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Robotics in Construction: State-of-Art of On-site Advanced Devices

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Abstract

Recently, robotic technologies have significantly improved, bringing considerable enhancements in many sectors; the main objective of this paper is to figure out if these innovations have also involved the building industry. To achieve this purpose, it has been considered crucial to first reshape and clarify some concepts, incorporating a much more flexible understanding of the term "robot", as well as the formulation of its future potential. Subsequently, it has been carried out an analysis of the various advanced devices that are currently available to be employed in the construction processes; the review includes a thorough classification of construction robots, divided into 18 families reflecting their purpose of use, and a dissection based on the term used to define them. The attention has been focused on the most updated and recent robots and, in their absence, on the most advanced machines prevailing. This operation has been achieved taking into account the development history of construction robots, as well as the analyses and classifications previously conducted, reconsidering them according to the just mentioned reflections. Furthermore, an in-depth exploration of the exoskeletons, as well as on a sophisticated robot recently developed by Schindler Group has been executed.

Keywords: Definition; robot; exoskeleton; autonomy; automated construction

1. Introduction

1.1. Definition of Robot

The branch of robotics is varied to such an extent that there is not even a commonly agreed definition for the term "robot", nor a universally recognized categorization. It is also important to consider that the term "robot" has evolved over time, aside from the technological progress and evolution of robotic artifacts. The definition given in 1979 by the Robot Institute of America (RIA) was "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of task". Today most of these definitions no longer fit with advances in the field.

A multitude of robots' classifications and valuations have been issued by different organizations and entities since. The Cambridge Dictionary defines the term robot as "a machine controlled by a computer that is used to perform jobs automatically" (Cambridge Dictionary 2020). Others point out their ability to perform sequences of actions automatically, or resemblance to humans in regards to their capability of reproducing behaviors (Oxford English Dictionary 2020, Merriam-Webster Dictionary 2020).

The International Federation of Robotics (IFR), recognizes the definition of the term "manipulating industrial robot" stated by the International Organization for Standardization (ISO) in ISO 8373: an "automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes which may be either fixed in place or mobile for use in industrial automation applications" (IFR 2019). As defined in ISO, a certain degree of autonomy is required. This degree of autonomy, which differentiates robots and other devices, is taken to mean "the ability to perform intended tasks based on current state and sensing, without human intervention". Therefore, the IFR's definition of robot comprises completely autonomous systems and mechanisms with partial autonomy, those with a certain human-robot interaction degree, and even full teleoperated devices (IFR 2019). ISO's standards on robotics are currently under revision, pending to be updated to try to outline and gather a common and comprehensive definition in this respect.

The Japan Robot Association (JARA, previously JIRA), defines robots regarding their level of self-sufficiency around six different categories in order of increasing autonomy: manual handling devices, fixed sequence robots, variable sequence robots, playback robots, numerical control robots, and intelligent robots (Coiffet and Chirouze 1983). Only the last category includes systems capable to sense the environment and respond to changes in order to continue performing their function. Opinions vary as to whether the first classes are considered robots in relation to other definitions. For instance, RIA does not contemplate classes 1 and 2 to be robots.

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Coalition), a public-private partnership between the European Commission and the robotics community, draws up a Multi-Annual Roadmap (MAR) updated every year and incorporating robot classification and evaluation. The MAR sets a series of abilities through which robots are classified, thoroughly defined over subcategories and their respective levels of development; the main abilities are Configurability, Adaptability, Interaction Ability, Dependability, Motion Ability, Manipulation Ability, Perception Ability, Decisional Ability, and Cognitive Ability. Analyzing the definitions of each level, it has been noted that a higher score obtainable by a robot in the various abilities corresponds to an increase of its capacity of carrying out a determined action autonomously. For example, a robot able to pick up objects with different shapes (level 8 of Grasping Ability, a subcategory of the Manipulation Ability), presents more versatility and so autonomy, compared to another robot which executes the same action on objects with known shape (level 3 of Grasping Ability). Therefore, it is possible to identify a direct correlation between a robot's degree of autonomy and its development level; the more it is independent in its tasks, the more it can be considered intelligent and sophisticated.

Taking into account the multiplicity of definitions and cataloging and in order to clarify the field of research as well as the terminology used, this paper has integrated both JARA and MAR studies with some considerations: the wide range of devices embraced by JARA's cataloging have been considered, yet only from level 6 onwards they have been named "robots", identifying instead as "machines" those included in the preceding classes.

In the following chapters, some considerations on construction robots have been outlined, by focusing on their current development level.

2. Overview of the Solutions Developed for on-site Application

Japan has been the first country working on the development of this technology with the intent of automating the on-site construction processes; as early as 1978, JIRA and MITI (Ministry of Trade and Industry), established a committee directed by Professor Yukio Hasegawa, with researchers of the main contractors taking part (Cousineau and Miura 1998). The first efforts led to the realization of simple devices able to repetitively carry out specific tasks (Bock and Linner 2016). The majority of these devices, which are defined as "STCRs" (single-task construction robots) by other authors but called "machines" within this paper, because of their low level of intelligence, have been subsequently integrated into more complex environments, in order to enhance their effectiveness. Indeed, from 1985 onwards, construction sites started to be structured and transformed into mobile factories, to overcome the lack of intelligence of the first machines available for on-site operations (Bock and Linner 2016). Though, this last method implies the whole construction site to be turned into a manufacturing facility, which is a rather inflexible environment that requires time to be set and results feasible almost exclusively in tall buildings projects. Anyways, since technology is constantly improving, robots can now be produced with smaller and more powerful components, and equipped with more advanced sensors and software; therefore, they can be much more autonomous and, at the same time, interact or cooperate with humans better than in the past. Therefore, today's approach is to develop advanced robots that are able to operate in unstructured environments, being able to adapt to various building sites without completely altering the procedures of conventional construction (Bock and Linner 2016). Anyways, other aspects apart from robots' technology itself must be further deepened in order to actuate a significant improvement in construction processes.

With these premises, the investigated devices have been organized into 18 families, on the basis of their purpose of use. The classification, which incorporates and reorganizes the distinctions already developed by other authors, e.g. (Levy 1990, Jackson 1990, Cousineau and Miura 1998, Russell and Kim 2002, Best and de Valence 2002, Bock and Linner 2016), includes devices with different degrees of development. However, within the analysis of the available technologies, the attention has been focused firstly on the most updated and recent robots and, in their absence, on the most advanced machines.

2.1. Families of Construction Devices: Robots and Advanced Machines

2.1.1. Site Measuring and Monitoring Robots

devices are developed to accomplish tasks that can vary from monitoring and measuring, to surveying and inspection. They reduce the time spent to carry out these operations

Figure 1. Site Measuring and Monitoring Robot

Figure 2. Site Measuring and Monitoring Robot.

and, at the same time, acquire a total number of data significantly greater than the one obtained with traditional methods. The application of these systems brings improvements to the overall productivity of construction as well, because the 3D information extracted from the multi-sensor robots can be incorporated into BIM technology and used in different design phases. Despite many substantial improvements can still be achieved in this task, the devices in this category can be considered robots, since they can be provided with numerous technologies, such as laser scanners, GPS receivers, cameras, magneto-meters or LiDAR (Light Detection and Ranging) systems, which also allow them to autonomously navigate and avoid obstacles when necessary. A subclassification within this category distinguishes terrestrial devices from aerial ones; the former are robotic platforms provided with wheels or chain tracks, while the latter are drones, also called UAVs (Unmanned Aerial Vehicles). In the second case, the robots can scan vast areas in a short time, but the number of equipped sensors used to increase accuracy largely affects the weight and the cost of the system, as well as the dimensions and the flight range.

2.1.2. Earth and Foundation Work Robots

These devices are capable of removing, loosening and lifting soil automatically; in fact, they are sufficiently developed to be considered as robots. The advantage brought by this equipment consists also in the possibility of connecting many robots to automate a variety of tasks and optimize times and operations, reducing the total cost of the projects. The category includes robotized conventional machines, such as dumpers and excavators, which have been transformed in robots, by equipping them with multi-sensor systems, and new electric automated vehicles. The former offer a solution for the site automation in the short term, not only because the technology they integrate is established and constantly under development, but also because these devices can be employed without requiring considerable modifications to the comprehensive building process, nor requesting large investments for companies. Instead, the latter cut down CO_2 emissions and noise, and they can be modular since they are designed from scratch. In this last case, the improvement consists also in the elimination of the waste time; by separating the device into multiple elements, for example the mobile robot and the loading platforms, the first one can be continuously operative while the second ones are alternatively filled with soil and transported.

Figure 3. Earth and Foundation Work Robots.

2.1.3. Reinforcement Positioning and Tying Robots

These devices, which have been recently developed and marketed to improve the productivity and free human workers from repetitive tasks that are harmful to health, can execute these operations with extreme precision and also through severe conditions, such as intense heat or heavy rain. The devices in question can be considered robots as they can be provided with cameras, sensors, and software that allow them to operate autonomously byautomatically moving and detecting bars intersections. Positioning robots are generally equipped with on-board storage for hauling a set of steel bars, a manipulator and an end-effector to complete the operation, while tying robots have been developed with different forms and technologies. Indeed, the category includes modular gantry-style robots that can cover the whole width of a bridge or much more compact robots which can be easily carried by a single worker.

2.1.4. 3D Structure Producing Machines (3D printers)

This family focuses on 3D printers applied to building construction, a process known as “Construction 4.0”. These devices can build houses or other architectonic elements by using extrusion technology, which is depositing a material layer by layer; indeed, paste-type material (e.g. concrete, earth materials, expansive foam, steel) is pushed through a nozzle to form layers. The market offers a lot of solutions, with a huge variety in dimensions and functioning methods; some construction 3D printers are conventional 3D printers scaled in dimensions and they have a gantry style, while others are substantially a mechanical arm, some of them are modular, while others are provided with chain tracks to be moved. Another solution is given from 3D mini-printers which have different tasks and work in parallel to build a structure with any dimensions, reducing the construction time, but the only example of this

Figure 4. Construction 3D Printer.

technology is not commercially available. 3D printers can build with eco-friendly materials and they do not produce much waste since the materials are printed on-demand. On the other hand, they require an expensive initial investment and they can only build house walls so far; in fact, the printing operations are generally stopped to let the workers install rebars, plumbing, and wiring. So, even though these devices can have an important role in the revolution of the construction sector, they have not been considered robot within this paper, since they just reproduce the information of the digital model.

2.1.5. Bricklaying Devices

Brickwork is still considered a crucial construction method, despite the innovations achieved in the building sector and the materials technology throughout the years. It is a hard, repetitive and dirty job, and so it has been studied how to automate the process since the ‘60s. The early prototypes were mounted on a rail parallel to the wall and could only move along it, depositing mortar and quickly inserting individual bricks; instead, the most recent devices can handle any variations in the wall pattern by starting from a digital model. Indeed, the analyzed devices have been considered relevant within this paper only when the entire paradigm of bricklaying has been rethought; bricks, in fact, had their form, size and weight progressively adapted to workers’ hands and capabilities, so when the human factor disappears from the equation, it makes sense to modify as well instruments, objects, and processes employed. Therefore, the most interesting solution within this category, even though it is still in the testing phase, is represented by a device which includes a robotic arm, a system of conveyor belts, a saw, a router, and a laser system, being able to erect an entire building using bigger blocks instead of normal bricks.

Figure 5. Bricklaying Robot.

This robot, which is integrated into a truck and moved on-site, needs only to be loaded with pallets of blocks. The software analyzes the 3D digital model of the building and calculates the number, shape, and position of each block needed for the construction. Then, it automatically conveys and places the blocks in the right position with the telescopic robotic arm, after having applied on them the precise amount of adhesive.

2.1.6. Concrete Distribution Machines

The analyzed devices that have been developed to carry out this task are mostly machines that are teleoperated or run in a preprogrammed mode. The various solutions differ considerably in dimensions and functioning systems. Stationary devices include both crane-like structures and smaller systems. The first ones are inflexible because of their large working space but can turn in more versatile systems being used, for instance, to raise machinery and other objects; instead, the second ones can be used on the single floors, being installed on the ground and moved manually or being anchored to a column. In this last case, the robot consists of a manipulator made up of multiple connected segments that create a sort of rudimentary robotic arm that winds horizontally. It is equipped with an end-effector employed to swing the hose through which the concrete is provided. Differently, mobile devices consist of wheel-based platforms that can enhance the operating range because of the possibility to move them on individual floors. They can speed up the overall process of concrete distribution by working in parallel. As mentioned, some of them can distribute the concrete in a pre-programmed manner, but they have not been considered robots because of their low degree of autonomy.

2.1.7. Concrete Levelling and Compaction Robots

These devices have been developed to obtain improvements on the quality of concrete by enhancing both compressive and flexural strength through mortar vibration. Timing requirements given by the curing process of the mortar are tight, and concrete floor compaction is a critical process that needs to be done within a limited time following pouring. Most devices belonging to this category are responsible for both leveling and compacting activities, which are usually linked because of the operating mechanism. The most advanced devices with these functions are laser-guided or satellite-guided robots; generally based on a body unit with integrated sensor elements (laser and alkali-sensitive sensors, conventional and spectrum cameras, etc.), these robots comprise a wide range of scales in response to construction sites' specificities. Major autonomy is observed in those robots applied to reduced dimension work fields, due to their adaptive and responsive capacities, including automatic redirecting and obstacle overcoming. Other devices, designed to operate within larger surfaces, can present gantry-style structures attached to the ground through guiding rails, and their efficiency generally increases with the size of the floor area to be treated.

2.1.8. Concrete Finishing Robots

Devices able to execute floor finishing tasks have been developed to relieve workers from uncomfortable positions while carrying out these operations and to improve productivity, especially in larger buildings. The most evolved devices are robots equipped with control systems, that is sensors such as laser scanners and gyroscopes, which allow them to work and navigate autonomously, by recognizing their surroundings and avoiding the obstacles. The laser systems, which are also used to scan the irregularities of the floor, can be integrated into the robots or be part of external navigation equipment. Furthermore, different configurations of functioning systems are developed to obtain the required finishing; most robots use rotating trowel blades or discs, which are pushed toward the surface with a certain pressure, while others utilize controllable vibrating blades. Because of their weight, the operation of moving these robots to the different floors to continue the work can result inconvenient, but this deficiency has been overcome by designing modular robots that can be disassembled into lighter pieces.

2.1.9. Site Logistics Robots

Devices able to optimize site logistics operations can save money, free workmen from heavy duties, and enhance productivity, especially in the most extended (horizontally or vertically) construction sites. Therefore, in this category are included devices able to perform vertical and horizontal deliveries, but also storage activities. Moreover, these operations can be synchronized through a centralized scheduling system, in order to implement the efficiency of the overall process, by moving the materials from one floor to another, and across their extension. Since the devices in this family are significantly different from each other, ranging from mini-logistics horizontal solutions to massive lift platforms, the load capacities, speeds and degree of intelligence are variable. The smallest and advanced solutions are robots integrating AGV systems for the mobility; these autonomous robots are able to load materials and choose the route by themselves, detecting the dimensions of materials and avoiding the collision with other objects or people. By virtue of their sensors such as laser scanners, they can stop when they encounter an impediment and resume the movement when detecting that the road is clear; moreover, they can recalculate the route if the obstacle does not move. Their technology also permits them to autonomously get on elevators for moving to other floors. Otherwise, cheaper and less sophisticated devices that use pre-marked traveling routes are available.

Figure 6. Logistics Robot.

2.1.10. Welding Robots

The necessity to automated such a repetitive and hazardous task led to the development of devices that are also able to implement the quality of the final product. They are indeed more accurate than humans since they do not get tired, and are able, for example, to weld simultaneously the opposite sides of a steel element to avoid any possible distortion. The most advanced devices in this family are robots equipped with laser scanner, being able to detect the shape of the components they have to weld and the groove between them, in order to select the most suitable settings and ultimate the operation; moreover, they can be provided with other technologies, such as light sensors, arc sensors, or charge-coupled device cameras, used to control several parameters, like the welding quality, eventual failures, or welding wire lacks. They can as well detect the presence of workers in the surroundings and automatically stop the procedure if necessary. The devices in this category differ for working mechanism and scale some of them can be connected to the steel structure they have to work on, while others are mobile units that can be easily shifted from a column to another since they are provided with wheeled platforms and do not require any installation; in the first case, they can be equipped with guide rails to carry out the task by revolving around the component.

2.1.11. Facade Installation Machines

These devices have been developed to facilitate the installation of heavy and fragile components such as facade panels, which need to be moved with extreme precision; unfortunately, the level of automation achieved to this day by facade installations systems is not sufficient to consider them as robots. Despite the considerable progress and the sophistication acquired by the technology, the devices available in the market today do not meet the principles explained at the beginning of this research, which is the capacity of sense-elaborate-act. In fact, the current systems have been predominantly designed to operate in cooperation with humans, rather than in total autonomy. This family comprises devices with diverse forms, working mechanisms and degrees of autonomy; on the small/medium scale, there are manipulators mounted on mobile platforms which can be moved by workmen on the desired location across the different floors, while larger solutions are represented by more complex systems that also include the logistics of the panels. One of these solutions implies, for example, the installation of a rail skeleton on the outside the buildings; another system, which is more innovative but still in the research phase, consists of a cable-driven parallel robot that covers the entire facade and is equipped with a stabilized end-effector.

2.1.12.Tile Setting and Floor Finishing Devices

These devices are used to achieve the monotonous and repetitive tasks in question, improving the performance, the quality of the finished surfaces, and the safety in the construction sites. Their work can be subdivided into two different tasks: the laying down and spread of strips of mortar and the placing of rows of tiles over it. Some devices have been developed as separated units performing collaborative operations, while a higher level of autonomy is accomplished when the robots integrate both actions, but these solutions are not commercially available yet. Actually, there are not many examples of tiling robots and the most interesting and advanced solutions have been developed only by universities. The setting of these robots can be done manually or autonomously through the use of sensors, such as laser system, which are useful not only to establish vertical and horizontal reference lines for a more precise calibration but also to move through the given space by employing reference points, when the robots are equipped with wheels. Among the older devices, instead, there is a machine with a gantry-style structure and equipped with a robotic arm, that is able to cover larger areas, carrying out facade cladding; anyways, the preparation of the surfaces must be done by humans, as well as the installation of the device. Finally, automated paving machines for roads or pathways are already in the market and are suitable for outdoor use.

2.1.13. Facade Coating and Painting Robots

These devices have been introduced to prevent workers from the exposition to noxious paint particles, to reduce the potential risks due by working at extreme heights and to improve the quality of the finished work, since they are provided with specific spray nozzles, which can be regulated accurately, as well as other parameters, such as spray pressure and speed. They are designed with various forms and use different functioning mechanisms to accomplish their tasks; in addition, some of them have a specific design integrated with the facade they have to cover. In fact, there are devices able to move along the facade through guide rails, others that are suspended from the ceiling, and those provided with vacuum systems. Furthermore, some robots can operate on different facade surfaces and, if equipped with specific sensors, detect and avoid obstacles such as facade openings; others, whose end-effectors can be switched, are able not only to paint colored images but also to automate other finishing operations, such as cleaning or polishing. These robots have reached a considerable level of automation, nonetheless, they must be used only on almost flat facades and, to be effective, they have to cover a surface of at least 2000m^2 (Cousineau and Miura 1998).

2.1.14. Interior Finishing Robots

These devices have been constantly improved so as to achieve a high level of autonomy and be considered robots. They include an extensive variety of working mechanisms since interior finishing jobs comprise different tasks; in fact, there are manipulators mounted on mobile platforms that can apply plaster, mortar or wallpaper, and others able to install wall and ceiling panels, by making measurements and drilling holes. The most sophisticated robots can accomplish the assigned task in complete autonomy while others, less advanced, have been developed to assist human workers; the first ones can also be guided by integrated or external laser systems. In the case of the installation of ceiling panels, workmen are required only to set the desired drilling pattern or select it from BIM files; then, the robot can be placed just approximately, since it is able to autonomously find the precise position. Wallpapering operations have been automated as well, by realizing a robot able to cover with paper vertical sections of a wall in sequence; in fact, it can scan the surroundings, aligning itself to the surface by means of a distance sensor. Recently, an autonomous plastering robot has been unveiled; it is equipped with several advanced sensors and algorithms that allow monitoring the progress, comparing them to BIM, and 3D map its environment.

2.1.15. Fireproof Coating Robots

These devices have been improved for a long time; in fact, the first device developed to be a construction robot (1983) had the aim to carry out fireproof coating tasks (Cousineau and Miura 1998). They are intended to bring improvements in terms of efficiency, performance and working conditions. The most diffuse robots consist of mobile platforms equipped with manipulators; literature review reports also an example of a fireproof coating robot provided with a mechanism that allows its movement along the structure that needs to be sprayed. Both typologies must be equipped with mixing units, pumps, and hoses for the supply of the coating material. Furthermore, the development process highlights, as often happens, a gradual implementation of the autonomy of these devices, indeed, the most advanced robots in this family are able to independently execute this specific operation. Platform-based robots are usually able to adjust to different height by virtue of lifting systems, but are also designed to deal with columns and beams with distinct forms; being integrated with sensors and laser systems they can identify the profiles and then complete the operation due to robotic manipulators with high levels of DOF. Some of them can be linked to BIM as well.

2.1.16. Demolition and Renovation Devices

These devices have been developed to operate in potentially hazardous environments, in order to accomplish dismantling or renovation tasks, such as building demolition and asbestos removal; indeed, the most advanced device in this family is represented by an autonomous robot able to carry out this last operation, identifying the location and the shape of the beams to treat. It works similarly to fireproof coating robots, and therefore it is realized more or less with the same components: a mobile platform adjustable in height and a robotic arm. This robot is also provided with a rotary brush and a vacuum suction apparatus used to gather asbestos particles. Furthermore, various cameras help to supervise or control the process from a safe distance. Otherwise, devices whose processes have not been automatized yet include remote-controlled machines used to demolish existing structures. One of them consists of a manipulator, equipped with a water jet system and a vacuum one, mounted on a mobile platform; this machine is supposed to remove the concrete with the aid of pressurized water (hydrodemolition) and then separate the two elements with a centrifuge, recycling and reusing the second one, but it is still on a project level. For complete information, other devices have been designed in the past with the task of preparing older layers of concrete that needed to be integrated with a new pour and for the application of carbon fiber in order to reinforce existing concrete structures with vertical development.

Figure 7. Teleoperated Demolition Machine.

2.1.17. Floor Cleaning Robots

Although maintenance and service devices have not been considered in this list of families, a category containing floor cleaning robots has been included, to group all those devices that can be used at construction sites, which free human workers from repetitive and time-consuming labors. These robots generally consist of AGVs provided with vacuum mechanisms and other sensors (lasers, infrared, gyroscopic, ultrasonic, and cameras) to avoid obstacles and plan the cleaning route. They are not too different from similar robots employed in other contexts, except for the appropriate reinforcements in dimensions and power, useful for avoiding eventual overheating or damages caused by actuating in a rougher environment. The differences between the distinct devices are reduced to modifications in the technology used to implement the autonomous navigation system or consist of adjustments of the end-effectors applied. The market offers as well an example of a floor cleaning robot that has been developed only to gather in a determined area of the construction site dust and other debris, which are after collected and removed manually; in this way, the amount of waste collected can be higher. These robots can work not only during the working hours but also at night, tidying the site up and getting it ready by the arrival of workers.

2.2.18. Floor Marking Robots

Floor marking robots are essentially autonomous guided printers that are able to reproduce in 1:1 scale the information contained in the construction plans, by processing CAD drawings or BIM files. These devices eliminate the possibility of misunderstandings between the parties involved during the transmission of data and exclude the eventuality of mistakes while realizing the measurements and manual marking. So, they bring advantages in terms of time savings and precision, by carrying out all these operations at once; furthermore, they can operate overnight, setting the site for the following day. Therefore, these robots have not been developed to replace humans, since their usage makes sense because it is strictly related to manual work; in fact, marking operations would be skipped if robots integrated with BIM models were developed to carry out the subsequent operations. Anyways, as an intermediate step toward the complete automation of construction processes, this kind of robots turns out to be very useful; in fact, it is possible to set them not only to draw crosses or lines on the floor indicating the position of partition walls, but also to print other useful information, such as the height at which the equipment must be installed, the position of anchor bolts, piping, ducts, and even their name. The autonomous motion of these robots is usually obtained by integrating GNSS systems or linking them via Wi-Fi with conventional total stations, which constantly measure their position. These devices are generally equipped with ink-jet systems, even though the adoption of pen plotter systems and external laser instruments can reduce the weight of robots and their cost.

2.2. Schindler's R.I.S.E: Robotic Installation System for Elevators

A step forward regarding the automatization of construction processes has been taken by Schindler Group, by developing and revealing a sophisticated robot called R.I.S.E., the acronym of "Robotic Installation System for Elevators". It is an advanced system, which integrates several sensors and end-effectors, that is employed to facilitate the installation of elevators; it consists of a self-climbing platform, provided with a robotic arm, that measures the elevator shaft, identifies the presence of rebars by scanning the walls, and drills holes with high precision, concluding the process by accurately setting the anchor bolts. The repetitive and physically demanding operation of drilling multiple holes in concrete walls is conducted by the robot at every floor, in order to place the dowels on which the elevator guides will be mounted; for this reason, the advantages are even greater in high rise installation, where this quite simple and highly repetitive task which, however, demand significant precision, must be repeated hundreds of times. This innovative system, which has reached a remarkable level of development, has been recently employed by its manufacturer in several commercial complexes in Europe, even though it is not available on the market yet. The high sophistication of this technology may have also been achieved because this specific robot operates in the elevator shaft which is almost an ideal framework, being a structured environment free of humans.

2.3. Exoskeletons

Besides the above-mentioned robots, the market offers other devices that potentially can push towards an upgrade of building operations. In fact, in a survey reported in the "2019 Q4 Commercial Construction Index", which has been drawn up by USG Corporation and U.S. Chamber of Commerce, most of the interviewed contractors believe that advanced technologies can increase productivity (78%), improve schedule (75%) and enhance safety (79%) (USG Corporation and U.S. Chamber of Commerce 2019). In particular, wearable devices have obtained relevant percentages in this survey, to the point that 33% of the contractors consider to adopt them in the next three years.

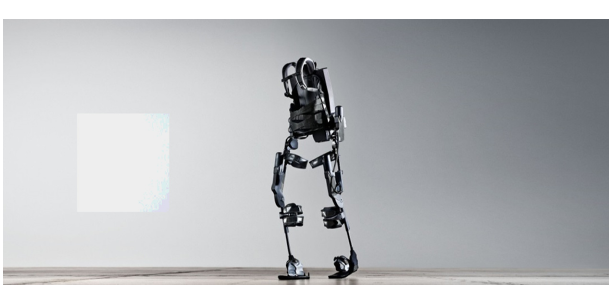

Figure 8. Example of Exoskeleton.

Exoskeletons, sometimes referred to as exosuits, are wearable accessories designed to enhance, reinforce or restore human capacities in terms of strength, speed, resistance, and precision; indeed, they allow workmen to perform their tasks more comfortably and with less effort, minimizing strains and injuries by providing lift support, weight dispersion, and posture correction.

Despite the design of previous basic prototypes created to assist limb movement, the "Hardiman" project, conducted by engineer Ralph Mosher in collaboration with General Electric and the US Armed Forces between 1965 and 1971 (Axel, et al. 2018), can be considered the actual starting point for the following developments of these devices, which nowadays are used in several fields, such as the military, the industrial and the medical ones.

In the construction sector, which is behind the others in terms of technology, exoskeletons full employment could be quicker than the robots one, since they require lower investments and they hardly encounter the opposition of workers unions concerned about the disappearance of jobs. Anyways, despite being developed as tools for workers rather than instruments to replace them and looking like an alternative or even an obstacle to the diffusion of autonomous equipment, they instead might be an intermediate step to promote the integration of robotics in the construction field, since they are usually developed by companies that also produce robots. Moreover, if their programming can still be considered simpler than the one needed for automated devices, on the other hand, exoskeletons imply to investigate new aspects of human-robot interaction, different components such as biosensors, and particular control algorithms.

In fact, exoskeletons can be designed with various levels of complexity, depending on their working system and technology; not only they can cover the entire body, just some extremities, or a specific body articulation, but also they can be made out of rigid materials such as metal or carbon fiber, or rather be composed of soft and elastic parts.

It is possible to identify 4 categories of industrial exoskeletons: a) back-assist devices, which supply assistance to the lumbar spine while raising objects, b) shoulder and arm-assist devices, as well as c) tool-holding devices, which help the upper limbs during overhead operations or while handling heavy instruments, and finally d) leg-assist devices, which support the joint movement of the lower extremities or may be used as alternative chairs (Howard, et al. 2020).

However, the main distinction between exoskeletons lies in the fact that they can be entirely passive, being propelled by human movements and working through materials, spring or dampers, or instead active, that is powered by batteries, electric motors, and equipped with sensors and actuators. Passive systems, also called mechanical exoskeletons, generally work by taking the weight from a specific area of the body and redistributing it to another one, for example from the arms and shoulders to the core and waist. Active systems are typically more powerful and allow to handle more weight, increasing the strength where needed. Moreover, some of them can be equipped with additional handling devices or independent robotic arms.

Although, the solutions that have more advanced capacities, at the same time require a higher degree of engineering and development; therefore, while several prototypes have been made, tested and refined, several studies have been focused on solutions with simpler functioning and lower costs, in order to accelerate the transition process from the R&D stage to the production one, since these devices can bring significant advantages.

Exoskeletons manufacturers claim, inter alia, a reduction of the risk of work?related musculoskeletal disorders (WMSDs); indeed, the rate of these problems, which are the principal injuries among workers and are caused, for more than one third, by overexertion in lifting, is 16% higher in construction than in all industries combined (Zingman, et al. 2017). This factor affects the economy as well and it is rapidly increasing; in the United States, for example, WMSDs had an economic impact of 367.1 billion dollars in 1996, while reaching 796.3 billion dollars in 2009-2011, with an increase of 117% (Howard, et al. 2020).

One of the commercially available exoskeletons, the “EksoVest” produced by Ekso Bionics, has indeed been developed to support workers during overhead tasks and works by exploiting a hydraulic system to redistribute the loads. It can provide up to 6.8 kg of vertical lift per arm, by means of a gas spring, to provide additional support during overhead tasks; it is worn like a backpack, secured to the hips and incorporates two mechanical shoulders.

EksoVest has been tested in a lab-based study, where 18 participants experienced its usability and 12 of them carried-out the simulated work for precise analyses. The experiment supported the efficacy of this particular device in decreasing physical requirements during drilling and wiring operations, yet the study presents some limitations, as the non-coverage of the complete range of the working-age population (15-64 years old, compared to 20-40 of the investigation), the absence of skilled workers as testers, the execution of the test in a controlled laboratory environment, and lastly, the impossibility of testing long-term effects (Nussbaum and Kim 2017).

However, there are also other studies and field trials, reported by the National Institute for Occupational Safety and Health of the United States (NIOSH), that investigate the possibility of exoskeletons to reduce the risk factors of load handling. In fact, as a new technology, exoskeletons are constantly under research by scientists from all over the world, in order to examine not only their capabilities but also the potential disadvantages they can entail. Preliminary results on a device designed to facilitate overhead works, for instance, revealed that the users had to make additional efforts when their arms moved beyond the planned range; however, in another case, users revealed the relief of certain types of pains during the usage of an overhead tool while wearing the exoskeleton. Anyways, the importance of considering how the devices are adapted to the specific task and the skills of the users have been highlighted in both investigations. In other studies conducted especially to analyze the effects of exoskeletons employed by painters and welders at construction sites, researchers revealed that these devices not only decrease total exertion while improving posture but also they reduce shoulder pain, therefore increasing productivity and work quality (Zingman, et al. 2017).

At the same time, exoskeletons present some disadvantages, which are in part due to their recent development but may also be caused by other factors. However, some of them can be overcome with further improvements in exoskeletons’ technology; for instance, the increased chest pressure and the addition of load on the spine, which have been reported in some studies can be solved by reducing the weight of the devices, as well as an advance in wearability can avoid pressure wounds and compressed nerves. Similarly, other encountered complications must be faced, such as the limitation in the mobility or the shifting of users’ center of gravity, which are especially risky when it is needed to move out of falling objects or in other unforeseen circumstances. Moreover, exoskeletons usage should be personal, not only to avoid constant changes and re-adjustments to different body shapes but also to prevent the lack of hygiene that could spread infectious disease. Finally, some studies showed that the use of exoskeletons can negatively affect the human recovery strategy after a collision.

Although, there are other implications, concerning the application of exoskeletons, which resolution must be figured out, such as the consequent increase of human distraction from other safety measures (Zingman, et al. 2017).

Besides, governance institutions as well are working on the theme to deepen the related aspects; NIST (U.S National Institute for Standard and Technology), for example, in 2016 pointed out the urgency of developing standards and test methods for exoskeletons. Something similar has also been the field of an R&D project carried out by the European Union a year before; the objectives included the creation of a database to define the potential hazards of an exoskeleton throughout its lifecycle and the strategies to decrease risks generated by its employment in the industry.

These devices, as well as robots, require to be further investigated and developed; indeed, exoskeletons’ long-term health effects are currently impossible to be outlined and future research is needed also to ensure their application is actually safe for workers (Zingman, et al. 2017).

3. Conclusions

This paper has firstly entailed a series of considerations, having regard to the lack of consensus in the definition of robots and the extents of the term. Taking into account the existing classifications and nomenclature, it has been specified which definition to consider as a reference point for this paper and discerned between advanced machines and robots within the device classification. This led, while analyzing the devices available for on-site application, to put special attention on the capacity of carrying out the different tasks autonomously while evaluating their intelligence; what results from the investigation is that fully automated processes are still far from a date and further developments in robotic technologies must be implemented. Indeed, although it may appear that a considerable degree of development has been reached, it is necessary to clarify that many of the most advanced robots are still in the testing phase and hence not commercially available; furthermore, some of them have been developed by the universities only within researches or experimentations, while others, especially the most outdated Japanese devices, have been designed and produced by companies for their own use. Besides, the examination of other solutions such as exoskeletons proved that they can both enhance the construction processes and benefit workers, but are in an early development stage and need to be further investigated.

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