NREL Transforming ENERGY

INDUSTRIALIZED AND ROBOTIC CONSTRUCTION

ADVANCES IN TERRESTRIAL CONSTRUCTION AND OPPORTUNITIES IN SPACE CONSTRUCTION

NASA

NAVEEN KUMAR MUTHUMANICKAM
STACEY ROTHGEB
SHANTI PLESS
JERRY DAVIS

Intro

Please contact NaveenKumar.Muthanickam@nrel.gov for the PowerPoint version of this presentation.

NAVEEN KUMAR MUTHUMANICKAM
RESEARCH ENGINEER
INDUSTRIALIZED CONSTRUCTION
INNOVATION (ICI)
NREL

SHANTI PLESS
SENIOR ENGINEER
INDUSTRIALIZED CONSTRUCTION
INNOVATION (ICI)
NREL

STACEY ROTHGEB
SENIOR ENGINEER
INDUSTRIALIZED CONSTRUCTION
INNOVATION (ICI)
NREL

JERRY DAVIS
LAB PROGRAM MANAGER
PARTNERSHIP DEVELOPMENT
NREL

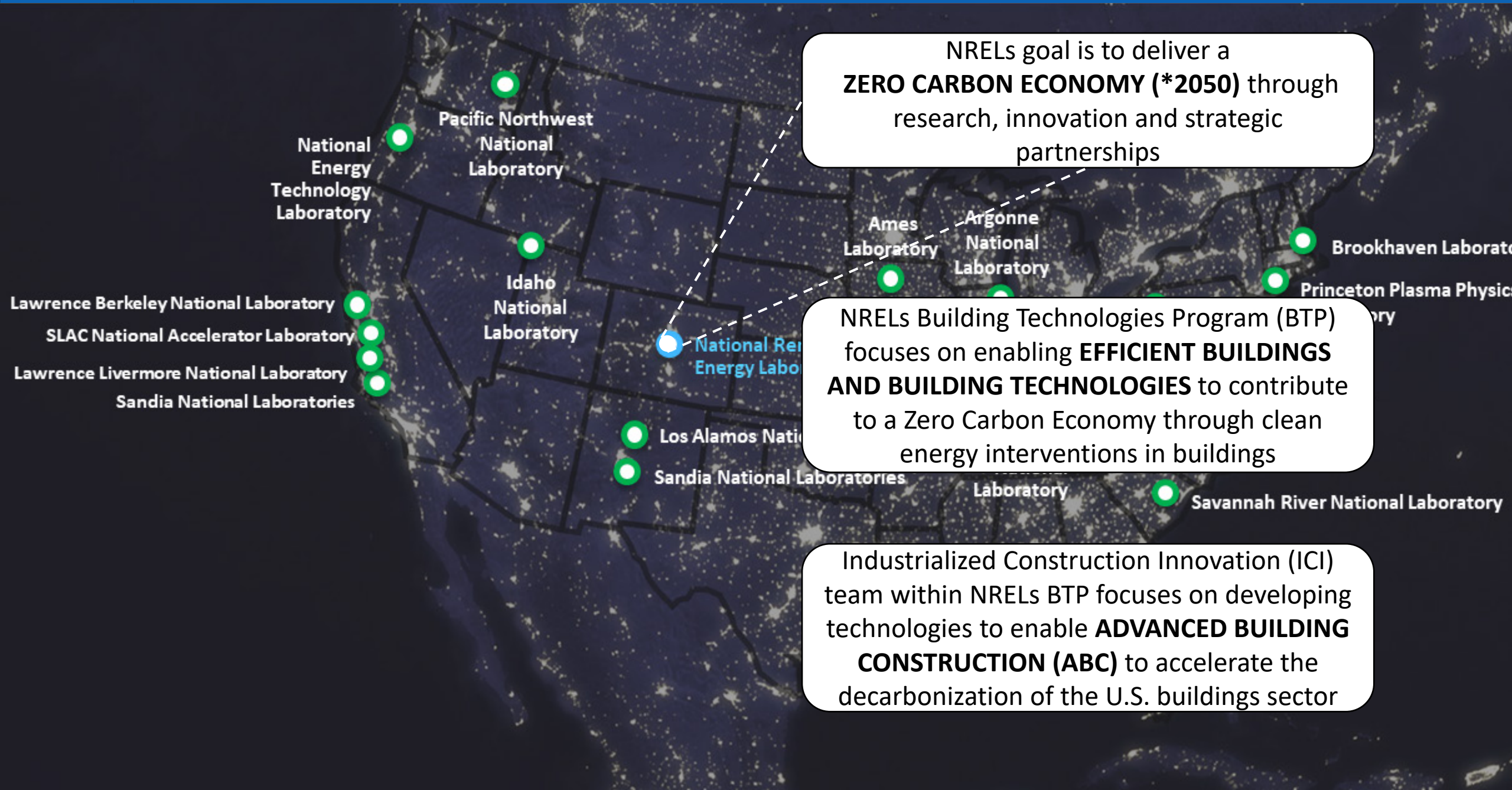
Overview of Presentation

TERRESTRIAL CONSTRUCTION

1. **Background** (NREL ICI,)
2. **Trends & Sample** (Glimpses of past projects + Systems approach)
3. **ICI efforts at NREL** (Modelling & Simulation, Deployment, Commercialization)
4. **Future Avenues** (Robotics for Systems Integration/outfitting in buildings)

SPACE CONSTRUCTION

Background

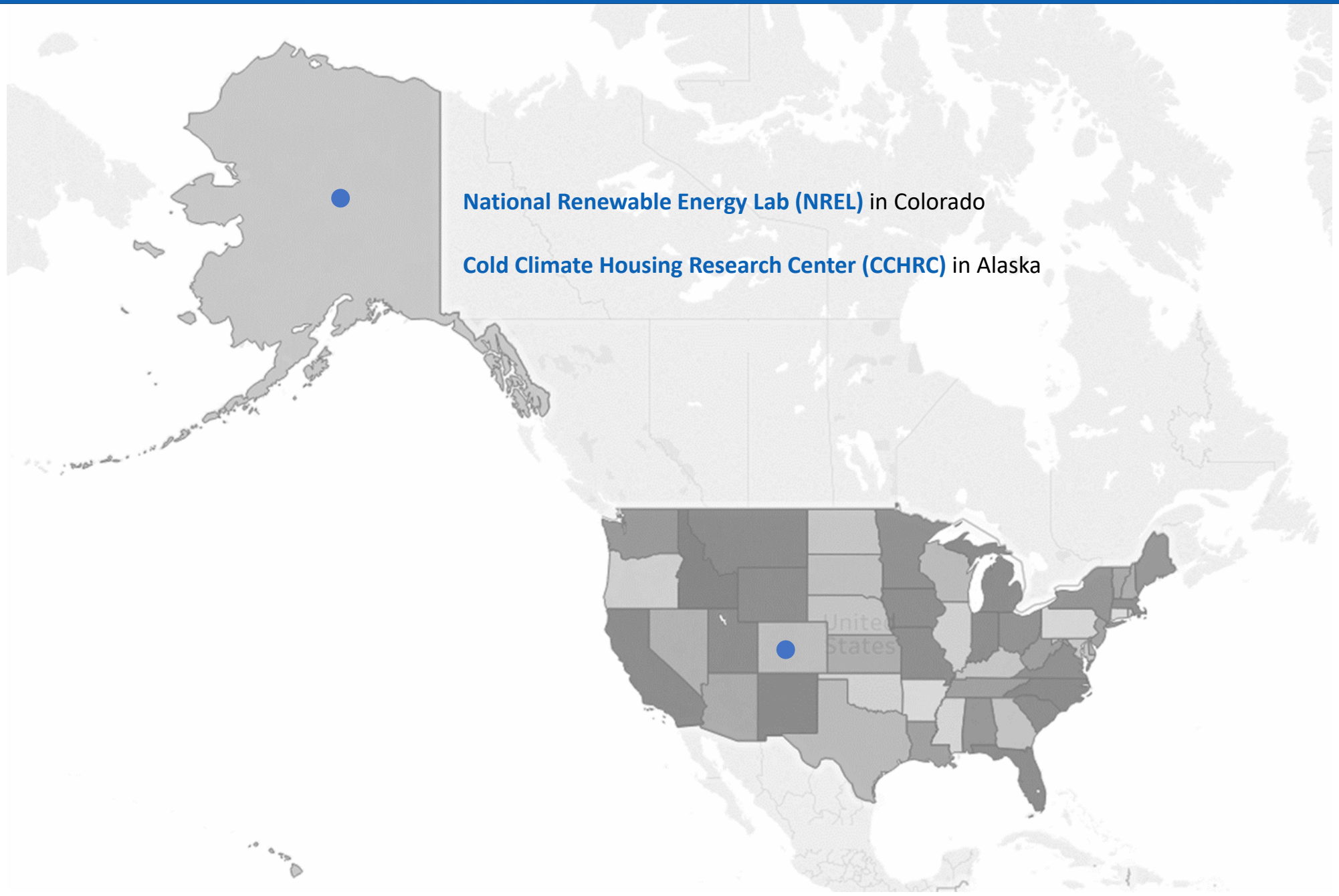


NRELs goal is to deliver a **ZERO CARBON ECONOMY (*2050)** through research, innovation and strategic partnerships

NRELs Building Technologies Program (BTP) focuses on enabling **EFFICIENT BUILDINGS AND BUILDING TECHNOLOGIES** to contribute to a Zero Carbon Economy through clean energy interventions in buildings

Industrialized Construction Innovation (ICI) team within NRELs BTP focuses on developing technologies to enable **ADVANCED BUILDING CONSTRUCTION (ABC)** to accelerate the decarbonization of the U.S. buildings sector

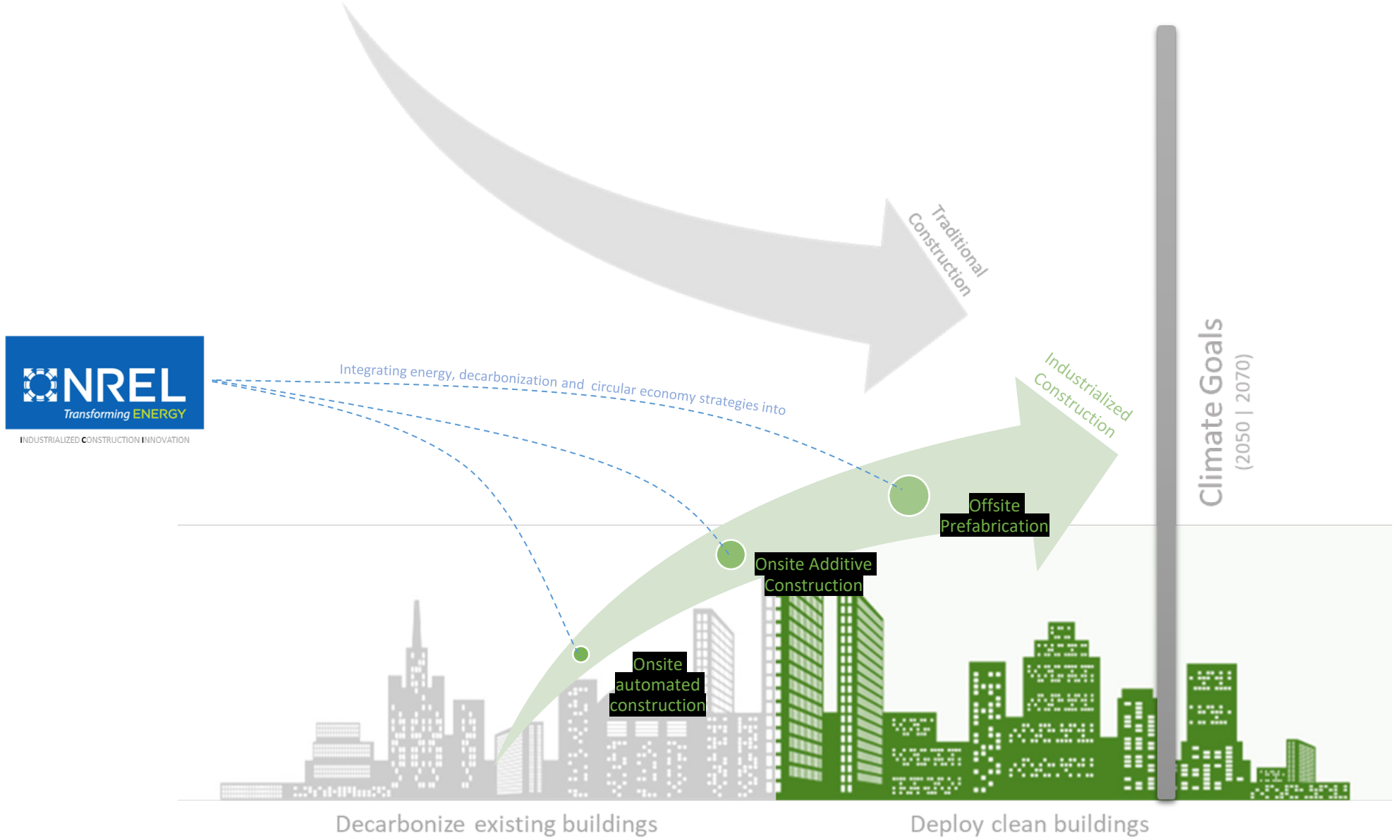
Background



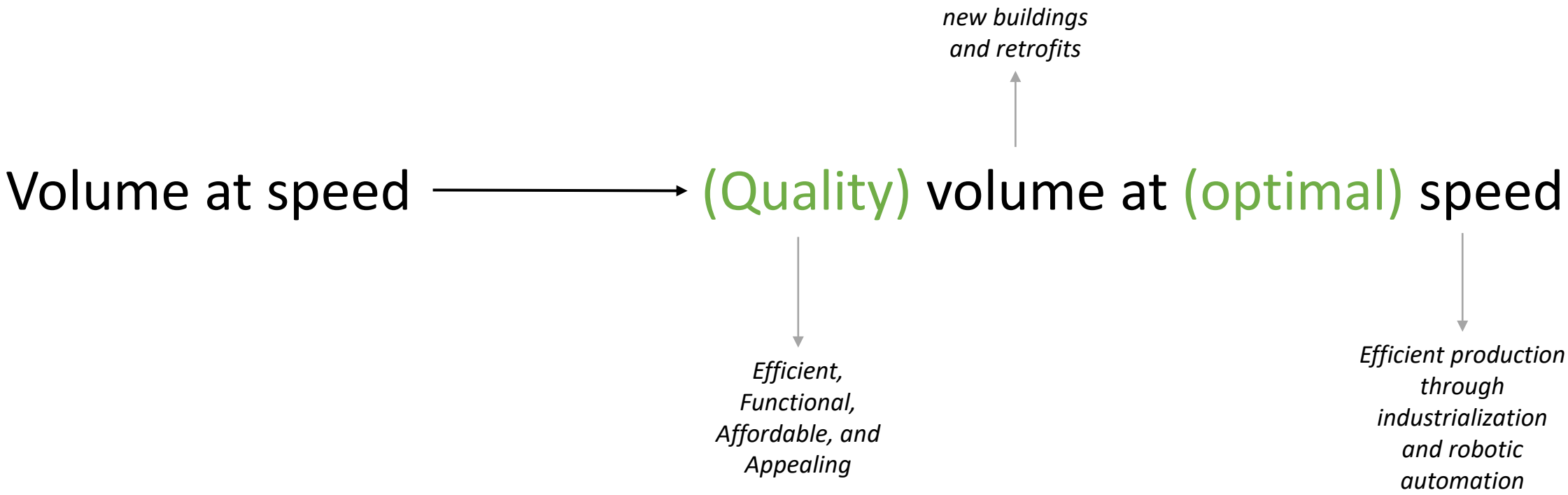
National Renewable Energy Lab (NREL) in Colorado

Cold Climate Housing Research Center (CCHRC) in Alaska

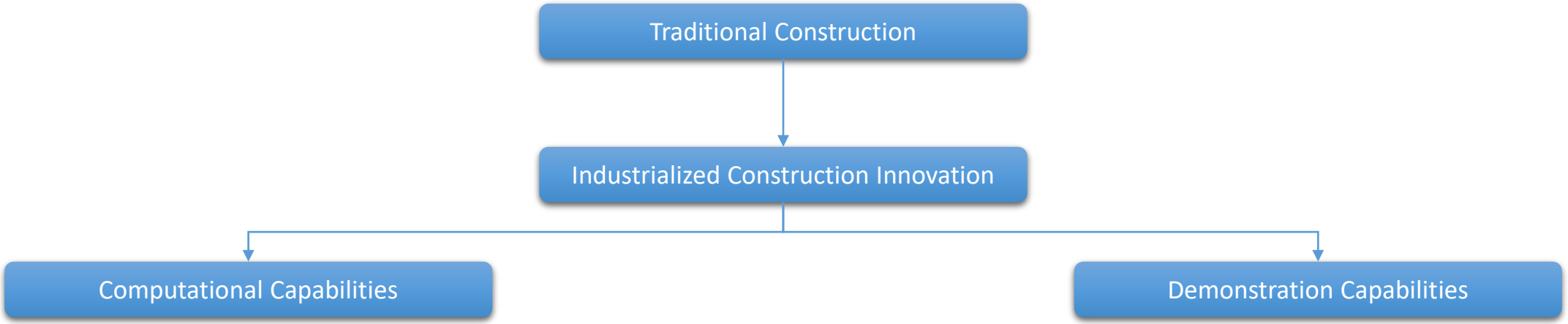
Background


NREL
Transforming ENERGY
INDUSTRIALIZED CONSTRUCTION INNOVATION
Traditional Construction
Integrating energy, decarbonization and circular economy strategies into
Industrialized Construction
Climate Goals
(2050 | 2070)
Offsite Prefabrication
Onsite Additive Construction
Onsite automated construction
Decarbonize existing buildings
Deploy clean buildings

Background


new buildings and retrofits
Volume at speed
(Quality) volume at (optimal) speed
Efficient, Functional, Affordable, and Appealing
Efficient production through industrialization and robotic automation

Background



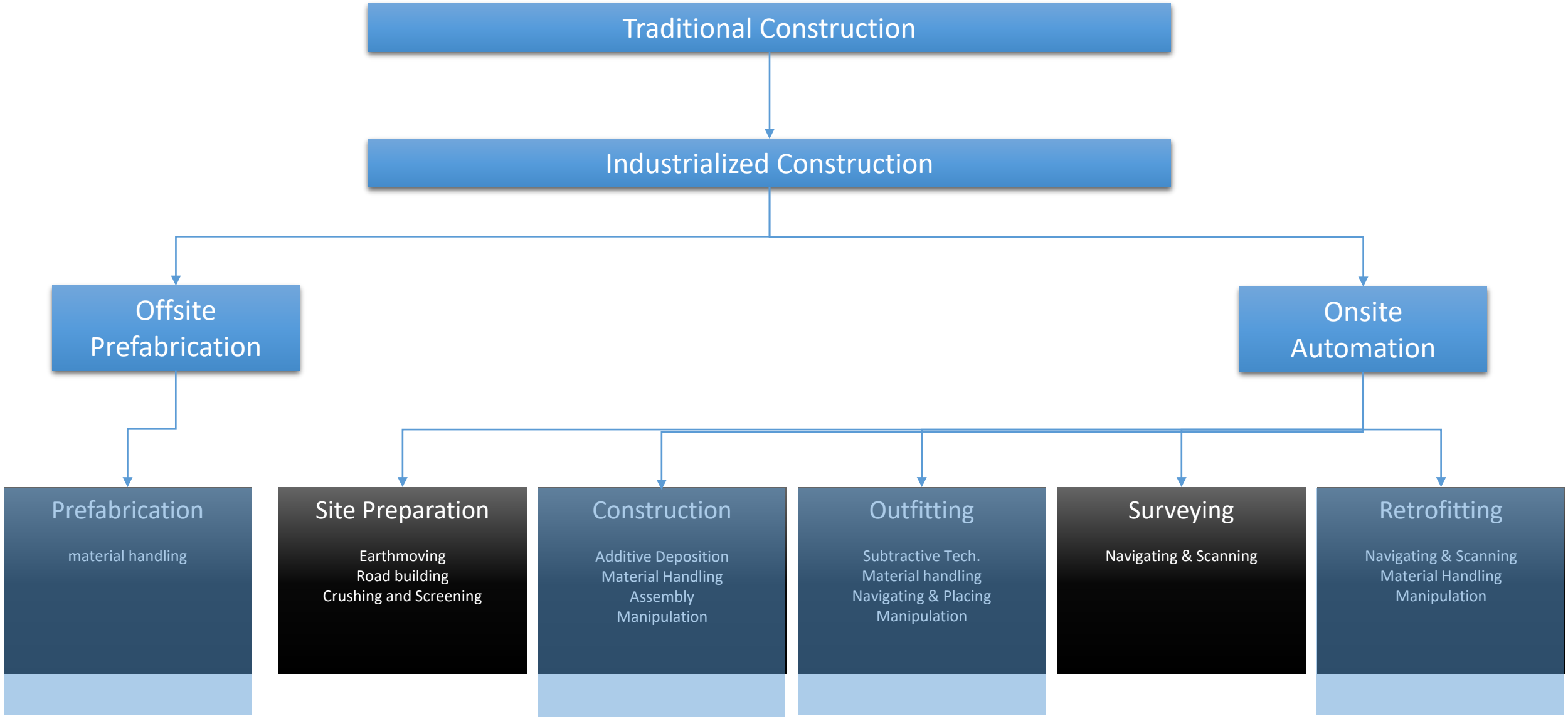
Modelling and simulation capabilities to support

Product Optimization	Process Optimization	Data Analytics
Thermal Simulations	Design for Manufacturing & Assembly	Multi-modal Data Collection (Camera, LiDAR, EMUs)
Airflow Simulations		
Daylighting Simulations	Factory Information Modelling	Machine Learning based post processing (Computer Vision, Object Detection, Classification)
Energy Simulations		
Hygrothermal modeling	Process Modelling	
Materials Research		

Testing and demonstration capabilities to support

Prototype Projects	Small scale Projects	Large Scale Projects
TRL 1-3 Research at NREL+ labs	**TRL 4-6 Research** with SBIR/STTR partners (startups and small businesses)	**TRL 7 -9 research + Path to commercialization of technology** with large scale partners

Background


Traditional Construction
Industrialized Construction
Offsite Prefabrication
Onsite Automation
Prefabrication
material handling
Site Preparation
Earthmoving
Road building
Crushing and Screening
Construction
Additive Deposition
Material Handling
Assembly
Manipulation
Outfitting
Subtractive Tech.
Material handling
Navigating & Placing
Manipulation
Surveying
Navigating & Scanning
Retrofitting
Navigating & Scanning
Material Handling
Manipulation

MODES OF ROBOTIC CONSTRUCTION

- Industrial Robotic Arms
- Rovers
- Quadrupedals
- Drones

Background

HABITABLE BUILDINGS = FUNCTIONAL BUILDINGS

FIGURE 11 An Ideal NZE Modular Housing unit for multifamily buildings as an output of DfEEinIC methodology by NREL and partners.

Background

Building as a system of systems

STRUCTURES

1. Fuselage
2. Cockpit

AVIONICS

3. Winglet
4. Flaps
5. Slats
6. Spoiler
7. Aileron
8. Stabilizers

MECHANICAL

13. Landing Gear
14. Wheels

CONTROL SYSTEMS

10. Flap Control System
11. Aileron Control System
12. Spoiler Control System

ENGINES

9. Turbine

-Years of development
-Standardized
-Standardized components

MECHANICAL

12. Boiler Plant
11. Chiller Plant
10. Air valves
9. Ducts

ELECTRICAL

16. Main board
15. Power supply
14. Conduits
13. Artificial Lighting

PLUMBING

21. Water storage tank
20. Water supply pipes
19. Grey water return pipes
17. Drainpipes

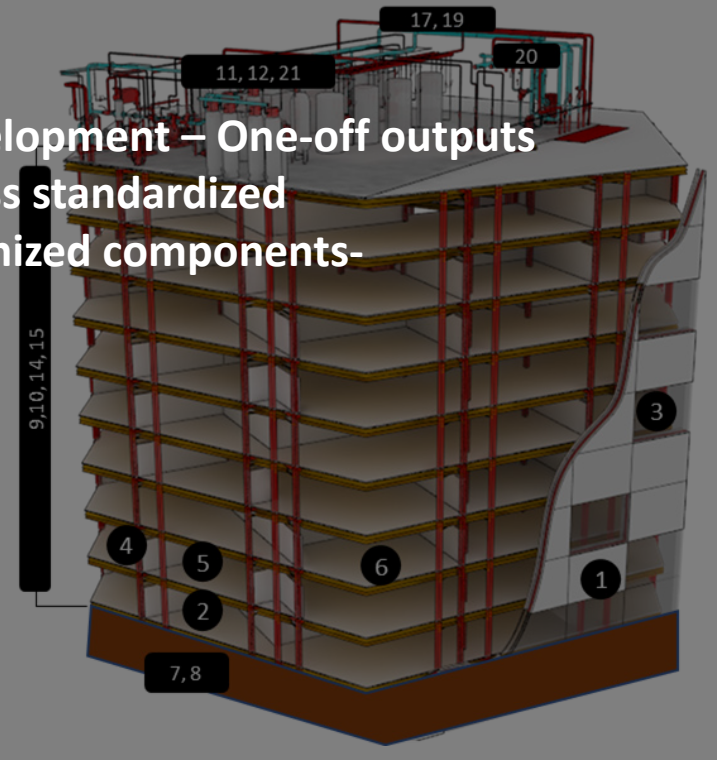
STRUCTURAL

8. Footing
7. Foundation
6. Slabs
5. Beams
4. Columns

ARCHITECTURAL

3. Windows
2. Interior walls
1. Envelope assembly

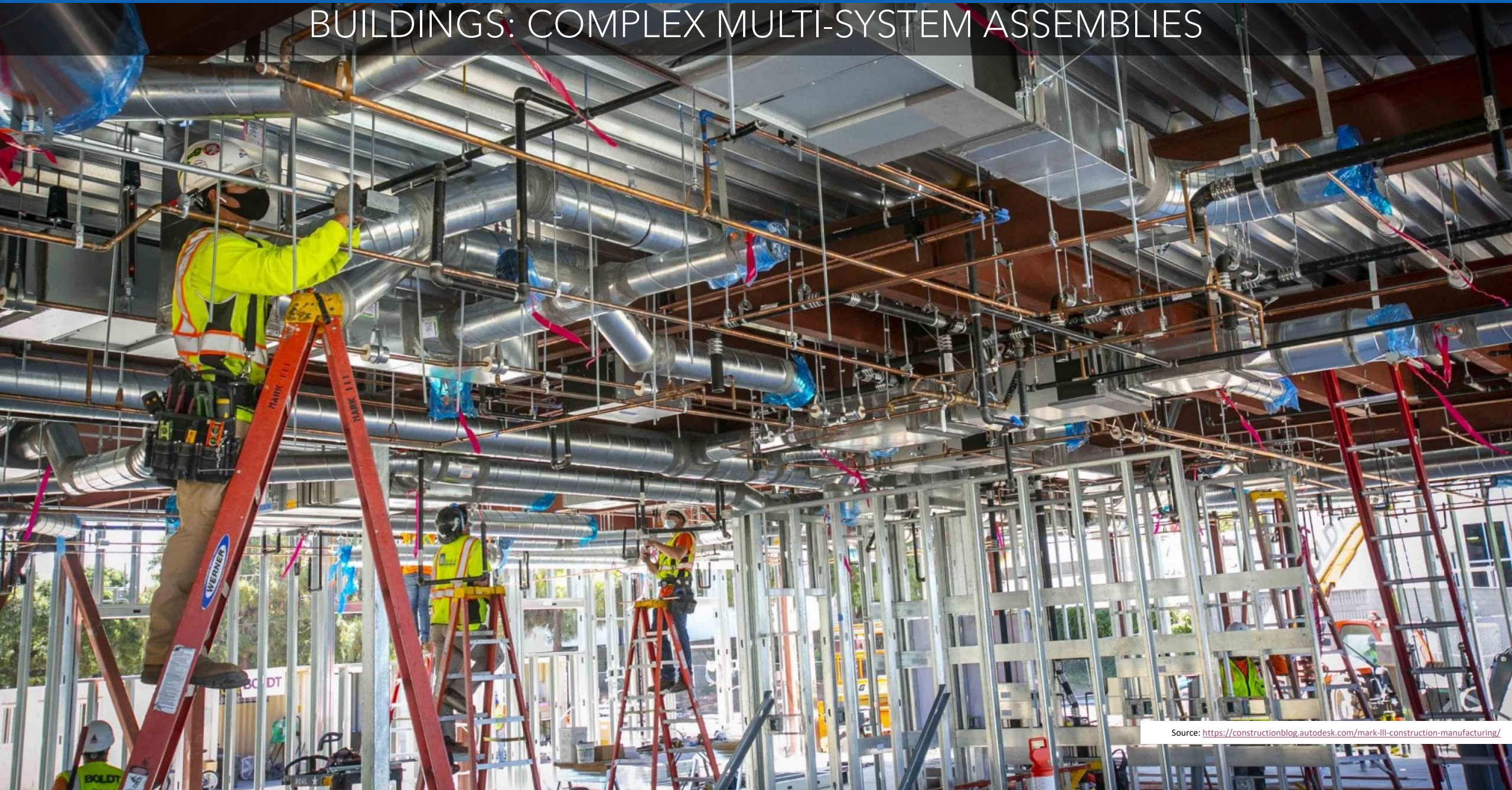
-Months of development – One-off outputs
-Less standardized
-Customized components-



Muthumanickam, N.K. (2021). Multidisciplinary Design Optimization Framework For Multi-Phase Building Design Process - Technology Demonstration Using Design Of Office Building And Robotically 3D Printed Habitat [Doctoral dissertation, The Pennsylvania State University]. *PSU Electronic Thesis and Dissertation for Graduate School Repository*. https://etda.libraries.psu.edu/catalog/24577nxm78

Trends

BUILDINGS: COMPLEX MULTI-SYSTEM ASSEMBLIES



Source: https://constructionblog.autodesk.com/mark-lll-construction-manufacturing/

INDUSTRIALIZED CONSTRUCTION: BUILDING COMPONENT PRODUCTION

Source: https://www.consigli.com/wp-content/uploads/2017/02/Lean-03-1.jpg

INDUSTRIALIZED CONSTRUCTION: BUILDING ASSEMBLIES

Source: https://www.asti.com/productization-a-vision-for-industrialized-construction/

INDUSTRIALIZED CONSTRUCTION: ONSITE ASSEMBLIES

Source: https://www.nytimes.com/2013/10/15/business/energy-environment/putting-robots-to-work-in-solar-energy.html

INDUSTRIALIZED CONSTRUCTION: OFFSITE MULTI-SYSTEM ASSEMBLIES

Source: https://www.bdcnetwork.com/blog/epic-rise-industrialized-construction

INDUSTRIALIZED CONSTRUCTION: IN-SITU CONSTRUCTION

Source: https://www.popularmechanics.com/technology/infrastructure/a26252/3d-printer-build-house-mit/

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

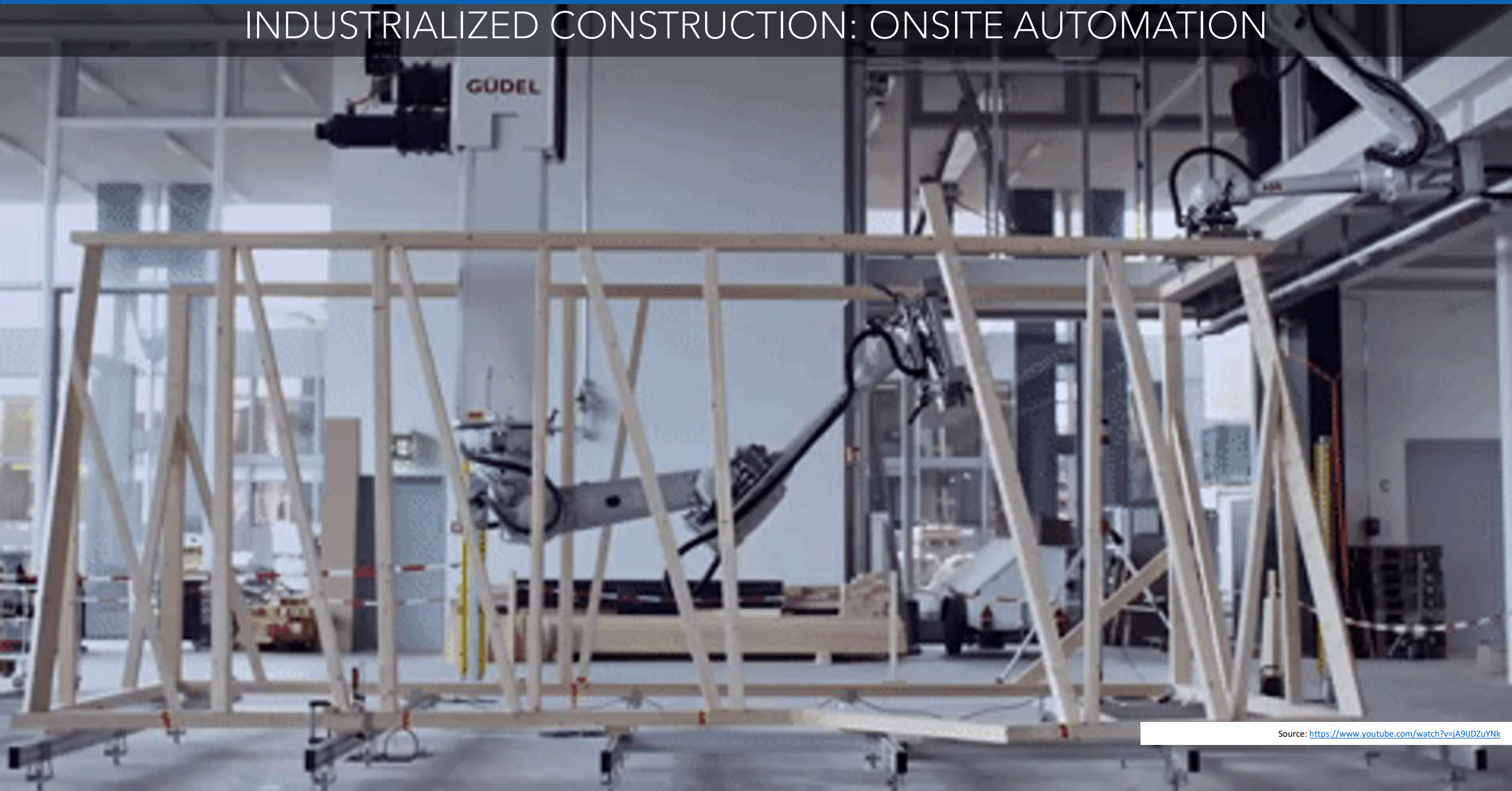
Source: https://www.archdaily.com/779906/new-construction-robot-lays-bricks-3-times-as-fast-as-human-workers

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

Source: https://www.archdaily.com/779906/new-construction-robot-lays-bricks-3-times-as-fast-as-human-workers

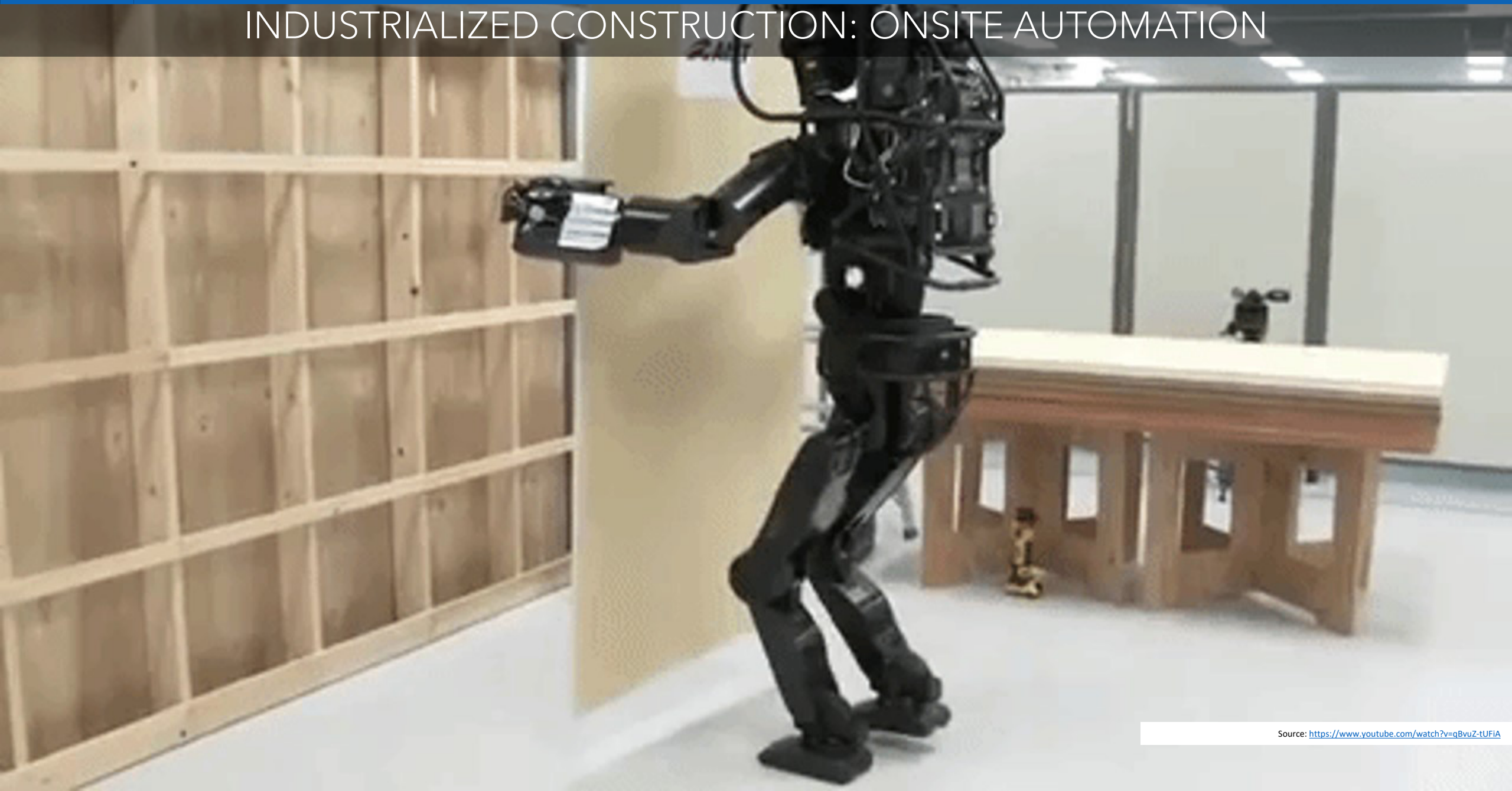
Trends

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION



Source: https://www.youtube.com/watch?v=jA9IJDZuYNk

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION



Source: https://www.youtube.com/watch?v=qBvuZ-tUFiA

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

Source: https://www.canvas.build/

INDUSTRIALIZED CONSTRUCTION: REMOTE ACCESS

Source: https://www.ribaj.com/products/q-bot-invests-2-million

INDUSTRIALIZED CONSTRUCTION: RETROFIT AND RENOVATION

Source: https://www.woodworkingnetwork.com/technology/robots-repair-veneer-imperfections-georgia-pacific

INDUSTRIALIZED CONSTRUCTION: FAULT DETECTION

Source: https://www.uasvision.com/2022/01/19/apellix-gets-nondestructive-testing-drone-patent/

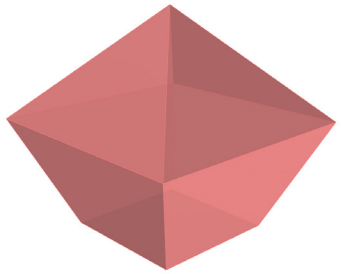
Project Samples – NASA 3D Printed Mars Habitat Challenge

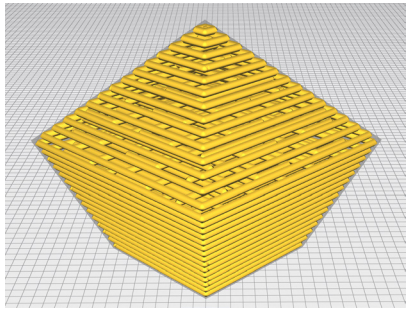
Virtual Construction Level
Mars

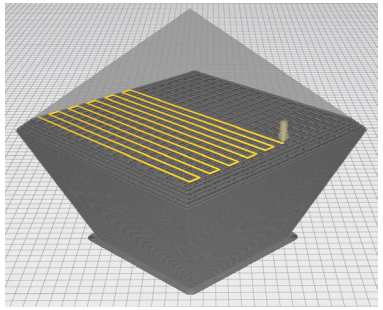
Actual Construction Level
Earth

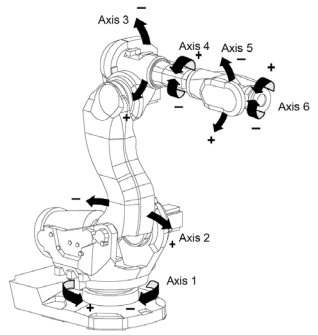
Project Samples – NASA 3D Printed Mars Habitat Challenge

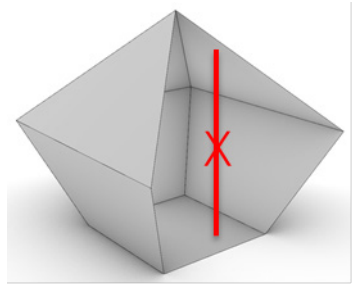
Model → Slice → Translate → Simulate → Construct

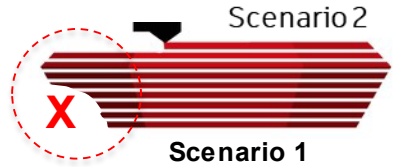








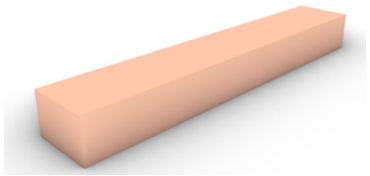




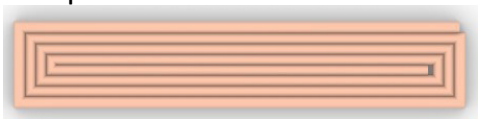
Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge

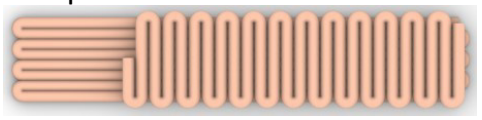
Model → Slice → Translate → Simulate → Manufacture



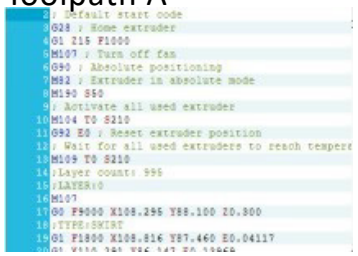
Toolpath A



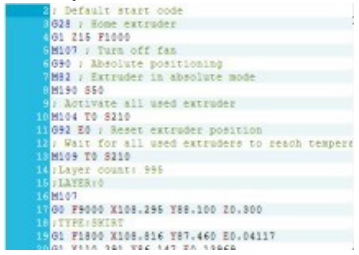
Toolpath B

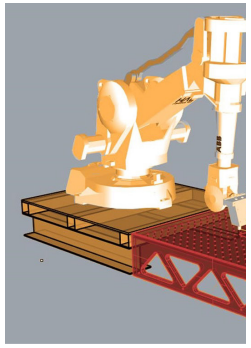


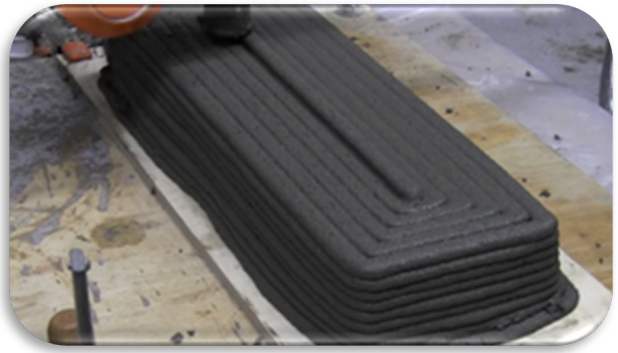
Toolpath A



Toolpath B







↑Structural performance

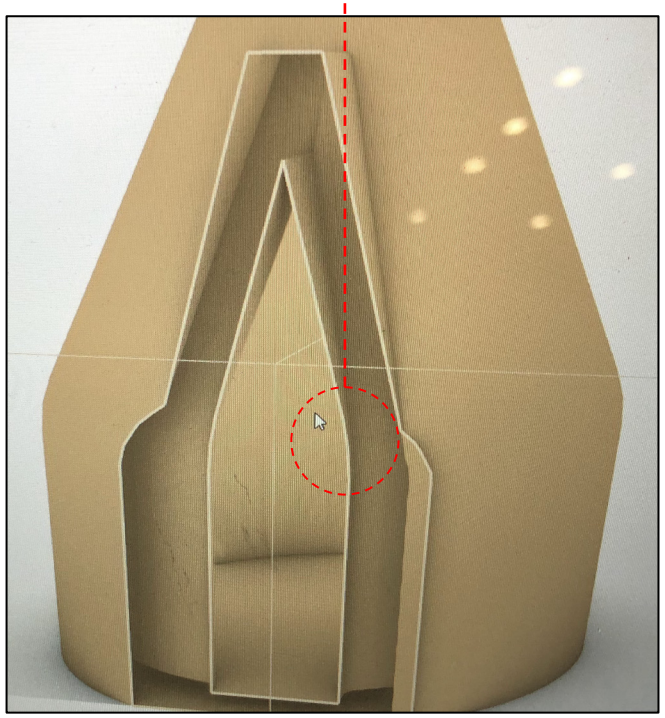
↑Complex Robotic Maneuvers

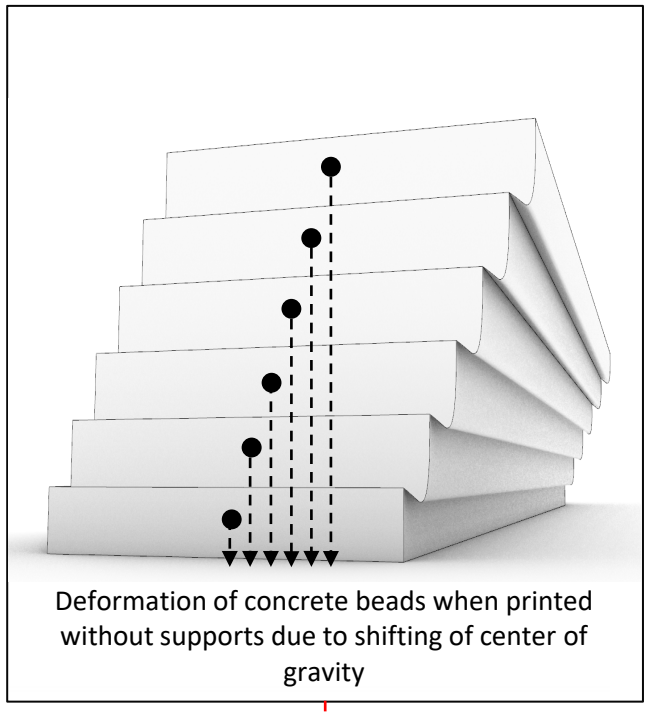
↑Robotic vibrations at turns

↑Concrete deformation (Less shape accuracy)

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge





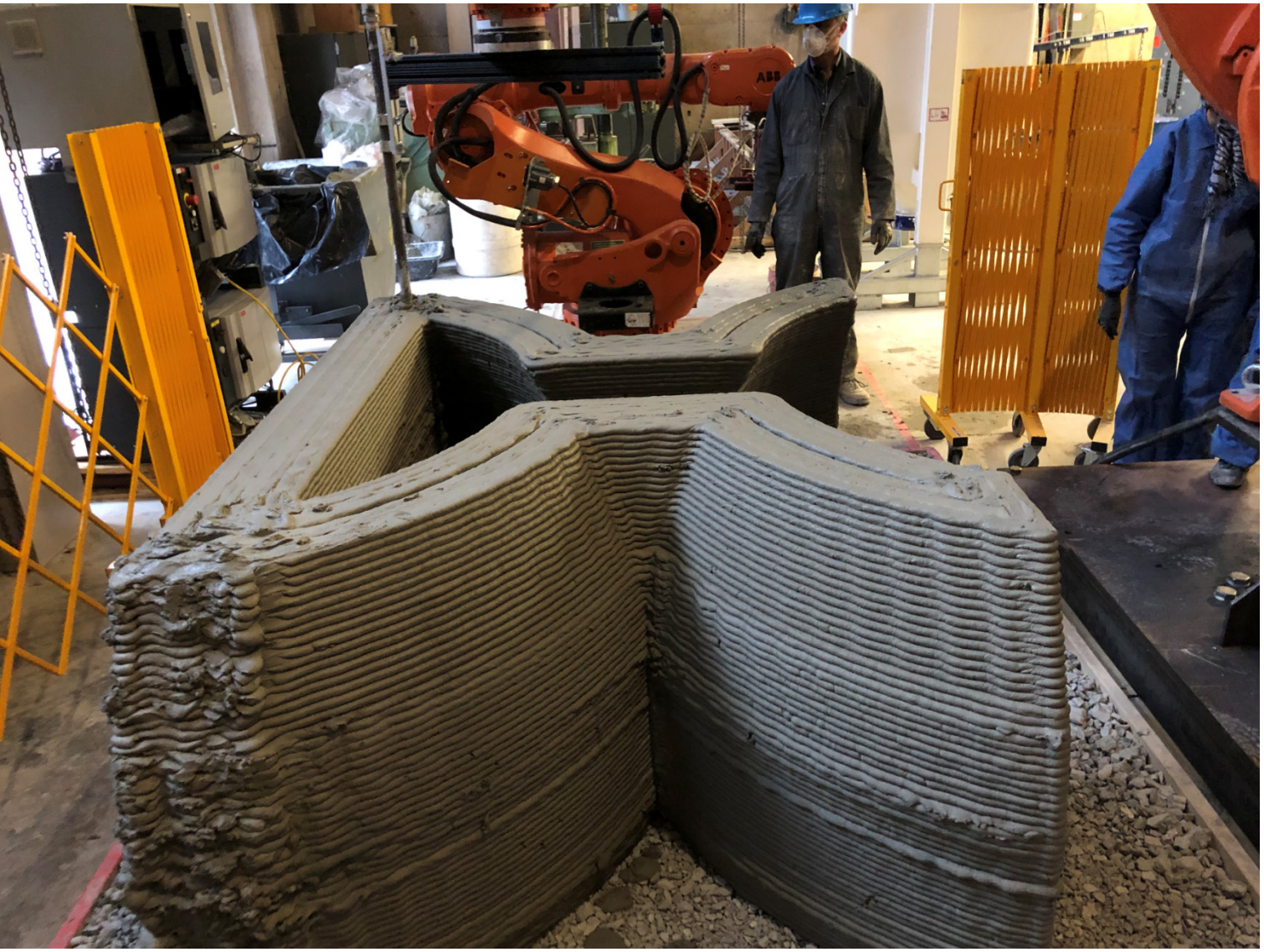
Deformation of concrete beads when printed without supports due to shifting of center of gravity

Design Variables:

- Angle of taper
- Material consistency (Concrete mixing ratio)

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge



Challenges:

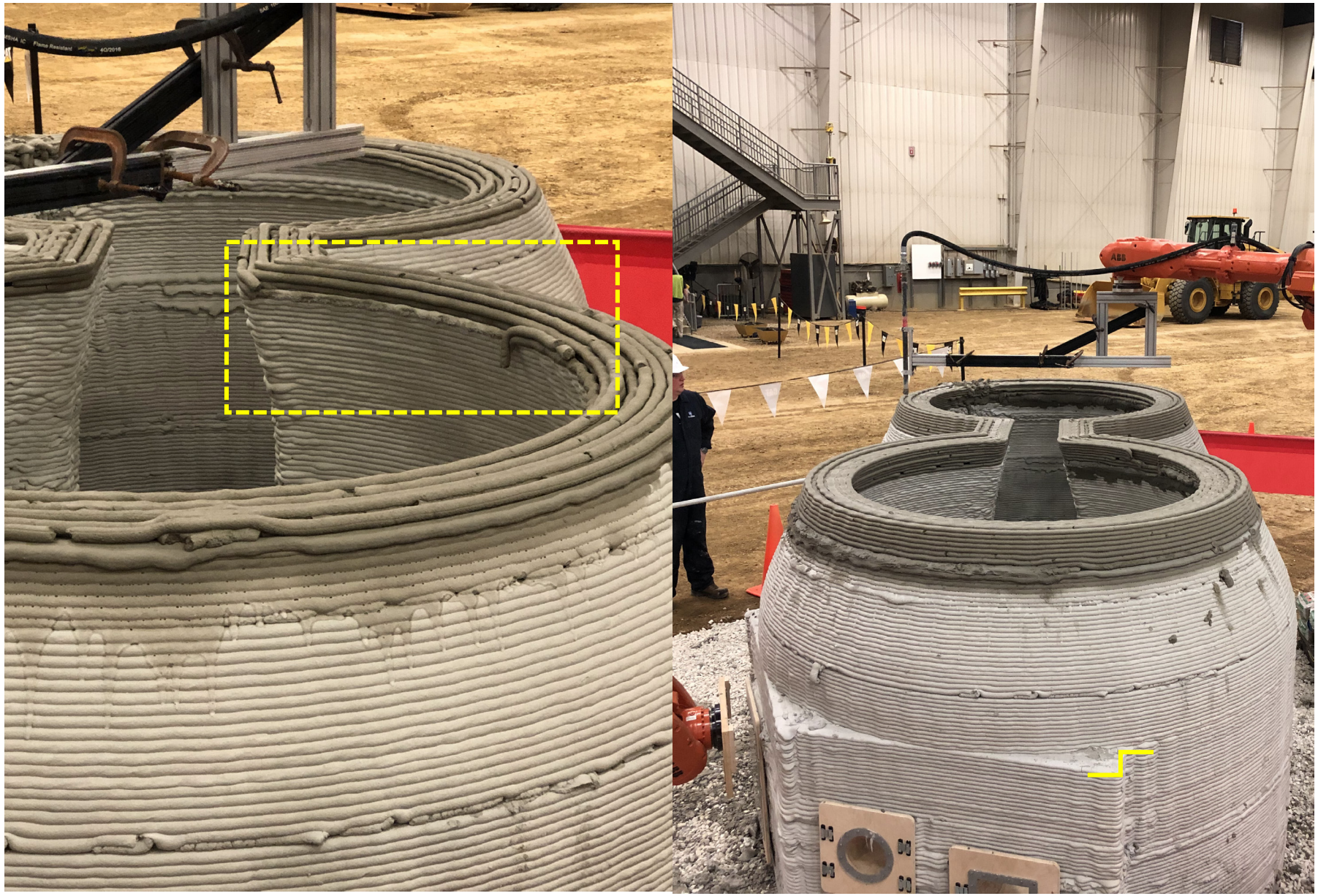
- Over-extrusion at edges/corners/ junctions

Design Variables:

- Fillet radius at edges/corners/junctions
- Robot speed at corners

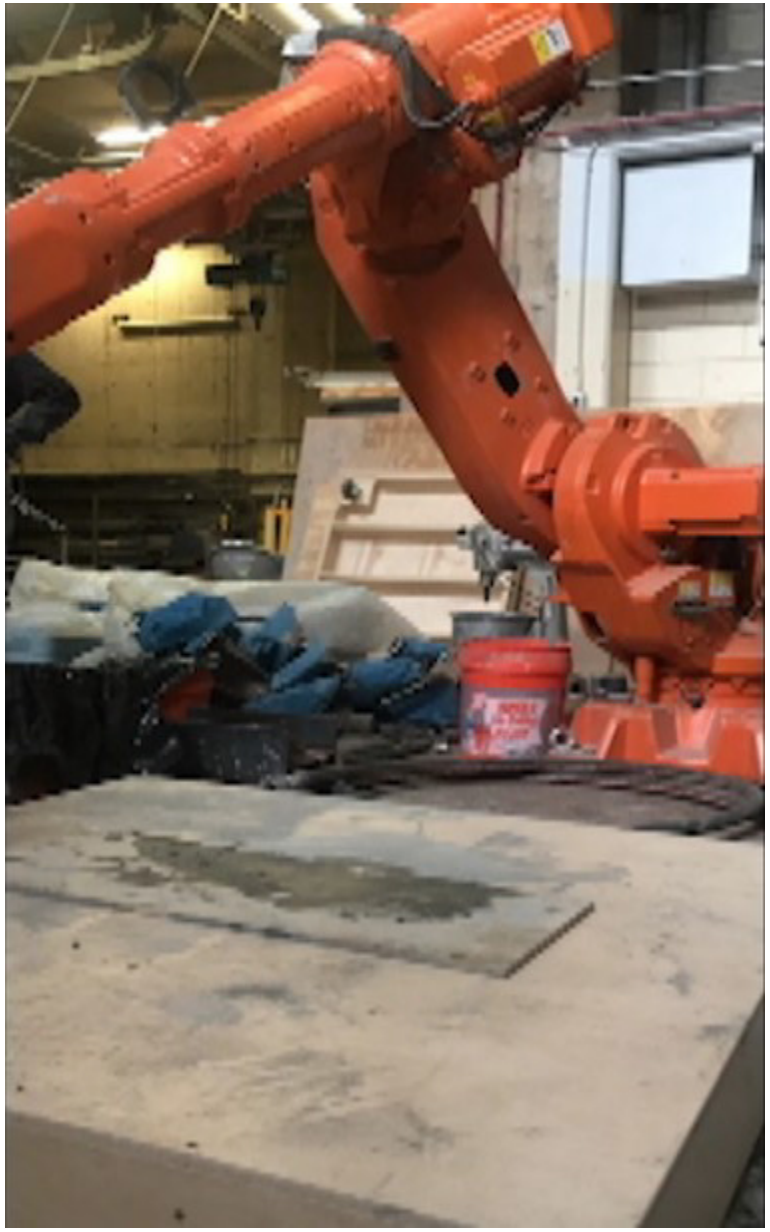
Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge



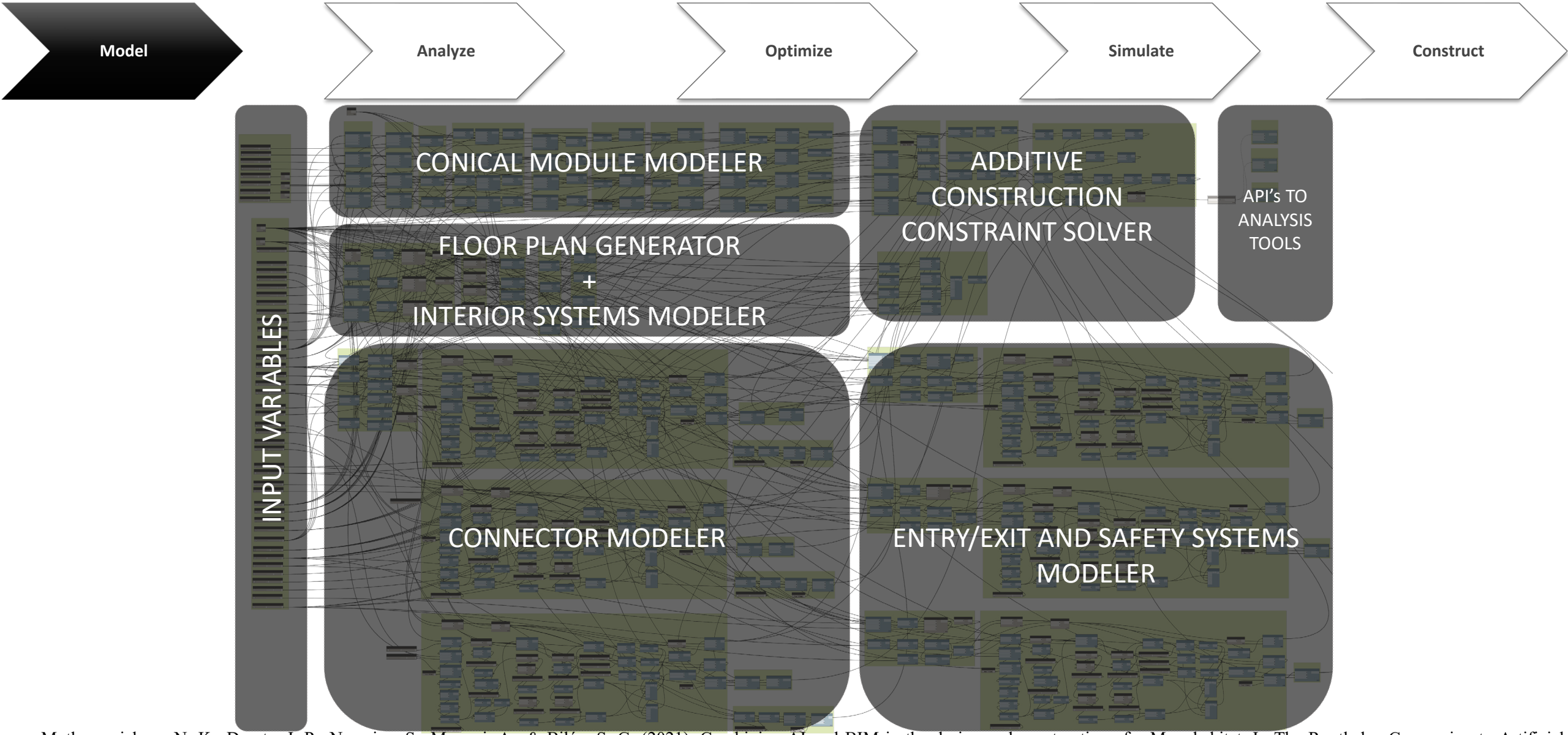
Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge



Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

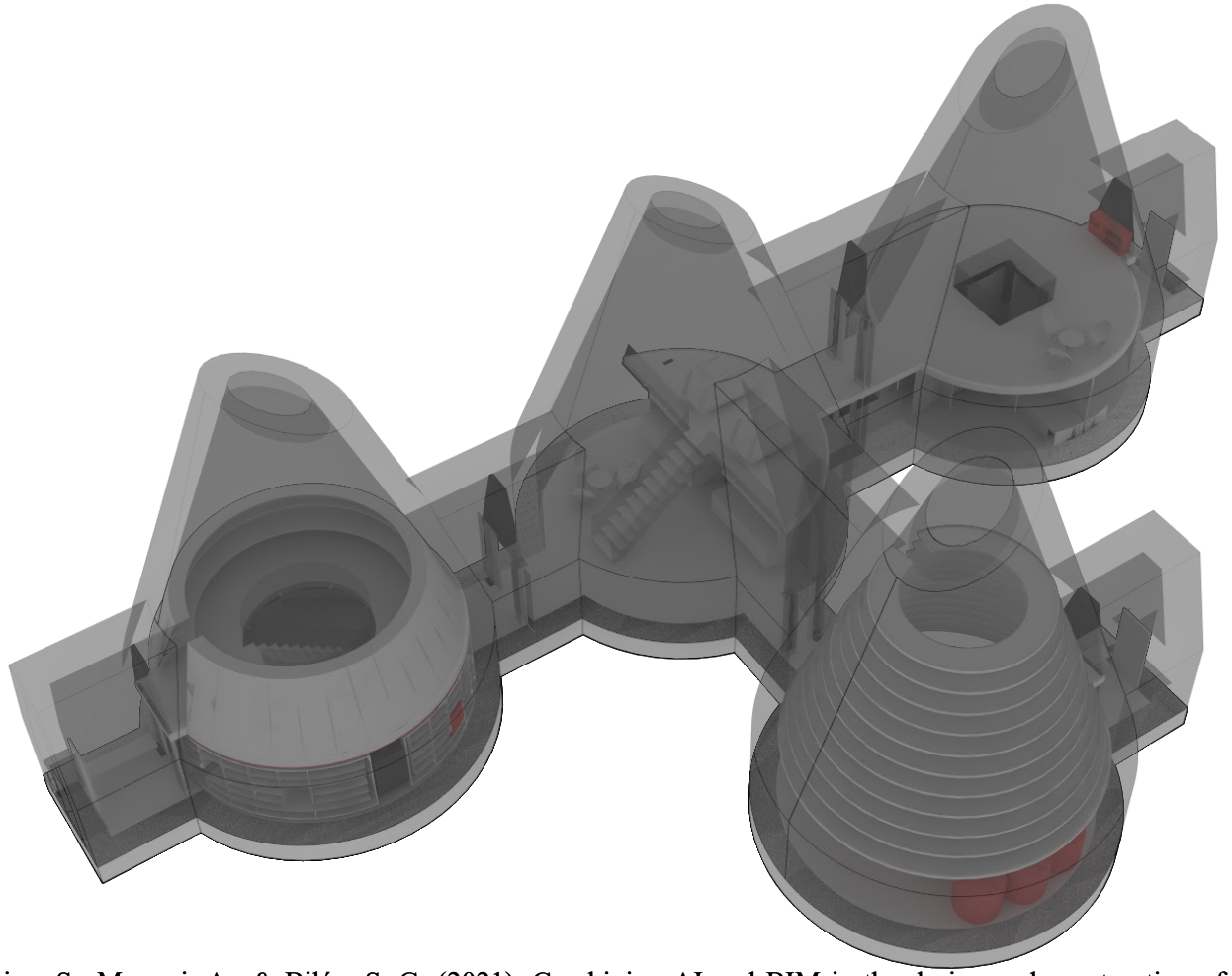
Project Samples – NASA 3D Printed Mars Habitat Challenge



Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge

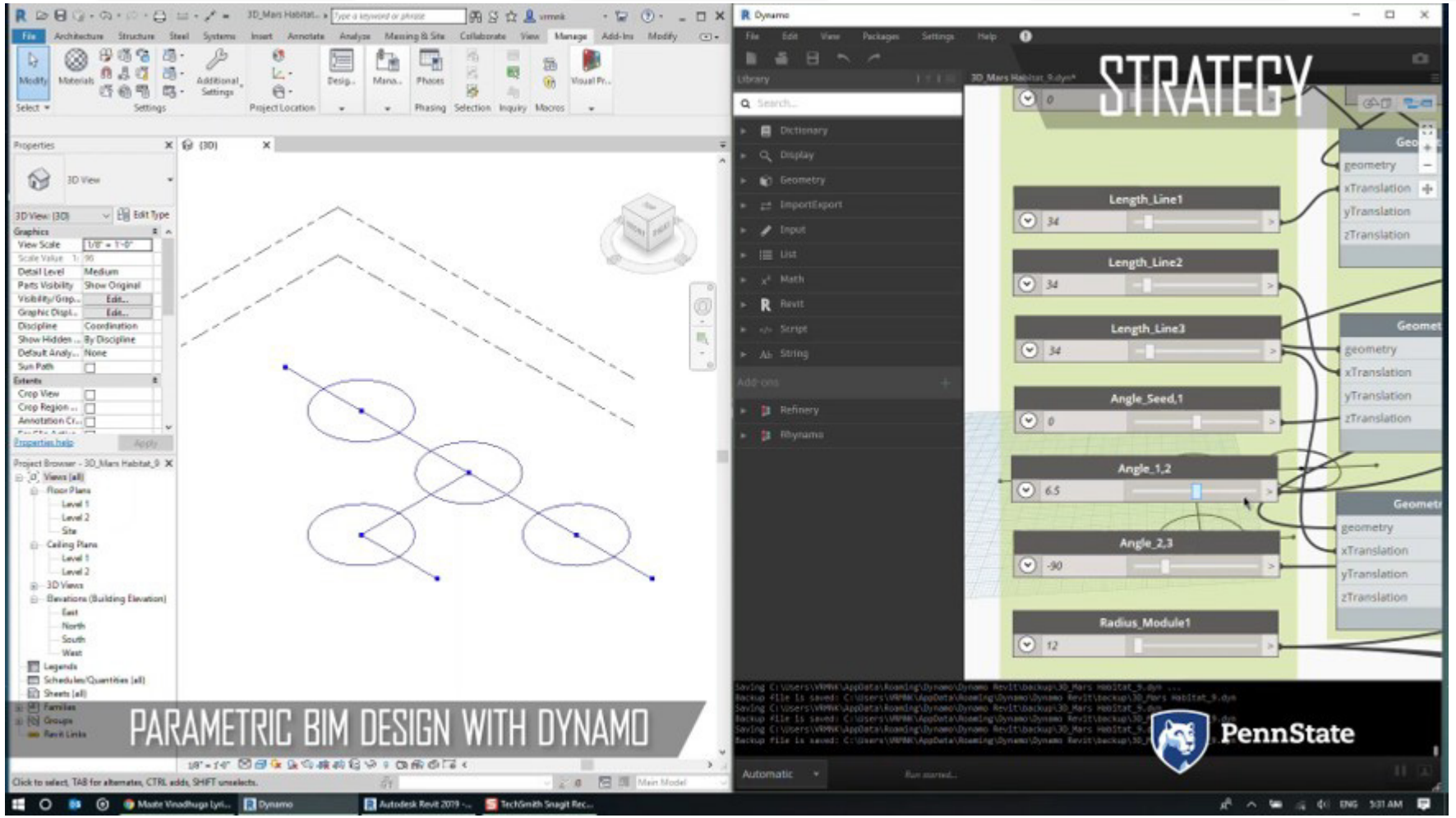
Model → Analyze → Optimize → Simulate → Construct



Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge

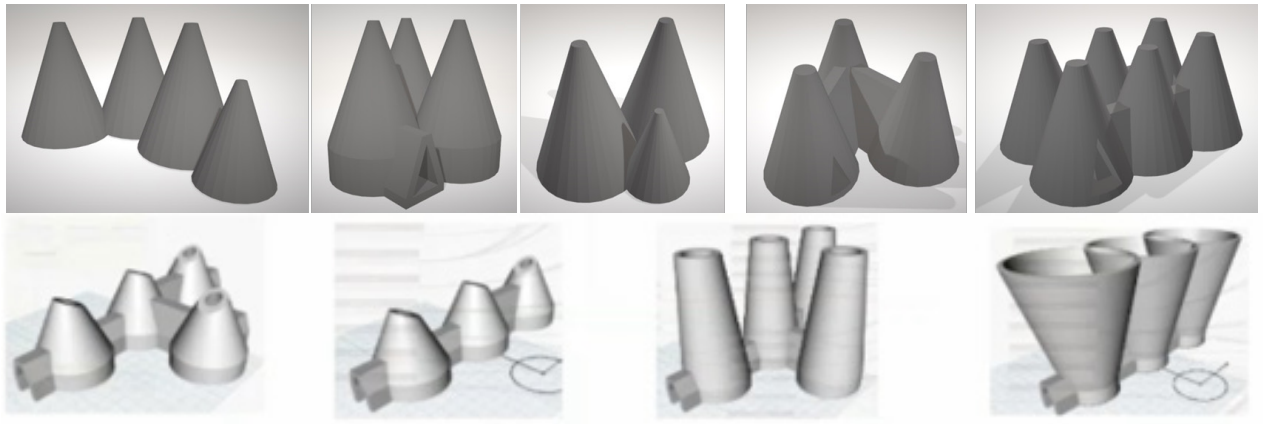
Model → **Analyze** → **Optimize** → **Simulate** → **Construct**

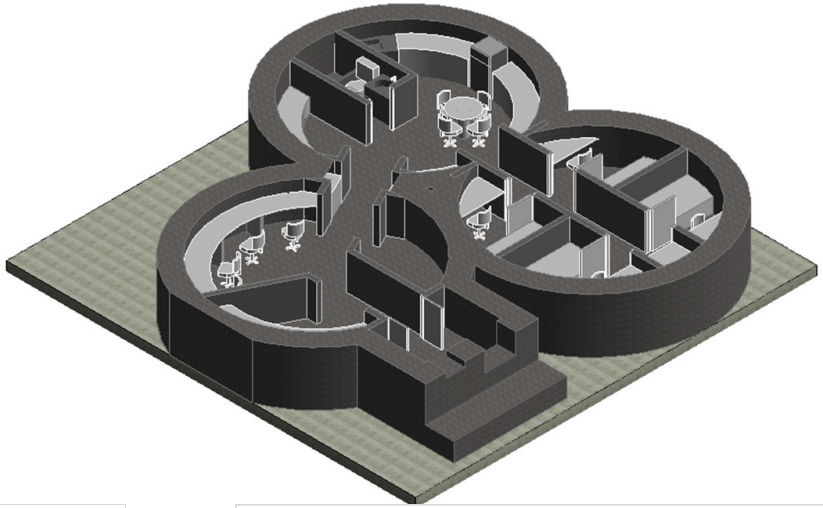


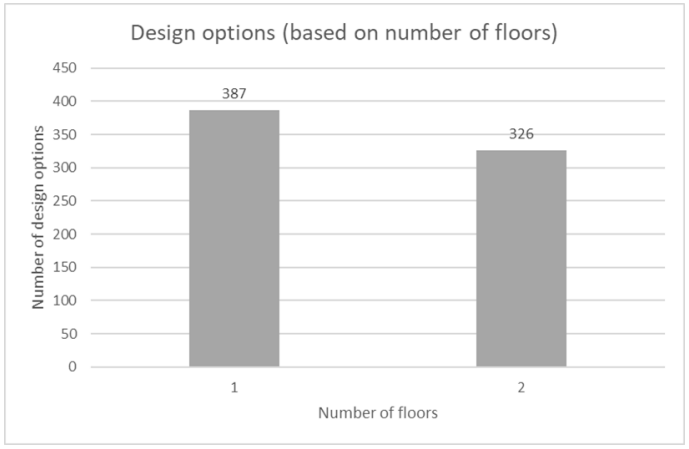
Muthumanickam, N.K., Duarte, J.P., Nazarian, S., Bilén, S. G., & Memari, A. (2021). BIM for Design Generation, Analysis, Optimization, and Construction Simulation of a Martian Habitat. In Proceedings of the American Society of Civil Engineers Earth & Space Conference (pp. 1208-1219), ASCE Earth & Space 2021. April 19-23, 2022. Online Conference. https://doi.org/10.1061/9780784483374.112

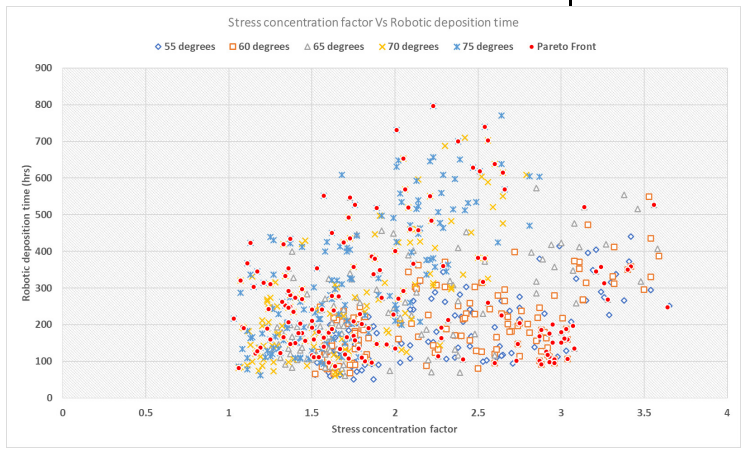
Project Samples – NASA 3D Printed Mars Habitat Challenge

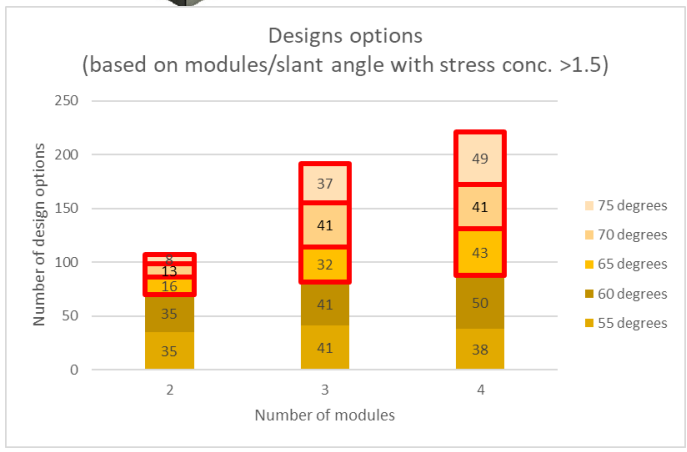
Model → **Analyze** → Optimize → Simulate → Construct







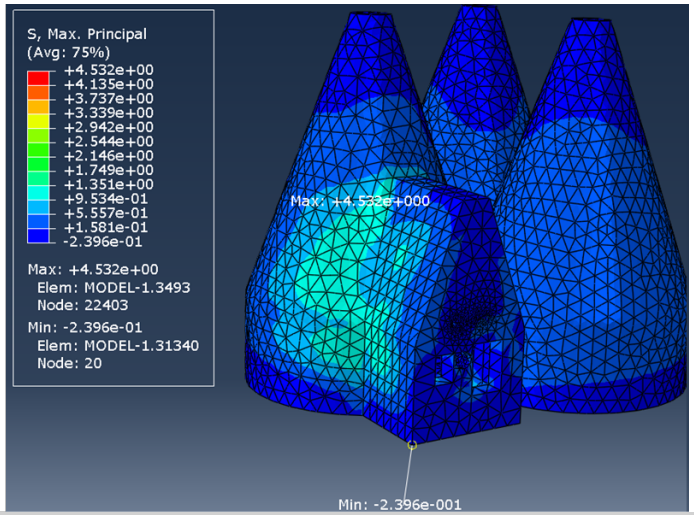


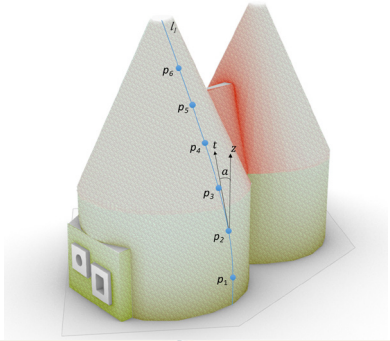


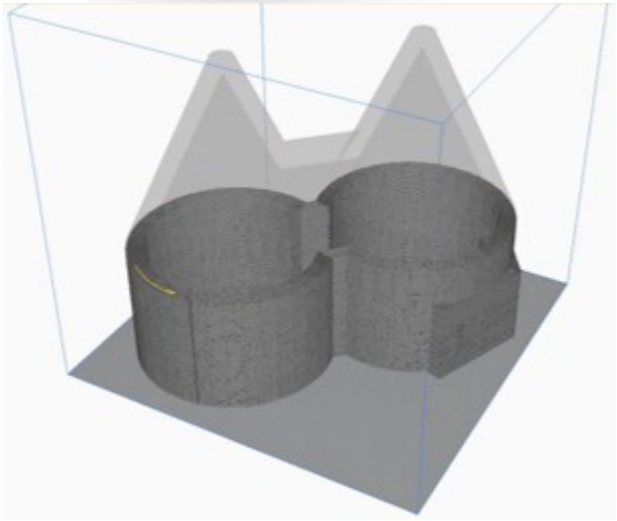
Muthumanickam, N.K. (2021). Multidisciplinary Design Optimization Framework For Multi-Phase Building Design Process - Technology Demonstration Using Design Of Office Building And Robotically 3D Printed Habitat [Doctoral dissertation, The Pennsylvania State University]. *PSU Electronic Thesis and Dissertation for Graduate School Repository*. https://etda.libraries.psu.edu/catalog/24577nxm78

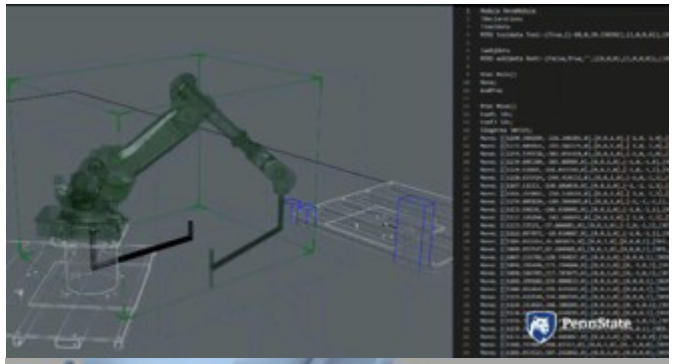
Project Samples – NASA 3D Printed Mars Habitat Challenge

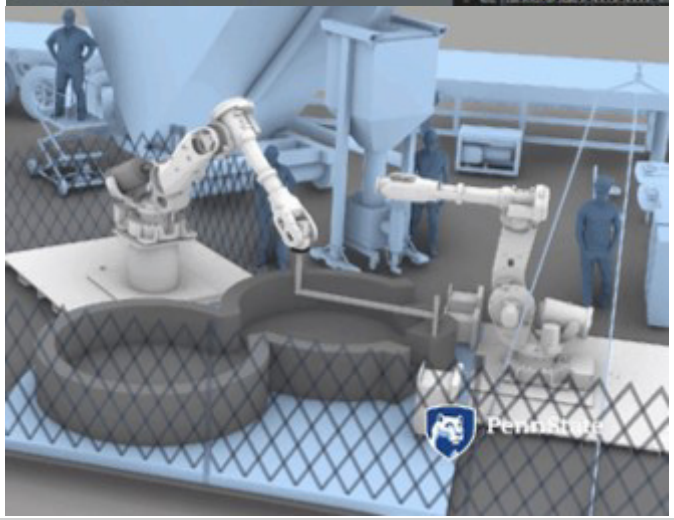
Model → **Analyze** → Optimize → Simulate → Construct











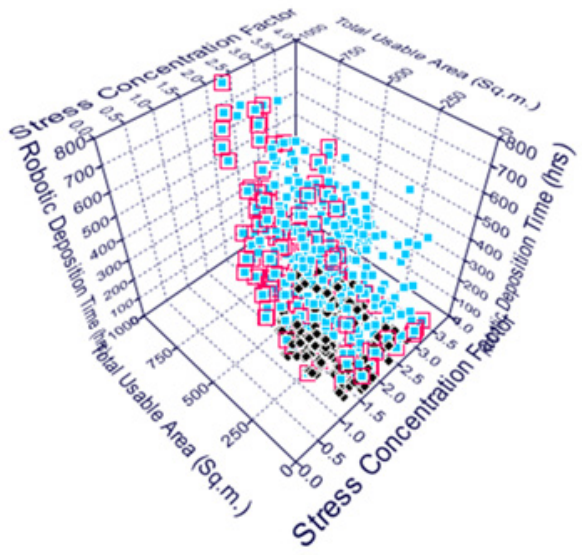
STRUCTURAL ANALYSIS ***TOOLPATH FAILURE DETECTION*** ***TOOLPATH CLASH DETECTION***

Muthumanickam, N.K., Duarte, J.P., Nazarian, S., Bilén, S. G., & Memari, A. (2022). Metamodels for rapid analysis of large sets of building designs for robotic constructability: Technology demonstration using the NASA 3D Printed Mars Habitat Challenge. In Proceedings of the American Society of Civil Engineers Earth & Space Conference, ASCE Earth & Space 2022. April 25-28, 2022. Denver, CO. https://learn.mines.edu/earthspace2022/

Project Samples – NASA 3D Printed Mars Habitat Challenge

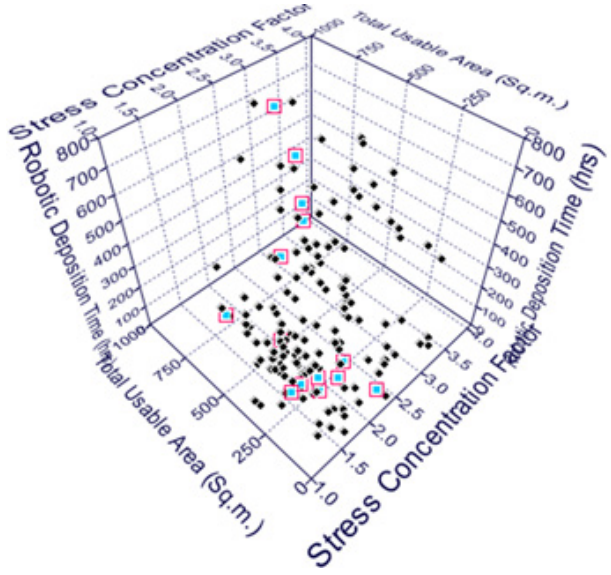
Model → Analyze → **Optimize** → Simulate → Construct

Conceptual



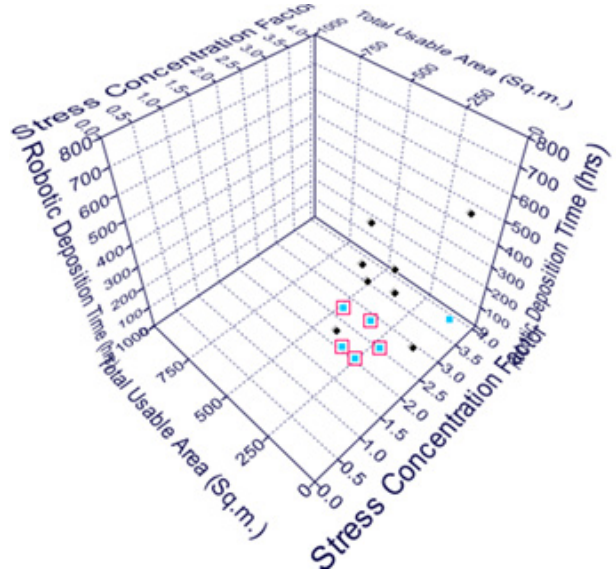
Total = 713
Feasible = 523
Pareto = 158

Preliminary



Total = 158
Feasible = 14
Pareto = 14

Detailed



Total = 14
Feasible = 6
Pareto = 5

◆ Unfeasible ■ Feasible ■ Pareto

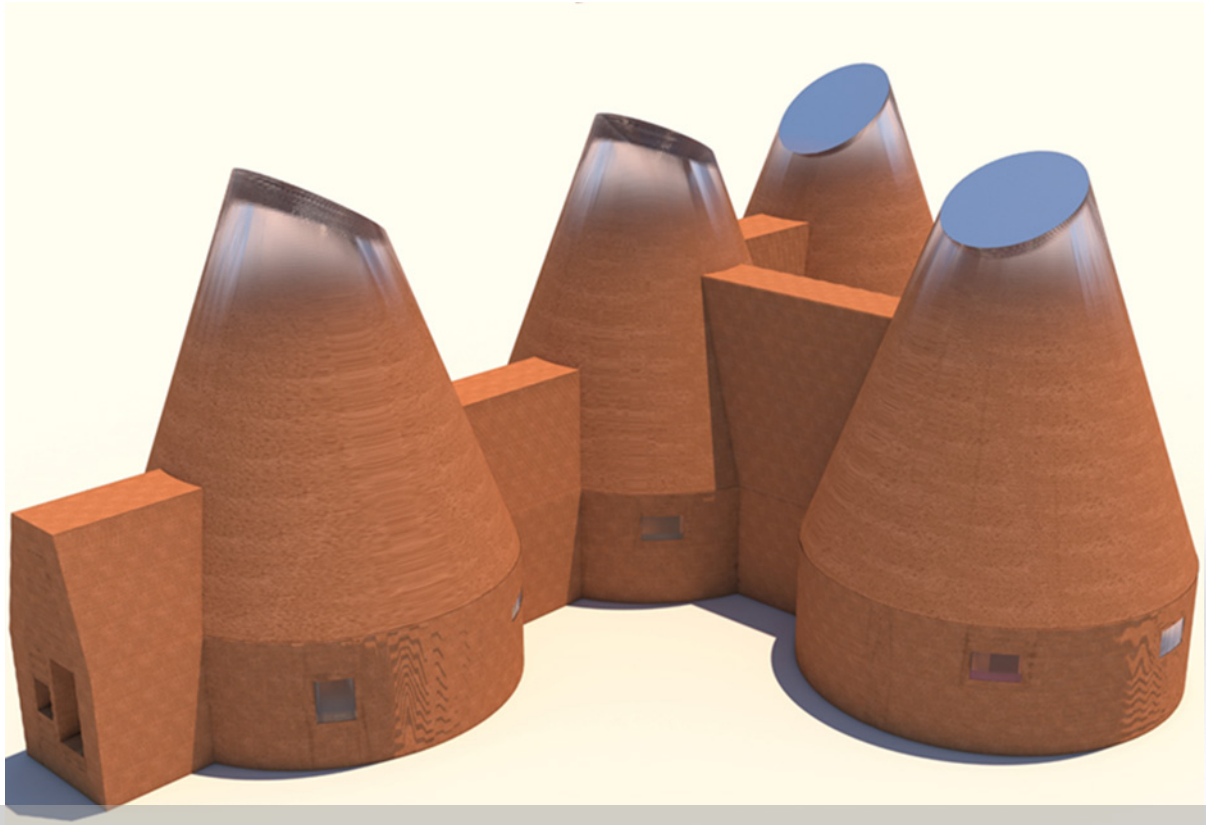
Muthumanickam, N.K. (2021). Multidisciplinary Design Optimization Framework For Multi-Phase Building Design Process - Technology Demonstration Using Design Of Office Building And Robotically 3D Printed Habitat [Doctoral dissertation, The Pennsylvania State University]. *PSU Electronic Thesis and Dissertation for Graduate School Repository*. https://etda.libraries.psu.edu/catalog/24577nxm78

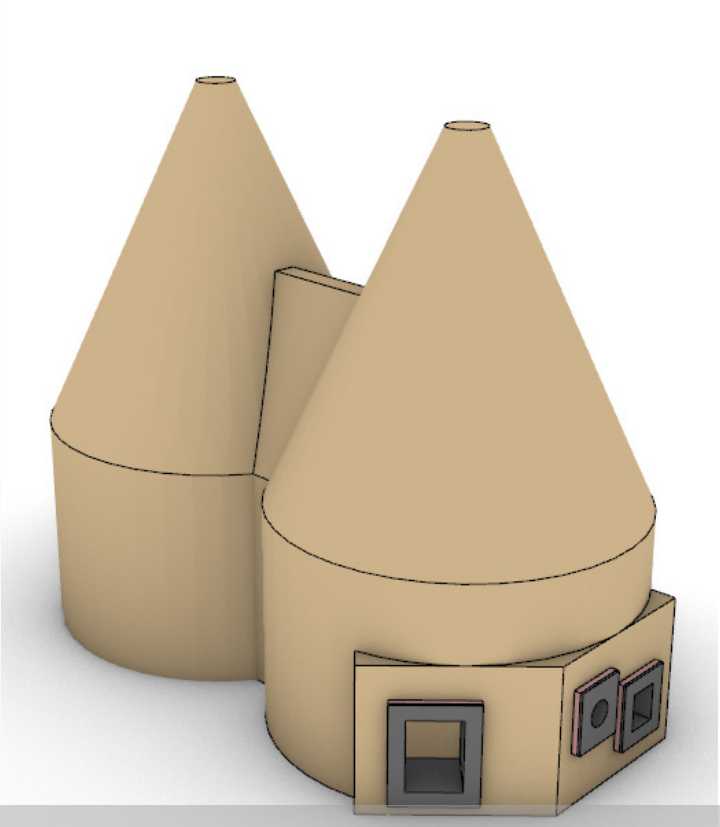
Project Samples – NASA 3D Printed Mars Habitat Challenge

Model → Analyze → **Optimize** → Simulate → Construct

VIRTUAL CONSTRUCTION LEVEL
MARS

ACTUAL CONSTRUCTION LEVEL
EARTH



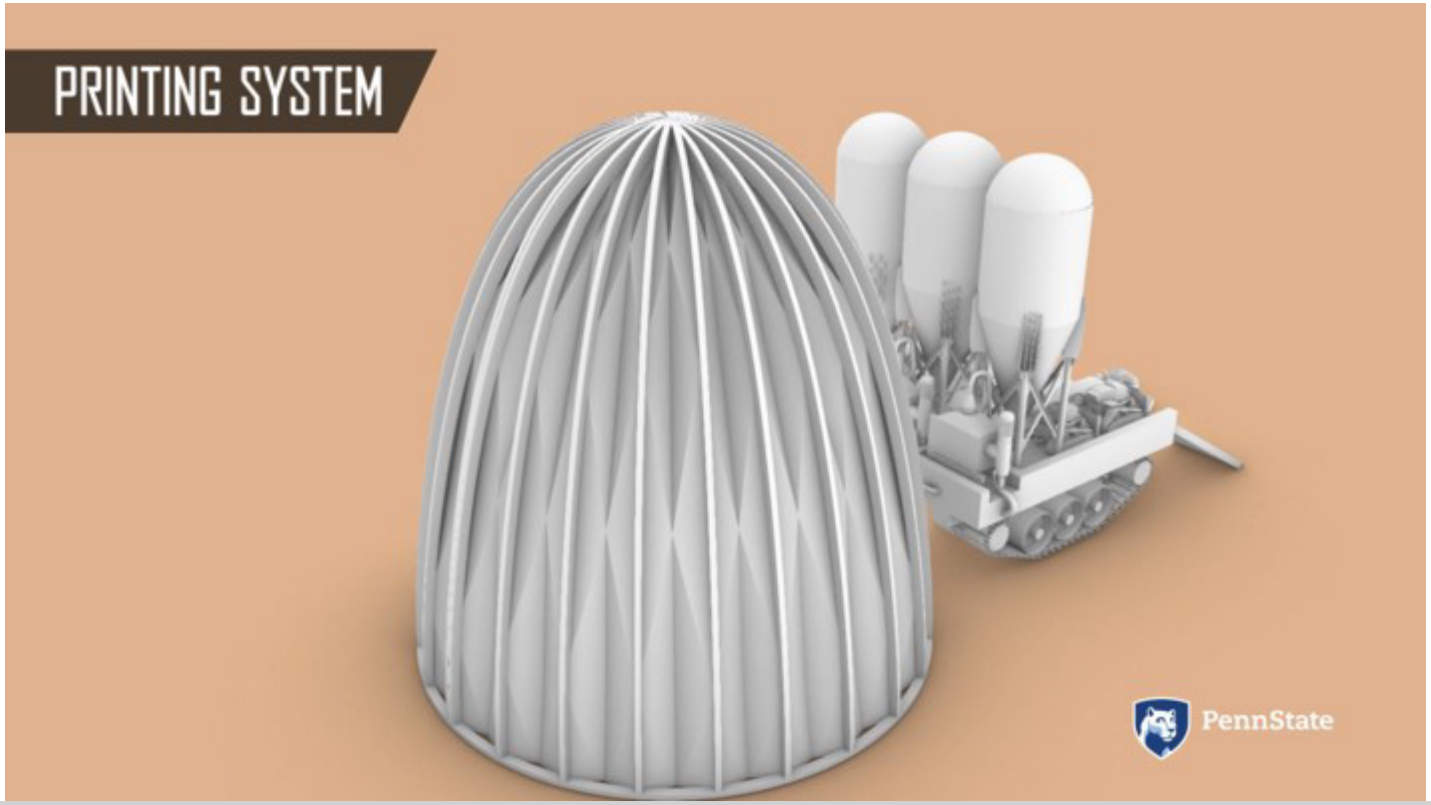


SELECTED DESIGN OPTIONS

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge

Model → Analyze → Optimize → **Simulate** → Construct

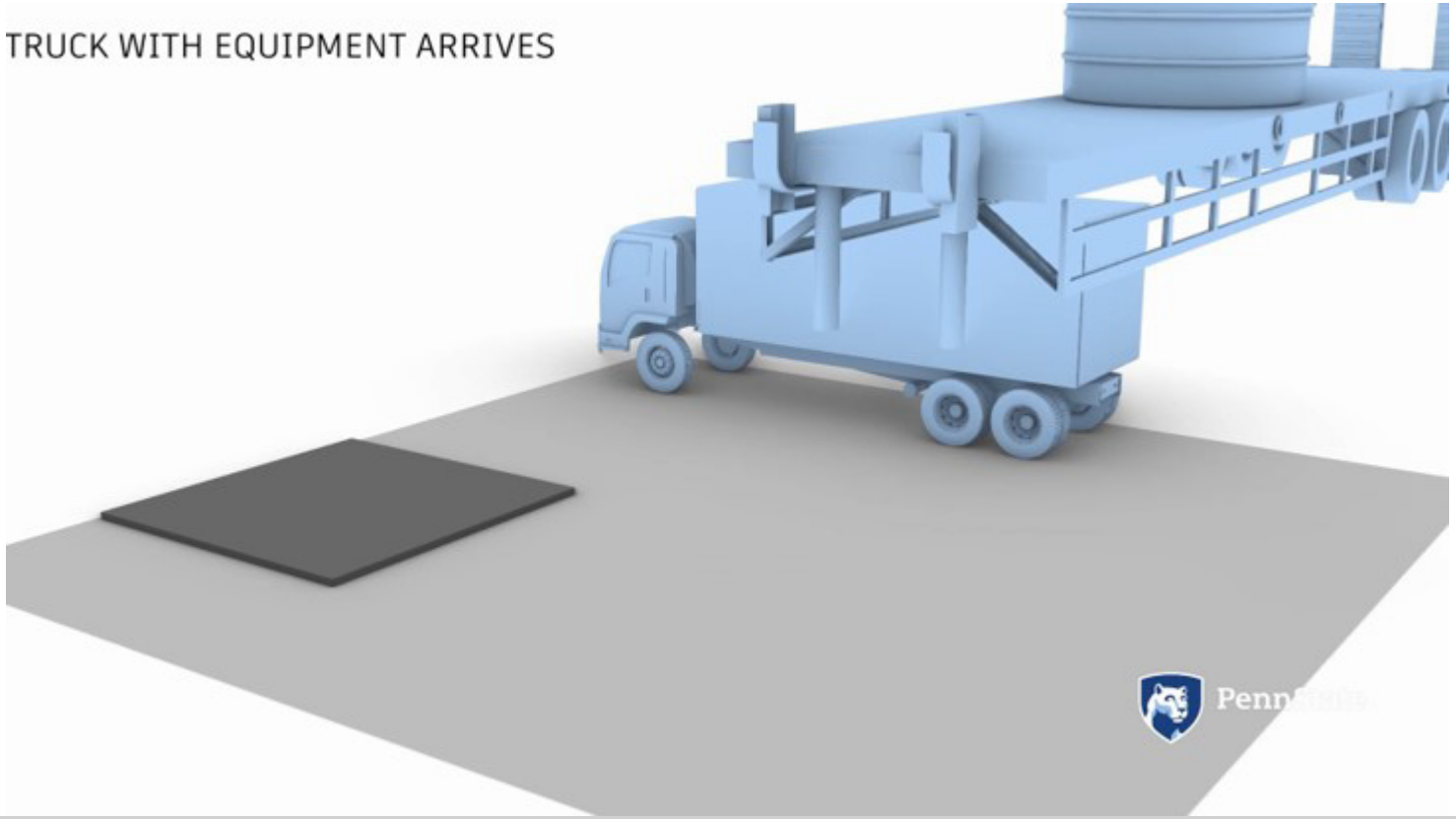


4D SIMULATION (VIRTUAL CONSTRUCTION). CREDITS – EDUARDO COSTA + NEGAR ASHRAFI + NAVEEN

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge

Model → Analyze → Optimize → **Simulate** → Construct

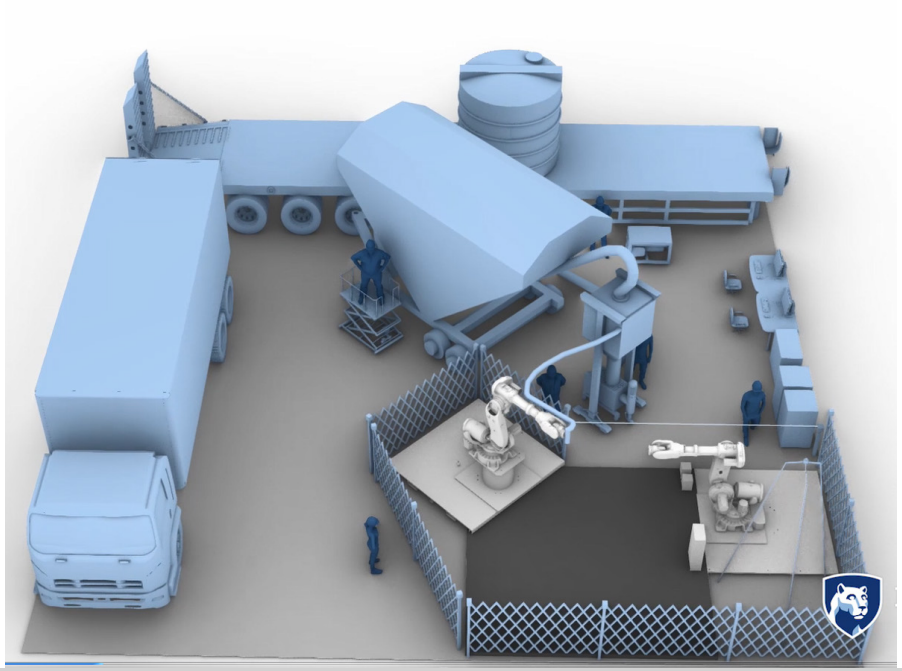


4D SIMULATION (ACTUAL CONSTRUCTION). CREDITS - NAVEEN KUMAR MUTHUMANICKAM

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge

Model → Analyze → Optimize → Simulate → **Construct**



ACTUAL CONSTRUCTION AT FINALS IN PEORIA, ILLINOIS

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

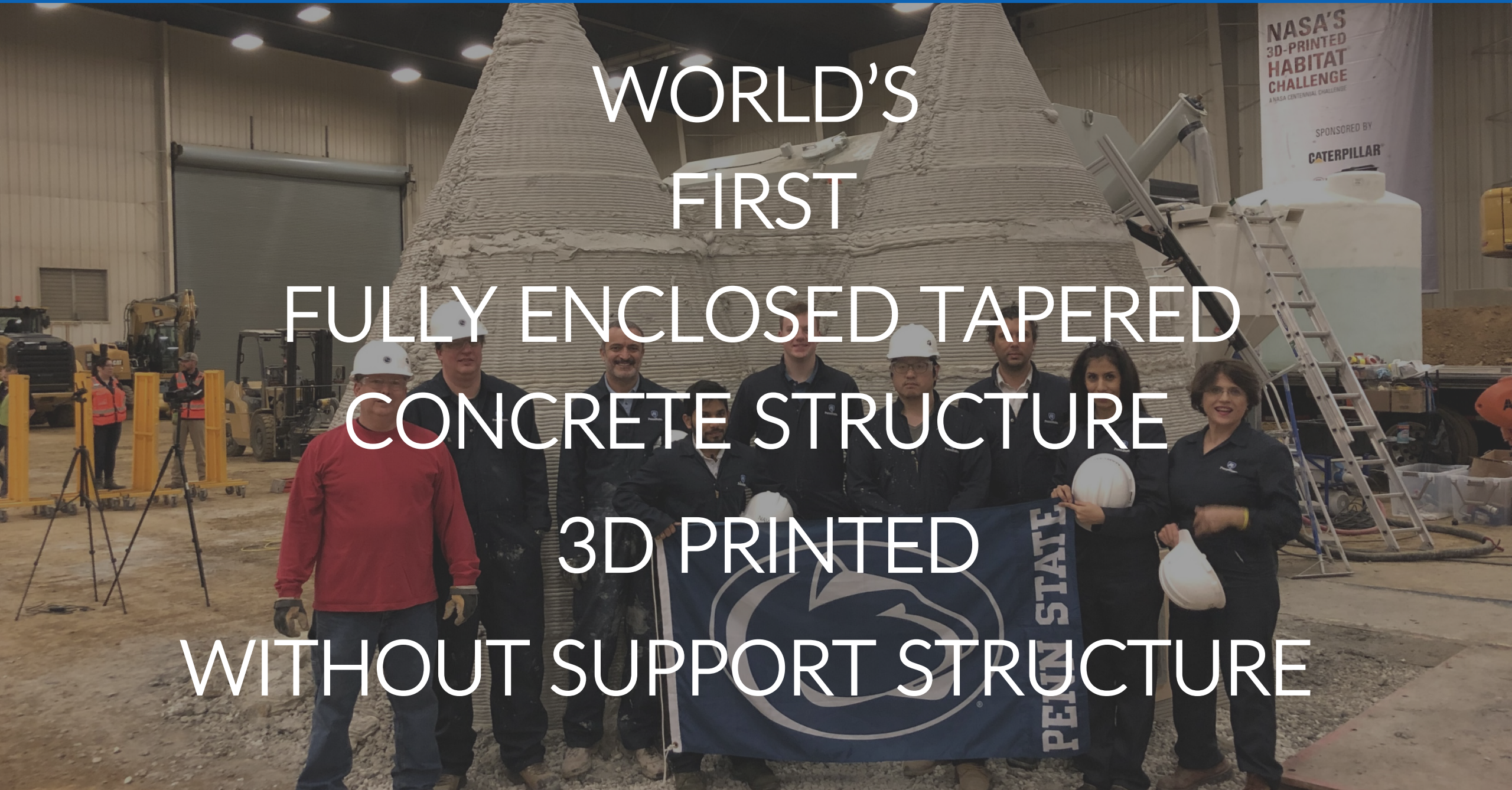
Project Samples – NASA 3D Printed Mars Habitat Challenge

Model → Analyze → Optimize → Simulate → **Construct**

ACTUAL CONSTRUCTION AT FINALS IN PEORIA, ILLINOIS

Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Project Samples – NASA 3D Printed Mars Habitat Challenge



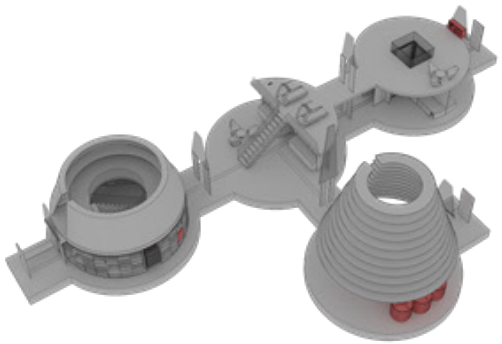
WORLD'S
FIRST
FULLY ENCLOSED TAPERED
CONCRETE STRUCTURE
3D PRINTED
WITHOUT SUPPORT STRUCTURE

Project Samples – NASA 3D Printed Mars Habitat Challenge

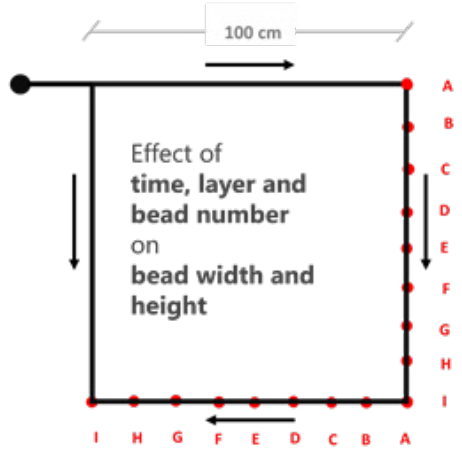
Muthumanickam, N. K., Duarte, J. P., Nazarian, S., Memari, A., & Bilén, S. G. (2021). Combining AI and BIM in the design and construction of a Mars habitat. In The Routledge Companion to Artificial Intelligence in Architecture (pp. 251-279). Routledge. https://doi.org/10.4324/9780367824259-17

Design for Industrialized &Robotic Construction

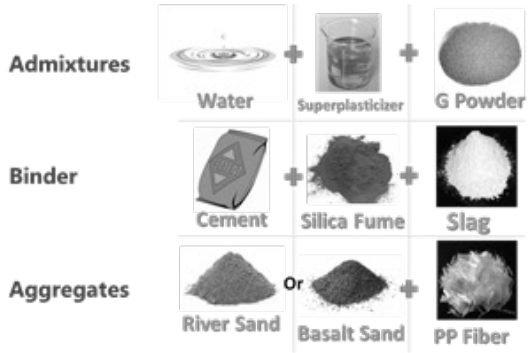
SYSTEMS DESIGN



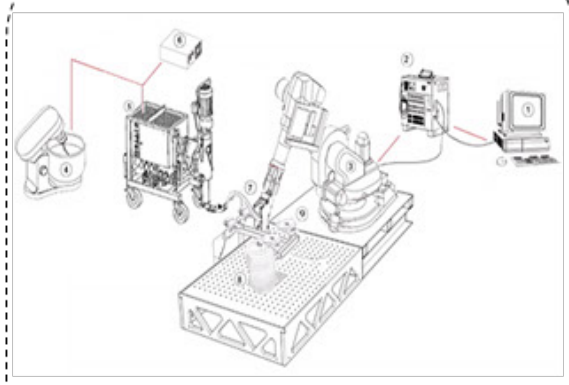
TOOLPATH DESIGN



MATERIAL DESIGN



PRODUCTION DESIGN



NREL ICI Efforts

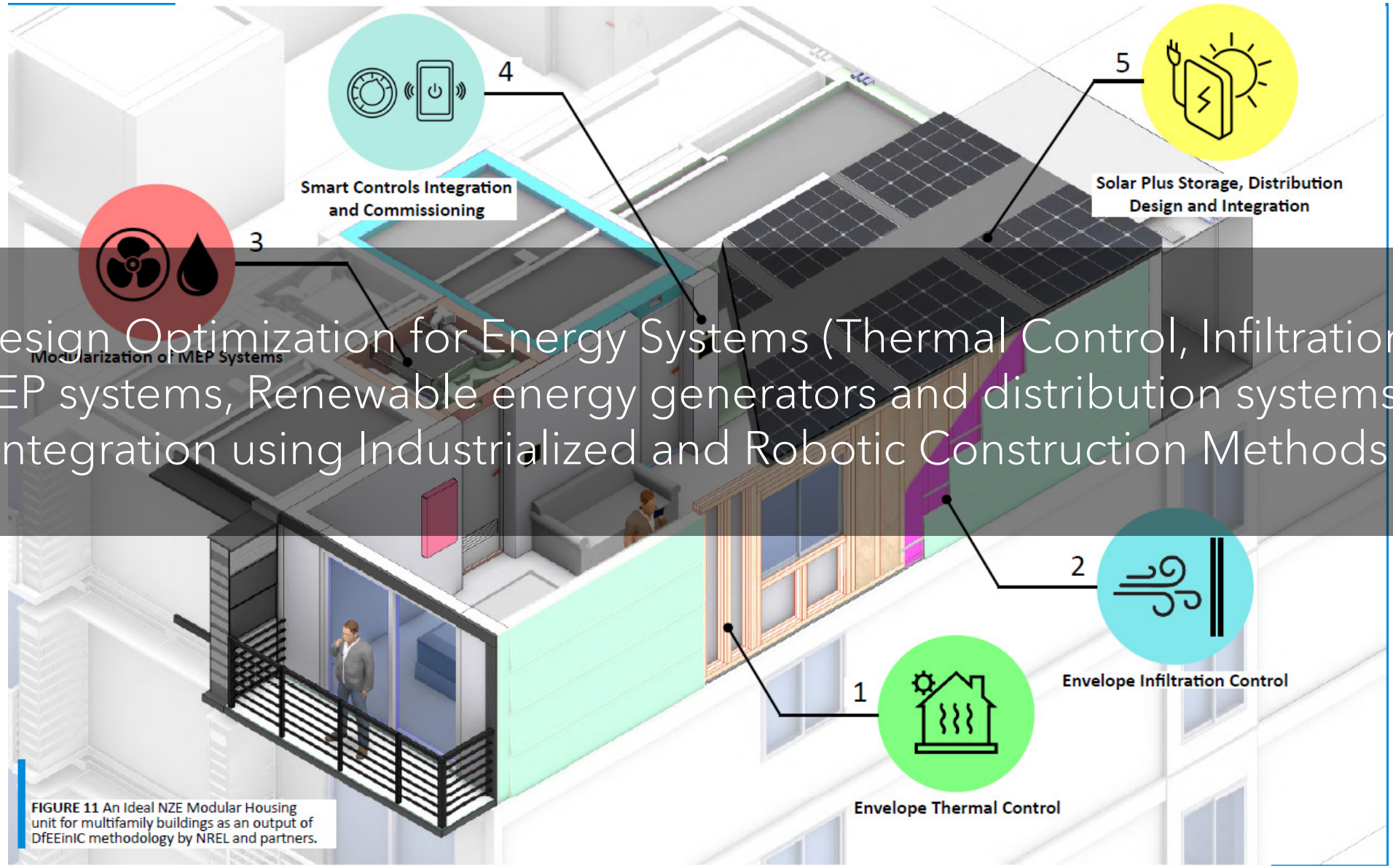


FIGURE 11 An Ideal NZE Modular Housing unit for multifamily buildings as an output of DfEEinIC methodology by NREL and partners.

Building Design Optimization for Energy Systems (Thermal Control, Infiltration Control, MEP systems, Renewable energy generators and distribution systems) Integration using Industrialized and Robotic Construction Methods

NREL ICI Efforts – Product Optimization

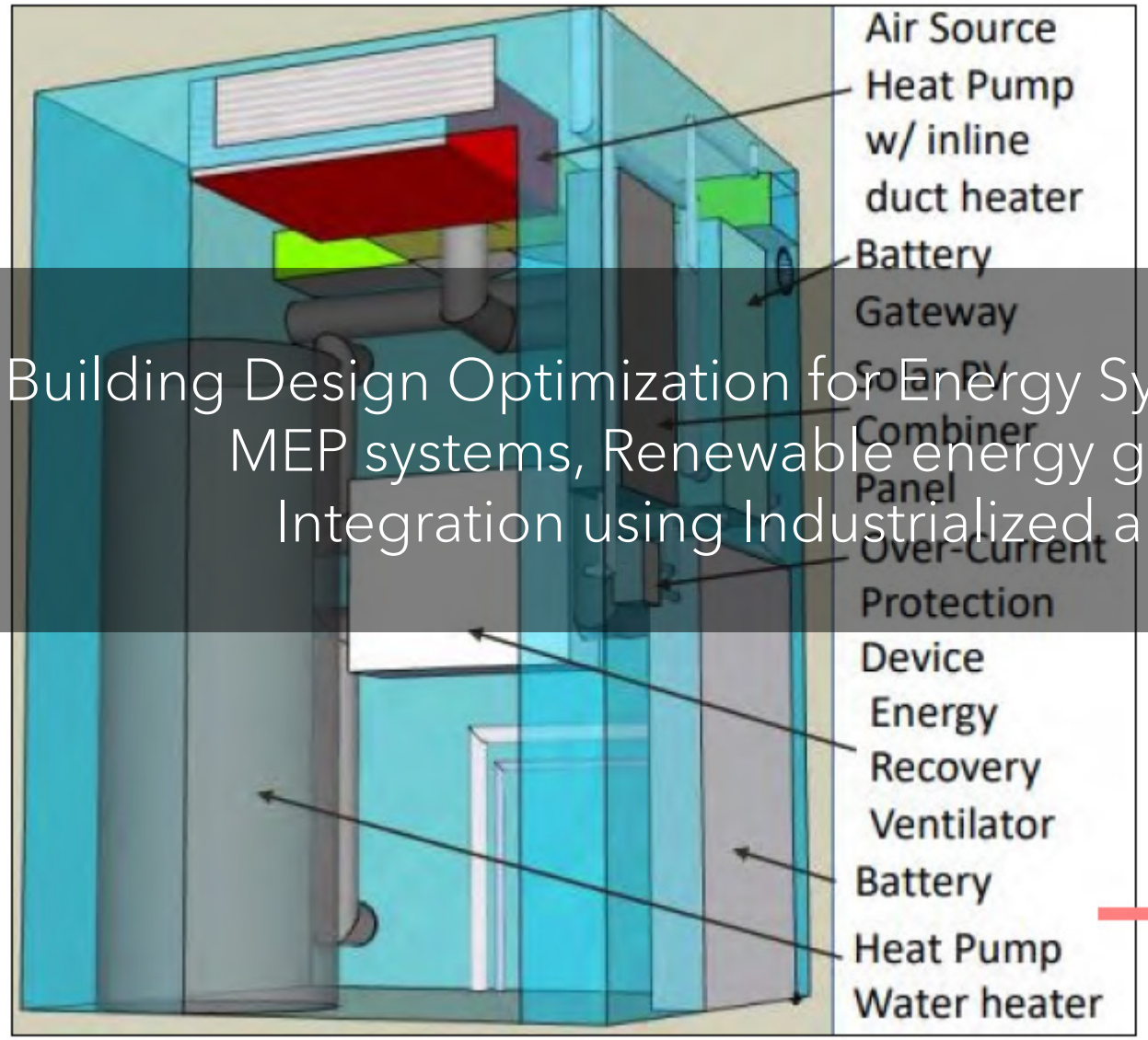


FIGURE 30 Illustrating 3D design of VEIC's Mechanical Pod for ZEM homes.

Building Design Optimization for Energy Systems (Thermal Control, Infiltration Control, MEP systems, Renewable energy generators and distribution systems) Integration using Industrialized and Robotic Construction Methods

NREL ICI Efforts – Process Optimization

Modelling and Simulation Efforts – Factory Information Model
Industry Partner : KBS Factory

NREL ICI Efforts – Deployment Optimization

Onsite Installation Process Optimization for Energy Systems Integration

Preparing to load the model...

NREL ICI Efforts – Robotic Technology Development

E-ROBOT Prize Winners

Phase 1 Winner

Apellix Aerial Robotics Spray Painting ...
Drone for Applying Multifunctional Control Lay...

Avideh Zakhor's team
Drone thermography for Building Envelope Retr...

Avideh Zakhor's team
Robotic system for air sealing /insulating attics

Friendly Robots Company
The Mayfly and the Aardvark

FunForm
Robotic Assisted Exterior Insulated Finish Syste...

NU Team PARIS
Precise Air-sealing Robot for Inaccessible Spa...

NYU E-ROBOT
EASEEbot

Team F.G.S. - Revolutionizing Robotic R...
Team F.G.S. - Revolutionizing Robotic Retrofits

Team R-STRIPE
The R-STRIPE Deep Energy Retrofit System

wall-EIFS
wall-EIFS

DOE E-Robot Prize TA – Robots for Energy Systems Integration In Buildings

Grand Prize Winner

Avideh Zakhor's team
RoboAttic

Friendly Robots Company
The Mayfly and the Aardvark

Team F.G.S. - Revolutionizing Robotic R...
Unified Retrofits - Holistic Robotic Retrofits

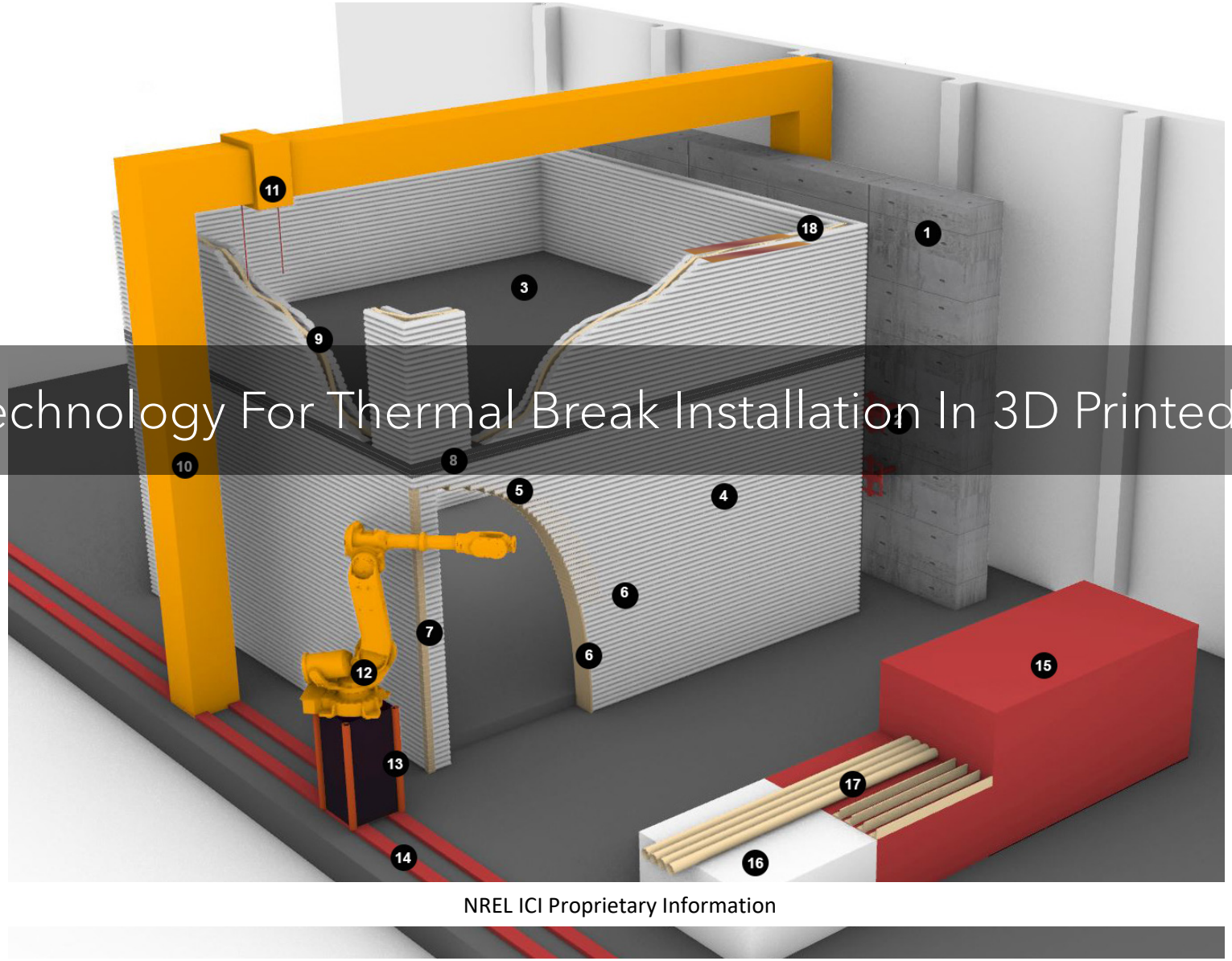
67
Teams

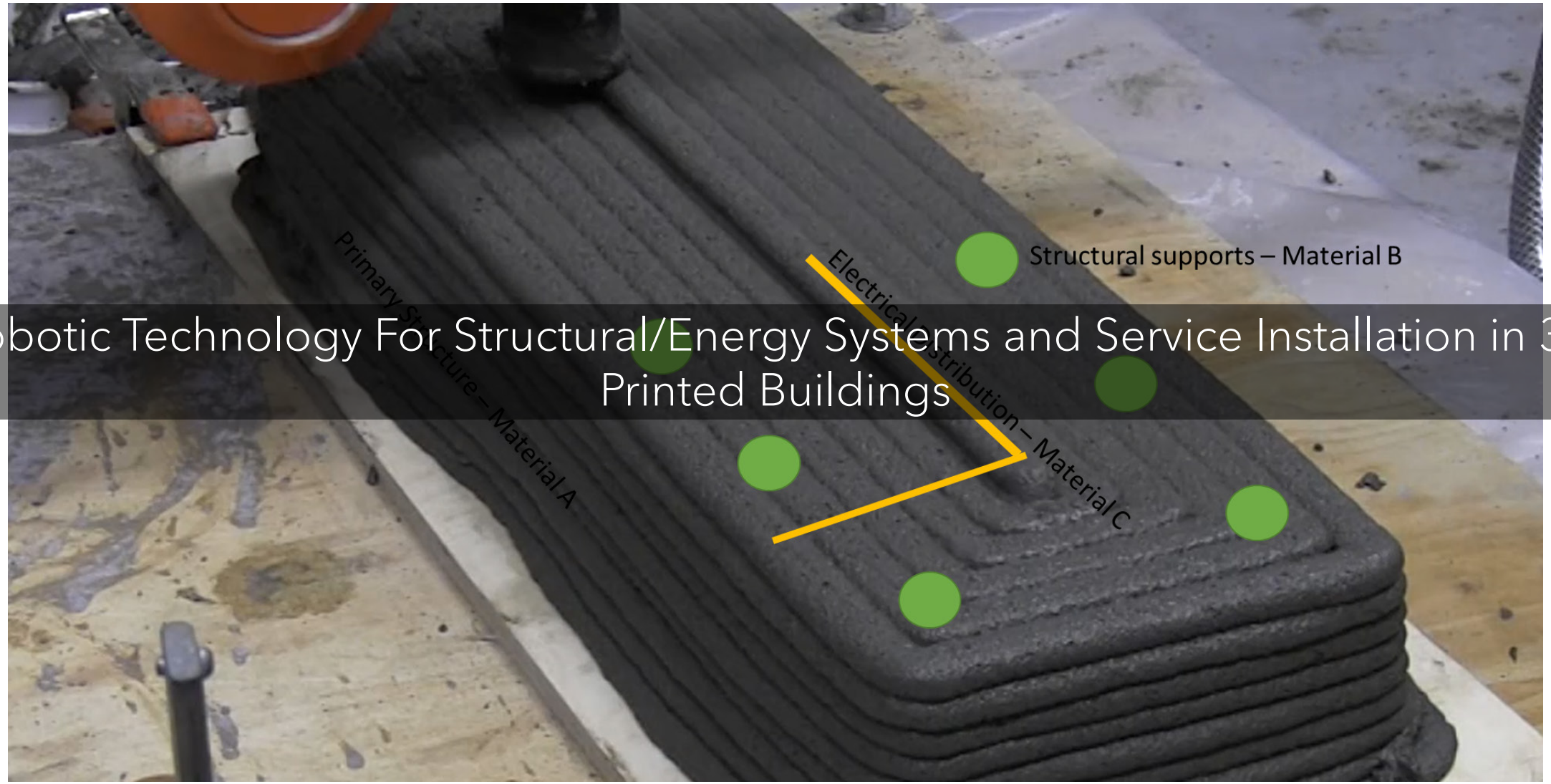
434
Innovators

Source: https://www.herox.com/EROBOT/teams

NREL ICI Efforts – Robotic Technology Development

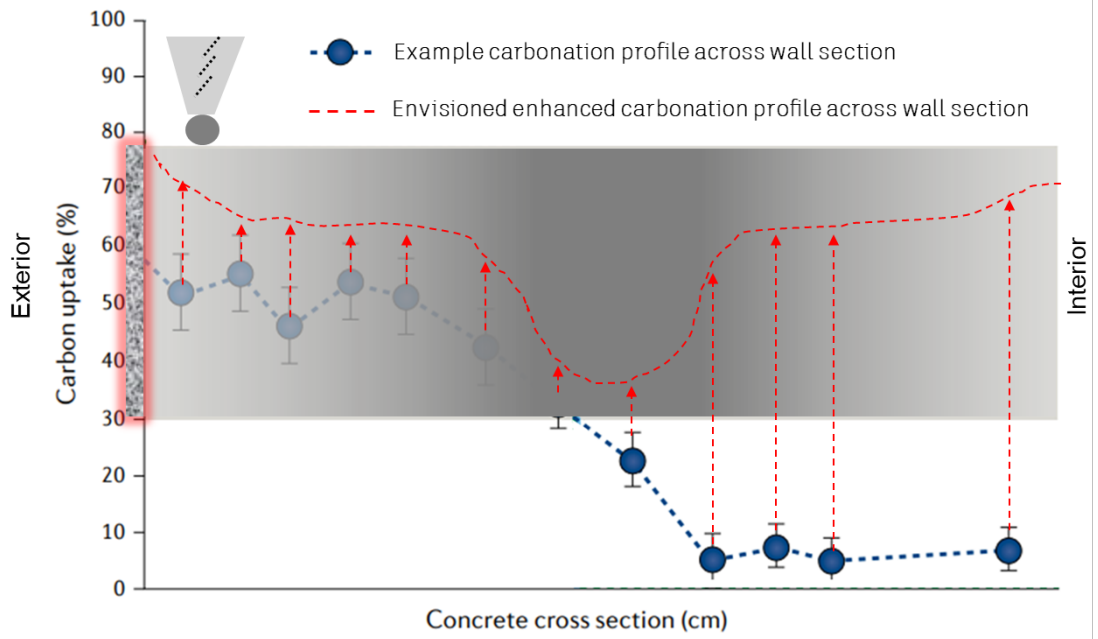
Robotic Technology For Thermal Break Installation In 3D Printed Buildings





Robotic Technology For Structural/Energy Systems and Service Installation in 3D Printed Buildings

NREL ICI Efforts – Robotic Technology Development



Functionally graded 3D printing to increase porosity

- Increased porosity near wall surface for increased CO2 uptake
- Gradual densification in middle for structural load bearing

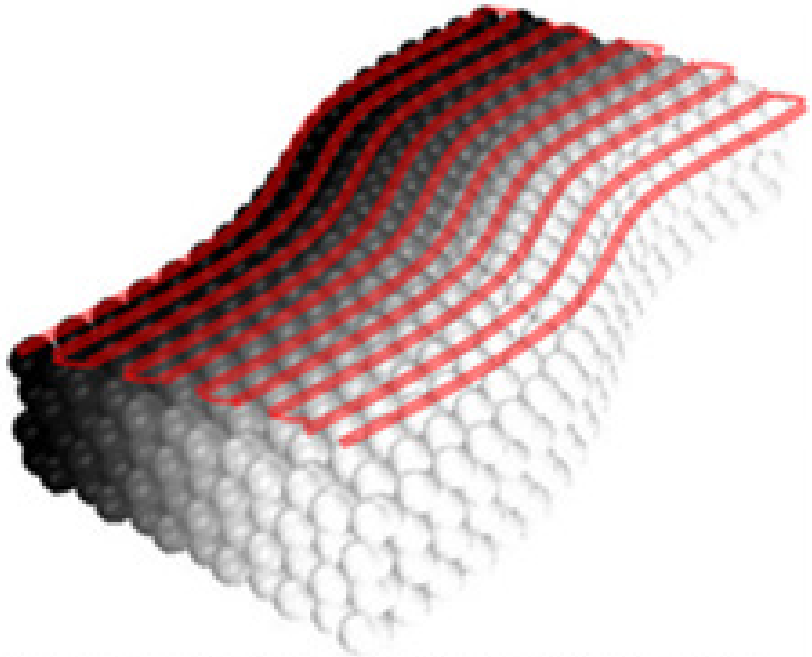
Demolition waste spray

- Increased SA
- Increased Carbonation
- Increased CO2 uptake

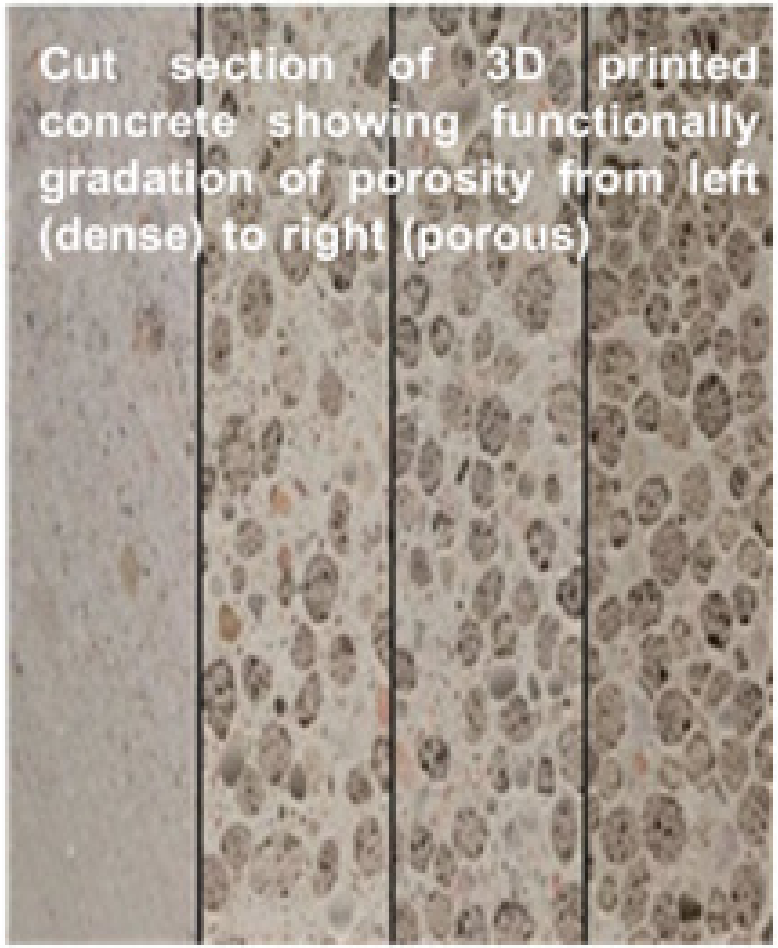
Short fiber reinforcement using rotational 3D printing that

- can act as chemically passive structural reinforcement
- is suitable to be infused within extrudable concrete paste

Robotic Deposition Technology To Control Microstructure of Concrete in 3D Printed Walls for Increased CO2 Uptake



CAD model of toolpath (red) for functionally graded concrete (gradation indicated with color)



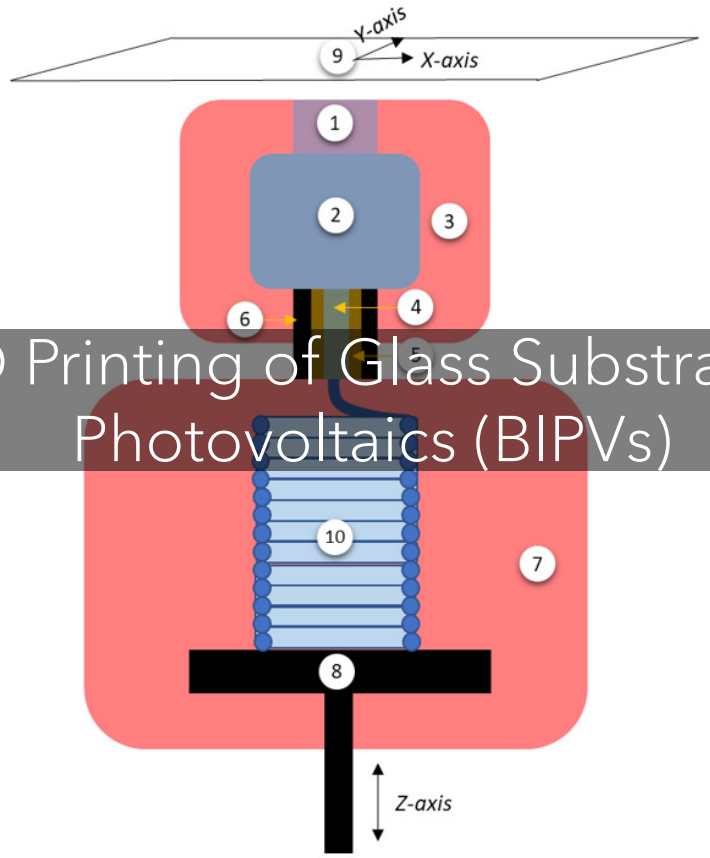
Accelerates Carbonation

Robotic Deposition Technology To Control Microstructure of Concrete in 3D Printed Walls for Increased CO2 Uptake

NREL ICI Efforts – Robotic Technology Development

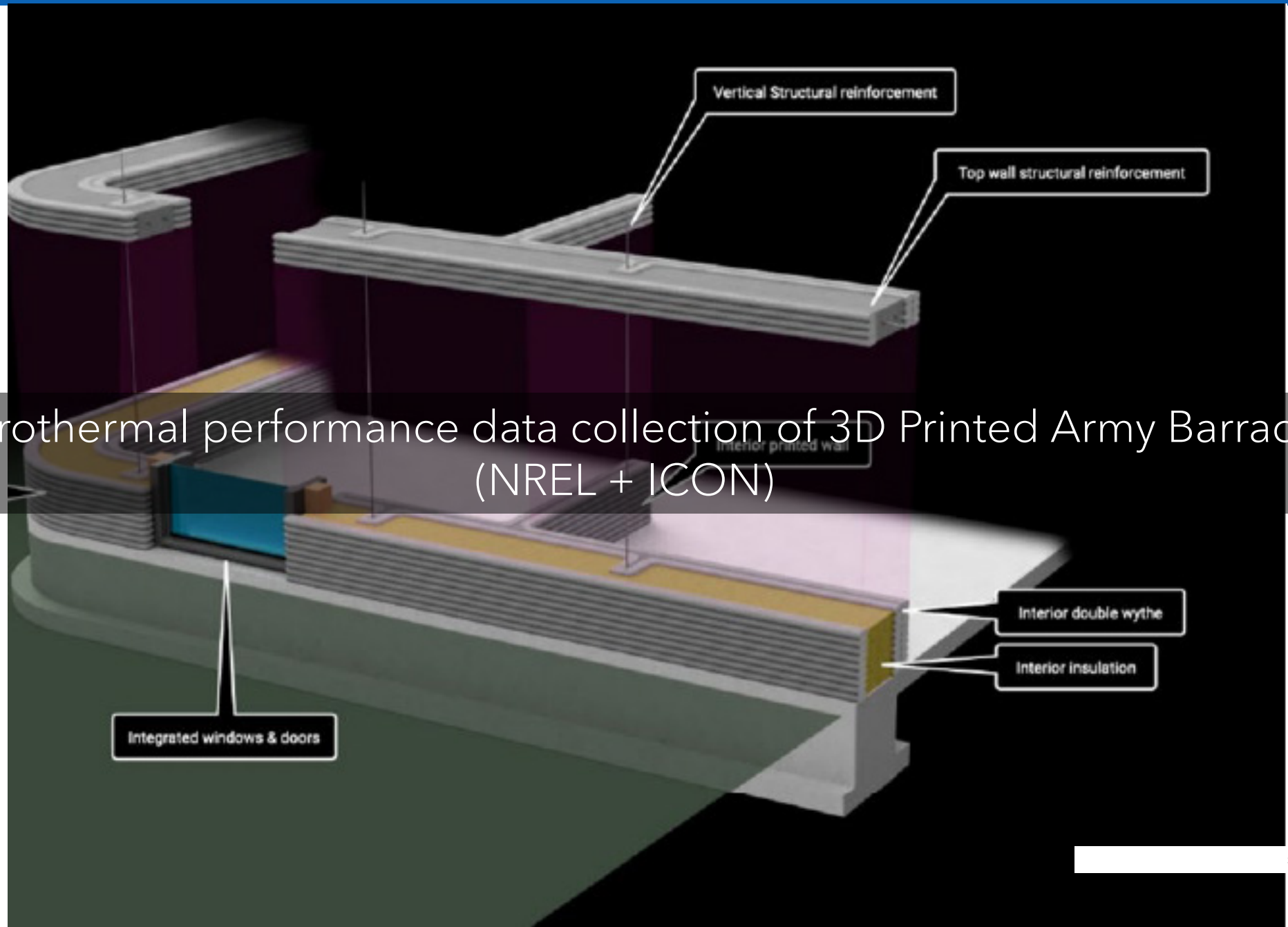
Robotically Controlled Electron Beam for Accelerated Curing Cementitious Materials in 3D Printing (Argonne + Fermi Lab + NREL)

NREL ICI Efforts – Robotic Technology Development



Robotically Controlled 3D Printing of Glass Substrates for Building Integrated Photovoltaics (BIPVs)

NREL ICI Efforts – Building Performance Assessment in Extreme Weather



Hygrothermal performance data collection of 3D Printed Army Barracks (NREL + ICON)

Source: https://austonia.com/icon-camp-swift

NREL ICI Efforts – Building Performance Assessment in Extreme Weather

Ongoing discussions about a potential project to 3D Print test house for Nome community in Alaska with emphasis on hygrothermal aspects of 3D printed buildings in extreme climates (permafrost conditions, extreme temperature gradients)

NREL ICI Capabilities

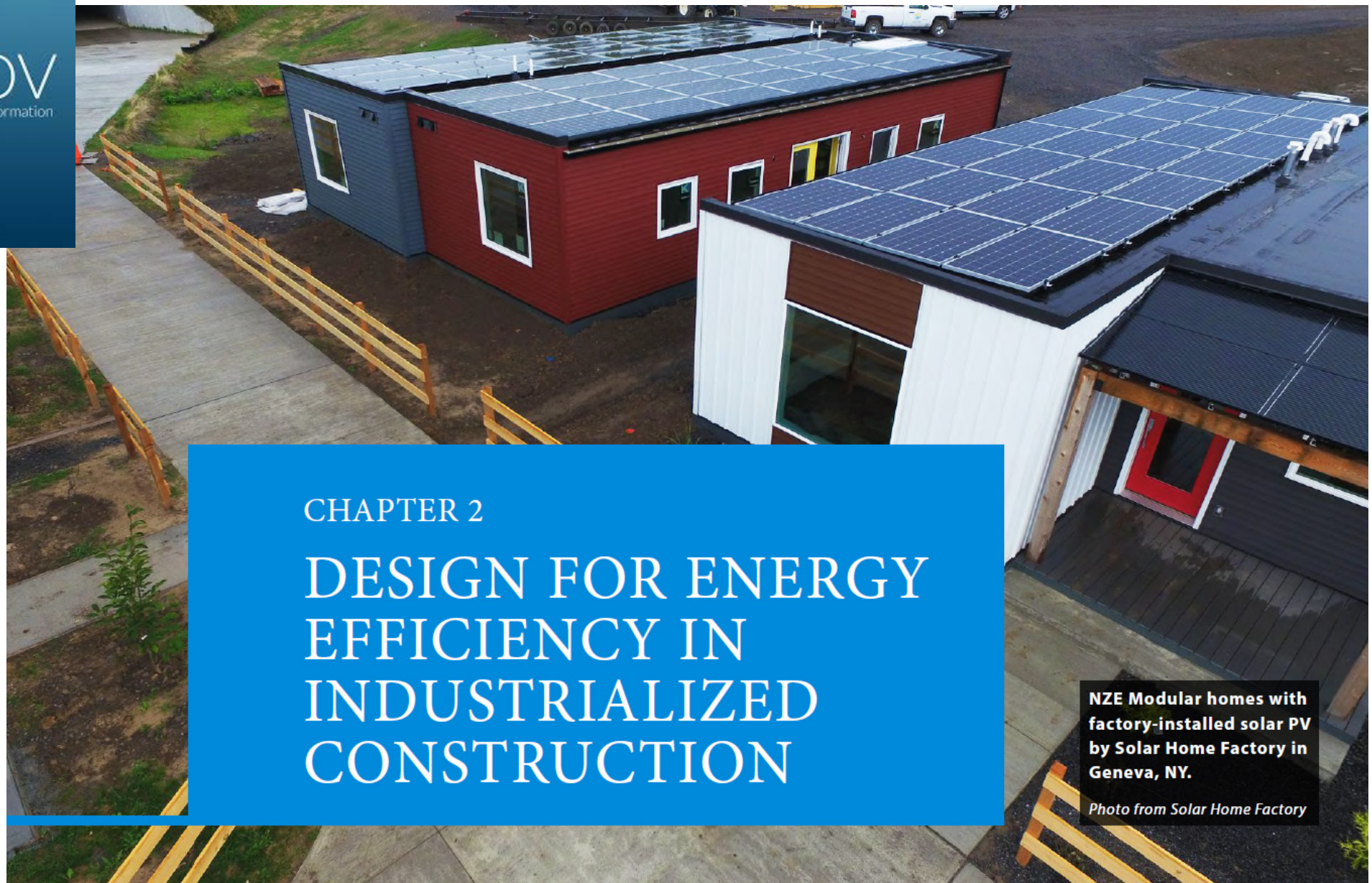
Larger industrial robot at Composite Manufacturing and Engineering Technology (CoMET) facility of NREL

Smaller industrial COBOT for small scale testing – Building Systems Outfitting – autonomous Pick and Place

NREL ICI Capabilities

NREL Capabilities

OSTI.GOV
Office of Scientific and Technical Information



CHAPTER 2

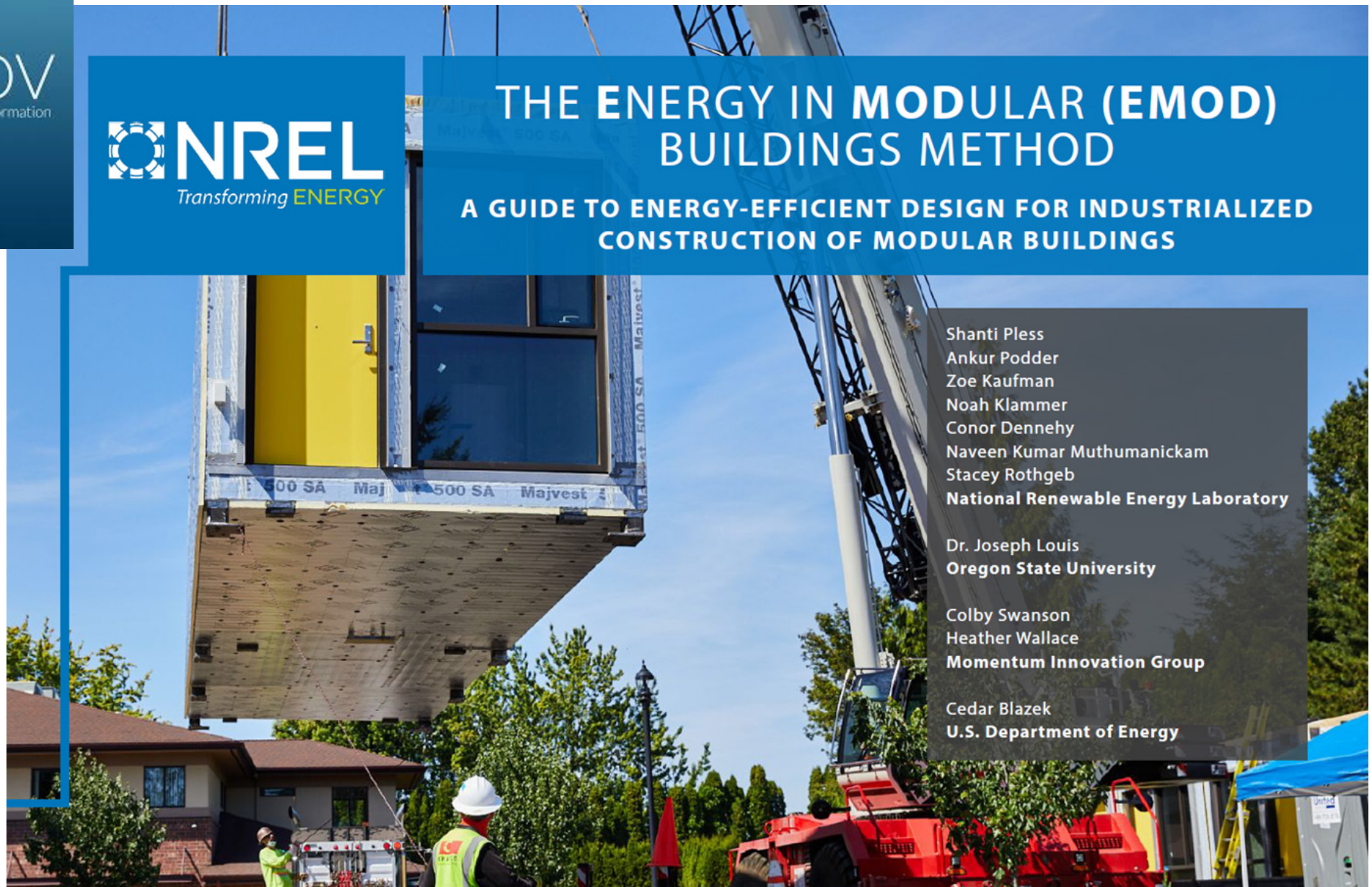
DESIGN FOR ENERGY EFFICIENCY IN INDUSTRIALIZED CONSTRUCTION

NZE Modular homes with factory-installed solar PV by Solar Home Factory in Geneva, NY.

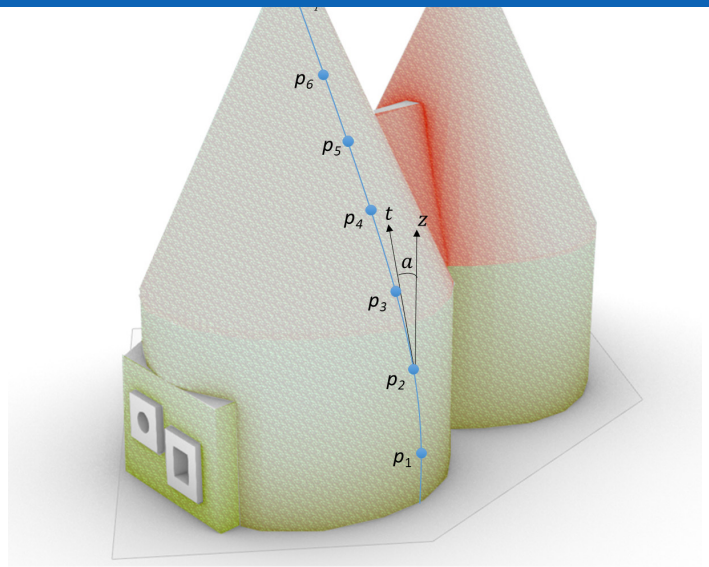
Photo from Solar Home Factory

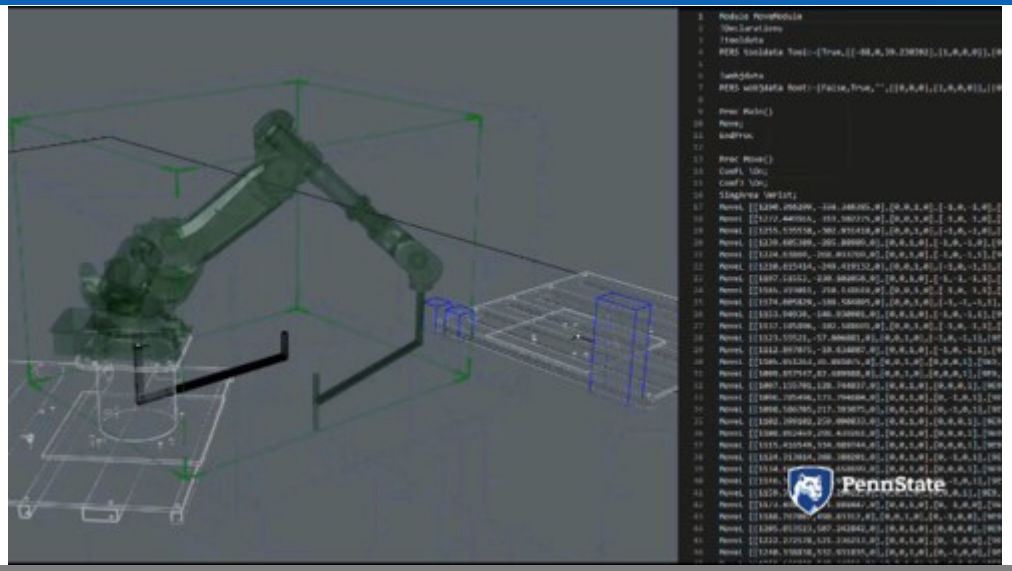
NREL ICI Publications

OSTI.GOV
Office of Scientific and Technical Information

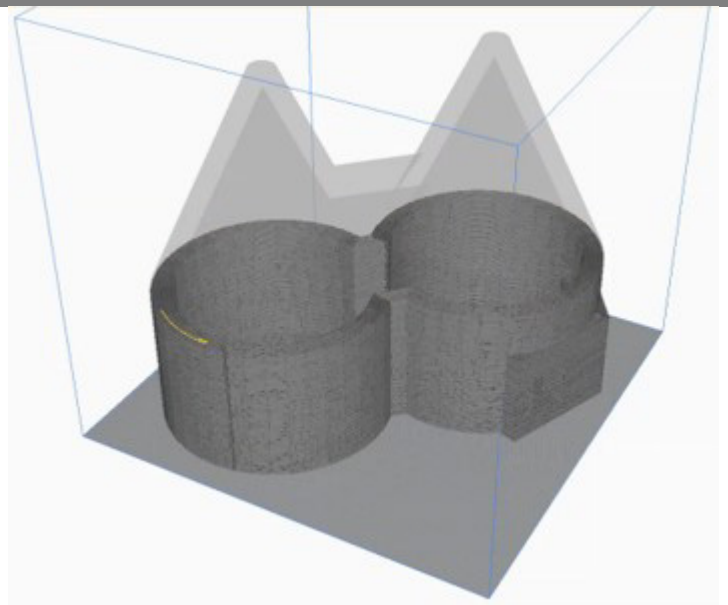


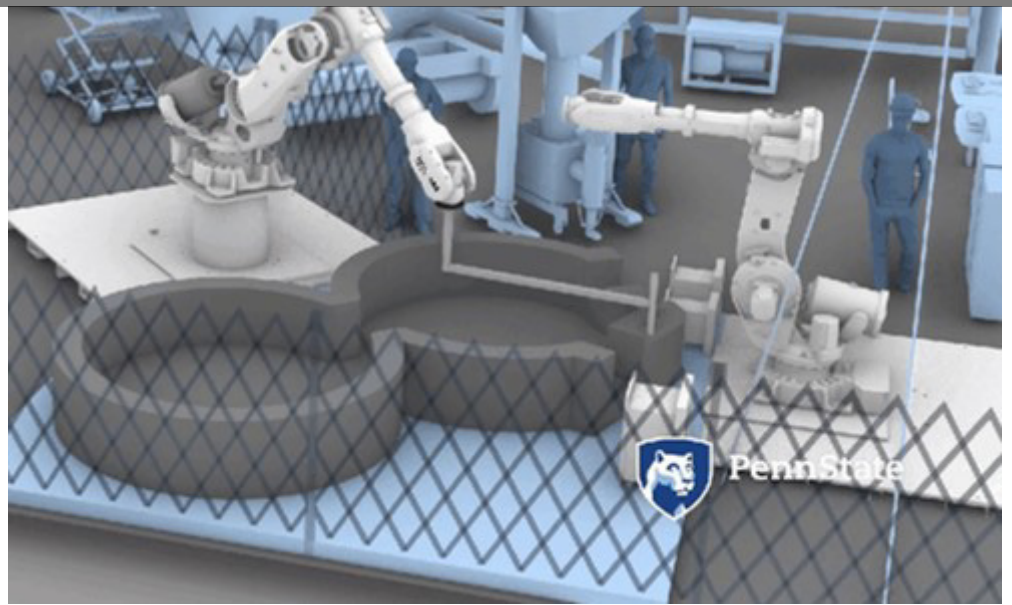
NREL ICI Publications





Muthumanickam, N.K., Duarte, J.P., Nazarian, S., Bilén, S. G., & Memari, A. (2022). Metamodels for rapid analysis of large sets of building designs for robotic constructability: Technology demonstration using the NASA 3D Printed Mars Habitat Challenge. In Proceedings of the American Society of Civil Engineers Earth & Space Conference, ASCE Earth & Space 2022. April 25-28, 2022. Denver, CO. https://learn.mines.edu/earthspace2022/

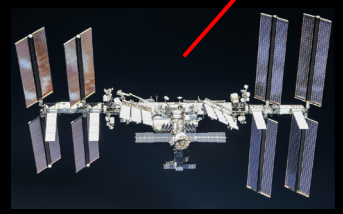




Terrestrial Vs Extra Terrestrial Construction

Building on extra-terrestrial bodies

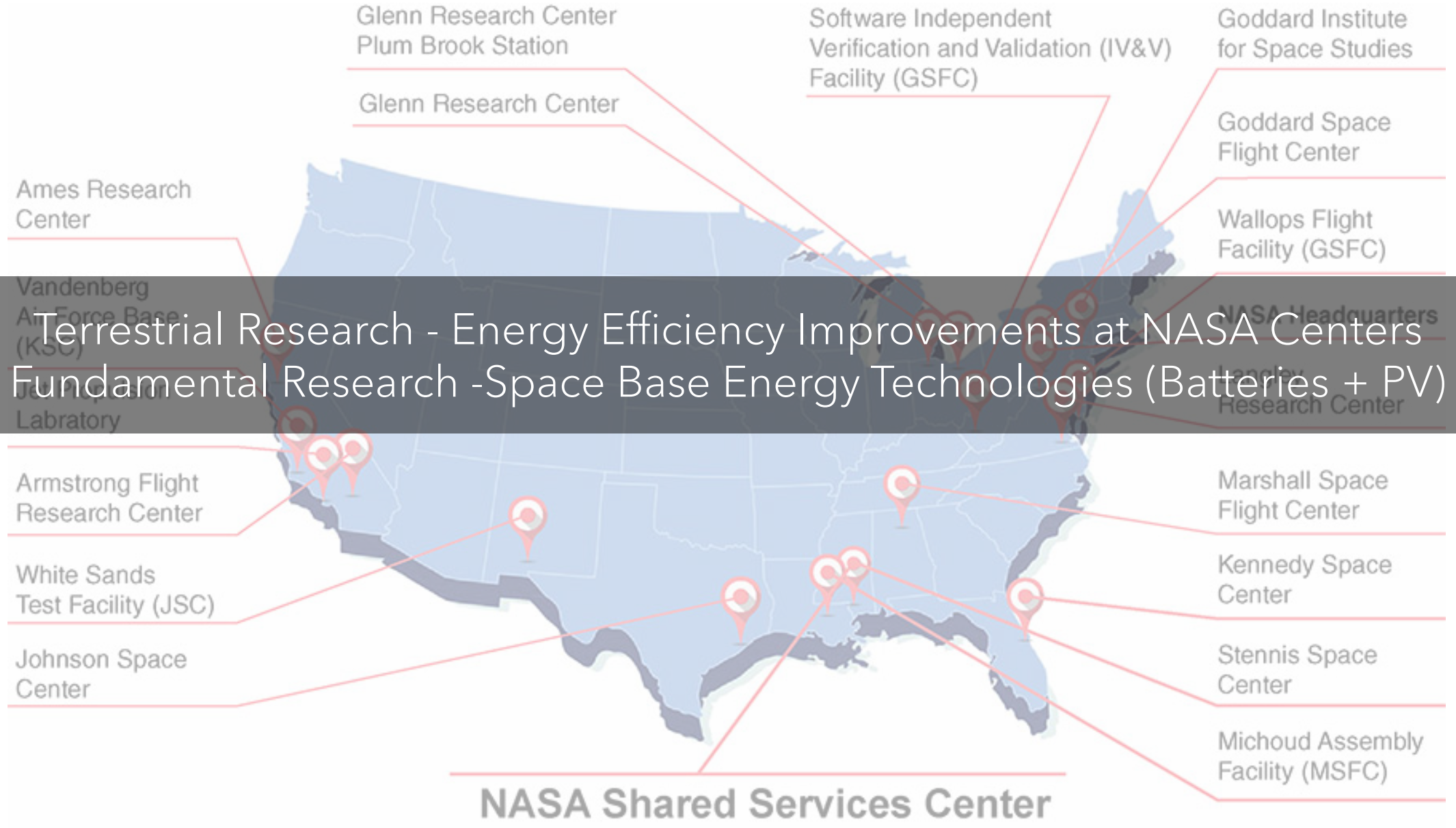
a system of systems that are functional
-structurally stable
-energy efficient
-thermally efficient
-habitable**
-remotely constructable
-easily deployable
-remotely controllable



Building in orbital space
a system of systems that are functional
-structurally stable
-energy efficient
-thermally efficient
-habitable**
-easily deployable (or assembly)
-remotely controllable

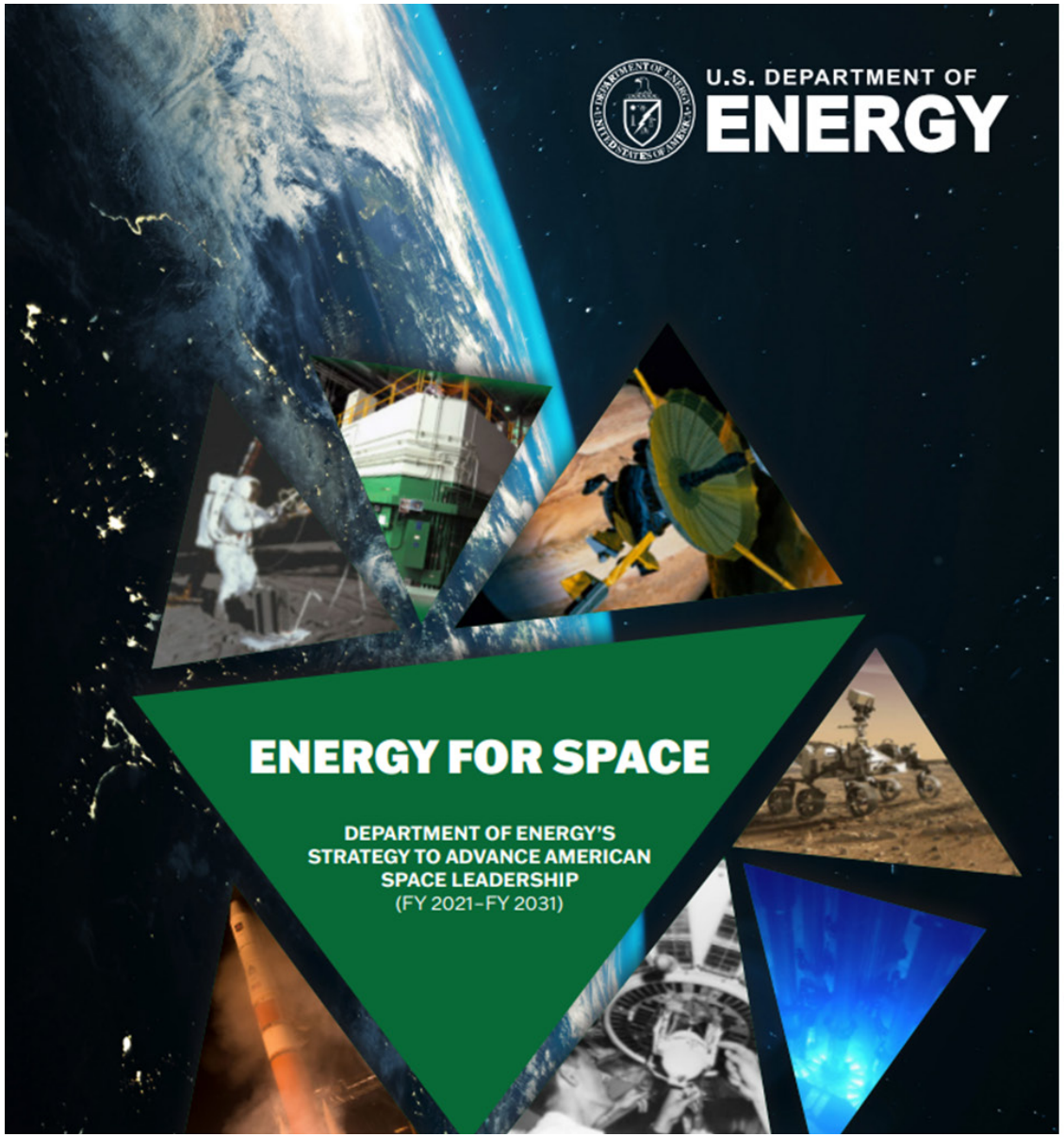
Building on Earth
a system of systems that are functional
-structurally stable
-energy efficient
-thermally efficient
-habitable**
-rapidly constructable

Past Collaborations - DOE/NREL + NASA



Terrestrial Research - Energy Efficiency Improvements at NASA Centers
Fundamental Research -Space Base Energy Technologies (Batteries + PV)

Future Avenues – DOE for Space



Source: https://www.energy.gov/sites/prod/files/2021/01/f82/Energy%20for%20Space-DOE%20Space%20Strategy%20Paper%2001-06-2021.pdf

S&T Capacity. As the largest sponsor of basic scientific research and development (R&D), DOE has built a diverse community of interdisciplinary S&T talent within the complex of National Laboratories and throughout U.S. colleges and universities. This world-leading S&T expertise can be brought to bear on answering the most difficult challenges facing U.S. space missions.

- **R&D Infrastructure**. DOE supports the world's most advanced and unique scientific facilities. These facilities support researchers both in the United States and abroad in advancing our understanding of the universe, from the subatomic scale to the cosmic scale. The discoveries made possible by these facilities push the boundaries of human knowledge across many scientific disciplines.
- **Emerging/Innovative Capabilities**. DOE provides expert knowledge and world-leading capabilities in nuclear and non-nuclear energy technologies, artificial intelligence (AI) and robotics, high-speed information technology, advanced manufacturing, microelectronics, materials for extreme environments, radiation science, isotope production, and a host of other areas. This engine of discovery can power crewed missions to the Moon and beyond, as well as pave the way for human habitats and a sustained presence on the surface of other planetary bodies.
- **Technology Commercialization**. DOE is one of the largest supporters of technology transfer in the federal government. Thus, DOE's R&D investments can aid in accelerating the commercialization and industrialization of space, forge new capabilities for sustainable expansion into the solar system, and provide benefits for life on Earth.

Future Avenues – NASA/NREL ICI Similarities in Areas of Research

NASA's MMPACT

NREL ICI Focus Areas

Offsite Prefabrication of Building Systems

- Heating Systems
- Cooling Systems
- Energy Generators
- Energy Storage
- Energy Distribution

Building Retrofit automation

- Envelope
- Thermal
- Energy
- Renewables

Robotic Automation in Construction

- Hygrothermal control layer installation
- Energy Generator Installation
- Energy Storage systems Installation
- Energy Distribution Systems Installation

Non-destructive evaluation of Buildings

- Sensors for multi-modal data collection of hygro-thermal and energy performance of buildings.
- Autonomous robots for remote monitoring of building energy systems
- Digital twins

Recycling

- Circular Economy Strategies
- BIM based serialization of construction assets for material tracking
- Material Flow tracking using supply chain tools like CELAVI/MFI

Future Avenues – NASA + NREL ICI Collaboration

Process Simulation Of Robotics For Systems Integration/Outfitting In Buildings

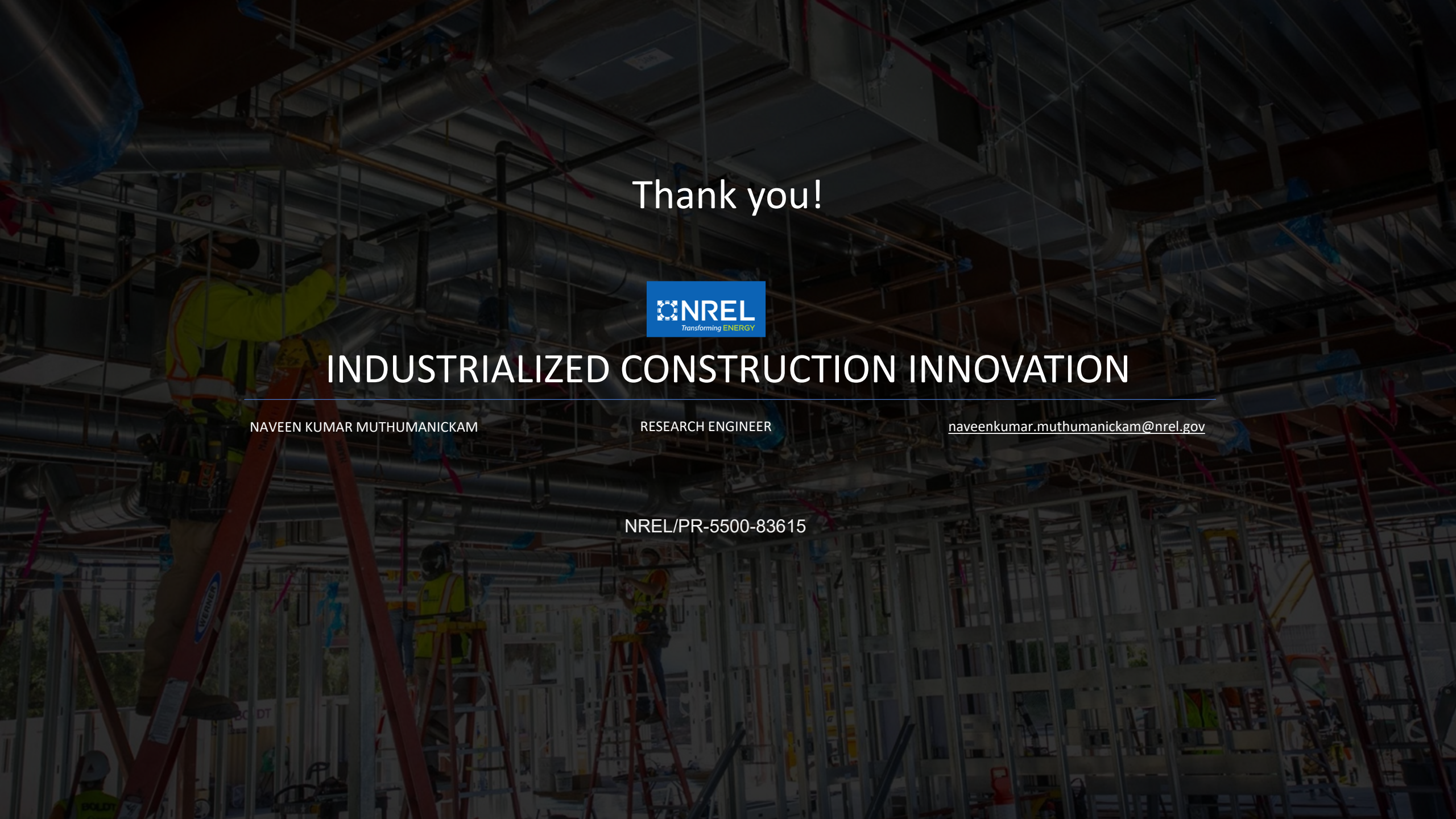
Computational simulation of robots performing control layer, energy systems and services installation

Robotic Technologies For Outfitting Of Buildings

Robotic technology development to install hygrothermal control layers in envelopes, energy generation, distribution and storage systems

Autonomous Non-destructive Evaluation of Buildings

Autonomous robots and sensor technologies to evaluate thermal, hygrothermal and energy performance of buildings using multi-modal data collection and digital twins



Thank you!

INDUSTRIALIZED CONSTRUCTION INNOVATION

NAVEEN KUMAR MUTHUMANICKAM RESEARCH ENGINEER naveenkumar.muthumanickam@nrel.gov

NREL/PR-5500-83615