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Robotics in Building Construction: Assessing Potential, Benefits and Implementation Challenges

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Abstract – This paper explores the integration of robotic technologies in building construction, with a focus on their potential benefits and associated challenges. It highlights how the use of robotic systems, particularly robotic arms, can enhance productivity, reduce construction costs, and minimize material waste. The study reviews existing literature on the application of robotics in key areas such as on-site construction, additive manufacturing, and off-site prefabrication. In addition, case studies including the Apis Cor Concrete House and the Collaborative Robotic Workbench (CRoW) are examined to illustrate the transformative impact of robotics on modern construction practices. The paper further discusses the broader implications of adopting robotic technologies, emphasizing the need for continued research and development to address existing limitations and improve scalability. Furthermore, the growing demand for robotic and assistive technologies, such as prosthetic systems, highlights their importance in scenarios where human involvement is limited or hazardous, including disaster response, extreme environments, and high-risk operations.

Keywords – Robotic Arms, Early Modern Robots, Collaborative Robotic Workbench, Robotics and Automated Systems, Additive Manufacturing.

I. INTRODUCTION

In contemporary times, there is a growing trend of incorporating robots into various occupational responsibilities, with a particular emphasis on substituting human labor, particularly in occupations that involve repeated actions. Broadly speaking, the field of robotics may be categorized into two distinct domains, namely industrial robotics and service robots. Robots are now used throughout several domains, including workplace settings, military operations, medical functions, hazardous environments, and agricultural activities. Moreover, the execution of some jobs, such as handling explosive chemicals, defusing explosives, or safely relocating them for containment purposes, may pose considerable challenges and potential risks to human individuals. This is particularly evident in industrial settings where frequent pick and place actions are required. Hence, it is plausible to substitute human labor with robots in many tasks.

The engineering of buildings is a vital economic activity; nonetheless, it is characterized suboptimal productivity and by inefficiencies. The use of automated systems and robotics is a promising solution to mitigate these limitations. Nevertheless, it is important to note that the construction sector currently exhibits a notably low rate of implementation. Numerous scholars have conducted study in the domain of integrating robotic technology into the realm of building construction, subsequent to the first endeavor in Japan throughout the 1980s [1]. The use of automation in construction processes leads to a reduction in construction time and an enhancement in quality control measures. The breadth of construction automation encompasses several phases of construction, including the prefabrication of construction components, the manufacture of construction materials, on-site construction activities, the recycling of structures, the operation and maintenance of buildings, and the demolition process. The basic principles governing building construction have remained mostly unchanged since the advent of concrete by the Romans in 100 BC.

Currently, concrete continues to be widely recognized as the predominant material used in building on a worldwide scale. In accordance with a recent assessment published by the Cement Sustainability Initiative (CSI), concrete ranks as the second most extensively used material worldwide, behind water. The global production of concrete amounts to around 10 billion tons annually. As a result, there have been several studies conducted on the use of concrete in the building of robotically produced, geometrically intricate, and non-standard loadbearing structures. In densely populated nations, there is a growing trend towards the building of skyscrapers in order to meet the increasing demand for improved living conditions. On one side, the issue of labor scarcity has become a prominent concern due to the growth of an aging population. On the other hand, the risks and challenges associated with construction escalate significantly as the height of structures increases.

Therefore, the utilization of robotics and automation technology is anticipated to alleviate these issues and apprehensions. To far, researchers have put forward a range of methodologies and systems that use automation and robotics technology for application in the building construction field. The utilization of robotic technologies in the field of building construction has faced several difficulties arising from the primary obstacles to the incorporation of robotics within the field of building construction, namely the diverse nature of construction processes and the intricate conditions prevalent in the construction environment. It is evident that the successful implementation of new technologies requires the attainment of certain attributes such as high payload capacity, reliability, and a broad workspace. Moreover, a significant number of robots are designed to do a single activity repeatedly, hence posing challenges in on-site route planning. Hence, the level of cognitive abilities shown by commercially accessible robots is now considered to be somewhat restricted. This limitation arises from the fact that robots are presently used in a limited range of potential applications, characterized by a relatively low degree of localization accuracy.

Several benefits can be derived from the implementation of sustainable construction techniques. These include a decrease in construction costs, a reduction in waste and emissions, the ability to carry out construction processes rapidly, the provision of a flexible working environment and various forms, adherence to planned time and cost processes, the capacity to operate in diverse climatic conditions, adaptability of sustainable construction techniques, and the minimization of risk ratios for workers, among others. The use of robotic technology into the realm of building construction holds promise for mitigating the inefficiencies and subpar production that now plague the sector.

The main aim of this article is to provide a comprehensive analysis of the potential advantages and obstacles related to the use of robotic arms in building operations. Through an analysis of case studies and current scholarly literature, this research elucidates the advantages and constraints associated with the use of robotic technology within various building environments. The findings of the research have the potential to provide valuable insights for future advancements in the sector, therefore making significant contribution to the development of robotic technologies in the domain of building construction. The remainder of this article has been organized as follows: Section II presents a review of early modern robots and robotic arms. Section III discusses the manner in which robotic arms works in the construction process. This section discusses concepts such as on-site manufacturing, additive manufacturing, and off-site manufacturing. Section IV presents key scenarios depicted in this paper: Apis Cor Concrete House, and the CRoW project. Lastly, Section V draws final remarks on the paper defining the potential of robotic technologies in building construction.

II. A REVIEW OF EARLY MODERN ROBOTICS AND ROBOTIC ARMS

Early Modern Robots

The emergence of electronics and the replacement of vacuum tubes with solid transistors paved the way for the development of microcircuits and faster computer systems, hence creating favorable conditions for the first advancements in robotic arm technology. The first patent for the "position controlling apparatus" was granted to Willard Pollard in 1938, as seen **in Fig 1**. The aforementioned device was a robotic arm used for spray finishing applications, with an electrical control system and five degrees-of-freedom. Despite the absence of a physical prototype, Pollard's conceptualization and enthusiasm for the utilization of automated robotic arms in industrial settings served as a catalyst for the innovative endeavors of subsequent individuals. Harold Roselund, an employee at De Vilbiss, successfully devised and subsequently produced an additional sprayer [2]. Both arms had a high level of sophistication relative to the era in which they were developed. Each arm used distinct mechanisms to facilitate movement at their respective joints. Nevertheless, the electronic controller systems fell short in terms of the precision necessary to enable widespread practicality. The inception of the contemporary age of robotics was initiated by the audacious use of two rather obscure appendages that were devised throughout the latter part of the 1930s.

The first introduction of Unimate's robotic arm occurred in 1962, as seen in **Fig 1.** The invention of the arm may be attributed to George Devol, with its subsequent marketing being undertaken by Joseph Engelberger. The first use of an industrial robotic arm took place at the General Motors facility situated in Ternstedt, New Jersey, specifically for the purpose of automating the diecasting process. In conclusion, the total number of units sold amounted to around 8,500. According to Lin, Chang, and Luh [3], industrial robots have transitioned from their initial development in laboratory settings to become integral components inside production environments. The use of nautical terminology such as roll, yaw, and pitch, in the degrees-of-freedom and robotic arm's motions is a noteworthy aspect of this approach.

Engelberger established the first robotics enterprise, known as Unimation, with the purpose of commercializing their two-ton robotic arm, known as the Unimate, from the Devol's Universal Automation robot. The company Unimation ultimately managed to sell a total of 8,500 units of their product, known as Unimates. In 1966, Kawasaki acquired the license from Unimation to engage in the production of industrial robot arms. The advent of competition was swift, with the emergence of Milacron, a company located in Cincinnati. In 1963, AMF Hermatool introduced the Versatran industrial robot, which became commercially accessible [4]. Subsequently, Japan imported this technology in 1967. Numerous academic institutions expressed their interest in exploring the practical uses of microelectronics and the possible implications of using robotic arms (see **Fig 2**).

Victor Scheinman, an investigator from the Stanford Research Institute, initiated the development of electrically driven articulated arms capable of maneuvering along six axes [5]. These arms were thereafter referred to as the Stanford arm. The robotic arms are now capable of doing more intricate jobs. Marvin Minsky, who was affiliated with the Massachusetts Institute of Technology (MIT) at the time, constructed a robotic arm intended for deployment by the Naval Research office. The purpose of this arm was to facilitate potential undersea research endeavors. The electro-hydraulic high-dexterity arm was operated by the use of twelve joints, each providing a single degree of freedom. Scheinman proceeded to make more progress in his studies pertaining to robotic arms. Considering the support of General Motors, Unimation effectively translated Scheinman's technological breakthroughs into the development of a Programmable Universal Machine for Assembly (PUMA).

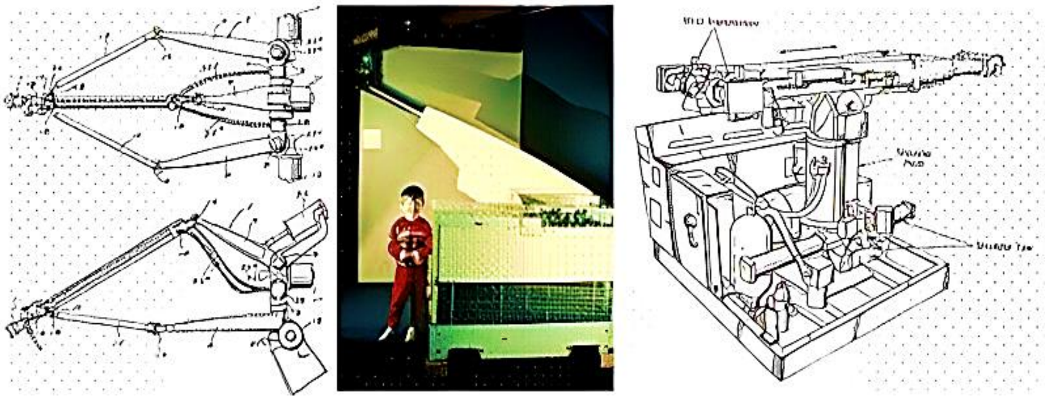

Fig 1. Robotic Arms from the Early 20th Century: The Pollard Painting Arm (Left) and the Unimate (Right).

Fig 2. A Chronological Arrangement of Four Notable Robotic Arms.

Robotic Arms

Robotic arms are a kind of robotic manipulator that has a resemblance to the human arm. The entities in question are comprised of a framework composed of mechanically sturdy connections connected either by rotating joints or translating joints. A robotic arm refers to a mechanical arm, which is typically computerized and has functionalities like to those of a human arm. The user provided a numerical reference without any accompanying text. A conventional robotic arm is typically composed of parts detailed in **Table 1**.

Table 1. Parts of the Conventional Robotic Arm

Parts	Explanations
Links and joints	In the context of a manipulator, a link may be thought of as a inflexible body that specifies the angle between two adjacent joint axes. The joints between the manipulator's stiff links enable for the links to move with respect to one another. The end-effector is positioned by relocating the connections.
Actuators	Similar to the muscles in your arm, actuators store energy in order to produce motion. The manipulator joints of a robot are actuated by actuators, which may be either pneumatic, hydraulic, or electrical (in this case, servo motors).
The controller	is a robot's primary information processing and command execution device. It is the 'brain' of the robot and directs its actions. Information regarding the robot and its working environment, as well as the programs that control the robot, are often stored and executed on a computer. Most robots have computer or microprocessor-based controllers, which include processing activities, programming, logic analysis, and data algorithms allow the robot to carry out its intended duty.
End-effector	An end-effector refers to a segment of the robotic arm that makes contact with its surroundings. The precise nature of this gadget is determined by the robot's function. The end-effector is used for a wide variety of tasks, including as grabbing, pushing, pulling, twisting, utilizing tools, inserting, welding, and assembling. Thus, surgical robots, grippers, welding torches, material removal tools,

	and tool changers with end-effectors designed expressly for conducting operations are the most common kinds of robot end-effectors.

Robotic arms are often examined in conjunction with robots because to their comparatively compact size and versatile capacity to perform a wide range of tasks typically performed by robots. An illustrative instance is the construction of a robotic arm using servo brackets made of aluminium. The use of aluminium is motivated by its advantageous characteristics, including its lightweight nature and inherent rigidity, which enable the robotic arm to closely emulate the functionality of a human arm. Likewise, the robot gripper is constructed from aluminum due to the same rationale. **Table 2** presents an overview of the sensors that are necessary for the functioning of the robotic arm.

Table 2. Essential Sensors for Fabricating a Robotic Arm

Sensors Required	Reasons
Force sensor	To effectively determine whether the arm holds something.
Accelerators	To issue response for the 1st, 2nd, and 3rd angles.
USB camera	To determine the angular orientations of objects.
Two infrared sensors	To detect radial range between the arm and the object.

III. HOW ROBOTIC ARMS WORKS IN CONSTRUCTION PROCESS

Typically, in cases where the arms need a designated support system and are subject to printing constraints, a rail system is often implemented to enhance the movement of robots along these rails. The extant body of scholarly material pertaining to the functioning of robotic arms within the construction industry has been classified into three distinct categories, namely additive manufacturing, off-site operations, and on-site operations. A comprehensive analysis of each sub-category is presented in the following sections.

On-Site Operations

Presently, several on-site activities within the construction industry, such as material handling, bridge inspection, and façade cleaning, pose significant risks to human laborers and need substantial energy expenditure. Multiple scholars are presently engaged in the evaluation of replacing manual labor with robotic technologies to effectively mitigate hazardous and monotonous on-site tasks, including but not limited to bricklaying, inspection, and cleaning. The integration of robotics into the field of bricklaying has been studied for a considerable period, with its origins traced back to the 1990s. Various activities have been explored for robots in this domain, including brick selection, material bonding, and the construction of brickwork structures. Over the past few decades, there has been a significant development in the automation of robotic bricklaying. An instance of the use of automated robotics in construction is shown by Khoshnevis [6], who successfully constructed a dry-stacked double leaf brick wall based on the application of a mobile robot. In their study, Stallkamp, Schlipsing, Salmen, and Igel [7] successfully included machine learning algorithms into the process of generating brick designs for robotic assembly. Ding, Zhou, and Akinci [8] have presented an approach for task-level planning in the context of robotic bricklaying, using a vision-based 3D model and Building Information Modeling (BIM) techniques.

The assessment of the structural integrity of infrastructure, like bridges, is a crucial undertaking within the realm of built environment management. However, these jobs pose significant challenges and are sometimes laborious for those involved. In recent times, there has been a significant proliferation of robots being used for the purpose of infrastructure inspection. An instance of the development of a specialized unmanned vehicle and two underwater robots for the purpose of examining a rollover pass bridge has been shown by Vasilijević, Mandić, Mišković, and Vukić [9]. Additionally, Dixon, Dawson, Zergeroğlu, and Behal [10] have designed a magnetic, wheeled robotic system specifically for the purpose of inspecting steel bridges. This robot is capable of traversing bridges that have square or circular steel constructions. Murphy and Sitti [11] have devised a climbing robot specifically designed for the purpose of inspecting steel bridges, particularly on flat steel surfaces. Robotic systems may also be used for the purpose of conducting inspections on various structures such as façades, tunnels, highways, and storage tanks.

The use of robotics has also been implemented in the domain of high-rise building cleaning, with the aim of enhancing operational safety. Historically, the task of cleaning tall buildings has been carried out by workers, which has inherent hazards for both the workers themselves and passersby in the vicinity. Wu et al. [12] have successfully devised a compact and self-governing robotic system designed specifically for the purpose of cleaning windows in tall structures. This innovative technology offers enhanced ease of operation and maneuverability. In their study, Lee et al., [13] have successfully designed and implemented a robotic system specifically designed for cleaning walls. This robot incorporates both dry and semi-drycleaning units, which have been shown to exhibit remarkable stability and provide exceptional cleaning efficacy throughout experimental evaluations. at addition to the task of façade cleaning, A study by Parrot et al. has successfully engineered a dry-cleaning robot, which integrates the silicone rubber brush for the purpose of effectively cleaning solar panels located at Thuwal, Saudi Arabia. Rome, Hertzberg, Kirchner, Licht, and Christaller [14] have used robotic technology for the purpose of cleaning sewers with significant diameters in a distinct domain. The aforementioned research provide evidence that robotic technologies have advanced to a level of readiness suitable for use in on-site construction activities. However, current robotic solutions in the field of construction are designed to do a single job and face challenges when confronted with many tasks inside a complicated on-site context.

Off-Site Operations

The construction industry has witnessed the emergence of off-site manufacturing, sometimes referred to as modular building, as a significant trend. This method entails the manufacturing and integration of discrete architectural parts, including wooden frames, steel frameworks, and precast concrete components within a regulated factory environment. Subsequently, these components are conveyed to the construction site to undergo the process of final installation. In a highly regulated setting, the use of robotics has the potential to boost efficiency, bolster safety measures, and minimize resource wastage in the context of off-site production. This is mostly due to the ability of robots to effectively handle and manage substantial loads and strenuous tasks. In the realm of concrete element manufacturing, the use of robots has shown to be beneficial in several tasks such as plotting and cleaning, production systems, de-shuttering and shuttering, concrete spreading, insulation, and cladding. Sun and Lal [15] have devised a virtual prototyping approach to facilitate the rebar cage robotic prefabrication for the production of concrete in the context of off-site manufacturing. The use of automation in concrete manufacturing within the building sector has been presented by Mechtcherine, Nerella, Will, Näther, Otto, and Krause [16].

The use of robotics in off-site manufacturing has the capacity to substitute human labor by facilitating the assembly of steel structures. Anane, Iordanova, and Ouellet-Plamondon [17] have devised a robotic assembly system (RAS) which utilizes assembly of steel structures and robotic arms for the construction at a location apart from the construction site. The process of building the steel structure requires four distinct processes, namely rotation, alignment, bolting, and unloading, together referred to as the RAS. Ham, Han, Lin, and Golparvar-Fard [18] have presented a novel assembly technique for steel frames in an off-site plant, which incorporates considerations of 3D manufacturability. The created method utilizes BIM framework of steel as an input to identify the junction zones inside an assembly line. Subsequently, the necessary production activities, such as the process of attaching components together using screws, are determined. Therefore, by implementing measures to prevent probable accidents during the steel assembly process, safety in off-site production may be enhanced.

Timber continues to have significant relevance as a construction material for residential structures throughout several nations, including the United States and Canada. Considerable study has been undertaken to explore the potential of timber frames, which possess a relatively low weight, hence facilitating the manipulation of wooden components by robotic systems. An automatic robotic cell for the gathering of cross-laminated panels of wood was constructed and simulated by Gereke, Schnider, Hurst, and Niemz [19]. Zhao, Ma, Feng, and Xiao [20] have devised a robotic manufacturing method that utilizes a robotic arm to affix laminated wood via the use of nails at a location apart from the site. The researchers have shown the capability of a robotic arm to successfully execute various manufacturing operations involving wood constructions via the integration of numerous instruments, such as a gripper, vacuum, and nail gun.

In their study, Dunky [21] introduced an innovative assembly technique for reversible wood structures. Naboni, Kunic, Kramberger, and Schlette [22] demonstrated that their suggested approach effectively facilitated the whole process, including design, simulation, and robotic assembly. The findings of their research suggest construction that this procedure has the potential to successfully accomplish intricate high-resolution assembly jobs for timber structures. Presently, there is a significant uptake of highly automated robots in off-site production owing to the regulated environment that this strategy offers. Nevertheless, the transportation of the constructed building components to the construction sites remains a necessary step in the off-site production process. One possible avenue for future development is the establishment of a robotic manufacturing platform in close proximity to the building site.

Additive Manufacturing

In the area of Rapid innovation and customization (RiC), 3D printing, typically known as additive manufacturing, has seen significant growth in recent years. The term "this" refers to the process of fabricating three-dimensional things by the controlled deposition of materials using computer-aided techniques. The use of AM enables the direct printing of building components using BIM or CAD models, eliminating the need for intermediary processes. This streamlined approach also facilitates the creation of structurally optimum designs. AM has been successfully used to fabricate whole buildings, including offices, cycling bridges, and residences. In contemporary use, the machinery necessary for AM is often integrated into robotic arms for the purpose of fabricating building elements. AM applications may be classified into three categories based on the building materials utilized: concrete, steel, and other materials.

Frazier [23] have successfully used AM techniques to fabricate a concrete bench. Significantly, the utilization of high-performance fiber-reinforced fine-aggregate concrete was employed, thereby obviating the necessity for formwork in the building stage. In a similar vein, Lim, Buswell, Le, Austin, Gibb, and Thorpe [24] have successfully fabricated concrete cantilevers using an additive manufacturing process, obviating the need for temporary supports, and resulting in a notable reduction in construction waste. The findings of their research suggest that it is necessary to assess the stability of concrete AM products at many levels, including the lacy section, individual layers, and the overall structure. In the realm of printing building structures, Chung, Elrahman, and Stephan [25] have implemented the use of anisotropic concrete and have established a revolutionary printing technique known as flow-based pultrusion. At now, in relation to productivity, additive manufacturing with concrete has worse performance compared to traditional production methods. In their study, Willmann, Block, Hutter, Byrne, and Schork [26] conducted a comparative analysis of the temporal and financial aspects associated with human construction and robotic fabrication techniques in the production of four distinct concrete walls. The researchers reached the conclusion that the use of robotic fabrication exhibited superior productivity compared to the manual approach specifically in the context of fabricating curved double-walls.

The building construction sector has embraced the application of AM for metal components in order to enhance the versatility of structural parts, minimize material use and waste, and enhance worker safety. The main AM processes associated with metals include electrochemical additive manufacturing (ECAM), sheet lamination, directed energy deposition (DED), and powder bed fusion (PBF). Wire and arc additive manufacturing (WAAM) is widely recognized as the most often used AM process for metal materials. This preference may be attributed to its cost-effectiveness and ability to achieve high deposition rates. Keating and Oxman [27] have presented a novel approach to robotic fabrication, which allows the production of metallic components with overhanging structures. This technique, known as multi-directional Wire Arc Additive Manufacturing (WAAM), demonstrates exceptional performance in terms of deposition placement stability, torch travel speed, and wire feed speed.

In addition to concrete and steel, researchers have explored the use of other materials, including tunable 3D printed core materials, polymers, and ceramics, for additive manufacturing (AM) usage within the construction industry. A comprehensive examination of the many materials used in additive manufacturing may be referenced in the work of Ford and Despeisse [28]. AM has the potential to be used in both on-site and off-site construction settings, enhancing the mechanical qualities of building components, and offering the advantage of reducing construction waste. Nevertheless, Asset Management is encountering many obstacles inside building sites, which encompass: One such constraint is the restriction in size. There are two primary challenges associated with the use of AM for printing massive construction components. Firstly, the inherent difficulty in implementing AM technology for such purposes is a significant obstacle. Secondly, the absence of comprehensive rules further complicates the utilization of AM in this context. AM is a relatively recent technological advancement in the field of Rapid industrialization and Commercialization (RiC). However, there is currently a dearth of rules pertaining to quality control in AM. Additionally, the use of AM necessitates a higher level of technical proficiency. The use of AM necessitates construction professionals to possess additional proficiencies in order to effectively control the associated equipment.

IV. CASE STUDIES

While the use of robotic technology in construction is prevalent globally, Turkey has yet to demonstrate significant implementation in this field. Hence, the selected case examples only pertain to foreign nations. This study examines three case studies conducted in Russia, France, and Italy. All of the aforementioned case studies have been published on the website.

Apis Cor Concrete House Project

One of the constructed instances examined in this research is a dwelling of 38 square meters, which was built in Russia by the Apis Cor Company during the month of December in the year 2016 [29]. The Apis Cor robot, as seen in **Fig 3**, is produced by a Russian business and is capable of constructing a home of 37 m^2 within a time frame of less than 24 hours. The apparatus in question consists of a mechanized appendage equipped with a feeding mechanism, which is used to introduce mortar into the building process via a nozzle that incorporates a valve. The use of this robotic arm enables the construction of circular-shaped dwellings, since the robot's motions are characterized by rotation and radial motion.

The manufacturer's documentation outlines the robot's parameters, which include a maximum operational area of 132 square meters, a maximum printing height of 3100 millimeters, and an effective printing area of 100 square meters each 24-hour period, omitting any door and window openings. One of the notable benefits associated with the use of this robotic system in the building of residential structures encompasses the capacity to program it for the execution of architectural projects, encompassing the layout and dimensions of various rooms in accordance with the specific preferences of the client. Additionally, using this technology facilitates expedited construction processes, hence reducing the likelihood of accidents and promoting a safer work environment. The robot has the capability to operate continuously, without being limited by temporal constraints such as day and night cycles, mealtimes, holidays, or vacations.

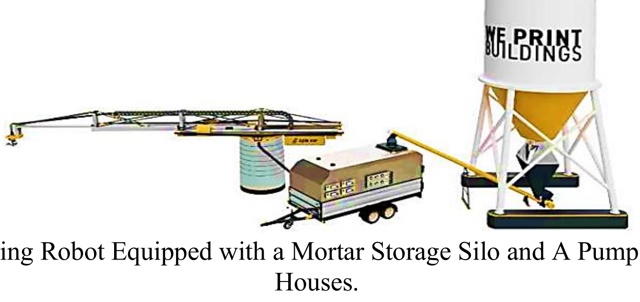

Fig 3. Apis Cor - A 3D Printing Robot Equipped with a Mortar Storage Silo and A Pumping System for Constructing Houses.

Conversely, the robot necessitates programming, is susceptible to malfunctions, and requires maintenance that necessitates expert assistance. In addition, the robot's operational capabilities are constrained within a certain range; and the circular configuration of dwellings poses challenges in terms of furniture placement and the installation of sinks in the bathroom and kitchen areas. The current capabilities of the robot do not include the assembly of windows or doors, nor the execution of slab work or house covering. It is recommended that these operations be performed by manual labor by skilled professionals in the fields of masonry and carpentry. The accuracy of the robot diminishes with time due to the effects of wear on its components.

Fig 4. Building a House Using the Apis Cor Robot and its Building Technology.

Additionally, the installation of the equipment requires both mobilization and demobilization processes. In order to carry out its building function, the robot actuator must be aligned with a certain reference point. The layer-by-layer building approach is used by the robotic arm in order to fabricate both the exterior and interior walls. The technique used in this process, known as contour crafting (as seen in **Fig 4**), involves constructing walls in a zigzag pattern to enhance their mechanical strength. It should be noted that steel reinforcing may or may not be included in this method.

The construction of the home included the use of on-site 3D printing, resulting in a total expenditure of $10,134. The materials employed in this process were concrete and fiberglass. The construction of this project primarily utilizes concrete as its primary material, with the use of horizontal fiberglass rods to strengthen the gaps between the concrete layers. This reinforcement process is facilitated by the use of a robotic arm. A fixed vertical system, situated centrally inside the designated printing area, has facilitated the acquisition of an organic shape via the operation of the arm. The project was successfully completed via the installation of the robot within a 30-minute timeframe, followed by a 24-hour printing process. It is worth noting that the printing operation took place in extreme weather circumstances, with temperatures reaching as low as -35 ºC. Following the completion of the printing process, the installation of doors and windows serves as a finishing element.

CRoW Project

The construction sector, which has yearly expenditures above one trillion dollars in the United States alone (Reached 1.5 trillion dollars by the end of 2022), has had a significant recovery after the dormant period caused by the global financial crisis. Currently, it accounts for 4.3% of the United States' gross domestic product. The sector has also seen a paradigm shift in its potentialities due to unprecedented advancements in digital and robotic technologies, which were inconceivable only ten years ago. Given the substantial value of private building in the United States, which amounted to about $900 billion in 2016, one would expect the construction industry to be at the forefront of adopting the latest technology to enhance efficiency and reduce expenses. However, Lauren Vasey, an engineer and architect, is intimately familiar with the obstacles that hinder such progress [30]. The individual asserts that there is a widespread desire for more digitization within the construction business; yet, several obstacles impede progress in this regard. The construction industry has a notable tendency to compartmentalize various processes and entities involved in the building production, such as contractors, designers, and fabricators. There is a lack of digital process and absence of feedback among the different components.

By using an augmented reality (AR) headset, the user of the Construction Robotics with Wearables (CRoW) system is able to digitally position the subsequent component of a construction project (see **Fig 5**). This process involves the analysis of data and the exploration of various placements via digital means. According to Ondrej Kyjanek, there is a prevailing anticipation within the profession for a breakthrough that would elicit a unanimous sentiment of awe and satisfaction, signifying the attainment of perfection. Project CRoW is an endeavor undertaken by Vasey and Kyjanek, in collaboration with their colleagues from the Computational Design and Construction (ICD) team, Bahar Al Bahar and Benedikt Wannemacher, with the aim of introducing a groundbreaking innovation to the construction sector.

The Collaborative Robotic Workbench (CRoW) integrates a generative-design methodology with the use of a KUKA LBR iiwa robotic arm, equipped with a gripper claw for the purpose of manipulating and relocating various components. The project was conceived and executed specifically for the 2018 KUKA Innovation Awards, an annual robotics competition centered on the concept of real-world interaction [31].

However, a crucial component is the use of an augmented reality (AR) user headset. Augmented reality (AR) enables users to digitally see and plan the placement of the next component by considering the materials and construction. This allows for the exploration of many possibilities and the assessment of relevant data prior to implementation. The precise motions of the robotic arm facilitate the accurate positioning of the subsequent component, which may then be securely fastened by the user using a nail gun. The CRoW made an appearance at the Hannover Messe, an event where continuous manufacturing facilitated the construction of a visually striking wooden sculpture. The equipment assumes responsibilities that have historically been performed by human hands, such as measuring, transporting, or holding objects, all the while continuously scanning and assessing the structure using sensors in order to compare it with the 3D model. The program has the capability to propose the optimal placement for the subsequent component from the perspective of the augmented reality (AR) headset, using its understanding of the model.

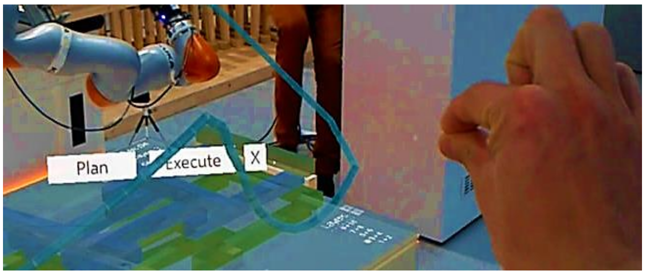

Fig 5. Determination of the Digital Position of the CRoW System.

Fig 6. Physical Configuration Using the Robotic Arm and Human Intervention.

According to Schöner, Dose, and Engels [32], designers possess the ability to exert control over the ultimate form of a building. Moreover, they have the option to impact the sequence of manufacturing. The AR system has the capability to gather extensive data, guided by the comprehensive overview provided by the 3D model of the project. Torque-measurement sensors are included into each axis of the robot's articulated joints, providing information on the force applied on each joint. Additionally, these sensors enable real-time assessment of the feasibility of the anticipated movement. By previewing the trajectory that the robot will traverse from point A to point B, the user is able to proactively strategize and prepare for any collisions or instances of interference. It is also feasible to preview a project's current state and compare it with components that have not yet been included, or even compare it with the ultimate overall structure.

Observing the CRoW in operation, one can readily envision the potential for sharing and expanding this process. In the event that an industrial-scale iteration of the system is used for constructing a residential dwelling, apartment complex, or high-rise structure, the data file produced by the actions of the robotic arm may be documented and improved upon. Subsequently, this refined data can be repeatedly utilized across various locations, ensuring builders a consistently duplicated outcome on each occasion. Architects or builders, equipped with appropriate knowledge, has the capability to analyze the data and make necessary modifications to motions, fastenings, or pressure points in order to align them with the specific requirements of the final product. During the presentation of the Innovation Awards, the CRoW team documented the motions of the LBR iiwa for the purpose of diagnostics, which Vasey suggests might potentially serve as a persuasive factor for potential buyers. According to the speaker, if individuals are just need to purchase the robot and access designs that may be modified using a generative or computational workflow, then the software operating in the background would include the intelligence.

As seen in **Fig 6,** the robotic arm of the CRoW system accurately sets a component by continuously assessing its physical configuration based on 3D frameworks. Subsequently, the operator securely affixes the component using a nail gun. This work is made possible by the ICD at the Stuttgart University. According to Park, Lee, Kwon, and Wang [33], it has been shown that the use of augmented reality (AR) is really much more efficient. This assertion is supported not only by our own study but also by other esteemed research institutes engaged in AR-related investigations. The observed phenomenon exhibits a significant departure from the norm, although it is notably more comprehensible when one is able to visually see the constituent elements and structural arrangement firsthand, as opposed to only relying on architectural blueprints.

Training construction workers to operate with augmented reality (AR) technology is comparatively more straightforward than instructing individuals on how to interpret and comprehend architectural designs. The CRoW serves as an additional illustration of the possibly restricted lifespan associated with the initial excitement around a new technological advancement.

Similar to the phenomenon of 3D printing, augmented reality (AR) saw a brief period of intense popularity among individuals who enthusiastically engaged in activities such as searching for virtual animals in public parks and urban areas via the widely popular game, Pokemon Go. However, similar to the unfulfilled potential of affordable 3D desktop printers, it seems that those times have come to an end. However, historical evidence suggests that initial consumer excitement may just serve as a testing ground for marketing strategies. The industrial sector is already undergoing a subtle revolution as a result of 3D printing, and in, Zheng, Li, and Wang's study [34] is of the opinion that augmented reality (AR) may also soon experience a similar transformation.

The CRoW may be seen as a proof of concept with no immediate intentions for commercialization. Future endeavors will mostly focus on its further advancement. The individual asserts that several novel issues and obstacles emerged over the course of the procedure that require resolution prior to proceeding forward. Vasey further asserts that the major function of ICD is to produce the foundational research necessary for reevaluating the ways in which emerging technologies pose challenges to established building methods and norms. The Institute often establishes collaborations with multidisciplinary partners within a robust research network, facilitating broad engagement between academia and industry.

V. CONCLUSION

The use of robotic technology has promise in enhancing the efficacy, productivity, and safety of building construction procedures. The use of robotic arms in additive manufacturing, off-site production, and on-site operations has the potential to result in cost reduction, waste minimization, and enhanced construction quality. The effective integration of robotic technology in building has been shown via case studies conducted in several nations. The Collaborative Robotic Workbench (CRoW) demonstrates the proficiency of robotic arms in accurately locating and securely attaching components. Nevertheless, there are some obstacles that need to be addressed in order to effectively navigate complicated on-site situations and ensure the provision of specialist assistance. Additional investigation and advancement are necessary in order to effectively use the capabilities of robotic technologies in the realm of building construction. The study yielded several positive outcomes. Firstly, the implementation of fast construction processes resulted in minimal environmental disturbance, including reduced noise, traffic density, and dust.

Additionally, the construction project achieved the desired cost and time objectives initially set forth. Furthermore, it was observed that the utilization of manpower led to lower material losses. Based on the available data, it is also anticipated that robotic building technologies have the potential to be used in the context of colonization on an alternative celestial body. One notable outcome is the minimal occurrence of adverse reactions to natural factors, such as temperature, oxygen levels, and wind speed, owing to the ability to operate in various circumstances. Consequently, the likelihood of occupational accidents during the construction process is significantly reduced. As seen by the case studies, it is possible to print any form without incurring extra time or expense. Robotic construction offers the simplicity of using robotic technology to pour various materials with load-bearing capabilities, provided certain parameters are met. There are many justifications for seeing robotic technology as influential agents in shaping the future.

CRediT Author Statement

The author reviewed the results and approved the final version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest

Data Availability Statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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