Robotic Intelligence

DM II Week 08

DES 212| Winter Term 2 | 2026 | 3 Credits
Instructor: Xun Liu

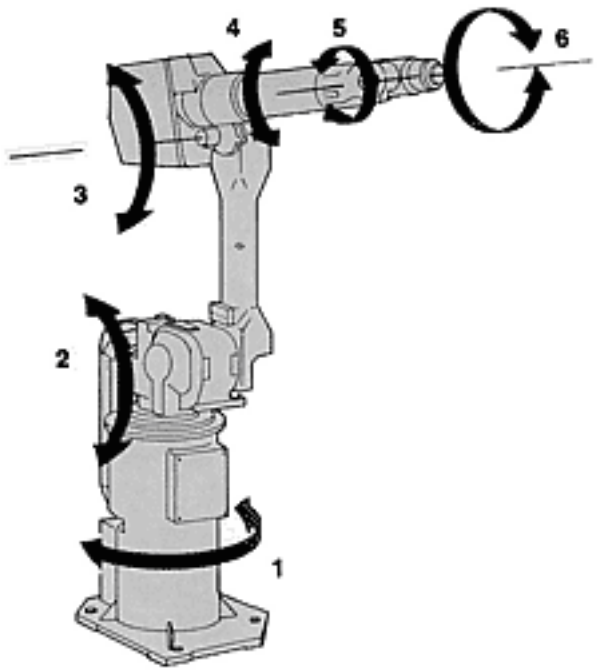
Content

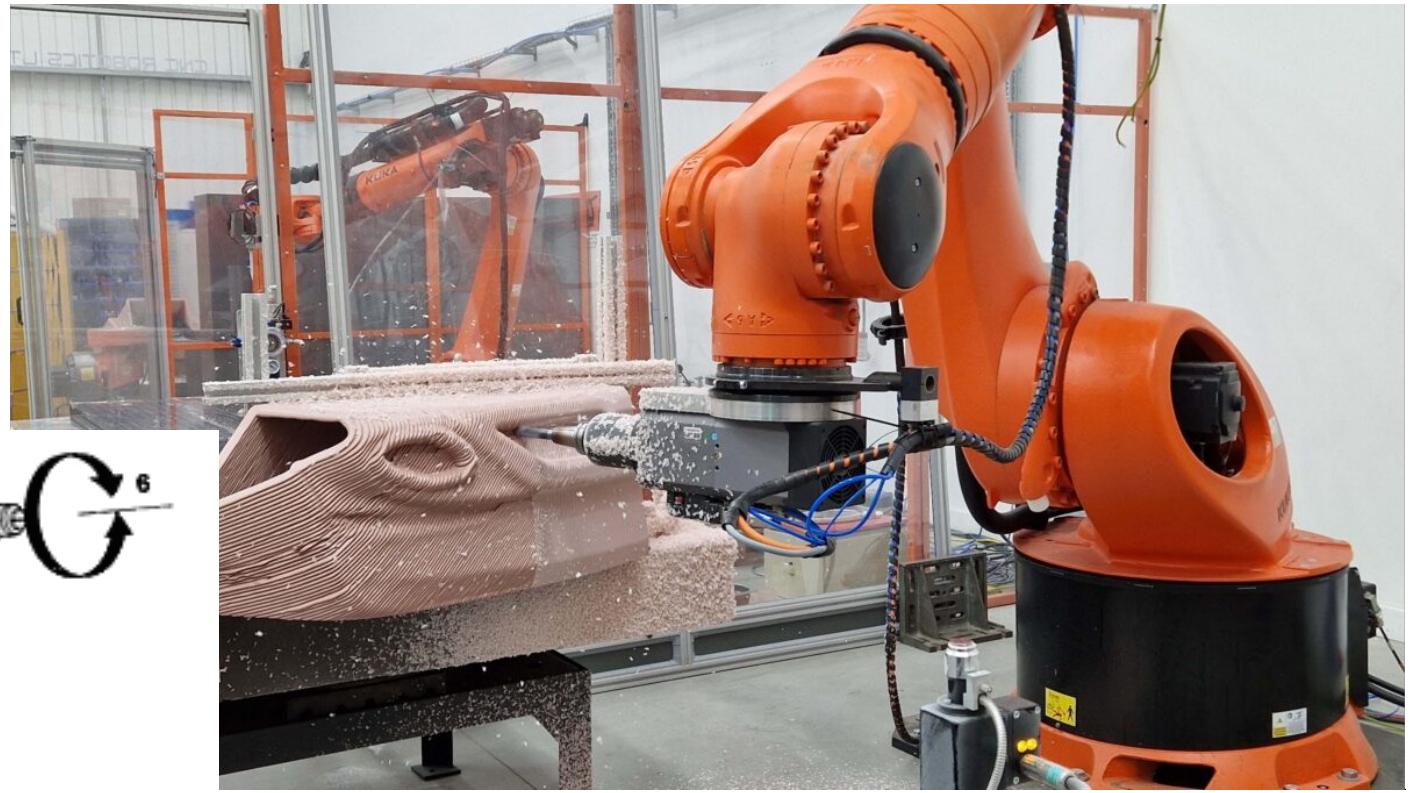
1. Why Robots? From CNC to 6-Axis
2. End-Effector Taxonomy: One Arm, Many Skills
3. How Robots Move + Multi-Agent Systems
4. Integration with Emerging Technologies
5. Where to Go Next

1. Why Robots? From CNC to 6-Axis

6-Axis Kinematics

- Layered (3D print) & planar (CNC) = 2.5D / fixed axes
- 6-DOF: base, shoulder, elbow, 3 wrist joints
- Same arm + different end-effectors = different tasks
- Gantry (XYZ only) vs robot arm (6-DOF)
- Robot arm = the 'universal machine' of fabrication





Resource: https://www.kuka.com/

The AI Layer

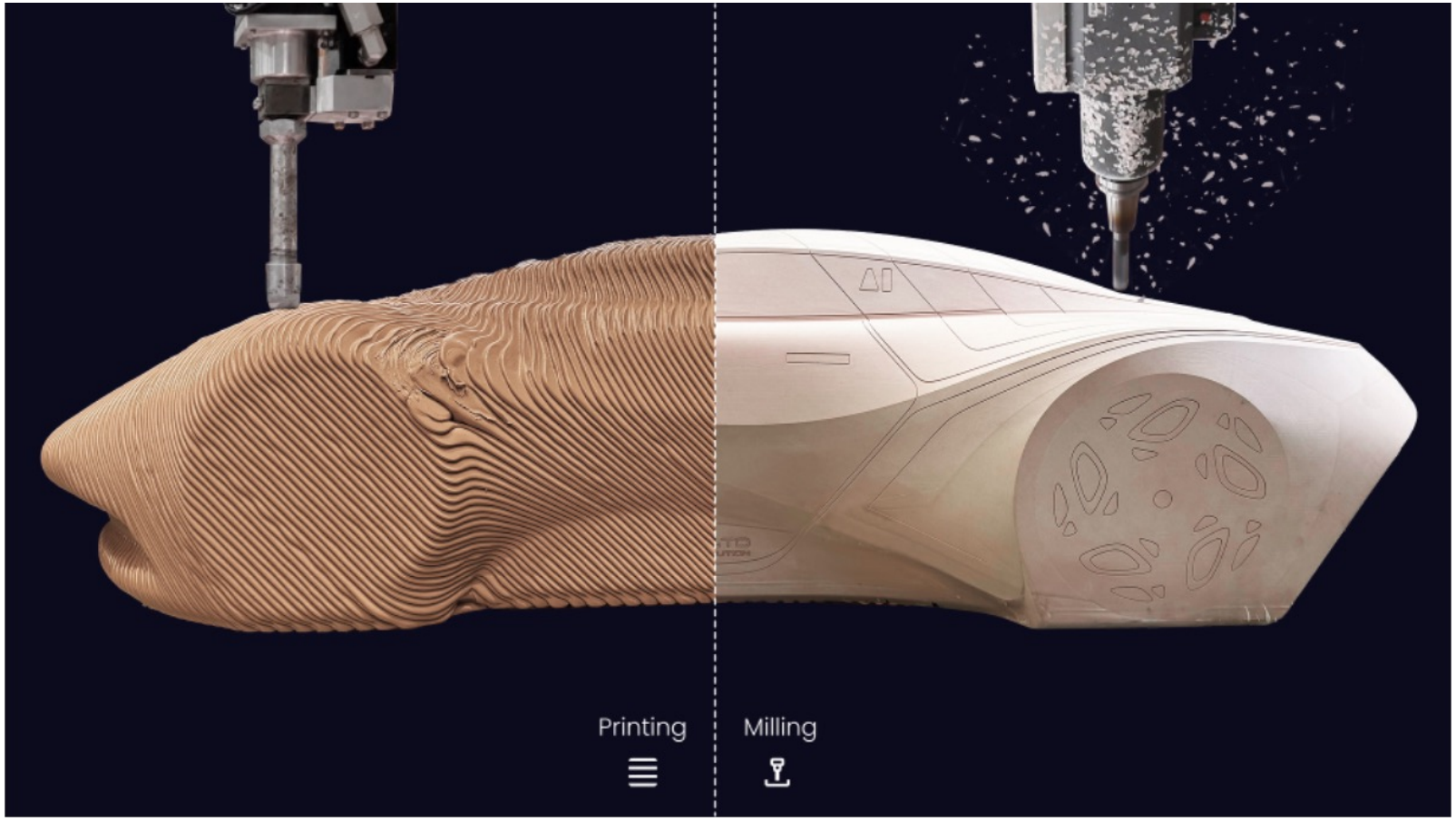
- Robots increasingly go beyond pre-programmed toolpaths
- AI-powered computer vision monitors print quality
- Adaptive toolpath adjustment in real time
- Direction: from automation → intelligence



Resource: https://ai-build.com/

The AI Layer

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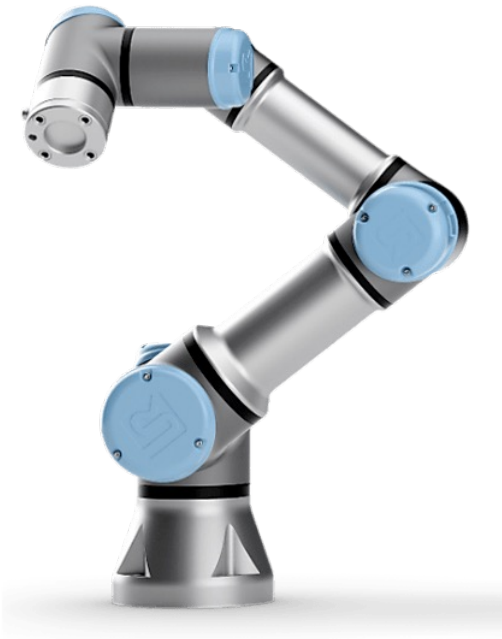
Resource: https://ai-build.com/

Robot Brands in Architecture

- KUKA — dominant in European research (ETH, Stuttgart)
- ABB — Penn Weitzman, widespread industrial
- Universal Robots (UR) — collaborative robots, DDS Lab uses UR30
- All connect to Grasshopper via plugins







Software Ecosystem

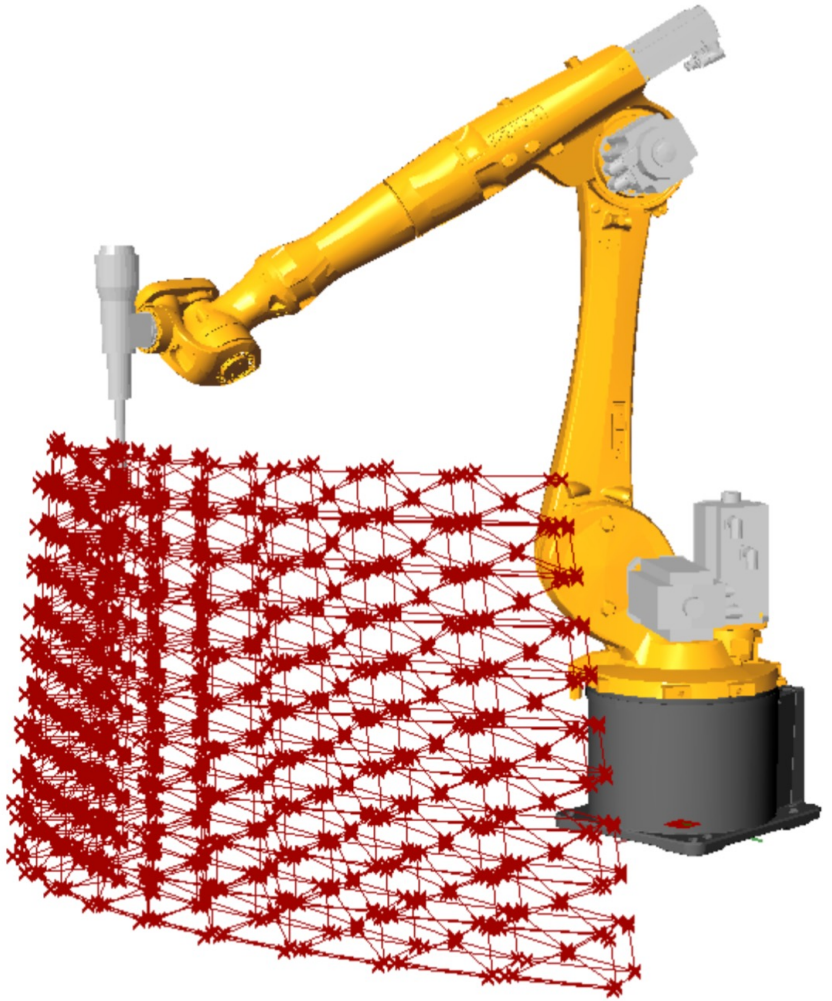
Grasshopper plugins:
- **Robots**
- KUKA|prc (for KUKA only)
- HAL Robotics
- **FURobot**

…

Compas-rrc (for ABB only)

- All integrate with Grasshopper
→ parametric-to-robot pipeline





Resource: https://www.food4rhino.com/en/app/furobot

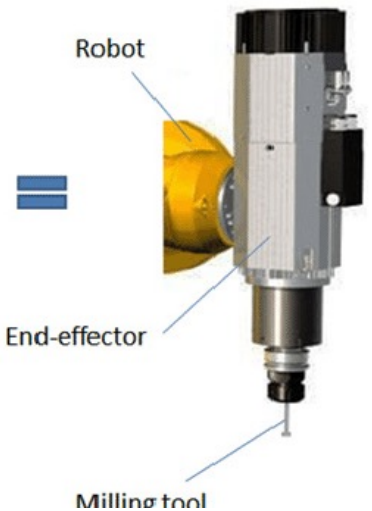
2. End-Effector Taxonomy: One Arm, Many Skills

The End-Effector Defines the Task

- End-effector = 'hand' of the robot
- The robot doesn't define the process — the end-effector does
- Types: **mill, extruder, winder, gripper, welder, sprayer…**
- One arm, swap tools → many fabrication processes









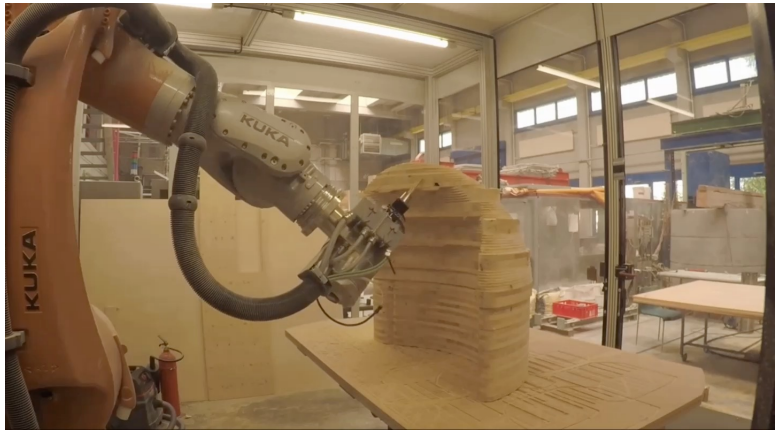
2.1 Milling / Cutting

Subtractive: spinning bit or hot wire removes material from solid block

Materials: foam, timber, stone — freeform surfaces in all 6 axes
6-DOF advantage: undercuts + double curves impossible with 3-axis CNC

Pros: High precision, mature tech
Cons: Material waste, dust, slow on stone





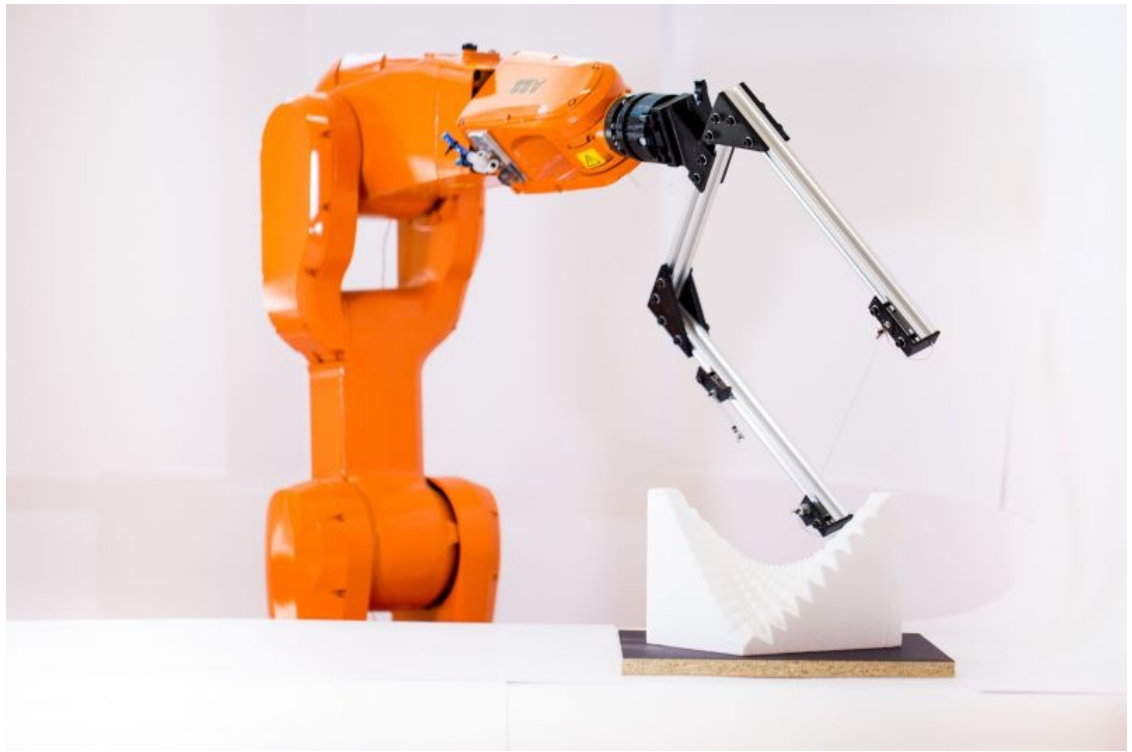
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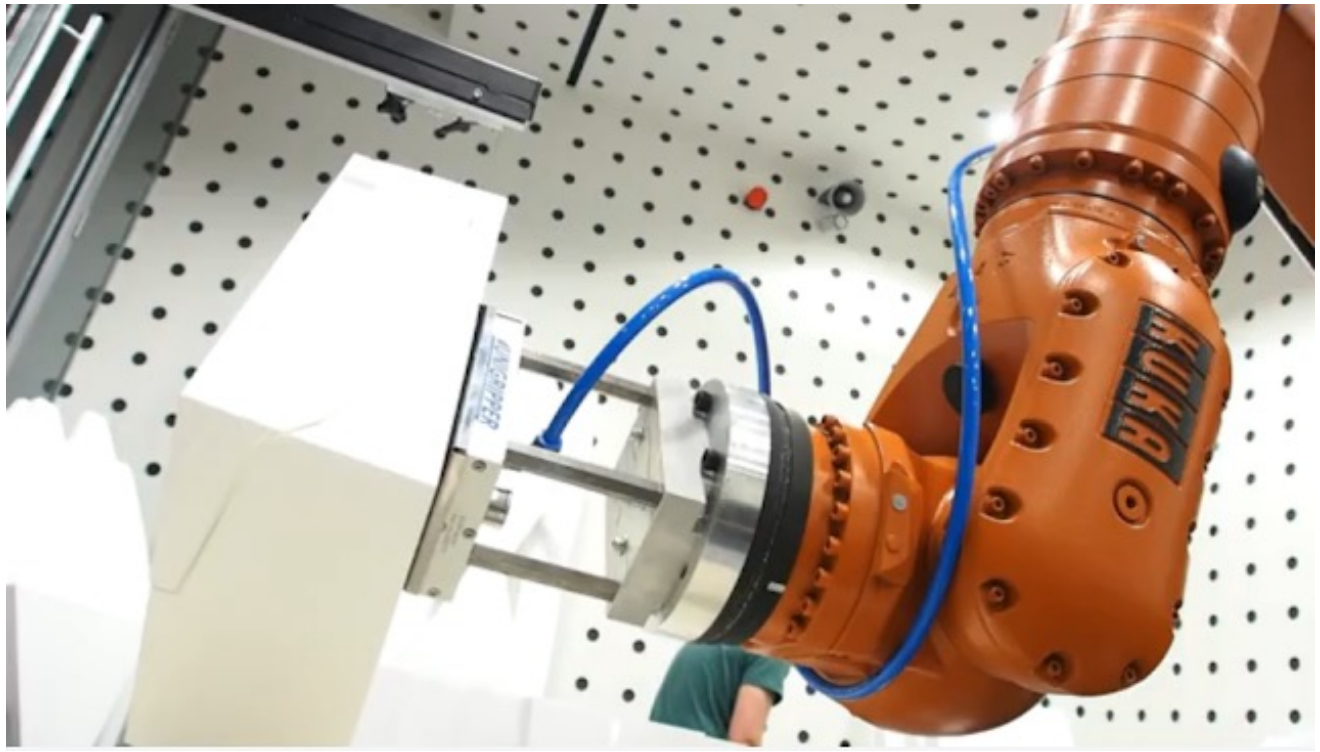


Digital Stone Project
Jose Luis García del, th
Generative Design Grou

Source: https://www.youtube.com/watch?v=YmOoyyITU7o

2.1 Milling / Cutting





Robotic Hot-Wire Cutting

2.1 Milling / Cutting



Robotic Hot-Wire Cutting
Gramazio Kohler Research / ETH Zurich

Source: https://vimeo.com/172539578

2.1 Milling / Cutting



Woodchip Barn
AA Design & Make programme

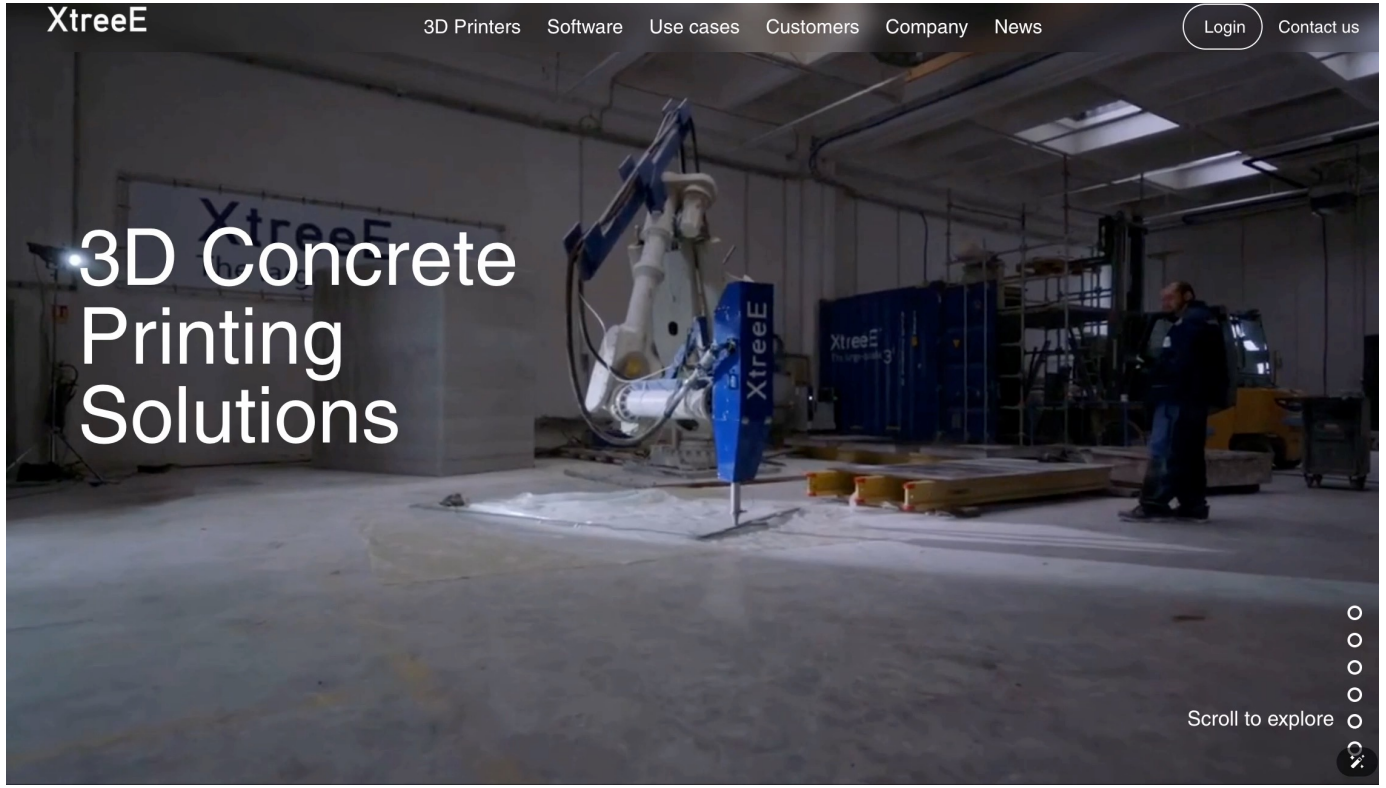
2.2 Extrusion / Printing

Additive: material extruded through nozzle, deposited layer-by-layer

Materials: concrete, clay, thermoplastics (PET-G), bio-composites, metal

6-DOF advantage: non-planar printing — curved paths, tilted layers, overhangs

Pros: Minimal waste, formwork-free, scalable
Cons: Layer lines, needs reinforcement



Resource: https://www.xtreee.com/

2.2 Extrusion / Printing





Eggshell Pavilion
Gramazio Kohler / ETH Zurich, 2022

Resource: https://www.designboom.com/architecture/eth-zurich-gramazio-kohler-digital-design-robotic-3d-printing-eggshell-pavilion-10-05-2022/

2.2 Extrusion / Printing



Eggshell Pavilion
Gramazio Kohler / ETH Zurich,
2022

Resource: https://vimeo.com/752965274

2.2 Extrusion / Printing

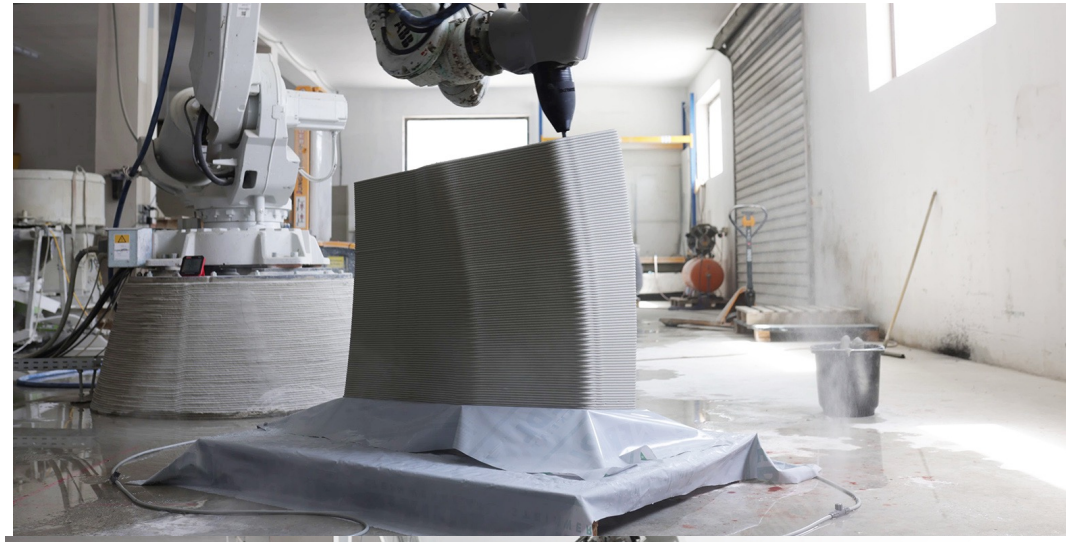


Striatus Bridge
Holcim + ETH + Zaha Hadid Architects, Venice 2021

Resource: https://www.zaha-hadid.com/design/striatus/

2.2 Extrusion / Printing







Striatus Bridge
Holcim + ETH + Zaha Hadid
Architects, Venice 2021

Resource: https://www.zaha-hadid.com/design/striatus/

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2.2 Extrusion / Printing



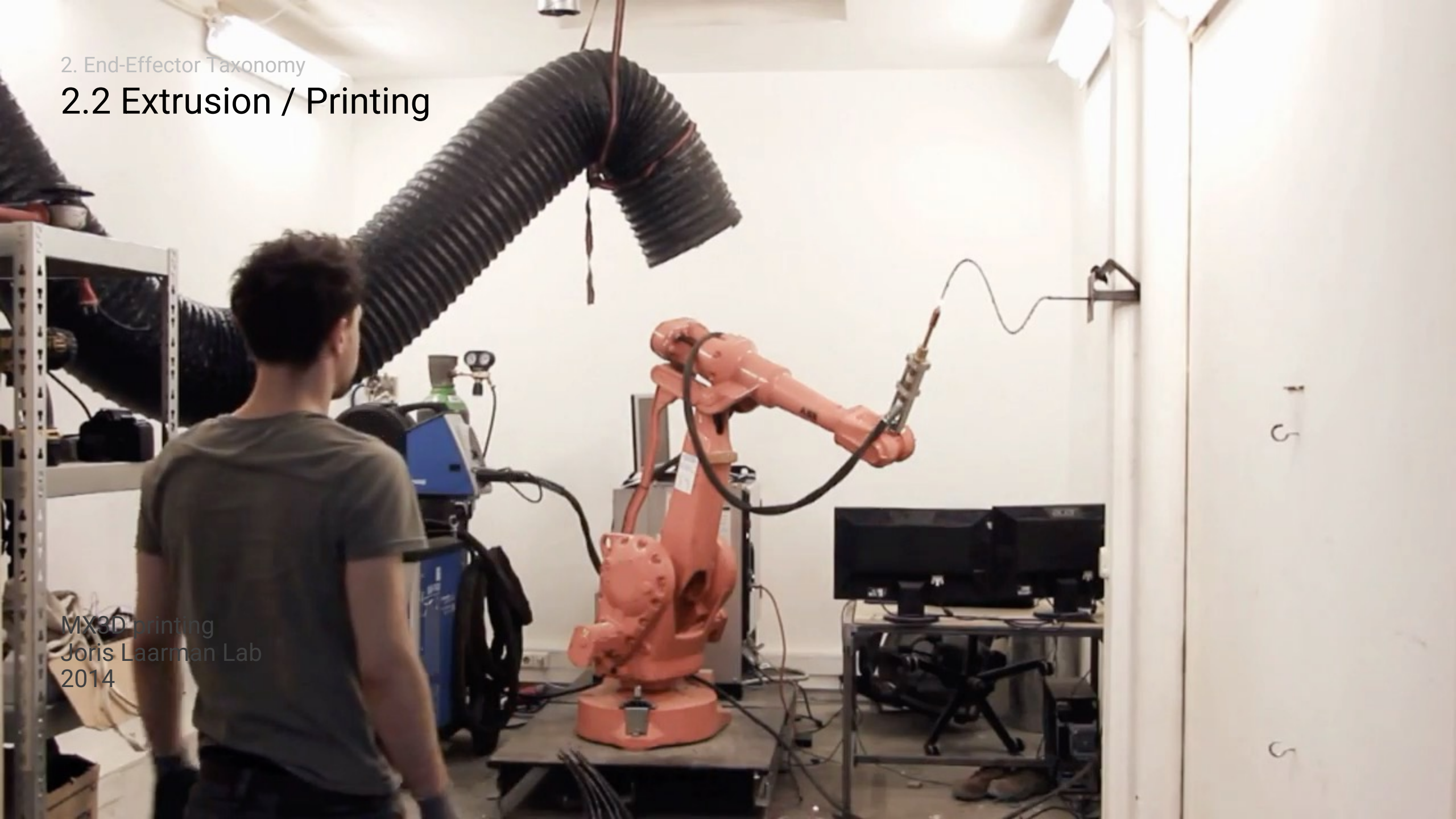


Steel Node
Takenaka + MX3D, 2019

Resource: https://www.designboom.com/architecture/mx3d-takenaka-3d-print-structural-steel-connector-12-12-2019/

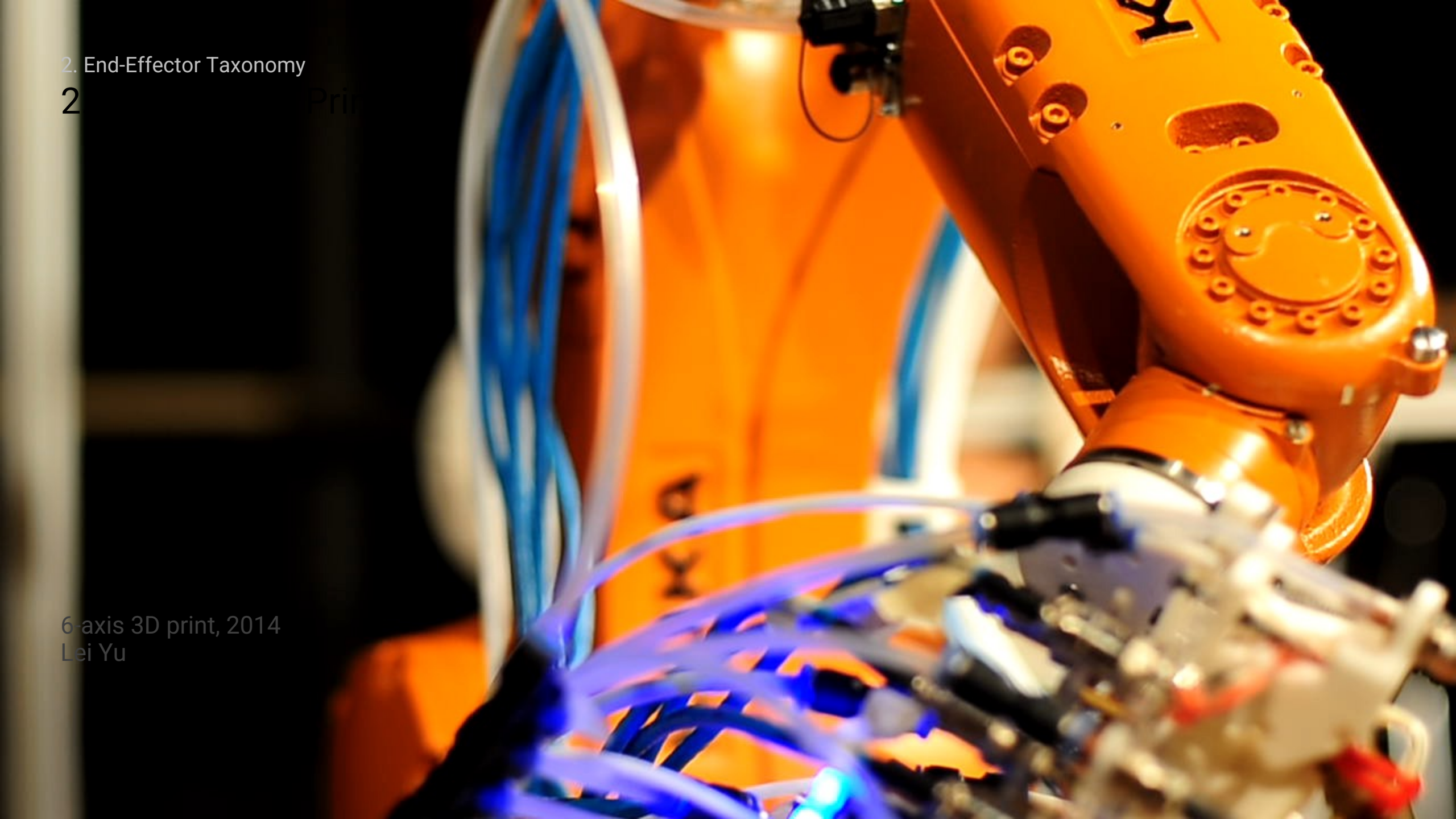

NEXT STEP
STRUCTU

2.2 Extrusion / Printing



MX3D printing
Joris Laarman Lab
2014

2 Prin



6-axis 3D print, 2014
Lei Yu

2. End-Effector Taxonomy

2.2 Extrusion / Printing



6-axis 3D print, 2014
Lei Yu

https://vimeo.com/117134365?fl=pl&fe=vl

2.3 Coreless Filament Winding

Continuous fiber wound around anchors; cures in place — zero formwork

Materials: glass/carbon/flax fiber + epoxy or bio-resin matrix

6-DOF advantage: precise tension control, complex 3D fiber paths

Pros: Extremely lightweight, material only where needed
Cons: Slow cure, recycling



Stigmergic Fibre :https://vimeo.com/94077316

2.3 Coreless Filament Winding



BUGA Fibre Pavilion
ICD/ITKE, University of Stuttgart, 2013

https://www.icd.uni-stuttgart.de/projects/icditke-research-pavilion-2013-14/

2.3 Coreless Filament Winding

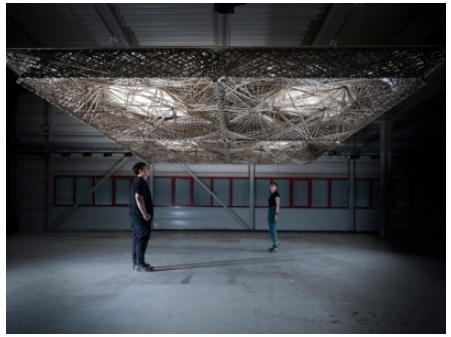


BUGA Fibre Pavilion
ICD/ITKE, University of Stuttgart
2013

Resource: https://www.icd.uni-stuttgart.de/projects/buga-fiber-pavilion/

2.3 Coreless Filament Winding











Pavilions
ICD/ITKE, University of Stuttgart,
2010 -

https://www.icd.uni-stuttgart.de/projects/

2.3 Coreless Filament Winding



ITECH Research Pavilion 2024
ICD/ITKE, University of Stuttgart, 2024

Resource: https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/itech-research-pavilion-2024/



2.4 Pick-and-Place / Assembly

Robot picks discrete elements, places at unique position/ rotation

Materials: brick, timber, stone, precast concrete, aggregate + string

6-DOF advantage: mass customization at zero extra cost per element

Pros: Conventional materials, reversible assemblies
Cons: Slow cycle, joining complexity



Resource: https://vimeo.com/52923299

2.4 Pick-and-Place / Assembly



Winery Gantenbein/ The Programmed Wall
Gramazio Kohler, ETH Zurich, 2006

Resource: https://gramaziokohler.arch.ethz.ch/web/e/forschung/52.html

2.4 Pick-and-Place / Assembly



Winery Gantenbein/ The Programmed Wall
Gramazio Kohler, ETH Zurich, 2006

Resource: https://gramaziokohler.arch.ethz.ch/web/e/forschung/52.html

2.4 Pick-and-Place / Assembly



DFAB House
Gramazio Kohler / NCCR Digital Fabrication, 2019

Resource: https://dfabhouse.ch/

2. End-Effector Taxonomy

2.4 Pick-and-Place / Assembly



Spatial Timber Assemblies
Gramazio Kohler / NCCR Digital Fabrication, 2019

Resource: https://dfabhouse.ch/

2.4 Pick-and-Place / Assembly



Mesh Mould— DFAB House
Gramazio Kohler / NCCR Digital Fabrication, 2019

Resource: https://dfabhouse.ch/

2.4 Pick-and-Place / Assembly



Semiramis
ETH Gramazio Kohler, 2021

Resource: https://gramaziokohler.arch.ethz.ch/web/e/projekte/409.html

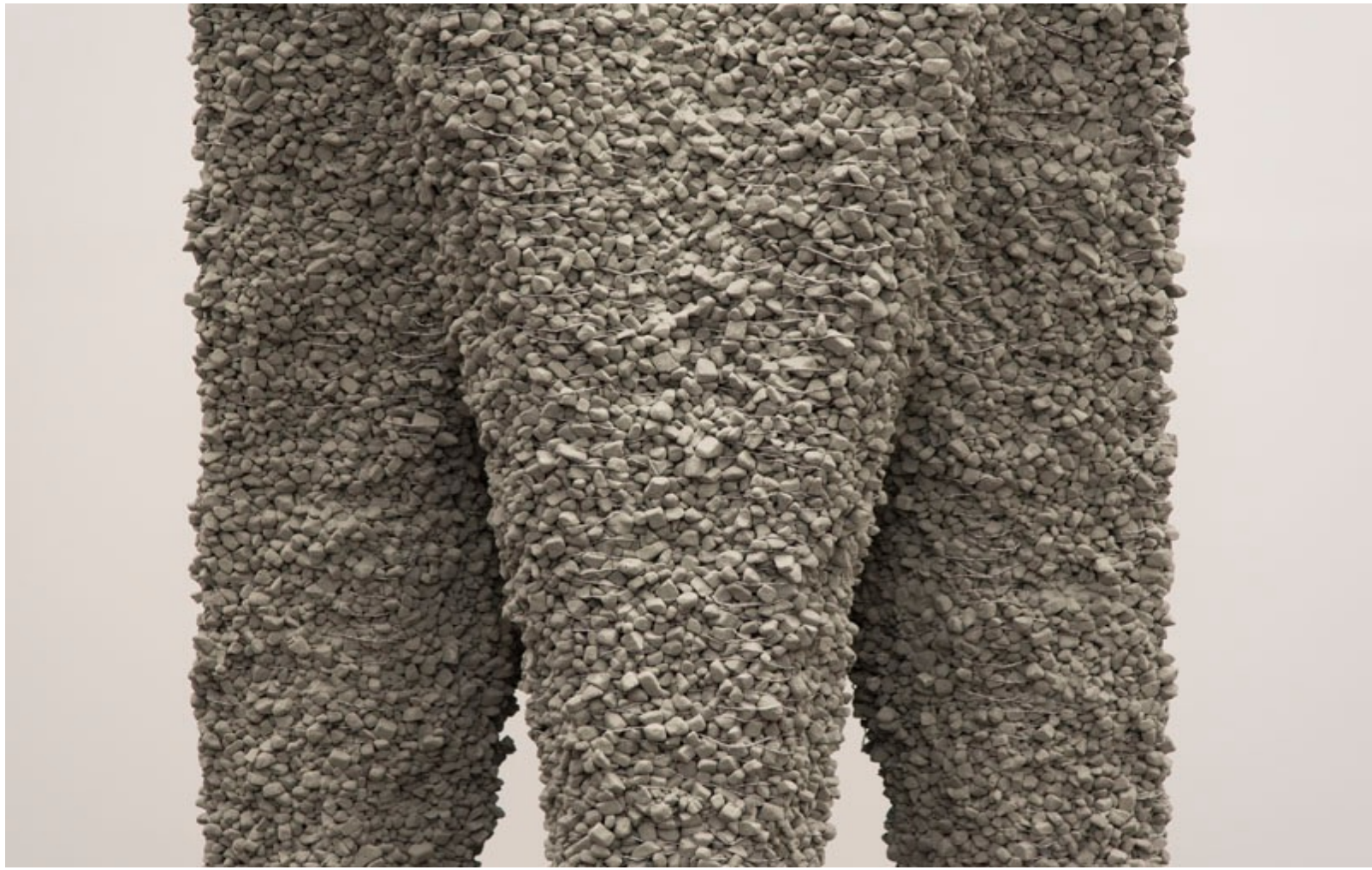
2.4 Pick-and-Place / Assembly



Semiramis
ETH Gramazio Kohler, 2021

Resource: https://gramaziokohler.arch.ethz.ch/web/e/projekte/409.html

2.4 Pick-and-Place / Assembly



Rock Print
Gramazio Kohler + MIT Self-Assembly Lab, 2015

Resource: https://gramaziokohler.arch.ethz.ch/web/e/forschung/297.html

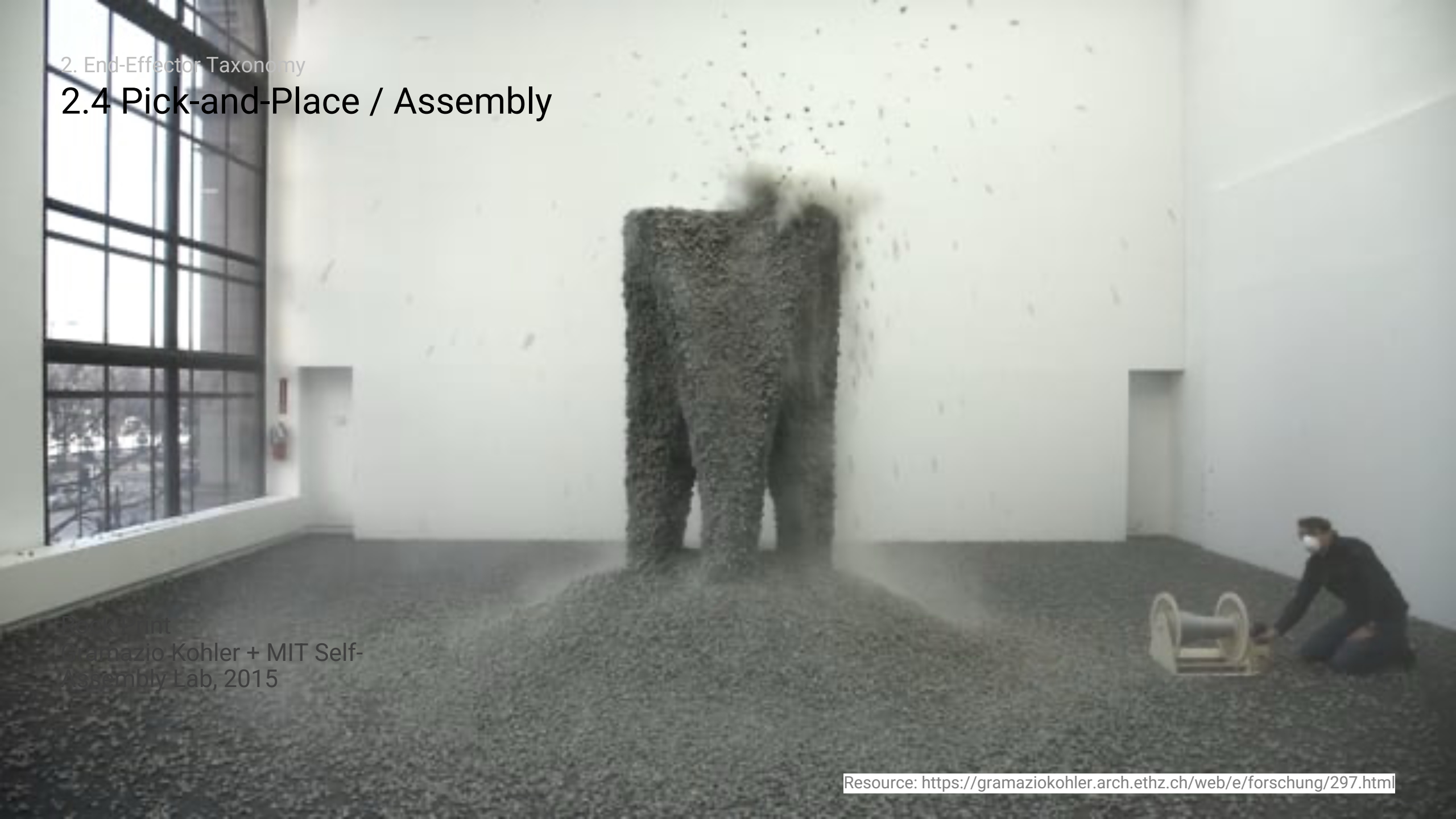
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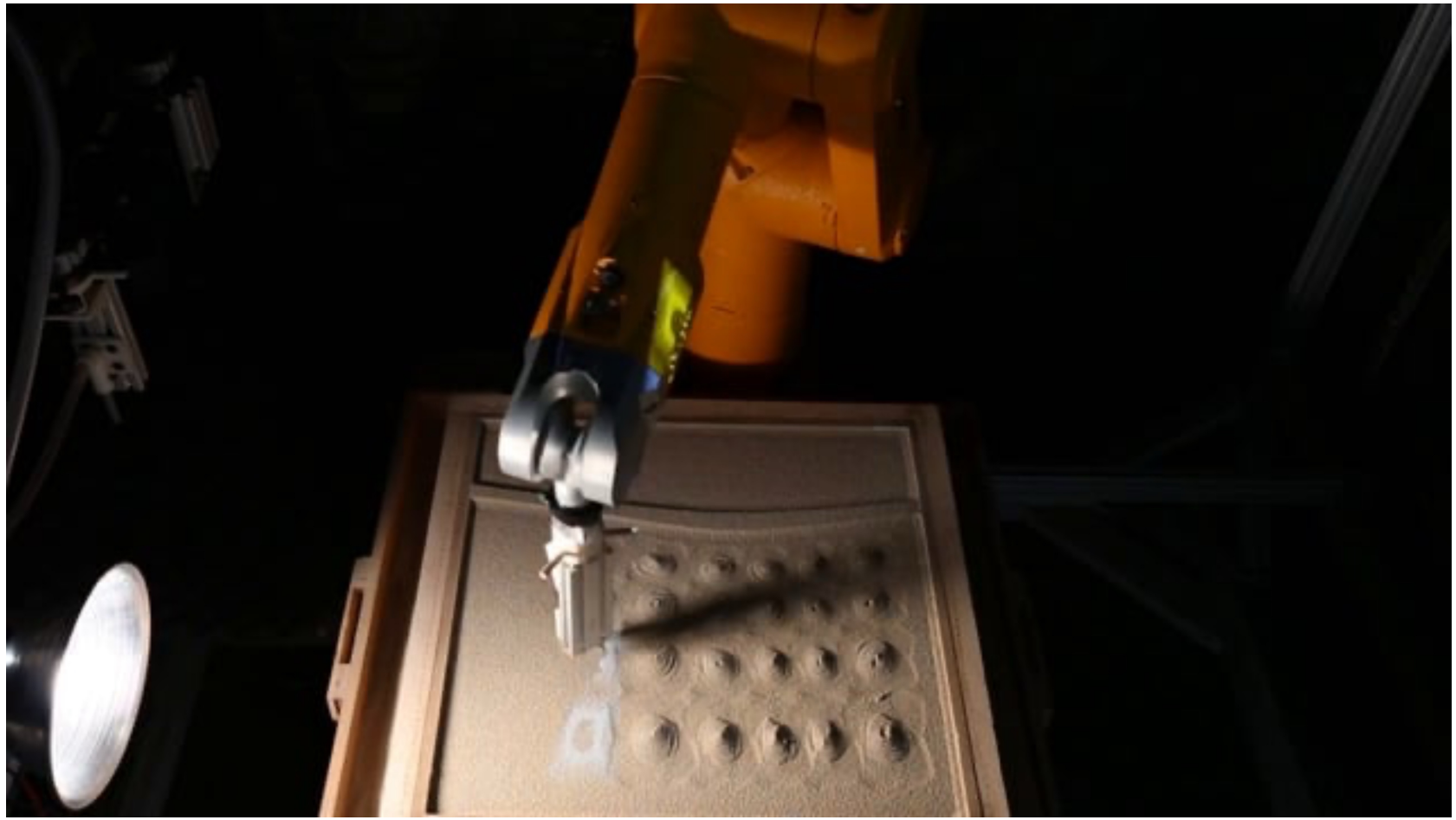
2.5 Loose Material (Sand/Gravel/Stone)

Manipulates unbound materials: excavation, scanning, adaptive placement

Materials: natural stone, gravel, sand, earth — locally sourced

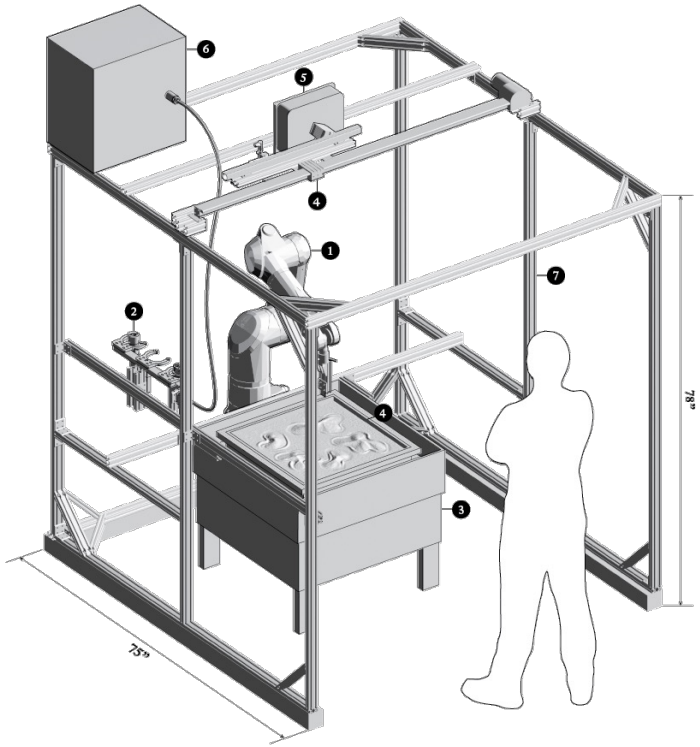
6-DOF advantage: real-time vision scans each unique element for optimal fit

Pros: Zero embodied energy, reversible, landscape-scale
Cons: Advanced sensing required



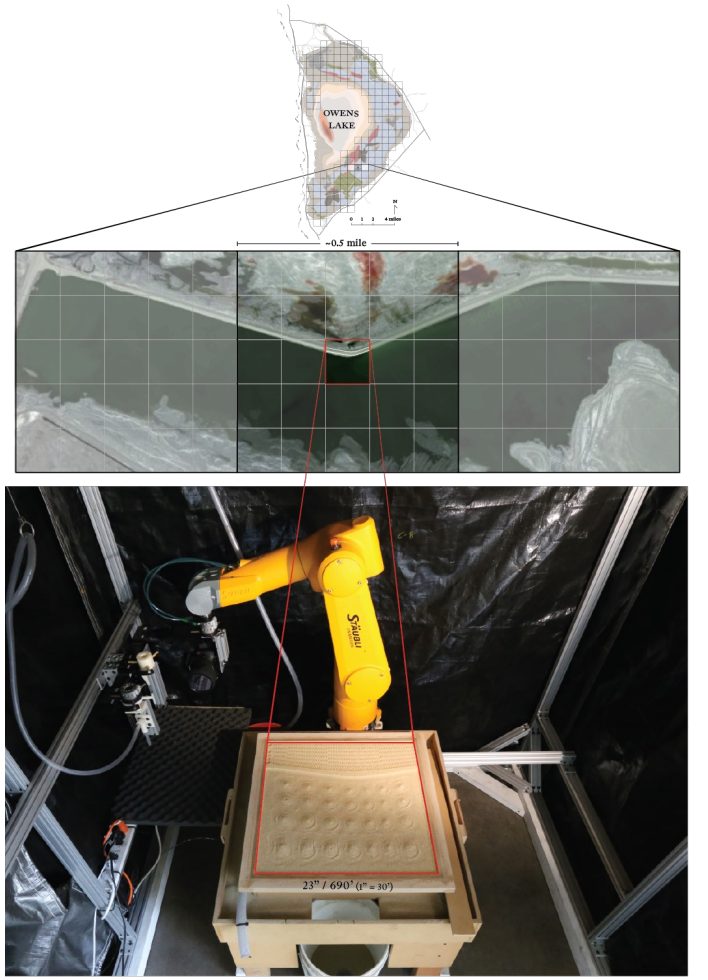
Resource:https://oorscapes.com/Rapid-Landscape-Prototyping-Machine

2.5 Loose Material (Sand/Gravel/Stone)



Rapid Landscape Prototyping Machine for Owens Lake

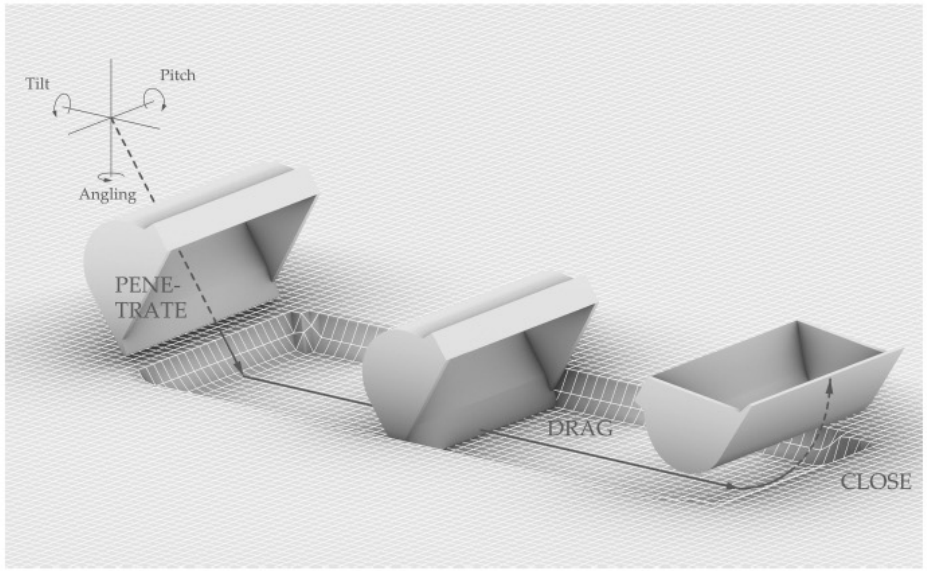
1. Stäubli TX60L 6-axis robotic arm with tool-changer
2. Tool holster with custom end-of-arm tools
3. Sand modeling bed with vacuum-forming setup
4. Sand model on bed
5. Automation Technology 3D laser scanner with linear actuator
6. Digital projector
7. Sand reservoir
8. 80/20 aluminum cage



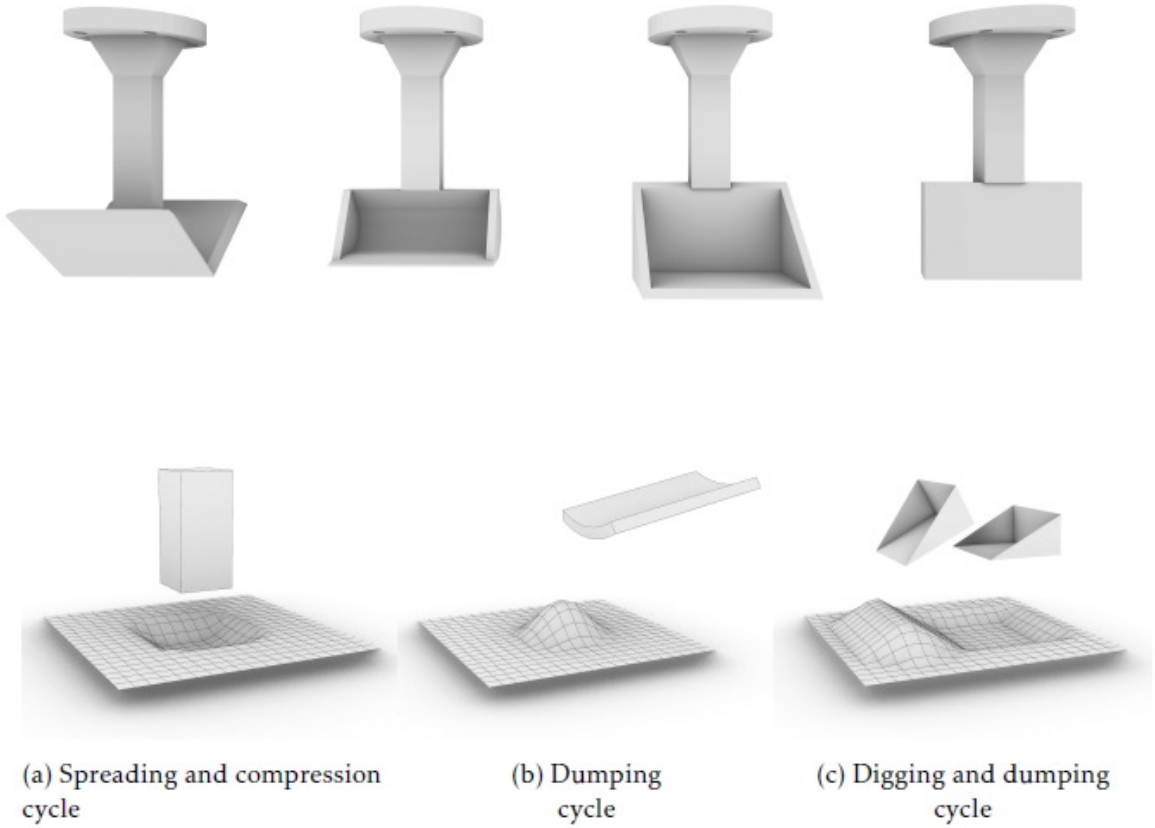
Rapid Landscape Prototyping Machine
Alex Robinson USC

Resource:https://oorscapes.com/Rapid-Landscape-Prototyping-Machine

2.5 Loose Material (Sand/Gravel/Stone)



Robotic Landscape
Christopher Girot & Hurkxkens,
ETH



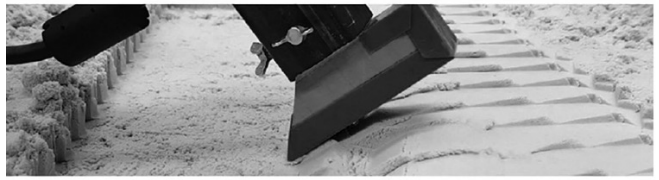
(a) Spreading and compression cycle

(b) Dumping cycle

(c) Digging and dumping cycle

2.5 Loose Material (Sand/Gravel/Stone)



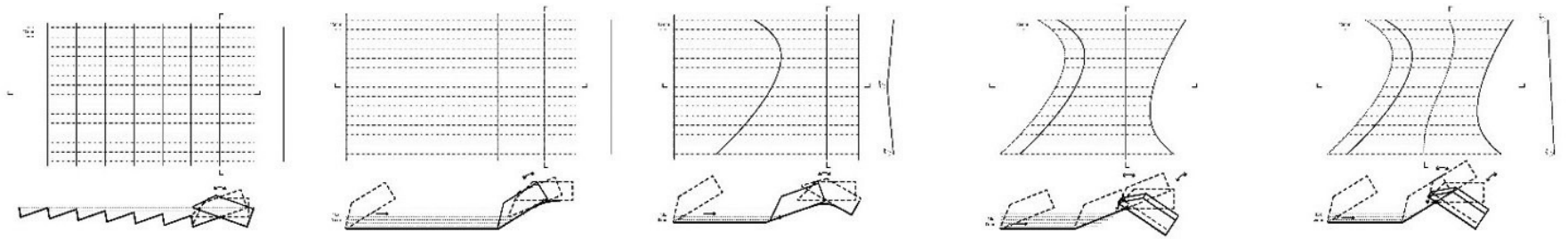






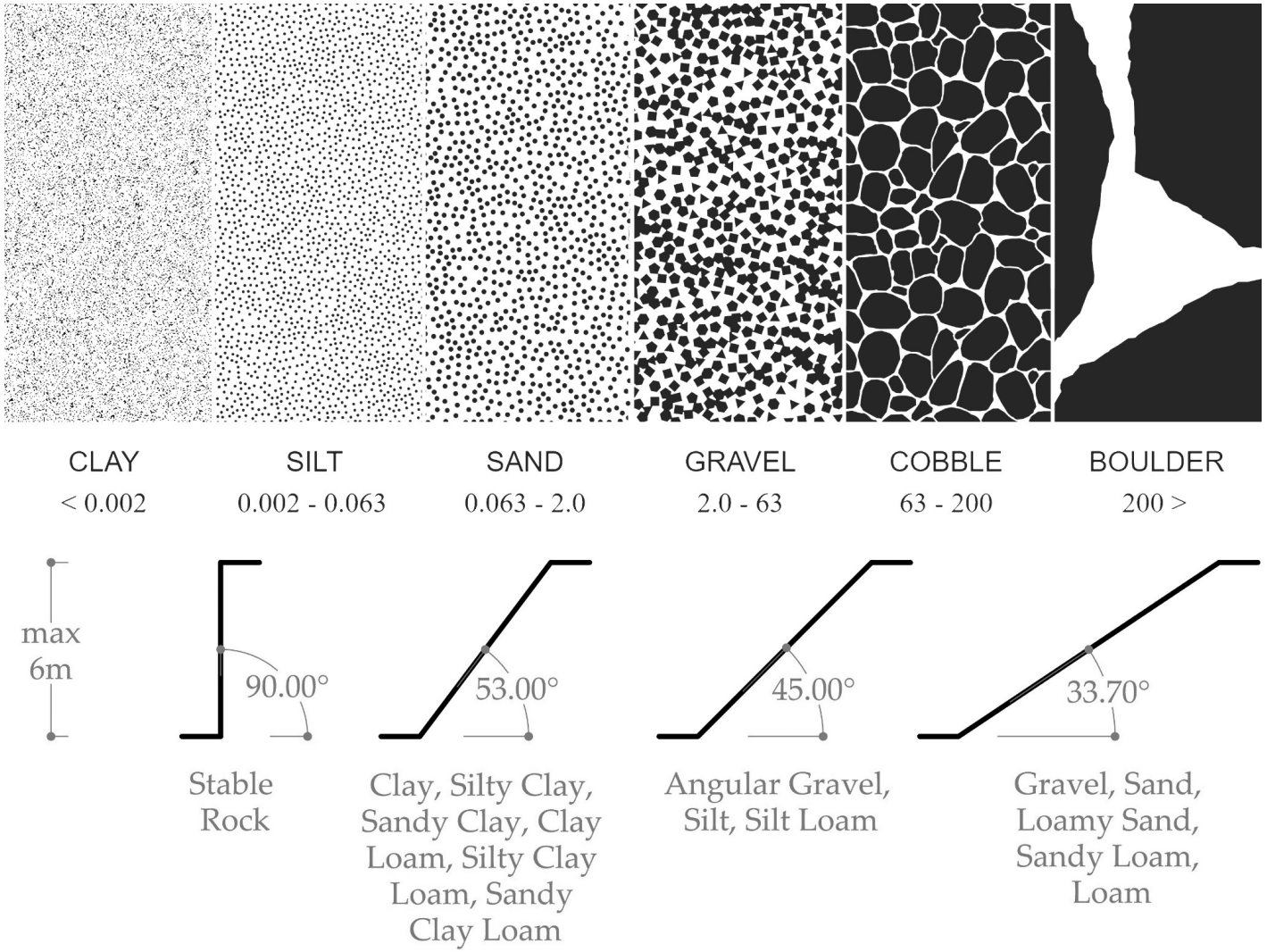


Robotic Landscape
Christopher Girot, ETH



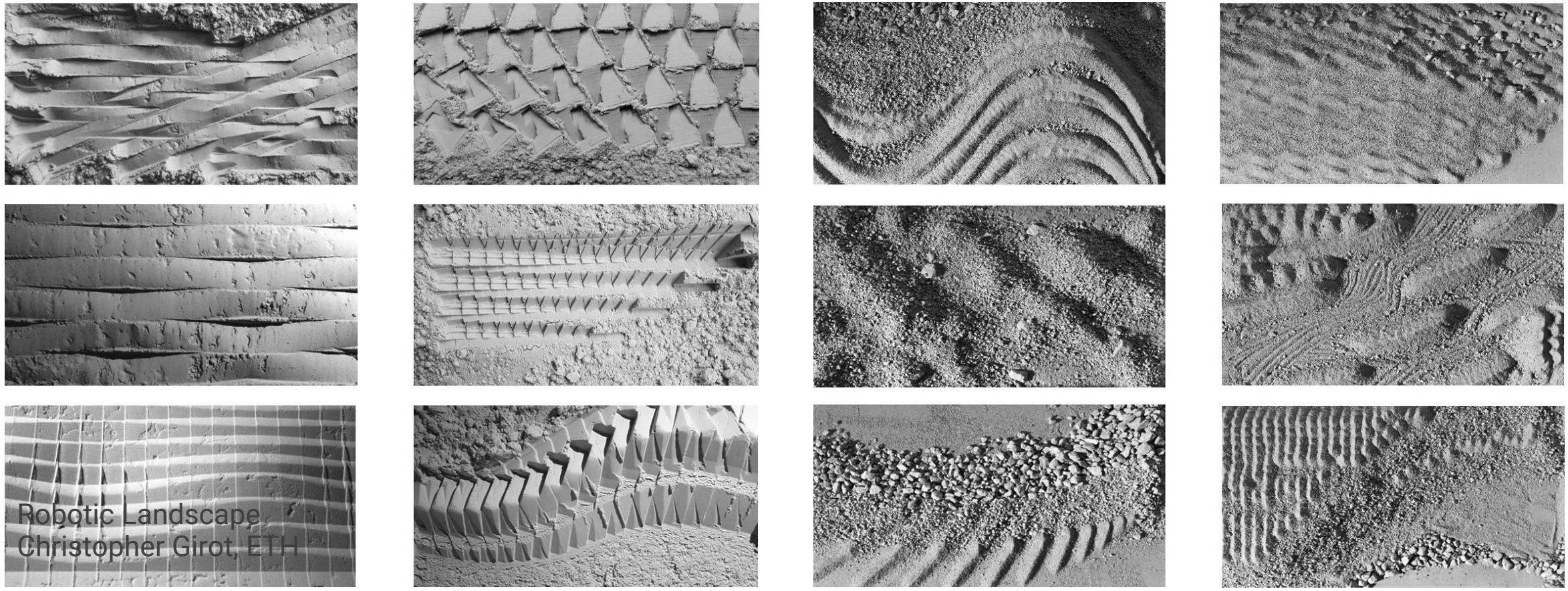
https://girot.arch.ethz.ch/

2.5 Loose Material (Sand/Gravel/Stone)



Robotic Landscape
Christopher Girot, ETH

2.5 Loose Material (Sand/Gravel/Stone)



2.5 Loose Material (Sand/Gravel/Stone)



Robotic Embankment Prototype
Girot + Hutter, NCCR dfab

https://girot.arch.ethz.ch/

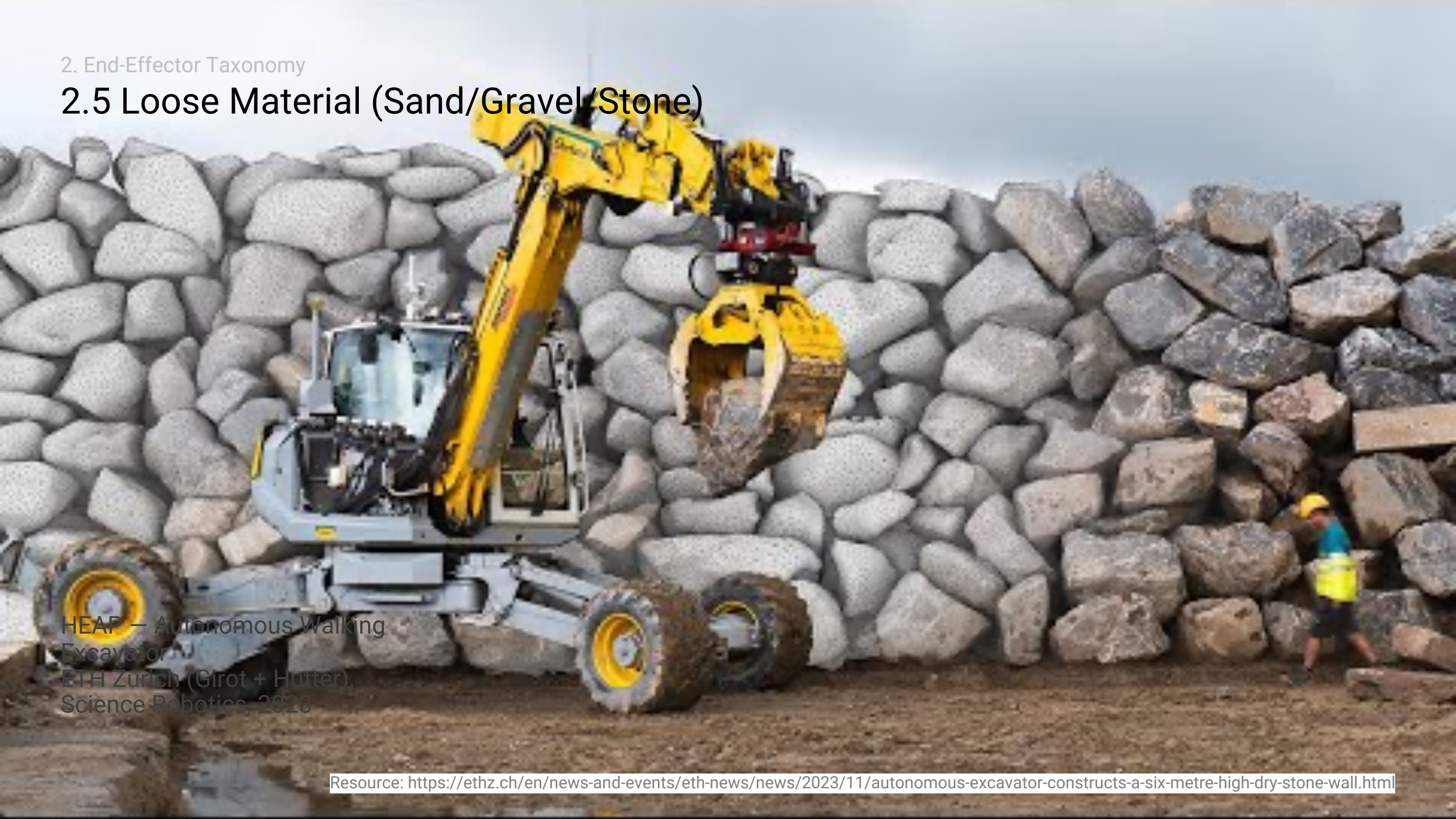
2.5 Loose Material (Sand/Gravel/Stone)



HEAP — Autonomous Walking Excavator
ETH Zurich (Girot + Hutter), Science Robotics, 2023

Resource: https://ethz.ch/en/news-and-events/eth-news/news/2023/11/autonomous-excavator-constructs-a-six-metre-high-dry-stone-wall.html

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3. How Robot Move

3.1 Mobile Robots

Autonomous robot on caterpillar base.
On-board 2D laser for self-localization.
Built the Mesh Mould wall at DFAB House.
Demonstrates on-site autonomous construction.



In situ Fabricator
ETH / NCCR dfab

Resource: https://link.springer.com/article/10.1007/s41693-017-0003-5

3.1 Mobile Robots

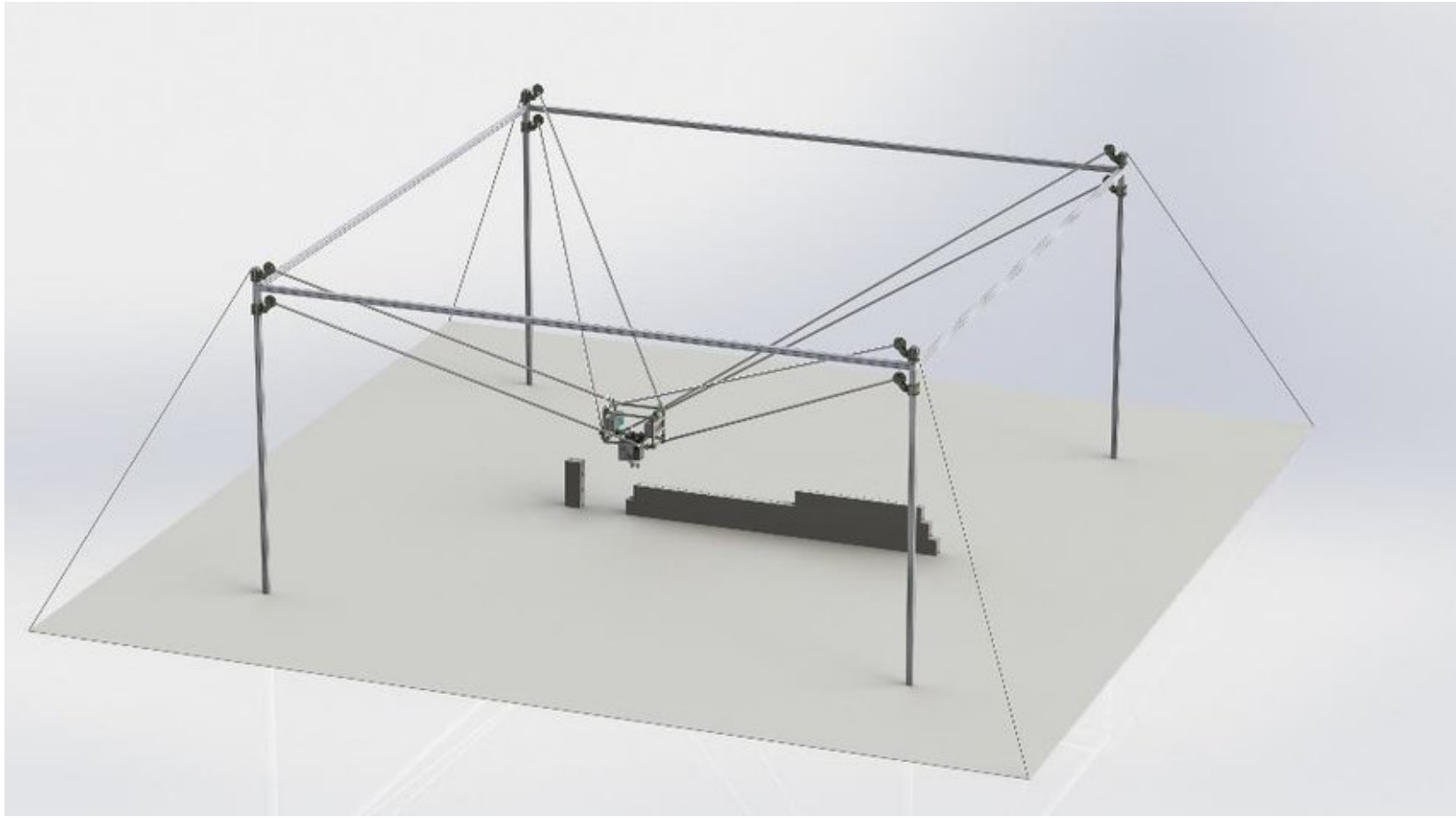


In situ Fabricator
ETH / NCCR dfab

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3.2 Cable-Driven Robots

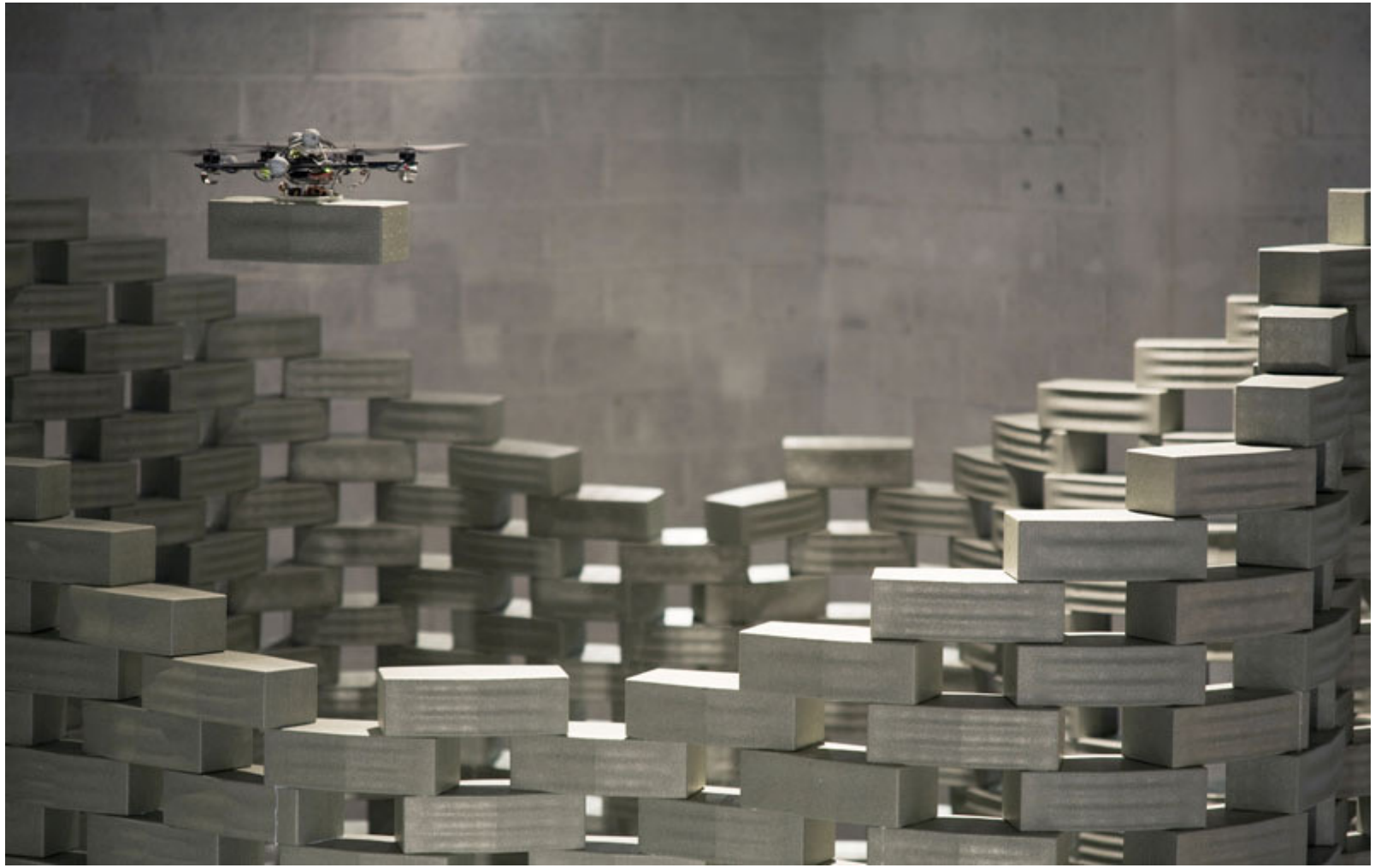
Lightweight robot suspended by cables.
Large workspace for on-site construction.
Cable-driven = scalable to building size.
Alternative to heavy gantry systems.



SPIDERobot
University of Porto

Resource: https://www.researchgate.net/publication/300412156_The_SPIDERobot_A_Cable-Robot_System_for_On-site_Construction_in_Architecture

3.3 Aerial Robotics

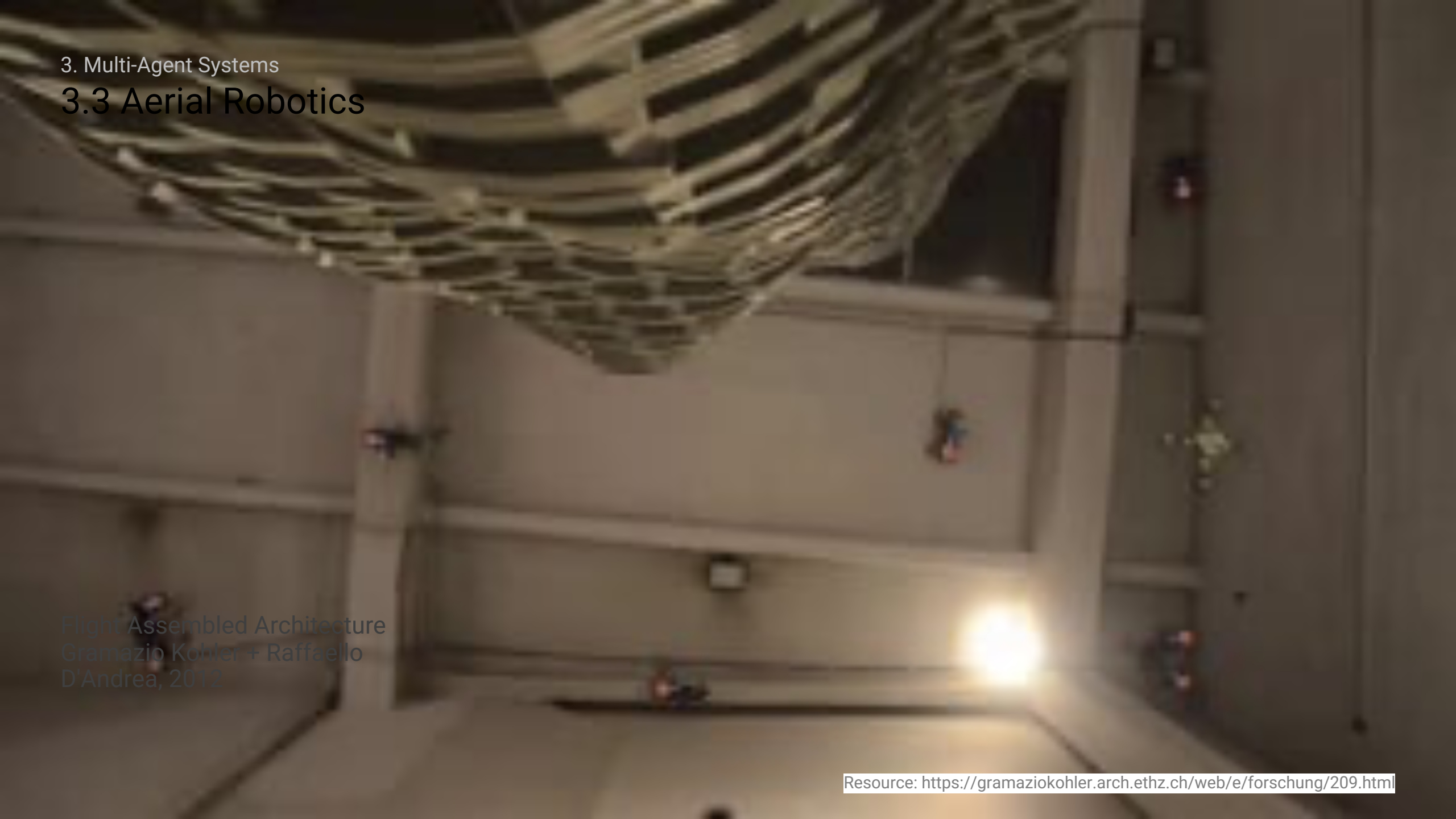


Flight Assembled Architecture
Gramazio Kohler + Raffaello D'Andrea, 2012

Resource: https://gramaziokohler.arch.ethz.ch/web/e/forschung/209.html

3. Multi-Agent Systems

3.3 Aerial Robotics



Flight Assembled Architecture
Gramazio Kohler + Raffaello D'Andrea, 2012

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3.3 Aerial Robotics



Aerial Additive Manufacturing
Robert Stuart-Smith / Penn,
published in Nature

Resource: https://www.dezeen.com/2016/02/24/movie-building-architecture-with-drones-gramazio-kohler-eth-zurich-interview/

3.3 Aerial Robotics



Aerial Additive Manufacturing
Robert Stuart-Smith / Penn,
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3.4 Collective Robotic Construction

Swarm of autonomous robots build structures
from foam bricks. No central controller,
no inter-robot communication.
Stigmergy:
each robot follows simple rules + modifies environment.



TERMES
Harvard Wyss Institute, Science, 2014

Resource: https://wyss.harvard.edu/media-post/termite-inspired-robots/

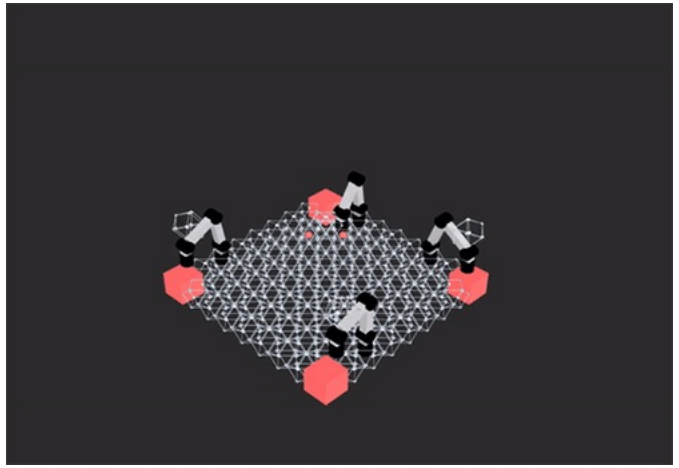
3.4 Collective Robotic Construction

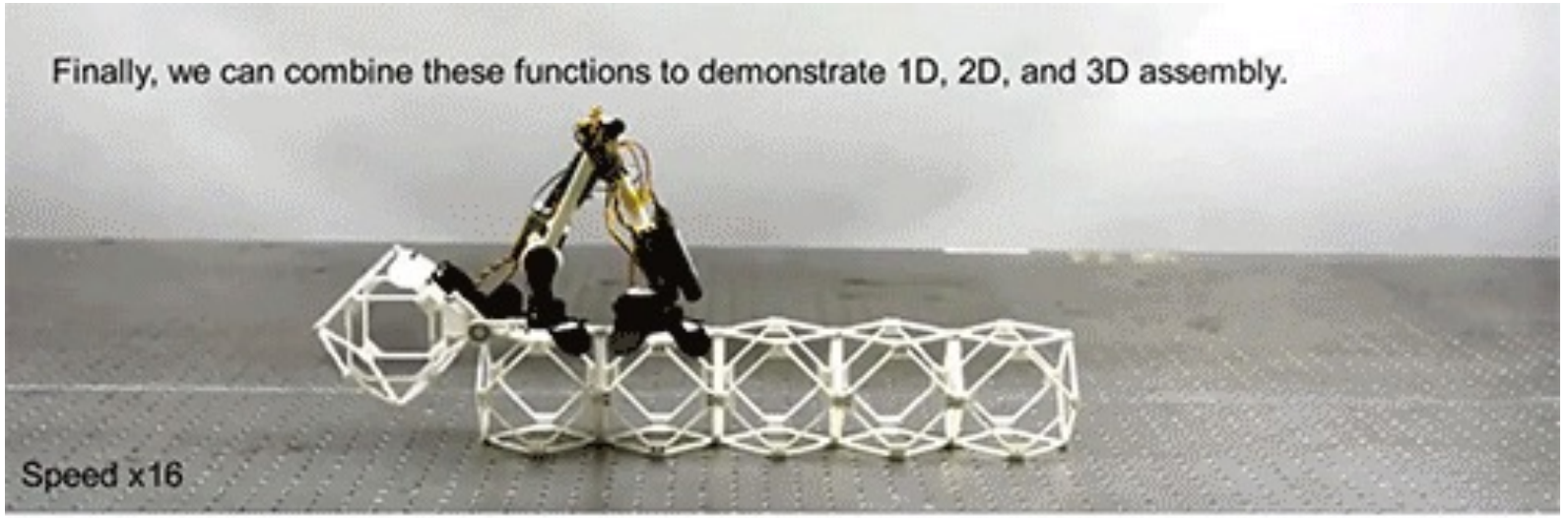


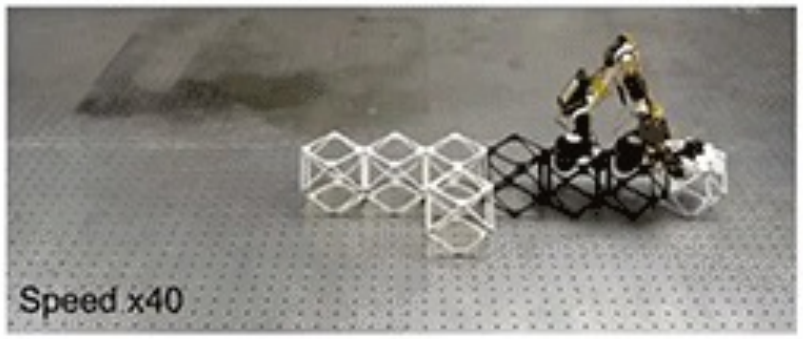
TERMES
Harvard Wyss Institute, Science
2014

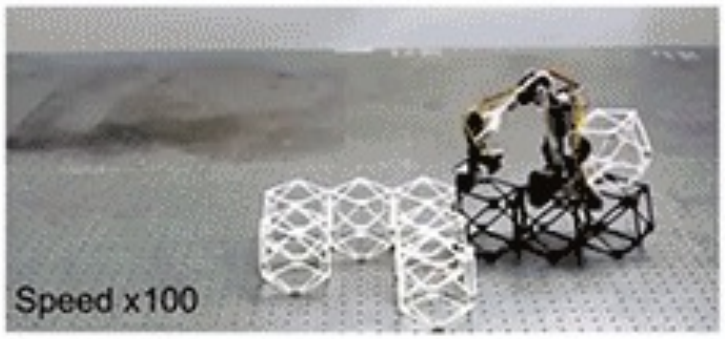
https://www.youtube.com/watch?v=LFwk303p0zY&t=13s

3.4 Collective Robotic Construction









Assembler robots,
MIT, 2019

Resource: https://news.mit.edu/2019/robots-large-structures-little-pieces-1016

3. Multi-Agent Systems

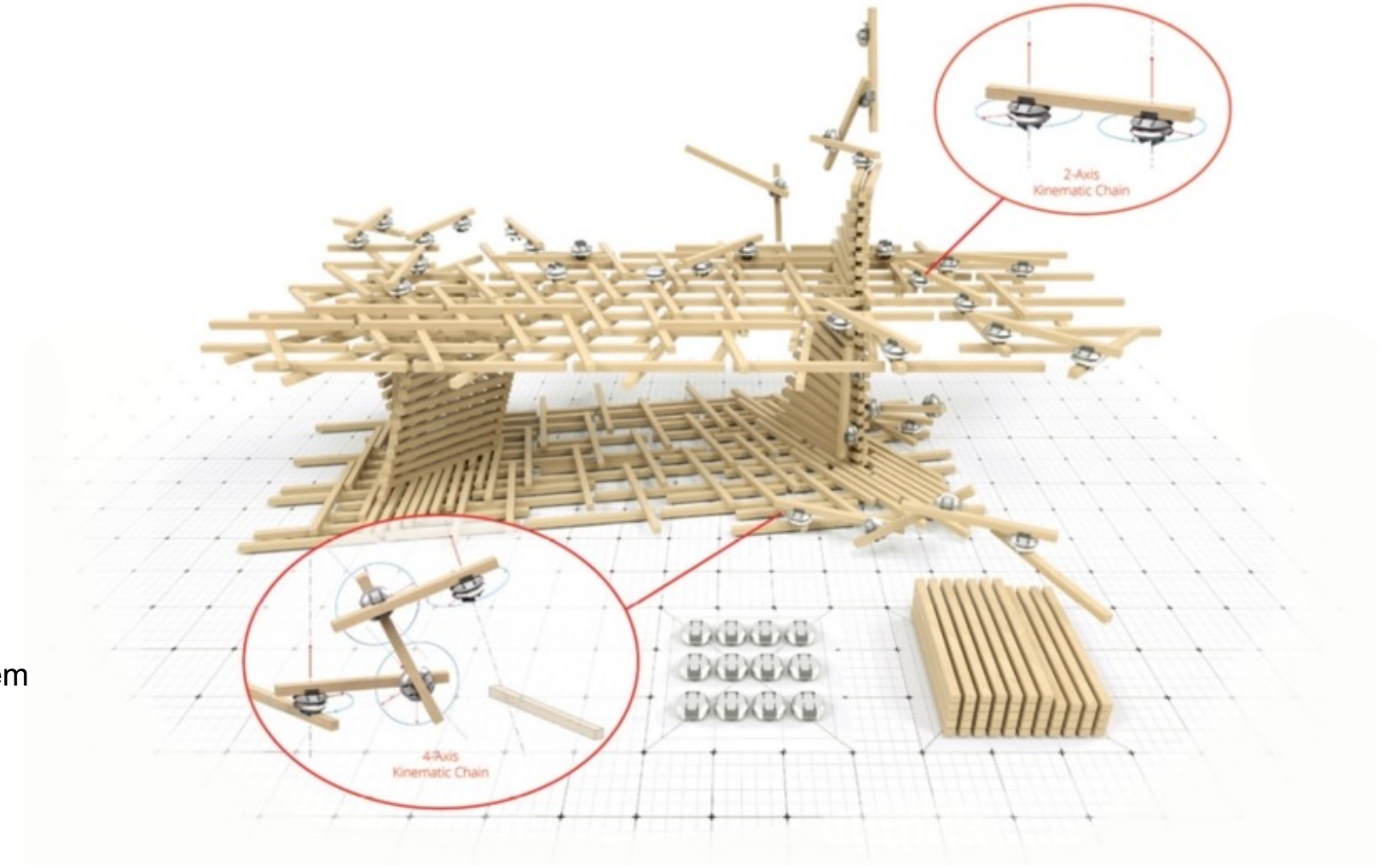
3.4 Collective Robotic Construction



Distributed Robotic Assembly System
ITECH 2018

Resource: https://vimeo.com/596399791

3.4 Collective Robotic Construction



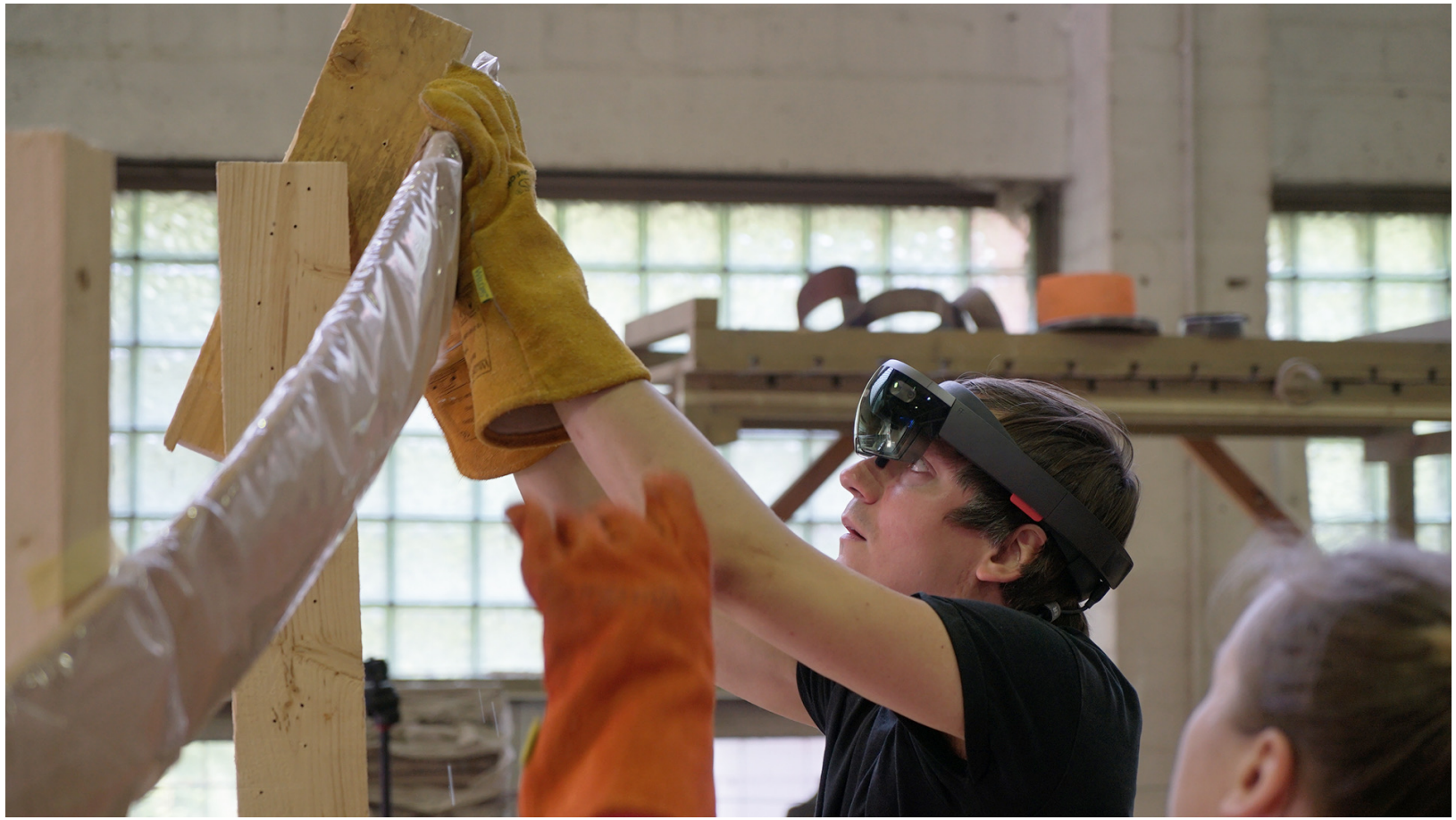
Distributed Robotic Assembly System
ITECH 2018

Resource: https://www.itech.uni-stuttgart.de/itech-thesis-projects/2018-distributed-robotic-assembly-system-for-in-situ-timber-construction/

4. Integration with Emerging Technologies

4.1 AR-Assisted Fabrication

Steam-bent hardwood using hand tools + HoloLens holographic guides. AR as alternative to full automation. Augmented human = craft dexterity + digital precision.



Steampunk Pavilion
Soomeen Hahm + Igor Pantic + Fologram, TAB 2019

Resource: https://soomeenhahm.com/steampunk-pavilion/

4.1 AR-Assisted Fabrication

2,000 timber beams assembled by students
with AR interface on phone while robot arm
held elements in position. COMPAS XR open-source framework (ETH + Princeton).

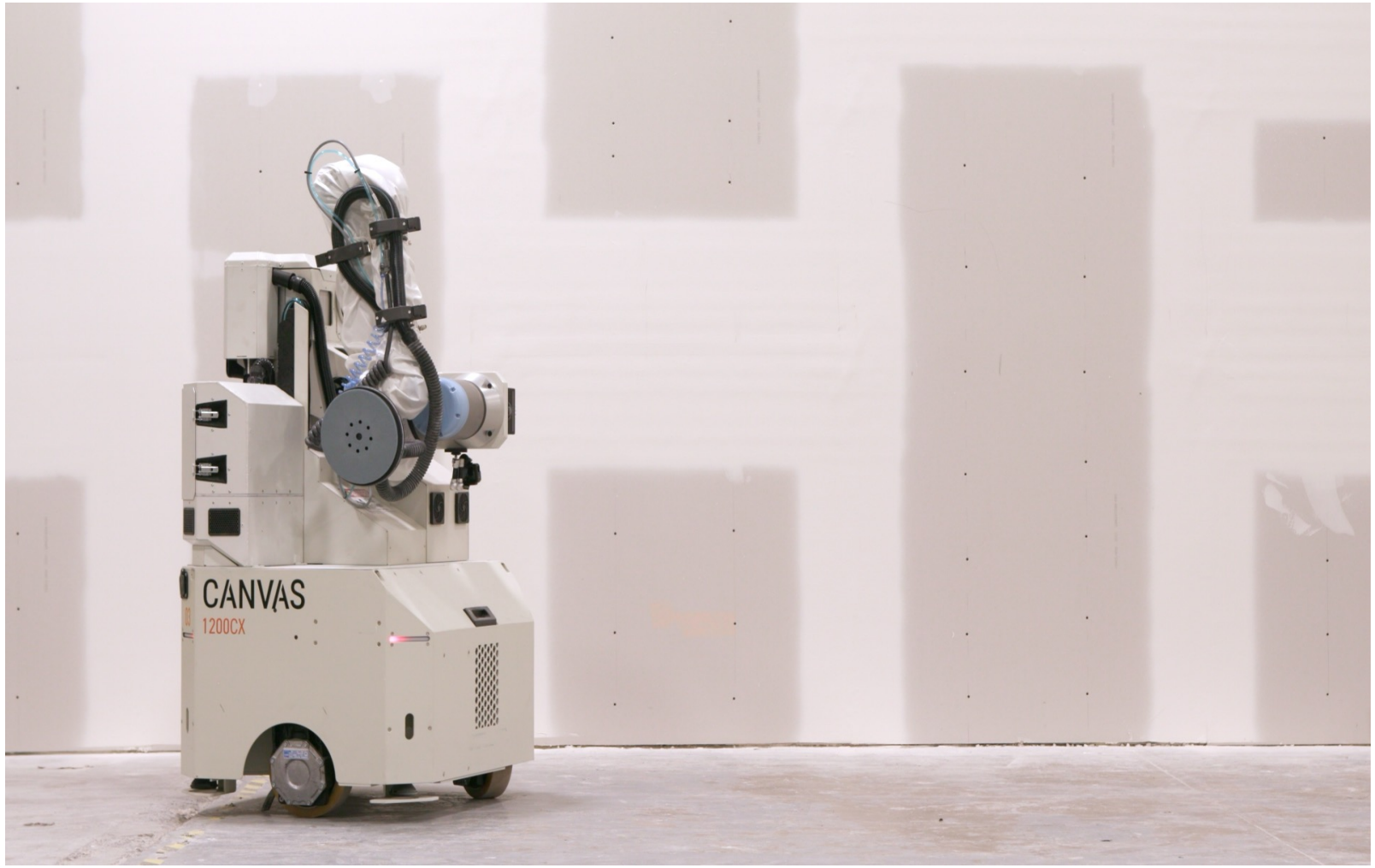


Caschlatsch
ETH MAS DFAB, Disentis/Mustér, 2024

Resource: https://arch.ethz.ch/en/news-und-veranstaltungen/news-kanal/2024/09/how-humans-and-robots-built-a-wooden-tower-in-disentismustr.html

4.2 Sensor Feedback / Adaptive Fabrication

Computer vision + LiDAR scans wall surfaces in real time. Autonomous drywall compound application. Deployed on commercial construction sites across the United States.



Canvas — Drywall Finishing Robot
Canvas, USA

Resource: https://www.canvas.build/

4.2 Sensor Feedback / Adaptive Fabrication

- Sense → Compare → Adapt → Fabricate
- This loop separates a robot from a tool
- Spot + Zepth: autonomous site inspection + reporting



HEAP — Autonomous Walking Excavator
ETH Zurich (Girot + Hutter), Science Robotics, 2023

Resource: https://ethz.ch/en/news-and-events/eth-news/news/2023/11/autonomous-excavator-constructs-a-six-metre-high-dry-stone-wall.html

4.3 AI + Robotics: Reinforcement Learning

- RL controls robot using force/torque + pose data
- Trained in simulation, deployed in reality
- Apolinarska et al., ETH / Autodesk Research, 2021
- First successful RL demo in architectural construction



Resource: https://www.research.autodesk.com/publications/robotic-assembly-of-timber-joints-using-reinforcement-learning/

4.3 AI + Robotics

Computer Vision



Resource: https://www.youtube.com/watch?v=STjHJYhmIvw

4.4 Human + Robot collaboration



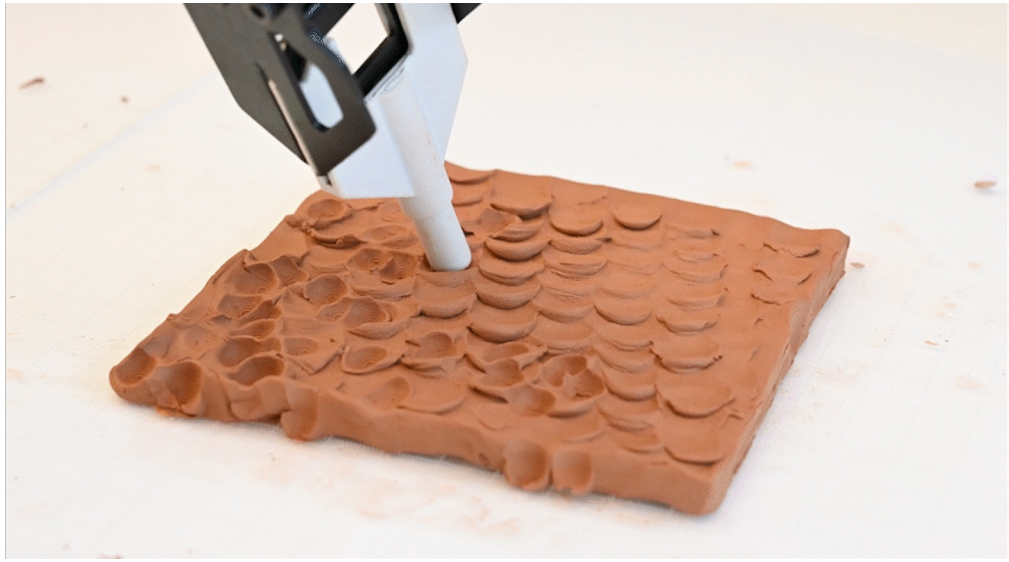


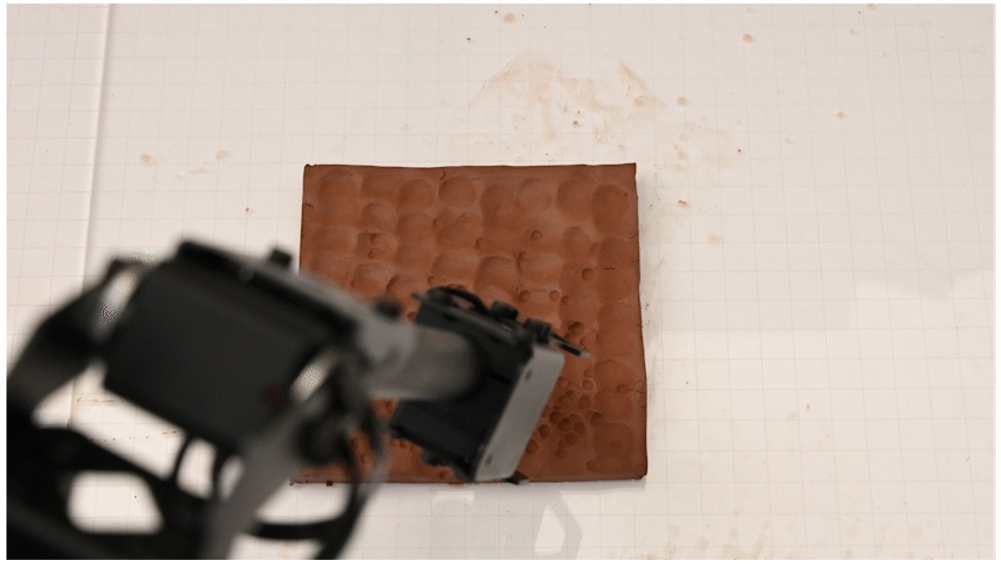
Ancient Future
BIG, 2025

Resource: https://www.research.autodesk.com/publications/robotic-assembly-of-timber-joints-using-reinforcement-learning/

4.4 Human + Robot collaboration



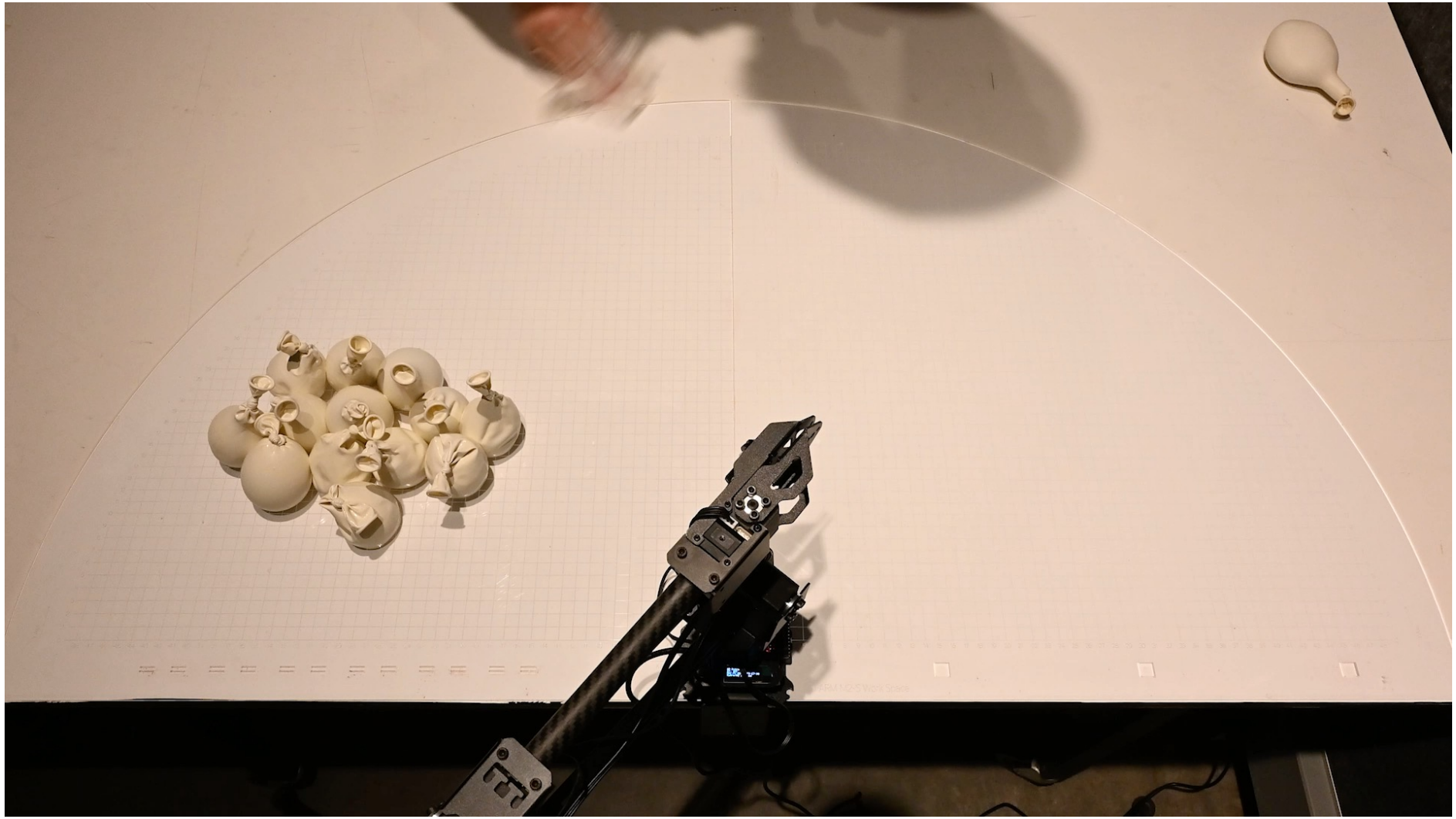






UBC Arch540
Jin Kuang + Ewen Hall

4.4 Human + Robot collaboration



UBC Arch540
Jin Kuang + Ewen Hall

4.4 Human + Robot collaboration





UBC Arch540
Jin Kuang + Ewen Hall

5. Where to Go Next

Master Programs with Robotic Fabrication

- ETH Zurich — MAS Architecture & Digital Fabrication
- Penn Weitzman — MSD-RAS (9-month STEM degree)
- Stuttgart — ITECH Master (Menges + Knippers)
- UCL Bartlett — Design for Manufacture MArch
- SCI-Arc — robotics research clusters
- IAAC — Institute for advanced architecture of Catalonia (Barcelona)

Workshops & Conferences

- DigitalFUTURES — annual, Tongji/UNSW (2026 Sydney)
- Rob|Arch — biennial, Assoc. for Robots in Architecture
- ACADIA — annual computational design conference
- FABRICATE — UCL biennial, free PDF proceedings

Resource: https://digitalfutures.world/

Local Connections

- DDS Lab at UBC — lab visit this semester (UR30)
- Fast+Epp — Vancouver, advanced fabrication
- StructureCraft — Vancouver
- SALA faculty: Satterfield (HiLo Lab), Annalisa Meyboom, James Huemoeller, Joe Dahmen
- Don't wait for grad school — start building now!

Resource: