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3D Printing Technology in Housing Projects Construction

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***Abstract*—**Realistically, 3-D printing as a technology has not yet reached the required maturity level to handle construction housing projects for citizens on a country scale. However, potentially, it has all of the required elements for addressing this issue. There are two main high-level elements of this technology that need to be capitalized on in order for the technology to reach its full potential: technical and logistical. This paper aims to cover how 3-D printing can be a viable technical solution for housing projects and describes the impact of 3-D printing technical features on the logistical aspects of completing a housing project. Additionally, a perspective about 3-D printing in Saudi Arabia will be presented in order to give the reader an idea of where the Kingdom stands in the deployment of this technology. Finally, a glimpse will be given regarding the potential utilization of this technology for space applications.

***Keywords*—**Large-scale 3-D printing, additive manufacturing, D-shape, contour crafting.

I. Introduction

IT is certainly desired that construction activities are completed faster, safer, with better quality and lower cost. Focusing on housing construction, this sector has been progressing rather slowly in terms of the utilization of new techniques in order to achieve the desired stated wish list. While a method such as pre-cast has been utilized in order to address some of the desired goals, pre-cast buildings have not become a global phenomenon in housing projects due to factors such as potential damage to the pre-cast structure during transportation, size limitation of pre-casted units, required equipment to handle installation of heavy pre-cast units and achieving satisfactory connections between pre-casted units.

It is possible to achieve a major breakthrough in housing projects by completely changing how we think about home construction making them safe to complete, easy to produce and available to anyone at low cost. If 3-D printing in housing projects becomes an established global phenomenon, the prices of owning or renting a house will collapse dramatically. Additionally, homelessness will be mostly eliminated leading to improvement in public health, reduction of crime rates, and in number of people who are living in poverty (by reduction of financial requirements associated with owning or renting a house).

The current known associated challenges which need to be addressed in order to achieve the desired goal can be split into two categories. The first type of challenge is technical such as achieving a balance between mixture flow and structure strength, work-ability, prevention of deformation, and cracks formation in the printed structure's corners. These types of issues can be addressed through research and development. The second type of challenge is logistical such as an initial high cost of 3-D printing equipment (this should reduce with time as the technology becomes more common), availability of required mixture, lack of binding legislative regulations, lack of formal standards as well as required knowledge and skills to run 3-D printing equipment or develop required software. These types of issues will require adaptation of the technology on a country level to establish required infrastructure from supporting manufacturers willing to invest in this field, setting the binding procedures, to investment in education like introducing a curriculum which emphasizes in theoretical and practical knowledge in schools for 3-D printing.

The vision of success for this technology is to have countries with established rules and regulations for construction of 3-D printed homes, schools with 3-D printing curriculum and fab-labs, and scientists that regularly explore methods to further improve this technology. Additionally, there should be a global competitive market full of manufacturers who can supply consumers with a 3-D printed house within a month with high quality and low price. This technology will be truly successful if the world can reconstruct cities affected by natural disasters or wars quickly without the need of making affected citizens refugees. We sincerely hope that we will live to see this change become a reality.

II. Construction Utilizing Large Scale 3-D Printing

The cost of traditional construction has increased rapidly over the years. This increase in costs will eventually result in the introduction of other technologies that are lower in terms of cost and more reliable in terms of sustainability. Moreover, labor productivity in the construction industry has exhibited a decline over the past 50 years [1]. A solution to avoid complications of addressing the root causes of the decline in productivity by labor is relying on machines and the additive manufacturing method (3-D printing). Printing in 3-D has become widely used for many applications in different industries, and one of these industries is construction. “Up until a few years ago, 3-D printing applications in the construction industry were largely confined to the production of affordable architectural models. However, more recently, several spectacular attempts to 3D print complete houses have been the subject of much publicity” [2]. In the past, it was simple for

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anyone to own a house in a short time of working; however, due to the inflation that affects world countries, it has become really difficult for anyone to own a house within a short period of time.

Large-scale 3-D printing is a special type of additive manufacturing that is utilized in building large-scale, heavy, and often permanent structures. The technology is currently capable of 3-D printing a house, and this has been done in countries such as KSA, US, UAE, and Europe. The technology can, potentially, be a substitution for traditional construction methods [2]. Sakin and Kiroglu mentioned the 3-D printed house that was produced in China where the parts were 3-D printed and shipped to Dubai. "The project ultimately reduced labor costs by 50% to 80% and construction waste by 30% to 60%" [3]. The main reasons of utilizing additive manufacturing in construction are cutting costs, optimizing completion schedule and simplifying the construction of complex architectural shapes. As per the research that was done by Sakin and Kiroglu, they refer to Austrian architect named Wolf D Prix. Wolf mentioned that, combining robots with the use of 3-D printed building components will make it much easier to build buildings with complex shapes; also, he added that, "Normally this part of the building would take eight months with 160 workers on the site, now we need eight workers on site, and it takes 12 weeks." [3]. The 3-D printing method will open huge opportunities for designers and people who want to implement ideas that are complicated to deploy in traditional buildings due to the technology's ability of printing a complex object with the same efforts required for printing a standard geometrical object such as square or circle. These examples maybe the beginning of a new global phenomena where 3-D printing dominates the construction industry.

There are multiple methods of construction utilizing 3-D printing and each one of them has its own benefits. Research on large-scale 3-D printing technologies could be classified as either gantry-based, robotic-arm based, or swarm-based [4]. Focusing on the gantry-based solution which is simply a scale-up of additive manufacturing to additive construction [2], the solution includes techniques such as; D-Shape and Contour crafting. The 3-D printing with D-shape is basically working by having a good amount of sand/powder, and there is a spraying that goes layer by layer until it reaches the end of the shape. It takes about 24 hours for the solidification process to be completed. D-Shape has the ability to print up to 6 x 6 x 6 m with up to 235-242 MPa shapes (Fig. 1) [4]. D-Shape can be utilized to design furniture of any sophisticated shape either inside or outside buildings. On the other hand, 3-D printing utilizing contour crafting (CC) is more suitable for construction due to its process automation capability that makes it very suitable for construction either on earth or other planets (Fig. 2), such as Mars [5]. CC is a recent layered technology that has a great potential in automated construction of whole structures as well as subcomponents. Relying on this technique, a single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run, embedded in each house all the conduits for electrical, plumbing and air-conditioning [5].

Fig. 1 D-Shape 3D Printing Technology [4]

Fig. 2 Icon's Vulcan construction system 3-D prints layer on layer using specially formulated concrete [11]

The CC process allows for architects to design and implement structures that are sophisticated or difficult to be constructed by human beings, the luxury of having various materials for outside surfaces and as fillers between surfaces may be used in CC (Fig. 3). This enhances the strength of walls to match those of traditional construction. Moreover, multiple materials that chemically react with one another may be fed through the CC nozzle system and mixed to have a better composition before deposition [5]. Regardless of the choice of materials, the surface quality in CC does not require further surface preparation. It is ready for painting by simply having an integration for automated painting system by utilizing a spray-painting robotics attached to the CC main structure that may paint each wall according to the desired specifications [5]. CC also allows for automated reinforcement, automated tiling of floors and walls, automated plumbing, automated electrical and communication line wiring, and utility conduits.

Fig. 3 Outside surface and inside [7]

Utilization of this technology will open the opportunity for people to complete construction of a house in short time and at low cost; for instance, the time required to complete a 200 m^2 two-story building will be shortened to less than 2 days according to Khoshnevis [5]. The speed of operation, and the efficiency of construction makes CC technology an incredible method for the utilization of resources. The stated features make CC a good solution for addressing housing problems at the countries level and supporting in resolving homelessness [6].

III. A Perspective of 3-D Printing in Saudi Arabia

The Kingdom of Saudi Arabia is recognizing the importance of introducing new technologies in construction for addressing the current/future demand in housing and to reduce cost, time and efforts associated with large scale projects. The Ministry of Housing in Saudi Arabia has undertaken an experiment project to build the first 3-D printed house utilizing CC and stated the following;

> "The aim of this experiment is to compete with the technological progress in the world of future construction, to benefit from the latest technologies in the world, and to be a pioneer in promoting the adoption of innovative construction techniques in the construction sector and the localization of its industry in the Kingdom in line with the objectives of the Kingdom's Vision 2030 and the National Transition 2020 Program" [8].

Constructed in collaboration with a Dutch company "Cybe", the 3-D printed house is located west of King Khalid International Airport in Riyadh. The house has been utilized to demonstrate the capabilities of this technology where the Ministry of Housing allowed specialists and workers to visit this house for promoting the technology in the Kingdom (Fig. 4).

Fig. 4 The first 3-D printed House in KSA by the ministry of housing in collaboration with Cybe [8]

The private sector in the Kingdom did not miss to see the potential in this technology. Dar Al Arkan has endorsed 3-D construction printing technology in collaboration with a company named Construction of Buildings on Demand. This partnership is aiming to commercially pioneer 3-D printed houses, with CC, in the Kingdom and support the economic diversity as part of the 2030 Saudi Vision. The company's vice president stated:

> "Our goal is to develop the Kingdom's real estate sector by integrating the latest trends and technologies, drawn from global best practices to enhance our industry locally and deliver on the objectives of Vision 2030 at many levels. The introduction of 3D construction printing will revolutionize our approach to construction and enable us to focus on greater flexibility of design, strengthen productivity and achieve higher cost efficiency. This will raise the industry standards, achieve excellence and position the Kingdom as a leader in this sector, while making us highly competitive in 3DCP technology" [9].

Fig. 5 Dar Al-Arkan 3-D printed structure with COBOD technology

Finally, Saudi Aramco has started taking an interest in this technology by supporting local communities in spreading awareness about 3-D printing through fab-labs. The company is also planning to construct its first 3-D printed house by 2022 as part of the Hawiyah Unayzah Gas Reservoir Storage Program. If this project meets the company's expectations in reduction of the construction schedule, it will be the first step for larger investment in 3-D printing technology.

Although there are currently no large-scale projects in 3-D printing in the Kingdom of Saudi Arabia, the country has taken the first steps in exploring this technology and some companies have started investing in what could potentially be the future of the construction industry.

IV. 3D Printing in Space Exploration

The cost of sending material into space is very high. While an accurate figure for the cost per pound of sending material into space is not available, a rough idea can be obtained from a study by NASA in 2012 estimating the cost per space shuttle lunch to be around $576 million dollars [10]. Based on the average cargo capacity of a space shuttle, the average cost of lunching a pound into space is a minimum of $10000 dollars. This extremely high cost of sending materials into space enforced the need to look for the best efficient and effective use of available cargo capacity. This is one of the reasons that has made 3-D printing an essential solution for material delivery into space.

Astronauts in the International Space Station (ISS) have limited storage inventory and a good number of the items that are available for maintenance are not utilized for a long period of time and some of which may never be needed. For such materials, the invested cost of shipping and utilized storage space is hardly providing any return on the investment. A 3-D

printing workstation in the ISS has contributed to reducing the cost of sent material. As 3-D printing machines use resins to create the desired object, there will be no need to ship a list of all potential items that may be utilized into space but rather send resins that can be utilized to manufacturer the desired material at the space station (Fig. 6). The use of 3-D printing in space has further expanded on the optimization of using sent resins by the creation of a 3-D printing machine that is capable of recycling 3-D printed material for the creation of new objects (Fig. 7). This optimization creates a significant cost saving by minimizing the need of sending resins into space.

Fig. 6 Picture Showing a Zero-G 3-D Printing Machine Created by Made in Space in Collaboration with NASA [10]

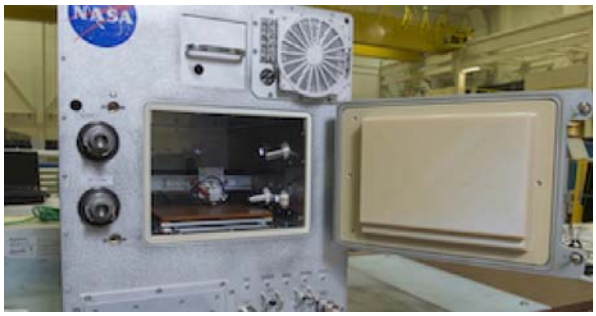

Fig. 7 Nasa's 3-D Printing Machine "Refabricator" [10]

The use of 3-D printing for the creation of food is being explored and researched for the personalization of prepared foods for astronauts and for the better utilization of the limited storage space as the components used to create 3-D printed food are in a compressed status. The compressed status of 3-D printed food and the consumption validity period could potentially provide a viable solution to address astronauts nutrition requirements for extended space travel.

The next major step for 3-D printing in space is the utilization of the technology on different planets. Humans have always dreamed of colonizing different planets for various reasons, some of which are related to territorial expansion nature that has been witnessed in the past in the form of expeditions to explore different contents or the need to look for additional resources. However, unlike how expeditions on earth were conducted on the only known life-supporting environment, space expeditions are conducted in hostile environments to all known forms of living creatures. These hostile environments pose the biggest challenge on the colonization of a different planet.

In order for humans to settle on a different planet (Mars, for example), infrastructure that includes shelters capable of providing protection from solar radiations, food and water growth/extraction mechanism, oxygen generation mechanism, and health fitness facilities, have to be present. Construction of such facilities by conventional methods will require tremendous transportation of resources from Earth to Mars. As stated earlier, the cost of transportation will be very high and it is unlikely that funding of such project will be secured. Additionally, the travel opening windows to other planets occur in a specific period of time (e.g. every two years for Mars) due to the rotation of planets around the Sun. This further complicates this mission. One of the few available answers to tackle this problem is the utilization of resources on the planet to build the desired infrastructure.

In order to decrease the life-threatening risks for humans in staying for an extended period of time at a different planet while building the required stated infrastructure, it has been proposed that robots which are capable of constructing required infrastructure with 3-D printing capabilities are initially sent to the desired planet for infrastructure construction. Fig. 8 is showing a concept by Team AI Space Factory. This team won Nasa's prize for 3-D printed habitat on Mars. The 3-D printed structure is, theoretically, capable of supporting life in Mars's thin atmosphere and will not collapse in the planet's low gravity which is one third of Earth's. Some of the essential features of the 3-D printing robots are the ability to utilize materials from host planet for construction, programmable with a set of instructions to conduct the desired work, ability to re-program via satellite, equipped with solar panels and a secondary energy source, equipped with sensors for navigation and assisted with support robots for maintenance. The goals achieved or envisioned in the 3-D printing space studies will contribute to the advancement of the technology in the construction industry on Earth.

Fig. 8 Team AI. Space Factory 3-D Printed Habitat Concept on Mars [12]

Our ambitious 2030 Vision is targeting competing with world countries and be ahead in many fields. The future of 3-D printing in space will be part of our life and we have to work hard in this field to harness all of the advantages it provides and ultimately set a leading example for other countries.

V. Conclusion

The use of 3-D printing in construction, as a technology, can be the next "smart phone" in revolutionizing the construction industry. With its features and flexibility, it will change today's perception of housing construction and construction in general. The initial deployment of 3-D printing has already started in the Kingdom at both awareness level through fab-labs and investments by private sectors. As more efforts are poured into the technology in research and development, the cost on end users will further decrease and housing problems worldwide will be eliminated making many people's dreams a reality. This technology's wide range of application from construction and education to space, makes its limits the sky and beyond.

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