

THE USE OF DIGITAL PATTERN RECOGNITION TECHNIQUES FOR VIRTUAL RECONSTRUCTION OF ERODED AND VISUALLY COMPLICATED ARCHEOLOGICAL GEOMETRIC PATTERNS

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ABSTRACT:

For the purpose of cultural heritage preservation, the task of reconstructing eroded and visually complicated architectural geometrical patterns is facing many practical challenges. Existing recording techniques have many limitations when dealing with patterns that are deteriorated or visually unclear. Unfortunately, until today, the task of reconstructing these patterns is still performed manually, or with the aid of some basic drafting software, which consumes time, effort and money. This study explores one possible solution, through utilizing digital techniques for reconstructing detailed historical Islamic geometric patterns. Its main hypothesis is that digital techniques offer many advantages over the human eye in terms of recognizing subtle differences in light and color. The objective of the study is to design, test and evaluate an automatic visual tool for identifying deteriorated archaeological Islamic geometrical patterns, and then restoring them digitally, for the purpose of producing accurate 2D reconstructed metric models. An experimental approach is used to develop, test and evaluate the specialized software. The proposed method was proven to be successful in capturing the accurate structural geometry of the deteriorated straight-lines patterns generated based on the octagon-square basic grid. This research also concluded that it is possible to apply the same conceptual method to reconstruct all two-dimensional Islamic geometric patterns. Moreover, the same methodology can be applied to reconstruct many other pattern systems. The conceptual framework proposed by this study can serve as a platform for developing professional software related to historic preservation.

1. INTRODUCTION

For the purpose of cultural heritage preservation, the task of reconstructing visually complicated archaeological geometrical patterns is facing many practical challenges. One of these challenges is posed by the fact that archaeological reality often deals with ornaments that are broken, incomplete or hidden. To preserve these delicate artifacts, it is important to produce accurate virtual reconstructions that can help professionals to make decisions and to test the different preservation scenarios.

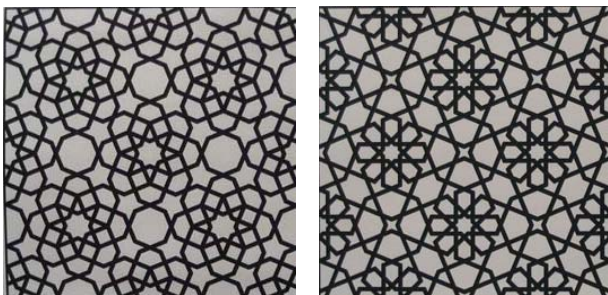


Figure 1. Examples of two Islamic pattern generated based on an octagon-square basic grid

Visually complicated patterns can be found in many cultural heritages of the world. Islamic Geometric Patterns present us with one example of such visually complicated archaeological ornaments, which are generated based on highly mathematical structures (Kritchlow, 1976; El-Said, 1993) (Figure 1). These ornaments were extensively used in architecture all over the Islamic world, from Spain in the west to China and Indonesia in the east (Jones, 1978), since the Seventh Century A.D. It is not

until recently that western scholars became aware of the importance of such art and came to acknowledge it as one of the most powerful forms of sacred art (Kritchlow, 1976; Abas and Salman, 1992). These objects are subject to erosion and vandalism, and as long-lived artifacts, they have gone through many phases of construction, damage, and repair.

Today, Archaeologists and Historians are faced with the challenge of preserving the delicate and precious details of these patterns. The tasks of efficiently and accurately reconstructing these visually complicated geometric patterns still pose many practical challenges. Existing reconstruction techniques have many limitations when dealing with patterns that are deteriorated or visually unclear. Recognizing faint traces of eroded or missing parts proved to be an extremely difficult task. This is also combined with the need for specialized knowledge about the mathematical rules of patterns' structure, in order to regenerate the missing data.

Although the computer offers many visual tools for handling these tasks, it also poses many practical challenges. The task of identifying spatial patterns is strongly related to the computer's ability to read digital images accurately enough to produce acceptable metric data (Jimenez and Chapman 2002). Unfortunately, existing techniques have limitations when dealing with reading and interpreting visually complex geometric ornaments. Almost all of these techniques rely heavily on the user's input, and on the subjective nature of our perceptual power in understanding the complexity and depicting color differences.

Based on these facts, the aim of this research is to explore the possibilities of using digital techniques for substituting human

power in accomplishing tasks related to historic preservation. To be able to reconstruct eroded patterns; recording techniques should be able to accurately and objectively read color information, then interpret such information through a visual tool that contains within its code some built-in mathematical intelligence that deals with the geometry of patterns. Therefore, this research investigates the use of algorithmic mathematics and computer vision to develop new ways of digitally analyzing, reconstructing and documenting geometric patterns. This is done by addressing the question of how to incorporate the mathematical rules of pattern structure with digital image techniques using computer tools to develop a program capable of reading and interpreting partially deteriorated Islamic patterns represented in digital image format, to simulate the missing parts and produce an accurate virtual reconstruction.

Although this research focuses specifically on Islamic patterns, the underlying goal is to develop general ideas and principles that might then be applied to other ornamental styles. The range of possible styles to investigate is huge, and this is only the first step before moving on with new forms of ornament.

1.1 Background

The art of Islamic symmetrical patterns has proven to be an elegant method for the study of symmetry (Kritchlow, 1976; El-Said, 1993). These patterns offer a rich source of research for artists and are also of interest to mathematicians, architects, archaeologists and others. Therefore, the development of an analysis tool can be very useful in studying and analyzing the evolution of Islamic symmetric repeated patterns, and also, to explore ways in which these patterns can be created algorithmically. Moreover, these patterns have strong relations with other sciences such as theoretical physics, crystallography, chemistry and biology (Abas and Salman, 1992; Kaplan, 2000).

It was not until the 1980s that mathematical research geared some of its interest toward exploring the field of Islamic geometric patterns as a method for the study of symmetry and mathematics (Grunbaum and Shephard, 1987). In fact Grunbaum and Shephard noted that the most exciting developments related to this field were only twenty years old. In 1987 they wrote a book that explores geometric patterns. It deals with mathematical analysis of tiling using regular polygons. Other research developed theories discussing the formation and analysis of mosaics, lattices and 2D plain ornaments (Wieting, 1982), and explored the relationships between tessellations and the different manifolds (Montesinos, 1985).

Since 1990 much research has been done to study and analyze the evolution of the Islamic symmetric repeat patterns, and to explore ways in which these patterns can be constructed algorithmically. Abas and Salman (1992) conducted an analytical study of different group patterns, through which they developed an algorithm based on group theoretic approach to be used with computer graphics to generate two-dimensional symmetric periodic patterns. Ostromoukhov (1998) extended Abas and Salman's analysis to develop mathematical tools for two-dimensional pattern analyses using planar symmetry groups and Cayley diagram.

In the field of computer graphics, many tools and algorithms were developed for automatic construction, drawing and visualizing of ornamental patterns. At the second SIGGRAPH

conference Alexander (1975) presented a system for drawing figures constrained to seventeen ornamental design types. Others have developed mathematical software such as Kali (Amenta and Phillips, 1996). This can be used to interactively generate different planar ornamental tessellations by applying the rules of symmetry. Andrew Glassner has developed many related computer algorithms. In 1996 he examined the synthesis of frieze patterns and the application of these symmetry patterns in computer graphics (Glassner, 1996). In 1998 he talked about the relationship between the geometry of reflection in a line, and specular reflection in a mirror (Glassner, 1998). In 2000 he demonstrated a method for creating a variety of patterns using hierarchies of symmetry elements and image-processing actions (Glassner, 2000).

Recently research in computer graphics adapted the technique of reconstructing geometric patterns by placing star units within a basic grid of polygons. Kaplan (2000) used this approach to develop a software implementation of the technique. The study of Kaplan and Salesin (2004) extends Kaplan's analyses to introduce a more generalized system within a novel parameterized collection of tiling formations. Moreover, they introduced the idea of absolute geometry, which allowed them to create designs on the sphere and in the hyperbolic plane. Arabesque software (Dispot, 2004) is a Java tool designed to help construct and draw patterns. It is particularly aimed at 3D artists wishing to use complex patterns for their scene settings. It can also be used as a special 2D drawing tool to design original patterns. It relies on a heavy use of symmetry groups. Recently, Kaplan (2005) presented a method for constructing transformable Islamic patterns by using different star unit "rosette" within the same basic grid of polygons. His construction was based on Hankin's "polygons-on -contract" method, which uses a grid of polygons as the basic grid.

2. METHODS

2.1 Research Design

This project explores the possibilities of incorporating the mathematical structure of Islamic patterns within the structure of digital images to develop a visual tool capable of interpreting partial evidence to simulate the missing parts. The definition implies two main tasks. The first task includes the development of the visual tool (computer program) and the second task includes testing and evaluating its performance. These tasks represent the first phases of developing professional software and can be situated under the umbrella of software engineering methods. Accordingly, it follows an empirical paradigm in developing its visual tool and uses experimentation as its main strategy.

In the first task of developing the software, both quantitative and qualitative approaches are used. A qualitative approach is used to design the program, while a quantitative approach is used through applying algorithms to pattern measurements. In the second task, qualitative approach is used evaluate its performance.

2.1.1 Pattern Analysis: An Islamic Geometric Pattern is defined mathematically as "a planar arrangement of line segments that together delineate copies of a small number of different shapes" (Kaplan, 2000). Although each pattern has

its own distinct geometrical design, the vast varieties of ornamental compositions are based on a simple constitutive geometry (Kaplan and Salesin, 2004).

Traditionally, all Islamic patterns were constructed by using a compass and a straightedge; therefore the circle becomes the foundation for all Islamic patterns (Kritchlow, 1976; Jones, 1978; El-Said, 1993). The generating force of patterns lies in the center of the circle, which represents the point at which all Islamic patterns begin. This decorative art is generated from a discrete geometrical unit using the circle as its basis, and then applying the principles of repetition, and symmetry to it (Kritchlow, 1976; El-Said, 1993). Although each pattern has its own distinct geometrical design, the vast varieties of ornamental compositions are based on a simple constitutive geometry, which is generated from a limited number of simple base grids of polygons. Figure 2 demonstrates the generation process of an octagon-square based pattern.

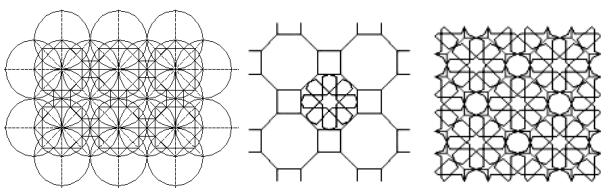


Figure 2. The generation process of an octagon-square based pattern

2.1.2 Target Population: The general goal for this research is to test an idea that can be applied to all types of Islamic Geometric Pattern. Therefore, the general targeted population includes all categories of Islamic Geometric Patterns. Nevertheless, for the purpose of conducting this study, the experiment specifically targets one group of these patterns, with the assumption that it provides a true representative sample of the general populations. This specific target population includes all straight-lines patterns generated based on the octagon-square basic grid. Patterns generated based on this basic grid were used extensively all over the Islamic world. They represent nearly twenty percent of all pattern combinations.

2.1.3 Sample Procedure and Treatment: The number of patterns that can be generated based on the octagon-square basic grid can be extremely large, and is related to the number of different probabilities of pattern combinations. The degree of complexity of these combinations is related to the complexity of the stars used to generate the final repeat star. To cover all levels of complexity, the population was divided into three main categories: simple, medium, and complex. The researcher used patterns' rules to generate an equal number of samples for the three different categories of complexity. Patterns were generated using AutoCAD tools and were constructed based on a well-established systematic method (Kritchlow, 1976; Jones, 1978; El-Said, 1993). Line patterns were generated with a fixed line width and were printed using black ink on (8.5 x 11 in) white sheets. For each pattern category, the researcher produced ten different pattern structures. Pattern's size, line width and arrangements were kept constant for all samples. Digital images with a fixed medium resolution (1600 x 1200 pixels) were taken for the chosen samples using an off-the-shelf digital camera (Canon, PowerShot A70). Finally, the resulting images were then saved using the PPM raster based image file format, which is used as an input to the developed visual tool.

2.1.4 Instrumentation: Program design was performed using computers supporting C, C++, OpenGL and the OpenGL interface API GLUT. The designed program itself was the main instrument, and was used to produce the experimental reconstructions of the deteriorated image.

2.2 Program Design

The design process includes two main phases: first, the conceptual design phase, which establishes the basic functions, operational characteristics and the overall organization of tasks. This phase also includes designing the visual interface, constructing tasks' flow chart, and investigating algorithmic approaches to identify workable techniques. The second phase is the implementation phase, which includes coding, testing, revising, and evaluating result.

2.2.1 Program Structure: The program is designed to input a PPM Image file format. It reads the image, saves it within a two-dimensional array and displays it on the screen. The algorithm treats the image as a discrete 2D array $I[m,n]$ of integer pixels, where m is the number of rows or scan-lines and n is the number of pixels per scan-line.

The program saves two copies in two different two-dimensional arrays. Then it displays one image on the screen with a menu that has a slide bar for controlling segmentation threshold. Based on user's selection, the program processes the second saved copy of the image to convert it to black and white image. The program interactively updates the image based on the user input and displays it on screen. After reaching the best visual result of image contrast, the user is required to define two center points of the repeated unit. This is done by clicking anywhere inside a central region and the program will process it to calculate the exact center point coordinates. Based on these coordinates, the program defines the boundaries of the repeat unit and then calculates the estimated position for all other center points in the pattern. These center points are then saved in a two-dimensional matrix for future processing. Next, the program scans and processes the repeated unit to locate all intersection points. Based on these intersection points, it produces one complete star unit using the principals of symmetry. Finally it copies this unit to all other center points' locations, which were saved earlier to produce the whole pattern. The program then displays the results on the screen and saves a copy to an EPS vector based image file format.

2.2.2 Image Processing: Image processing is done to improve image quality for extracting information and preparing the image for analysis. In this process, two main standard techniques of image processing for preparing the image for analysis are applied.

1. Color segmentation and enhancing colors contrast.
2. Converting the image to a black and white.

These tasks are controlled interactively by the user through adjusting a slide bar provided in the main menu of the program interface. The program converts the RGB color primary values from the scale of 0 – 255 to HSV color system; Hue on scale 0-360, Saturation and Value on scale 0-1. The program uses threshold/pixel-based segmentation (Snyder and Qi, 2004).

2.2.3 Pattern Recognition and Interpretation: Geometric patterns are generated from a basic geometric unit using the circle as its basis, and then applying the principles of repetition, and symmetry (Kritchlow, 1976; El-Said, 1993). In order to be able to reconstruct the pattern accurately, it is crucial to read the available data and define a repeated unit and interpret it based on pattern structure. This process includes defining the repeat unit based on the user input and then generating the whole basic grid based on that.

1. Defining the repeated unit:

The repeated unit of a geometrical pattern of octagon-based grid is defined by two centers. The user will pick any point within the central area of a star formation and the program will calculate and locate the center points. Unless the user selects two valid adjusting center points in a certain order, the program will not be able to define the repeated unit. Based on this unit, the program will calculate the distance between the two centers and automatically corrects the angles between them to calculate the area of the repeated unit. Based on user selection and pattern rules, the algorithm is designed to locate the two main triangle shapes of the repeated unit located on both sides of the center line connecting the two selections (Figure 3). The program needs only one side to generate the rest of the pattern. The choice of which is controlled by the user and based on the amount and quality of information retained in the image. Moreover, the program is designed to handle the eight different choices that might be selected by the user. These choices are related to the orientation of the main and secondary centres, and side selection.

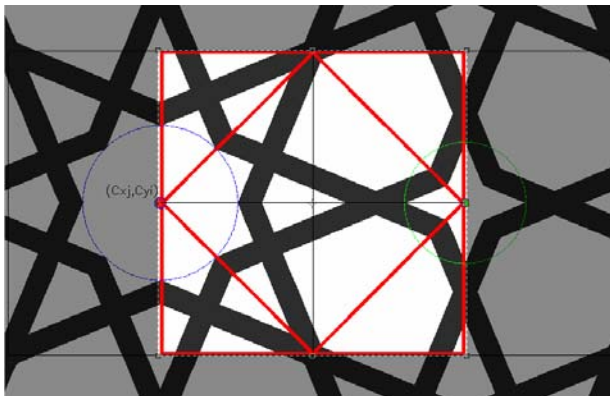


Figure 3. Defining the repeated unit and the area of run length scan

2. Generating the basic grid:

Based on the repeated units parameters defined by the user, the program calculates the rest of the center points using pattern-generating rules. The location of these points will provide the main matrix that will be used to generate the rest of the pattern.

2.2.4 Reading and interpreting the repeated unit: The repeated unit can be read through defining the intersection points that constitutes its shape and then connecting these points using vector data. To accomplish these tasks, many existing thinning and skeletonization techniques for extracting the centerlines of the image features were investigated (Hu and Li, 1994; Zou, 2003). Unfortunately, most of these techniques have problems with preserving line intersections (Zhong and Yan, 1999). The algorithm search resulted in defining one group of methods that deals successfully with preserving

intersection areas. These methods use a technique called run-length-wise processing (Hu and Li, 1994; Zhong and Yan, 1999). The run-length-wise processing approach is based on using pattern's line width to locate the intersection area. This technique starts by defining the convergence and divergence points of every intersection area, which mark the beginning and end of that intersection, and then using these locations to calculate the exact intersection point. It also takes advantage of the fact that geometric patterns have a uniform line width, which can be discovered by conducting simple mathematical procedures (Hu and Li, 1994). The process of defining the intersection points in a repeated unit includes four main tasks: run-length-scan of the repeated unit, locating convergence and divergence points, calculating the intersection points, and finally connecting them using vector data.

1. Run-Length-scan of the repeat unit:

The first step of run-length-wise operation is to find and mark intersection regions (Hu and Li, 1994; Zhong and Yan, 1999). Run-length scan is carried out on the saved black and white image of the area around the repeat unit. This region is highlighted in Figure 3. The first scan is carried out from the left to the right and black run-lengths are saved in a linked list. This scan process is repeated eight times (left-to-right, right to left, top to bottom, bottom to top, diagonally from the upper left corner to right bottom corner, etc).

2. Locating convergence and divergence points:

After saving run-lengths in linked lists, each list is processed to find the convergence and divergence points that define the intersection regions (Hu and Li, 1994; Zhong and Yan, 1999). These points are found by checking the current run-length with the previous run-length on the previous scan line for any overlap. There can be four cases:

- Case 1: no overlap (Line starts or ends).
- Case 2: One overlap (Line continues).
- Case 3: Two overlaps (Convergence or divergence condition).
- Case 4: More than two overlaps (More than one intersection).

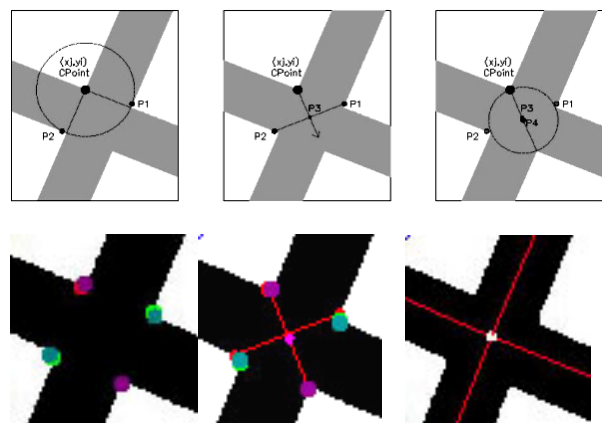


Figure 4. The process of calculating the exact coordinates of the intersection point

3. Calculating the Estimated Intersection Points and connecting them Using Vector Data:

Calculating the estimated intersection locations is done through a simple geometric method using the convergence and divergence points, as shown in Figure 4. For each convergence

or divergence location, one intersection point is calculated. This means that for every intersection area, a number of intersection points are located. The exact location of the final intersection is calculated by averaging all these points as shown in Figure 5.

Connecting the intersection point is done by simply scanning the area between each two points to check if it is covered all the way by black pixels. If white pixels are found the program does not connect them. Final lines are then saved in an array of a line structure.

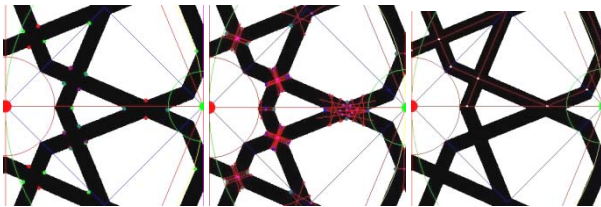


Figure 5. The process of calculating the exact location of the final intersection points

4. Pattern generation:

Pattern generation includes two main steps (Figure 6):

- a) Generating one complete star unit by applying the principles of repetition and symmetry.
- b) Constructing the whole pattern through copying the star unit to the basic grid pattern generated earlier, and trimming the pattern based on image boundary.

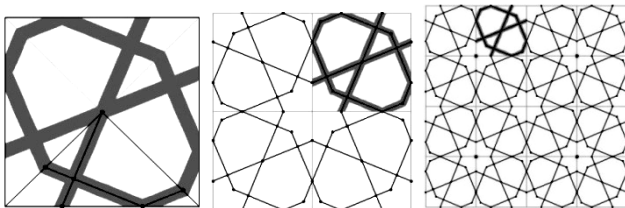


Figure 6. The process of pattern generation using the defined repeated unit

2.2.5 Program output: The program is designed to output the final reconstructed pattern as a line vector drawing (Postscript), a black and white PPM image, which is based on the user's input contrast value and the main measurements of the reconstructed pattern. Moreover, the program is able to calculate any pattern measurements by using these basic measurements

3. RESULTS AND DISCUSSION

Experiments were designed to test the performance of the program in reconstructing the right geometry of deteriorated patterns. It also tests the effects of different pattern complexity levels on the out-put results. Experiment samples were chosen randomly from the different groups of complexity. The aim of this group of experiments is to test the effect of shape and location of deterioration on the structural accuracy and repeatability.

The main conditions for accurately defining the right intersection points are: smooth lines, clean intersections, and

enough data of the repeat unit to generate the whole structure. Figure 7 displays the result of applying program's algorithms to an original deteriorated repeated unit.

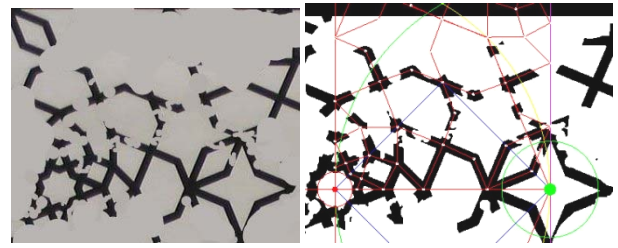


Figure 7. 13 The Original Input Image vs. the Results of Applying Program's Algorithm to a Deteriorated Repeat Unit.

No matter the degree of deterioration, the program was able to produce the whole pattern structure, if enough information of one repeated unit is available. The performance of the program relies solely on finding one intact repeat unit. The different experiments have also shown that pattern complexity has no effect on the result. Also, different shapes and locations of the repeated unit do not affect the structural accuracy of the final reconstructions. Figure 8 displays two original deteriorated patterns of different complexities and their reconstruction results.

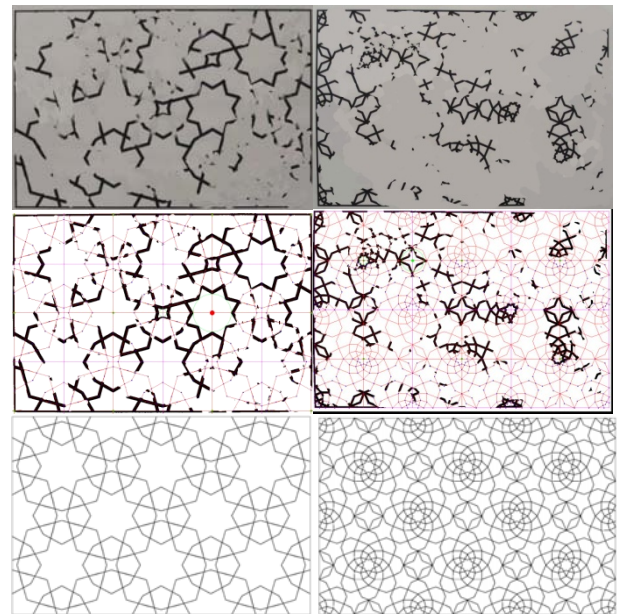


Figure 8. Two original deteriorated patterns of different complexity levels, screen shots of the reconstruction process and the final output vector line data.

4. COCLUSIONS

The proposed method is proven to be successful in capturing the accurate structural geometry of the deteriorated straight-line patterns generated based on the octagon-square basic grid. Nevertheless, a lot needs to be done to improve its performance to deal with real life objects. The developed tool is not assumed to be professional software; rather, it only provides a solution to the idealized problem. This represents a first step in solving real life challenges. Dealing with real life objects requires applying

more sophisticated image processing techniques in order to prepare it for analysis.

The general goal for this research is to develop a method that can be applied to reconstruct all types of Islamic Geometric Patterns. Therefore, based on the fact that all Islamic patterns share the same general properties (El-Said, 1993; Jones, 1978), it is possible to apply the same conceptual method to reconstruct all two-dimensional straight-line Islamic geometric patterns. Nevertheless, to be able to apply the method to work on patterns generated based on different base grids, algorithms need to be modified to identify the exact pattern's repeated unit in relation to its basic grid properties.

Many pattern systems can be good candidates to develop methods for automatically recreating their structures by applying the same methodology. The automation of any pattern system requires a clear structured hierarchy that can be translated into mathematical formulas, a clear visual appearance of the patterns, to make it possible to digitally identify pattern information, and a defined vocabulary of shapes.

The designed digital tool proved to be efficient in capturing the correct geometry of low-resolution digital images. Resolution starting from (200 pixels/image) to (600 pixel/image) is enough to process almost all patterns. Moreover, this also means that digital techniques are more capable of recognizing complex geometry than the human eye.

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