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Robotics and automation safety risks in construction

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Evolving technologies such as robotics and automation have the potential to transform the American construction industry. While these technologies improve productivity and safety, they also introduce new safety risks to construction workplaces. This study conducts a scoping review to identify and analyze safety risks associated with robotics and automation in construction. Literature data was collected from the Scopus database using keywords and snowballing approaches. Following PRISMA-ScR, A total of 104 peer-reviewed articles and 33 industry and government reports between 2015 and 2025 were selected based on criteria related to construction robots and safety implications. From the literature data, robotic applications were categorized into eight groups and safety risks were categorized into four categories. A cross-cutting analysis found that mechanical and psychosocial risks dominated across all robotics and automation technologies. Risk mitigation strategies were proposed based on the analysis results. Integrating worker safety and health priorities early in the workplace transformation process, including risk mitigation strategies such as job hazard analysis, while applying the hierarchy of controls, and prevention through design strategies for each of these technologies, may help protect and enhance construction worker safety and health.

KEYWORDS

automation, construction, risk, robotics, safety

Introduction

The construction industry encompasses new construction, alteration, and/or repair under North American Industry Classification System (NAICS) code 23. Job activities within NAICS code 23 include residential and commercial building construction, heavy and civil engineering construction (which includes construction of water and sewer lines, highways, and bridges), and specialty trades like roofing, plumbing, electrical, drywall, and painting (NIOSH, 2018). Construction has lagged other sectors in the speed of adopting and fielding advanced technologies such as robotics and automation (Gharbia et al., 2020). Robotics and automation technologies are defined as systems that perform tasks independently using sensors, AI algorithms, and control theory, or through human tele-operation (Liang et al., 2021). Factors unique to the industry account for this delay. Overcoming these ongoing challenges could help make construction a faster, more efficient, and safer process and revolutionize the industry (Yang et al., 2022; Delgado et al., 2019). The first factor to consider is the changing and distinct workplace environments, layouts, workflows, and landscapes inherent in construction. Second, the job tasks involved in construction are often complex and labor-intensive (Liang et al., 2020). A third reason for the relatively slow adoption rates of advanced technologies is the high cost of implementation in a generally low-margin industry (Liang et al., 2021). Another factor that complicates changes in construction involves its large and diverse workforce (with high turnover), a large percentage of small construction firms that may not have resources for technological advances, and some language barriers. In 2023, the U.S. construction sector employed approximately 11.8 million workers, with approximately one-third of the industry consisting of Hispanic workers. Despite these challenges, the adoption of advanced technologies in construction is increasing. Substantial efforts have been made to find the best ways to introduce robotics and automation in construction (Xiao et al., 2022), yet highlighted the need for safety-awareness and risk-mitigation research on the hazards associated with construction robots (Liang et al., 2024). The following two sections discuss the occupational hazards in construction and regional construction robotics adoption.

Existing occupational hazards in construction

The construction industry has many traditional hazards that contribute to high rates of injuries, illnesses, and fatalities. These industry hazards involve traumatic injuries and musculoskeletal disorders (MSDs), as well as respiratory, noise, electrical, and chemical exposures. Each of these hazards may be considered when making decisions concerning the adoption and implementation of robotics and automation. The leading causes of construction fatalities involve the OSHA Focus Four hazards of falls, struck-by, caught in and caught between, and electrocutions (Albert et al., 2020; Lombardi et al., 2011). Even when workers survive, many have significant injuries, such as traumatic brain injuries or other issues requiring rehabilitation. These hazards and outcomes place enormous emotional, medical, and financial burdens on their families. These traumatic injuries also result in significant costs to employers, including lost productivity, loss of skilled workers, and increased workers' compensation costs (Dong et al., 2013; 2017). MSDs are soft-tissue injuries caused by prolonged exposure to repetitive motion, force, vibration, and awkward postures. Overexertion is the cause of most MSDs in construction (Dong et al., 2019). Although work-related MSDs in construction have declined, days away from work have increased from about 8 to about 13 days. Some of the trades with the highest rates of MSDs and back injuries include masonry, concrete, drywall, roofing, flooring, and plumbing (Dong et al., 2012; Wang et al., 2017).

Many construction tasks generate airborne hazards. These hazardous exposures can cause respiratory diseases (e.g., silicosis, asbestosis, chronic obstructive pulmonary disease (COPD), and lung cancer) and can reduce a worker's length and quality of life (Borup et al., 2017; Wang et al., 2016). Some of the construction tasks that generate airborne hazards include: abrasive blasting, tuck-pointing, cement finishing, wood cutting and sanding, masonry work, painting, gluing, cleaning with solvents, welding, and using diesel-powered equipment (Dement et al., 2014; Dement et al., 2017). In 2010, over 50% of construction workers reported exposure to vapors, gas, dust, or fumes at work twice a week or more (CPWR, 2013). Hearing loss is another major hazard in construction. Approximately one in five (20.4%) construction workers reported some hearing trouble in 2015. This is approximately one-third higher than the proportion of workers with hearing trouble for all industries combined (16.3%) (Masterson et al., 2015). Within the U.S. construction industry, 44% are exposed to hazardous noise, and about 31% of these noise-exposed construction workers are not wearing hearing protection (Tak et al., 2009). Noise exposures come from many sources, including hand tools, larger machinery, heavy equipment, and generators. Construction trades with the highest prevalence of hearing loss include welders, ironworkers, laborers, boilermakers, carpenters, sheet-metal workers, and brick masons.

Robotics and automation offer potential interventions to these hazards. For example, UAVs can prevent fall hazards during inspections, exoskeletons can reduce MSDs risks in overhead tasks, and demolition robots can remove human workers from high-risk zones (Liang and Cheng, 2023). However, these technologies also introduce new hazards. A review of CFOI data from 1992 to 2017 by Layne (2023) found that there were 41 robot-related fatalities during this period. Another study by Sanders et al. (2024) reviewed OSHA Severe Injury Reports and found that 77 robot-related accidents occurred between 2015 and 2022. Of the 77 accidents, 54 injuries involved stationary robots and 23 injuries involved mobile robots. The stationary robots primarily caused finger amputations and bone fractures, while the mobile robots resulted in fractures to the legs and feet. As the use of robots expands, and more workers utilize collaborative and mobile robots, injury risk and exposures may increase (Liang and Cheng, 2023), reflecting the need for a review of safety risks during adoption.

Regional robotics adoption differences

Robotics adoption in construction varies significantly across global regions, with the US trailing behind Europe and Asia in deployment and integration. While there is no standardized robot density metric for construction as there is in manufacturing (e.g., robots per 10,000 workers), comparative indicators such as market penetration, investment levels, and technology deployment reveal clear regional disparities. In Europe, firms have widely adopted autonomous bricklaying systems (e.g., SAM by Construction Robotics), robotic rebar tying, and modular prefabrication technologies, supported by EU-wide sustainability mandates and innovation grants (Xu et al., 2025). In Asia, countries like Japan and South Korea lead in deploying swarm robotics, robotic exoskeletons, and unmanned aerial vehicles (UAVs), driven by national automation strategies and acute labor shortages (Liu et al., 2024). China, in particular, has invested heavily in robotic prefabrication plants and AI-driven site monitoring systems, contributing to Asia Pacific's significant share of the global construction robotics market (Grandview Research, 2024). Some Asian and European countries have made significant progress in adopting advanced technologies in the construction industry. The Asia Pacific region has the highest market value of $453.2 million followed by North America and Europe in size. The market growth rate is also highest for the Asia Pacific region at 18.8% (Grand View Research, 2025).

In contrast, the U.S. construction industry has been slower to adopt robotics despite its leadership in research and venture capital investment. Technologies such as autonomous earthmoving equipment (Built Robotics) and robotic floor layout printers (Dusty Robotics) have gained traction, but deployment remains limited to select firms and pilot projects. According to BuiltWorlds' 2025 Equipment and Robotics Benchmarking Report, approximately 46% of U.S. construction firms reported using robotics on active projects, down from 65% in 2024, indicating a gap between interest and implementation (BuiltWorlds Benchmarking Program, 2024). While startups have attracted substantial funding, the industry's fragmented structure and lack of centralized policy coordination have hindered widespread adoption.

Several structural and economic factors contribute to this lag. Although U.S. labor costs are among the highest globally, especially in unionized, urban markets, many small and medium-sized contractors lack the capital and scale to invest in automation (Faremi, 2024). The short-term nature of most construction projects makes it difficult to justify the upfront costs of robotics without a clear return on investment, and the lack of repeatable environments limits scalability. The complexity and variability of construction sites further reduce the applicability of standardized robotic systems. Labor unions, while not uniformly opposed to automation, have historically prioritized job preservation over technological readiness, particularly in sectors like manufacturing and logistics. Similar dynamics may influence construction, contributing to regulatory friction and cautious deployment. Additionally, permitting and compliance processes for robotic systems vary widely across states and municipalities, creating delays and uncertainty that discourage experimentation (Guerra et al., 2022). Safety concerns also persist, especially around human–robot collaboration in unpredictable site conditions, where liability and insurance frameworks are underdeveloped (Tehrani and Alwisy, 2023).

Workforce-related barriers further complicate robot adoption. Despite a labor shortage exceeding 500,000 workers nationwide (ABC, 2024), there is limited infrastructure for retraining existing personnel to operate or maintain robotic systems. Most vocational programs still focus on traditional trades, and few offer modules on automation or robotics integration (Tang et al., 2022). Resistance to change is also prevalent among field workers and site managers, many of whom are skeptical of new technologies due to past implementation failures or fear of job displacement. These challenges are compounded by the absence of a national robotics strategy, resulting in inconsistent safety standards and limited cross-sector collaboration (Xu et al., 2025).

Together, the lag of robotic integration findings shows the need for a coordinated U.S. strategy that aligns with academic innovation. Without such measures, the U.S. risks falling further behind in the global transition toward robotics and automation in construction. Various advanced technologies are beginning to reach the US market and end users including unmanned aerial vehicles (UAVs or drones), exoskeletons, autonomous vehicles, remote-controlled mobile equipment, additive manufacturing (or 3D printing), robotics, and building information modeling (BIM) (Bock, 2015; 2017). Prefabrication and modular construction are also gaining in popularity. These technologies are beginning to replace manual labor for applications such as bricklaying, inspection, and cleaning (Delgado et al., 2019). New approaches may support productivity and quality while addressing labor shortages and reducing the overall cost of construction projects. In addition, new technologies can improve worker safety for certain tasks (Yang et al., 2022; Liang and Cheng, 2023). Despite the advancement of construction automation and robotics and several reviews on this topic (Armeni et al., 2024; Liang et al., 2024; Xiao et al., 2022), there are still limited reviews focused on safety and health risks associated with construction robotics. Liu et al. (2024) pointed out that the safety of construction robots is one of the key future research directions. Adesiji et al. (2025) reviewed the safety considerations when deploying robots in various workplaces. Okpala and Nnaji (2024) and Sun et al. (2023) reviewed safety risk perspectives among wearable robots and small mobile robots.

The objective of this study is to review existing robotics and automation technologies in construction and identify the safety and health risks associated with those technologies. This paper will first provide an overview of the construction industry and its traditional hazards. Then, we will define research questions and conduct a scoping review to categorize robotics and automation technologies that are beginning to be used in construction. Finally, we will discuss the safety and health impact that the introduction of those technologies may have on the industry and answer the research questions.

Research methodology

This study conducted a scoping review to summarize recent developments in construction robotics and automation and discuss their safety risks. A scoping review was suitable for emerging topics and with various sources of literature (Arksey and O'Malley, 2005; Okpala and Nnaji, 2024). We follow PRISMA-ScR guidelines. Three research questions were identified:

- Q1: What is the current development of robotic applications in construction, and how can they be grouped into different categories?
- Q2: What are the safety risks associated with each robotic application category?
- Q3: What are the mitigation strategies for construction robot safety risks?

To answer these research questions, we first searched for and collected relevant literature. Figure 1 illustrates the research procedure and the results of data collection. Scopus was used as the primary database for collecting literature, which has been used in many review papers as the search database due to its comprehensive coverage (Liang et al., 2021; Xiao et al., 2022; Okpala and Nnaji, 2024). The keyword string for the data collection was defined as follows:

[TITLE-ABS-KEY(robot) AND TITLE-ABS-KEY(construction) AND TITLE-ABS-KEY (safety risk)]

The keywords were defined to answer the three research questions (robot, construction, and safety risk). Then, we limited the search results to peer-reviewed journal and conference articles published in the past decade (2015–2025) and in English, which captures the period of accelerated technology adoption and ensures the quality of the paper. The search resulted in 236 articles. Next, we thoroughly reviewed each article and only included relevant articles,

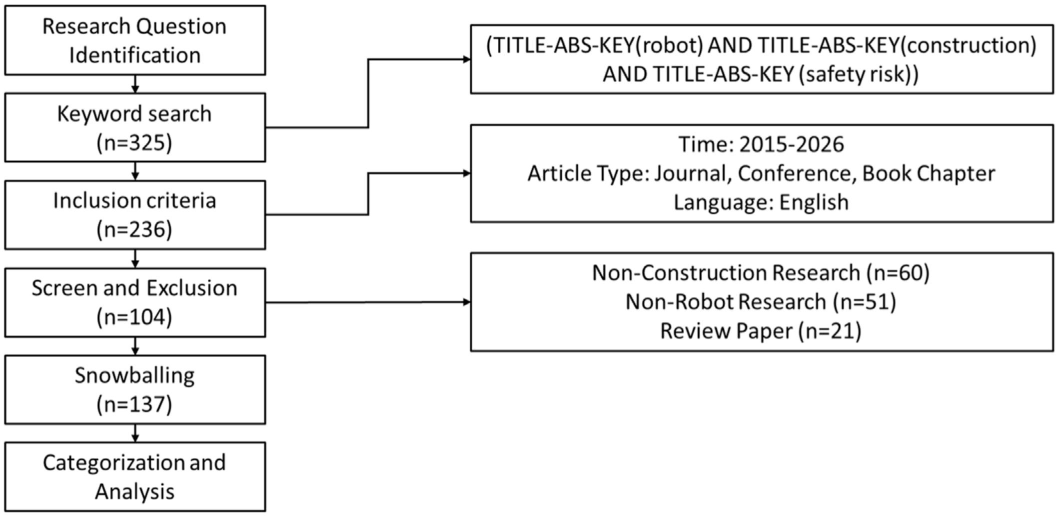

FIGURE 1
Scoping review research procedure.

which resulted in 104 articles. The excluded articles were due to non-construction research (e.g., manufacturing, agriculture, and medical), review articles, or non-robot research (e.g., hazard and risk analysis for traditional construction sites). Finally, we applied the snowball approach to include relevant industry and government reports, statistical data, and presentations, resulting in a total of 137 articles.

Robotics and automation applications in construction and associated risks

Applications of robotics and automation in construction can fall into several categories including:

- Artificial intelligence (AI) and Building Information Modeling (BIM)
- Additive manufacturing/3D printing
- Automated installation or assembly of building components
- Use of unmanned aerial vehicles (UAVs) and robots for inspection
- Prefabrication and modular construction
- Exoskeletons/wearables
- Demolition robots
- Automated heavy equipment and vehicles

Depending upon the application, the level of autonomy can vary from manual to fully autonomous with various levels of autonomy in between. Level of autonomy directly impacts how humans and robots interact, and the Society of Automotive Engineers defines six levels of autonomous driving (SAE, 2021). Similarly, Liang et al. (2021) utilized six levels of autonomy to categorize human-robot collaboration in construction.

The following sections consider occupational safety and health implications, both positive and negative, of each category. Advanced technologies can increase productivity while reducing many hazardous exposures; however, in some cases they could create new hazards. For example, new forms of human-machine interaction may potentially contribute to increased ergonomic risks, electrical hazards, and robot-worker collisions (Murashov et al., 2016). For each application, it may be beneficial to consider the trade-off between hazard reduction and hazard creation to help improve workplace safety and health. Table 1 provides a summary of technology categories, the associated benefits, risks, potential mitigation strategies, and key references that apply. A discussion of Table 1 is provided in the sections below. The categorization and analysis answer research questions 1 and 2.

Artificial intelligence (AI) and building information modeling (BIM)

AI has the potential to improve construction processes, operations, and productivity. It can reduce waste and allow for real-time adjustments to the construction process. AI is machine intelligence that has integrated a variety of problem-solving techniques and permits greater visualization and planning. AI has the potential to enhance the use of robotics and automation on construction sites in a variety of ways (Abioye et al., 2021). As the use of AI expands in construction and other industries, it is important that it be used in a responsible and ethical manner. This could include the potential for worker displacement and need for retraining, as well as, the importance of data privacy and practices, trust, liability, and the impact of organizational culture (Liang et al., 2024). Many of these issues can be addressed in an organization through effective job hazard analysis, written policies, and worker training (Table 1).

BIM software platforms are the current state of the art for architecture, engineering, and construction. BIM uses an intelligent three-dimensional model (or digital twin) to represent digital assets for a construction project during a building's life cycle. This technology integrates real-time data to enhance project management and operational efficiency while providing more

TABLE 1 Advanced technology benefits, risks, and mitigation strategies.

Advanced technologies	Benefits	Associated risks	Hazard mitigation strategies	References
Artificial intelligence and building information modelling	Building efficiency, quality, productivity, collaboration, visualization, planning, hazard ID and Prevention, Real-time adjustments, Reduced waste	Ethical concerns, Job loss, Privacy, Trust, Liability, Psychosocial	Job hazard analysis, written policies, training and certification, PPE	Liang et al. (2021), Chenya et al. (2022), Abioye et al. (2021), Ding et al. (2016), Sidani et al. (2018), Azhar et al. (2012)
Additive manufacturing/ 3D printing	Building efficiency, quality, productivity, reduced waste, fabrication of complex forms, reduced expenses, faster	Struck-by, caught in, electrocution, MSD, structural collapse, psychosocial, job loss, poor weather	Prevention thru design, job hazard analysis, proximity sensors, emergency stops, observe safe distances, training and certification, PPE	Stefaniak et al. (2021), Wu et al. (2016), Ambily et al. (2023), Tay et al. (2017), Pasco et al. (2022), Moini and Rabiei (2025)
Automated installation or assembly of building components	Building efficiency, quality, productivity	Struck-by, autonomous moving parts, entry into safeguarded area, electrical malfunction, job displacement	Proximity sensors, job hazard analysis, observe safe distances, emergency stops, training and certification, PPE	Liang et al. (2017), Liang et al. (2021), Yousefizadeh et al. (2019), Tavares et al. (2019), Reinhardt et al. (2019), Willmann et al. (2016)
Unmanned aerial vehicles/ inspections	Access to dangerous environments, surveys, inspections, monitoring	Falls, Struck-by, Distractions, Distress, Psychosocial	Prevention thru design, job hazard analysis, training and certification, PPE	Jeelani and Gheisari (2021), Zhou et al. (2022) Hogan et al. (2025), Yang et al. (2023), Starý et al. (2020)
Prefabrication and modular	Building efficiency, quality, productivity	Falls, Struck-by, electrocution, crane or forklift accident	Prevention thru Design, Job hazard analysis, Training and Certification, PPE	Ferdous et al. (2019), Pasco et al. (2022), Subramanya et al. (2020), Fard et al. (2017), Innella et al. (2019)
Exoskeletons/wearables	Reduced MSDs, Improved Productivity, Heavy Lifting, Reduced fatigue and Injuries, Enabling older workers	MSDs, falls, usability concerns, high cost of adoption, low worker acceptance rate	Prevention thru design, training and certification, PPE	Gagnon et al. (2023), Jain et al. (2021), Zhu et al. (2021), Nnaji et al. (2023), Gonsalves et al. (2024)
Demolition robots	Productivity, reduced fatigue, reduced injuries	Struck-by, caught in, autonomous moving parts, entry into safeguarded area, electrocution, operator error	Prevention thru design, job hazard analysis, proximity sensors, emergency stops, establish risk zone, observe safe distances, use spotters, training and certification, PPE	Derlukiewicz, (2019), Wang et al. (2025), Lee et al. (2022), Rausch et al. (2024)
Automated heavy equipment and vehicles	Productivity, quality, worker protection, automated excavation, earth moving, reduced noise, improved safety	Struck-by, caught in, electrocution, autonomous moving parts, entry into safeguarded area, operator error, challenging terrain and obstacles, job displacement	Prevention thru design, job hazard analysis, proximity sensors, emergency stops, observe safe distances, training and certification, PPE	Bai et al. (2024), Ha et al. (2018), Melenbrink et al. (2020), Khan et al. (2022), Long et al. (2024), Kurinov et al. (2020)

accurate models. It can help to improve building efficiency, risk management and safety, and information sharing across product stakeholders while reducing costs (Ding et al., 2016; Sidani et al., 2018). BIM improves collaboration across designers, contractors, and owners and helps control product costs through improved visualization and planning. As technology advances, BIM is being used to integrate advanced technologies including robotics and automation into the building's life cycle (Chenya et al., 2022).

Additive manufacturing (AM)/ 3D printing

AM, or 3D printing, builds objects from a digital design file by adding layers of material on top of each other. While AM (the process of creating an object one layer at at time) is an emerging technology that makes up "the fourth industrial revolution" (Babalola et al., 2023), it has become mainstream in many types of manufacturing industries. General industrial AM processes are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (Stefaniak et al., 2021).

AM is growing in construction and other industries. AM process categories most relevant to construction are material extrusion, binder jetting, powder bed fusion, and directed-energy deposition. AM can create construction tools and products, architectural models, components such as walls and columns, and now entire buildings on a large scale (Wu et al., 2016). AM techniques may allow for faster construction, lower and sustainable waste, and less expensive construction projects. The future of construction will likely integrate processes that allow organizations to take advantage of both conventional and AM technologies (Ambily et al., 2023; Tay et al., 2017).

While several types of AM processes are important in the industry, the extrusion method with concrete or cement-based materials has seen the largest growth (Labonnote et al., 2016; Pasco et al., 2022; Grandview Research, 2023). 3D concrete printing (3DCP- digital fabrication of cementitious material) has the potential to revolutionize the way structures are built. 3DCP involves the layer-by-layer deposition of concrete or cementitious materials, guided by computer-aided design models and dispensed through a nozzle, to create complex structures, components, or architectural elements. 3DCP uses specially formulated concrete or cement mixtures (not conventional concrete) and minimizes material waste. Forms are not necessary in some applications; in other applications, concrete forms are used (and can be created using AM).

Concrete printers include gantry and robotic arm systems. These systems differ in size, flexibility, and precision. Gantry solutions cater to larger projects, such as housing and commercial buildings, due to their size. Gantry-style printers sit over the print area and move a printer head or nozzle along three axes. Robotic arm concrete 3D printers incorporate a crane-like structure with six axis, allowing for greater flexibility, detail, and reach than gantry printers. Reviews and developments of the 3DCP and related AM processes, along with research gaps, are available in the current literature (Moini and Rabiei, 2025; Buswell et al., 2018; Bhardwaj et al., 2019; Ambily et al., 2023). Reviews are published summarizing advances in 3D printed concrete materials (Zhang et al., 2019).

Occupational safety and health issues related to AM techniques should be addressed to realize the benefits of these technologies and protect construction workers (Roth et al., 2019). For known construction hazards such as struck-by, caught-in, MSDs, or electrocution, relevant data concerning the type of hazard(s), exposure assessment techniques, and appropriate controls exist but may need to be adapted for use in the 3DCP work environments. 3DCP may also present unique or novel occupational health and safety challenges from the new processes and materials. Many of these challenges can be addressed through prevention through design, job hazard analysis, maintaining safe distances from moving parts, and use of proximity sensors (Table 1). Addressing knowledge gaps related to occupational safety and health and 3DCP may improve our ability to assess hazards and exposures and implement appropriate controls.

Automated installation or assembly of building components

Automated installation and assembly robots build components and structures. Most installation and assembly robots fall into two categories. The first are manipulators, such as industrial robot arms. The second category includes cable-type machines, such as cranes with high degree of freedom and payload capacity for large and heavy materials (Liang et al., 2017; Liang et al., 2021). Given the large scale and dynamic nature of construction projects, robot mobility is often necessary (Melenbrink et al., 2020). For example, mobile robots are being used for navigation and assembly material collection. Despite visions of future robotic construction, in practice, human workers still share the same workplace with robots.

The primary objective of installation and assembly robots is to connect components that pose challenges for a single human worker to handle. For example, installing drywall, window panels, or curtain walls often requires at least two human workers to complete. Drywall installation robots follow worker demonstrations to pick up drywall panels and manipulate them to the target locations (Wang et al., 2021). Similarly, window panel robots collaborate with human workers to manipulate heavy and large glass panels during installation (Yousefizadeh et al., 2019).

Construction robots excel in repetitive tasks, and in that regard have some similarities to robots being used in manufacturing and warehousing. The most common construction assembly robot is the bricklaying robot, which employs robot manipulators to pick up bricks or blocks. These robots follow a layering pattern for placing bricks at designated locations. The semi-autonomous masonry (SAM) robot is an example of a masonry robot that is being used for practical scenarios (Construction Robotics, 2024). Industrial robot arms or cable robots and BIM are used in the bricklaying process (Ding et al., 2020). Fiducial markers are attached to each brick and help the robot to visually recognize it. Tiling is another example of a repetitive task. The tiling robot uses sensors for self-localization and precise tile placement (Liang et al., 2020). Certain construction tasks require precise handling, such as welding, caulking, and bolting, and are well-suited for robots. In the welding process, human-robot collaboration is used to assemble beams through tack weld by human workers, followed by robotic seam welding (Tavares et al., 2019). The caulking or joint filling process by robots requires using precise measurements for accurate filling. Bolting, on the other hand, requires appropriate force to be applied by robots.

In another construction application, robotic or digital fabrication involves assembling or cutting intricately designed components such as timber, carbon-fiber structures, and concrete elements (Reinhardt et al., 2019; Willmann et al., 2016). This category of robots is either placed in an offline factory cell, like a manufacturing assembly line, or employed on-site. The offline factory setup provides a controlled environment, which is more straightforward for robotic fabrication (Yang et al., 2024). Typically, a stationary robot is used for offline fabrication. On the contrary, the on-site version operates within an unstructured environment. In this case, vision systems, fiducial markers, and sensors aid in localizing the mobile robot and aligning workpieces with the digital model. Task trajectories are planned using the designed model and machine learning algorithms. Either a single robot or a team of robots conducts these trajectories during fabrication (Hogan et al., 2025).

Despite their construction benefits, robots used for installation and assembly of building components may introduce new hazards to human workers. The robots may not know the location of workers and other objects putting them at risk. Collision, crushing, or struck-by are robot-related incidents that could occur. Electrical malfunctions are also possible. The primary causes of robot-related incidents involve engineering errors (e.g., machine malfunctions), human-related issues, and poor environmental conditions. Job hazard analysis is essential to address these hazards. Further, the use of proximity sensors, effective training, and use of PPE can all help to increase job site safety (Table 1).

Use of unmanned aerial vehicles (UAVs) and robots for inspection

Within the construction and building sector, inspections ensure job quality and find defects. It can be challenging for human workers to inspect narrow, hazardous, or hard-to-reach environments like bridges, tunnels, building exteriors, or duct systems. Inspection robots and UAVs (an aircraft that has no pilot and is controlled remotely or autonomously) can operate in remote and inaccessible locations, which reduces the need for workers at elevation or in other hazardous environments. Today, UAVs are essential to construction because of their low cost and ease of use. They are used for aerial mapping, monitoring workflow, and inspecting or monitoring for safety (Jeelani and Gheisari, 2021).

Inspection robots usually operate alone without workers nearby. As a result, three areas of consideration are inspection sensors, mechanical design, and operation methods. First, inspection robots commonly use vision sensors, including cameras, laser scanners, and light detection and ranging (lidar), to examine surface structures to identify cracks and check alignments (Zhou et al., 2022). Image processing and computer vision algorithms, such as object recognition and semantic segmentation, analyze images and reconstruct 3D point cloud models of buildings (Kim et al., 2019). These non-contact, non-destructive methods offer the advantages of easy maintenance, accessibility, and high accuracy for structural health monitoring and inspection. Additionally, other non-destructive sensors and evaluation methods (e.g., ultrasonic or thermographic) are used to inspect structural deformation or assess building retrofits (Mantha et al., 2018; Menendez et al., 2018).

Next, the mechanical designs of inspection robots address two scenarios. First, small robots, including bio-inspired robots, are suitable for narrow pipelines or duct systems (Starý et al., 2020). Specially designed mechanisms can help navigate unstructured and complex environments (Duan et al., 2023). Second, UAVs and drones with vision sensors and imaging capabilities have enhanced infrastructure and building inspections through their ability to easily access high places (Bolourian and Hammad, 2020). Traditional inspection methods for elevated bridge underdecks, tunnel ceilings, or building exterior walls, have involved special under-bridge inspection trucks and aerial work platforms. However, vertical moving robots with climbing mechanisms, such as vacuum suction, cable-suspended systems, or rail-based mechanisms, are able to use sensor feedback, path planning algorithms, and control methods to navigate unstructured vertical environments for inspection tasks (Yang et al., 2023).

Finally, operation methods control inspection robots. The methods are either tele-operation or full autonomy. Tele-operation involves human operators using human-machine interfaces or mixed reality headsets to monitor status and remotely control the inspection robot. For autonomous operation, robots can either follow predefined plans to collect inspection data or determine their own inspection plans (Hu and Liang, 2025; Cheng et al., 2025). UAV inspection is an example of following a predefined trajectory and collecting images to reconstruct 3D building models. Autonomous inspection robots combine sensors, such as lidar, GPS, laser range finders, cameras, and IMUs (inertial measurement units), along with path planning algorithms to navigate within buildings and construction and infrastructure sites (Mantha et al., 2018).

Another evolving operation method is simultaneous localization and mapping (SLAM). SLAM techniques enhance mobile robot navigation capabilities. These capabilities are important for GPS-denied environments like indoors, bridge underdecks, or tunnels. SLAM techniques create a map and model of the environment for localization and navigation path determination (Xu et al., 2020). Emerging multi-robot systems with swarm SLAM algorithms can further help expedite the exploration process (Hogan et al., 2025). With the emerging SLAM methods, mobile robots can inspect hazardous environments, eliminating the need for human intervention.

Several studies have evaluated the risks associated with UAVs (Jeelani and Gheisari, 2021; Alizadehsalehi et al., 2020) (Table 1). Most of the potential hazards relate to a UAV colliding with and striking or distracting a worker and potentially causing a fall. When workers are at elevation, distraction by UAV could potentially cause a worker to fall. There are also concerns with worker distraction and stress (Jeelani and Gheisari, 2021). A significant benefit of using drones is the potentially reduced need for workers at elevation and the corresponding reduced fall exposure. Use of drones to perform inspections at elevation is an application of prevention through design.

Prefabrication and modular construction

Prefabricated and modular construction processes use off-site manufacturing to improve the construction process. These building approaches are growing in the United States as use of automation expands. In prefabrication, building components are made in a more controlled and standardized manufacturing environment than what is available at traditional construction sites. In some cases, the off-site manufacturing of building components is automated. Prefabrication occurs at a specialized facility, in which materials are assembled to form a final product during installation such as prefabricated concrete walls or a prefabricated roof frame. In modular construction, most of the building is made off-site and delivered to the location for assembly. Modular construction is often more customizable than prefabrication (Ferdous et al., 2019).

Prefabrication often involves a single trade, such as electrical, piping, or rebar, but prefab can vary. Different levels of prefabrication range from component subassemblies (such as light fittings and windows) to nonvolumetric preassembly (including panels and ceiling service modules) to volumetric preassembly (such as bathrooms and staircases) to whole building modules. In prefabricated and modular construction, building components like bathrooms have pre-wired light fixtures and exterior walls built in a factory. Those components are then transported to the construction site. Prefabricated and modular construction can reduce costs, time, waste, and manpower. Modular construction may have worker safety and efficiency advantages (Pasco et al., 2022); however, more research can help fully understand the costs and benefits (Subramanya et al., 2020).

Use of modular or prefab construction can significantly reduce causes of injuries and fatalities in construction while improving quality and productivity. These causes are lowered because manufacturing sites have greater control and less hazardous exposures compared to onsite construction. Prefabrication can help to maximize work occurring at ground level and reduce falls from scaffolding and ladders. It can also reduce the need to work in hazardous environments such as excavations (Fard et al., 2017).

However, prefab construction has its own risks (Table 1). Transporting and installing large bulky items on site can increase the potential for workplace struck-by incidents. Often, these building components are transported to the construction site on a tractor-trailer as an oversized load. Prefab materials are often large and too heavy to be lifted into place by workers. A large crane or forklift is often used on site to move these building components into place for assembly and their use can create other hazards. Most of the injuries associated with prefab construction such as falls or struck-by occur during installation of building components (Innella et al., 2019).

Exoskeletons and wearables

Construction safety management is challenging because of the complex, coordinated, and mobile nature of construction work. Real-time monitoring of the location and physical state of construction workers is now possible with modern wearable devices and sensors. Data collected from the device is helpful to evaluate worker safety and health and reduce hazards. The benefits of these new technologies also come with potential risks as described below.

Exoskeletons are wearable technologies sometimes used in construction to assist with performing repetitive tasks and overhead work, lifting and carrying objects, standing for longer periods, and holding tools (Gagnon et al., 2023). Greater use of exoskeletons in construction could reduce physical demands on workers, MSDs, and fatigue in various parts of the body (Jain et al., 2021; Gonsalves et al., 2024). They can also enable older workers to perform physical tasks that may be difficult otherwise. Exoskeletons come in two varieties—powered and passive. Powered exoskeletons, which augment the user, are in early development. They are bulky and tethered, and they are not ready for safe use in construction. Passive exoskeletons assist the power of the user's body, and many brands and models are available. Passive exoskeletons focus on one area or body part to assist or augment, such as the back, shoulder, and/or knees. This is important in construction as the back and shoulders are two of the body parts/joints at highest risk for MSDs. Passive exoskeletons are simple, lightweight, and easier to use.

Exoskeletons have been studied in other industries, but the exploration of exoskeletons in construction is more recent. Research has focused on three areas: manual material handling for lower back support, passive arm-support exoskeletons for overhead work, and knee-assistive exoskeletons for kneeling and squatting construction tasks. Studies have shown that for each of these cases, there are positive results in reducing pain and discomfort. In fact, Zhu et al. (2021) proposed the use of various types of exoskeletons based on the trade-specific MSD risk and benefits of the exoskeleton type.

Using a task-specific (shoulder/back assist) exoskeleton can reduce construction worker MSDs, but the benefits, challenges, and criteria for adoption should also be considered (Table 1). Some of the potential benefits include reduced MSDs and fatigue, ease of use, and enhanced safety. Use of exoskeletons also has the potential to help address the aging construction workforce. Exoskeletons could potentially allow older workers to continue working and performing physically demanding tasks that they otherwise could not. Some of the challenges include a lack of generalizable results, worker acceptance, potential for unintended injuries including falls, cost-benefit analysis, and impact on workflow and quality (Nnaji et al., 2023). Some risks associated with using exoskeletons include mechanical concerns, human error, and control errors which can all impact adoption (Nnaji et al., 2023).

Demolition robots

Demolition involves dismantling, wrecking, and removing buildings or structures (OSHA, 2020). Heavy excavating equipment has been used for demolition work for complete removal or for retrofitting and repurposing. This work can be difficult, dirty, and dangerous. Common hazards related to general demolition include falling from heights, being struck by falling or flying objects, or even loss of stability and tip overs (Derlukiewicz, 2019).

Common excavating machine hazards are being struck by the machines, being struck when the machine overturns, or being struck by falling objects or debris (Ertas and Erdogan, 2017). Many excavating machine operators have been injured or died when structures collapsed and struck the excavating equipment and operator. Bureau of Labor Statistics (BLS) data for excavating/loading machine operators between 2009 and 2018 reveal 124 fatalities and 3,520 injuries involving days away from work (Bureau of Labor Statistics, 2020a; Bureau of Labor Statistics, 2020b). Over a third (35.2% of fatalities and 37.9% of injuries) resulted from contact with objects or equipment. For various construction occupations between 2011 and 2013, excavating/loading machine operators had the third-highest rate of work-related fatalities at 32.2 deaths per 100,000 full-time employees (FTEs). Of these fatalities, 11 occurred by contact with objects, representing a rate of 12.2 deaths per 100,000 FTEs (approximately seven times higher than all construction occupations) while 15 occurred from transportation incidents, representing a rate of 16.7 deaths per 100,000 FTEs (CPWR, 2015).

Demolition robots are being used on construction sites. A demolition robot resembles a small excavating machine without a cab, and greater power. The articulating arm uses hydraulics to control a hammer, breaker, or other attachment. Demolition robots use a cabled or wireless remote control, removing the operator from many hazards. Demolition robots have grown in popularity and represent the largest percentage of robots in construction. They are also being used to facilitate resource recovery of building components following demolition (Rausch et al., 2024; Lee et al., 2022).

Operating a demolition robot from external locations can help protect workers; however, it is still important to remain diligent to avoid danger (Table 1). If the operator is located within the demolition robot's hazard zone, the operator could be struck or crushed by moving parts of the robot. The Washington State Fatality Assessment and Control Evaluation (FACE) program issued a Hazard Alert for two workers who were struck by demolition robots and severely injured while in the hazard zone (Washington FACE, 2019). Other studies are looking at ways to enhance the safety of demolition robots (Wang et al., 2025). It is important to conduct a job hazard analysis when using this technology and to establish risk zones for operation. Use of spotters can also be an effective way to help prevent injuries.

Automation of heavy equipment and vehicles

Heavy equipment and vehicles (HEVs) are used in construction site preparation to clear debris, level, and perform earthmoving tasks, as well as to transport construction material in later phases (Ha et al., 2018). However, this necessary work has multiple safety hazards associated with it. HEVs, such as excavators, loaders, and dump trucks, are associated with falling, struck-by, rollover, caught between, noise, vibration, and electrical hazards. These hazards are substantial; for instance, struck-by incidents are the second leading cause of death among construction workers and approximately 75% of struck-by fatalities involve heavy equipment (CPWR, 2023).

In response to safety concerns, labor shortages, and a growing demand for operational efficiency (CPWR, 2025), there has been a gradual transition in the construction industry to the use of automated HEVs. Traditional heavy equipment and vehicles like excavators, bulldozers, rollers, pile drivers, earthmovers, compactors, and booms are increasingly being equipped with automation capabilities (Ha et al., 2018; Melenbrink et al., 2020; Gharbia M. et al., 2020). This technological shift remains in its early stages, with many automated HEVs and their associated technologies still in prototype phases. However, autonomous HEVs are being used as 35% of contractors stated they use automated heavy equipment on their jobsites (BuiltWorlds Benchmarking Program, 2024). Automated HEV use rate probably varies based on company size and the specific nature of the construction tasks given the early stage of this technology.

The integration of automation into HEVs has begun because of advancements in remote operating systems, AI algorithm models, GPS devices, and positioning technology like LIDAR (light detection and ranging) and cameras (Bai et al., 2024; Kurinov et al., 2020). Remote control systems enable workers to operate the HEVs from external locations. AI algorithm models optimize HEV logistics to minimize task duration. GPS devices provide spatial awareness for precise operations. LIDAR instruments, which employ laser beams for distance measurements, and cameras ensure the automated HEVs navigate the jobsite safely (American Geosciences Institute, 2025).

The degree of automation, ranging from remote-controlled systems to fully autonomous vehicles, depends upon the site conditions and equipment requirements. For instance, jobsites with semi-permanent roadways can accommodate automated trucks on programmed routes supported by GPS tracking and LIDAR navigation (Long et al., 2024). However, more dynamic jobsites often use remote controlled HEVs such as rollers and bulldozers. These technological advancements not only enable individual HEVs to perform tasks autonomously, but they may also lead to collaboration between multiple autonomous HEVs for seamless workflow (Khan et al., 2022).

While automated heavy equipment and vehicles have the potential to enhance worker safety, it is necessary to discuss the safety benefits and challenges associated with their implementation. Automated HEVs could protect workers from extreme weather, heights, and unstable ground conditions by removing the worker from the hazardous area and reducing the chance of human error. Automated HEVs could also prevent struck-by and caught-in incidents caused by human errors or visibility limitations. They could also reduce operator injuries and fatalities by eliminating the need for workers to occupy vehicle cabs. Additionally, many automated HEVs are being developed as electric vehicles, which may result in reduced noise hazards.

However, the use of automated HEVs introduces new safety concerns (Table 1). Software malfunctions or sensor failures could result in equipment-related accidents. Insufficient training or awareness among workers and bystanders may increase risks in construction environments. Therefore, effective communication and extensive training are necessary for safe collaboration between human workers and autonomous HEVs.

Summary of associated risks

Based on the analysis, we have clustered the associated risks into four categories: mechanical, ergonomic, psychosocial, and environmental risks. Table 2 lists all advanced technologies associated risks in four categories. The mechanical/physical risks involve physical hazards from moving objects, operation locations, or machine malfunctions. Struck-by, caught-in, fall, structural collapse, autonomous moving parts, falls, and entry into safeguarded areas are in the mechanical risks category. These hazards typically cause high-severity and acute risks that can lead to traumatic injuries or fatalities. The ergonomic risks relate to physical strain on workers due to poor posture or repetitive motion when working with robots. MSDs are in this category. Some examples include overhead drilling or working on a sloped roof. In each case these activities can be automated or enhanced through the application of robots. Ergonomic hazards generally have moderate severity but often result in chronic health conditions.

The psychosocial risks include hazards caused by cognitive and emotional stressors. This category consists of ethical concerns, such as bias and discrimination, job loss and displacement, accountability, transparency, and data privacy. Other concerns include exposure to substances introduced by robots, materials used in applications of robots, or the environment, which include electrocution, poor weather, electrical malfunctions, and challenging terrain. These hazards vary in severity and can be linked to other risk categories. For example, challenging terrain can lead to the caught-in hazard under mechanical risks or poor posture under ergonomic risks.

Risk mitigation

The use of robotics and automation benefits from a well-documented job hazard analysis and risk assessment during design, operation, and maintenance activities. Job hazard analysis is a systematic approach to evaluating each job task, worker, and work environment to identify hazards and take steps to eliminate or control them (OSHA, 2002). Risk assessment often involves both leaders and workers who are familiar with workplace operations including the safe use and application of automation and robotics. Risk assessment evaluates each task that the robot performs. In situations involving an individual robot, these steps occur when the robot is being programmed. Once the hazard analysis has occurred, safety or control measures are considered and implemented to reduce risk.

TABLE 2 Advanced technology risks and categories.

Advanced technologies	Mechanical/Physical	Ergonomic	Psychosocial	Environmental
Artificial intelligence and building information modelling			Ethical concerns, job loss, data privacy, trust, liability, psychosocial	
Additive manufacturing/3D printing	Struck-by, caught in, structural collapse, falls from height, mechanical failure, software glitch	MSDs	Psychosocial, job loss	Electrocution, poor weather, noise, dust
Automated installation or assembly of building components	Struck-by, autonomous moving parts, entry into safeguarded area		Job displacement	Electrical malfunction
Unmanned aerial vehicles/ inspections	Falls, Struck-by		Distractions, distress, psychosocial	Noise, poor weather
Prefabrication and modular	Falls, Struck-by, crane or forklift accident			Electrocution
Exoskeletons/Wearables	Falls	MSDs	Usability concerns, high cost of adoption, low worker acceptance rate	
Demolition robots	Struck-by, caught in, autonomous moving parts, entry into safeguarded area		Operator error	Electrocution, noise, poor weather
Automated heavy equipment and vehicles	Struck-by, caught in, autonomous moving parts, entry into safeguarded area, mechanical failure, software glitch		Operator error, job displacement	Electrocution, challenging terrain and obstacles, noise, poor weather

Effective risk mitigation in the construction industry follows the traditional hierarchy of controls. This hierarchy applies to conventional construction and automation and robotics that are now being used. The hierarchy includes a set of actions in preferential order based on effectiveness at mitigating the known hazard: (1) elimination, (2) substitution, (3) engineering controls (such as machine guards or process enclosure), (4) administrative controls (such as exposure limitations, training, and work practices), and (5) personal protective equipment (PPE) (such as hard hats and gloves). The elements at the top of the hierarchy (e.g., elimination or substitution) are more effective and therefore, incorporated before elements near the bottom (e.g., PPE) when possible.

For each risk mitigation strategy there are emerging technologies that apply. For example, rather than constructing a roof on site at elevation which poses a fall hazard, components can be prefabricated through offsite automation and transported to the construction site for assembly. This is an example of elimination. A light curtain is an engineering control which creates an invisible barrier that, when broken, immediately stops a robot's movement, preventing potential collisions with humans. Other types of proximity warning systems, such as those based on radio frequency identification (RFID), are also engineering controls which can help to maintain a safe worker-to-machine distance. In addition, use of an exoskeleton device to assist with overhead drilling may be considered a type of PPE that can aid in preventing MSDs. Effective training is also an important component of risk mitigation. Workers should receive training on the safe operation of robots. Awareness programs using virtual reality or other advanced approaches can help workers recognize the potential hazards before a serious injury or fatality occurs.

Prevention through design (PtD) reduces occupational hazards by designing them out and focusing efforts on the top of the hierarchy of controls (Behm, 2005). PtD builds on the existing, traditional hierarchy of controls and moves it earlier in the process. PtD can and has improved worker safety and has been adopted in many countries (Gambatese et al., 2005). It has advanced at a slower pace in the United States, in part, because it is not legally required, and design professionals have not embraced it as standard practice (Coleman and Thomas, 2023). The use of robotics and automation to reduce hazardous exposures to workers is an example of PtD, as well as, the elimination/substitution actions under the hierarchy of controls. Robots can be used to perform hazardous jobs and eliminate the hazardous exposure to human workers. Examples of this include use of automated flaggers in highway work zones and robotic roofing to eliminate the substantial fall hazard to human workers.

Using BIM software platforms can potentially improve occupational safety and health in part by facilitating prevention through design. Constructors can use BIM to assess jobsite conditions and recognize hazards early during the design and engineering phases of construction (Azhar et al., 2012). This application can improve site layout and safety planning. BIM also provides methods for managing and visualizing real-time safety plans and site status, as well as supporting safety communication. Furthermore, the use of BIM encourages partners to conduct risk assessment and planning (Lu et al., 2021). Recent BIM advances include fall hazard identification and prevention, integration of sensor technologies for improved safety, and integrated wearable technologies (Abioye et al., 2021). These technologies have the potential to significantly improve construction site safety.

While there are current gaps in robotic safety standards specific to the construction industry, the OSHA Technical Manual mentions several hazards associated with the use of robots in the workplace. These include human and control errors, unauthorized access, mechanical failure, environmental sources, power failures, and improper assembly or use (OSHA, 2021). OSHA's manual outlines some common causes of robot-related incidents: 1) mechanical errors, 2) control errors, 3) environmental interference, 4) power failure, 5) human error, 6) unauthorized access, and 7) poor installation. Additionally, other current safety standards (RIA/ANSI 15, 2009; ISO 10218-1, 2011; ISO 10218-2, 2011) also provide feasible control methods, including lowering robot speed and human-robot separation monitoring. The discussed risk mitigation strategies answered research question 3.

Conclusion

The future of the US construction industry is advancing because the industry is on the verge of a technological revolution. Historically construction has been slow to embrace new technologies; however, significant research and development are occurring. Robotics and automation technology adoption has lagged in the US for various reasons inherent to traditional construction. These include complex and unstructured environments, the uniqueness of each construction site, the large scale of construction, challenges related to human-robot collaboration, and the widespread on-site construction. Despite relatively low adoption rates, many of these advanced technologies are beginning to be used on U.S. construction sites. Many of these technologies have shown great promise for improving the safety and health of construction workers. In some cases, safety and health can be improved by removing human operators from hazardous environments or by allowing remote operation. Robotics and automation are impacting the built environment and improving the efficiency of construction. Even so, it is important that as the new technologies reach the market, they should be introduced thoughtfully in a manner that mitigates negative impacts while improving worker safety and health.

This scoping review investigates what robotics and automation technologies in construction are, the associated risks, and how to mitigate them. Our analysis groups robotics and automation technologies into eight categories (AI and BIM, additive manufacturing and 3D printing, automation installation and assembly, UAV and inspection robots, prefabrication and modular construction, exoskeletons and wearable robots, demolition robots, and automated heavy equipment and vehicles) and identifies associated risks, which are further grouped into four risk categories (mechanical, ergonomic, psychosocial, and environmental) and their severity levels. The mitigation strategies are proposed and guided by the hierarchy of controls theory and Prevention through Design framework.

Based on the review and analysis, future directions for research on automation and robotics in the construction industry include: diffusion of advanced technologies across the industry while dealing with significant shortages of skilled labor, development of technologies that will improve productivity while addressing the greatest occupational safety hazards (Focus Four Hazards), a strong business case and cost/benefit studies for adoption of these technologies (especially for small contractors), human workers and robot collaboration in dynamic environments, barriers to adoption and ways to address them, integration of BIM and other technologies for intelligent risk management and severity modeling, development of effective standards and codes to support wider adoption, and psychosocial and organizational factors for technology acceptance (Mantha et al., 2025). By addressing these issues through a program of applied research, the construction industry can forge a path toward a collaborative, safer, and more sustainable future.

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