Current Robotics Reports (2020) 1:13–18
https://doi.org/10.1007/s43154-020-00003-8

ROBOTICS IN MANUFACTURING (JN PIRES, SECTION EDITOR)

Robotics and Additive Manufacturing in the Construction Industry

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Published online: 24 January 2020

Abstract

Purpose of Review Robot-assisted construction brings several advantages to the construction process—increased quality, reduced risk, faster work cycle. There are numerous automation developments aiming for incorporation in the construction. Nowadays, additive manufacturing rapidly becomes the desired process in many manufacturing areas, mainly due to its advantages in free form automatic execution of parts or structures.

Recent Findings Recent studies show that the robotic technology can help improving the additive manufacturing process. This can be achieved by optimised deposition process, inclusion of temporary supports and/or post-treatment. Existing software products allow for the simulation of the production process as well as the prediction of the material properties, whereas advanced measurement systems permit precise measurement of the as-built geometry.

Summary This paper summarises recent development in robotics and additive manufacturing for construction industry.

Keywords Steel construction · Additive manufacturing · Robotics

Introduction

Automation in construction, as in any other manufacturing sector, is seen as an important and desirable characteristic [1, 2]. The first attempts for building automation date back to the 1970s when robots were used to increase the quality and productivity in prefabrication of modular homes in Japan [3]. Since then, there were numerous developments by industry and academia aiming at the improvement of the productivity in both on- and off-site activities, covering several types of single-task robots (bricklaying [4], installation of finishes [3], façade cleaning, installation of steel beams [5, 6], among others), large scale prefabrication automation for modular construction [7, 8] or improved performance of the workers by the use of exoskeletons. A comprehensive summary of the existing technologies including market review can be found in [9]. More recently, additive manufacturing is attracting the attention of the construction sector; an example is the MX3D bridge in the Netherlands [10] or the ARUP lighting node [11], and also applications in concrete [12] and robotic timber construction [13]. Yet, automation is still far from being fully exploited in the construction sector [14], especially with respect to on-site applications. There are several challenges that explain this difficulty; some of them are related to the building tradition and the scale of the problem [15•], whereas others result from constraints of the robotic technology [9].

Automation usually relates to repetitive tasks that can be performed by machines or robots; that is why, for example, the automotive industry has benefitted greatly from automating several tasks in the production process [16, 17]. However, automotive production is a very structured and a well-organised process because it produces the same product thousands of times, while this is not the case of the construction sector. Building manufacturing presents the unique feature that it is linked to a specific location that very often imposes geometrical constraints to the final product, besides different specification related to safety aspects. Furthermore, building manufacturing is also a large-scale process with flexible geometries and multitude of different uses that need to be accommodated over a very long service life. Also, the building site is typically a non-structured environment, full of obstacles which makes it computationally challenging for a robot to

This article is part of the Topical Collection on *Robotics in Manufacturing*

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operate independently [18]. This is further complicated because of the co-existence of humans and robots, whose interaction presents its own challenges [19]. Finally, building developments are implemented as single investment operation that very often require last minute changes, because unlike other man-production industries, the customer usually enters the process well before the building is finished.

The understanding of these problems is important for their resolution and/or prevention, which are often associated with a particular application. The authors consider that additive manufacturing has great potential for future applications in both in and off-site construction. As the available technology for large scale metal 3D printing is not sufficiently developed at present for achieving the desired quality (high residual stresses and distortions), it is a good example for addressing an overall view of the construction problem. This paper focuses on three important features which can contribute towards more active exploitation of the technology, namely the quality of the material properties, the optimization of the production cycle and the integration of human-machine interaction. Firstly, the existing applications and technologies applicable to construction are summarised, then the three main problems are discussed.

Additive Manufacturing in Construction

In construction, additive manufacturing (AM) is rapidly gaining popularity mainly due to the advantage of constructing any shape directly from a CAD model without intermediate step, while also allowing for optimised structural designs. There are already a few applications of 3D printed structural parts and entire structures; in 2017 at MIT, USA, the possibility of building a big 3D-printed 3.6 m high dome with 15 m diameter [20], more examples being found in [21]. Meanwhile, the first 3D-printed house in Europe, The Bod, was built in Denmark [22]. Robotic in situ fabricator for reinforced concrete structures was presented in [23], which was used for the construction of the DFAB house in Switzerland [24]. More recently, an entirely 3D-printed house in Dubai was finished [25].

Clearly, the applications are mainly focussed on common building materials such as steel and concrete, but also new possibilities of sandwich composite structures with tuneable 3D-printed core materials [26] are possible. The available technologies depend on the material and application, a review of the robotic technology associated to the different processes is given in [27].

Regarding concrete additive manufacturing, there are three main processes applicable to construction—concrete printing, contour crafting and d-shape. A comprehensive summary can be found in [12, 28]. Many of the examples mentioned above were built using concrete additive manufacturing, but the process still needs significant optimization. A recent study compares the robotic and conventional in situ fabrication shows that the conventional approach overperforms robotic one for regular structures (straight concrete wall); the robotic fabrication only becomes more effective for fabrication of double curved walls [29].

Metal additive manufacturing can be also done in several ways, among which the most popular are power bed fusion (PBF), where a powder material is fused together in an enclosed chamber or direct energy deposition (DED) which is a wire-fed process using different power sources. A brief description of the available techniques is given in [21], whereas more detailed explanation is presented in [30] in the context of aviation industry. Among all production techniques for steel construction, the most suitable in term of speed and layout is a sub-category of DED named wire and arc additive manufacturing (WAAM). A major drawback of this process, however, is the final material and geometrical properties—high residual stresses and distorted shapes. Possible improvements of the WAAM process are further discussed in the following sections in the context of material properties, production cycle and human-machine interaction for the robotic technology.

Finally, AM is also possible with other materials besides steel and concrete, mostly various types of polymers. In this case, the main issue for structural applications is the resistance of the material [31]. This challenge can be partially overcome by the use of lattice structures whose dimensions and arrangements can be optimised. An example is the large 3D structure (about 6 m tall and 13 m wide) [32] printed in carbon fibre reinforced acrylonitrile butadiene styrene.

Material Properties

Similar to welded parts, WAAM fabricated parts undergo fast cooling which results in the formation of internal defects, non-homogeneous material properties, residual stresses and distorted geometry. Given the similarities between fusion welding and AM, a review of classical welding concepts applicable to AM is presented in [33], where the review is extended to the optimization of the distance between two adjacent layers (hatch distance), considering geometric, energy and thermal criteria. Since the formation of residual stresses depends on the heating-cooling rate, the 3D-printed metallic parts depend on the building sequence [34–36], which is one of the main factors in the development of residual stresses in the geometry. Hence, the AM process can profit from the optimization of the deposition orientation for single or multi-part components [37]. The dependency of the building orientation to the material strength was studied in [38], where the variability of the material properties with respect to the printing direction was confirmed. The research covered PH1 and

316L stainless steel coupons extracted from PBF-printed elements with different orientations (0, 45 and 90 degrees).

Furthermore, the formation of residual stresses can be optimised based on the deposition sequence leading to favourable patterns and/or significant reduction of the stress amplitudes. The residual stresses can be also controlled by the adoption of an additional support structure. A routine for finding the optimum position of temporary supports for reduction of residual stresses is presented in [39].

As the final material properties are process-dependent, they can be seen as a function of the wire feed rate, arc current, wire offset, preheat, inter pass temperature and torch speed. Nowadays, in the research community, it is common to perform welding simulations [40], where, for example, residual stress distributions can be predicted by finite element calculation by introducing the correct material properties and a proper definition of the heat source considering, for instance, the arc current, wire offset, inter pass temperature and torch speed. This same strategy can be adopted for the WAAM process, where a simulation of the deposition process can be used to predict the properties of the final product. An attempt for the validation of this strategy is presented in [41], where it was shown that it is possible to establish a correlation between the micro-structure and the process through simulation. However, the real step forward would only be achieved after the complete control over the material characteristics is taken over. To achieve this, the incorporation of real-time monitoring in the process simulation in combination with machine learning algorithms is required, so that the deposition can be executed at higher speed and quality.

Further improvements of the WAAM can be achieved with process variants such as cold-working techniques, interlayer heating and/or cooling, preheating and shielding devices; different improvements are described in [42•]. The material properties can be further improved by the incorporation of different post processes such as heat treatment and cold rolling [30] and more recent processes as laser treatment [43].

Production Cycle

The construction sector–related specifics mentioned above interfere with the current production cycle of a building. The construction process is characterised by the collaboration of several engineering specialities with the investor at the design and execution stages and contractor during the execution.

An attempt for the incorporation of the whole cycle into a single database is represented by building information modelling (BIM). It is constantly being improved with its 7th dimension including 3D model, construction planning, cost estimation, environmental impact assessment and building operation [44–47]. Even though it has been recently made compulsory for large construction projects in UK, its acceptance rate remains low [15]. There are several reasons for this such as the fact that construction companies usually work with lower profits and cheap labour [15], but also that the current set up simply works. While manual work can be effective for conventional construction tasks, i.e. straight pieces and standard connections, when special and more complicated tasks are considered the manual process may not be as efficient as illustrated by the example of a double curvature concrete wall [23]. It is precisely in these situations that AM can make a difference. In cases where AM processes are adopted for construction, the current two-step procedure of design and execution can be merged into a unique production cycle with increased quality and efficiency.

The usual AM manufacturing process includes a CAD model which is a 3D model of the desired piece usually in STL (stereolithography) file format. This model is further processed by the so-called slicing software, which generates layers to be printed step by step which is then translated to a robotic cell code describing the required kinematics and dynamic for execution of the structure [48••].

However, in this approach, the building parameters can be only explicitly considered "by feeling" hence, the resulting material and geometrical properties are random as discussed in the previous section, the deposition strategy can significantly influence the final material properties, but it is also very important for the final geometry of the printed piece. The thickness of the layers, for instance, has direct impact on the accuracy of execution for curved and free form shapes which can be also optimised [49, 50]. Another geometrical issue related to the deposition process is the overhang constraint—the unfinished part is subject to stress state different from the final ones, in this context large overhangs may lead to premature failure, which can be partially eliminated using temporary support structures. In addition, when building with inclination, execution can be problematic due to the torch orientation in automatic production and/or the possibility of overflow of the liquid weld pool. Design recommendations for these issues are given in [51] in the context of excavator case study.

Hence, a truly efficient production process can only be achieved by considering the building parameters (wire feed rate, arc current, wire offset, etc.), the as-build geometry (by real-time measurement) incorporated in the AM process. Nowadays, there are several ways to precisely measure the 3D geometry of pieces using different techniques depending on the desired accuracy [52••]. It is also possible to measure the temperature field in the molten pool [53] and compare it with the simulated temperature. If this "knowledge" is incorporated in an intelligent production system, the executed piece as well as the adopted production parameters can be tuned while being manufactured in order to achieve the final properties as close as possible to the initially desired ones. This would involve real-time edition of the CAD data, where the initially planned geometry is compared with the executed one; adjustment of the initial toolpath planning corresponding to the updated CAD data and finally, this information should be transmitted to the robot controller in an efficient way for execution. In this process, the component can be produced at once, avoiding unnecessary trial and error processes in order to choose the best parameters for execution.

However, a fully autonomous system, however, would only be possible by the incorporation of AI and ML algorithms which will choose the best production properties in the production process. This requires sufficient data on the production of the various pieces in order to be able to identify trends and correlations between the various parameters which influence the production process. In this context, the building and maintenance of database of AM production processes is the key to the future success of this technology.

Human-Robot Interaction

The previous sections discussed how a component should be executed in order to achieve the desired material and geometrical properties in a production's efficient way. However, in addition, additive manufacturing is a robot-assisted process [27], hence the interaction between human and robot is essential for achieving the final product.

The usual industrial robotic set-up would involve a pre-programmed single task robot working in a closed space, isolated from the human co-worker. Nowadays, there is a shift towards more collaborative set-ups [54], where robots work alongside human and are able to perform more than a single task in an intelligent manner. There is a drive for a shift from computer and software to direct and physical interaction. For example, nowadays, it is already common to use a touch screen for navigation on screen or voice commands [55], with facial and fingerprint recognition being also part of the everyday technology [56]. In fact, this is part of the strategic agenda for robotic development [57] which targets the development of instructable interfaces, physically interactive interfaces for collaborative working or standardised autonomous ones. In this context, three levels for system development are recognised: (1) human-robot co-worker scenario involving a joint action between the human and their robotic counterparts; (2) flexible systems which include a higher level of sophistication of the developed technology and (3) integration of several systems together which communicate between themselves and with the human [58–60]. These three levels can be seen as the incremental future development of an intelligent system.

The first level would require the development of the interaction between the human and robot in a flexible way so that the final objective is achieved. For that, a possible development should account for transition from the CAD data to slicing software to the robotic path implementation including the robot simulation software [48••], [61] where the human role would be to monitor and validate the process. In the future, the process development would converge to more autonomous functionality by the incorporation of several sensors which can give feedback to the robotic system. Finally, the goal would be to incorporate several robots and humans working together.

Conclusions

The current state of development shows that the construction sector is still far from being fully automated. However, there are several developments in the field that clearly demonstrate the interest of academia and the industry. An emerging application for construction is additive manufacturing using different materials. A driving force for this development is the architectural desire for freeform structures, which is usually followed by engineering developments. This is confirmed by the several attempts to build using 3D printing in the recent years. Aiming to show the current state of application this paper focused on metal additive manufacturing for steel construction. It identified problems for its application, namely the high residual stresses and distortions of the fabricated pieces.

The discussion covered the quality of the material properties, the optimization of the production cycle and the integration of the human-robot interaction. It was highlighted that the AM process can significantly benefit from the integration of existing software products with advanced sensors into the production. This can lead to an intelligent system which is able to incorporate direct deposition, machining and finishing for producing a final product with the desired quality. The interaction between human and robot is also considered essential for the functionality of the process, and the discussion highlighted possible paths for future development, where the ultimate objective would be to achieve fully autonomous systems incorporating artificial intelligence and machine learning algorithms.

As an outlook to the future, the authors anticipate that even more applications of additive manufacturing technology will be seen in the construction sector, and this will contribute towards a fast change of the traditional ways of building. On the other hand, the robotics technology will evolve by the incorporation of the existing sensors in the production process together with real-time simulation which will contribute to increased quality and shorter production cycles.

This paper did not discuss the problems associated with the standardisation of such process for its application in real structures; however, the development of the discussed technology is the necessary step forward for future standardisation and application of the additive manufacturing in steel construction.

Funding Information This work was partly financed by FEDER funds through the Competitivity Factors Operational Programme-COMPETE and by national funds through FCT–Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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