Intro

Please contact NaveenKumar.Muthanickam@nrel.gov for the PowerPoint version of this presentation.
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)
NREL's goal is to deliver a **ZERO CARBON ECONOMY (*2050)** through research, innovation and strategic partnerships.

NREL’s 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 NREL’s BTP focuses on developing technologies to enable **ADVANCED BUILDING CONSTRUCTION (ABC)** to accelerate the decarbonization of the U.S. buildings sector.
National Renewable Energy Lab (NREL) in Colorado

Cold Climate Housing Research Center (CCHRC) in Alaska
Efficient, Functional, Affordable, and Appealing

Volume at speed \(\rightarrow\) \textbf{(Quality) volume at (optimal) speed}

Efficient production through industrialization and robotic automation

new buildings and retrofits
Background

Traditional Construction

Industrialized Construction Innovation

Computational Capabilities

Modelling and simulation capabilities to support

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

Demonstration Capabilities

Testing and demonstration capabilities to support

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

Traditional Construction

Industrialized Construction

Offsite Prefabrication

- 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

Onsite Automation

- Retrofitting
  - Navigating & Scanning
  - Material Handling
  - Manipulation
Background

MODES OF ROBOTIC CONSTRUCTION

- Industrial Robotic Arms
- Rovers
- Quadrupedals
- Drones
HABITABLE BUILDINGS = FUNCTIONAL BUILDINGS
Background

Building as a system of systems

- Years of development
- Standardized
- Standardized components

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

Trends

BUILDINGS: COMPLEX MULTI-SYSTEM ASSEMBLIES

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

INDUSTRIALIZED CONSTRUCTION: BUILDING COMPONENT PRODUCTION

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

INDUSTRIALIZED CONSTRUCTION: BUILDING ASSEMBLIES

Source: https://www.asti.com/productization-a-vision-for-industrialized-construction/
INDUSTRIALIZED CONSTRUCTION: ONSITE ASSEMBLIES

INDUSTRIALIZED CONSTRUCTION: IN-SITU CONSTRUCTION

Source: https://www.popularmechanics.com/technology/infrastructure/a26252/3d-printer-build-house-eml/
INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

Trends

INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

Source: https://www.youtube.com/watch?v=jA9lJDZuYNk
INDUSTRIALIZED CONSTRUCTION: ONSITE AUTOMATION

Source: https://www.youtube.com/watch?v=qBu2cK5RA
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

Trends

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

**THIN ATMOSPHERE**
**COLD TEMPERATURES**
**LOW GRAVITY**
↑Structural performance
↑Complex Robotic Maneuvers
↑Robotic vibrations at turns
↑Concrete deformation (Less shape accuracy)

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)

Challenges:
- Over-extrusion at edges/corners/ junctions

Design Variables:
- Fillet radius at edges/corners/junctions
- Robot speed at corners

TRUCK WITH EQUIPMENT ARRIVES

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

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

Offsite Production Process Optimization for Energy Systems Integration
Onsite Installation Process Optimization for Energy Systems Integration

Preparing to load the model...
### E-ROBOT Prize Winners

<table>
<thead>
<tr>
<th>Phase 1 Winner</th>
<th>Avideh Zakhor’s team</th>
<th>Avideh Zakhor’s team</th>
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<tbody>
<tr>
<td>Apellix Aerial Robotics Spray Painting...</td>
<td>Drone thermography for Building Envelope Retr...</td>
<td>Robotic system for air sealing /insulating attics</td>
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<tr>
<td>Drone for Applying Multifunctional Control Lay...</td>
<td><a href="#">FunForm</a></td>
<td>NU Team PARIS</td>
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<tr>
<td>Friendly Robots Company</td>
<td>Robotic Assisted Exterior Insulated Finish Syste...</td>
<td>Precise Air-sealing Robot for Inaccessible Sp...</td>
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<td>The Mayfly and the Aardvark</td>
<td>Team F.G.S. - Revolutionizing Robotic R...</td>
<td>Team R-STRIVE</td>
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<td>NYU E-ROBOT</td>
<td>Team F.G.S. - Revolutionizing Robotic R...</td>
<td>The R-STRIVE Deep Energy Retrofit System</td>
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<tr>
<td>EASEbot</td>
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**DOE E-Robot Prize TA - Robots for Energy Systems Integration In Buildings**

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- **67 Teams**
- **434 Innovators**

Source: [https://www.herox.com/E-ROBOT/teams](https://www.herox.com/E-ROBOT/teams)
Robotic Technology For Thermal Break Installation In 3D Printed Buildings
Robotic Technology For Structural/Energy Systems and Service Installation in 3D Printed Buildings
Robotic Deposition Technology To Control Microstructure of Concrete in 3D Printed Walls for Increased CO2 Uptake

- Example carbonation profile across wall section
- Envisioned enhanced carbonation profile across wall section

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
Robotically Controlled Electron Beam for Accelerated Curing Cementitious Materials in 3D Printing (Argonne + Fermi Lab + NREL)
Robotically Controlled 3D Printing of Glass Substrates for Building Integrated Photovoltaics (BIPVs)
Hygrothermal performance data collection of 3D Printed Army Barracks (NREL + ICON)
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)
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
CHAPTER 2

DESIGN FOR ENERGY EFFICIENCY IN INDUSTRIALIZED CONSTRUCTION
THE ENERGY IN MODULAR (EMOD) BUILDINGS METHOD
A GUIDE TO ENERGY-EFFICIENT DESIGN FOR INDUSTRIALIZED CONSTRUCTION OF MODULAR BUILDINGS

Shanti Pless
Ankur Podder
Zoe Kaufman
Noah Klammer
Conor Dennehy
Naveen Kumar Muthumanickam
Stacey Rothgeb
National Renewable Energy Laboratory
Dr. Joseph Louis
Oregon State University
Colby Swanson
Heather Wallace
Momentum Innovation Group
Cedar Blazek
U.S. Department of Energy
Terrestrial Vs Extra Terrestrial Construction

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

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 extra-terrestrial bodies
a system of systems that are functional
-structurally stable
-energy efficient
-thermally efficient
-habitable**
-remotely constructable
-easily deployable
-remotely controllable
Past Collaborations - DOE/NREL + NASA

Terrestrial Research - Energy Efficiency Improvements at NASA Centers

Fundamental Research - Space Base Energy Technologies (Batteries + PV)
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**

**In Situ Fabrication and Repair**

**HABITAT STRUCTURES**
- Prefabricated structures
- Thermal, hygrothermal, and energy performance
- Automated installation

**NON-DESTRUCTIVE EVALUATION**
- Capabilities with the following features:
  - Rapid and accurate
  - Non-destructive
  - Automated

**RECYCLING**
- Capabilities with the following features:
  - Rapid and accurate
  - Non-destructive
  - Automated

**SYSTEM OF SYSTEMS / APPLICABILITY AND CONSIDERATION**
- Interoperability between ISFR, Prefabrication, Automation, and ISFR concepts

**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!

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INDUSTRIALIZED CONSTRUCTION INNOVATION

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