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Parametric Iranian-Islamic muqarnas as drivers for design for fabrication and assembly via UAVs: parametric analysis and synthesis of Iranian-Islamic muqarnas.

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PARAMETRIC IRANIAN-ISLAMIC MUQARNAS AS DRIVERS FOR DESIGN FOR FABRICATION AND ASSEMBLY VIA UAVS

Parametric Analysis and Synthesis of Iranian-Islamic Muqarnas

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Abstract. This study proposes a DfMA (from design to assembly) based on Unmanned Aerial Vehicle (UAV) and uses Iranian-Islamic Muqarnas as the case study due to their geometric modularity. In Islamic architecture, different geographic regions are known to have used various design and construction methods of Muqarnas. There are four main specifications of the Muqarnas that define to which category they belong; first, its three-dimensional shape, that provides volume. Secondly, the size of its modules is variable. Third, its specific generative algorithm. And finally, the 2-dimensional pattern plan that is used in the design. First, this study presents thus a global analytical study that drives a generative system to construct Muqarnas, through a careful balance of four specifications. In this second step, the paper reports the result of using a parametric tool, Grasshopper and parametric plugins, for creating a generative system of several types of Muqarnas. This synthetic translation aims at expanding our understanding of parametric analysis and synthesis of traditional architecture, advancing our understanding towards using parametric synthesis towards UAV-based fabrication of Muqarnas, by taking advantage of their inherent repetition and recursion.

Keywords: *Muqarnas, Iranian-Islamic Architecture, Generative System, Parametric Architecture, UAV*

ملخص. تقترح هذه الدراسة إستخدام DfMA (من التصميم إلى التجميع) مبتنى عن مركبة جوية بدون طيار (UAV) وتستخدم المقرنس الإيرانية الإسلامي كدراسة حالة نظرا إلى قابلية إضافة وحدات هندسية. وفي المعمارية الإسلامية، تشتهر المناطق الجغرافية المختلفة باستخدام أساليب التصميم والبناء المختلفة في المقرنس. هناك أربع مواصفات رئيسية للمقرنس لتحديد الفئة التي تنتمي إليها؛ الأول، شكله الثلاثي الأبعاد، والذي يوفر الحجم. ثانيا، حجم نمائطها

متغير. ثالثا، الخوارزمية التوليد المحددة. وأخيرا، خطة النمط الثنائي الأبعاد التي تستخدم في التصميم. اولا، تقدم هذه الدراسة دراسة تحليلية عالمية تدفع إلى نظام تكاثري لبناء المقرنس، بتوازن دقيق بين أربع مواصفات. في هذه الخطوة الثانية، تنشر الصحيفة نتيجة إستخدام أداة البارامتريك، جراسهابر و بلاكينها، لإنشاء نظام تكاثري من أنواع عديدة من المقرنس. وتهدف هذه الترجمة التركيبية إلى توسيع فهمنا لتحليل المعمارية البارامتريك، الى فابريكيشن مبتنى عن UAV باستخدام تكرار للمقرنس التقليدي.

الكلمات المفتاحية: *المقرنص، المعمارية الإيرانية الإسلامي، المعمارية البارامتريك، مركبة جوية بدون طيار.*

1.Introduction

The paper presents a study on parametric analysis of the Iranian-Islamic Muqarnas and analyses its components, geometric relations and construction methods that should be considered when constructing one. This study aims to use Muqarnas a driver to generate a DfMA base on the UAVs and parametric fabrication.

Muqarnas are one of the most ornamented vault types, considered one of the archetypal forms of Islamic architecture. Muqarnas were invented in the early 10th century and they have changed a lot over time in terms of design and construction methods in different geographical areas, from east of Asia until Spain and west of Africa (1). Muqarnas is considered as a complex kind of decorations that initially, aim to generate three-dimensional facades involving shadow and light and create unparalleled lines, and secondly to develop more surfaces to apply more micro decorations (2).

In Islamic architecture, different geographic regions use various design and construction methods of Muqarnas. There are four main parameters of the Muqarnas that define their classification; first, their three-dimensional shape, that provides volume. Secondly, the size of their modules is variable. Third, their own specific generative process-algorithm, and finally, the 2-dimensional pattern plan that is used as a basis in the design. We present thus a global analytical study that drives a generative system to construct Muqarnas, through a careful balance of the four parameters.

In the first step, this paper reviews studies on traditional Muqarnas (both Iranian and non-Iranian) and relevant parametric approaches. In the second step, the study aims to create a general generative system for Muqarnas. The creation of a generative system for Muqarnas is driven towards the creation of three-dimensional fabrication of their components so that these are assembled automatically using a swarm of UAVs. This particular drive imposes specific constraints in the parametric system, as the assembly of the final components, we posit, can only take place in a pick and place fashion.

2. Background

In Iran, there are some initial examples of Muqarnas before the Arab invasion to Iran (651 AD). These examples are mostly known as decorative elements. The oldest ones probably left from the *Median* era (5th century BC). *Dokan Davood*, *Sakavand Rock Tombs* and the *Tomb of Davood Dokhtar* can be named as oldest examples of Muqarnas in Iran. The first example of Muqarnas, which is very close to 16th century Muqarnas, was built in the *Masjid Jam-e Shiraz* and belongs to the *Safavid* dynasty (ninth century AD). However considerable development of Iranian Muqarnas starts from the *Seljuq* dynasty (10th century AD). From that period until now, Muqarnas construction has continued and during the 15th to 16th AD centuries, the most complex Muqarnas in Iranian architecture had been formed (3).

One of the oldest Muqarnas studies was conducted by the astronomer and mathematician *Jamshid Kashani (Al-Kashi)* in the 14th and 15th century. *Al-Kashi* explains about the applied mathematics in the book *Meftah-o Al-Hesab* (1420). In chapter 9, *Al-Kashi* describes geometric rules and relations that can be used to design and construct a Muqarnas (4). The table below reviews the various viewpoints on Muqarnas:

TABLE 1 Viewpoints on Muqarnas

Researchers	Source	Viewpoints
Abbas Zamani	Muqarnas, decoration in Islamic historical monuments of Iran, 1966	In this research, Muqarnas is divided into four categories: 1. Muqarnas at concave surfaces 2. Muqarnas in the quarter dome 3. Muqarnas in horizontal and vertical tiers, 4. beehive shape Muqarnas. In each of the four cases, it has been introduced as a decorative element.
Titus Burckhardt	The foundations of Islamic art, 1980	Muqarnas is a special phenomenon of architecture and a structure to transfer the weight of the dome to its square base. Muqarnas reflects celestial motion to the terrestrial. (functional and aesthetic aspects)
Donald Newton Wilber	Iranian-Islamic Architecture: The Ilkhanate, 1981	Muqarnas is a decorative element and it is defined for filling a concave area or surface with two or more quarter dome shapes in which each row is further forward than the row below.
Mahdi Makinejad	Muqarnas tiling in Iranian architecture, 2015	At the beginning, this element had a structural role and was used to fill the corners, but over time, in addition to the structural function, it also took on a decorative role.

2.1. PARAMETRIC APPROACHES

In 2004, *Takahashi* classified the Muqarnas, based on their plane design (e.g. square). For example, Muqarnas in Andalusia and North Africa (called Moroccan-Andalusian Muqarnas) are known as square-shaped cells (5). This classification could not apply for Iranian-Islamic Muqarnas. Although, the Iranian style is also based on a 2D plan, however each 2D pattern could make several different 3D shapes. In Iranian-Islamic Muqarnas, the factors in dimension Z could be varied, but in *Takahashi* classification, Moroccan-Andalusian Muqarnas is characterised regardless of third Dimension. *Mohammad Yaghan* has studied a lot in terms of regeneration Muqarnas with CAD systems (6) and decoding historical muqarnas patterns (7). Although these studies can be used to reconstruct the old Muqarnas, according to the *Mohammad*, his approaches cannot design new ones (8).

Nader Hamekasi has invented a parametric strategy to model the Muqarnas. His strategy is based on using the b-spline curves. In this strategy, Muqarnas 2D pattern plane is divided into its layers and transfer into the different levels, considering the concave surface behind (9).

2.2. MUQARNAS COMPONENTS

This study aims to inspire traditional Muqarnas to generate parametric ones. Iranian-Islamic Muqarnas consist of different types of components that achieving a deep understanding with componentisation the muqarnas would help us to redefine its structure, parametrically.

In general, Iranian-Islamic Muqarnas consist of 8 main components; *Shamseh*, *Taseh*, *Toranj*, *Shaparak*, *Parak*, *Tee*, *MooshPa* and *Takht*. Also, Muqarnas includes many other components like *Madani*, but these 8 components have been used more than others so far (4).

2.3. MUQARNAS SHAPE

Iranian-Islamic Muqarnas can be classified into the 4 categories in terms of shape; *Jolo Amadeh* (means Come forward), *Rooy-E-Ham Rafteh* (means to overlap), *Moalagh* (means hanging), and *Laneh Zanboori* (means Beehive shape). Also, there are other types of classification of Iranian-Islamic Muqarnas, such as: based on materials, based on geometry, based on ages, etc.

1. ***Jolo Amadeh:*** This kind of Muqarnas is built by carving the stone and It has moderate stability. It's very simple geometrically and usually doesn't have any additional decoration. It has a very heavyweight and is made in the interior or exterior surfaces of the building.

2. ***Rooy-E-Ham Rafteh:*** After caving the stone, additional decorations are attached. decorations are made of materials such as plaster, stone and brick. This type of Muqarnas is like the *Jolo Amadeh*, but with more complexity in decoration and it has moderate stability either.

3. ***Moalagh:*** Its shape is similar to stalactites and is formed by attaching various materials such as plaster, tiles to the inside of the concave surface. This type of Muqarnas looks dangling and it doesn't have high stability.

4. ***Laneh Zanboori:*** It looks like small hives stacked on top of each other and it has a lot of similarity with *Moalagh*. (3)

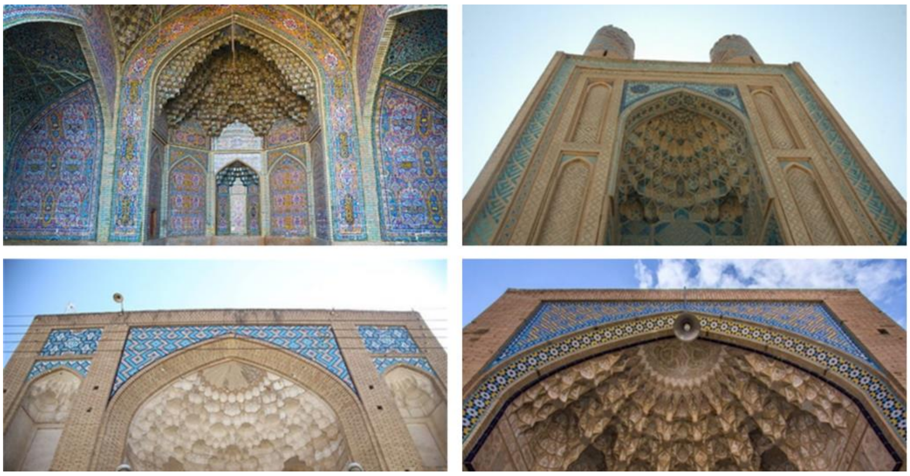

Figure 1. Bottom Left: Shrine of Fatima Masumeh, Jolo Amadeh – Top Right: Oshtorjan Mosque, Rooy-E-Ham Rafteh – Bottom Right: Agha Bozorg Mosque, Moalagh – Top Left: Nasir Molk mosque, Laneh Zanboori

2.4. TRADITIONAL CONSTRUCTION METHODS

Iranian-Islamic Muqarnas traditionally are built in three ways. There exist some other construction methods, but these three methods are most common between the traditional architects thus forming an a-typical cannon:

1. **Superimposed (*Barikeh-e Tagh*):** In this method, first, concave surfaces are built to support the Muqarnas elements. Then the elements are put on the surfaces so that there is no space between the Muqarnas and surface. In this method, the supporting surface named *Posht Band* that means to support from the back (10).
2. **Suspended Layer (*Takhteh Gachi*):** In this method with the help of the 2D patterns plan, patterns' cells are built in the ground then move to the different levels and combined with the architectural structure. Afterwards, each Muqarnas is attached to its relevant elements (11). In this method, there is a space between the Muqarnas and structure (*10*).

3. **Corbeled Muqarnas (*Aviz dar*):** In this method, Muqarnas is carved from stone or wooden blocks. The Muqarnas elements are carved from the middle of the dome (or vault) to the outlines (10).

2.5. MUQARNAS GEOMETRY

Decorations in Islamic architecture are inspired by Islamic philosophical concepts and mathematics plays an important role to convey these concepts (12).

The oldest classification of Muqarnas has done by *Jamshid Kashani* (Persian astronomer and mathematician, 14th and 15th century). *Al-Kashi* divided the Muqarnas, based on the 2D pattern plan and 3D geometry, into 4 categories. This classification has been used for several decades by traditional architects (13).

1. **Simple Muqarnas:** It's a kind of Muqarnas in which lines are drawn instead of curves and cells are repeated. In the 2D pattern plan, only two shapes, square and rhombus, are used. Half-square and half-rhombus might be used too. Also, all cells' sides are in the same length.
2. **Stretched Muqarnas:** The height of each level of the Muqarnas could be different.
3. **Curvy Muqarnas:** This kind of Muqarnas looks like the simple Muqarnas in the 2D pattern. But in the three-dimensional shape, curves are also used.
4. **Shirazi Muqarnas:** In this type of Muqarnas, other types of polygons are used in the 2D pattern. polygons such as triangle, pentagon and hexagon, octagon and polygonal stars.

Also, in this classification, each Muqarnas niche consists of 5 main components (14).

3. Parametric Strategies

In traditional Iranian architecture, 2D patterns always play the main role to design and construct a Muqarnas (13). To create a generative system, this study initially develops parametric strategies to create a 2-dimensional pattern plan (2DPP). on one hand, this 2DPP would help us to have an outline of modules 3D shapes and on the other hand, 2DPP can show us the right placing of the modules and guide us to generate assembly methods.

3.1. PARAMETRIC 2DPP

Several traditional patterns have been examined in terms of digitalisation and finally, the pattern *Shamseh* has been chosen, as it is a better fit for modular production. Although *Shamseh* (or Islamic star) is present in many post-Islamic historical monuments in Iran, but in this research, the two-dimensional pattern of Isfahan Mosque (*Masjid-i-Jame*) has been analysed.

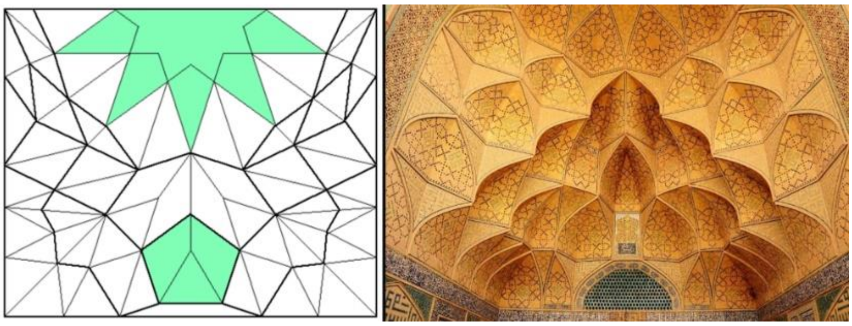

Figure 2. Masjid-i-Jame Isfahan (Source: tishineh.com)

To create a parametric 2D plan inspired by *Shamseh* pattern that used in the *Majid Jame*, the idea is creating several points toward two vectors. These points will be used to create 2 polylines. X-axis and the rotated X-axis are used. The angle used to rotate the axis is obtained by dividing a numeric variable by 360. The numeric variable would be the number of requested niches to have in 360 degrees. The point 0,0,0 is used to move and create several points. To create two polylines, the last point and first point have been ignored and two polylines are created. Then with the command 'rotation', a complete pattern would be created. The number of rotations is as same as a numeric variable in 360 degrees.

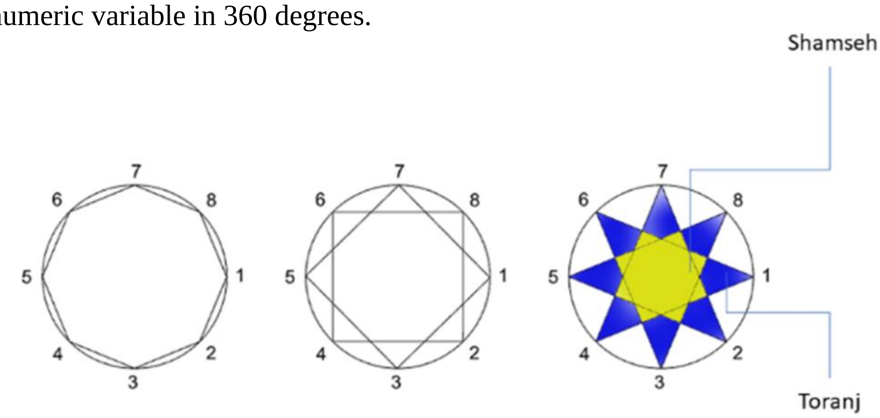

Figure 3. Islamic Star pattern is one of the most used patterns in Iranian-Islamic architecture decoration. In Persian architectural literature, Islamic star named Shamseh and each Shamseh is surrounded by several Toranj.

3.2. PARAMETRIC 2DPP

As mentioned, several parametric strategies have been compared in terms of digitalisation produce. To understand the procedural difference of the strategies, finding algorithm bugs and gaps,11 done parametric sketches have been reviewed and compared. Advantages and disadvantages of each digital strategy, in the point of view of the fabrication feasibility and UAV based assembly, the possibility of adding joints and structure of components have been assessed. Finally, the strategy below has been selected to be used to be assembled by UAVs.

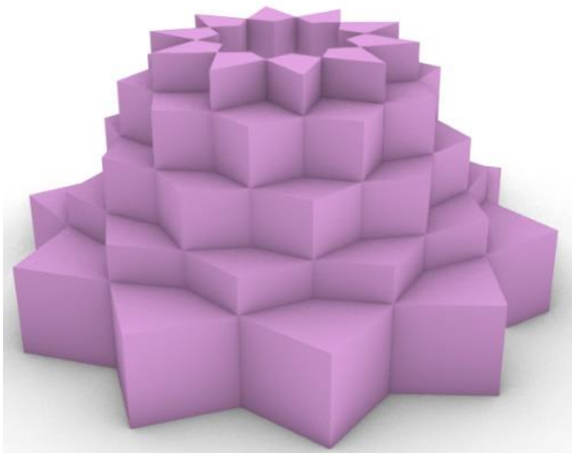

Figure 4. A complete dome made by parametric modules

Each mould should be extracted from its specific unit in the designed parametric pattern. After creating Muqarnas pattern (and before 360-degree rotation), the units in the pattern must be separated to turn to separate surfaces. Then, the surfaces are extruded to turn to the volumes (or modules). The height of modules can be the same or vary, in this study, the same height is used. Each module transfers to its defined level. The height of the modules is used, to define the levels. For example, the height of the third floor will be the sum of the heights of the first and second floors' modules (mass addition). However, to add the joints, an overlap is needed to add between two top and bottom modules. To do so a formula has been created to specify each modules level (2h+10; h is the height of the modules). This formula can be changed for other types of modules or structures. After putting the modules in the appropriate levels, they should have arrayed them to have a complete dome.

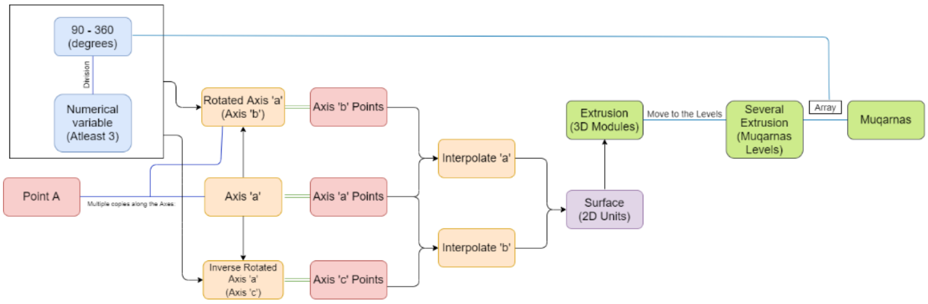

Figure 5. Illustration of final algorithm

4. Structural Design

As discussed, the Muqarnas is known as the decoration and traditionally doesn’t play any structural role, but in this study, as the aim is to use Muqarnas as the vault, the structure has been optimised to have an independent Muqarnas standing on its own weight. To keep the structure and proper weight transfer, the modules are optimised in terms of joints and shape. This optimisation makes the modules spread their load to the modules below.

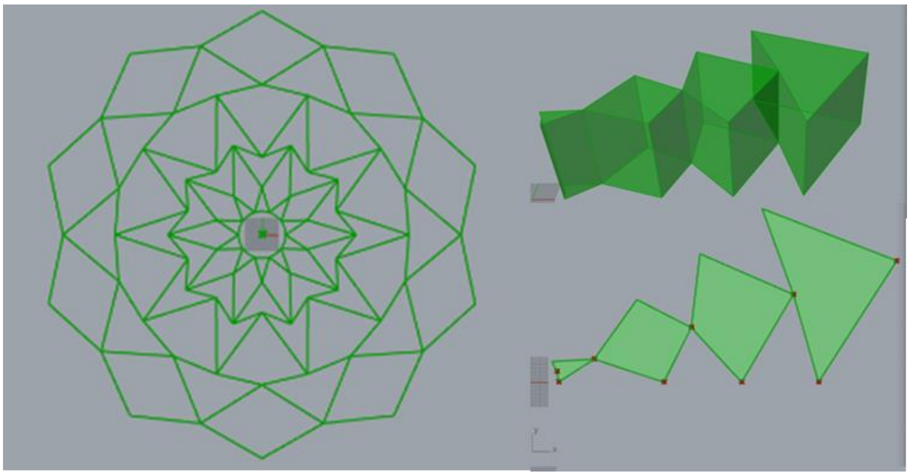

Figure 5. Each mould should be extracted from its specific unit in the designed parametric pattern.

4.1. MODULES’ SIZE

This parametric Muqarnas has 5 rows and due to the nature of Muqarnas, each row has its specific components in terms of size. (In the traditional Muqarnas the shapes don't change but size becomes smaller from bottom to top. But in our study, the components' shapes become a little bit different, although the difference is not obvious after assembly). So, this parametric Muqarnas has 5 sets (more levels can be added) of shapes and sizes and modules get heavier and bigger from bottom to top. The number of modules in each row are the same and can be changed parametrically.

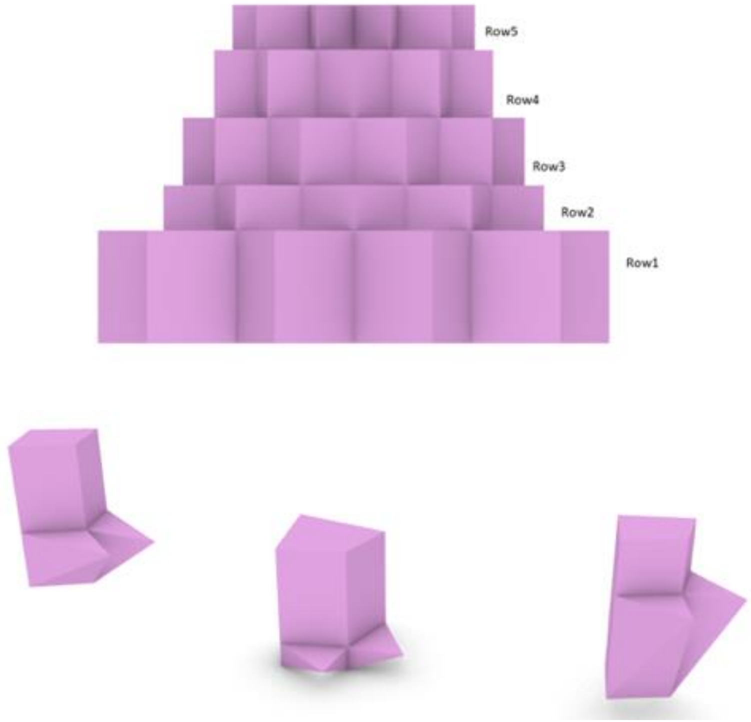

Figure 6. Modules' shapes are varied in each row

4.2. BACKREST

In this study, each module is transferring the weight of itself and modules above to the modules below. In traditional Muqarnas, particularly in complex and Shirazi types (in Al-Kashi classification), the arcs and triangle shape components can be seen below each mould. Usually, this is known as tile decoration and doesn’t have any structural role but in our Muqarnas, it has been inspired for structural consideration.

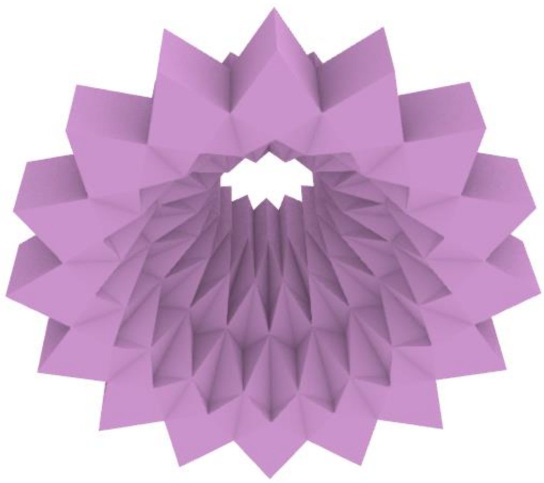

Figure 7. Backrest: inspired by the traditional decoration

Each Muqarnas has two backrests on both sides that provide enough spaces for the two moulds above. In this way, each module is supported by both the side modules and the bottom modules. Also, it could provide an overlap surface between two modules which allows adding more joint for large scale and different materials.

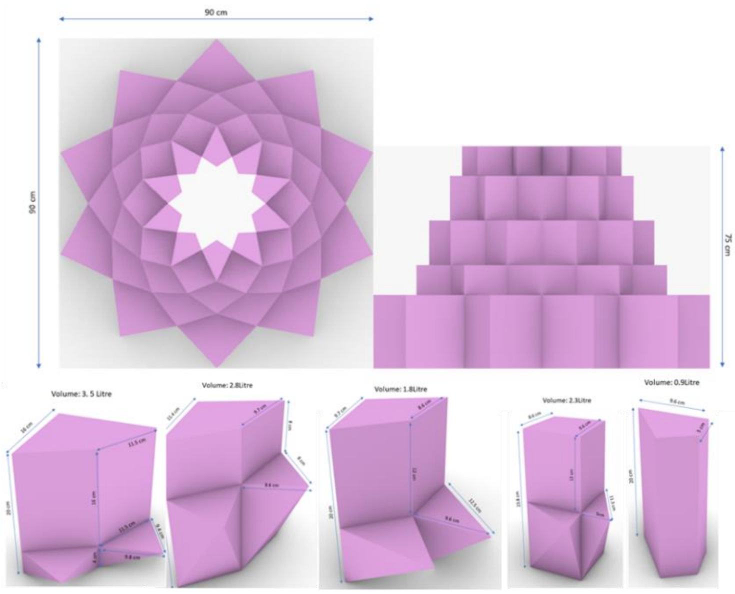

Figure 8. This Muqarnas includes 5 types of modules (5 rows). Modules' sizes get smaller from the bottom up.

4.3. UAV-BASED ASSEMBLY: PROPOSED ASSEMBLY SKETCH

Modules assembly will be carefully analysed in the next part of the research and will be reported in another paper. However, in this paper, a sketch is proposed to be examined under scale. The proposed assembly strategy aims to use a board that the first-row pattern should be carved on it.

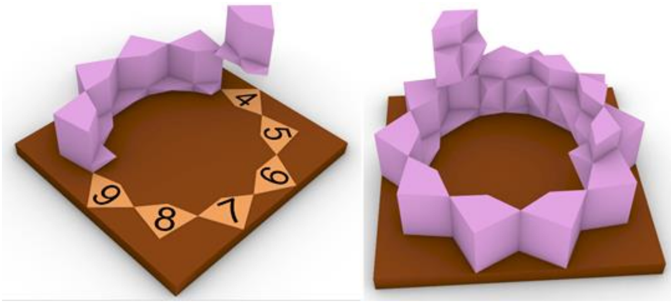

Figure 9. The border of the first row's components would be drawn on a board and programmed drone will put the first set of components on relevant units. Then, the components will be put on above each other, row by row.

Drone should pick each module from the picking site. In the picking site, components would be placed with the right orientation. Picking site will be helpful to lead the programmed drones and minimise the drone flying distance and rotation.

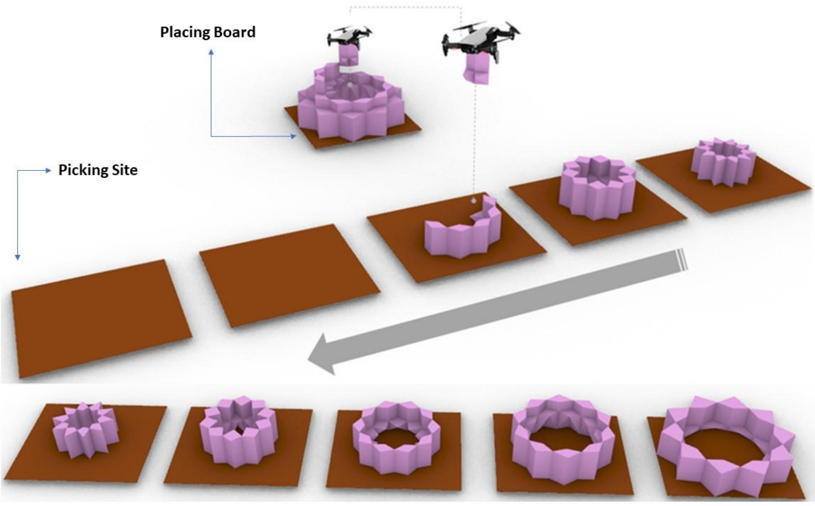

Figure 10 Placing Board and Picking-site: Each board in picking-site would be moved after picking up all its modules.

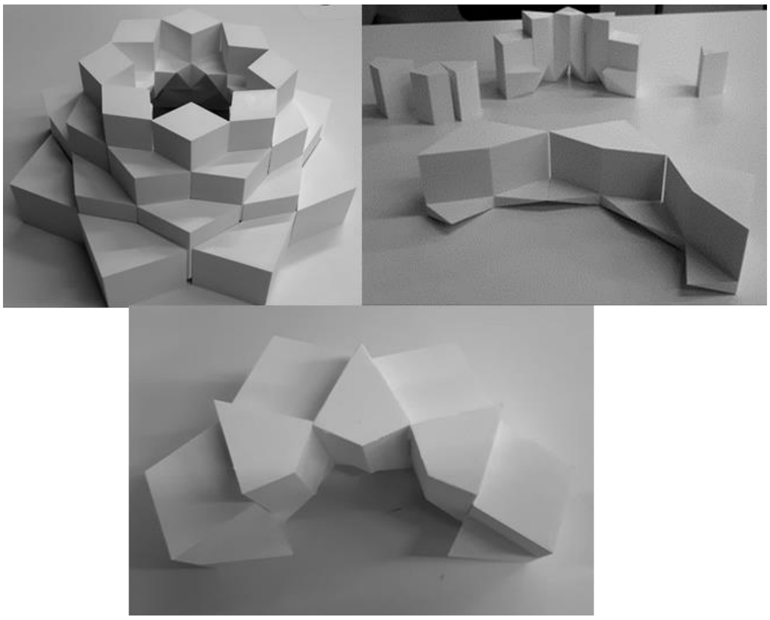

Figure 11 The modules have been 3d-printed under 1/3 scale to test the structure resistance and have been assembled.

5. Conclusion

In the first stage, this paper focused mostly on the analysis and extraction parametric features of the Iranian-Islamic Muqarnas and its encoding into a modular system. In the second stage, this paper formulated a parametric generative production and then tested an assembly strategy under the scale.

The parametric algorithm introduced in this paper could generate a diverse variety of designs of Muqarnas. Although Muqarnas traditionally is considered as the decorative element, but this study considers the four main specifications mentioned bellow to define the parametric Muqarnas as a structural element:

1. Volume (length, width and height), 2. Scale, 3. algorithm, 4. two-dimensional pattern plan.

The main advantage of this methodology is that all four mentioned specifications can be changed parametrically.

This study analysed generativity the feasibility of the design and production of Muqarnas modules. Mentioned picking and placing technique, from above, would be helpful to generate an assembly model based on UAV. The parametric design causes the modules to have a reliable structure. This parametric approach can be potentially expanded to other DfMA strategies.

Also, the proposed methodology of this paper could be used to analyse the vernacular architecture, parametrically. This vernacular synthesis would be helpful to redesign the vernacular architectural shapes and create modular generative systems from them. It should be considered that this UAV-based DfMA is still under progress. In the next phase, additional structural testing will be analysed. After ensuring the strength of the structure (in particular, lateral forces analysis) and assembly model efficiency, the programmed UAVs would be examined to make a complete Muqarnas under the scale.

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