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3D Printed Sustainable House: Futuristic Solution

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"*3D printing technology has the potential to revolutionize the way we make almost everything*"

-Barack Obama

Abstract **The construction industry has embraced digitisation and industrialisation in response to the necessity to extend its productivity, optimise material consumption and improve workmanship. Additive manufacturing (AM), more widely referred to as 3D printing, has driven substantial progress in these respects in other industries, and variety of national and international projects have helped to introduce the technique to the development industry. like other innovative processes not covered by uniform standards, appropriate assessments and testing methodologies to regulate the standard of the 3D-printed end products, while optional, are advisable 3D printing (sometimes mentioned as Additive Manufacturing (AM)) is that the computer-controlled sequential layering of materials to make three-dimensional shapes. it had been first developed within the 1980s, but at that point was a difficult and expensive operation then had few applications. it's only since 2000 that it's become relatively straightforward and affordable then has become viable for a good range of uses. 3D printing systems developed for the development industry are mentioned as 'construction 3D printers'. A 3D digital model of the item is made, either by CAD (CAD) or employing a 3D scanner. The printer then reads the planning and lays down successive layers of printing medium (this are often a liquid, powder, or sheet material) which are joined or fused to make the item.**

Keywords —3D Printed House, Sustainable, Futuristic, Construction, Additive Manufacturing

I. Introduction

Concrete is that the most generally used construction material on this planet. The current concrete construction industry faces several challenges. One of them is the high cost. According to a recent study conducted by Boral Innovation Factory, formwork is responsible for about 80% of the total costs of concrete construction in the Sydney CBD (central business district). In fact, this is typical for concrete construction worldwide. The significant amount of wastage generated within the construction is another challenge. Formwork may be a significant source of waste, since all of its discarded sooner or later, contributing to a generally growing amount of waste within the housing industry. The construction industry is responsible for generating approximately 80% of the total waste in the world. Furthermore, the traditional approach of casting concrete into a formwork limits geometrical freedom for the architects to create in various geometries, unless very high costs are purchased bespoke formworks. Rectilinear forms not only limit the creativity of the architects, but they're also structurally weaker than curvilinear forms due to stress concentration. Another challenge is that the slow speed of construction (i.e. long and hard to control lead time). The concrete construction often comprises many steps including material production, transportation, and in-situ manufacture of formwork, and every step is time consuming. Moreover, the current concrete construction industry is labor intensive and has issues with safety. On average, 35 construction employees per day are seriously injured. In addition, over one-quarter of construction deaths are caused by falls from a height. Last but not least, the present housing industry has serious issues with sustainability. In general, the present construction methods and materials aren't environmentally friendly. The entire construction process, including off-site manufacturing, transportation of materials, installation and assembly, and on-site construction, emits huge amounts of

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greenhouse gases and consumes large quantities of energy. 3D printing technology is recently gaining popularity in housing industry. In the previous couple of years, different 3D concrete printing (3DCP) technologies are explored. This paper presents the present progress of 3DCP technologies.

II. The 3D Printing Technology and Materials Information

The starting point for any 3D printing process is a 3D digital model, which can be created using a variety of 3D software programs, for Makers and Consumers there are simpler, more accessible programs available or scanned with a 3D scanner. The model is then 'sliced' into layers, thereby converting the design into a file readable by the 3D printer. The material processed by the 3D printer is then layered according to design and process. As stated, there are a number of different types of 3D printing technologies, which process different materials in different ways to create the final object. Functional plastics, metals, ceramics and sand are, now, all routinely used for industrial prototyping and production applications. The different types of 3D printers each employ a different technology that processes different materials in different ways. Similar technique for 3D printing is selective laser sintering (SLS) that laser is used to melt particles of powder together to create an object. Materials used in the SLS technology usually have high strength and flexibility. The most popular ones are nylon or polystyrene. The materials available for 3D printing have come a long way since the early days of the technology. There is now a wide variety of different material types, that are supplied in different states (powder, filament, pellets, granules, resin etc). Specific materials are now generally developed for specific platforms performing dedicated applications (an example would be the dental sector) with material properties that more precisely suit the application. Nylon, or Polyamide, is commonly used in powder form with the sintering process or in filament form with the Fused Deposition Modelling (FDM) process. It is a strong, flexible and durable plastic material that has proved reliable for 3D printing. Acrylonitrile Butadiene Styrene (ABS) is another common plastic used for 3D printing and it is widely used on the entry-level FDM 3D printers in filament form. It is a strong plastic and comes in a wide range of colors. Polylactic Acid or Polylactide (PLA) is a bio-degradable plastic material that has gained traction with 3D printing for this reason. It can be utilized in resin format for laser-based stereolithography (SLA) and digital light processing (DLP) processes as well as in filament form for the FDM process. It is offered in a variety of colours, including transparent, which has proven to be a useful option for some applications of 3D printing.

III. Patent Search

There are a number of patents regarding the use of 3DP in the construction of buildings, the most important of which are shown here. They will be useful as influence when designing the 3-D printer to be used in this project and also to be aware of what potential royalties may be required to be paid. Here are shown some examples of which solutions which were discovered in 'Free-D Printing: Phase 1 Research' by the author.

i) Being able to print numerous lines of material simultaneously as is laid out in this patent is crucial for ensuring a rapid build time which is vital for this project to succeed. The sections being printed for this project will take into account this factor and be used to print four lines simultaneously, the two outer rows plus two inner rows.

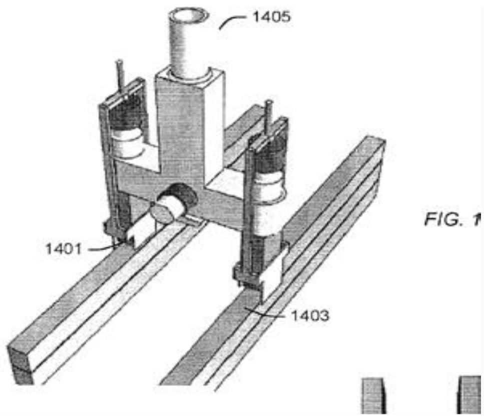

Figure 1 US Patent 7878789: Multi-chamber vibrating valve for cementitious material

ii) This patent regarding the use of an inner rib to bind the outer faces together and increase structural strength of the printed sections. This patent is unavoidable as it will be necessary to ensure structural strength and that the outer walls are bound together. For this project the use of numerous inner rib sections to bind the printed section together will be used rather than just the one which would not be sufficient.

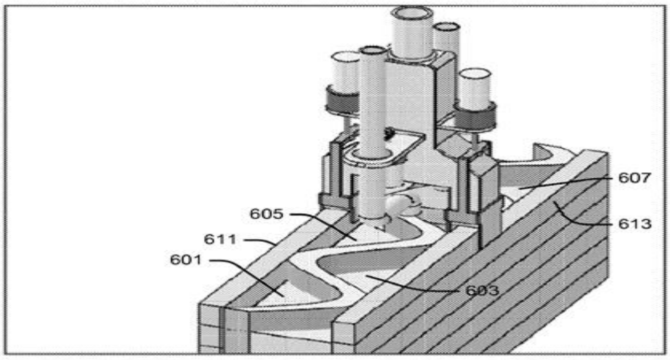

Figure 2 US Patent 7874825 B2: Nozzle for forming an extruded wall with rib-like interior

iii) This patent regards the use of a trowel head to produce different surface finishes. The options include a trowel to smooth over the printed layers as the head goes and the one in the figure above which provides a pattern of parallel lines. For this project such a print head is not required as the buildings will be rendered with earth after being produced to give a smooth and aesthetically pleasing finish.

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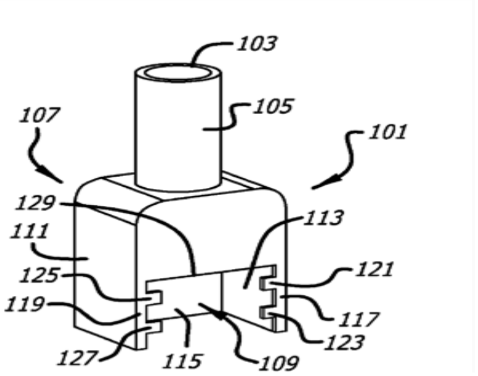

Figure 3 US Patent 8801415 B2: Contour crafting extrusion nozzles.

iv) This patent regards the use of a gantry system for building a printer on which the print head can move on 3-axis in order to print 2.5D forms. The Y axis (front to back) and Z axis (up and down on the arms) are suitable for this project but the X axis (along the rails) is not because it requires very flat land in order to print properly. With the use of four uprights in a frame the printer would be able to account for different levels on the ground and adjust to ensure printing is level.

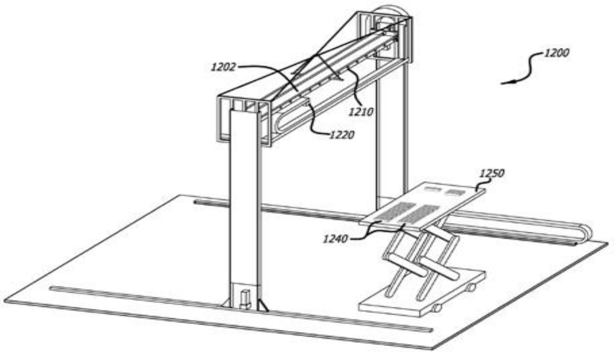

Figure 4 US Patent 8029710 B2: Gantry robotics system and related material transport for contour crafting.

v) The box frame used in this printer design is far larger than required for this project but the use of four uprights on the corners would be more suitable for the printer design used in this project than the rails used in the previous patent because the printer would be able to account for any uneven ground and adjust accordingly.

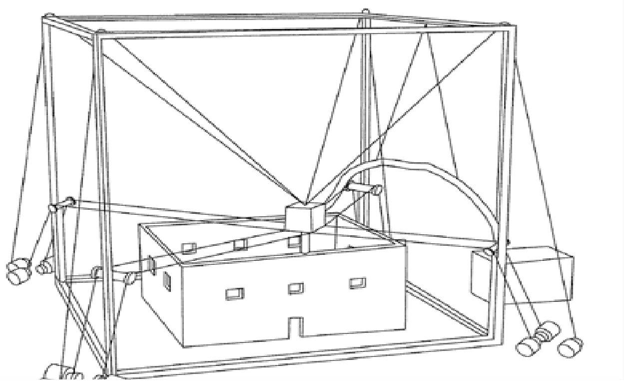
Figure 5 US Patent 7753642 B2: Apparatus and method associated with cable robot

vi) This patent regards mounting the 3-D printer onto a vehicle which can be offloaded to print a building and then loaded back on to drive to the next plot and print a building. For this project it is crucial to be able to move the printer around to produce houses close to where they will be constructed and also to be able to be moved from village to village so to mount the printer to some kind of vehicle is something that will be used for this project where possible.

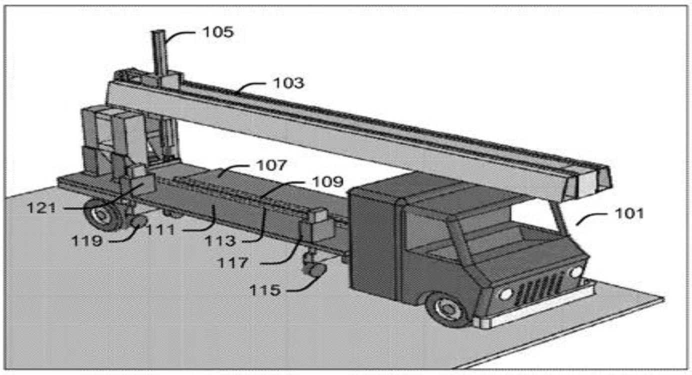

Figure 6 US Patent 7814937 B2: Deployable contour crafting.

IV. 3D CONCRETE PRINTING

Concrete is mixed with water and pumped into a hose by a mixer-pump located on the side of the set-up. The hose is connected to the printer head situated at the end of the vertical arm of a motion-controlled 4 degree-of-freedom (DOF) gantry robot serving required print area. Under the pressure of the pump, the concrete is forced towards the printer head, an element consisting of several parts allowing the concrete to be printed at the desired location, at the desired speed, and under the desired angle. The end part of the printer head is the nozzle, a hollow steel element with a designated section from which the concrete filament leaves the printer and is deposited on the print surface. Several nozzle openings have been tried.

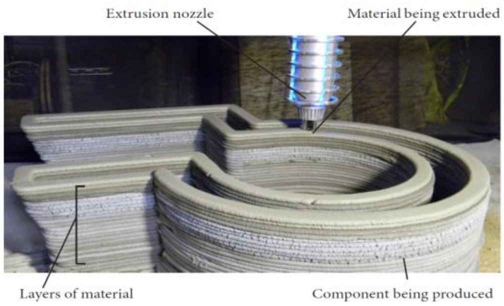

Figure 7 3D concrete printer in operation

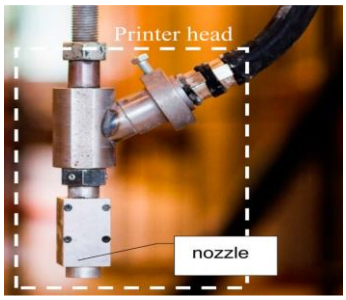

Figure 8 Printer head and nozzle

DOI : 10.35291/2454-9150.2021.0470

Figure 9 printing head with a feeder screw

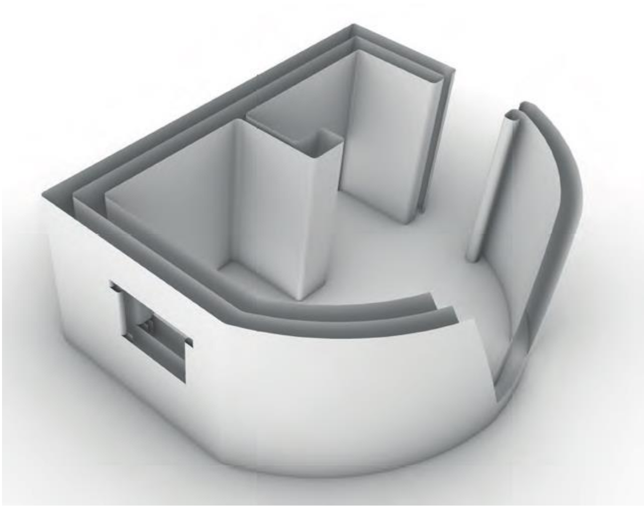

Figure 10 3D rendering of the small house in 3D Printing

Figure 11 3D rendering of the small house in 3D Printing

Figure 12 Gantry Robot

Printer head movement to be programmed such that the orientation of the nozzle always remains tangent to the tool path. Otherwise, twisting of the filament will occur. Nozzle opening, determining a workable default print head speed and pump frequency (and resultant pump pressure) setting was the result of a parameter sensitivity test programmed. Obviously, these three parameters are closely interrelated, and highly dependent on the concrete viscosity as well (which is, in turn, a function of the concrete mix composition and water/cement ratio). In corners the speed and frequency are reduced, depending on curve radius. The height of the print head above the print surface has considerable influence on the geometry and properties of the printed product. Again, a default setting has been found by running a parameter sensitivity test programmed.

This results in a relatively predictable printed filament of which the section is practically equal to the nozzle opening. The printed result can be influenced by pressing the print head into the printed product. The mortar is comprised of:

- Portland cement
- Siliceous aggregate with an optimised particle size d
- limestone filler and specific additives for ease of pumping,
- Rheology modifiers for obtaining thixotropic behavior of the fresh mortar
- Small amount of polypropylene fibers for reducing crack formation due to early drying

Performance of the mortar with regard to strength development and speed of strength development can be easily adjusted by adding accelerators and/or by changing the ratio Portland cement/limestone filler.

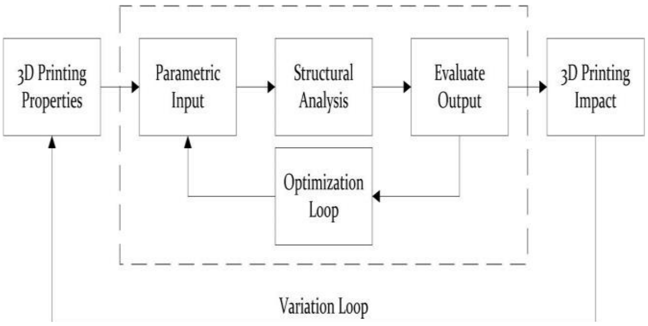

Figure 13 Research model

V. 3D Printing of Buildings for Construction of the Sustainable Houses

3D printing technology to use building will be increase sustainability. Houses can build based on the material life cycle, that can be used in evaluating the environmental sustainability of building materials. Creating the buildings with complicated shapes, may become one of the biggest advantages for most architects. Their imagination will be able to defeat previous obstacles related to limitation of traditional techniques of building. 3D printing may transform nowadays architecture, nevertheless, this technique should be developed taking into consideration sustainability issues both for material selection and construction method. There are numerous advantages coming from developing 3D technology in construction and most important ones could be resumed as: Lower costs – the cost of printing construction elements of houses is much

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lower than traditional construction methods, also material transportation and storage on sites is limited; Environmental friendly construction processes and the use of raw materials with low embodied energy (i.e. construction and industrial wastes); Reduced number of injuries and fatalities onsite as the printers will be able to do most hazardous and dangerous works. Wet construction processes are minimized, so that building erection process generate less material wastes and dust compared to traditional methods; Time savings – time required to complete the building can be considerably reduced. On the other hand, there is still a lot of anxieties that needs to be considered. The main unknown is, if developing the 3D printing technology will not take jobs from thousands of qualified workers.

VI. Benefits of 3-D printing

❖ **Cost comparison**

There are a variety of ways in which the utilisation of 3DP in construction will provide financial benefits over other construction methods with the largest of these being reduced labour costs which amount to 55% of total construction cost. In terms of labour required during the production of components, the 3DP method will require only one person to load the materials (mixture of soil, straw and water) into the printer and to control the graphical interface from which the components are printed. For the assembly of the building from the printed components it will require only two unskilled persons to move, lift and assemble the components to produce the final building and the time required will depend on the size of the building.

When compared to rammed earth and poured concrete walls which require costly formwork, especially when bespoke to the project, 3DP does not require any so that cost is also saved. Rammed earth and poured concrete wall construction methods further require high quantities of labour to produce the formwork, pour or ram the material into the formwork and then remove the formwork, move to the next wall and repeat. These methods both require a minimum of four people to prepare the material and produce the walls and to produce a house, double that of the 3DP method being developed in this project and also for a longer number of hours. Thus, both labour cost and hardware costs would be reduced in comparison to these two methods.

❖ **Accuracy**

The accuracy provided via the use of Computer Numerical Control (CNC) utilised by 3DP is a further benefit of 3DP over other construction methods because it ensures that the buildings can be built without errors. Human error can lead to longer build times and increased costs for labour and materials, both of which can be avoided through the use of 3DP.

❖ **Safety**

The construction industry is currently the most dangerous profession in the world, causing the most deaths and non-fatal injuries of any occupation. For example, the construction industry in the rural area around 6% of all workers but 20% of all deaths in the workplace. These figures are even higher in developing countries where safety gear and training are less common. Using 3DP these deaths and injuries can be avoided entirely as the fabrication is all performed through robotics.

❖ **Almost zero material waste**

The main advantage of using 3D printing in the construction industry is saving a lot of production costs on material waste. That's because a 3D printer, such as robotic arms, uses exactly the amount of material they need. Producing buildings layer by layer and with lattice structures inside allows for a huge cost reduction. Not only that, but they are also capable of using recycled materials. This factor also benefits the environment. 3D printing has a much smaller impact than traditional ways of manufacturing. An Italian company called WASP took 3D printing into a great development and designed one of the largest 3D printers in the world capable of producing homes out of local materials and using green energy (hydro, wind or solar power). This means much smaller emission, which is a big problem in today's construction industry. Last year we talked about the first family to move into a 3D printed house. In France and is called the Yhnova project. It took only 54 hours to print the house and the overall cost was about 20% cheaper than building a traditional house. Additive Manufacturing can really help to build a better future for the construction industry.

❖ **Cost-effectiveness of 3D printing in the construction industry**

As mentioned above, using Additive Manufacturing allows for less material usage and involves fewer people to work on construction. 3D printing is also a much faster technology. Those factors radically reduce the costs of building any 3D printed construction. While 3D printing structures, we use just the amount of material we need, therefore we are eco-friendly and save money. This aspect can really bring the costs down. 3D technologies also reduce supply costs. We can also save a lot of time, 3D printers don't need to eat or sleep, their working hours are more adjustable and they are a lot faster than people. And the faster you build, the more money you save.

❖ **Innovative design**

The last, but just as important benefit of using 3D printing in the construction industry, is all the innovative solutions it brings. 3D technologies can improve your project planning as they can be used already at the design stage. Starting from CAD plans of the buildings, which are technical drawings with all the parameters. Based on those drawings, a 3D model of the construction can be made to meet the clients' expectations and show them the best design solutions. Addressing the client's issues and presenting the right answers to their questions is crucial. Additive Manufacturing helps here. As we just mentioned with 3D

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technologies, you can present your clients with 3D visualizations of the structure, but that 3D model can be 3D printed. 3D models allow for high personalization of the structure. Moving on to large scale projects, Additive Manufacturing gives us new design freedom allowing for the production of new shapes and solutions to our needs. We have never had such a great possibility to customize structures. Not only the structures themselves but also the locations. It's easier to set up a 3D printer somewhere for a few days than move all the workers there. Also, some of the machines don't even need electricity as they run on green energy, which means that we can reach undeveloped areas easier.

VII. Spider Diagrams

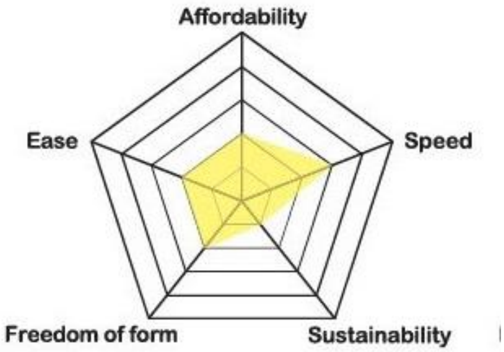

Figure 14 Poured Concrete Construction

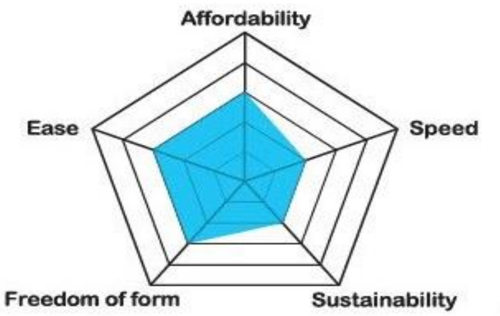

Figure 15 Brick Construction

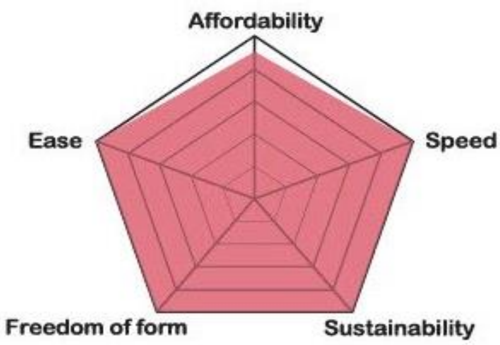

Figure 16 3D Printing Construction

VIII. 3 D Printing Applications in Building Industry

Office of the Future in Dubai

The 3D printed office was designed for the United Arab Emirates National Committee as the headquarter for the Dubai Futures Foundation. The so-called "Office of the Future" primarily serves as a meeting space for parties from all over the globe. The 3D printed office is a fully functional building featuring electricity, water and telecommunications and air-conditioning systems.The 3D printed house was produced in China. After the parts had been printed, they were shipped to Dubai. The project ultimately reduced labor costs by 50 % to 80% and construction waste by 30% to 60%. It is considered as the catalyst behind the construction 3D printing revolution happening in Dubai.

Figure 17 (a) Side view of Office of the Future in Dubai

Figure 18 (b) Front view

Apis Cor Printed House in Russia

A Russian company has done just, with a 400-square-foot-home being built from scratch in just 24 hours in Moscow. The cost of the building is $10,000, highlighting just how much potential the 3D printing technology has for the future. The house was built entirely on site using nothing but a mobile 3D printer, which makes all the results impressive. It is a house that is certainly habitable and short on space. The fact that it was produced at such low-cost in 24 hours. All the walls and foundations of this structure were printed with a concrete mixture and other parts such as windows, fixtures and furniture being added after construction. The house was finished with a fresh coat of

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paint with the final cost of the entire project totaling a modest $10,134.

Figure 19 (a) Front view of Apis Cor House in Russia

Figure 20 During 3D printing process

IX. CHALLENGES AND OPPORTUNITIES

Technologies for 3D printing, or more broadly additive manufacturing, have proliferated in recent years, and have captured the public's imagination as a revolutionary way to democratize small-scale, customized manufacturing for the DIY community. In the design of buildings and bridges, 3D printing has proven to be a valuable technique for creating intricately detailed scale models in a fraction of the time required by traditional methods. In both cases, the general-ized layer-by-layer material deposition process is a compelling way to achieve geometries of nearly infinite complexity with ease.

But 3D printing has also permeated markets beyond the consumer and model scale, with increasing buzz about applying the technology to large objects, such as full-scale buildings. This prospect is exciting for several reasons: reduced construction waste through highly precise material placement, increased capacity for complex geometries for both functional and aesthetic purposes, and new possibilities for integrating building component functions into a single, streamlined assembly.

Advances offer compelling support for a new vision of construction for civil structures. However, several key challenges remain to be met before these techniques can be used in a widespread, cost-effective manner, especially in terms of structural behavior and performance. There is an exciting and important opportunity for the structural engineering community to have a strong voice in the further development of these new techniques to ensure that safety and material efficiency are prioritized.

One set of challenges relates to the materials and composites proposed for 3D printing of civil structures, many of which are new to this application or new in general. While a great deal is known about traditional structural materials such as steel, concrete, and timber, the behavior and properties of materials produced through heated extrusion, layered deposition, and sintered powders are less well understood, and need to be studied and developed with long-term building applications in mind. Furthermore, the layer-by-layer fabrication approach should be reconsidered for appli- cations with structural functions. In many materials and techniques, this leads to sig nificant anisotropy in strength and ductility, due to poor bonding between layers, limiting the efficacy of printed parts.

A final set of challenges relates to the ques tion of formwork. While 3D printing promises to reduce or eliminate construction waste, the difficulties of supporting a structure as it is constructed remain for geometries that cannot be fabricated as vertical extrusions. Small-scale 3D printers address this problem by printing support structures concurrently with the final objects, which can be dissolved or detached once the print is complete. A similar approach could work at the building scale, but more research is needed to determine how to implement this effectively, ideally in a way that involves re-usable or recyclable support material.

Looking forward, it is clear that many such challenges lie ahead before the promise of 3D printing can be broadly achieved for building structures, but the recent, rapid development of increasingly realistic proofs-of-concept is highly encouraging. The continued contributions of pioneering structural engineers are critical to help push this transformative technology from small-scale geometric representation to high- performance, full-scale structures.

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