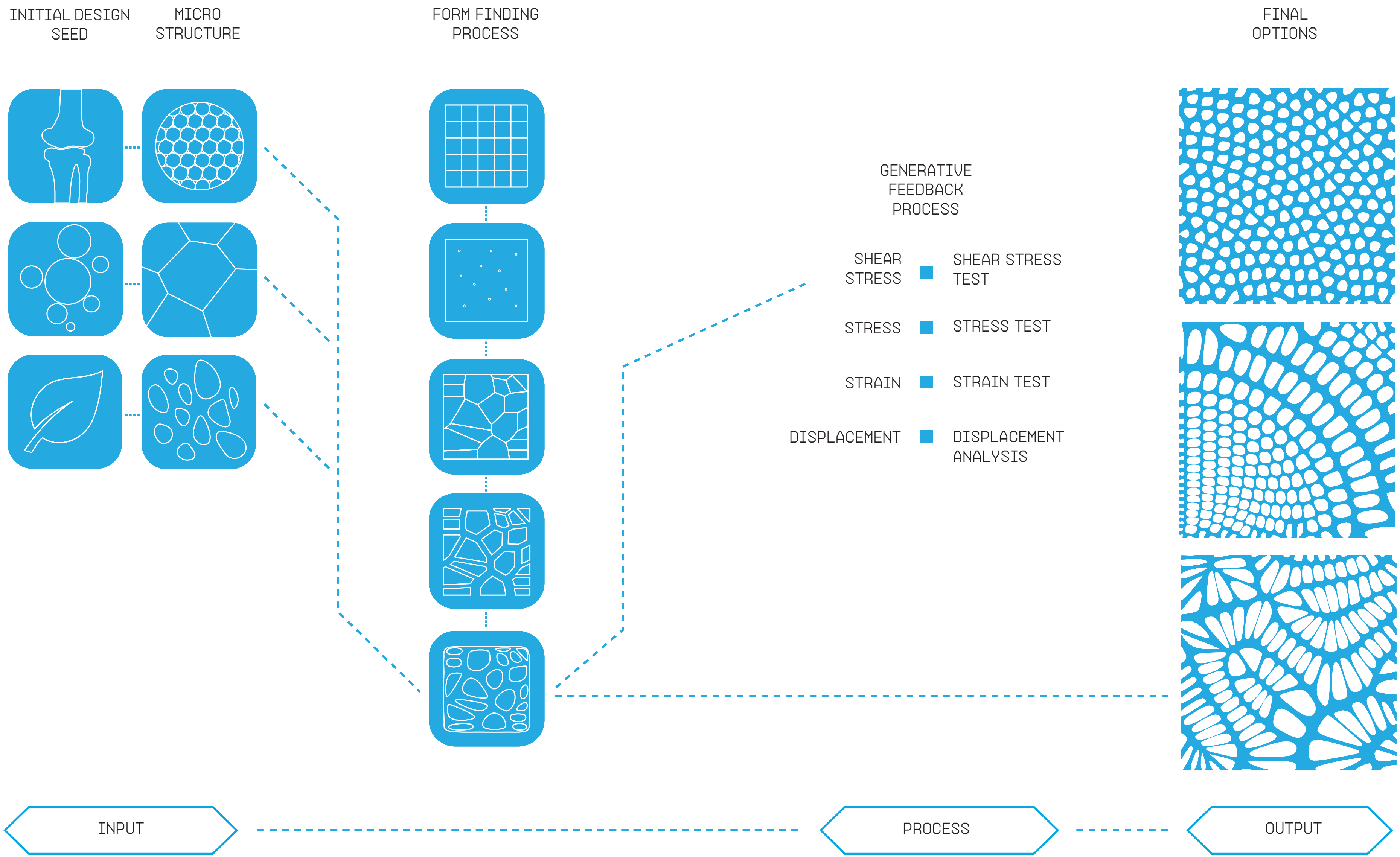

540


PowerMILL Robot Pro 2016 TIME LIMITED licence [Editable Project * Q_026_4_A]
File View Insert Draw Tools Help
Projection Line Finishing
Export Stock Model
Robot Library
Robot Cell
Robot Control
Enable graphics ON
A1
A2
A3
A4
A5
A6
E1
Tool control
Tools
Moves
Robot Program
Simulation Analysis
Delcam

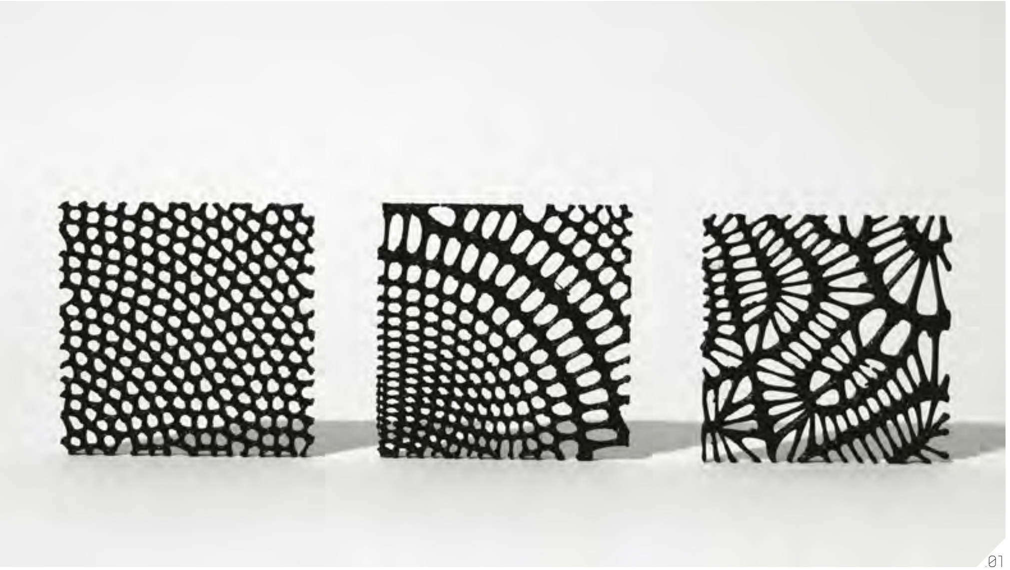




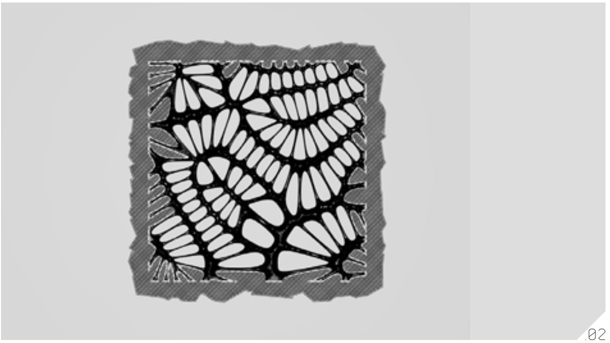
-BONES MICROSTRUCTURE-
/
/
Bones microstructures recorded
at different level of magnification,
with the aid of different instruments.
//



-PANELS ITERATIVE APPROACH-
/
/
Figure showing the process behind the design of the panel.
//



.01



.02

.03

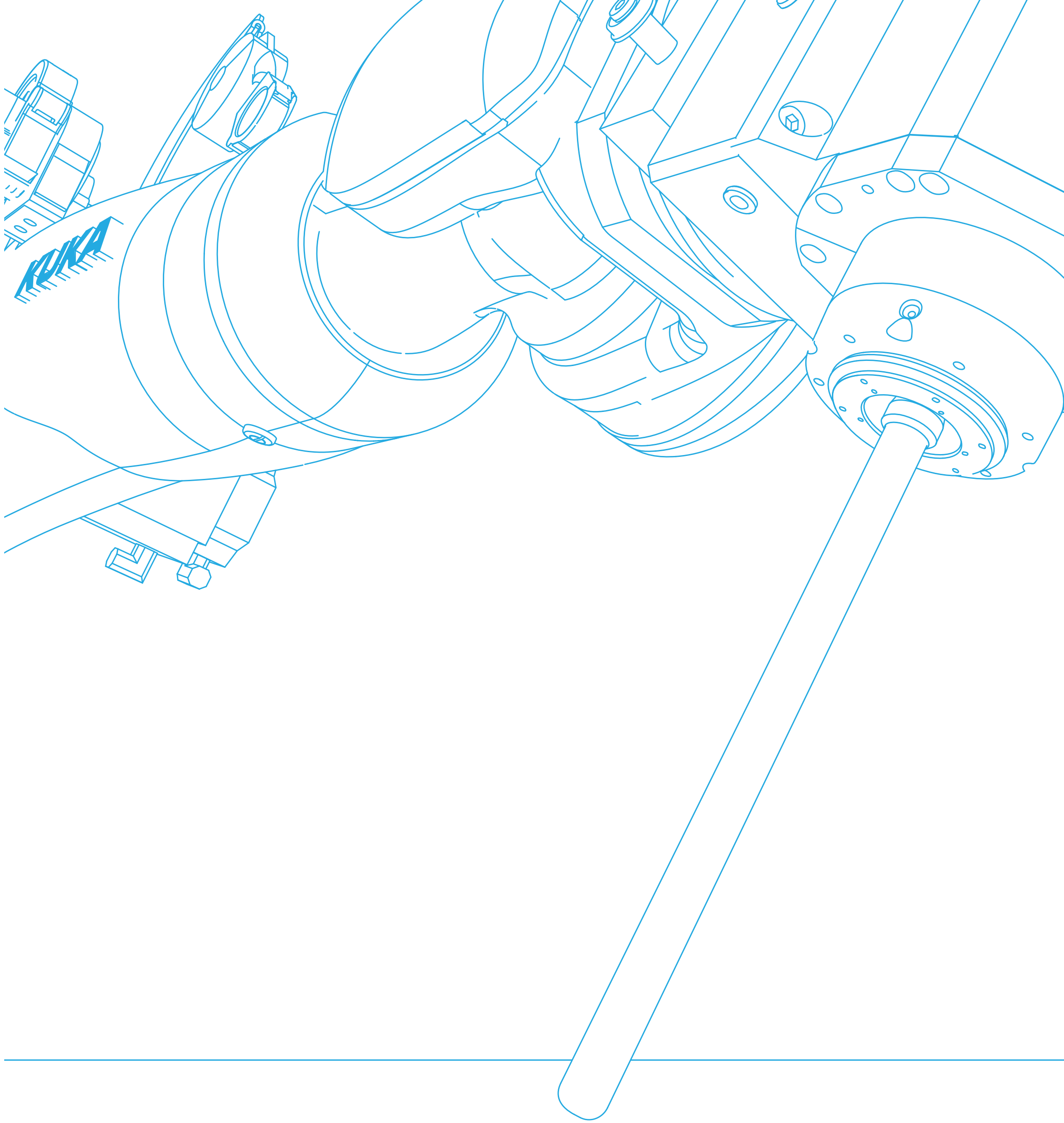
.04

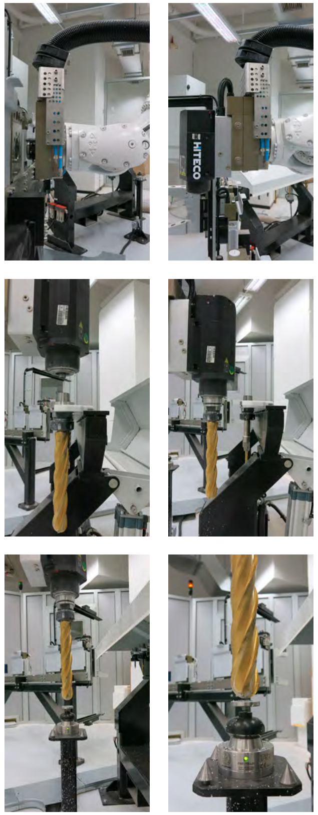
.06

-3D PRINT INITIAL RESEARCH-
/
/
Once the intended result is achieved with the 3d modellation , the next step is to create some physical model.
.01
Initaial research shows 3D printed panels reduced in scale to fit in a hand.
/
.02
Washable material support
/
.03 .04 .05
Each represent a different point of the panel, which then is printed 1:1 scale.
//

FA
BRI
CATI
ON

ROBOT

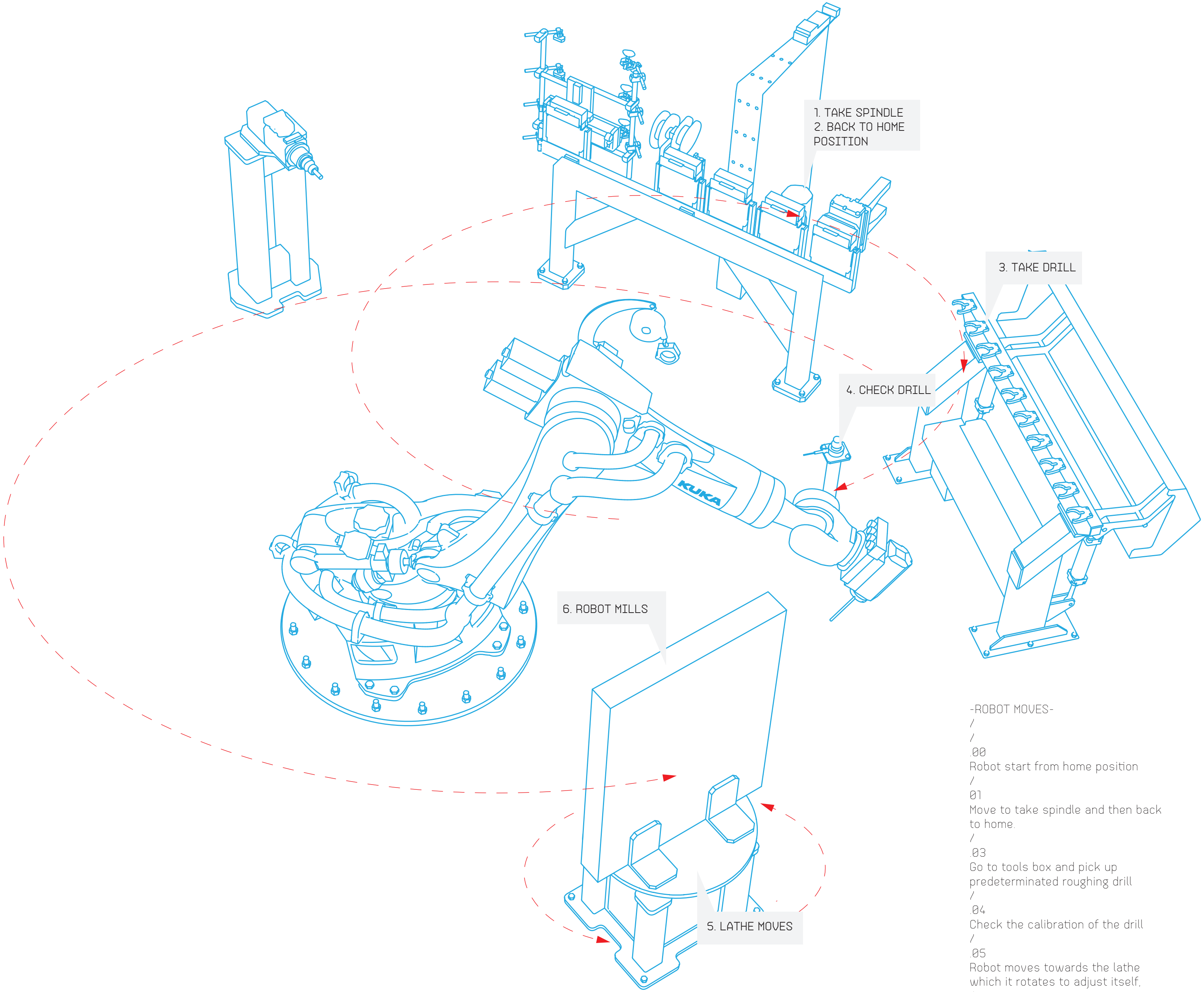




01

02

03



-ROBOT ARM MOVES-

/

/

01 Robot take spindle.
02 Take tool.
03 Check tool.

//

-ROBOT MOVES-

/

/

.00
Robot start from home position

/

01
Move to take spindle and then back to home.

/

.03
Go to tools box and pick up predeterminated roughing drill

/

.04
Check the calibration of the drill

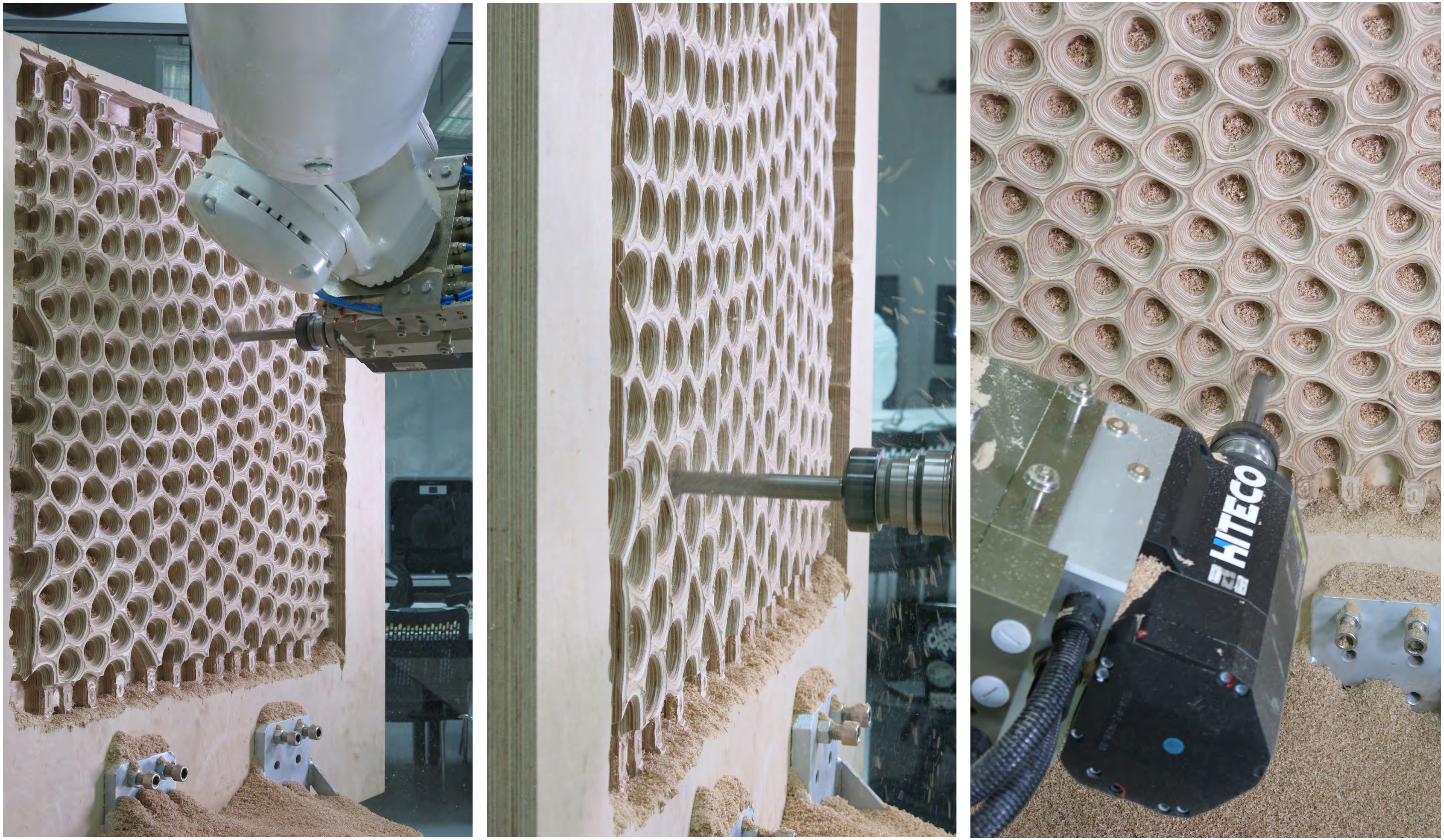
/

.05
Robot moves towards the lathe which it rotates to adjust itself.

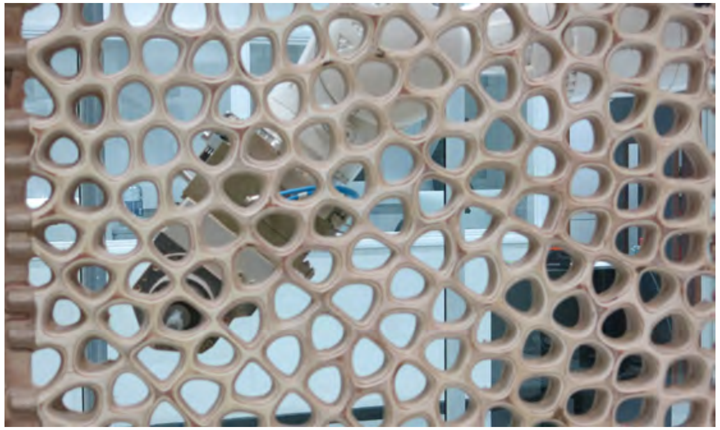
/

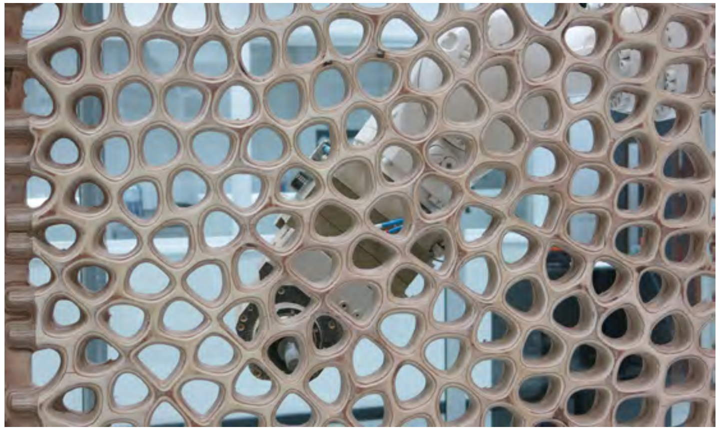
.06
Robots start milling. When the roughing phase its done, it picks another drill for the dinish details.

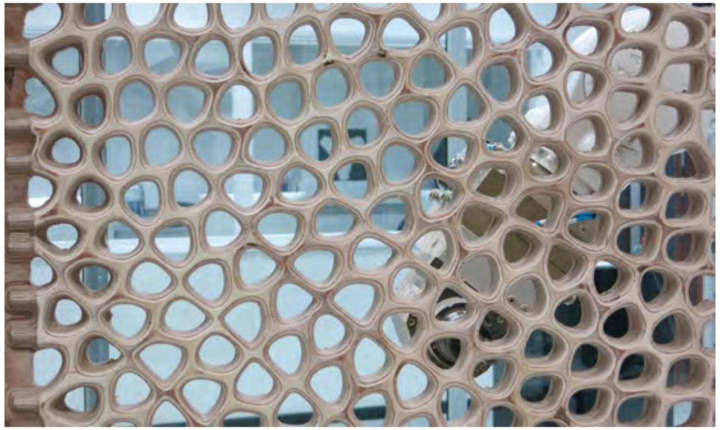
//



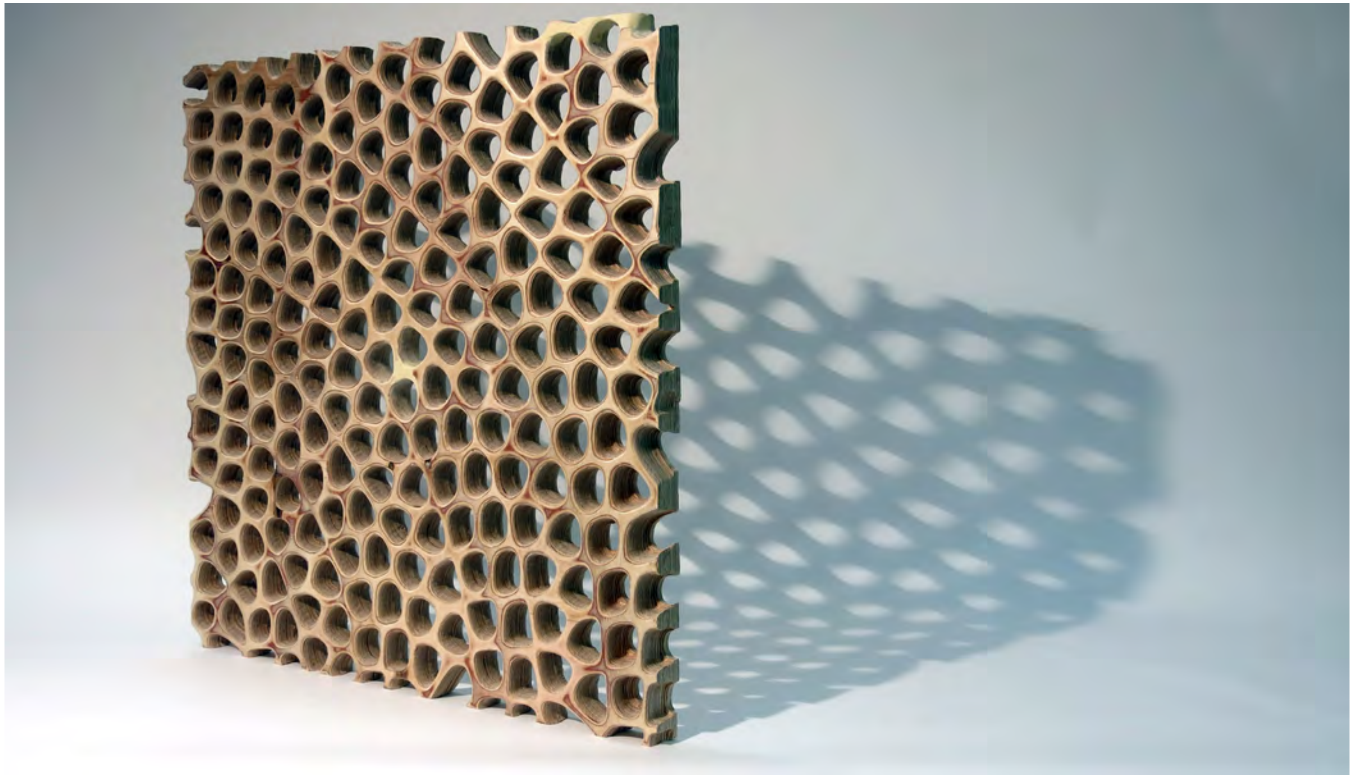
-FABRICATION PROCESS-
/
Morphogenetic pattern, robot milling.
//



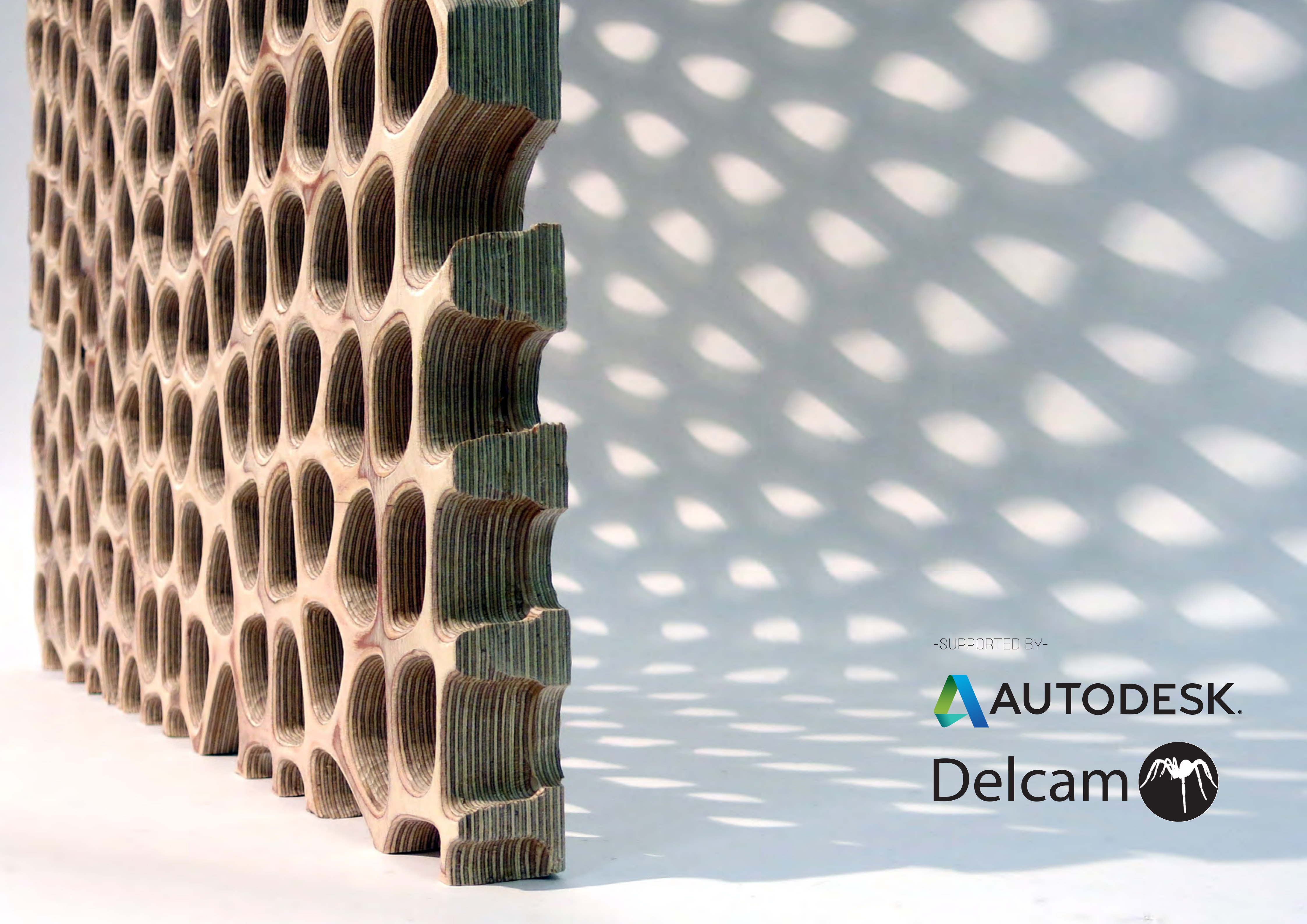




-FABRICATION PROCESS-
/
Robot movements.
//



-FABRICATION PROCESS-
/
Final result.
//


-SUPPORTED BY-
AUTODESK.
Delcam


DRIVE
VOLKSWAGEN GROUP FORUM
HUMAN
FACTOR
ENDLESS PROTOTYPING
01.07. - 27.08.2016
© Quayola
ARS ELECTRONICA LINZ
DRIVE. Volkswagen Group Forum Berlin
www.drive-volkswagen-group.com

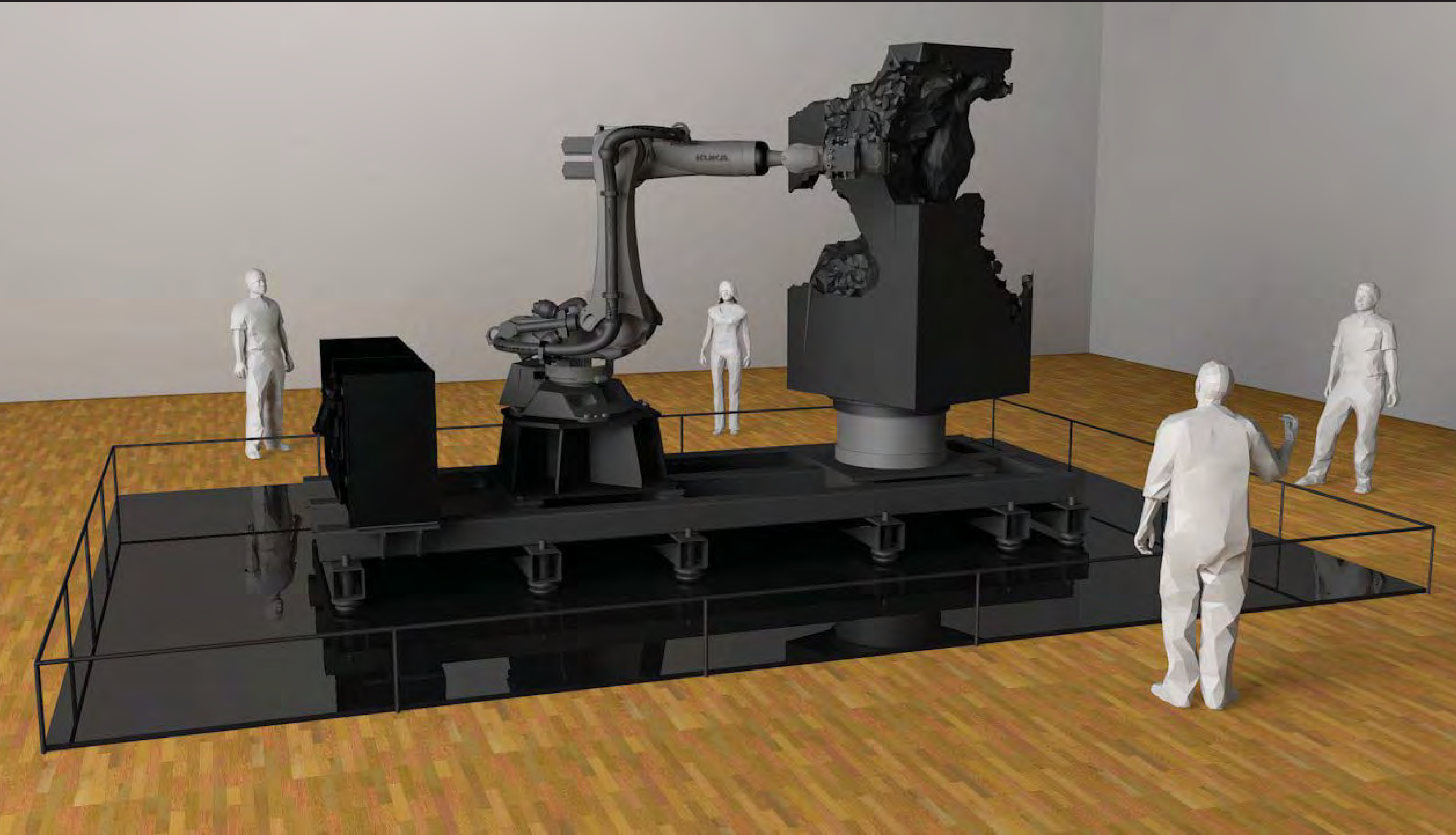
The Sculpture Factory

The Sculpture Factory is a new iteration of Captives, Quayola's ongoing series of physical and digital sculptures inspired by Michelangelo's unfinished masterpieces

It is a further step into Quayola's exploration of classical art and iconography, investigating dialogues and the unpredictable collisions, tensions and equilibriums between the real and artificial, the figative and abstract, the old and new.

The Sculpture Factory is a new performative installation that explores and questions old paradigms of craftsmanship and man-made objects of perfection.

A large robotic arm re-interprets the traditional heritage of classical sculpture by live-carving


KUKA

Quayola is working with high-end robotics partners to develop a custom plug&play robot-
ic-milling
setup to be toured around the world for a series of exhibitions .

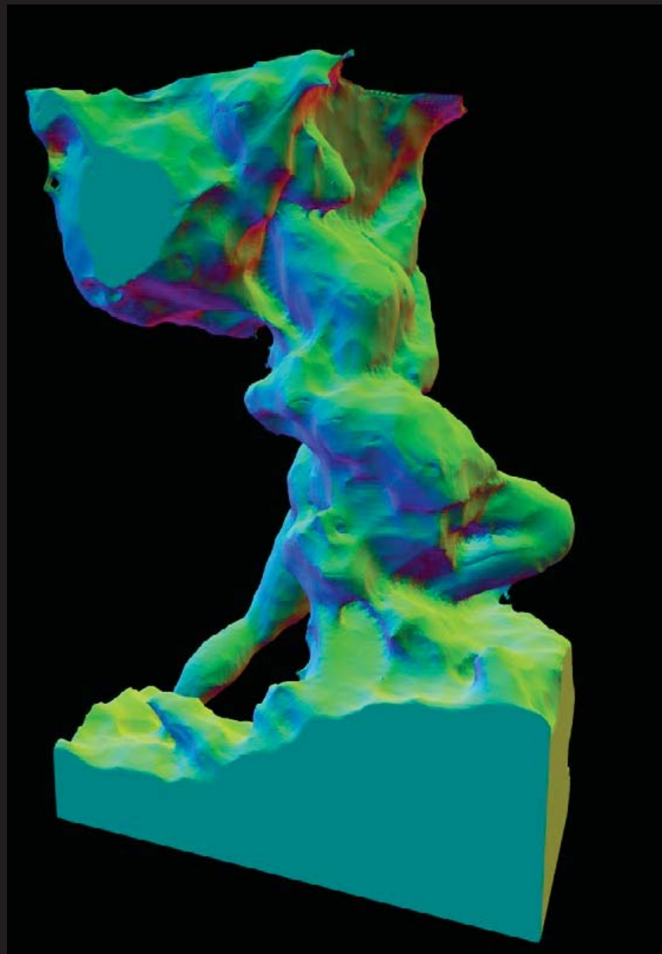
Each show consists in a robotic-sculpting performance to create a series of
pieces live
during one or more weeks of continuous operation.

Source

All the produced pieces in the exhibitions are variations and reinterpretations of the Laocoön and His Sons, one of the most iconic ancient sculptures that has been a ground in spiration for generations of artists throughout history (including Michelangelo's unfinished Captives).
The geometry has been acquired through a combination of 3d-scanning and 3d-modelling.

Digital Sculpting

The geometry of the original sculpture is subject through a series of computational processes via custom software specifically built for the project.
Algorithmic formations are digitally grown from and within the sculpture to simulate endless variations.
The designs are then transformed into set of instructions for the robotic milling process

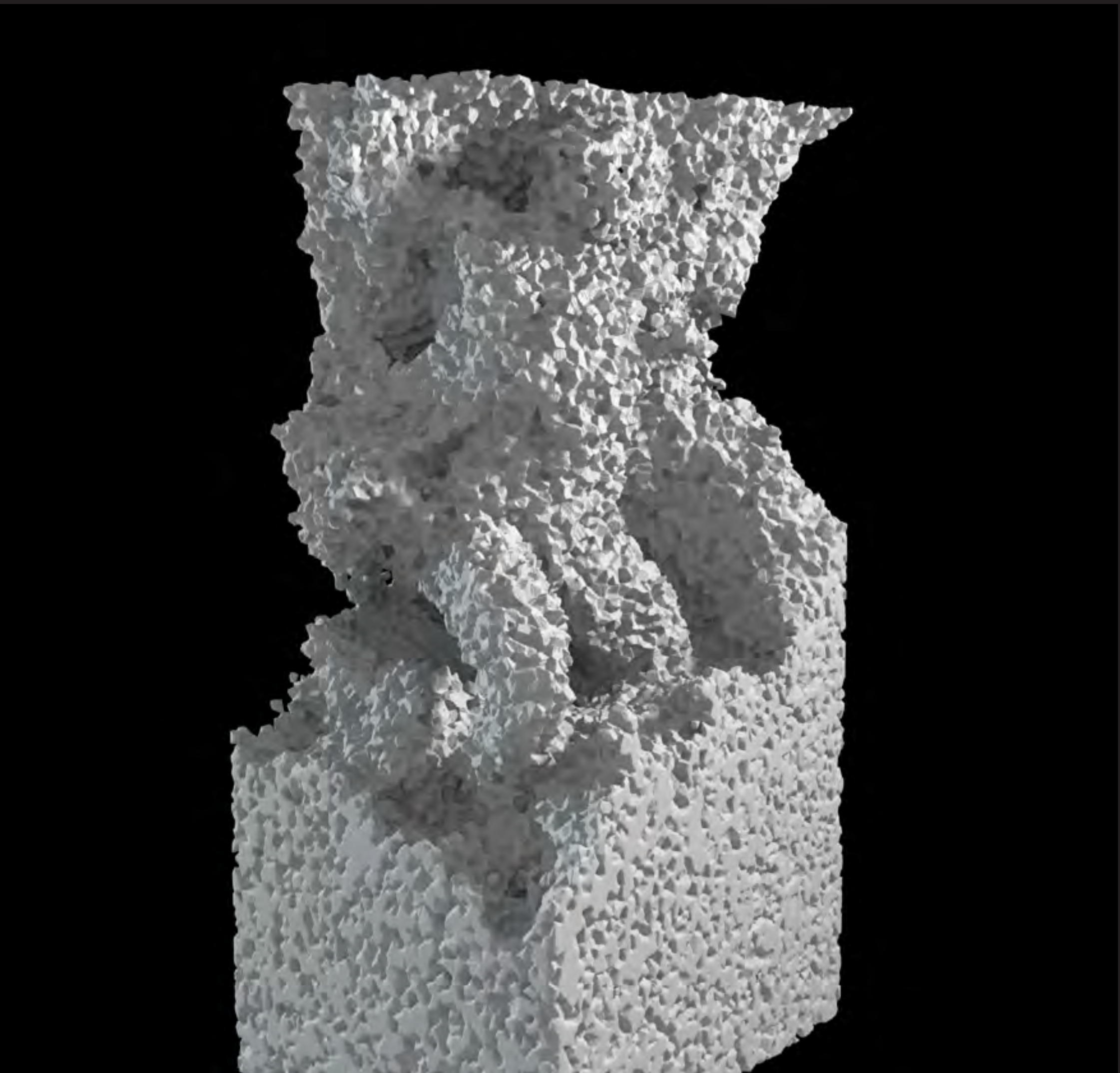


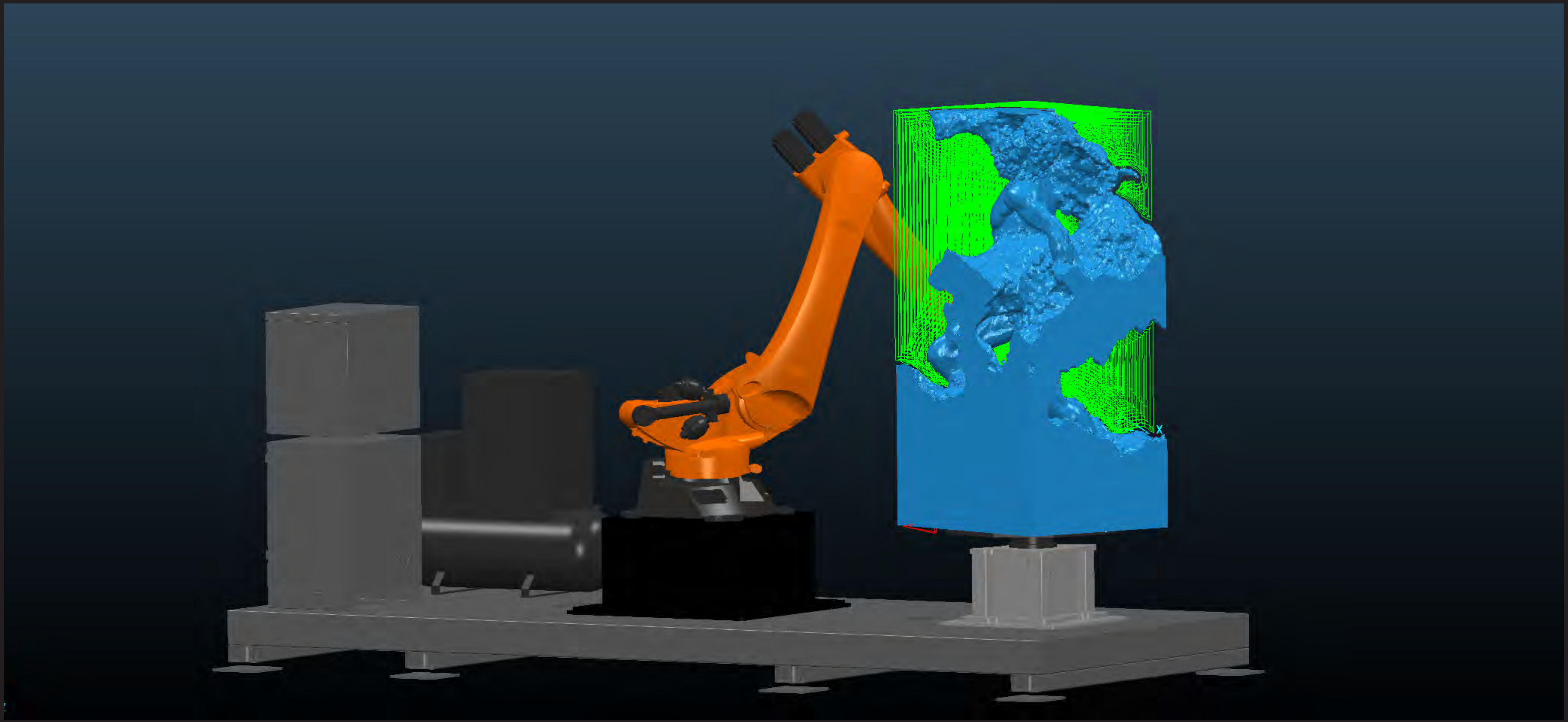

Physical Sculpting

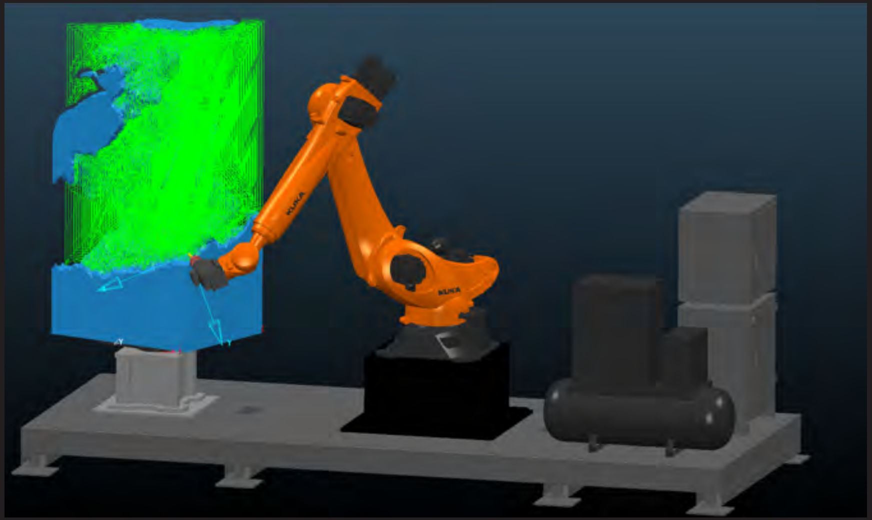
The aim of the milling is not to seamlessly replicate a digital model but on the contrary is part of the design process itself. The milling artefact and limitations are the base of a very specific visual language.
The inherited aestheticks of robotic-milling become a metaphor for the sculptor's hand.
Just like the visible chisel marks of Michelangelo's unfinished sculptures, the artefacts left by the robots

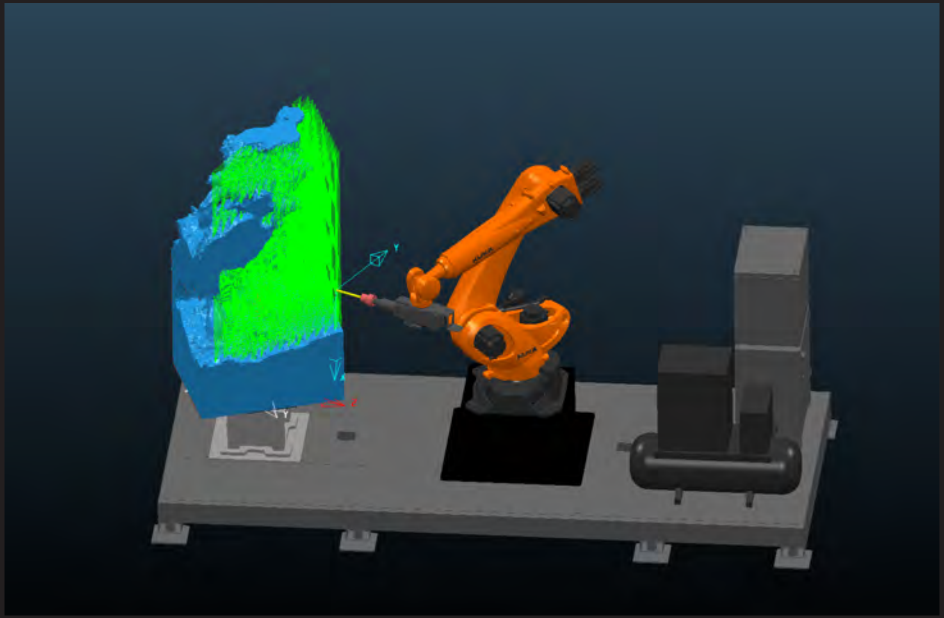
Surface marks left by chisel on Michelangelo's Captives

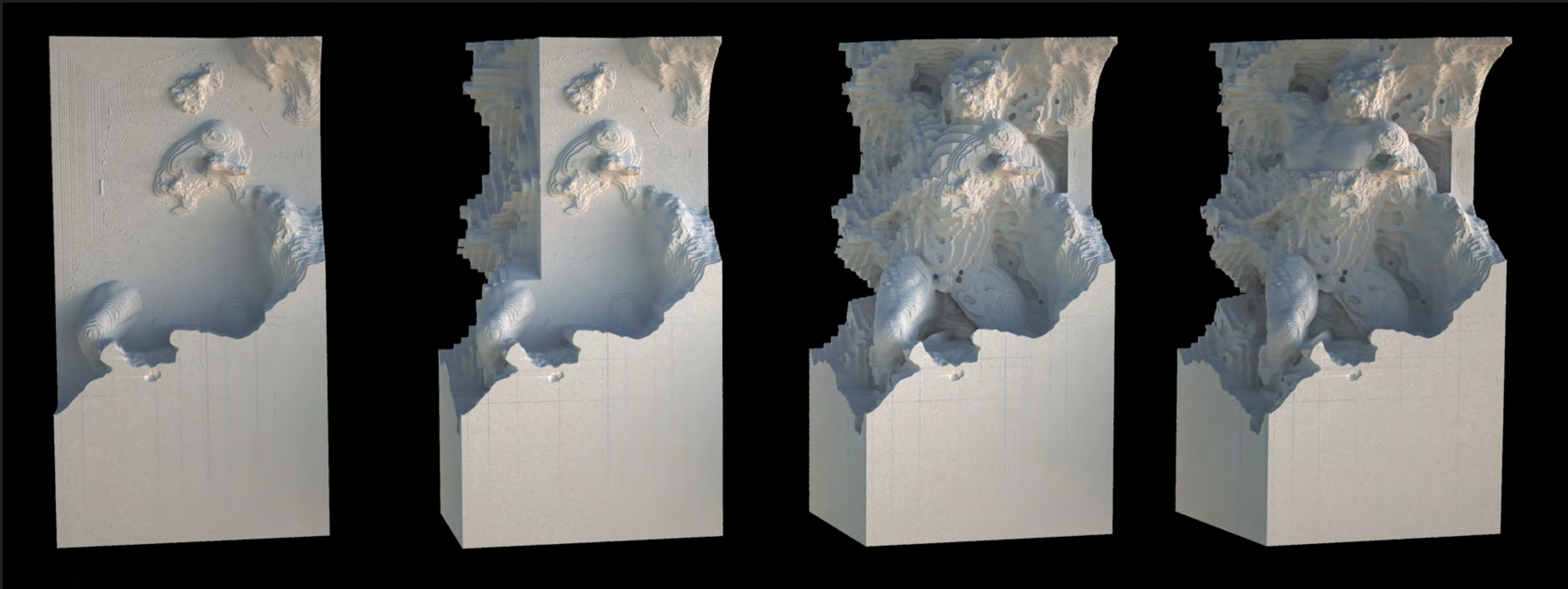
Studies on possible surface marks left by robotic milling

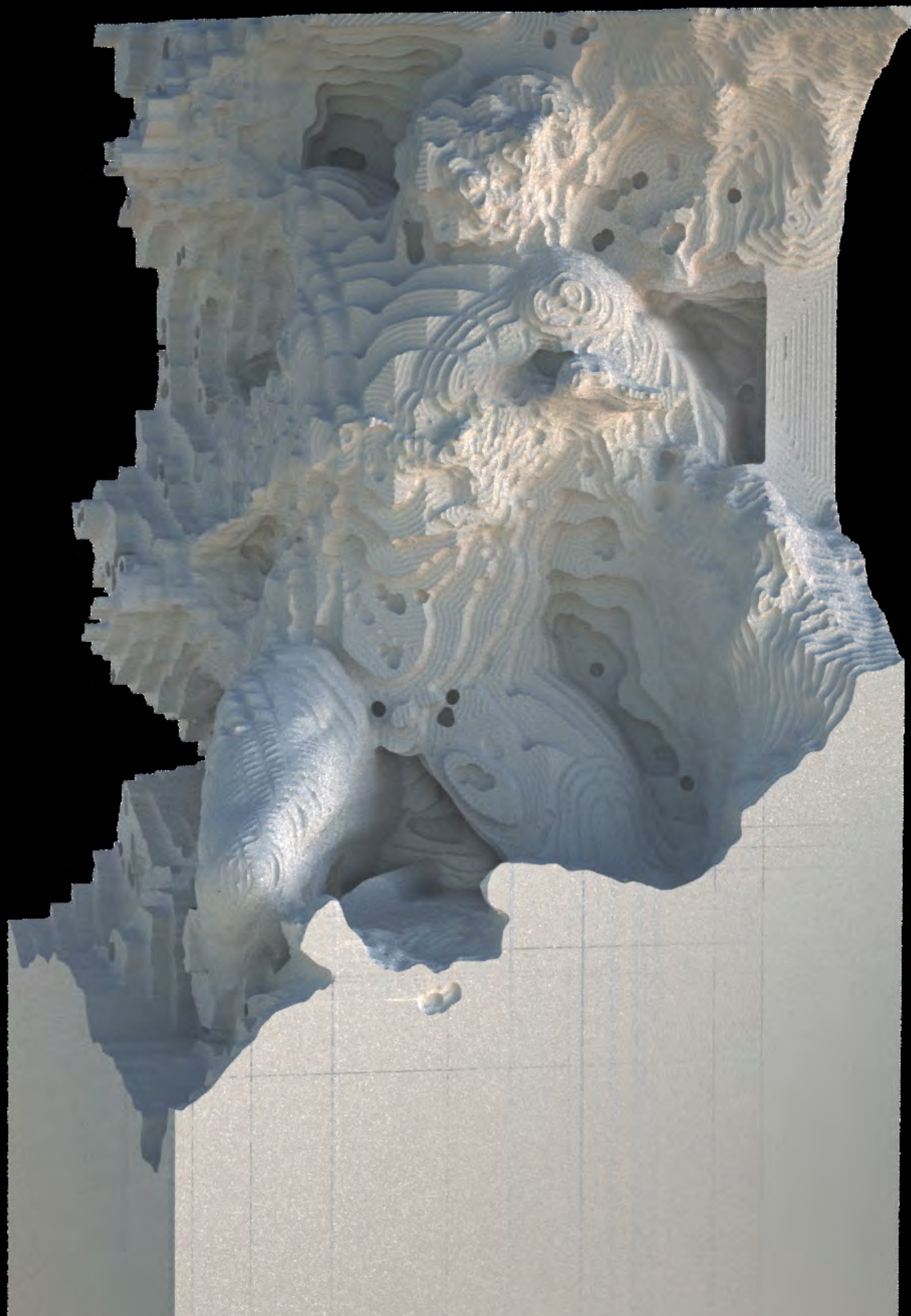











MKG

DAR LAB

DIGITAL ARCHITECTURE ROBOTICS

THANK YOU