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ARTIGO

ROBOTS IN ARCHITECTURE BEYOND CONSTRUCTION: A REVIEW OF DEFINITIONS, CLASSIFICATION AND USES

ROBÔS EM ARQUITETURA PARA ALÉM DA CONSTRUÇÃO: UMA REVISÃO DE DEFINIÇÕES, CLASSIFICAÇÕES E USOS

ROBOTS EN LA ARQUITECTURA MÁS ALLÁ DE LA CONSTRUCCIÓN: UNA REVISIÓN DE DEFINICIONES, CLASIFICACIÓN Y USOS

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ABSTRACT:

In 1959, the first robotic arm was installed in the automotive industry. Since then, the use of robots and automation is increasingly common in all fields. Millions of robots are used in the automation of repetitive tasks, tasks of great complexity or precision and in unhealthy environments. In the field of architecture, the use of robots allowed the shape creative exploration, through fabrication and assemble techniques. Its application in architecture began in the 1980's, and its use is still, mainly, for academic purposes. In this context, the lack of papers that deepens into general history, definition, classification and uses in architecture leads to an incorrect identification of gaps and exploration potential. This paper presents (1) a general history of robots, discussions on their definition and classification and (2) to analyze their state-of-art in architecture showing research gaps and trends. Journals and conference books were analyzed in order to identify the types of robots and their use in the field. The definition and classification were compared with the uses in architecture in order to identify the research gaps and tendencies. As a result, there is a panorama on the uses of robot in architecture and identification of potential research in the area.

KEYWORDS: Digital fabrication; digital assembly; robotic applications

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RESUMO:

Em 1959, o primeiro braço robótico foi instalado na indústria automotiva. Desde então, o uso de robôs e automação é cada vez mais comum em todos os campos. Milhões de robôs são utilizados na automação de tarefas repetitivas, de grande complexidade ou precisão e em ambientes insalubres. No campo da arquitetura, o uso de robôs permitiu a exploração criativa da forma, através de técnicas de fabricação e montagem. Sua aplicação na arquitetura começou na década de 1980, e seu uso ainda é, principalmente, para fins acadêmicos. Nesse contexto, a falta de artigos que aprofundem a história geral, definição, classificação e usos na arquitetura leva a uma identificação incorreta de lacunas e potencial de exploração. Este artigo apresenta (1) uma história geral dos robôs, discussão sobre sua definição e classificação e (2) análise do estado-da-arte em arquitetura, mostrando lacunas e tendências de pesquisa. Periódicos e anais de conferências foram analisados a fim de identificar os tipos de robôs e seu uso na área de arquitetura. A definição e classificação foram comparadas com os usos em arquitetura para identificar as lacunas e tendências de pesquisa. Como resultado, têm-se um panorama sobre os usos de robôs em arquitetura e identificação de potenciais pesquisas na área.

PALAVRAS-CHAVE: Fabricação digital; montagem digital; aplicações robóticas

RESUMEN:

En 1959 se instaló el primer brazo robótico en la industria automotriz. Desde entonces, el uso de robots y automatización es cada vez más común en todos los campos. Millones de robots se utilizan en la automatización de tareas repetitivas, tareas de gran complejidad o precisión y en entornos insalubres. En el campo de la arquitectura, el uso de robots permitió la exploración creativa de la forma, a través de técnicas de fabricación y ensamblaje. Su aplicación en la arquitectura se inició en la década de 1980, y su uso sigue siendo, principalmente, con fines académicos. En este contexto, la falta de trabajos que profundicen en la historia general, definición, clasificación y usos en arquitectura conduce a una identificación incorrecta de vacíos y potencial de exploración. Este artículo presenta (1) una historia general de los robots, debates sobre su definición y clasificación y (2) un análisis de su estado del arte en arquitectura que muestra las brechas y tendencias de investigación. Se analizaron revistas y libros de congresos para identificar los tipos de robots y su uso en campo. La definición y clasificación se compararon con los usos en arquitectura para identificar las brechas y tendencias de investigación. Como resultado, se tiene un panorama sobre los usos del robot en la arquitectura y la identificación de potenciales investigaciones en el área.

PALABRAS-CLAVE: Fabricacíon digital; montaje digital; aplicaciones robóticas

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INTRODUCTION

Robots are increasingly present in our daily life, direct or indirectly. The International Federation of Robotics (IFR) estimates that there were more than 3 million active industrial robots in 2020 producing our everyday objects. Domestic and professional robots are also becoming usual, with more than 30 million units sold in 2020 for cleaning, entertainment, logistics, defense and other purposes.

Automation is a key process in reducing the repetitive manual labor, while enabling creativity, especially in areas such as architecture. Computer-aided design (CAD) technologies such as 3D modelling, parametric modelling, and many others led to the exploration of new spaces and shapes in architecture (BURRY, 2016). Robots could then perform fabrication and assembling.

Robots are an interesting resource for architecture and construction. They can be used in the creative exploration of complex-shaped projects or in standard construction. Although one of its uses may be the automation of construction and substitution of manual labor (similar to what occurs in the automotive industry), there is a large number of research and applications that explore its creative use. Robots allowed the use of complex shapes at a lower cost and in less time than manual labor, sometimes with geometries that would not be possible to be achieved manually.

The creative use of robots in architecture also affects the design process and final result, as an integrated solution between the design, the fabrication method and the assembly method. In contrast, the simple automation of a traditional process may not affect the final design, as it is only focused on productivity, rather than the creative possibilities enabled by the robot.

Therefore, in this paper, applications regarding creative exploration and geometrical exploration will be considered as architectural applications. Applications regarding the automation of traditional practices and substitution of manual labor will be considered as construction applications. This paper will focus on the creative exploration, therefore, the architectural application of robots.

Many studies on the use of robots in architecture adopt a bibliographical approach; however, they often disregard their general history, only superficially analyzing their definition and classification. This leads to some errors – such as using the term "robot" as a synonym for "robotic arm" – or results in an incorrect identification of gaps and exploration potential.

Robotic arm is the main type of robot used in architecture, with a greater focus on the fabrication process – as shown in the term "digital fabrication" – than on assembly, which lacks a proper term, such as "digital assembly". However, many other types of robots, with diverse applications, are yet to be explored in the field. This paper aims to present the general history, definition and classification of robots, and to analyze their state-of-art in architecture, showing research gaps and trends. This paper derives from a doctoral thesis, which aims on developing a methodology for using robotic assembly in architecture, exploring different uses of robots in architecture.

OBJECTIVES

This paper main objective is to identify the research gaps and trends in robots in architecture. through the comparison of the definition and classification of robots with the results from a quantitative survey of research papers. As mentioned, the focus of this paper is the gaps and trends in architecture, therefore, aiming at creative exploration.

METHODOLOGY

The main research from which this work derives was exploratory and experimental (GROAT; WANG, 2013), and used the Research By Design methodology (HAUBERG,2011). This paper corresponds to a section of the literature review of the main research.

The literature review was divided into two parts. For the introduction, definition, and classification, relevant papers and authors were considered. For the research gaps and tendencies, a quantitative survey of research papers was used. The database used for this quantitative survey was composed of (1) the Cumulative Index of Computer Aided Design (CumInCAD), (2) proceedings from the Robotic Fabrication in Architecture, Art and Design (Rob|Arch), (3) proceedings from the FABRICATE conferences, (4) the Construction Robotics journal and (5) the Made By Robots special issue of the Architectural Design journal.

This database has a focus on architecture, rather than a general view on robotic construction, focusing mainly on creative exploration. It is important to consider that, despite its name, the Construction Robotics journal derives from the Association for Robots in Architecture and has a focus on the architectural exploration of robots. The founder, Sigrid Brell-Cokcan, also directs her research towards the creative exploration of robots in architecture instead of productivity and replacing the manual labor.

THE ORIGIN OF ROBOTS

The need to control, fabricate, imitate and simulate life is inherent to human nature. Human beings have been searching for artificial humans and animals since the beginning of humankind, way before computers or artificial intelligence, which led to the development of automatic machines. From a simple lever to a complex hydraulic arm, they all try to imitate a biological mechanism at some level.

Discussing robots requires understanding their development throughout history – what preceded them, when they first appeared and what is considered a robot today.

The first mention of artificial humans or animal dates back from ancient history, usually addressed as "automaton" (from the Greek αὐτόματον, meaning "act willingly") (WALLÉN, 2008). Those can be found in Greek mythology, such as Talos, the automata that guards the Island of Crete, the golden ladies of Hephaestus, or the automata of Daedalus (BULFINCH, 2015; SIMÕES, ALVAREGNA, LEFÉVRE, 1976). Although part of a mythology, these artificial beings instigated and inspired the creation of automated machines, leading to the development of several complex machines such as the Antikythera (SWEDIN, FERRO, 2007) or the Aeolipile. Greece is considered the birthplace of modern mechanics, with the book "Mechanical Problems" – despite the debate over its authorship, with some scholars attributing it to Aristotle and others to Architas (WINTER, 2007; DUGAS, 1988).

Other civilizations have also developed some complex machines in the antiquity, such as flying birds and human automata in China in the 10th century BC (NEEDHAM, 1991) or automata guards in India (NORMAN, 1983). Some of these reports and texts tend to mix reality and imaginary situations or myths; however, they still led to the development of mechanics on the Orient.

As Greece and its colonies were conquered by the Roman Empire, they continued the application and development of mechanical theories. After the fall of the Roman Empire, the caliph of Baghdad collected the roman texts, leading to a great development on mechanics in the Arab Empire in the 9th century (WALLÉN, 2008; KOETSIER, 2001; ROMDHANE, ZEGHLOUL, 2009).

The Renaissance brought a new interest on the antique literature, as well as on the texts preserved by the Arab Empire, leading intellectuals and inventors to revisit the Greek inventions (WALLÉN, 2008). Leonardo Da Vinci was one of these inventors, describing the concepts of automaton pulling carts or even automated vehicles (SCHOLZ, 2007). René Descartes was also influenced by the concept of automaton, comparing the human body to a complex machine, a metaphor that he used largely and introduced in the biological sciences (VACCARI, 2008).

During the next centuries, several human-shaped automata were developed, usually related to toys for the nobility, especially on the 18th century, when Swiss craftsman created small dolls with precise and natural movements (WALLÉN, 2008). These automata defied the limits of mechanics, leading to new developments such as programmable automata, which used perforations or reliefs to store the sequence of movements. Some famous examples are “the musician,” “the draughtsman,” and “the writer,” by Pierre Jaquet-Droz. While “the draughtsman” could draw four different animals, “the writer” would write any 40-letter-long letter using a quill (WALLÉN, 2008). After the beginning of the 20th century, the production and search for automata declined and that for robots arise. So, what is the major difference between an automaton and a robot?

The word “robot” comes from the Czech word “robota,” which means “forced labor” and was introduced by the Capek brothers in the beginning of the 20th century (HOCKSTEIN et al, 2008). Its first appearance was in “Opilec” by Joseph Capek, in 1917 (CAPEK, 1925), becoming famous after the play “Rossum’s Universal Robot” from Karel Capek, in 1921 (CAPEK, 1929). The play was about artificial humans that would perform tasks for actual humans, until a rebellion would end civilization as we know (CAPEK, 1929). Despite his intentions on criticizing the fast technological advances, the play brought a new perspective and conceptualization of “artificial humans.” This new perspective influenced other authors, such as Isaac Asimov, leading to the book collection “Robots” and the famous “I, Robot” (ASIMOV, 1994). Robots started to feature in books, TV shows, and movies, filling the popular imagination.

According to the Oxford Languages, an automaton is “a machine that performs a function according to a predetermined set of coded instructions, especially one capable of a range of programmed responses to different circumstances,” while a robot is “a machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer.” Both definitions are quite similar, describing machines capable of performing actions automatically; however, they differ as to the way they can be “programmed.” As cited, automata are basically mechanical machines programmable by perforated discs or cylinders with reliefs, while robots are based on computer programming and electronics, thus being electronic machines.

The development of electronics in the first half of the 20th century led to the creation of the first digital computer in 1948, the Small-Scale Experimental Machine (SSEM) (GARFINKEL, GRUNSPAN, 2018), and the first numeric controlled machine, developed at the Massachusetts Institute of Technology (MIT) in 1951 (WALLÉN, 2008). Few years later, robots went from science fiction to reality, when the first robotic arm (Unimate) was installed in General Motors’s assembly line, in 1959 (WALLÉN, 2008; GARFINKEL, GRUNSPAN, 2018). The Unimate led to such an increase in productivity that, in 1961, General Motors included more than sixty robots, making it the biggest car producer in the world (WALLÉN, 2008; HOCKSTEIN, 2007). In a few years, robotic arms would be all over the world, with Unimation licensing its production to Nokia and Kawasaki. These arms were programmed by storing positions on their system, repeating these positions without the use of computers.

The 1970s brought several improvements, such as the first six degrees of freedom robotic arm from Kuka in 1973 (KUKA), the development insertion of microprocessors and sensors and their use on robotics in 1974, the first national robotic association (JIRA) and the use of robotic arms in the viking I and II probes. Improvements on robotic arms and other types of robots continued in the following decade, being important to highlight the change in programming paradigm, when Kuka and other developers started to produce industrial robots that could be programmed directly by a computer (KUKA 4). This allowed them to be used in customizable fabrication and assembling. The development of new sensors, Big Data, and processing capacity in 2018 were major changes that led to the development of collaborative robots by Universal Robots, being followed by other companies shortly after.

The aforementioned robots are basically robotic arms with three or more degrees of freedom (DoF), but several other types of robot were developed. In commercial terms, the International Federation of Robotics (IFR) divides robots into industrial and service robots (professional and domestic use). Robots are currently used not only in industries, but also in military (such as drones, tele-tanks and others) (SPRINGER, 2013), agriculture, logistics, medicine (HOCKSTEIN, 2007), and even in cleaning or hotel services. The word “robot” is also used for Robot Process Automation (RPA) and web-bots (or simply bots) (DORAN. GOKHALE, 2011; AALST, BICHILER, HEINZI, 2018) – both of which are related to the development of artificial intelligence and machine learning, and may be considered by some authors as virtual robots. However, can they?

WHAT IS A ROBOT?

With the development of new technologies and knowledges, concepts can change over time. This is quite common in the field of computing, such as artificial intelligence: algorithms and techniques considered high-tech in the 80’s are trivial today, and may not be even considered as artificial intelligence anymore. Several concepts of robots that were brought out over time, became outdated or incomplete. This section aims to discuss the concept of a robot nowadays.

The International Organization for Standardization (ISO) 8373:2021 specifies the vocabulary for robots and robotic devices, defining a robot as a “programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning” (ISO 8373:2021). Although, some organizations, such as the International Federation of Robotics (IFR) uses the definition of the previous standard, that defines a robot as an “actuated mechanism programmable in two or move axes with degree of autonomy, moving within its environment, to perform intended tasks” (ISO 8373:2012). For specifying that the robot will be moving within a physical environment, such definition excluding web-bots and other artificial intelligence programs that exist only within the virtual space; however, it does not specify that a robot must be an electronic device. According to this definition, a machine using clockwork mechanism, programmed with a perforated disk, which moved in one or more axes, such as Pierre Jaquet-Droz’s “the draughtsman” – clearly an automaton – could be considered a robot. The IFR also brings the ISO definition of an industrial robot, which is quite similar to that of a general robot, only more restrict, adding the fact that it needs to be automatically controlled, reprogrammable, and multipurpose (International Federation of Robotics; 2020).

Although these definitions often do not specify that a robot must be based on electronic mechanisms, this is an implicit information. Erico Guizzo (2018) cited the definitions of robot formulated by Rodney Brooks, from Rethink Robotics, and Gill Pratt, Toyota's Research Institute CEO, who understand robot as an electronic-based machine able to sense or capture information from the environment through sensors to take decisions and perform its intended task on the physical world. These definitions not only imply that robots are electronic-based machines, but also that they use sensors to capture information and "feel" the world. Of course, this could be referring to complex sensor or information capture, such as robotic vision, but could also suggest simple end-course switchers, ultrasonic measuring, air-quality sensors, and many others. From the simplest domestic printer to a complex robotic arm, all of them have some kind of sensor aimed to define its position on space (or, at least, set its initial position).

Kate Draling (DRALING, 2017, apud SIMON, 2017), from the MIT Media Lab defines a robot as a "physical machine that's usually programmable by a computer that can execute tasks autonomously or automatically by itself". Anca Dragan (DRAGAN, 2017, apud SIMON, 2017) also has an interesting definition about robots, according to which they would be physical personifications of artificial intelligence agents, allowing them to perform tasks in the real world. This can refer to the capacity of a robot to perceive the environment through robotic vision, speech recognition and other sensors, and, based on that, perform its task. Artificial intelligence could be defined as the branch of computer engineering that creates machine and programs that imitates human behavior or perform tasks that require human intelligence (OED ONLINE, 2020). In this sense, every robot has a certain degree of artificial intelligence, so that they interact with the world and modify it somehow. Another important point brought by those definitions is the need for the machine to perform some task in the physical world in order to be considered a robot. Therefore, web-bots and other applications that only interact in the virtual environment could not be considered as robots. These definitions are summarized below (Table 1).

	Physical machine and Autonomous	Electronic	Programmable and reprogrammable	Sense capability	Interacts with real world	Artificial intelligence
Oxford English Dictionary (OED ONLINE, 2020)	✓		✓			
ISO 8373:2012	✓		✓		✓	
ISO 8373:2021	✓		✓		✓	
Rodney Brooks (BROOKS, 2018, apud GUIZZO 2018)	✓	✓		✓	✓	
Gill Pratt (PRATT, 2018, apud GUIZZO 2018)	✓	✓		✓	✓	
Anca Dragan (DRAGAN, 2017 apud SIMON 2017)	✓	✓			✓	✓
Kate Draling (DRALING, 2017 apud SIMON 2017)	✓		✓			

Table 1. Robot's Definitions by Author

Source: Author

Based on these definitions, we can conclude that a robot must:

- Be a physical machine.

- Comprise electronic and mechanical parts, with at least two moving axes.
- Perform tasks automatically, with or without human aid.
- Be programmable and reprogrammable, allowing its use on several applications or situations.
- Sense, interact, and perform task on the real world.

Despite fulfilling most of these criteria, some machines cannot be considered as robots. A remote-controlled car, for instance, would not be a robot due to its lack of sensors and capacity of performing task automatically. An autonomous vehicle, on the other hand, would be a robot, since it can sense the environment and perform its tasks automatically.

CLASSIFICATION

Once defined, robots can be classified. The ISO classification of the IFR classifies robots according to their use and mechanics (International Federation of Robotics, 2020). As to use, robots are divided into industrial and service, whereby industrial robots would be used in industrial applications, different from service robots, further divided into professional and domestic. This classification system is widely generic and used to analyze the growth in each sector, since the same robot could be placed on one class or another depending on its use.

Regarding their mechanical structure, robots could be divided into six categories: Cartesian, selective compliance assembly robot arm (SCARA), articulated, parallel/delta, cylindrical, and others/non-classified. Although this classification analyzes the robot and its motion, many robots are not included and put together in “others,” such as autonomous vehicles, humanoid robots, or new types of robots that are being developed. Therefore, a broader classification must be made in order to contemplate all types of robots.

Robotic arms are probably one of the most famous types of articulated robot. However, many other types of robots have been developed in the last few decades. Since the second half of the 20th century, studies in bioengineering tried to understand not only the movements of animals, but also the tissues involved in these processes. The traditional robotic arm tries to recreate the human arm and its capacity, even enlarging it. Despite all the progress, the lack of deformation and adaptability of rigid bodies still represent limitations of these machines, as natural soft systems are able to deform (RUS, TOLLEY, 2015). This led to the development of robots that are based on natural systems, such as muscles and tendons, which stiffens and deform according to pressure. Those are called “soft robots” and are constituted by flexible materials that can deform or stiffen with the use of fluids, wires, materials with memory, and others (MANTI, CACUCCIOLO, CIANCHETTI, 2016).

Soft robots are being widely explored in several applications due to its adaptability (MANTI, CACUCCIOLO, CIANCHETTI, 2016; TRIVEDI et al, 2008; GARCIA et al, 2007) and resistance to impact (RUS, TOLLEY, 2015), such as exoskeleton (ASBECK et al, 2014) or object manipulation (MUXFELDT, KLUTH, KUBUS, 2014). After the introduction of the term “soft robots,” traditional robotic arms and other robots based on rigid materials were defined as “hard robots” (TRIVEDI et al, 2008). This is now used as the first level of robot’s classification. Deepak Trivedi (TRIVEDI et al, 2008) present a classification based not only on the type of material used, but also on discretization and redundancy, which influence the degree of freedom of the robot.

A robot can be classified as discrete, which means that its members are clearly separated, or continuum, which means that the robot is visually a unity. This can be easily noticed when comparing a six-DoF robotic arm with a soft robot, such as the starfish (RUS, TOLLEY, 2015).

The robotic arm has easily distinguishable separated members, as well as its joints and movements, thus being classified as a discrete robot. On the other hand, the soft robot is seen as a unity, sometimes even made of a single continuous piece of material that is activated by hydraulic pressure, thus being considered as a continuous robot.

A robot may also be classified as nonredundant, redundant, or hyperredundant according to its movements. If a robot has only one configuration of its members and joints for its nib to achieve a certain point in space, it is considered as being nonredundant. This is the case of most Cartesian robots, such as 3D printers and others. If it has two or more configurations, such as the case of most robotic arms, then it is a redundant robot. Some authors only consider robots as redundant and nonredundant, while others use the terms hyperredundant or megaredundant to describe robots that would have a huge number of configurations and, possibly, infinite degrees of freedom (TRIVEDI et al, 2008). This classification can be used either by fixed robots such as robotic arms or by movable robots, such as autonomous vehicles and some humanoid robots.

This paper will adopt the ISO's mechanical structure classification used by the IFR (International Federation of Robotics, 2020), combined with the material, discretization, and redundancy classification of the study by Deepak Trivedi (TRIVEDI et al, 2008), besides considering whether the robot is fixed or movable. Robots will be classified as movable if they are able to move its base by their own, such as minibuilders or quadcopters and other autonomous vehicles. As a single robot can serve different purposes, the classification based on robot's use will not be used in this study. The uses will be analyzed later on, but not for the sake of classification. The diagram below (Figure 1) illustrates the whole classification based on: (1) material, (2) discretization, (3) redundancy; (4) fixed/movable; and (5) mechanical structures.

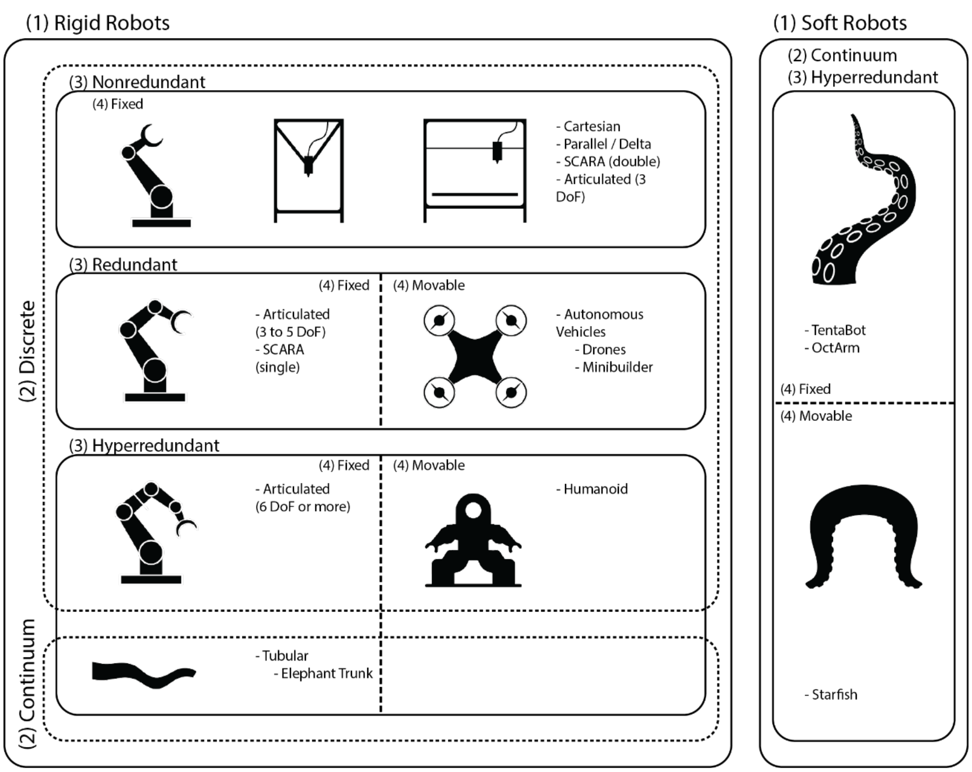

Figure 1. Proposed classification of robots (based on the ISO 8373:2012 and TRIVEDI et al, 2008).

Source: Author

This classification cannot be seen as static and, as new robots are being developed, it will probably change to accommodate new types of robots, with new materials and configurations. Some robots can be considered as hybrid or an association of other robots. Robots with both soft and hard materials may be considered as semi-soft or hybrid. Robotic arms can be associated with Cartesian robots or autonomous vehicles to enhance their capacities and mobility. Such associations between two or more categories can be treated as "complex robots."

ROBOTS IN ARCHITECTURE

Robots feature in the industry – especially in the automobile sector – since 1959. However, architects have started to show interest in their use only recently. How are robots being used in architecture?

There are two major ways to use robots in architecture. The first one is based on the substitution of human labor in processes that are dangerous, dirty, exhausting, and repetitive. The second one is based on new possibilities brought by their creative and exploratory use. Although some authors use the first approach to defend the use of robots in architecture (as well as cost and time reduction), this was not what motivated the main use of robot in architecture.

This is similar to the first uses of CAD in architecture. Although it could be used simply by its automation towards architectural design, it was mainly used due to its new modelling possibilities, such as non-uniform rational B-splines (NURBS) modelling, which allowed working with shapes and spaces that were not possible or quite difficult to be explored before (KOLAREVIC, 2005). Likewise, the use of robots in architecture continues to accelerate the potential of exploration and creative expression (REINHARDT, SAUNDERS, BURRY, 2016).

Explorations of robots in architecture began in the 1980s (BRELL-COCKAN, BRAUMANN, 2012; SOUSA et al, 2016), primarily boosted by the need for using complex-shaped pieces, such as occurred with the Basilica de la Sagrada Familia. Gaudi's designs are full of complex and unique pieces, and the desire for reducing its production time without losing its precision led to the use of robots (BURRY, 2016). In 1989, a stone-cutting robot was introduced to the construction to produce complex-shaped columns (BURRY, 2016) that were difficult and time-consuming to produce manually. In 2001, a 7-DoF robotic arm was also used for cutting stone, being able to perform 95% of the cuttings needed (BURRY, 2016).

Despite the success of robots in this work and others, robots only came into focus in 2006, with the work of the Gantenbein Vineyard's façade and the foundation of the Gramazio Kohler Research, in ETH Zurique. The design combines a simple material (the brick) with sophisticated modelling, in which the disposition and rotation of each element are unique, to use the effect of bright and dark pixels, creating an image on the façade. This variation made it impossible for the bricks to be layered by hand, requiring a robotic approach for its assembly (BONWETSCH, GRAMAZIO, KOHLER, 2007).

Several comparisons were made in this project regarding manual and robotic assembly, such as the constant production flow, which allowed a precise schedule, and the production costs, which were lower using the robotic arm (110 euros/m^2) compared to manual assembly (125 euros/m^2) (BONWETSCH, GRAMAZIO, KOHLER, 2007). Despite the discussion about substituting human labor by robots, the major impact of this work was to demonstrate that robots could be used in tasks that were outside the scope of manual labor (BRELL-COCKAN, BRAUMANN, 2012). Of course, this was not the first brick-layering project that used a robotic arm, with other examples from the decade of 1990's; however, they had technological limitations (HELM et al, 2014) and less flexibility (GRAMAZIO, KOHLER, WILLMANN, 2014). With the glimpse of possibilities and break of a barrier to the architectural creativity and production, the community (especially academic) turned their attention to the application of robots in architecture (BRELL-COCKAN, BRAUMANN, 2012).

Only four years after, in 2010, several other universities equipped themselves with robotic arms, such as Harvard, Carnegie Mellon University, Michigan University, and the University of Stuttgart (WILLMANN, KNAUSS, BONWETSCH, 2016). In the same year, the Association for Robots in Architecture was founded, leading to the Rob|Arch: Robotic Fabrication in Architecture, Art and Design conferences and books. The first conference, held in 2012, points out that more than 20 universities around the world were developing research on the applications of robots in architecture (BRELL-COCKAN, BRAUMANN, 2012).

The Gramazio Kohler Research group continued developing research in the area, advancing knowledge on the use of robotic arm for brick layering, such as in the Oscilating Structures and Pine Loop projects (HELM et al, 2014; DORFLER et al, 2016), as well as on placing members for complex timber structures (SONDERGAARD, AMIR, EVERSMANN, 2016; GRASER et al, 2020). Besides robotic arms, the group also explored the use of drones for brick layering (GRAMAZIO, KOHLER, WILLMANN, 2014) and wire interlacing (MAYER, GRAMAZIO, KOHLER, 2017).

Another excelling group is the Institute for Computation Design and Construction (ICD) of the University of Stuttgart, led by Achim Menges, and their collaboration with the Institute of Building Structures and Structural Design (ITKE), led by Jan Knippers, in the form of the ICD/ITKE Pavilions (BRELL-COCKAN, BRAUMANN, 2012). The 2010, 2011, and 2015/16 editions were based on robotic milling of plywood sheet. The 2012 edition brought a biological inspiration and tried to use the flexibility potential of the robotic arm, creating a pavilion based on the intertwining of resin-imbibed wires and the morphological principles of an exoskeleton (KNIPPERS et al, 2015). The 2013/14, 2014/15, and 2016/17 editions followed the same strategy using different biological inspiration, such as spider and beetles (DOERSTEALMANN et al, 2015). In addition to the traditional use of a robotic arm, these projects explored its innovative potential.

Besides studying robotic arms, the ICD also developed research with drones (WOOD, YABLONINA, AFLALO, 2018) and their association with robotic arms (MAYER, GRAMAZIO, KOHLER, 2017), as well as with minibuilders and string interlacing (YABLONINA, MENGES, 2018). Each robot has a type and level of flexibility, reach and collaborative potential, thus being best suited to certain applications. In some cases, the intended application dictates what type of robot to be used; in others, strategies and methods are developed for a specific robot to perform an intended application.

When compared with the robotic arm, autonomous vehicles such as drones and minibuilders can perform their task in a wider area. Drones, for example, can move freely and have been used in swarm for tasks such as stacking and weaving, although their precision might be influenced by environmental factors. Minibuilders can move on any plane and other complex-shaped surfaces, enabling them to climb walls and carry objects. Both of these can usually handle but small payloads and only rotate objects on its plane. Moreover, they may have a small robotic arm attached to perform rotations in other axes, but they are quite limited.

Some experiments also used Cablebots and Cartesian robots. Employed in stacking operations and 3D printing, Cablebots are cable-driven robots, similar to spidercams. Due to this factor, it can easily adapt to different shapes and environments, with easy transportation and assembly/disassembly (SOUSA et al, 2016). Cartesian robots are usually the simplest ones, with a delimited work area and three axes. Other types of robots were also designed and used for some specific tasks, considering its geometry, movements and desired effect.

QUANTITATIVE SURVEY OF RESEARCH PAPERS

A search combining the keywords "architecture" and "robots" can lead to thousands of results in databases such as Elsevier and Google Scholar; however, such a search retrieves several papers on architecture of robots rather than on robots applied to architecture. To avoid this type of mislead, the bibliographic survey was performed on databases, conferences, and journals aimed exclusively to the field of architecture. The keywords were searched in the Cumulative Index of Computer Aided Design (CumInCAD) database from 2010 to 2022, and their frequency of use was evaluated. Proceedings and books from the Robotic Fabrication in Architecture, Art and Design (Rob|Arch) and the FABRICATE conferences were analyzed in the detail, as well as the Construction Robotics journal and the Made By Robots special issue of the Architectural Design journal.

As explained, this database, proceedings and journals aim at the architectural explorations. Therefore, the papers analyzed focus, mainly, on the creative exploration and possibilities enabled by robots. Despite its name, the journal Construction Robotics also focuses on creative exploration and architecture, as explained in the methodology.

By using the search keywords "robot," "robots," "robotic" and "robotics" in the CumInCAD database, 723 papers were found. The search keyword "robotic", was present in 78% of the papers, being the most present. We noticed an increasing number of publications up from 2010, peaking in 2016 and 2020 (Figure 2). The decrease in 2021 and 2022 may be due to the postponement of conferences, suspension of experiments, and other factors related to the COVID-19 crisis.

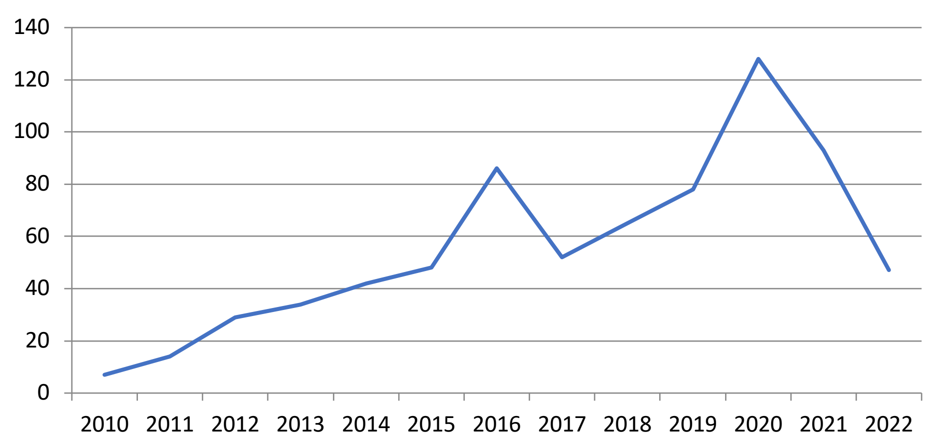

Figure 2. Publications in the CumInCAD database about robots.

Source: Author

Considering materiality, 12 of the 723 papers found contained the search keyword "soft robotics" (with three publications in 2015, 2017, 2019, and 2020) – less than 2% of the total. No paper contained the search keyword "soft robot." Despite not containing the search keyword "hard robot" or similar, all other papers can be considered to use or be related to hard robots, since it is the most common type of robot regarding its materiality.

Usually, a robot can be used for fabrication or assembly in architecture. Among all papers found in CumInCAD, 287 contained the search keyword "robotic fabrication" and are related to processes such as milling or 3D printing. Only 23 contained the search keyword "robotic assembly," being related to processes such as stacking bricks and positioning pieces. The other papers' keywords do not make it clear whether they are related to fabrication or to assembling.

The figure below (Figure 3) shows this distribution of search keywords among the papers found.

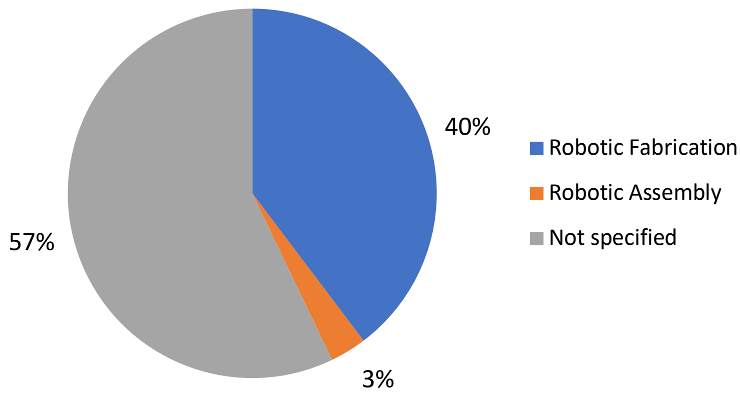

Figure 3. Publications in the CumInCAD database about robots by keywords.

Source: Author

The papers found in the CumInCAD give an overview of the growth over the past years and major category (fabrication) of use of robots in architecture. The papers on the Rob|Arch conference (2012, 2014, 2016 and 2018), FABRICATE conference (2011, 2014, 2017 and 2020), Construction Robotics journal (from 2017 to 2022), and Made By Robots issue by Architectural Design (2014) were further analyzed considering the type of robot used and its specific use, totaling 247 papers. Papers regarding theoretical aspects of robots in architecture or based on software and user interface were excluded from the analysis due to the lack of practical experiments and uses. Since the conferences and journals did not occur or were not published every year, we analyzed the whole period of 2011 to 2022.

The types of robots used (Figure 4) and their respective categories (Table 2) were identified. The robotic arm was the most common type among the ten types of robots identified (considering that a robotic arm was classified both into fixed and movable categories), being used in almost 88% of the experiments, especially of an industrial model with minor or no modifications. Cartesian robots and drones are usually also commercial models, comprehending about 2.8% and 2.4% of the experiments, respectively. Therefore, the other eight types of robots used comprehended only 6.8% of the experiments.

As showed before, robotic arms were historically the first and most used robots in industry. According to the World Robotics 2019, the number of new robotic arms installed in 2018 were around ten times the number of other robots installed. They were also used in several experiments of the Gramazio Kohler Research and ICD. Some authors point out that this wide use is due to its flexibility, degrees of freedom, precision, safety, reduction of their cost on the last years, and the possibility of being equipped with almost any tool (REINHARDT, SAUNDERS, BURRY, 2016; BRELL-COCKAN, BRAUMANN, 2012; BONWETSCH, GRAMAZIO, KOHLER, 2007; BUDIG et al, 2014; MIRJAN, AUGUGLIARO, ANDREA, 2016), thus being extremely interesting to be used in the field of architecture (HACK et al, 2014). Its use is so wide that some authors incorrectly use the term “robot” as a synonym for “robotic arm.”

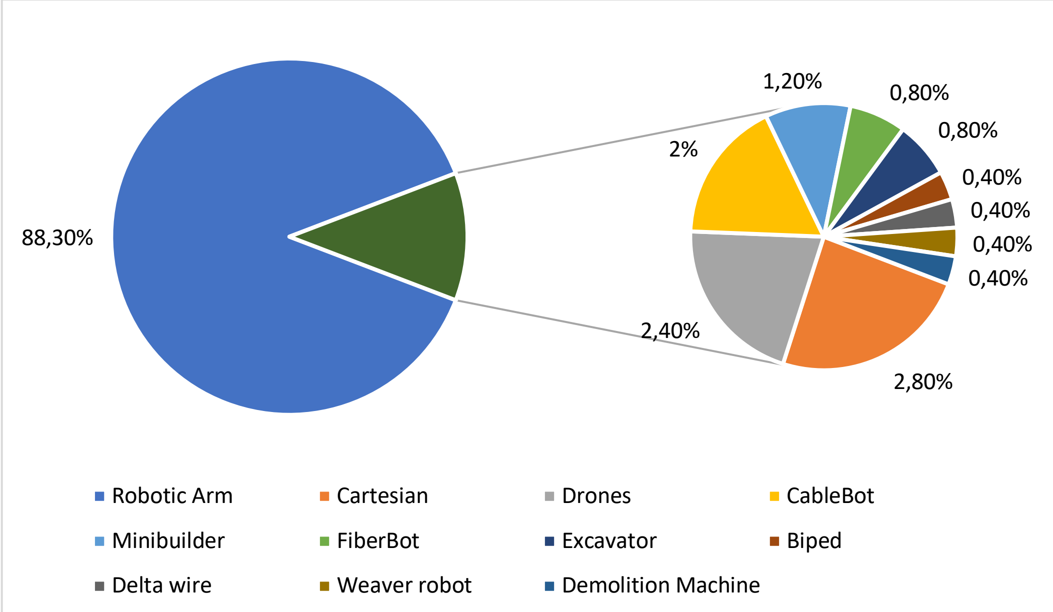

Figure 4. Types of robots identifed and their frequency.

Source: Author

Table 2. Classification of robots identified.

Source: Author

Level 1	Hard Robots					Soft Robots
Level 3	Nonredundant	Redundant		Hyperredundant		
Level 4	Fixed	Fixed	Movable	Fixed	Movable	
Types of Robots	- CableBot - Cartesian - Weaver robot - Delta wire	- Robotic Arm	- Robotic Arm (association with autonomous vehicle) - Excavator		- Drone -MiniBuilder - Fiberbot - Biped - Demolition Machine	

The other types of robots are often non-commercial, being developed by the author or research group itself (based or not on modifications of existing projects and products). They appeared only in three categories: fixed nonredundant robots, movable redundant robots and movable hyperredundant robots. The analyzed papers showed no examples of hyperredundant fixed robots, continuum robots or soft robots applied in architecture.

Regarding the production processes, the use of robots was first categorized under two main groups: fabrication and assembly. Fabrication includes any process in which the shape or properties of the material used are modified, such as in 3D printing, milling, and wire cutting. In turn, any process in which the object or component is just positioned or connected, without modifying its properties, was considered as assembly. Thirty-six different uses were identified in the analyzed papers, and the major 17 of these were categorized (Table 3). Uses that were considered specific and appeared in only one paper were combined in the category “others,” which sum 19 different uses in the fabrication category using robotic arm and 2 uses also in the fabrication category using the demolition machine and excavator. Although only one paper cited the possibility of using a robotic arm as disassembling tool, this use was considered in our classification, for being a unique approach compared to the other ones.

Fabrication:	Assembly:
- Milling (2D-3D): volumes and planks - Milling (3D): linear elements and beams - Sawing: natural logs - Wire cutting (hot wire or saw-wire) - Sheet bending - Bar bending - Cold metal forming - 3D printing - Concrete aspersion - Clay modelling - Thermoforming - Weaving with resin[1] - Others	- Stacking (2D or 2,5D); - Positioning objects (3D); - Traditional weaving[1] - Collaborative welding - Disassembling

[1]Traditional weaving just assembles the thread, not changing its properties, thus being considered an assembly process. In turn, weaving with resin changes the properties of the thread by adding a stiffener component, thus being considered a fabrication process.

Table 3. Robotic uses categorized by Fabrication and Assembly.

Source: Author

Around 77% of the papers analyzed are about fabrication experiments and only 23% about assembly – similarly to the trend on papers from CumInCAD database. In about 46% of the fabrication experiments, such as 3D printing experiments, the final product did not require any assembling, while the other 54% always required some level of assembly. Therefore, more than 41% of all experiments described in the papers still required the use of manual assembly. The distribution of types of robots used in fabrication (Figure 5) and assembling (Figure 6) follows the trend seen above, with the major use of robotic arms (respectively, 91% and 80%).

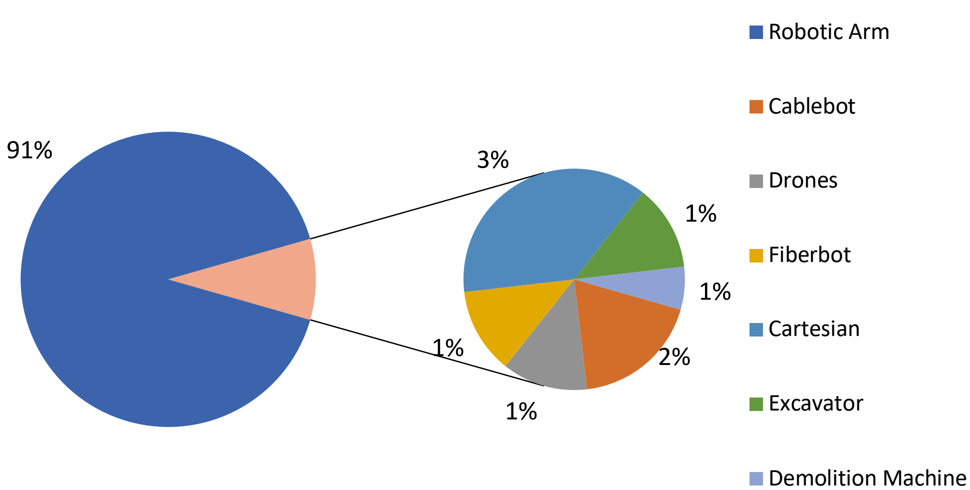

Figure 5. Distribution of robots used for fabrication by type.

Source: Author

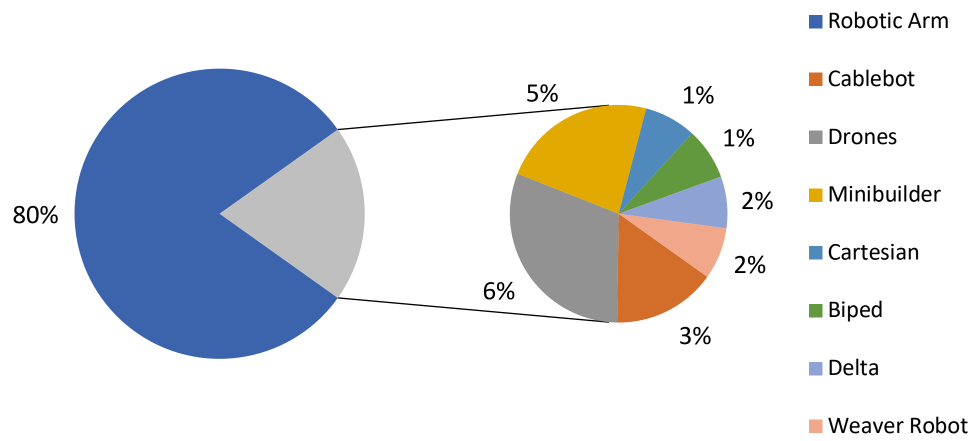

Figure 6. Distribution of robots used for azzembly by type.

Source: Author

Except for the robotic arm, all other types of robots (CableBot, drones, minibuilder, fiberbot, Cartesian, weaver, delta wire, biped, excavator and demolition machine) had only six uses: stacking, traditional weaving, weaving with resin, 3D printing, stone splitting and earth-moving tasks. Except for stone splitting and earth-moving tasks, all other 36 uses appeared in experiments that used robotic arms (Table 4). Since the processes of milling volumes and beams are quite similar, both were grouped into the "milling" category, as well as stacking and positioning objects, which were grouped into "stacking/positioning". The five main uses were 3D-printing, stacking/positioning objects, milling, wire cutting, and weaving with resin (Figure 7). These uses sum 69% of the experiments, with predominance of 3D-printing (26.3% of the total).

Table 4. Uses and types of robots.

Source: Author

		Robotic arm	Cablebot	Drones	Minibuilder	Fiberbot	Cartesian	Biped	Delta	Weaver Robot	Demolition Machine	Excavator
Fabrication	Milling	✓										
	Sawing	✓										
	Wire cutting	✓										
	3D Printing	✓	✓				✓					
	Sheet bending	✓										
	Bar bending	✓										
	Cold forming	✓										
	Thermoforming	✓										
	Concrete aspersion	✓										
	Clay modelling	✓										
	Weaving with resin	✓		✓		✓						
	Others	✓									✓	✓
Assembling	Stacking/Positioning	✓	✓	✓				✓				
	Traditional weaving	✓		✓	✓				✓	✓		
	Welding	✓										
	Disassembling	✓										

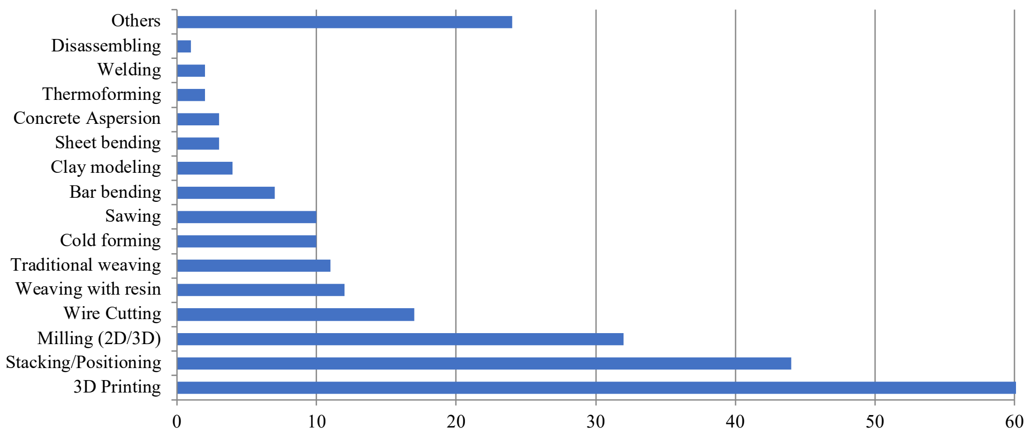

Figure 7. Major uses for robots in architecture.

Source: Author

RESULTS AND DISCUSSION

In this paper, we analyzed the trends of the use of robots in architecture over the past decade, both in the annual CAD conferences using CumInCAD and in specific events and publications. The analyzed papers present experiments based on the creative exploration of robots rather than the mere substitution of manual labor. Even experiments such as brick stacking brings complex shapes that would not be achieved manually.

The analysis of robot's definition and classification shows that several categories and types of robots were little or no explored in the field of architecture. For example, soft robots accounted for less than 2% of the papers on robots found in the CumInCAD database and were completely absent on the analyzed events and publications. Although their history is quite recent, Google Scholar shows an increase in the number of papers on soft robots outside the architectural field, going from 67 papers in 2010 to 5.230 in 2022. This trend was not followed in the architectural field.

Hard robots usually have high precision and use materials to avoid deformation, being easy to determine its position and movements (RUS, TOLLEY, 2015; TRIVEDI et al, 2008). Considering that complex shapes and low-tolerance architecture demands high precision, the low use of soft robots in these segments is justifiable. Soft robots might have a lower precision, but they can easily adapt to different shapes and environments and be more resistant to impacts (MANTI, CACUCCIOLO, CIANCHETTI, 2016; TRIVEDI et al, 2008; GARCIA et al, 2007; MUXFELDT, KLUTH, KUBUS, 2014). In turn, hybrid or semi-soft robots may provide a balance between precision, adaptation, and resistance.

Robotic arm was the most common type of robot used (88%), followed by Cartesians robots (2.8%), drones (2.4%) and Cablebots (2%). This might be due to historical and commercial reasons, as robotic arms are the most common type of robot commercially available, or due to its flexibility. Such a higher rate may also be due to an affinity towards the anthropomorphic characteristics of a robotic arm, such as its movements, which mimic that of a real arm – and literally carry the name "arm," – and its use to substitute humans in complex and repetitive tasks that require precision. Despite its flexibility, robotic arms also have limitations and may not be the best solution to all tasks. Some examples try to amplify the scope of operation of the robotic arm by using horizontal tracks (BONWETSCH, GRAMAZIO, KOHLER, 2007), vertical axes (AEJMELAEUS-LINDSTROM et al, 2017), or association with other robots, such as autonomous vehicles (HELM et al, 2014).

Nevertheless, the volume and way that a robotic arm works may be an obstacle in some tasks, such as in some weaving examples. In the case of the ICD/ITKE 2016/2017 pavilion, this was solved by using a drone in collaboration with the robotic arms (FELBRICH, FRUH, PADRO, 2017; SOLLY, FRUEH, SAFFARIAN, 2018). The angles of a robotic arm likewise pose limitations to milling (ROBELLER, WEINAND, 2016) and generating sequences of movements that avoid collisions (SONDERGAARD, AMIR, EVERSMANN, 2016). Therefore, one should always evaluate whether the robotic arm is the most suitable robot for certain tasks, geometries and environments.

Other types of robots found in this survey usually have a lower cost than an industrial robotic arm – even for some commercial examples, such as drones – enabling their use in swarms or even in collaboration with other types of robots. They also have different characteristics that influence the choice of robot used.

Regarding the fabrication and assembly uses, most of the experiments on the events and journals focus on fabrication (77%), and a considerable number of experiments still required manual assembly. Some of these are as simple as connecting a few pieces, relying on numerous techniques that aim at facilitating the process, such as custom joints for each pair of pieces. However, in other cases, a deeper exploration of robotic assembly could be beneficial to the experiment, due to its complexity and creative possibilities.

Interestingly, we found 3D printing to be the most common use of robots, accounting for 26.3% of the experiments. The item “3D Printing” comprehends polymer FDM printing, as well as metal printing, clay, concrete, and others; therefore, future reviews should further analyze this use of robots. The following most common use of robots was for stacking/positioning, featuring in about 18% of the experiments. All “assembling” uses represent only 23% of all experiments, which means that stacking/positioning comprehends almost 80% of all assembly experiments.

Milling and wire cutting were the third and fourth most common use, respectively, followed by weaving with resin and traditional weaving, showing a certain interest in these techniques – especially that with resin (or polymer compounds), due to its capability of being soft and easy to mold before the curing. This technique is comparable to 3D printing (“soft” during the pour and hardening after that) and has potential to future studies.

Overall, there has been a decrease in the number of publications regarding robots on the CumInCAD database and the number of papers on the Construction Robotics Journal has also decreased in 2021 and 2022 compared to 2020. This may be due to problems related to the COVID-19 crisis, as cited before, or may indicate a shift on the field. Although there were not any conferences since the beginning of 2020, some events occurred in the end of 2022, such as the symposium “Robots That Build: The Extension Of Man”. The next Rob|Arch and Fabricate conferences are schedule to happen in 2023 and 2024, respectively. In those conferences it will be possible to understand if the decrease in the number of publications was due to the pandemics or to shifts and changes in the field, such as a new focus on the software and user interface rather than on applications.

To summarize, the five major research gaps we identified were:

1. There is a lack of exploration of soft robots or hybrid/semi-soft robots in architecture.
2. No paper regarding the use of continuum robots or SCARA robots in architecture was found – although it is known that SCARA robots have already been used in the industry for 3D printed houses.
3. Robotic assembly only corresponds to about a fourth of the experiments, although many experiments that used robotic fabrication still required some level of assembly.

4. Robotic assembly usually corresponds to stacking/positioning, therefore other types of assembly could be more explored.
5. Only a single experiment employed robots to modify the arrangement of architectural elements over time, allowing the architecture to adapt to the environmental conditions. In contrast, all the remaining experiments considered the final design as static.

Also, the major five research trends we identified were:

1. Robotic arms are the most used robot, usually due to its flexibility and possibility to be used in several projects.
2. There is a focus on robotic fabrication rather than assembly.
3. Most of the uses regarding robots in architecture are related to different types of 3D printing, those do not always require any assembly.
4. Stacking/positioning is the second most common use of robots.
5. The redundant and hyperredundant robots used were usually movable (except robotic arms), showing a probable trend towards movable robots, probably due to limitations regarding fixed robots.

CONCLUSIONS

Robots are increasingly present in our daily-life and its use in the field of architecture grows each year. Its use can be both related to productivity or to creative exploration, in this paper considered, respectively, as a construction application and an architectural application. The use of robots in construction can improve its precision, schedule, and cost, while reducing the time spent on hazardous or repetitive tasks (BROQUE. FISCHER, 2022). While this approach addresses some important problems, it does not take full advantage of the robot's capabilities. The creative exploration tends to push the boundaries of applied robotics and how it affects the design, focusing on integrated solutions.

Different associations, journals, symposiums, and conferences will focus on one approach or the other, depending on its objectives. The IAARC (International Association for Automation and Robotics in Construction), as well as the ISARC conferences, focus on the construction applications of robots. The Rob|Arch and FABRICATE conferences, for example, focus on the architectural application of robots. Ideally, it will be possible to combine both, with productivity enabling the creative exploration in a broader way, into a new architecture.

If NURBS modelling, parametric design, and other computational tools allowed us to design complex-shaped architecture, robots allow an easier and more precise fabrication and assembly. More than that, they allow a creative exploration and expression that was not possible before. Although the possibilities offered by using robots in architecture are countless, only a few types of robots have been used up to date.

This paper gathered information on the state-of-art of robots applied to architecture, demonstrating some gaps and possibilities of research in the field. Robotic applications in architecture go beyond the mere substitution of manual labor; rather, they allow the use of new techniques, materials, shapes, and complexity. These applications also go beyond using a robotic arm as a standard solution. They have limitations and might not be the most suitable or cheap resource to be used in that task.

Given the scope of this article, other questions were not addressed, such as: should any particular tasks be performed by a robot? If so, how can a robot improve it? How can robotic labor be integrated with human labor? And how can both collaborate to get the most out of robots as creativity-driven tool?

Another important factor grasped from the types of robots used is the need for collaboration between research groups from the fields of architecture, robotics and computing. This is fundamental for the development of new robots specifically aimed for architecture, so that the field would not depend exclusively on commercial robots.

This study also indicates a greater focus on fabrication processes, thus pointing to the need for more exploration on assembly. Chronologically, there was first an automation of the design process, followed by fabrication (with digital fabrication techniques, some showed in this paper). In this sense, the next logical automation should be that of the assembling process, in which case we may employ the term “digital assembly.”

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