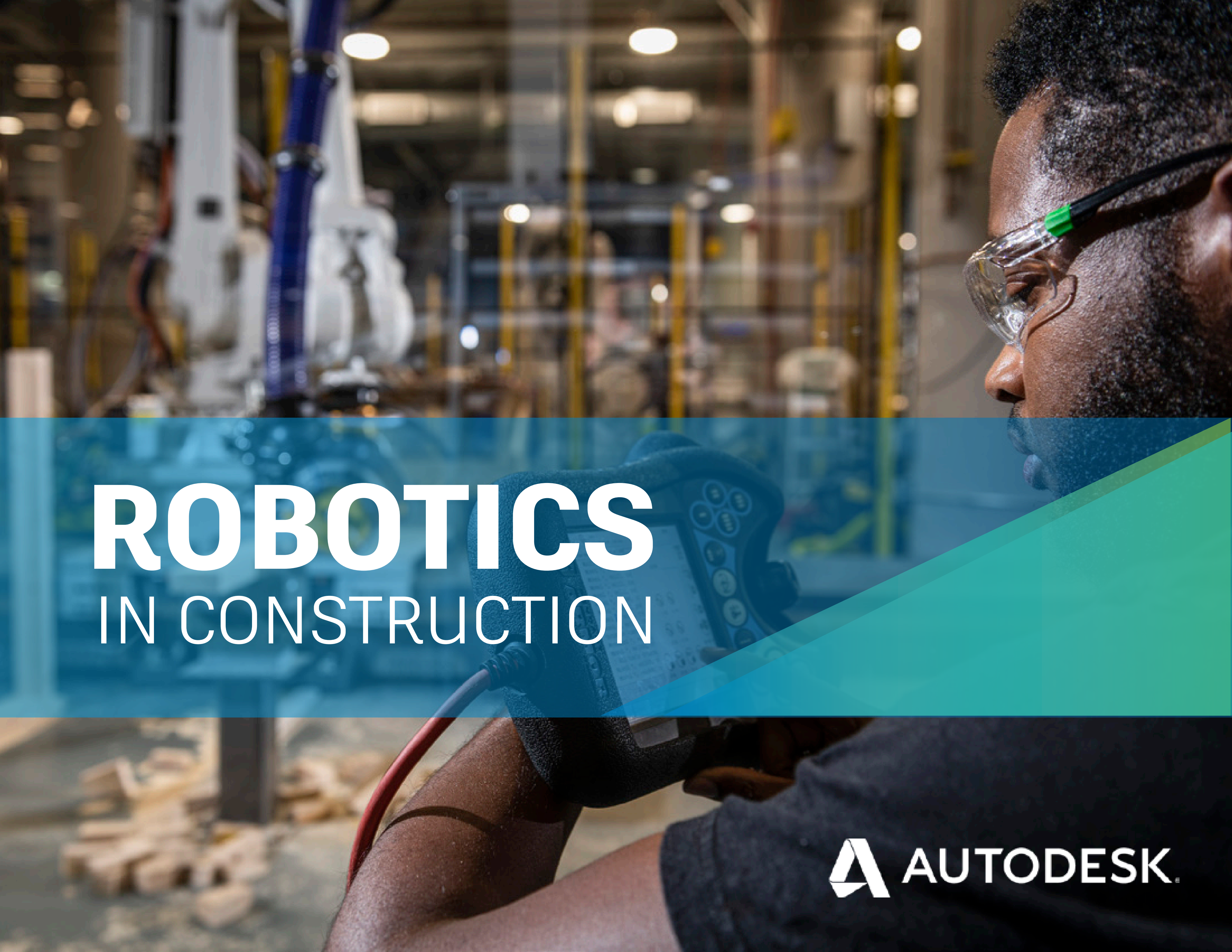
ROBOTICS
IN CONSTRUCTION



AUTODESK

INTRODUCTION

A BRIEF HISTORY OF AUTOMATION IN CONSTRUCTION

While some may think using robotics in construction is a new development, it is actually the continuation of a larger story about automation in construction that goes back thousands of years. The Terracotta Army, a collection of terracotta sculptures depicting the armies of China's first emperor, Qin Shi Huang, and buried with the emperor in his necropolis, utilized offsite construction and prefabrication techniques when built in 210 BCE. More recently, the past century has had a number of attempts at industrializing construction, from the Sears Modern Home, a catalog and kit house sold by Sears, Roebuck, and Company through mail order, shipped by railroad boxcar and assembled on-site, to Lustron houses, prefabricated enameled steel houses developed in the post-World War II era United States in response to the shortage of homes for returning GIs. The late 1970s and 80s saw a rich period of industry-driven development, particularly in Japan. Facing fears of a labor shortage due to an aging population and younger workers flocking into high-tech industries (fears still relevant today), a number of Japanese companies such as Shimizu Corporation and Takenaka Corporation invested in construction automation and robotics to great effect, developing robots and remotely-controlled devices used for all sorts of tasks, including material handling, excavation, concrete placement, concrete finishing, rebar placement, fireproofing, structural steel, interior and exterior finishing, earthworks, as well as integrated construction automation systems and prefabricated homes. While many of these technologies did not end up widely adopted, they successfully adopted techniques from manufacturing into practical construction utilization. Today, improvements in robotics, software, and organization have allowed a new wave of automation in construction to rise, with new developments and collaborations happening across academia, government, and industry.

WHY ROBOTICS IN CONSTRUCTION? WHY NOW?

Construction is one of the highest waste industries in the world. While it is difficult to get exact figures of the waste produced on a typical construction site, some estimate that as much as 30% of the total weight of building materials delivered to a building site are wasted. According to the American Institute of Architects (AIA) Sustainability Discussion Group (2008), 25% to 40% of total waste comes from building construction. Building construction consumes 40% of global energy and 40% of the world's raw materials. The scale of material waste alone within current construction processes is a major issue worth addressing. Further, population increases in areas such as Sub-Saharan Africa and India indicate that a large percentage of near-future building projects will need to be constructed in resource-scarce areas where supply chains are nonexistent or underdeveloped. With a rapidly growing population in a world of dwindling resources, the construction industry will need to find ways to build more with less.

Additionally, the construction industry faces a number of challenges related to labor. Construction continues to lag behind other industries in labor productivity, continually ranking relatively low in labor productivity indices, which measure the time a person a worker spends on-site over how much productivity or output is achieved. While measuring labor productivity in construction is rife with difficulties and has been a matter of debate, existing US Bureau of Labor Statistics estimate of labor productivity in construction suggest that construction has not only been not rising at the level of other industries, but that in some cases, productivity has even been declining for many decades. While newer measurements indicate the issue may not be as negative as previously thought, construction still lags behind other industries. Another issue is the construction industry's much-bemoaned shortage of skilled labor. While this reflects a dip in vocational training in the United States and indicates the need for more training and retaining, it is also an opportunity for more automation to fill the gap. Industries such as manufacturing, aerospace, and even the service sector have realized productivity gains through the automation technologies, and now such technologies are beginning to become more available for construction.

A CONFLUENCE OF CHALLENGES AND OPPORTUNITIES

While the construction industry faces these challenges, it is also presented with a greater number of opportunities for automation. Robotics technologies are being developed and more widely distributed at an ever-greater pace, creating a positive feedback loop that leads to lower costs, more research, and more development. In 2018, the construction industry is in a technology-adopting period, with general robotics technologies being translated into specific use cases solving problems in construction.

It is within this context that in June 2018, Autodesk and MassRobotics held the Robotics in Construction Summit at the Autodesk BUILD Space in Boston. The event was held in order to bring together the robotics community and the construction community in the Boston area, and encourage a discussion between these two communities. Whereas construction companies need solutions to specific problems, robotics companies need to find specific use cases to apply robot technologies they develop. Working together provides a win-win for everyone involved.

The Autodesk BUILD Space (BUilding, Innovation, Learning and Design) is a collaborative research & development workshop based in a 34,000 sq. ft. facility in South Boston. Through a major investment in infrastructure and tools made available to firms, startups, and organizations of all types, the BUILD Space seeks to encourage this confluence of opportunity to create the future of building.

MassRobotics is a Boston-based nonprofit innovation hub and startup cluster focused on needs of the robotics community, the largest such robotics hub in the United States. MassRobotics' mission is to help create and scale the next generation of successful robotics and connected device companies by providing entrepreneurs and innovative robotics/automation startups with the workspace and resources they need to develop, prototype, test, and commercialize their products and solutions.

CURRENT DEVELOPMENTS IN ROBOTICS IN CONSTRUCTION

There are multiple threads of research and development advancing the state of robotics in construction today, from private industry to the government and academic sector. The two main approaches could be characterized as opportunity-driven development and problem-solving development, and we've selected the following presenters at the Robotics in Construction Summit as exemplars of these approaches. Opportunity-driven development, such as the work being done by academic researchers at NCCR Digital Fabrication or NASA's Swamp Works lab, pushes the boundaries of what is possible by experimenting with and designing new construction techniques and technologies. Problem-solving development, such as the work done by Construction Robotics or Bensonwood Homes, uses robotic technology to solve current problems on the ground today in market applications. Both approaches are necessary, and by bringing them together and finding beneficial and concrete market applications for experimental technologies, the vast potential underlying robotics in construction can be further realized.

ROBOTICS IN CONSTRUCTION SUMMIT

In June 2018, the Autodesk Technology Center in Boston hosted a Robotics in Construction Summit in collaboration with MassRobotics in which 136 guests from industry and academia explored how robotics and automated construction technologies help us build more, better, with less negative impact. Grouped by industry perspective, the 4 panels featured 16 panelists, including noteworthy thought leaders such as David Mindell of Humatics, Oliver Smith of Skanska, and Noni Pittenger of CW Keller & Associates, Inc. The day concluded with guests walking over to MassRobotics for a post-summit reception.

OPPORTUNITY-DRIVEN DESIGN: NCCR DIGITAL FABRICATION

EXPERIMENTS IN ON-SITE DIGITAL FABRICATION AND PREFABRICATION

NCCRs, or National Centers of Competence in Research, are a research funding initiative of the Swiss government conducted by the Swiss National Science Foundation. Each center is hosted and supported by a Swiss academic institution and focuses on a thematically-limited area of research, with a network of partners in the academic sphere and beyond. These cross-disciplinary research networks focus on high-risk, high-return research of strategic importance for the future of the Swiss economy.

Russell Loveridge is the Managing Director for NCCR Digital Fabrication. Initiated in 2014 and based out of ETH Zurich, NCCR Digital Fabrication is comprised of 150 researchers and 28 professors from different areas of expertise, including architecture, structural design, materials science, computer science, robotics, and control systems engineering. NCCR Digital Fabrication aims to lead the development and integration of digital technologies within architecture and future building processes.

With a 12-year mandate and research funding, NCCR Digital Fabrication has a framework to test out ideas and execute long-term projects that commercial firms often can't afford. Their research centers around two major challenges: on-site digital fabrication, bringing new technology onto construction sites, and bespoke digital prefabrication, by using the safe environment of the lab to test new ideas for robotics in construction.

ON-SITE DIGITAL FABRICATION

NCCR Digital Fabrication's On-Site Digital Fabrication projects aim to bring digital fabrication onto building sites. Researchers investigate integrated design, planning and robotic control methods, develop versatile on-site fabrication robots, and examine cooperation models for man-machine and machine-machine interactions. According to Loveridge, the guiding question for these projects is "What can we do to get these technologies out there to give us capabilities we don't have?"

The first question the team decided to tackle was "how can we build in concrete without any formwork?" To solve this problem, they first developed an in-situ fabricator, an on-site robotics system. Like others bringing robots that can move on the construction site, the team faced the challenges of localization and precision. According to Loveridge, the biggest thing they learned was "the only thing that matters for robots on the construction site is where the tool is. You don't have to worry about where the robot is or the platform is. As long as we know where the tool is, all the reverse schematics can be calculated."

MESH MOULD

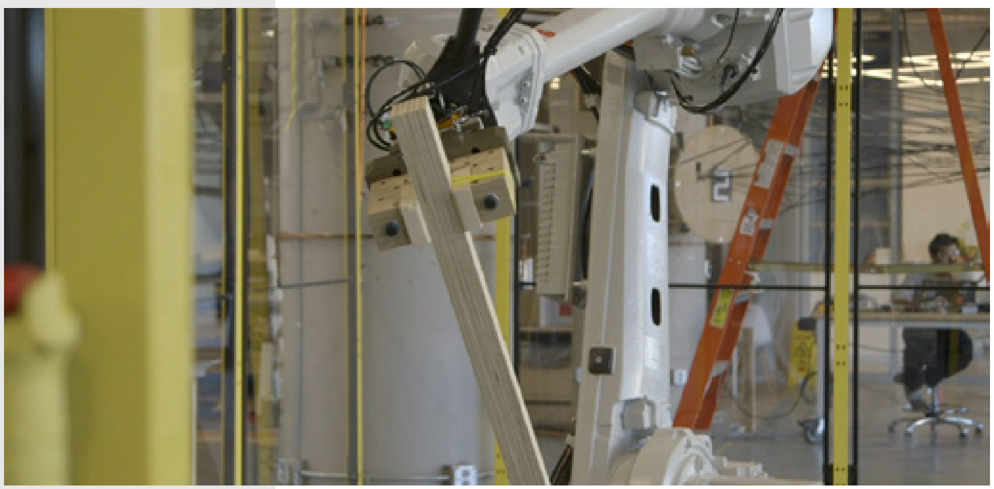
The end result of bringing the in-situ fabricator to concrete is a project known as Mesh Mould, a waste-free robotic fabrication process for fully load-bearing, non-standard concrete constructions. Mesh Mould allows walls and columns to be made without any formwork, by using a computer-generated digital model in conjunction with robots to fabricate a high-precision steel mesh dense enough to retain fluid concrete. While Mesh Mould can be used to build standard concrete walls, it is especially beneficial for curved and non-standard shapes. Mesh Mould project seeks to make non-standard reinforce concrete architecture sustainable and economically

feasible by eliminating the need for expensive custom formwork.

In 2016, Mesh Mould won the Swiss Technology Award, a first for a construction technology. Since winning the award, the team has upscaled Mesh Mould to be able to build on-site and constructed the first Mesh Mould walls on-site in real-world conditions. Made with 6mm rebar, the project used normal concrete with some additives to increase its viscosity, allowing it to be pared during its plastic phase and creating a coating for the rebar. The Mesh Mould process can eliminate the need for formwork on any kind of geometrically curved walls that a robot can possibly build.

BESPOKE DIGITAL FABRICATION

The NCCR Digital Fabrication team is also at-work on pushing forward the possibilities of prefabrication. According to their stated research goals, "Bespoke Digital Prefabrication augments the advantages of manufacturing through the use of digital building technologies. It enables custom-designed, large-scale digital prefabrication of complex architectural elements. Researchers work at the 1:1 building scale, developing resource-efficient material systems, joining methods, design tools and computational technologies."



NCCR researchers developed a new digital timber construction method that expands the range of possibilities for traditional timber frame construction by enabling the efficient construction and assembly of geometrically complex timber modules. Since robotics aren't constrained by angles that are easy for people to cut, the framing can be cut at any angle, minimizing the amount of timber and opening new possibilities. Unlike traditional timber frame construction, Spatial Timber Assemblies can manage without reinforcement plates because the required rigidity and load-bearing result from the geometric structure.

The way it works is one robot guides a timber beam as it is sawed to size, while a second then drills the holes for connecting the beams. The two robots then work together to position the beams as arranged in the digital model. To prevent collisions when positioning the individual timber beams, the researchers have developed an algorithm that constantly recalculates the path of motion for the robots. Finally, workers manually bolt the beams together.

PROBLEM-DRIVEN DEVELOPMENT: BENSONWOOD

AUTOMATED OFFSITE CONSTRUCTION

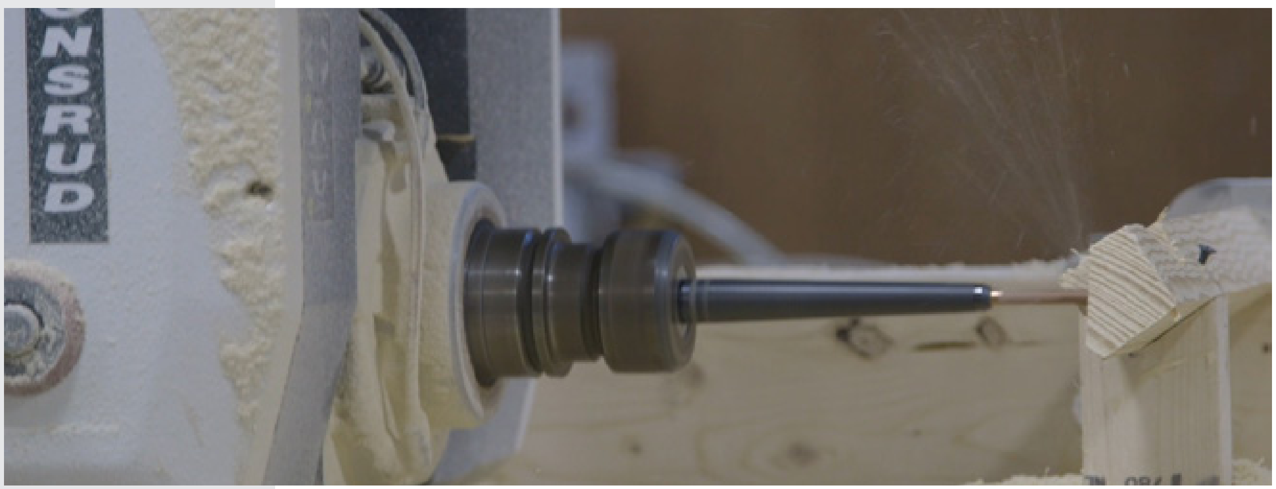
For the past 45 years, Tedd Benson and his company Bensonwood has been leading the revival of timber frame home building in the United States. Dedicated to finding a better way to build and inspired by the evocative and durable timber homes and barns throughout New England, Benson has spent his career bringing the old craft timber framing into the 20th century with new technology and equipment. Benson has also spent his career as a forward-looking pragmatist, finding practical implementation of cutting-edge technology for the decades, from building machinery in the 1970s, programming and applying software in the 1980s, to embracing CNC machines in the 1990s.

Bensonwood has developed high-end timber frame projects, mostly traditional-style homes but also modern and commercial structures, in every state throughout the US, as well as in England, Canada, Germany, and Japan. In 2012, Benson spun off a sister company to Bensonwood called Unity Homes, in order to take all the automation, technology, and expertise developed at Bensonwood down into market to build affordable, high-performance homes. All of Unity's offsite-fabricated homes are net-zero energy ready and use no fossil fuels, relying on air-source heat pumps instead. Benson credits the tightness and efficiency of Bensonwood and Unity's homes to marrying advances in software with advances in automated production hardware.

AUTOMATED HOMEBUILDING AND OFFSITE CONSTRUCTION

When Bensonwood and Unity design a new project, they design a complete BIM model with all building information embedded, "every part and piece, every wire, every pipe, every nail, every bolt." They then deploy that model to their CNC and other automation equipment, all in the same software. Benson calls this a BPM, or Building Production Model, instead of BIM, as the model is used for all design, engineering, and machine information all in one place.

In 2018, Bensonwood opened a new automated homebuilding factory in Keane, NH. Whereas for the previous 17 years, Bensonwood employed automation mostly for cutting and shaping, the Keane facility builds prefabricated homes in a completely automated process using state-of-the-art robotics from a variety of European firms, including Hundegger, Weinmann, Isocell, Joulin, and Routech.



PROBLEM-SOLVING DEVELOPMENT: CONSTRUCTION ROBOTICS

AUTOMATED ONSITE CONSTRUCTION

Construction Robotics (CR) was founded in 2007 with the goal of developing affordable, leading-edge robotics and automation equipment for the construction industry. Construction Robotics' first and flagship product is SAM100 (Semi-Autonomous Mason), a bricklaying robot for onsite and prefabricated masonry construction. SAM is designed to work with a mason, assisting with the repetitive and strenuous task of lifting and placing each brick. The mason continues to own the site setup and final wall quality, but with improved efficiency through the operation of SAM.

SAM can be thought of as a mobile prefabrication lab for brickwork. Builders can use SAM to build walls offsite, or bring SAM on-site to get prefab quality while reducing shipping costs.

SAM in conjunction with CR's 3D brick mapping software streamlines the building process from digital design to fabrication. The software automatically corrects for any variation in the as-built dimensions, allowing masons to resolve problems before beginning production. Complex and custom patterns can easily be executed by SAM.

SAM is constantly capturing and uploading a variety of data points, including the number, size, and placement of each brick, the date, time, and temperature, the mortar slump, bed gap, ambient RH, and more. CR's software provides a real-time feed that allows for monitoring of daily progress from anywhere and at anytime, with detailed analytics displaying SAM's performance.

OPOPORTUNITY-DRIVEN DEVELOPMENT: NASA'S SAMP WORKS

SOLVING CONSTRUCTION PROBLEMS ON SPACE AND EARTH

Robert Mueller is a Senior Technologist at NASA and the co-founder of NASA's Swamp Works lab. Swamp Works, based out of Kennedy Space Center in Florida, was created to be a lean development environment for innovation within NASA. Mueller realized that in order to keep NASA innovative, it had to carve out an environment that would empower people to innovate, which can often be difficult in a bureaucracy. In order to develop the right tools and the right culture for innovation, Mueller helped create the Swamp Works as a special innovation environment within NASA. By leveraging partnerships across NASA, industry, and academia, and utilizing iterative testing to quickly drive design improvements and rapidly develop towards application, Swamp Works has driven exploration towards the technologies needed for working and living on the surfaces of other bodies in our solar system.

ADDITIVE CONSTRUCTION WITH MOBILE EMPLACEMENT (ACME)

The first step in establishing a presence on other planets, whether it's a base on the Moon, on Mars, or a mining operation on an asteroid, is building shelter to protect humans, robots, and equipment. NASA's answer is the Additive Construction with Mobile Emplacement (ACME) project, which seeks to utilize 3D printing technology to provide shelter from the extremes of the deep space environment, including both solar and deep space radiation, extreme thermal swings, micro-meteroids, and exhaust plumes from outgoing rockets (which due to the lack of atmosphere, sandblasts everything within up to 5km at 2,000 meters per second).

In addition to withstanding extreme environments, developing shelters in space presents another obvious challenge: launch costs and rocket payload volumes make it cost-prohibitive to send heavy construction materials and supplies from Earth. In order to be feasible, extraplanetary habitats will need to be built with local materials.

LIVING OFF THE LAND... IN SPACE

One of Swamp Works core technologies is developing in-situ resource utilization (ISRU), which Mueller refers to as "living off the land in space." ISRU is the idea of harnessing the resources available at destination, whether it is Mars, the Moon, and asteroid or elsewhere. Living and working in deep space means crew members have less access to the to the life-sustaining elements and critical supplies available on Earth, and the farther humans go into deep space, the more important it will be to generate their own products with local materials.

The primary resource available to build structures on other planetary surfaces is regolith. Regolith is the surface layer of loose material and crushed rock that sits on top of bedrock. It includes all the rocks, gravel, and dust, from large boulders to tiny particles, and it exists on Earth, other planets, moons, and asteroids. Regolith is also what a civil engineer might recognize as construction aggregate. The Moon is covered in aggregate, which is a huge opportunity for building. Swamp Works in exploring ways to exploit regolith for as many uses as possible, using one of two approaches: extracting resources out of the regolith, usually with chemical process, or using the regolith as a raw material for building structures. Iron, titanium, aluminum, and other metals can be extracted from regolith, or the aggregate can be used to make concrete.

In order to build the structures, Swamp Works is investigating methods of using robotic construction technologies, primarily 3D printing, in conjunction with Lunar and Martian regolith.

One method involves outfitting the ATHLETE (All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer) Robot, a six-limbed lunar rover created by NASA's Jet Propulsion Laboratory at the California Institute of Technology, with a 3D print head. Another method being investigated by Swamp Works is additive construction with sintered regolith, which is particularly promising for the construction of landing pads. Sintering involves heating the regolith to just-below-melting temperatures (1200 - 1500 C), which makes the dirt stick together and forms a brick-like material. Robotic 3D printers can then use the material to build landing pads or walls of a habitat.

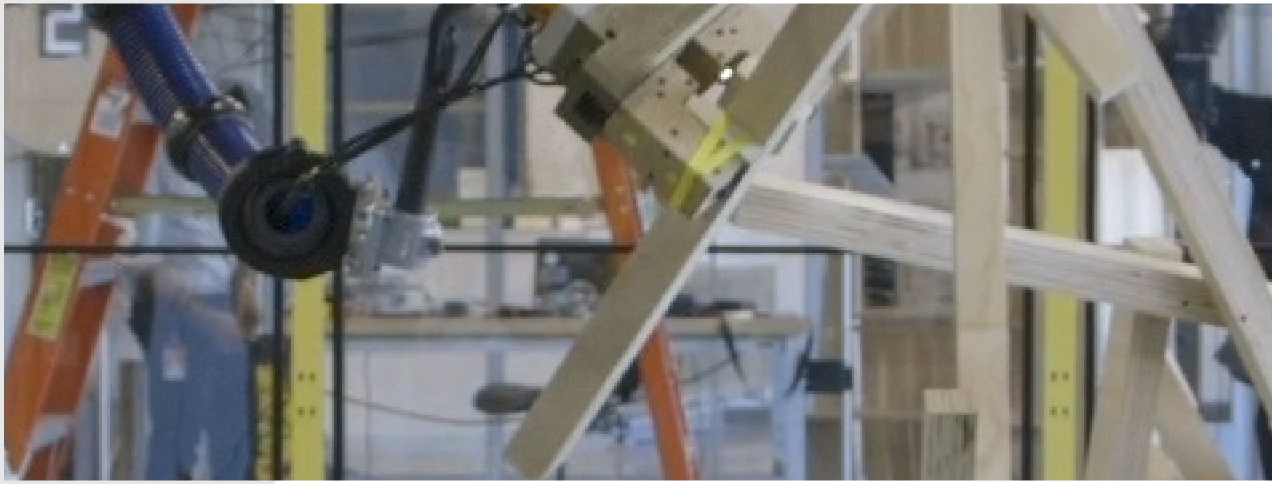
Swamp Works is also working to develop a Zero Launch Mass 3D Printer, referring to the zero launch mass of construction materials the printer will enable by allowing structures to be 3D printed on demand, with building designs transmitted digitally from Earth and printed in space.

In order to utilize the regolith to actually build also requires reinventing cement. While 3D printed concrete structures on Earth have typically used Portland cement, a shortage of limestone in space makes this prohibitive on the Moon or Mars. To solve this, the team at Swamp Works formed a polymer concrete by mixing 30% thermoplastic polymers with 70% crushed rock (basalt). The resulting material is easy to extrude, so it can put on a robot arm with print head for printing structures. It's also a lot stronger than concrete.

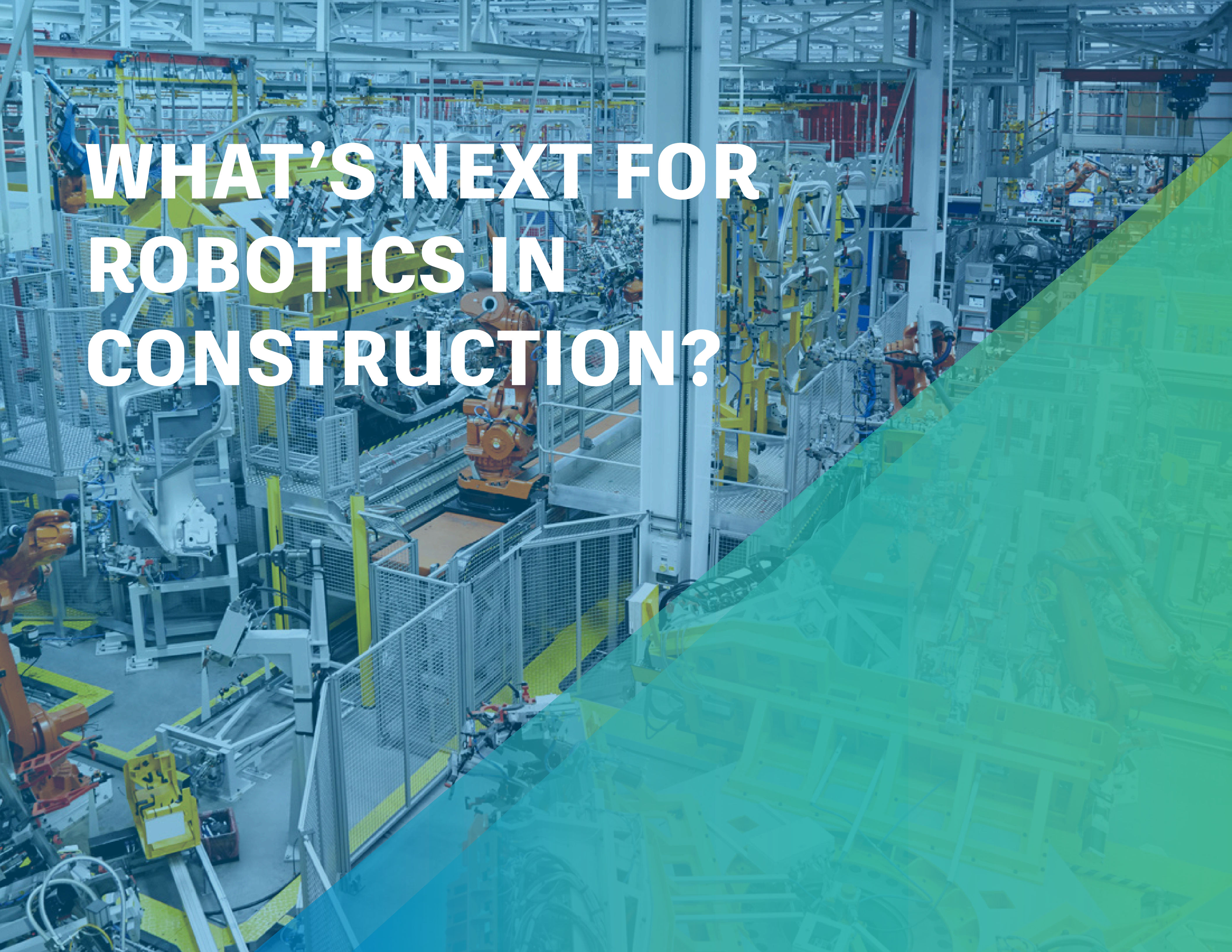
SOLVING PROBLEMS ON EARTH

Polymer concrete can also have a big impact closer to home. As awareness of the plastic problem spreads, polymer concretes could have a role in helping to reduce the amount of plastic trash in the planet's landfills and oceans. Plastic bottles can be recycled to form that are polymer concretes stronger than conventional concrete, providing better building materials while also reducing the amount of discarded plastic and lowering the carbon emissions of the cement industry. As one example, the United States Army currently burns the many plastic bottles used in the field. Swamp Works wants to help take those bottles and mix them with local materials such as sand to build structures. The use of polymer composite concrete from local recycling stream polymers and granular materials has the potential to disrupt the construction industry.

NASA has partnered with the US Army to help solve the shared challenge of building long-term outposts in remote locations but here on Earth. Most notably, Swamp Works worked with the US Army Corps of Engineers and the US Army Engineer Research and Development Center on the Automated Construction of Expeditionary Structures (ACES) project. The goal of the project is to develop automated construction systems to replace the plywood-based B-huts barracks currently used by the Army. The resulting 3D printed concrete structures will take less time to build, require less mass brought in-theater, provide better protection, require fewer personnel, produce less waste, and will mimic local construction styles so they can be left for local populations to inhabit when finished. Working out of the Construction Engineering Research Laboratory (CERL) in Champaign, Illinois, the ACES team used a large Robotic Gantry 3D Printer to print a 512 square-foot barracks b-hut. Caterpillar also partnered with the project, and will help explore commercialization opportunities for the technology.

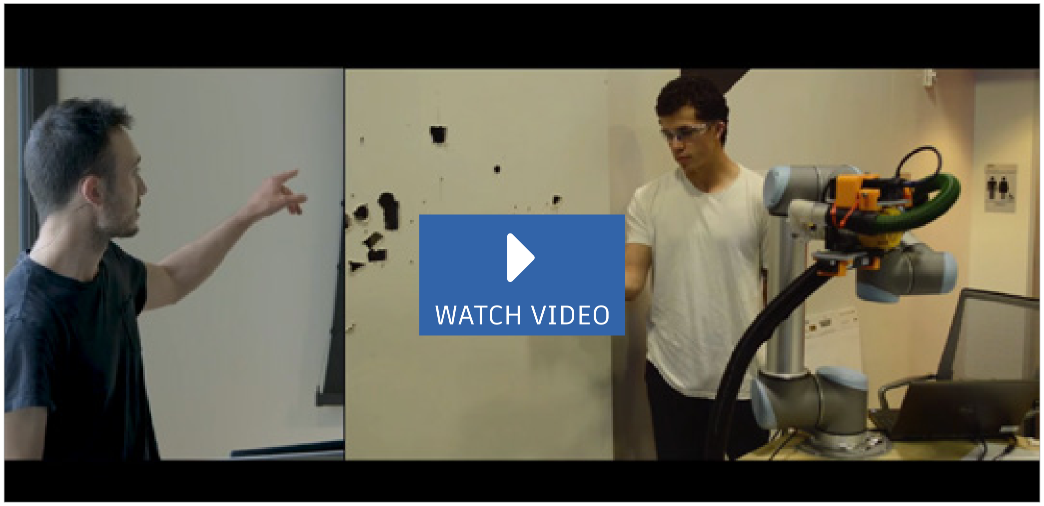


WHAT'S NEXT FOR ROBOTICS IN CONSTRUCTION?



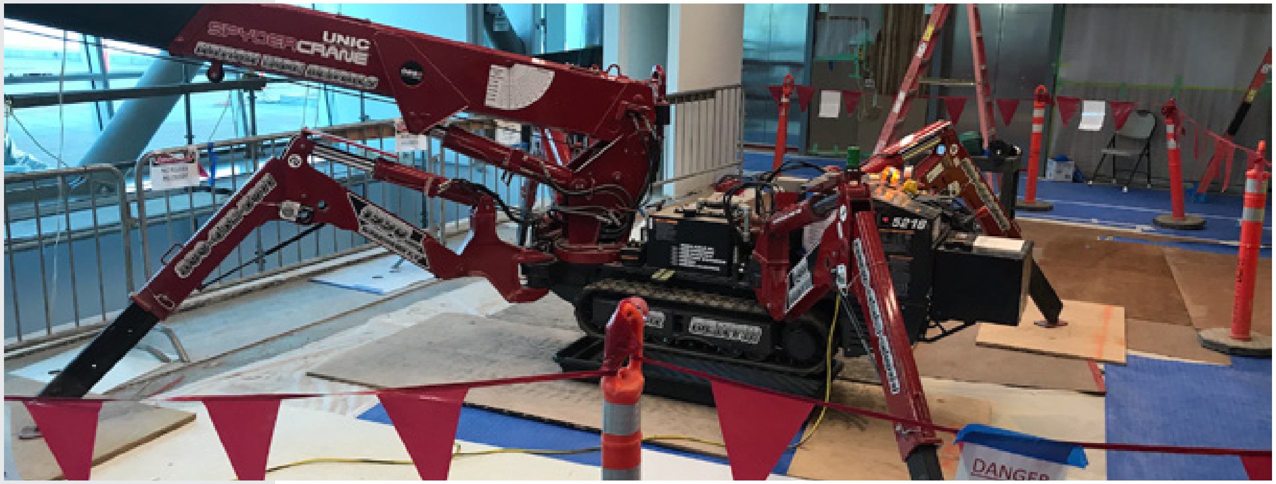
EXPLORING THE FUTURE: THE WORK OF AUTODESK'S ROBOTICS LAB

The Autodesk Robotics Lab, formerly known as the Applied Research Lab, is a small team based out of Autodesk's Pier 9 technology center in San Francisco that builds real-world prototypes across a variety of technologies and subjects in order to help understand the future of cutting-edge technology. One of their main goals is to explore new ways of interacting with robots. In the video below, Nicholas Cote shares some of the Lab's latest projects, including Hive, a pavilion built by human and robot collaboration, SHRMP (Supervised High-Rate Metal Printing), Mimic, an open-source Maya plugin for controlling industrial robots, CIRA (CAD-informed Robotic Assembly), a drywall cutting project, as well as the "Digital twin" and "Electric sheep," which explore controlling and teaching robots through VR interfaces.



BUILDING THE FUTURE: PARTNERING TO DRIVE NEW DEVELOPMENT

The work being done today in bridging the worlds of robotics and construction is exciting, fascinating, and encouraging, yet there is much more work to be done. While automation in construction has a rich and long history, we are still only at the beginning of a new era, one that will see longstanding traditional workflows in construction transformed with the help of robotics and automation. As the population of our planet rapidly rises and the demand for new buildings with it, and as we face environmental challenges here on Earth and opportunities to expand into space, construction faces unprecedented new challenges as well as bold new opportunities.



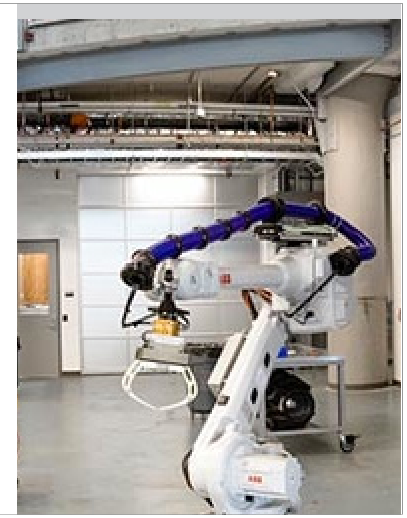
RESOURCES

RESOURCES

The Autodesk BUILD Space, Boston, MA

The Autodesk BUILD Space (BUilding, Innovation, Learning and Design) is a collaborative research & development workshop for the future of building located in South Boston. The 34,000-sq-ft facility houses workshops for metal fabrication, machining (CNC & Manual), wood working, water jet cutting, large format routing, laser cutting, composites, glass, ceramics, textiles, steel forming, robotics and 3D printing. The Autodesk BUILD program provides space for research, industry and startup teams to collaborate, experiment, and build projects or prototypes.

Learn more about: Autodesk Build Space



Mass Robotics

Mass Robotics is an independent, Boston-based non-profit organization serving as an innovation hub for robotics and connected devices. They help bring together innovative startups and existing technology organizations to nurture the next generation of talent and promote economic growth and innovation.

Learn more about: Mass Robotics

Autodesk Robotics Lab

Autodesk's Robotics Lab is a part of Autodesk Research based out of San Francisco that prototypes and crafts a future vision for robotics in architecture, construction, manufacturing and entertainment.

Learn more about Autodesk Robotics Lab

Autodesk Technology Center at Pier 9, San Francisco

Learn more about Autodesk Technology Center at Pier 9

NCCR Digital Fabrication

Learn more about NCCR Digital Fabrication at ETH Zurich

Bensonwood and Unity Homes

Learn more about Bensonwood and Unity Homes

Construction Robotics

Learn more about Construction Robotics and SAM-100

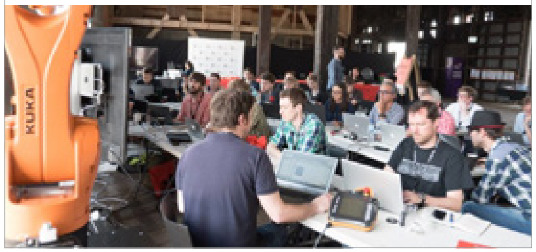
NASA Swamp Works

Learn more about NASA's Swamp Works at Kennedy Space Center

ROB|ARCH

The ROB|ARCH conference series is a collaborative effort between the co-hosting universities, industry partners, and the Association for Robots in Architecture in exploring robotic fabrication is art, architecture, and design.

Learn more about: Robjarch



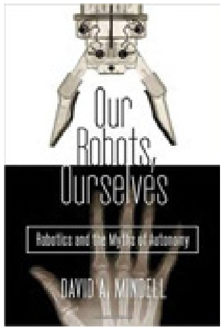
"The Return of the Future: A Second Go at Robotic Construction" by Martin Bechthold

Harvard Graduate School of Design's Martin Bechthold looks back at the first robotic boom during the 1980s and 1990s when millions of Japanese yen were invested in developing robots that could address the shortage of construction labour.

Learn more about The Return of the Future: A Second Go at Robotic Construction

Our Robots, Ourselves: Robotics and the Myths of Autonomy by David Mindell

MIT Professor and Humatics CEO David Mindell offers a fascinating behind-the-scenes look at the cutting edge of robotics today, debunking commonly held myths and exploring the rapidly changing relationships between humans and machines.



Learn more about: David Mindell and Our Robots, Ourselves: Robotics and the Myths of Autonomy

"The Future of Work and Automation Will Kick-Start Jobs, Not Kill Them"

Autodesk CEO Andrew Aganost answers the question: are robots coming for your jobs?

International Association for Automation and Robotics in Construction (IAARC)

IAARC is an organization dedicated to advancing Automation and Robotics in Construction, and has held the annual ISARC (International Symposium on Automation and Robotics in Construction) conference since 1984.

Terracotta Army and the Mausoleum of the First Qin Emperor

Read more from National Geographic on one of the earliest-known use cases of prefabrication in construction.

The US Green Building Council

Learn more about the US Green Building Council

European Commission, Construction and Demolition Waste (CDW)

Learn more about the Eurpoean Commission, Consstruction and Demoition Waste

US Bureau of Labor Statistics: Construction

Learn more abou the US Bureau of Labor Statistics: Construction