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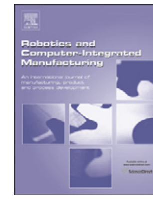

Marble mosaic tiling automation with a four degrees of freedom Cartesian robot

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ABSTRACT

The art of mosaic has arisen thousands of years ago. Despite all those years and all the attention it has received till today, mosaic tiling is still being carried out manually and mosaic tiling processes have never been changed except the tool and material developments.

In this paper; history of the mosaic art, the ancient and today's mosaic tiling processes are mentioned briefly. A Cartesian robot with four degrees of freedom is designed and manufactured for mosaic tiling automation. An algorithm for mosaic tiling and the control of robot, named "MOSTIL" is developed. The control software interprets a pattern file that is prepared using an existing two-dimensional (2D) CAD package and computes the pieces' locations of the pattern and guides the robotic arm. As a result of this work, some experimental applications for several mosaic patterns which are designed using a 2D CAD software and saved as "dxf" format, are carried out by the robot automatically.

1. Introduction

Mosaics are artworks, often of large dimensions, used in floor and/or wall decoration. They are made by placing together pieces of marble or travertine of different dimensions and geometries to compose a picture or a pattern [1].

The rise of the mosaic art is difficult to determine but historians are generally in agreement that the origins emerged in the orient. In Mesopotamia, in the 4–3rd millennium BC, Sumerians developed a type of mosaic composed of slender cones of baked clay with some base ends painted red, black, and white. These were embedded in mud brick walls to create a decorative protective coating in geometric patterns, perhaps derived from textile or matting materials. A large section of a Sumerian wall of half-columns (early third millennium BC) from Erech (Uruk), decorated with these patterns, is preserved in the Staatliche Museum, Berlin. These decorations started the architectural mosaic applications [2].

The art of mosaic has become a fashion in Italy after the second century AD. The mosaics describing the life in the sea, hunting scenes, domestic activities, and the mythology; have decorated the houses, stores and baths. In this century; mosaics were used as carpets. By the time of the Roman Empire; the art of mosaic was expanded to Mediterranean, North Africa, and Europe [2,3].

The mosaic art has reached the highest population during the Byzantine Empire. Mosaics produced in various parts of the Byzantine Empire are among the finest extant. Materials such as gold, silver, and colored glass were used in mosaics in this time [2–5].

In early mosaic techniques; mosaics were made of layers which are composed of tightly packed pebbles, sand, smashed tiles, and lime. The surface where the mosaic will be tiled was covered by these layers and the mosaic tiles were affixed to the top with a layer of mortar created from fine sand and lime. The method by which mosaics are made has not changed much since ancient times. Advancements in tools and materials have made the process easier, quicker and the results more varied and visually appealing, but over all the process is the same [6]. In Fig. 1, manual mosaic tiling process is given.

In today's mosaic tiling applications; mosaic is often created in a frame to prevent tiles from slipping or breaking off the edges. This frame can be made from various materials such as wood, metal, concrete, or resign with an aluminum core depending on the size, shape and intended purpose of the mosaic.

Today's mosaic artists employ many of the same techniques used by ancient mosaic artists. Indeed, mosaic has changed little over the centuries. Innovations in materials have allowed artists to make mosaics in any static form along with flexible mosaics that can be repositioned anywhere [6].

Mosaics today are far more versatile than their antique counterparts and somewhat more durable, but the process by which mosaics are created, and the time it takes to produce a mosaic has remained the same. Mosaic is still a labor intensive,

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time consuming art form that deserves special respect and appreciation [6]. Some mosaic examples used indoor and outdoor are given in Fig. 2.

Despite all the manual mosaic tiling processes since the ancient times, there has been a few published studies about mosaic tiling automation. Therefore, the studies about mosaic tiling automation are quite new. Oral and Erzincanli developed a software for tiling mosaics automatically by picking up the marble pieces from the supply stations and placing them according to their coordinates. In this work, Oral and Erzincanli have formed square and quadrangle shaped mosaic configurations using computer controlled SCARA robot [7].

Kaya, Berkay, and Erzincanli developed software for tiling glass mosaics by Ultimate Puma 500 type industrial robot that has six degrees of freedom in their study. In this study, software converts the computer image to mosaic picture by using Borland C# [8].

Navon developed a floor tiling robot which has a six degrees of freedom for assembling large prefabricated components into walls and floors [9]. In this paper, distinctly from the Navon's study, mosaic tiling robot produces prefabricated components.

Fig. 1. Manual mosaic tiling.

Fig. 2. Mosaics used indoor and outdoor.

The purpose of this work is to make mosaics automatically which have been carried out manually for thousands of years by a fast and flexible software and hardware system. For this purpose; Cartesian robot that has four degrees of freedom is designed and manufactured. The geometrical data of the mosaic pieces are obtained from 2D CAD software. The mosaic pattern created by a 2D CAD program is interpreted by the software and mosaics were formed by software controlled Cartesian robot's pick and place applications.

2. Robot design for mosaic tiling

Following good manufacturing processes, gaining time and cost advantage, providing faultless products/services and customer satisfaction are important for companies. It is obviously seen that automation enters all the fields of industry today. Companies started to use robots for products of high quality. By the arrival of the robots; companies have obtained standard manufacturing and reduce in the labor/material costs. In addition to they have had the advantage of working in the unhealthy and tight conditions.

Manual mosaic tiling processes cannot satisfy the customers' requests rapidly. To manufacture mosaics according to the customers' requests and to form different mosaic configurations as fast as possible, a rapid manufacturing system composed of software and hardware is needed.

According to these circumstances, a Cartesian robot is designed and manufactured for mosaic tiling. The Cartesian or a rectangular manipulator is an arm which moves in a rectilinear mode, that is, to the directions of the XYZ coordinates of a Cartesian coordinate system [10]. The robot used in this work, is a Cartesian robot that has four degrees of freedom. Distinctly from the classical Cartesian robots, it has a rotation in the Z-axis. It has 11520 cm^3 workspace and movements in the X and Y axes are driven by stepper motors and timing belt mechanisms. The up and down movement in the Z-axis is driven by a pneumatic cylinder [11].

By a suction cup assembled to the pneumatic cylinder, marble pieces can be picked and transported. Because of the surface roughness of the marble pieces, bellowed suction cups are preferred for this application. The holding and releasing forces of the suction cup are calculated using Eqs. (1) and (2) [12]:

$$F_H = m(g + a)S \quad (1)$$

$$F_A = \frac{F_H}{n} \quad (2)$$

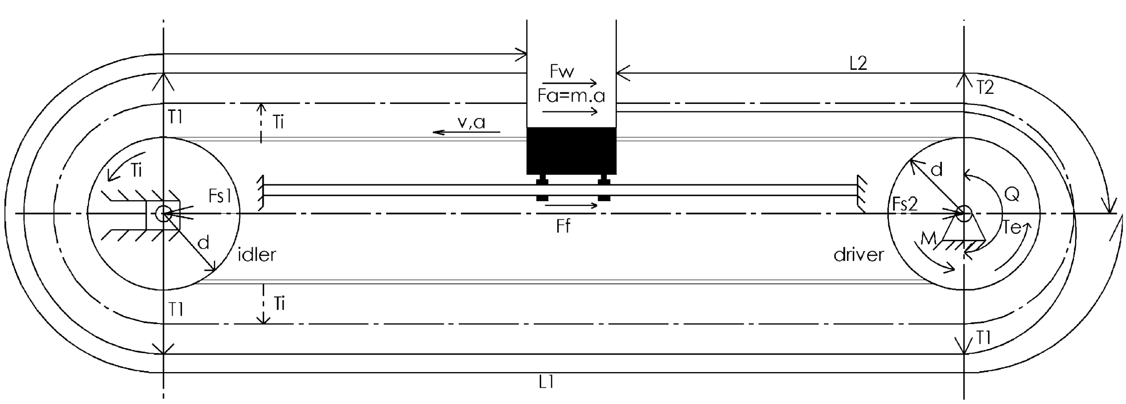

Fig. 3. Forces acting in timing belt drives.

where F_H is the holding force (N), F_A the releasing force (N), m the mass of the marble piece (kg), g the force of gravity (m/s^2), a the acceleration of the suction cup (m/s^2), n the number of suction cups, and S the safety factor (1.5–2).

The optimum pressure for the suction cup and the diameters of the suction cups can be obtained by using Eq. (3) [12]:

$$F_H = (P_o - P_u) A n_3 \eta z \frac{1}{S} \tag{3}$$

where P_o is the atmospheric pressure (N/m^2), P_u the vacuum pressure (N/m^2), A the area of the suction area (m^2), n_3 the coefficient of deformation (0.9–0.6), η the efficiency of the system, and z the number of the suction cups.

Timing belt mechanisms are used in positioning of the mosaic tiling robot in the X and Y axes. The tensions and torques acting during the motion of the robot are given in Fig. 3 [11].

During operation of belt drive under load, a difference in belt tensions on the entering (tight) and leaving (slack) sides of the driver pulley is observed. It is called effective tension, $\boldsymbol{T}_e$, and represents the force transmitted from the driver pulley to the belt:

$$T_e = T_1 - T_2 \tag{4}$$

where $\mathbf{T}_1$ is the tight tension and $\mathbf{T}_2$ the slack side tension.

The driving torque, $\boldsymbol{M}$ is given by Eq. (5):

$$M = T_e \frac{d}{2} \tag{5}$$

where $\boldsymbol{d}$ is the pitch diameter of the driver pulley.

In linear positioners, the main load acts at the positioning platform (slider). It consists of acceleration force $\boldsymbol{F}_a$ (linear acceleration of the slider), friction force of the linear bearing, $\boldsymbol{F}_f$, external force (workload), $\boldsymbol{F}_w$, the weight of the slide $\boldsymbol{F}_g$ parallel to the belt in inclined drives, inertial forces to accelerate the belt, $\boldsymbol{F}_{ab}$, and the idler pulley, $\boldsymbol{F}_{ai}$ (rotation). $\boldsymbol{T}_e$ is given Eq. (6) [11]:

$$T_e = F_a + F_f + F_w + F_{ab} + F_{ai} \tag{6}$$

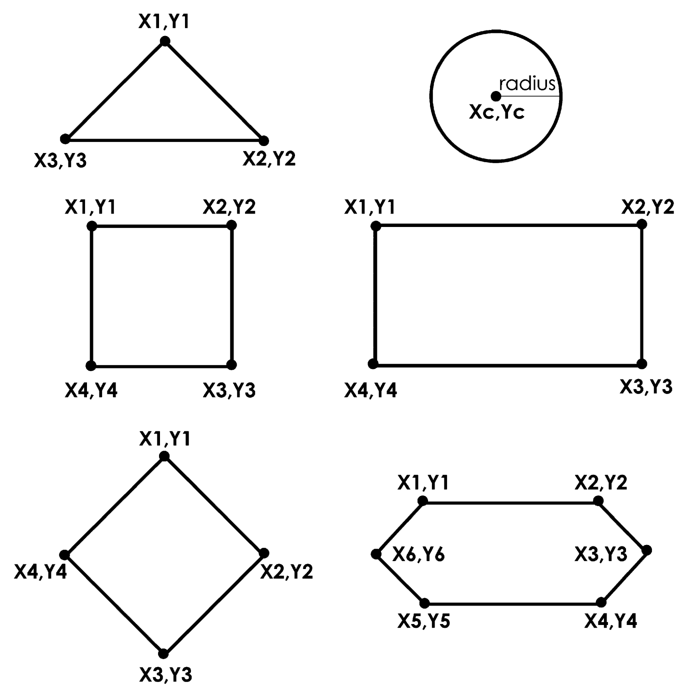

Fig. 5. The geometries of the mosaic pieces.

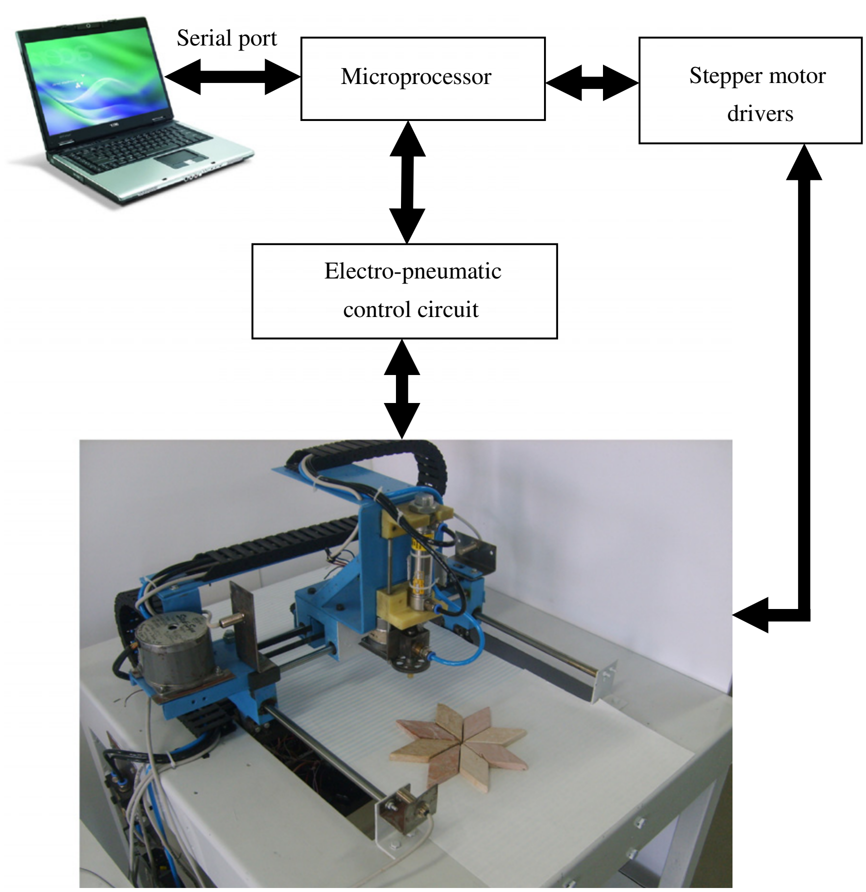

Fig. 4. The control process and mosaic tiling robot.

The individual components of the effective tension, $\boldsymbol{T}_e$, are given by Eq. (7) [11]:

$$F_a = m_s a \tag{7}$$

where $\boldsymbol{m}_s$ is the mass of the slider or platform and $\boldsymbol{a}$ the linear acceleration rate of the slider

$$F_f = \mu_r m_s g + F_{fi} \tag{8}$$

where $\boldsymbol{\mu}_r$ is the dynamic coefficient of friction of the linear bearing (usually available from the linear bearing manufacturer), $\boldsymbol{F}_{fi}$ is a load independent resistance intrinsic to linear motion (seal drag, preload resistance, viscous resistance of the lubricant, etc.) [11]:

$$F_{ab} = \frac{W_b L b}{g} a \tag{9}$$

where $\boldsymbol{L}$ is the length of the belt, $\boldsymbol{b}$ the width of the belt, w_b the specific weight of the belt and $\boldsymbol{g}$ the gravity:

$$F_{ai} = \frac{2J_i\alpha}{d} = \frac{m_i}{2}\left(1 + \frac{d_b^2}{d^2}\right)a \tag{10}$$

where $\boldsymbol{J}_i$ is the inertia of the idler pulley, $\boldsymbol{a}$ the angular acceleration of the idler, $\boldsymbol{m}_i$ the mass of the idler, $\boldsymbol{d}$ the diameter of the idler, and $\boldsymbol{d}_b$ the diameter of the idler bore (if applicable) [11].

It is seen in the control process of the system given in Fig. 4 that the communication between the software and the control/drive circuits is provided by the PC's serial port. The digital signals for the stepper motor motion are sent to the microprocessor and then to the driver circuits by the software. The pneumatic cylinder and the vacuum system are controlled by the communication between the software and the timing relays. In Fig. 4, mosaic tiling robot is shown.

The elements of the control system are

- microprocessor,
- stepper motors and drivers,
- electro-pneumatic control elements and circuit,
- serial port, and
- mosaic tiling software.

The three axes motion control circuit of the robot provides the motion communicating with software by RS232 serial port. 120 MHz DSP microprocessor and timing relays are used in this circuit in order to control the vacuum system and the pneumatic cylinder. Three stepper motors are used in mosaic tiling robot; two for the linear motion in the *X* and *Y* axes, one for the rotational motion in the *Z*-axis.

Two compressors are used in this application; one for the pneumatic cylinder's motion and the other for the vacuum pressure that is needed in order to pick the mosaic pieces.

3. Mosaic tiling software

The purpose of the mosaic tiling software is to produce rapid, various sized/shaped industrial mosaics. The general idea is to

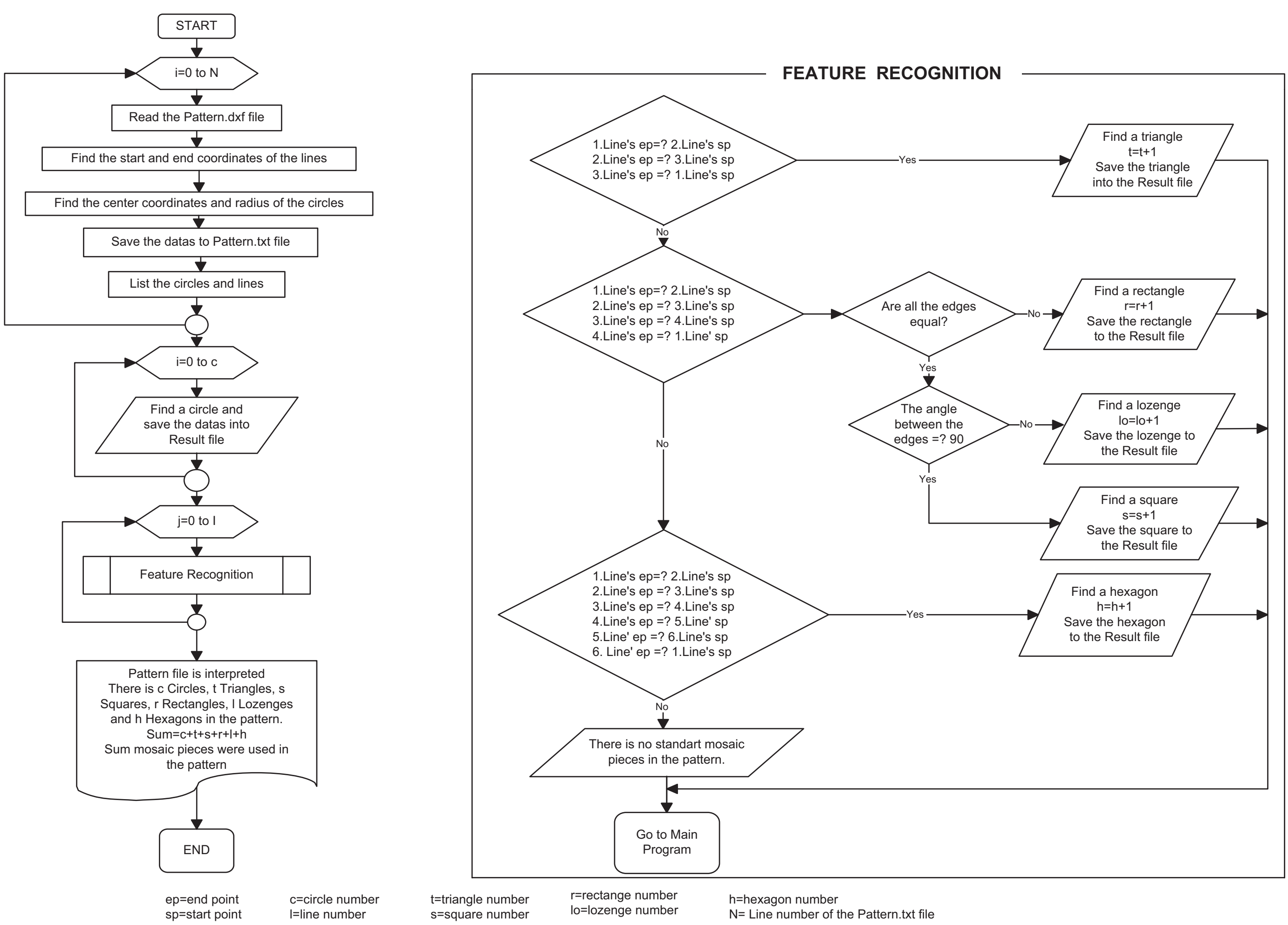

Fig. 6. The feature recognition algorithm (FRA).

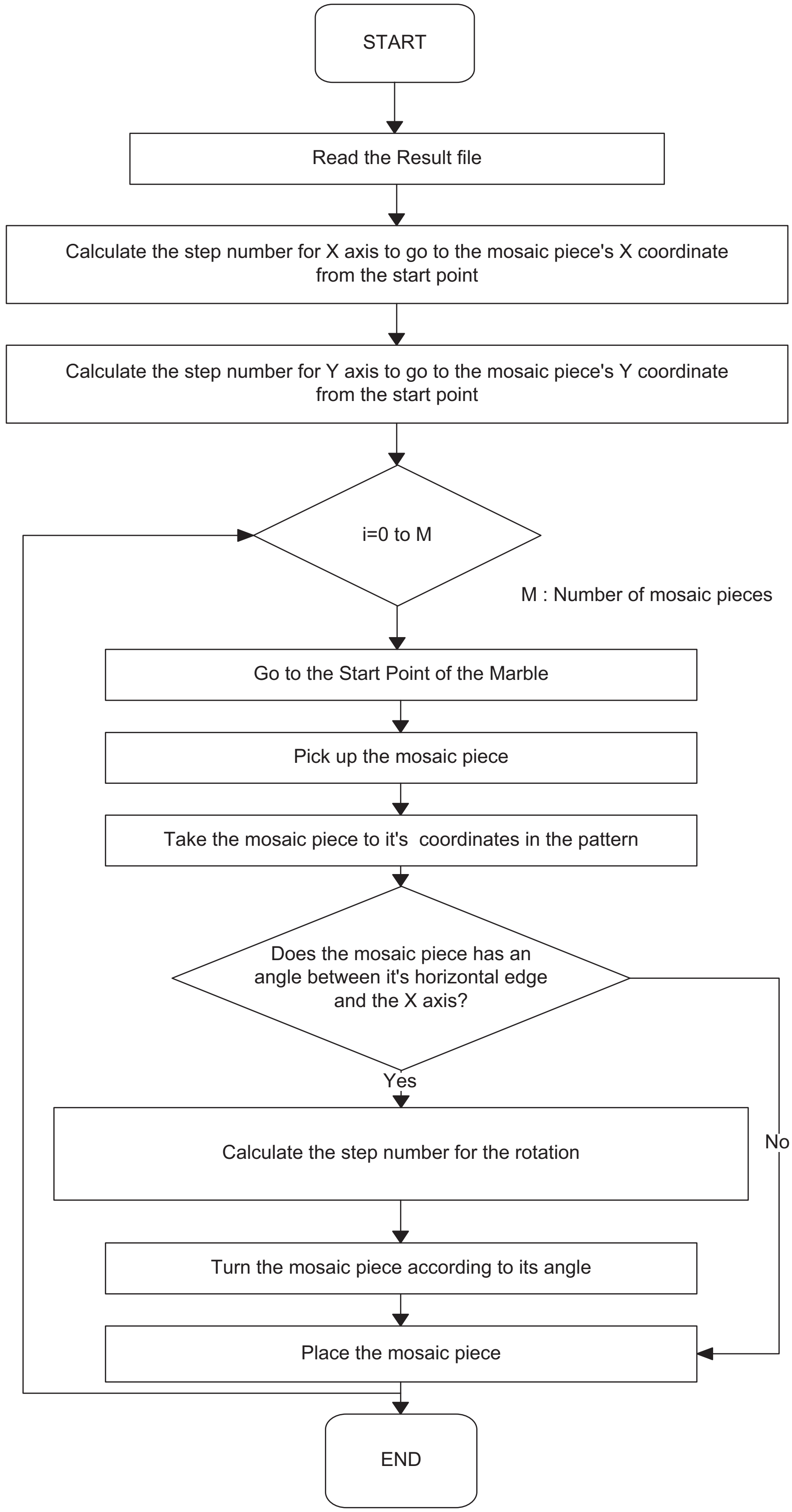

Fig. 7. The control algorithm of the mosaic tiling robot.

form the mosaic pattern automatically that is designed using any 2D CAD program. For this idea, mosaic tiling software is developed to analyze the designed mosaic pattern file that is "dxf" formatted and identify the geometric data of the mosaic pieces which are composing the mosaic pattern. This software is developed by Java programming language and can be used in any platforms.

Mosaic tiling software is basically consisted of two different algorithms working together. One of the algorithms is a simple feature recognition algorithm. It is developed to analyze the mosaic pattern file which is designed by using 2D CAD software. By interpreting the mosaic file the algorithm renders the geometric data of the mosaic pieces. The other algorithm is the robot control algorithm which controls the motions of the robot according to the data from the feature recognition algorithm.

3.1. Feature recognition algorithm

The first step for the automatic tiling process of the 2D CAD designed mosaic pattern file is feature recognition. Feature recognition; is a modeling interface that transfers the mosaic pieces' geometric data from CAD systems. The design of a mosaic pattern represents features implicitly. Recognition of features, therefore, requires knowledge of the method of representing a geometric part. There exist several ways, two-dimensional (2D) and three-dimensional (3D), of modeling a part [13–15]. This algorithm is developed for recognizing dxf formatted 2D CAD files which are designed for mosaic tiling and determining the coordinates, geometries and sizes of the mosaic pieces in the pattern. Marble parts are represented by the combinations of circles and lines. The circle is defined by the *X*, *Y* coordinates of the center point and the radius, line is defined by the *X*, *Y* coordinates of its start and end points.

The mosaic tiling software is developed considering the standard mosaic pieces (like circle, triangle, square, rectangle, lozenge, and hexagon) used in industry and mosaic patterns are designed with these mosaic pieces.

The recognition of features requires that geometric data be organized in an appropriate manner. In Fig. 5, the geometric shapes of the features used in mosaic patterns are given. The features composing the 2D mosaic pattern must be designed in sequence. As it is seen in Fig. 5, the lines composing the features are following an order and the last line joins the first line at the last point. First point and the last point of a feature is the same.

In recognizing the features; first the equality between the first line's end point and the sequent line's start point is found. The first line's start point is the first point of the feature and it must be the last line's end point to compose a closed feature such as triangle, square, etc. except circle. For example, in the square recognition algorithm; four sequent lines are found and one line's endpoint is the sequent line's start point. Now the feature can be rectangle, lozenge or square. Following this, the lines are analyzed according to their lengths. If all the lengths of the lines are equal the probabilities are decreased to two. After comparing the angles between the lines the recognition is finished and the feature is classified whether it is a square or a lozenge.

In the flow diagram of the feature recognition algorithm (Fig. 6), 2D CAD Pattern.dxf file is interpreted and the drawing components are saved in Result.txt file. The circles and lines are analyzed. Circles are directly saved into the Result file. Lines are examined according to the relations between them and the geometries and sizes of the mosaic pieces are determined.

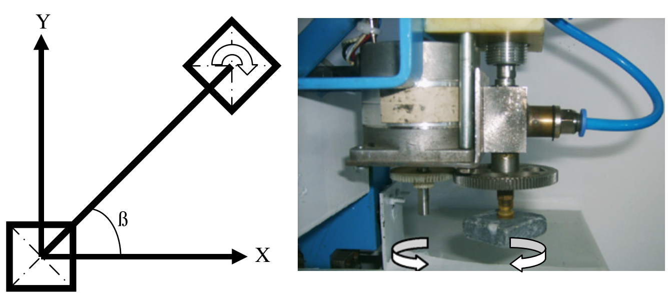

Fig. 8. The rotation angle of the mosaic piece and the gear system.

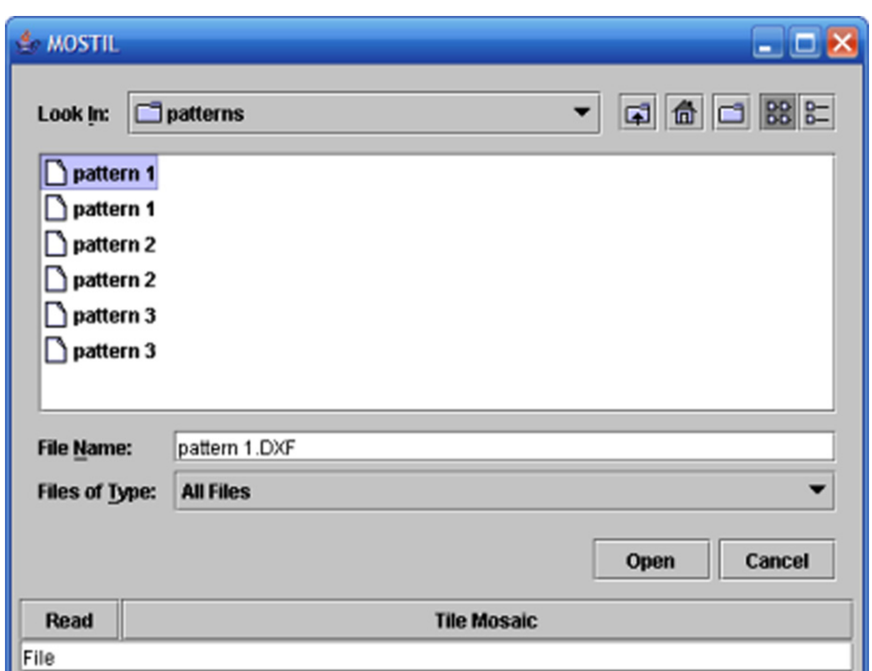

Fig. 9. The mosaic tiling software interface.

3.2. The control algorithm

As the next step, the control algorithm calculates the data for the robot's movements needed for mosaic tiling. As it is seen in the flow diagram in Fig. 7, at first the algorithm checks the robot gripper position and brings them to the start point.

The step numbers that are needed for the stepper motors according to the each mosaic piece's coordinates are calculated. Then the mosaic piece is picked, taken to its center of gravity coordinates, rotated and placed by the robot.

The *X*- and *Y*-axis stepper motors travel 0.0397 mm per step. Considering this value, the numbers of steps needed to reach the coordinates of each mosaic piece are calculated by Eq. (11):

$$\text{The number of steps at the } X \text{ and } Y \text{ axes} = \frac{L_x \quad \text{or} \quad L_y}{0.0397} \qquad (11)$$

L_x is the *X* coordinate of the mosaic piece and L_y the *Y* coordinate of the mosaic piece.

The stepper motor which is used for rotation in the *Z*-axis has a 1.8°/step sensibility. Gear systems which used in the rotation axis are seen in Fig. 8. With the ratio of the gears the stepper motor travels 0.5625°/step. If the mosaic piece has an angle between the *X*-axis and its horizontal edge seen in Fig. 8, the step number at the *Z*-axis is calculated by Eq. (12):

$$\text{The number of steps} = \beta \times (0.5625) \qquad (12)$$

3.3. The mosaic tiling software interface

An interface is developed for the four degrees of freedom Cartesian robot to make the mosaic tiling process automatically. The interface is developed by Java programming language so the software can be used in any platforms. The software can interpret any CAD file that is in "dxf" format. Software first reads the CAD file then recognized the features and saves them to the Result file. Finally guides the robot to tile the mosaic pieces according to the data from the Result file.

The mosaic tiling software named "MOSTIL" can be seen in Fig. 9. The software is easy to use that mosaic tiling process can be done by clicking a few buttons.

The "Read" button activates the feature recognition algorithm and the software starts to analyze the CAD file. After recognizing the features, the numbers and the sizes of the mosaic pieces are given in the text field. According to this information, mosaic pieces are located to the supply stations. "Tile Mosaic" button activates the control algorithm and guides the robot to compose the pattern as same as the CAD file.

4. Experimental works

In this study, several mosaic patterns including variable shaped/sized marble pieces are formed. The pattern files are designed by SolidWorks 2006 CAD program. These patterns are interpreted and automatically formed by the computer controlled robot. By the control algorithm of the software Cartesian robot picks the mosaic pieces which are formerly placed into the supply stations and starts tiling.

In the square matrix pattern shown in Fig. 10, only the same sized square marble pieces are used and tiled in a 5×5 matrix form. The pattern file is designed using a 2D CAD program.

The pattern is read by the software and the marble pieces are identified. After picking up the marble pieces from supply station, the pieces are tiled by the robot. Since one type of marble piece is used and tiled side by side in this example, only one supply station is defined. Number of the supply stations is defined according to the number of the marble geometries in a pattern. In this example, the automated mosaic tiling process by one suction cup as shown in Fig. 10 takes 33.5 s.

To prevent time lost, multiple suction cups are designed for tiling. With the application using multiple suction cups processing time is decreased approximately to 20 s. The application with the multiple suction cups is given in Fig. 11.

Other experimental patterns that are formed by the software controlled robot are given in Fig. 12.

5. Conclusions

In this work; four degrees of freedom Cartesian robot is designed and manufactured for mosaic tiling processes. It has seen that Cartesian robot can be successfully used for tiling mosaics using specially created software named "MOSTIL."

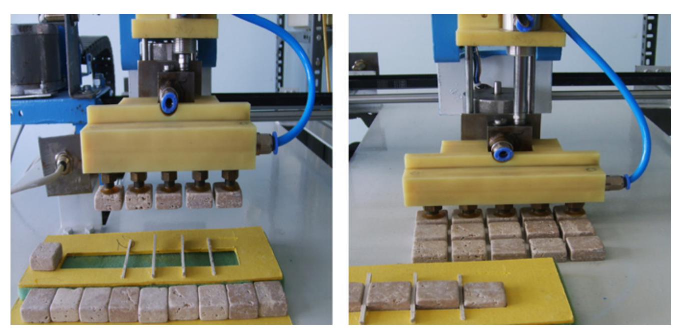

Fig. 11. Application with multiple suction cups.

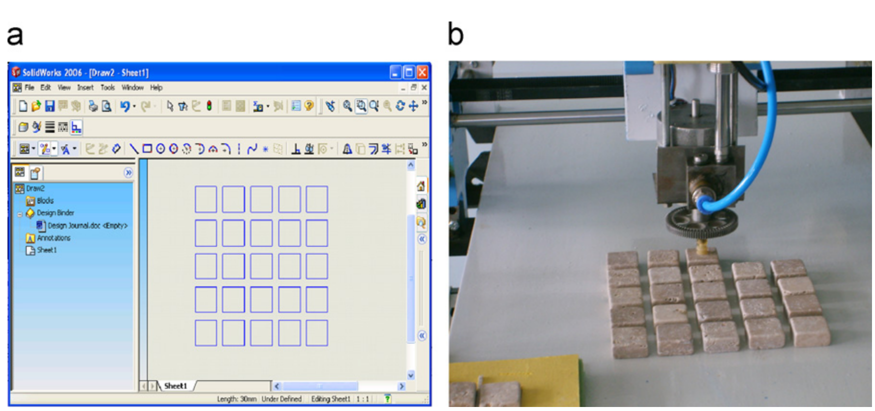

Fig. 10. Preparation of mosaic in CAD environment and tiling process: (a) SolidWorks interface of square matrix pattern. (b) Square pattern tiling with robot.

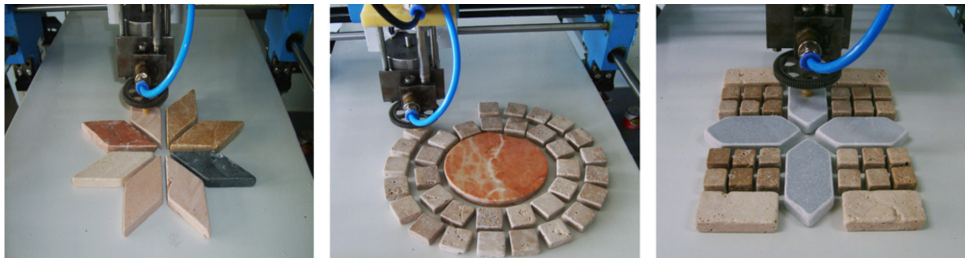

Fig. 12. Other pattern examples that are formed by the software controlled robot.

By this system, any sized circular, triangular, square, rectangular, lozenge, and hexagonal shaped mosaic pieces can be tiled automatically.

This work has formed an important step for mosaic tiling automation. As a result of this work, some advantages can be obtained over hand made mosaic tiling which has been carried out for centuries. These advantages could be outlined such as; faster tiling process, less error due to less labor work, less labor costs and more flexibility for complex pattern configurations.

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