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# INTERACTIVE PLAYSCAPES: EXPLORATIVE DESIGN AND ROBOTIC FABRICATION TECHNIQUES

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**ABSTRACT:** This research focuses on material-based practices and explorations by utilizing the carbon fiber fabric performance characteristics as a significant driver in the design and fabrication strategies. While the integrative aspects of computational design have been extensively used for the inclusion of environmental, manufacturing, or economic considerations, material information should be similarly employed as a generative driver. The paper describes and evaluates a full-scale prototype of installation for social play actuated in the heart of Beirut city, hence integrating material research with methodologies optimizing fabrication techniques for complex, performance-driven structures. The introduction of carbon fiber composites into the construction sector defines potential challenges to the design process, knowing that these components need to be light and cost-effective in their production. At the same time, advanced technologies, such as digital fabrication, need to dwell upon their limitations regarding time optimization, material restrictions, and relations between automated and manual labor. Many applications show that carbon fiber system has proven to be a novel building material to improve structures. Regarding the fabrication techniques utilized, milling is a vital process, where the material subtraction rate is one of the essential features to be established in addition to its final weight. However, factors such as shape precision and surface quality are constraining factors in the increase of material removal regarding robotic fabrication. Hence, in this work, machining strength and surface roughness are considered restricting to the optimization of machining parameters in order to obtain a maximum material removal rate.

**KEYWORDS:** Lightweight Material; Carbon Fiber; Generative Design; Robotic Fabrication; Playscapes; interactive design.

## 1. INTRODUCTION

Cities around the world require spaces that satisfy the socio-cultural relationships of peoples. Therefore, it is necessary to create multiple areas that counter the lack of communication and interaction. In this era, we are experimenting with different ways of living: "The growth and development of cities, together with the various social changes, has led to a substantial thickening of complexity." The British geographer Ronald John Johnston (2000), believes that modernization is a process of social change resulting from the spread and the adoption of new characteristics by expansive and apparently more advanced companies. Modernization involves social mobilization, leading to the growth of a more effective and centralized system of political and social control. On the other hand, technologies become progressively an integral part of human behavior and the spaces in which we live, so that correctly designing the interface between the user and the architecture (or others) within the urban space becomes a challenging task. In order to create new experiential alternatives and functional services, it is necessary to know the society in terms of the needs and preferences of the people who comprise it.

Nowadays, research has extended its interests to interactions with other disciplines, considering the speculative natures of art and science, psychology and aesthetics, no longer contrasting but complementary, connecting them to the architectural project in the form of attention to spatial orientation, the perception of privacy, social interaction and other experiential aspects of human behavior.

The research undertaken during the Global Summer School in 2018 with the collaboration of the Institute for Advanced Architecture of Catalonia (IAAC), has investigated the experimental field of the interaction between architecture and social sciences in an attempt to establish a new design method that refers to perceptions, moods, and feelings to refine the architectural-social characteristics of public places.

The research has developed a precise question: it is possible to create new architectural horizons within which public spaces are configured as tools for sharing and social growth in which human beings while maintaining their individuality can interact empathically to build a socially satisfying common future?

It is possible to consider the potential of public space starting from the conception of the body as a medium, whose extension becomes the fundamental element for concretely intervening on the interactivity between it and space and, consequently, on social interaction.

The concept of density comes into play: it determines the number of individuals in a square meter and the desire to increase or decrease the factor becomes a design tool in order to create situations in which the inhabitant lives a specific condition (positive or negative) emotionally experiential.

These transformations require new ways of interaction that support the new and old ways of communicating and living and, consequently, a modern architecture (which is currently at a turning point due to the need to theorize and create places capable of supporting the computer advancing). Antonino Saggio says: "Today's formula can only be New Subjectivity No longer Existenzminimum but an existence that expands and is enriched to make individuals more and more people alive and free and no more numbers of a statistical yearbook." We, humans of the third millennium, divide our activities between real and digital worlds; our daily life is characterized by continuous access to the elaboration of a high quantity and variety of information. New technologies and social media modify the sensitivity, perceptions, and imagination of human beings in a more incisive and pervasive way, emphasizing that while new technologies increase both the hypothetical potential for interaction and a greater inclination to "virtual" empathy towards their online relationships. Both the possibility of having a "shielded" socialization tool that facilitates the most introverted personalities by giving them those social skills; on the other, they deprive the development of a denser social interaction and trigger a greater difficulty in supporting face-to-face interactions, which represent a crucial moment of social relationality.

The lack of face-to-face social interaction and the sharing of facial expressions (Facial Action Coding System) can have a negative effect on the brain leading to hiring behaviors that show signs of other psychological disorders, including antisocial behavior and mental isolation with increased individuality and consequent worsening of health towards anxiety, depression and other pathologies. This tendency to isolation has undermined the traditional centers of socialization of cities, consisting of squares, streets, parks, and more in general, from all public places with aggregative function. Accordingly, this research questions the ways in which new technologies can be used to find solutions to complex social problems.

## 2. NEW POTENTIAL OF THE PUBLIC SPACE

The technological culture of design, intended as a conceptual tool for forecasting and controlling the impacts of technology on the environment, recalls the need to introduce new contents in the environmental design of buildings, extracted from the most up-to-date evolutionary trends in the disciplinary field of architectural technology of adjacent areas. In this sense, the research on materials is a field of primary importance, both for the optimization of the performance of the architectural organism during the phases of use and for its eco-effectiveness in the other moments of the life cycle.

One of the key objectives of sustainable development, as defined by the Brundtland report, our Common Future in 1987, is to reconcile the aspirations of social progress, economic development, environmental protection and conservation of natural resources, guaranteeing the equity of access to resources for future generations. The construction sector plays a crucial role in achieving this goal, due to the considerable amount of material and energy resources it uses, and the environmental impacts associated with the production of materials and components and construction, renovation.

Fig.1: Cloud Gate, Anish Kapoor, Chicago, Millennium Park, 2006

According to Theodore Kaczynski, “we are now aware of the importance of creating new spaces in which people can overcome the lack of communication and mutual interaction necessary for the healthy development of society. One of these is the recreational public space in which the inhabitants spend their free time.” A study carried out in 2006 on 1000 public spaces worldwide; indicate four effective factors to improve the usability of urban spaces. The first is to allow social interaction for the public; the second concerns the comfort and attraction of such space; the third is the activity of the people in these spaces, the fourth factor is the continuity of spaces and the easy access to them.

Compared to the consideration of Kaczynski, we are now aware of the importance of creating new spaces in which people can overcome the scarcity of communication and mutual interaction necessary for the healthy development of society. One of these is the public recreational space in which the inhabitants spend their free time. The results of a study accomplished in 2006 on 1000 public spaces around the world, indicate four highly effective factors to improve the usability of urban spaces: the first is "allowing social interaction for the public" (to allow social interaction for the public). The second concerns the requirements of being "comfortable and attractive" (comfort and attraction of such space). The third is the activity of people in public spaces (the activity of people in these spaces). The fourth factor is "continuity of spaces and easy access to them" (continuity of spaces and easy access to them).

## 3. EXPLORATIVE DESIGN IN DIGITAL FABRICATION: CASE STUDY OF MAWJA

The objective of this section investigates the implementation of unidirectional woven carbon fiber fabric (CFF) in lightweight and large structures. This section is divided into two parts. The first part will give a brief summary of material properties and fabrication process and their impact on the form-finding methods. It discusses the material properties and looks at how the production method influence the design. The second part integrates the material knowledge, the fabrication and assembly methods and the time constraints, into the typology that have been defined in the first part.

The criteria for this research is the implementation of unidirectional woven carbon fiber fabric that would reinforce a large outdoor public playscape.

### 3.1 Research methods

The conducted research is investigated upon the design and fabrication of a full-scale outdoor playscape, bounded to a volume of 3x7x1m, over a period of 12 days. The performance of the material and the fabrication constraints are integrated within the design process, whereas the robotic fabrication technique is explored in the fabrication stage.

Semi-autonomous Fabrication Method and assembly

The initial geometry of the low-density polyurethane form is first generated through Rhinoceros program and Grasshopper plug-in. Subtractive manufacturing, milling using a Kuka robotic arm, was the method of fabrication for the initial geometry. Based on the dimensions of the polyurethane panels, the geometric system is divided into ten layers, each of 10cm height. The overlapping of the milled units ensured a homogenous structure with an equally divided load. Figures 2 and 3 indicate the division that has been optimized using Grasshopper plug-in Galapagos (Rutten, 2010) where this evolutionary problem-solving process analyzes specific parameters in order to produce optimized relations between every milled unit and eventually meet the design criteria.

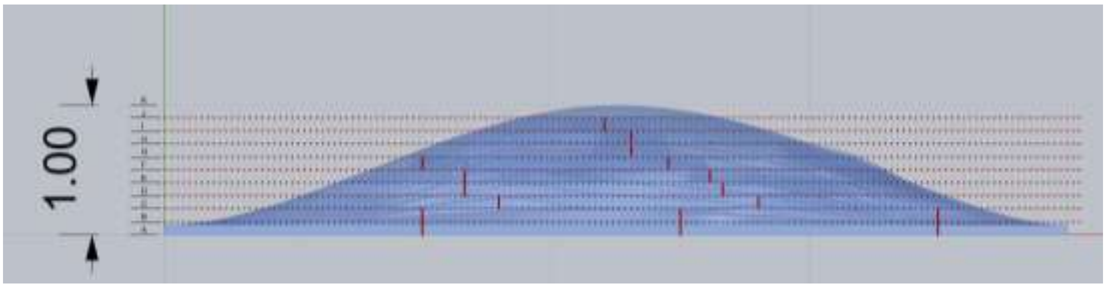


Fig.2: Front elevation showing the overlap of the unit.
Reference: Designed by the authors - July 2018

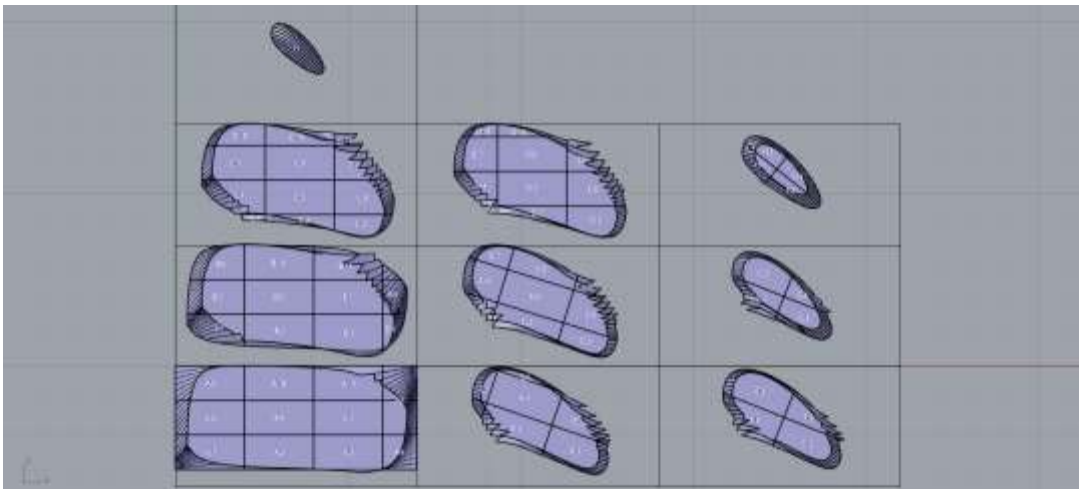


Fig.3: Top view of the layers each assigned an alphabetical and numerical reference.
Reference: Image by the authors - July 2018

After setting the fabrication strategy, the robot motion was simulated within Rhino and Grasshopper. The generated toolpaths were then converted to .src for the KUKA robot with the Grasshopper plug-in KUKA PRC (Braumann & Brell- Cokcan, 2011). During fabrication, the polyurethane panels were fixed to a 2.4x1.2m horizontal platform, shown in figure 4.

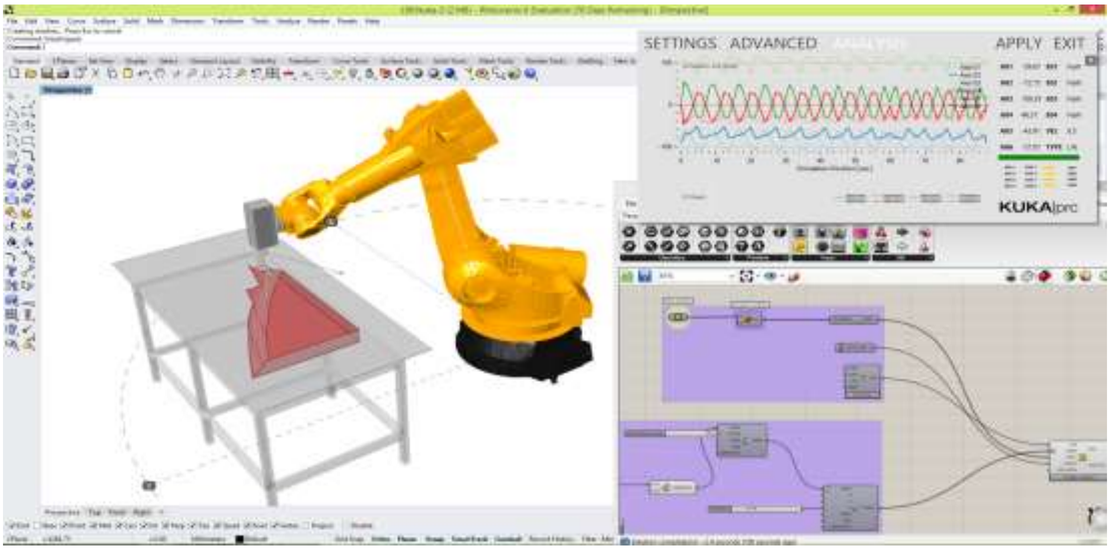


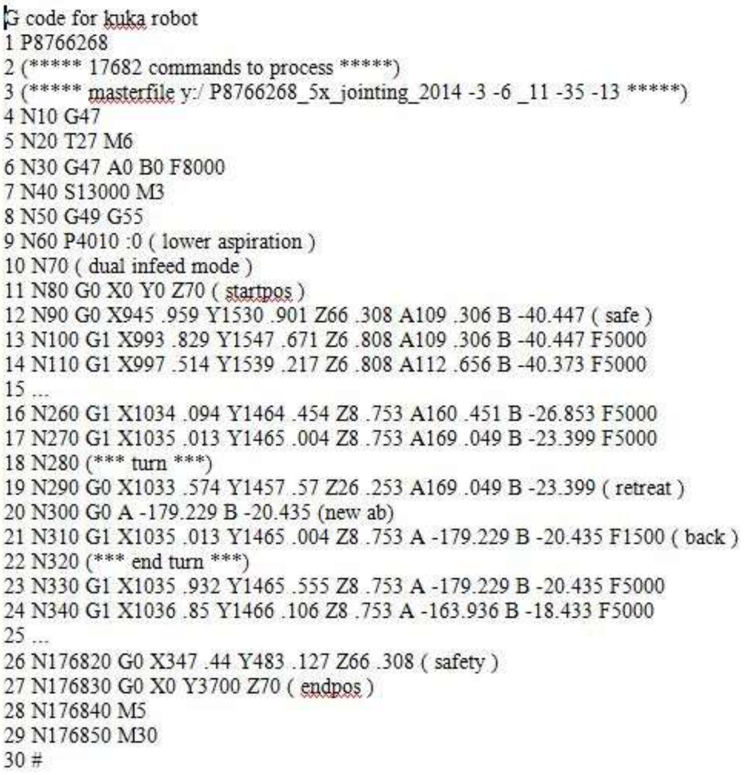
Fig. 4: Simulating the milling process using Kuka|Prc.
Reference: Designed by the authors - July 2018

The desired panels are cut out by the robot. With a practical speed of 3meters/second, the time needed for each panel to be milled was approximately thirty minutes. By equipping the robot with a 18,000rpm spindle, the fabrication process of all 72 panels was completed in 4 days (Table 1) with immense accuracy and efficiency.

Table 1: Time taken by every stage of project to be executed.

| Stage | Time (days) | Comment |
|---|---|---|
| Design | 2 | |
| Digital fabrication | 4 | Including production of digital fabrication files |
| Structure preparation | 2 | Surface treatment and applying cementitious overlays |
| Carbon Fiber Application | 4 | Including primer application and fabric positioning |

The generated code that resulted from this simulation rendered to a script translates the tool path into the machine code. The g-code in Figure 5 shows the translation of a digital simulation into code lines that indicate positions of points in space. The generated code was then evaluated by running the test 20cm above the machine table and with low speed, checking by that for any singularities. All components were milled within one day. Each component was marked by its distinct number, corresponding to that of the original digital model.



```
G code for kuka robot
P8766268
(***** 17682 commands to process *****)
(***** masterfile y:/ P8766268_5x_jointing_2014 -3 -6 _11 -35 -13 *****)
N10 G47
N20 T27 M6
N30 G47 A0 B0 F8000
N40 S13000 M3
N50 G49 G55
N60 P4010 :0 ( lower aspiration )
N70 ( dual infeed mode )
N80 G0 X0 Y0 Z70 ( startpos )
N90 G0 X945 .959 Y1530 .901 Z66 .308 A109 .306 B -40.447 ( safe )
N100 G1 X993 .829 Y1547 .671 Z6 .808 A109 .306 B -40.447 F5000
N110 G1 X997 .514 Y1539 .217 Z6 .808 A112 .656 B -40.373 F5000
...
N260 G1 X1034 .094 Y1464 .454 Z8 .753 A160 .451 B -26.853 F5000
N270 G1 X1035 .013 Y1465 .004 Z8 .753 A169 .049 B -23.399 F5000
N280 (*** turn ***)
N290 G0 X1033 .574 Y1457 .57 Z26 .253 A169 .049 B -23.399 ( retreat )
N300 G0 A -179.229 B -20.435 (new ab)
N310 G1 X1035 .013 Y1465 .004 Z8 .753 A -179.229 B -20.435 F1500 ( back )
N320 (*** end turn ***)
N330 G1 X1035 .932 Y1465 .555 Z8 .753 A -179.229 B -20.435 F5000
N340 G1 X1036 .85 Y1466 .106 Z8 .753 A -163.936 B -18.433 F5000
...
N176820 G0 X347 .44 Y483 .127 Z66 .308 ( safety )
N176830 G0 X0 Y3700 Z70 ( endpos )
N176840 M5
N176850 M30
#
```

Fig.5: G-code generated from the drawing
Reference: Image by the authors - July 2018

Due to the optimization of the polyurethane overlaying system, the assembly process on site was cut down to overlaying the panels in place according to the digital model. The whole process was accomplished by ten participants within one day. The structure appears as a wave with a height of 1m and a ledge of maximum 0.36m protrusion, shown in figure 6.

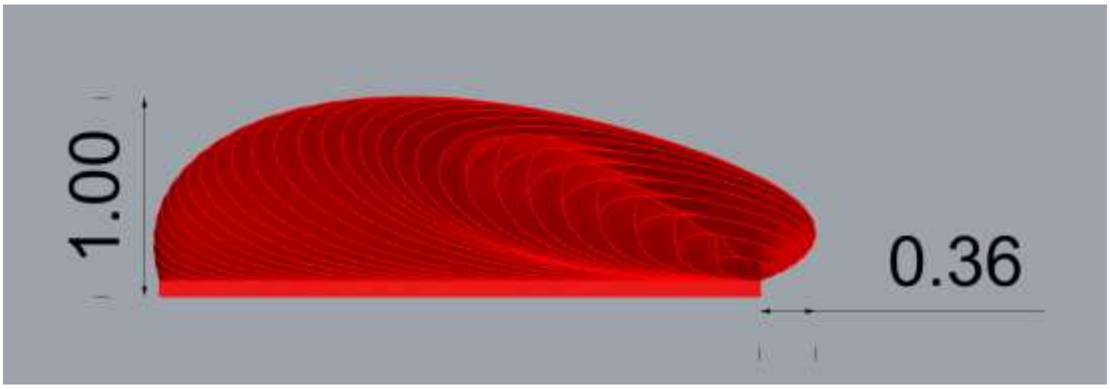


Fig.6: Side elevation showing the cantilevered section.
Reference: Designed by the authors - July 2018

### 3.2 Material performance

Although the integration of computational design has been including functional, environmental, and economic data, material information hardly ever been considered, let alone employed as a generative driver. It is as if the considerable dominance of shape-oriented representational design techniques based on figurative geometry in most present-day CAD packages are still considered as contemporary design thinking. However, materiality is still conceived as a passive characteristic of shape and materialization, conceived as of lesser importance to the creation of form. Unidirectional carbon fiber fabric is high tensile strength structural reinforcement material usually utilized for shear strengthening. It can compete with the strength of I-beams when mixed with resin (in the case of this project epoxy resin). The question in this case is how can the material – in particular carbon fiber mesh systems – manipulate, optimize or limit the design and the fabrication processes and eventually alter in the architectural outcome?

Josef Albers identified material behavior itself as a creative domain for developing new modes of construction and innovation in architecture. This section therefore aims at exploiting the strength, lightness, and variability possible with carbon fiber filament system when paired with computation, digital fabrication, and hand assembly.

The use of contemporary fabrication techniques have constantly concurred with heavyweight and extended period of production. In the last decades, carbon fiber applications have been increasingly used in buildings because of their lightweight nature and other properties. With its weather-resistant properties and high strength:weight ratio, it exceeds the application of concrete and steel in large-lightweight structures. A significant body of work related to applying fiber composite materials to architecture and design without the need for elaborate molds or formworks has been developed (Menges & Knippers, 2015). Simultaneously, advancement in robotics and autonomous control have become more prominent in relation to design and fabrication through research projects (Jokic et al., 2014). The advancement in technology and applications in these realms consequently inspired this research to explore the possibilities of using carbon fiber mesh in a different and efficient technique to reinforce a structure.

"Carbon fiber, like any composite material, is created from two dissimilar materials that, when combined, act as one. As the name suggests, carbon reinforcement fibers are joined within a resin matrix. When these two component materials are combined through a process known as a lay-up, the carbon fiber and resin form a new material with physical properties surpassing those of either constituent materials separated. Composites ordinarily offer their greatest strength along the direction or axis that the fibers run. This characteristic allows the possibility of optimizing the composite’s strength based on the orientation of its fibers. On the other hand, there are hundreds of types of resins available, such as epoxy, and each has its own distinct chemical and physical characteristics". Typically, there are two main techniques for applying the unidirectional carbon fiber fabric onto a structure. For this project, dry lay-up was employed given the time constraints faced. The dry application technique is divided into 4 main stages, figures 7, 8:

Surface treatment, Applying cementitious overlays, (Epoxy) Primer- Resin Application, Fabric Positioning & Lamination:

- Surface treatment: with the use of brushes and ensuring that the corners are fully reached, the polyurethane structure was cleaned from any debris.
- Applying cementitious overlays: in order to protect the polyurethane structure from being decayed by the applied resins, a protective 1cm cementitious overlay was applied.
- Epoxy primer and hardener base coat: The special Epoxy Resin Base Coat is mixed at a ratio of 2/1 with the Epoxy Hardener. The applied product was (Sikadur); a thin and even coat of the mixed resin was applied to the surface of the structure.
- Fabric positioning & Lamination: The fabric was laid along the shorter direction of the structure in which the load will be distributed. A thin layer of mixed epoxy resin topcoat was then applied to ensure the fabric took the intended position.

Fig.7: Dry application method
Reference: Photographed by the authors - July 2018

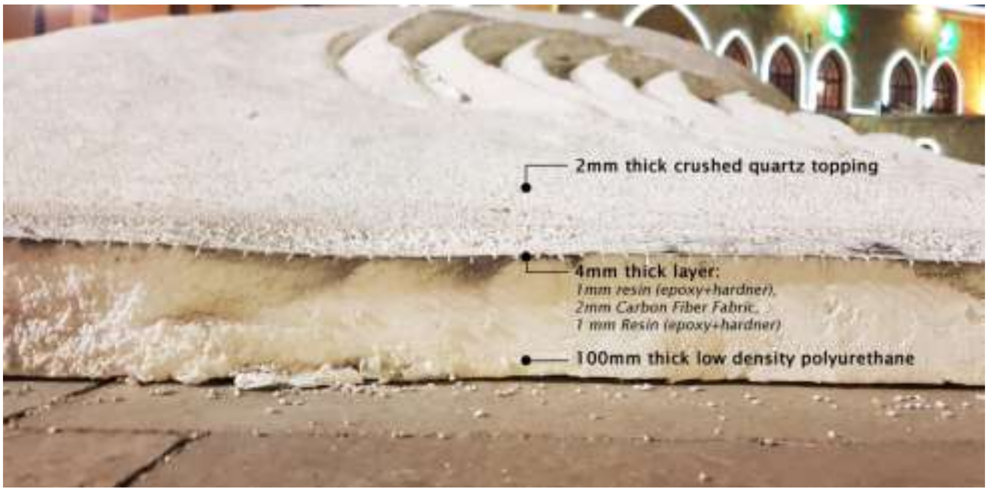


Fig.8: Structural and Finishing Layers of the structure
Reference: Photographed by the authors - July 2018

"By definition, unidirectional carbon fiber fabric is a type of carbon reinforcement that is woven and features all fibers running in a single, parallel direction. The fabric has no gaps between fibers, and those fibers lay flat. This allows for the concentrated density of fibers that provide maximum longitudinal tensile potential in the direction of the fiber grains". During the layup process, the fabrics were arrange to overlap by 7cm from each side to achieve strength without sacrificing stiffness. Unidirectional fabrics also had a very lightweight, which allowed for more controlled layups.

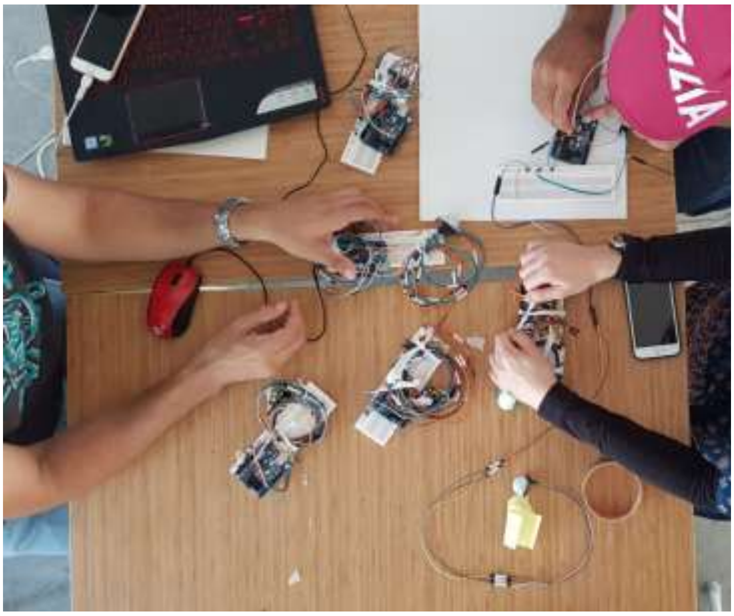
One major disadvantage of unidirectional CFF its inefficiency in parts that require a great anisotropic strength property (strength in all directions), cracks along the short direction were observed in the final structure, shown in figure 9.

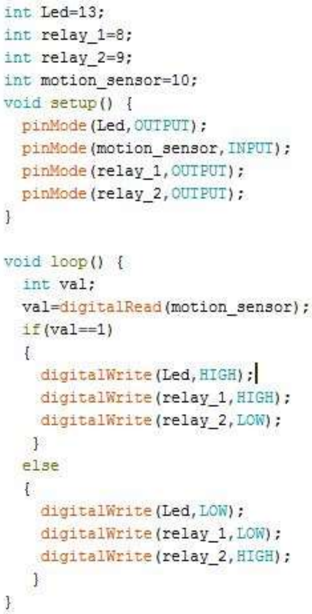
Fig.9: Cracks taking the same direction as the laying of the CCF
Reference: Photographed by the authors - July 2018

### 3.3 Interaction Design

Nowadays, designers are adopting advanced technologies as a way to create smarter and more engaging environments. Few are trying to enhance the experience of space for people. *Mawja* was created to directly influence the emotional state of users through participatory acts. As interactive space in architecture is a relatively new area with little literature on the framework, this paper attempts to highlight the importance of introducing an interactive intervention in attempts to activate a public space.

The interactive design was introduced through lighting up the installation using LED light strips. These were controlled through Arduino boards that were linked to motion detectors, which detect the presence of users approaching it, and send an order to the light strips to light up. The motion detectors were located on the two corners of the installation, covering an area of 2 meters radius. A total of 6 Arduino boards were used to cover both sections of the installation. Figure 10 shows the assembling of the boards and the code used to generate the interaction.





```
int Led=13;
int relay_1=8;
int relay_2=9;
int motion_sensor=10;
void setup() {
  pinMode(Led,OUTPUT);
  pinMode(motion_sensor,INPUT);
  pinMode(relay_1,OUTPUT);
  pinMode(relay_2,OUTPUT);
}

void loop() {
  int val;
  val=digitalRead(motion_sensor);
  if(val==1)
  {
    digitalWrite(Led,HIGH);
    digitalWrite(relay_1,HIGH);
    digitalWrite(relay_2,LOW);
   }
  else
  {
    digitalWrite(Led,LOW);
    digitalWrite(relay_1,LOW);
    digitalWrite(relay_2,HIGH);
   }
}
```

Fig.10: Photo of Arduino boards being assembled (left) Code generated from Arduino (right)
Reference: Image by the authors - July 2018

## 4. RESULTS

As mentioned, the research aims at exploring the possibility of creating advanced architectural horizons within which public spaces are configured as tools for sharing and social growth interacting empathically to build a socially satisfying common future.

Regarding the advanced architectural horizons, the research studied new methods of applying a high performance light weight material (Carbon Fiber Fabric) using robotic fabrication methods in order to produce the installation in a very short period of time and with very high precision.

The experimental implementation of CFF onto morphed surfaces was successful onto reaching a lightweight outcome in a short period of time. However, and in order to improve the performance of the material, the research suggests to wrap the installation (add CFF to the base), reducing by that the observed cracks and improving its resistance to compressive forces. Regarding the polyurethane structure used as a base to the structure, the research suggests to use a different fabrication process: using 1x1m polyurethane blocks (figure 11) instead of boards to optimize the precision of the model, reduce the use of adhesives between layers, reduce waste materials and exploit the potentials of the KUKA robotic arm.

As for the social interaction, the installation, which stayed on display for 15 days, proved to create a platform of interaction, indicating an improvement of the usability of the urban space. The physical use of the installation happened at the level of sitting, running and jumping, satisfying a comfortable and attractive spot in the context (figure 12). The users remained interested in exploiting this playscape throughout its display time and expressed their satisfaction into having a playful and comfortable installation to activate the space.

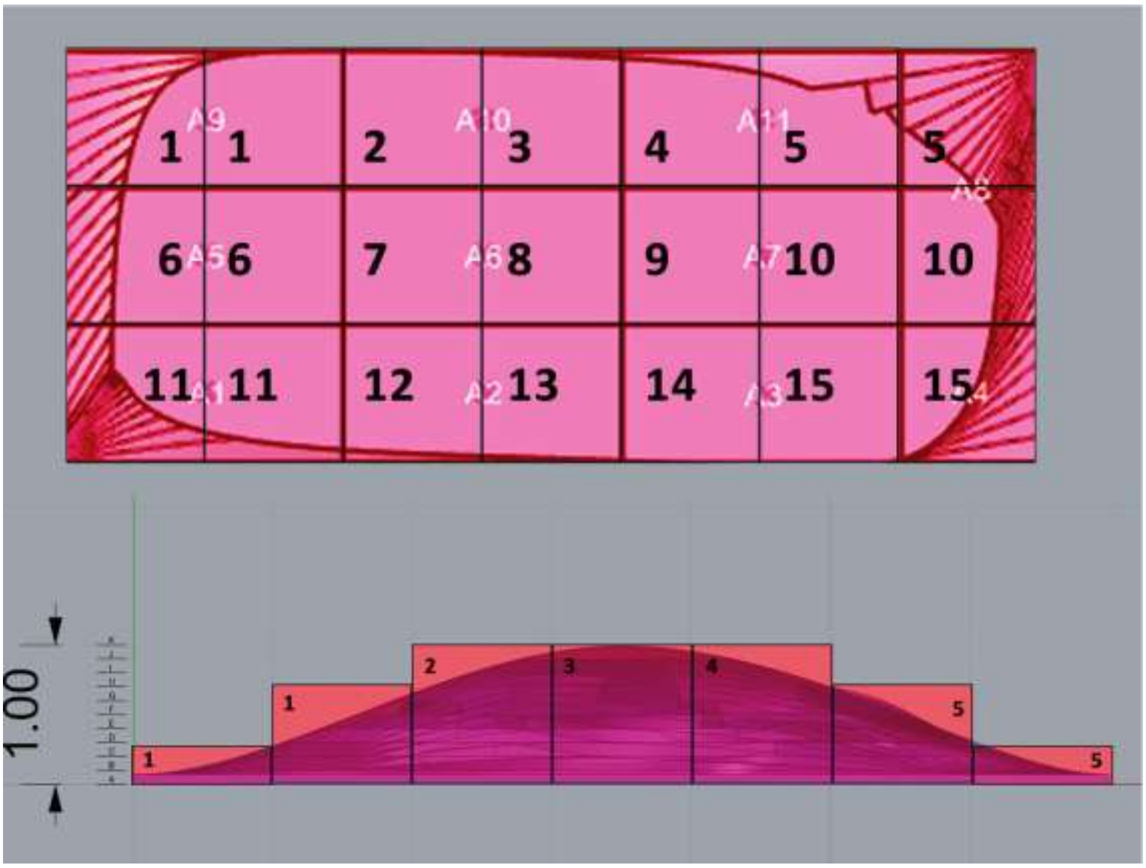


Fig.11: Proposed enhancement in the fabrication strategy
Reference: The authors - July 2018

Fig. 12 Interactive Playscape creating a social play experience in Beirut Central District
Reference: Photographed by the authors - July 2018

## 5. CONCLUSION

The research in this paper focused on material-based practices and explorations by utilizing the material performance characteristics to be a major driver in the design and fabrication strategies.

It explored the entire design process and its integration with fabrication strategies: from form-finding and optimization to fabrication, considering a continuous coordination by the architect over the whole design and fabrication process. The resulting structure is structurally stable and efficient. Moreover, the aesthetics suggest the new design possibilities of technology and their complex outcomes.

As the case study indicates, the robotic milling performed with a high material-efficiency in fabrication stage. This fabrication strategy clearly allow for a higher resolution outcome than the traditional milling geometries created from CNC. However, it has been concluded that the material assembly could follow a different approach in order to reduce the material waste and exploit the utmost possibilities of robotic fabrication.

Although the novel application of unidirectional carbon fiber fabric conveys advantages in material efficiency, there still exists certain inadequacies, one of which is the material waste resulted in the volume difference of the polyurethane structure. The waste may be minimized through the optimization of the basic structure, possibly by using a hollow structure. Regarding the material (CFF) and its application, aesthetic considerations may be necessary, especially for intricate areas such as the openings of the fins.

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