ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
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BUILDING AUTOMATION REVOLUTION

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ABSTRACT

This paper summarizes the developed 3D printing (3DP) processes in the Building Architecture Fields, commonly known as Additive Manufacturing of Concrete (AMoC), and examines the advantages and challenges vs the current traditional building. AM is an innovative building and construction (B&C) method, still in its infancy but being developed and improved continuously.

1. Using Three-Dimensional Printing in Construction and Architecture Fields

1.1. Building printing

The construction industry has traditionally relied on specifications and two-dimensional (2D) drawings to convey material properties, performance details and locational information – using small-scale models to create the object for evaluation as part of the design process. Increasingly, specifications and 2D drawings are being replaced by three-dimensional (3D) modelling in the virtual environment of building information modelling (BIM). Another alternative to 3D modelling is the use of advanced 3D solid modelling techniques in combination with digital fabrication methods (Buswell 2008). This form of modelling is known as rapid prototyping [1]. Components are made by adding, or building-up, material to form an object. In this process also called Additive Manufacturing (AM), the 3D objects are ‘sliced’ and represented as a series of 2D layers, with layer-based processes sequentially adding each

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layer to build up the desired object. It is the selectivity and control of the material that enables the freedom to build any desired geometry, which is the fundamental advantage of these processes [1].

According to Lim [2], there are a number of drivers pushing construction towards automation, with the main ones being reduction in labour for safety reasons, reduction in construction time on site, reduction in production costs and an effort to increase architectural freedom. Vähä [3] adds quality, reliability, life cycle cost savings and the simplification of the workforce as further considerations. Automated bricklaying, sprayed concrete and precast techniques are some of the numerous examples of automation that are already in use in the construction industry [2].

There are three major 3D printing building projects. WinSun, a Chinese company printed in Shanghai group of houses 200 m^2 each in less than a day with a printer at sizes 150 (at length) X 10 (at width) X 6.6 (at height) m. The houses were made of high-grade cement and glass fiber that cause for a better strength than reinforced concrete. In 2015, Villa and five story apartment were printed as not as one-piece and were assembled on site. The second project was in 2014 demonstrated by Qindao Unique Technology. The printer was at sizes 12 X 12 X 12 m with an accuracy of mm level and used materials as glass reinforced plastic. The third project is Amsterdam-based. DUS Architects developed KamerMaker – a 3D printer of 6 m tall which fabricated canal-house with 12 rooms. KamerMaker used polypropylene to produce components with dimension of up to 2.2 X 2.2 X 3.5 m and later on were assembled in site [4].

Currently, in this field there are main large-scale processes targeted at construction and architecture in the public domain, namely: Contour Crafting, D-Shape (Monolite) and Concrete Printing. All three have proven the successful manufacture of components of significant size and are suitable for construction and/or architectural applications. The deposition head mounting is frame, robot or crane mounted. Contour Crafting has been developed to be a crane-mounted device for on-site, in-situ applications. Both D-Shape and Concrete Printing are gantry based off-site manufacturing processes, although there is no specific reason why either process cannot be used on-site. The three processes are all similar in that they build additively. However, the processes have been developed for different applications and materials, which results in each having distinct advantages. The D-Shape process uses a powder deposition process, which is selectively hardened using a binder in much the same way as the Z-Corp 3D printing process. Each layer of building material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to be solid. Once a part is complete, it is then dug out of the loose powder bed [5] [2].

Contour Crafting has been in development for some years and is based on extruding a cement-based paste against a trowel that allows a smooth surface finish created through the build-up of subsequent layers. It has been developed to address the issue of high-speed automated construction, and the current deposition head is capable of laying down material to create a full width structural wall with the minimum use of material [6] [7].

Print speed theses methods are also affected by the building material and binder deposition rate. Contour Crafting avoids lengthy cycle times between layers by printing an entire layer with two passes of the deposition head. The process uses a large diameter extrusion resulting in a high layer build-up rate, minimizing the printing time. On the other hand, D-Shape uses a gantry with multiple nozzles mounted in series that requires a single traverse per layer, although the building material must be pushed over the entire build area, compressed and flattened. Concrete Printing utilizes a single deposition nozzle, which unlike D-Shape, means that only the required material volume is deposited for the build; however, the single nozzle approach inevitably limits the deposition rate because the nozzle must traverse the entire build area. Increasing the cross-sectional area of the extrusion correlates directly with the deposition rate, as does the number of nozzles simultaneously depositing [8] [9] [10].

The goal in this domain is to replace many cranes and even construction workers with printing systems. They would work by using the three-dimension design model created on CAD software, to create a layer by layer pattern on the building just as a normal three-dimension printer works today. Most of the innovation in this area will have to come from the creation of the appropriate materials [11].

1.2. Concrete Printing

The 3D concrete printing is a gantry-based 3D printer which can print up to 9 x 4.5 x 2.8 m. Concrete mixed with water is pumped to the nozzle in the end of the printer head that enables concrete filaments to leave the printer at desired speed, location orientation [12]. 3D concrete printing is a construction method that enables fabricating a building and 3D complex geometries layer-by-layer [13] and involves in process extrusion of cement-based mortar in a layer-by-layer process. The main ingredients of the mix are sand, cement, fly ash, silica fume and polypropylene fibers [14] [4]. This print process can be carried out without the use of labor-intensive formwork and has the ability to incorporate functional voids into the structure [9] [14]. Compared to contour crafting, the process has been developed without the trowels used in contour crafting so that a smaller resolution of depositing (4 – 6 mm in terms of layer depth) is required to achieve greater levels of 3D freedom and greater control of internal and external geometries [2] [4] and the finishing and post-processing of concrete printing differ from contour crafting because it produces the characteristic ribbed finish which can be controlled and designed to exploit the effect. However, if a smooth finish is required, either the wet material is trowelled during the building process or the printed finish is ground to a smooth surface. This must all be completed manually because this step is not yet automated [2]. CC needs to maintain uniform level of viscosity for smoother surface finish and structural strength [4].

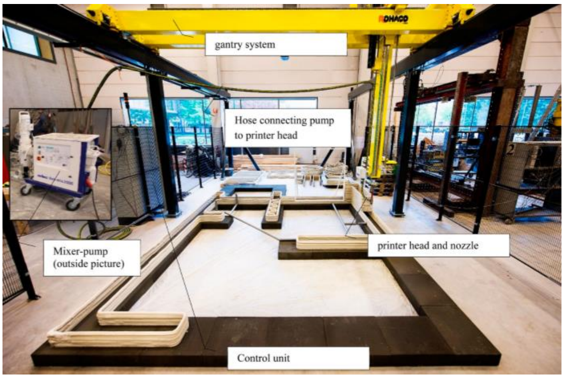

Figure 1. 3D Concrete printing at TU Eindhoven [12]

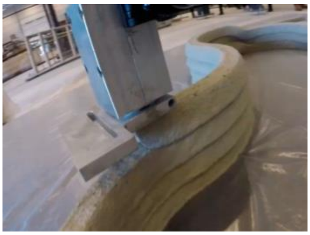

Figure 2. 3D Concrete printer in operation [12]

1.3. Contour Crafting (CC)

Contour crafting (CC) is an additive fabrication technology that uses computer control to produce large 3D structure (>1 meter). Contour crafting extrudes a cement-based paste against a trowel along the contour of the wall – the external and internal skins of the wall, that later is backfilled with concrete or other materials. That allows a smooth surface finish created through the build-up of subsequent layers [15] [4]. Materials that have been tested with CC are: thermoplastics, thermosets and various types of ceramics. In some cases, sand and waxes used as supportive materials for bulge structures. All of these materials are available, cheap and room temperature hardening. Khoshnevis et al. experimented speckling plaster compound and clay to produce shapes square, convex and concave properties. In addition, they fabricated successfully with the cc machine a wall with dimension of height 1.5 m X 0.6 m composed of cement-based mortar [15].

Some of the important advantages of CC compared with other layered fabrication processes are better surface quality, higher fabrication speed and a wider choice of materials. The key feature of CC is the use of two trowels, which in effect act as two solid planar surfaces, to create surfaces on the object being fabricated that are exceptionally smooth and accurate. The layering approach enables the creation of various surface shapes using fewer different troweling tools than in traditional plaster handwork and sculpting. It is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core [11]. The most prominent implication of CC is in the field of construction where a gantry system carrying the nozzle moves on two parallel lanes installed at the construction site. A single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run. Conventional structures can be built by integrating the CC machine with a support beam picking and positioning arm, and adobe structures [6] [16] [19].

CC process enables several important advantages. First, it allows architects to design structures with functional and exotic architectural geometries that are difficult to realize using the current manual construction practice. Moreover. Various materials for outside surfaces and as fillers between surfaces may be used in CC. Also, multiple materials that chemically react with one another may be fed through the CC nozzle system and mixed in the nozzle barrel immediately before deposition. The quantity of each material may be controlled by computer and correlated to various regions of the geometry of the structure being built. This will make possible the construction of structures that contain varying amounts of different compounds in different regions [7]. In addition, the quality of surface finish in CC is controlled by the trowel surface and is independent of the size of the nozzle orifice. Consequently, various additives such as sand, gravel, reinforcement fiber and other applicable materials available locally may be mixed and extruded through the CC nozzle. Regardless of the choice of materials, the surface quality in CC is such that no further surface preparation would be needed for painting surfaces. Indeed, an automated painting system may be integrated with CC. Another advantage is relate to the use of smart materials. Since deposition in CC is controlled by computer, accurate amounts of selected construction materials, such as smart concrete which could more rapidly adjust printing circumstances, may be deposited precisely in the intended locations. This way the electric resistance, for example, of a carbon filled concrete may be accurately set as dictated by the design. Elements such as strain sensors, floor and wall heaters can be built into the structure in an integrated and fully automated manner. Finally, many processes of building and construction could be executed using CC automatically. Because of its layer by layer fabrication method, a contour crafting based construction system has the potential to build utility conduits within walls. This makes automated construction of plumbing and electrical networks possible. For plumbing, after fabrication of several wall layers, a segment of copper (or other material) pipe is attached through the constructed conduit onto the lower segment already installed. The inside (or outside) rim of each pipe segment is pretreated with a layer of solder. The heater ring heats the connection area, melts the solder and, once the alignment is made, bonds the two pipe segments. Using these components various plumbing networks may be automatically imbedded in the structure [1] [14] [17] [18].

Figure 3. Contour crafting building printer [3DPrint.com]

Figure 4. Contour crafting made concrete form wall [15]

1.4. D-Shape

The D-Shape is a gantry-based powder-bed 3D printer which can print up to 6 X 6 X 6 m of architectural shapes. The D-shape process uses layers of powder (sand/stone powder) and a binder (chlorine based liquid) rather than the cement-like paste used in other methods. This involves a powder deposit process, where the powder is selectively hardened using a binder. Each layer of the material is laid to the desired thickness, compacted and then the nozzles, mounted on a gantry frame, deposit the binder where the part is to be solid. Once a part is complete, excess material is dug out to expose the 3D component [2] [4] [15]. This automated building system, which uses sand and binder to create stone-like freeform structures, enables the constructions of full-size sandstone buildings without human intervention. The D-Shape process has many advantages over traditional formative processes (the use of formwork with concrete) as well as other construction 3D printing processes. This process can use any sand-like material and produces little waste, as the leftover sand, which has not stuck to the object, can be reused elsewhere. The materials used are all naturally occurring substances requiring very little processing before use in the fabrication process and so the end product is very similar to natural stone [8].

Figure 5. Concrete printing Printer [www.3DPrint.com]

2. Advantages and Challenges of Three-Dimensional Printing vs Current Construction Methods

2.1. Advantages

Three-dimensional printing has several advantages over conventional construction methods. First, additive manufacturing offers the possibility of creating, in a short timeframe, complex 3D objects, with fine details, from different materials. Through 3D printing, the customer has the possibility to create complex objects and shapes that are impossible to be obtained through any other existing technology [19].

In the field of construction virtually every wall, floor, panel, partition, structure and facade is unique in dimension, which means either standard sized materials are cut down to fit, or bespoke moulds are created to form each component. There is a clear cost-based opportunity to save time and materials by reducing waste and the need for formwork making. The computational design environment promises the freedom to design. Furthermore, three-dimensional printing may remove the need for replication of components, giving designers freedom to make each part unique [2].

Additionally, building in these techniques could significantly accelerate speed of finishing construction projects, reduces cost, and improves safety [13]. Khoshnevis claims that the contour crafting method increases the building construction speed to a great extent. He states that estimates show that the contour crafting method will be capable of completing the construction of an entire house in a matter of hours (e.g. less than 2 days for a 200 m^2 two-storey building) instead of several months [20].

Another important advantage of creating objects using 3D printing technology instead of traditional manufacturing methods is the waste reduction. As the construction material is added layer after layer, the waste is almost zero and during the production, it is used solely the material needed for obtaining the final object. On the other hand, in the traditional manufacturing processes, based on subtractive techniques, the manufactured product is made through cutting or drilling an initial object, thus leading to a substantial loss of material. In this vein, it is also important to note that some of the materials used in 3D printing have improved properties in terms of strength and provide a wide range of superior finishing details, compared to the materials used when manufacturing objects through traditional technologies [19].

Moreover, since the additive manufacturing is a computer-controlled technique, it reduces the necessary amount of human interaction and requires a low level of expertise for the operator. Therefore, the costs of operating these 3D printers are significantly lower compared to the traditional way of manufacturing. Furthermore, the process ensures that the final product represents a perfect 3D version of the digital design, with almost no errors that could have appeared when using other existing technologies. Finally, the advantages of this technology are not limited only for manufacturers, but also to end-users. The customers also have the possibility of printing items in remote locations taking into account the fact that Internet is nowadays widespread and in some countries is even a legal right of the citizens [21].

Moreover, a major advantage of 3-D printing is the separation of product design from manufacturing capabilities. Since design and manufacturing can be easily outsourced in 3-D printing, designers can contract with firms to produce, ship, and collect proceeds for goods based on their designs. Alternatively, a consumer can download a CAD software design for a replacement part online – as easily as he/she would download digital music – and then download and print the part on his/her 3-D printer [22].

Developing AM technology could leverage other scientific breakthroughs. Revolutionary advances at the interfaces between previously separate fields of science and technology are ready to create key transforming tools in fields such as nano-, bio, info-, and cognitive based technologies, including scientific instruments, analytical methodologies, and radically new material systems. The innovative momentum in these interdisciplinary areas must not be lost but harnessed to accelerate unification of the disciplines. However, as in any technology, manufacturing must be advanced for the products that the researchers develop. AM may offer a novel new means toward the incorporation of technologies into prototype and finished products. Moreover, such an interdisciplinary approach could offer even greater design flexibility and higher part quality within AM-produced components.

Modern AM techniques use materials such as liquid, solid, and powder polymers; powder metals; and ceramics. Individual material options are thus limited to thermoplastics, elastomers, ferrous metals (steel alloys), non-ferrous metals (e.g. aluminum, bronze, Co-Cr and Ti), and some ceramics (e.g. SiO2, TiO2). New composites with other materials may offer greater opportunities to extend the present limitations of materials in AM [23].

The combination of AM and nanomaterials offers a particularly intriguing avenue for perhaps overcoming some of the fundamental materials and design limitations that presently stymie AM engineers and designers. Nanotechnology offers a novel approach for AM with its potential to both complement existing techniques and create wholly new nanocomposites. The National Nanotechnology Initiative defines it as “the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications” [11]. When shrinking the size scale from the macroscale to the nanoscale, or bulk to molecule, materials can change their fundamental properties. At the nanoscale, objects can exhibit unique optical, thermal, and electrochemical properties that differ from the properties of the bulk material or molecules. These properties strongly depend on the size and the shape of nanostructures [24].

Similarly, the convergence of AM with bioengineering technologies could further escalate AM's promise. In the past decade, significant advances have been made in using AM to "print" tissue scaffolds – biocompatible materials that, when implanted into the body and integrated with biological cells, assist in the regeneration of tissue. The geometric freedom offered by AM allows for the creation of scaffolds that are optimized to encourage cellular growth, while maintaining strength. In addition, recent advances have been made in direct printing of human tissue. These "bio-printers" could eventually permit the routine printing of replacement organs for transplant [25].

2.2. Challenges

Concrete is the most used for building for his properties – it is strong, cheap, durable, fire resistant, and available in most countries and can be applied in any shape. However, concrete as structural material faces challenges that are recognized. The production of the cement includes burning of slag in the kiln and therefore concrete production is an energetic process that causes significantly global CO_2 pollution (about 5%). There are other compositions that are being explored but concrete is a cheap raw material and therefore the industry has no drive to exchange the material [12].

Another major challenge of 3D printing is its high cost. At the actual price of the device and materials, the 3D printing is the best solution when one needs to print a small number of complex objects, but it becomes expensive to print a large number of simple objects, when compared to traditional manufacturing techniques. In addition, the 3D printing becomes unprofitable when printing large size objects. The cost of a 3D printed large object is significantly higher than if it had been traditionally manufactured. Due to the material costs (especially regarding the moulds), the additive manufacturing is not always the best technical choice, most of the mould's materials being degradable over time and sensible at outdoor exposure [26].

Another important problem three-dimension printing arouses is counterfeiting and violating intellectual property of designers. Additive manufacturing presents new opportunities for counterfeiting. Once a printing file is generated, it can be used by anyone with an appropriate 3D printer to produce the object the file describes. CAD files stolen from online databases or cloud-based storage can be converted to STL files fairly simply. Counterfeiters need not even reverse-engineer a copy; theoretically, they can simply pay a hacker to steal CAD or STL files and manufacture the real thing from original plans. They can even search for items to counterfeit on the Internet. With the advent of affordable laser scanners, reverse engineering which enables to find the method of printing from a given product, take on new life. This possibility poses an even more serious threat. Scanners typically do not generate STL files, but they do generate point cloud data, which are the starting point for building the STL file, and several packages make the conversion from point cloud to STL relatively straightforward [27] [28].

Because STL files incorporate process information as well as design parameters, a counterfeit object made employing a stolen STL file should (nominally) function as well as the original design. However, laser scanning does not guarantee a functional equivalent. Objects produced with additive manufacturing may have the same geometries as traditionally manufactured objects, but they typically have different material properties. For example, metal parts formed by sintering have a different microstructure than parts milled from metal stock [29]. Other differences may emerge from flaws in the additive process. Stress concentrations often exist at the junction of two layers. There may be voids between layers. Layers may not cure uniformly. The bottom line is that although it is now easy to print out a copy of a turbine blade, printing a blade to look exactly like the real machined artifact does not guarantee its functionality in operation. One can easily see how this kind of counterfeiting, if such parts were to make their way into the supply chain, could result in catastrophic failure, leading to equipment damage, injury, and even loss of life. Although additive manufacturing machines remain more expensive than color printers and still require significant skill sets to operate, that is changing rapidly, and additive manufacturing has already greatly simplified counterfeiting operations for manufacturing objects [28].

Therefore, the ease of replicating objects via additive manufacturing presents new challenges to the IP system as well. The question of ownership and copying of original ideas has sparked considerable debate. Current limitations of 3D printing, which vary by printing technique, include relatively slow build speed, limited object size, limited object detail or resolution, high materials cost, and, in some cases, limited object strength.

Beside the predicted labor reduction there is still need for physically labor creating the moulds and placing the cement reinforcement [12].

One of the most prominent limitations is the issue of surface finish. The main contributing factor to poor surface finish in AM processes is the stair-stepping effect. The stair-stepping effect is more pronounced in direct metal deposition and fused deposition modeling. SLS/SLM has less stair stepping effect because the powder bed provide support for the selected fused or melted powder but they also suffer from poor surface finish as a result of gluing un-melted powder (from powder bed) on the component surface. To reduce the stair-stepping effect in the literature, reducing layer thickness is proposed [30]. Reducing the layer thickness will adversely affect the speed of the process as well as the properties of part produced. There are various attempts at improving the surface finish of AM [31]. In the literature, though, the surface finish achieved is not comparable with the one achievable in traditional manufacturing methods. Furthermore, AM is yet to be made feasible for mass production because of all the underlying factors mentioned above. Productivity of AM process is still very low especially due to simple large volume parts. To address this issue, Brajlih et al. [32] developed a method for measuring achievable speed and accuracy of AM technology. This tool is very useful in comparing achievable speed and level of accuracy from any AM machine. Despite different research efforts in improving the speed of AM [33], not much has been achieved. It is still below what is considered acceptable for mass production. There are a number of issues that need to be resolved before AM can compete with traditional method like casting in terms of mass production.

Another significant issue which limits development of AM is a relative failure in repeatability. This is also a major concern which has made the AM technology not to be fully accepted as a result of highly sensitive nature of AM technologies to environmental variation. There is always a variation in part produced at constant process parameters (Hague, 2006). Moreover, a large scale of projects and printing materials are needed for improvements to be developed [4].

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