# The Design and Implementation of a Large-scale 3D Printing System with Tensegrity and Cable-suspended Parallel Robotic system

Haeyeon Kim [1] , Ju Hong Park [2]

[1] Pohang University of Science and Technology
godus@postech.ac.kr
[2] Pohang University of Science and Technology
juhpark@postech.ac.kr

**Abstract.** In this paper, a novel design of 3D printing system is presented. We proposed a large-scale 3D printing system with tensegrity structure and cable-suspended parallel robotic system(CPR). It has an advantage in the construction field, especially for building habitats in extreme environment such as Mars. Compare to a currently used 3D printer, and it has lightweight and a wide range of workspace. We implemented a 3D printer with CPR and tensegrity framework. The project is an initiation of a long-term research; accordingly, this paper limits its work scope by demonstrating the 3D printability of the system with CPR and developing a tensegrity framework. To validate 3D printability, we independently tested two scenarios. One is a table-size 3D printing validation as a fast prototype, and the other one is a small building-size 3D printing for testing large-scale 3D printability. As a validation, we used an LED bulb attached on a 3D printer head to trace its movements in workspace. We illustrate that the use of CPR is highly effective and scalable system for a large-scale 3D printing; additionally, tensegrity could be an effective alternative for its structural framework.

**Keywords:** Digital Fabrication, 3D Printing, Tensegrity, Cable-Suspended Parallel Robotics

## 1 Introduction

It is highly challenging to build habitats on Mars using conventional construction technologies. 3D printing could be an alternative solution for such an extreme environment where humans cannot efficiently work and where earth materials cannot be utilized. A project, called ‘SpaceX to Mars City,’ attempted to 3D print buildings using the Martian bricks that are made of dust gathered on Mars [1]. Researchers found that this material was stronger than metal [2]. However, current large-scale 3D printing depends on rigid robotic systems, such as a gantry crane or a robot arm system that are heavy to be moved, have a limited workspace, and are difficult to manipulate [3]. An interdisciplinary collaboration involving mechanical and structural engineering, and architectural design resulted in the development of a novel 3D printing system that is composed of a tensegrity structure and cable-suspended robotic system resulting in a transportable, scalable, and, reconfigurable system. Cables and motors attached to a tensegrity structure can automate the movement of a 3D printer head (extruder) in a civil or an urban-scale workspace. The lightweight tensegrity structure enables spaceships to transport the system to Mars with relatively low cost.

A tensegrity system maintains its structural integrity through the balance between tensile and compressional forces [4]. It consists of carbon fiber tubes for compression members and high strength cable for tension members. The proposed lightweight tensegrity system succeeds in enabling the transportation of the system from Earth to Mars, implementing the system on site. To develop a scalable system, we use a cable-suspended parallel robot (CPR) system, like the Skycam [5]. A CPR is a robot controlled by cables attached to motors instead of linked rigid body system. The presentation illustrates the process of design and implementation of this hybrid 3D printing system for an extra-large lightweight 3D printing for a place where it is extremely difficult or costly to build one. A 3D printing experiment using eight-strut tensegrity structure (Figure.1) with a workspace of 1 x 1 x 1 m. The demonstration aims to prove the potential of the discussed 3D printing system with minimal and lightweight components.

While 3D printing in industrial manufacturing has been rapid to be integrated, the building and civil practice have been slow in utilizing it. The tensegrity structure combined with a cable robotic 3D printing system has proven to suit for 3D printed habitats in remote areas including Mars. However, working on tensegrity and CPR-based 3D printing has shown new opportunities as well as challenges. The latter part of this paper will discuss these. Further studies involve precise control of a 3D printer nozzle in a larger workspace [6]. Future steps foresee the development of a 3D printing system in extreme environments, such as high heat, heavy rains, and heavy dust.

**Fig.** 1**.** Eight-strut tensegrity structure built in this project. An extruder head is located at the center of the structure. Stepper motors are installed on bottom struts.

# 2 Context

## 2.1 Previous research

In this paper, we propose a novel 3D printing system that can make us possible to build habitats in Mars. There are many cases of building habitats using 3D printers at present. The Russian company, Apis Cor, has even built a 3D printer capable of printing a building in 24 hours and complete a 132 square meter house [7]. Besides, the Italian manufacturer WASP has produced the largest 3D printer on the market today, with a 12m height and a 7m width. This 3D printer can make buildings up to six meters in length [8].

The 3D printing system that is currently used in architecture fields commonly operates by using a rigid robot arm. The system is currently undergoing tremendous progress. It is highly accurate and can print any objects even in complex geometry. However, as the size of the system increases, the weight also increases exponentially, resulting in higher energy usage and structural materials to maintain its stability. Also, it can print in an area only where the robot arm can exist, so that the workspace is relatively small.

On the other hand, there is another kind of large-scale 3D printer. It is a 3D printer with a cable-suspended parallel system introduced in 2015 named 'Large-scale 3D printing with a cable-suspended robot' [9]. In this project, researchers built the 3D printer that can print a shape of 2.16 meters in size and has an accuracy of 1 cm. The extruder component is connected to the cable, which is controlled by changing the length of cables attached to motors and the extruder. The system can print in any range that the extruder can go to, which in turn makes it possible to print in a wide range of workspaces. It also has the advantage of being able to build any 3D shape using this printing system and can find and correct errors using geometric feedback. Polyurethane foam was used as the primary printing material, and shaving foam was used as the supporting material. However, the time to print object took a very long time of 38h, and it needs to be improved regarding materials to be used in building buildings.

## 2.2 Development

The system we are proposing is a hybrid 3D printer that combines a tensegrity framework and cable-suspended parallel systems, which is suitable for large-scale printing objects. Tensegrity is a synonym of tension and structure integrity. This 3D printing system is based on the combination of loading members, and tensional prestress that maintains mechanical stability. Recently NASA is working on a project to create a structure that can withstand impacts on Mars using diverse tensegrity structure systems. These structures maintain their shapes even when they are exposed to an external impact, and they have the advantage of being lightweight but robust so that it retains its shape even if it is rolled at any rate.

The advantages of the 3D printing system using the cable-suspended mechanism are shock-resistant and the lightweight of the overall structure. This system will be particularly advantageous when used in extreme environments such as Mars. The 3D printers must be transported in order to be able to work in environments where it is hard to go or work for people. When we focus on the system weights, the design we propose has tremendous advantages. Also, by using a tensegrity structure, it might be easier to land from a spaceship.

The cable-suspended mechanism also allows the printer to be controlled simply by turning on the motor, which allows for fast control and energy-efficient operation. In addition, the delicate length of the cable can be adjusted, allowing for control that is more precise. We developed the overall system with two steps; CPR system and tensegrity framework in this paper as shown in Figure 3. The detailed explanation will be followed in later part in this paper.

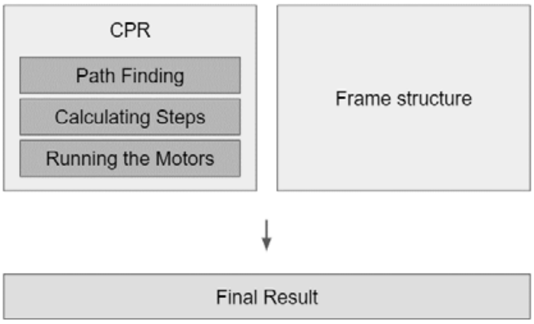

**Fig. 3.** Developing process of new 3D printing system

# 3 Build Process

## 3.1 Tensegrity framework

First, we created a cube-shaped tensile structure using eight struts that has same structure that was used in the NASA project. Each corner has a length of 1m, the material is a carbon fiber tubes, and each rod is subjected to tensile force by a rubber band. The balance of this force kept the structure maintain the shape even when we took our hand off, and it was very light enough to be lifted by one hand with a weight of around 10 kg.

The length and weight are one-dimensionally proportional when we are using same diameter tubes. Therefore, if length increases to ten times, the weight of about 3 kg is expected to be about 30 kg. It leads more innovative convenience than conventional 3D printer is. The Figure 1 shows a tensegrity structure that we designed with a motor attached to every corner, and a PLA extruder suspended to show the design we are suggesting.

### 3.2 Cable-suspended Parallel Robots

We made cable-suspended parallel robots of two sizes in total for the experiment. First, to verify the performance, a cube-shaped frame with 900mm size was produced. We put a stepper motors at the four upper corners of frame and attached winches to the end of each motor to wind the cable. Each of the four cables is connected to one extruder and the length of the cable can be adjusted as the motor rotates. In order to level each corner of the extruder while it is moving, it is better to cable all eight corners with motors, but this will be dealt with later.

After we completed the first experiment with 1m CPR printer, we built a building-size robot to verify the performance of bigger size object. Four motors were installed at the four corners of the corridor balcony inside the building. In addition to that, the cables were connected to each motor in the same way as before to hang the extruder. Width, length and height are 4700mm, 7000mm and 7150mm each. The large-size 3D printer with CPR will be easily installed by simply installing a motor at each corner without much effort. The size of two CPR 3D printer are shown in the table 1.

**Table. 1.** Size of the CPR 3D printer

| | Width | Length | Height |
|---|---|---|---|
| Small size CPR | 900mm | 900mm | 900mm |
| Building size CPR | 4,700mm | 7,000mm | 7,150mm |

## 4 Method

We have done three steps to get our 3D printing system working. The first step is to find the path that the extruder should go through to print the desired model. The second step is the process of calculating the number of steps required for each motor to rotate in order to move for extruder these paths. The final step is to operate the motor using Arduino according to the steps that are obtained in the second step. Each of these processes will be explained in detail below.

### 4.1 Path-Finding

In the first process, to find the path of an extruder, we start with slicing the given model from top to bottom. Following the horizontally sliced parts, the path will start from the bottom to the top. This pathfinding process is similar to the conventional commercial 3D printing method. In conventional 3D printing, there is a thickness between the outer and inner part of each model so it must be considered to fill the inside of wall. However, in this experiment, we consider the model has only the outer part so that the extruder moves along to the closed curve for each layer. Because one layer consists of closed curves, the extruder will have the same starting and ending points when drawing this curve. These starting points for each layer were connected in a vertical line so that the extruder could draw all the layers at once. All of these processes are written using the Rhino command and Rhinoscript code.

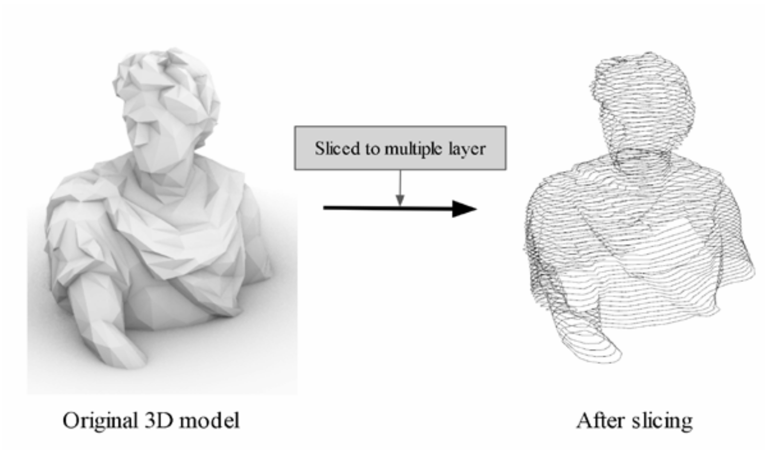

**Fig. 5.** Original and sliced 3D model for test

The following models as shown in figure 7 are used in this experiment. The model is the torso of Greek, and it is to be printed in the small size 3D printer. The actual height of the model is about 500mm high. The second model is an experimental model used in a building-sized robot, which is the whole body of the Greeks. The actual height is about 5000mm, which is about two stories high in a typical building.

In this experiment, we attached the LED on the end of the extruder so that we can see how the extruder moves without actually printing object. As a result, we used a method to check the model shown by combining all the pictures of the LED shown in each of the many pictures taken every 10 seconds. This method can shorten the time required for the experiment, and the actual printing process will be further developed after increasing the accuracy of the system.

### 4.2 Calculating Steps for Each Motors

In the previous step, we obtained the path to which the extruder should pass. In this second step, we need to know how many steps to rotate the motor to make extruder move along the path. When printing a circle on a 3D printer, for example, it splits the circle into several small straight lines and prints it because it cannot print the actual curve. Following this idea, we took multiple points by splitting the curve in a constant interval and got multiple straight lines connecting these points. Therefore, the extruder will move along not a smooth curve, but a connection of multiple small straight lines to make a path. At every point, we can calculate every four lengths of cables that are connected to the extruder. We should change as the length difference between one point to another point. The formula for this calculation is shown as below formula (1)-(3). To change the length of the cable, we should also calculate the according to steps for motors. Since the length change of the cable is proportional to the motor steps, we should calculate the ratio between the two. We used the formula (4), (5) to calculate the ratio. We mainly used two value; one is the diameter of a winch, and the other one is the SPR, which means steps per rotation. With the formula, we got the ratio as 60. The motor we used is a micro stepper motor, which requires 3200 steps to rotate one wheel.

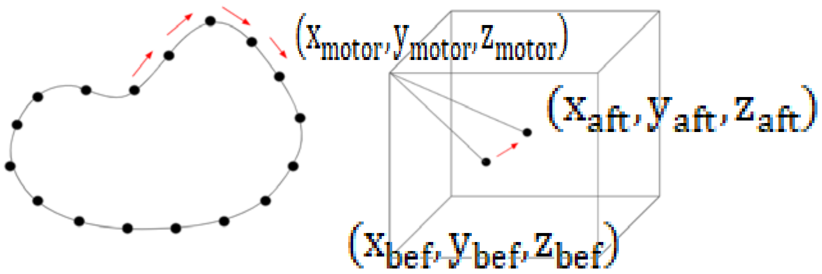

**Fig. 7.** Points to move

$$\mathrm{l}_{\mathrm{aft}} = \sqrt{(x_{motor} - x_{aft})^2 + (y_{motor} - y_{aft})^2 + (z_{motor} - z_{aft})^2} \tag{1}$$

$$\mathrm{l}_{\mathrm{bef}} = \sqrt{(x_{motor} - x_{bef})^2 + (y_{motor} - y_{bef})^2 + (z_{motor} - z_{bef})^2} \tag{2}$$

$$\mathrm{length} = l_{aft} - l_{bef} \tag{3}$$

$$\mathrm{ratio} = \frac{\mathrm{steps\ \ per\ \ rotation}}{2\pi \mathrm{d}_{\mathrm{winch}}} \tag{4}$$

$$\mathrm{steps} = \mathrm{length} * \mathrm{ratio} \tag{5}$$

The steps of the motor must always be an integer. The cable length difference is likely to have a decimal point because we split it into tiny pieces to soften the curve. In this way, errors occur little by little in the number of steps per straight line. Therefore, as the experiment progresses, the error becomes more substantial when it comes to an end. We will continue to discuss this in the later part.

### 4.3 Running the Motors

We first obtained the steps of each motor independently. The final procedure is to apply these steps to each motor to move along the path. The amount of steps data is tremendous because the curve was split into a substantial number of straight-line segments. Therefore, these steps should be stored in the SD card and inserted into the Arduino. In Arduino, we programmed to read the SD card line by line and make each motor to rotate clockwise or counterclockwise as much as the steps. Since the number of steps the four motors must rotate is different, the time the motors end to rotate will be different. It may cause the extruder to become non-level when moving. However, since we broke curve to very short increments, there will be no problem in practice. The overall procedure of the system is shown in figure 8 below.

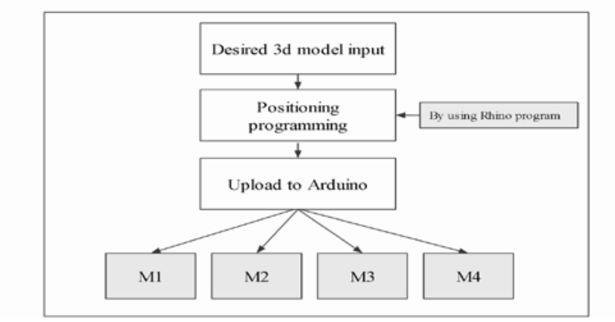

**Fig. 8.** Overall procedure

## 5 Results and Discussions

One consideration for building habitats using 3D printers on Mars is to transport using spacecraft. The primary requirement in transporting a 3D printer includes restrictions on a machine's weight and dimensions. Additionally, we need to consider the moment when a spacecraft lands on Mars and a 3D printer needs to be installed; it must be able to withstand external forces. Tensegrity structure, which we use as the frame of the system, has flexibility and has substantial advantages against external force. In particular, since the string part of tensegrity has elasticity, it is capable of massive displacement when the prestress is applied. This fact allows us to increase the size limit when loading the system into a spacecraft.

The advantage of the combining system of cable-suspended parallel robot and tensegrity is the reduction of weight. Commonly used 3D printers in construction fields use a gantry system, which uses rack and pinion as an actuator on solid yet heavy metal structural frames. Other types of 3D printers consist of robot arm controlled by servomotors and belts, and their body weighs about hundreds or even thousands of kilograms. For example, P1 BetAbram, the 3D printer for house construction, weighs 500kg and Machines-3D’s 3D Constructor; also the other model weighs 2,340kg. However, for cable-driven 3D printers, the weight can be significantly reduced since cables can replace many most gantry parts [10].

The developed printing system has advantages in terms of energy efficiency. Conventional 3D printers for construction are composed of gantry actuator type, and they have mainly X, Y, and Z-axes. Of these three axes, the Z-axis should support the most of the body, including the part where extruding proceeds. Unlike this axis, the other axes have a smaller magnitude of force than the Z-axis because they are responsible for moving parallel to the ground. Overall, the force received on each axis in a conventional 3D printer is not balanced making specific motor need much force. However, in a cable-controlled 3D printing system, the four motors are arranged in parallel. This system has the effect of balancing the force received by each motor when moving the end-effector. This fact, along with the weight reduction of the actuator part, makes it have considerably more energy efficient. We experimented with printing a torso using a small-sized 3D printer and printing a whole body of the torso using a building-size 3D printer. In this part, we analyze the results of each experiment.

### 5.1 A Table-Size 3D Printer

Figure 9 shows the result of an experiment with a 1-meter printer. The total time taken for the experiment is 2 hours and 40 minutes. Compared with the model used as the existing input value, it seems to be slightly distorted. However, we can distinguish the head part in the middle and body part in the bottom of the resulting model.

**Fig. 9.** Result of a table-size printing

**Fig. 10**. Result of a building-size printing

### 5.2 A Building-Size 3D Printer

The result of an experiment with a building size printer is shown in figure 10. The total time taken for the experiment is 4 hours and 50 minutes. It is difficult to distinguish the shape of people passing through the hallway and, due to daytime shooting, the upper LED part of the model cannot be distinguished by the sunlight; however, we can demonstrate that the 3D printing could be achievable in this large-scale workspace (scalability). We did not change any parameters from the previous table-size 3D printing other than the new shape - a Venus sculpture.

The developed frame consists of 12-strut tensegrity with 48 cables. When we enlarge the size of the structure to the building size, we should consider the buckling problem. To check this, we used the structure analysis software called PushMePullMe 3D [11]. Since the maximum length of the bar element was 500mm, we designed the 1/10 scale down model with this software [12]. Applied gravity 1 and prestress 70%, the maximum stress to the strut was 0.3MPa. Set the Elastic modulus of the material to 21,000. The analysis is illustrated in figure 11.

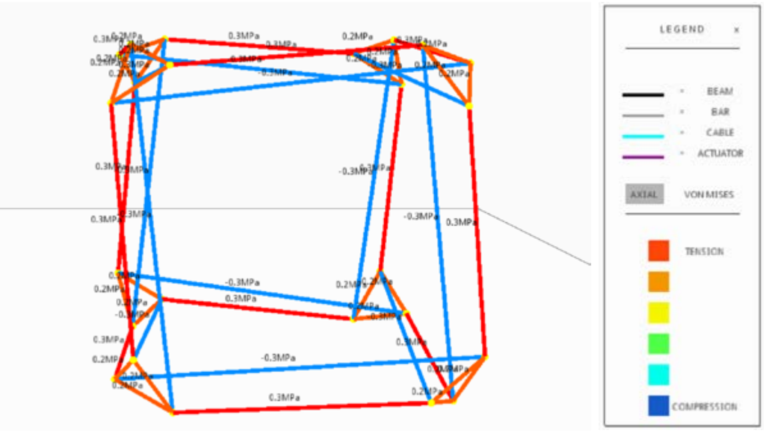

**Fig. 11**. Structure stress analysis simulation on PushMePullMe

### 5.3 Precision Winch System

In order to increase the precision of the system, we developed a winch system. The winch we used for the previous experiment was caused the displacement of an extruder position. While the cable was wound around a rod, it increases the range of position errors. As a solution, we combined a screw rod at the end of the motor so that cable could be wound along the groove of the rod when the motor rotates. Also to prevent unwinding or twisting of the cable, we installed a cable holder to cover the rod. The final winch system is shown in following figure 12.

The radius of the rod is 8 mm, and it can wind the cable 25.13 mm length when the motor rotates one turn. The distance between each groove is 1 mm, and the total length of the rod is 150 mm so that the cable can be wound about 3770 mm in total. This system removes the error from the radius change while winding the cable, but it involves the other error because the point cable comes out from the rod is to keep changing. Therefore, we should continue to study to find a way to wind the cable precisely.

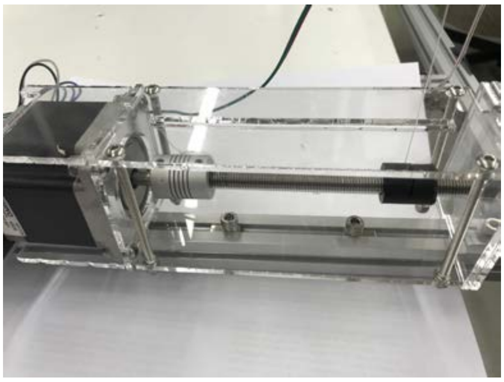

**Fig. 12**. The developed precision winch system

# 6 Conclusions

In this paper, we proposed a novel 3D printing system that combines tensegrity structure and cable-suspended mechanisms. In order to realize this, we made a 1m size tensegrity structure and proposed a new 3D printing model. The structure is designed using carbon fiber tubes and has a lightweight that is easily movable. Besides, two sizes of the 3D printer were built to test the movement of the extruder. As a result, it was found that the accuracy was higher in the experiment with the small size printer, and the larger the size, the more the error occurred in the accuracy.

The cause of the error can be various, but mostly, the change of the winch diameter has the most effect on error. As the size gets bigger, the cable winds up a lot on the winch. It leads to the significant difference of the winding amount between the start and end of the print operation. Since the radius of the winch is the main value for calculating the ratio between the length of the cable and steps, the ratio becomes larger as the printing process goes on. Because of this, the model tends to be printed larger as the print time passes. To solve this problem, we should always keep the amount of wound cable around the rotating part be the same at all times. In other words, one part where the cable is wound and the rotating part should be separated.

Another cause of the error is the method that we calculate the steps as mentioned above. Since the step of the motor must always be an integer, there is a limit to precisely controlling the length of the cable. Since there are some errors for every step, the result will have more significant error, which is the sum of every error, at the end of the printing process. To solve this problem, we can program it to check if the difference exceeds a certain range and fix the position of extruder periodically. It can make the printer stop printing and adjust the position again. In order to implement this, there are some methods, for example, adding GPS to the extruder or measuring the distance between the extruder and each motor using LIDAR.

The expected effects of our proposed system are as follows. First, when building habitats using our advanced 3D printers, it will make us possible to reduce significantly the hardworking of people, and it will be useful for construction in extreme environments, such as on Mars. In particular, it solves the weight problem, which is the biggest reason that we could not bring a currently used 3D printer for construction to Mars before. It also has the advantage that it can be used safely against the impact that occurs when landing on Mars by using tensegrity structure. By making it possible to build habitats, which is an essential element necessary for a person to survive on Mars, it will be an essential basis for expanding the area of human activity to Mars. Based on this foundation, it is expected that the advantages of human research activities and securing resources will be obtained.

# References

1. NASA awards AI spacefactory for MARSHA, a 3D-printed vertical Martian habitat, https://www.3ders.org/articles/20180726-nasa-awards-ai-spacefactory-for-marsha-a-3d-printed-vertical-martian-habitat.html
2. Wan L., Wendner R., Cusatis G.: A novel material for in situ construction on Mars: experiments and numerical simulations Construction and Building Materials, 120, pp. 222–231 (2016)

3. Barnett E, Gosselin C. Large-scale 3D printing with a cable-suspended robot. Additive Manufacturing. 2015 Jul 1;7:27-44.
4. Calladine C.: Buckminster Fullers “Tensegrity” structures and Clerk Maxwells rules for the construction of stiff frames International Journal of Solids and Structures, 14, pp. 161–172 (1978)
5. Duan Q., Duan X.: Analysis of Cable-actuated Parallel Robot with Variable Length and Velocity cable Procedia Engineering, 15, pp. 2732–2737 (2011)
6. Pusey J, Fattah A, Agrawal S, Messina E. Design and workspace analysis of a 6–6 cable-suspended parallel robot. Mechanism and machine theory. 2004 Jul 1;39(7):761-78.
7. Harbaugh J.: Five Teams Win a Share of $100,000 in 3D-Printed Habitat Competition, https://www.nasa.gov/directorates/spacetech/centennial_challenges/3DPHab/five-teams-win-a-share-of-100000-in-virtual-modeling-stage
8. DELTA BIG 66, http://www.wasp3d.net/products/delta-big-66/
9. Gosselin C, Duballet R, Roux P, Gaudillière N, Dirrenberger J, Morel P. Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders. Materials & Design. 2016 Jun 15;100:102-9.
10. The 15 best construction 3D printers in 2019 (March 2019). (2019, March 8). Retrieved March 25, 2019, from https://www.aniwaa.com/house-3d-printer-construction/
11. Yiatros S., Yiatros S.: Development of the online interactive software "Push Me-Pull Me", https://www.academia.edu/14716006/Development_of_the_online_interactive_software_Push_Me-Pull_Me_
12. Shehadeh, M., Shennawy, Y., & El-Gamal, H. (2015). Similitude and scaling of large structural elements: Case study. Alexandria Engineering Journal,54(2), 147-154. doi:10.1016/j.aej.2015.01.005