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Patterning automation of square mosaics using computer assisted SCARA robot

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SUMMARY
Today mosaics are used as decorative elements both indoors and outdoors. Mosaics can be obtained by combining small pieces of stone, glass, wood and glazed tiles together to make some picture and illustration. Mosaic-making processes are carried out manually for thousand years. Complexities involved in piece selection, surface detection and mould fitting have limited the automation of this process. In this work, software that makes the mosaic patterning process automatic is developed. For this purpose, software named SMT V2 has been developed to obtain different mosaic patterning. The software also tested with experimental applications by selective compliance articulated robot arm (SCARA) robot on real environment using different shaped marble pieces and successful results are obtained.

KEYWORDS: Marble mosaic; Mosaic tiling; Mosaic tiling automation; Mosaic patterning; Robotic tiling.

1. Introduction

Mosaics are an art form, often of large dimensions, used for the decoration of building surfaces such as floors and walls. They are made by placing together small pieces (the *tesserae*) of natural stone, terracotta, marble, paste, etc. to compose a picture or a pattern. Mosaics consist of small pieces of glass or other materials (stone, ceramics) held in place by mortar.[1,2] Making mosaic is to make a picture by joining together small pieces of stone, glass, glazed tiles, etc. This form of decoration is often used for panels or floors, but is especially effective on curved surfaces, such as ceilings and vaults. Mosaics can be found both indoors and outdoors. The art of mosaic, in one form or another, has been practiced for thousands of years. In the beginning of the 20th century mosaics gained in popularity with the 'Art Nouveau' movement. Modern developments in materials and production techniques are evidence that mosaics are still popular.[3–5]

Inspite of all the technological developments in the marble industry, today mosaics are still prepared manually but this situation should be expected to change rapidly. Robotic systems are promising accelerated production, lower costs, elimination of human errors. Manual tiling is not as fast and flexible as it should be. Each customer has different requirements, such as colour, image, style, size, etc. Each mosaics style requires a special mould or drawing to tile each piece in the correct position and orientation. Automation will enable correct placement of pieces without additional equipment such as a mould (for basic patterns) or drawings (for complex layouts). Computational environments are of course ideal for designing contemporary mosaics, and are starting to be used for that purpose.

In previous works, Oral and Erzincanli have successfully used a SCARA robot for tiling mosaics to create square and rectangular configurations. The marble pieces were handled using a single vacuum cup end effector.[6] Mosaics were composed using only the same geometrically shaped marble pieces. Mosaics that are composed of differently shaped marble pieces were not considered. Kaya, Berkay and Erzincanli formed glass mosaics by image processing. They used a 6-DOF (degrees of freedom) Puma 500 robot to form glass mosaics in their study. An image file (jpeg file) is separated into parts by image processing and the glass colours and shapes are identified. According to the data obtained by image processing, glass mosaic pieces are placed to the tile charger magazine. Puma 500 robot forms the mosaic by picking these glass pieces and placing them to their corresponding coordinates.[7] There may be some differences between the mosaic and the image because of the limited shapes and colours of mosaic pieces. Inal used 4-DOF Cartesian robot for marble mosaic tiling automation.[8] Inal's study produces mosaics mostly for the manufacturing systems which are withstanding the commissions according to the requests of consumers.

The aim of this paper is to carry out automation of square marble mosaic tiling by a software controlled selective compliance articulated robot arm (SCARA) with 4 DOF.

2. Robotic System for Tiling Mosaics

In this study, a SCARA robot has been used for automatic mosaics patterning and tiling. SCARA designed in Japan, is generally suited for small parts insertion task for assembly lines, such as electronic component insertion.[9] The SCARA robot is a 4-DOF robot, with three revolute joints and one prismatic joint. The two horizontal joints are shoulder and elbow and are controlled by stepper motors. It operates on X–Y plane where q_1 and q_2 represent the shoulder and elbow, respectively. The vertical movement is controlled pneumatically in the Z-direction. The fourth axis is rotation around the vertical axis. SCARA robot used for mosaic tiling

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Fig. 1. SCARA robot.

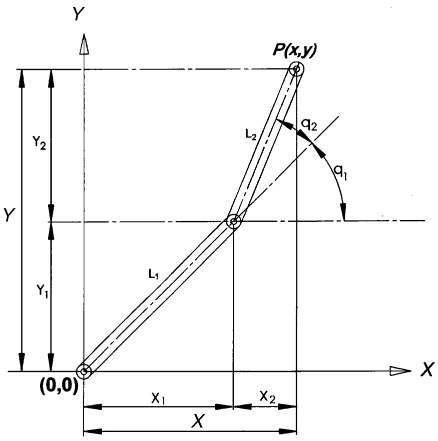


Fig. 2. SCARA robot link parameters.

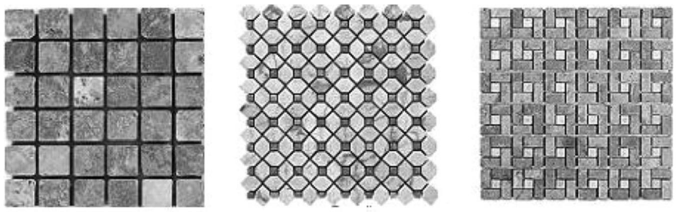
automation is shown in Fig. 1. The technical specifications of the SCARA robot are as follows:

First arm rotation angle (shoulder) $(q_1) = 200°$
Second arm rotation angle (elbow) $(q_2) = 215° \; 39' \; 7''$
Wrist rotation angle $= 450°$
First arm length $= 250$ mm
Second arm length $= 147$ mm
Z-axis course (up and down) $= 75$ mm

2.1. Kinematics analysis of the SCARA robot

Determination of the coordinates where marbles pieces will be placed and their angle of rotation is an important aspect of this study. The two-dimensional centre of gravity in top view of each piece is considered for positioning marble pieces. Placement of pieces in the correct coordinates relies on the determination of the link angles of SCARA robot arm. In application, marble pieces are positioned in X–Y plane. For this reason, there is no need to consider the up–down movement of the SCARA robot in Z-plane for kinematics analysis. Robot kinematics is described by referring to Fig. 2.

Motion control is implemented only for angles q_1 and q_2. This is an inverse kinematics problem. Inverse kinematics transforms the output position (x,y) into the joint coordinate (q_1 and q_2). The position of the arm end refers to tip of the manipulator. Coordinates of any point, X and Y can be written



(a) (b) (c)

Fig. 3. Samples of the rectangular mosaic configurations: (a) all marble dimensions are equal and (b, c) repeatedly using patterned marble parts.

as

$$X = L_1 \cos(q_1) + L_2 \cos(q_1 + q_2), \tag{1}$$

$$Y = L_1 \sin(q_1) + L_2 \sin(q_1 + q_2). \tag{2}$$

For the 2-DOF robot, the reverse solution can be derived by solving Eqs. (1) and (2) for q_1 and q_2. Angle q_2 is calculated using Eq. (4). Angle q_1 is calculated using Eq. (6).[9–12]

$$\cos q_2 = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2} \tag{3}$$

$$q_2 = \cos^{-1}\left[\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right] \tag{4}$$

$$\tan q_1 = \frac{(y(l_1 + l_2 \cos q_2) - x\, l_2 \sin q_2)}{(x(l_1 + l_2 \cos q_2) + y\, l_2 \sin q_2)} \tag{5}$$

$$q_1 = \tan^{-1}\left[\frac{y(l_1 + l_2 \cos q_2) - x\, l_2 \sin q_2}{x(l_1 + l_2 \cos q_2) + y\, l_2 \sin q_2}\right] \tag{6}$$

3. Worked Mosaic Configurations

Marble pieces are patterned to obtain the figures which have the desired size and geometry after raw marble is machined, cut and polished. These patternings are shortly called mosaic configurations. Some examples of rectangular mosaic configurations are shown in Fig. 3.[13,14] Mosaic configurations can be created specifically for use in wide areas or borders. Configurations are created by picking and placing marble pieces in one or more sizes and geometries.

3.1. Mosaic made from identical marble pieces

These mosaics are the commonly produced mosaic types in industry and they are used for coating big surfaces generally. In this study, to speed up the mosaics tiling process when using identical marble pieces, we tested utilization of a novel end effector assembly with more than one vacuum cup. This type of end effector could be used for tiling of square, rectangular and bordure patterns with a computer assisted SCARA robot. For this purpose, five vacuum cups were used on the end effector and successfully applied. The end effector with five vacuum cups is shown in Fig. 4.

In mosaic tiling automation, the control points of marbles is shown in Fig. 5. Control points are two-dimensional centre of gravity in top view of marble pieces. The five pieces of marble can be handled all at once. The control points of

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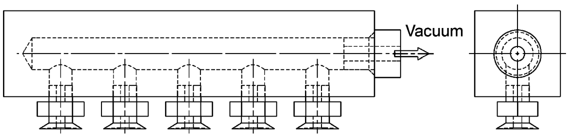


Fig. 4. The end effector with multiple vacuum cups.

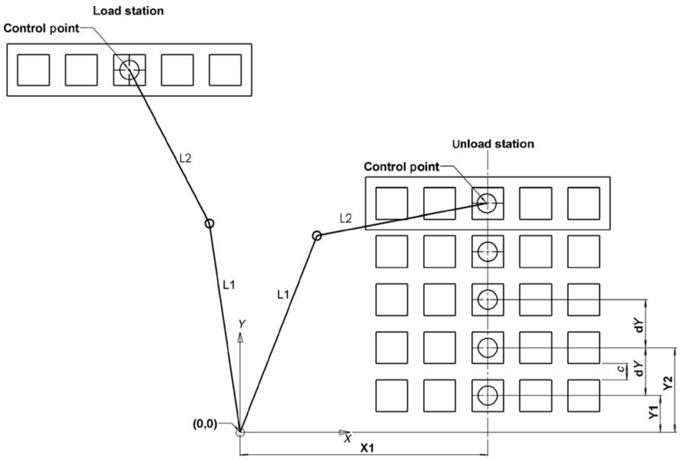


Fig. 5. The control points of marble pieces.

marble pieces and how they fit in the mosaics pattern when an effector while using five vacuum cups is shown in Fig. 5. In this placement process, the X-coordinate for each five-piece group is the same and the change in Y-coordinates depends on the vertical spacing between the marbles and the height of marbles.

$$\mathrm{d}y = a + c, \tag{7}$$

where dy is the distance between marble's lines, a the height of a marble piece and c the vertical space between marble's lines. X_1, Y_1 determines the placement of the first line and their values are determined by the user. The coordinates of subsequent placements are calculated using Eqs. (8) and (9)

$$X(i+1) = X(i), \tag{8}$$

$$Y(i+1) = Y(i) + \mathrm{d}y, \tag{9}$$

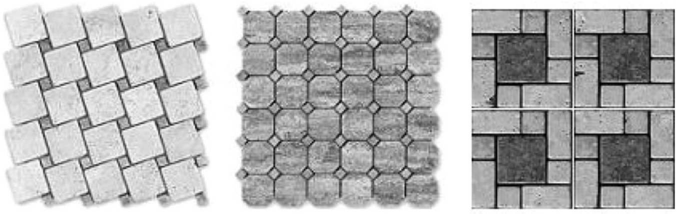
where i is the number of line, $X(i)$, $Y(i)$ the coordinates of marble control point in ith line. The increase in tiling speed is directly proportional to the number of vacuum cups. The decrease in pick and place cycles can be calculated using the Eq. (10) assuming vacuum cup number is equal to the number of marble pieces in X-axis.

$$\mathrm{d}C = N_x N_y - N_y, \tag{10}$$

where dC is the decrease in number of cycles, N_x the number of marble pieces in X-axis, N_y the number of marble pieces in Y-axis and $N_x N_y$ the number of cycles made by a vacuum cup.

3.2. Repeating patterns

Some examples of more complex mosaics configurations are shown in Fig. 6. These mosaics may consist of two or more different types of marble pieces. The difference in pieces could be in colour, shape and/or size. When these parts are put together, totally different, alternative configurations could be obtained. Once the repeating pattern is identified it can be used to obtain larger and altered configurations. An example for geometric relations between repeatedly used marble pieces are discussed in the following sections.



(a) (b) (c)

Fig. 6. Repeating patterns.

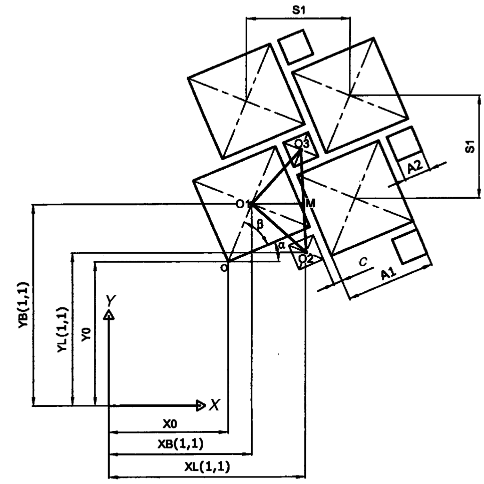


Fig. 7. Locations of two different marble pieces.

3.3. An example for geometric relations between the repeating patterns

In this section, geometric relationships for an example (Fig. 6a) will be discussed in detail. In this example (Fig. 6a), marble pieces are rotated with an angle α from the horizontal axis. The marble pieces for this configuration have two different sizes. The geometric relationships of configuration shown in Fig. 6a are described in Fig. 7. The gap distance c between the marble pieces is constant. To calculate placement coordinates, first, the distance between the centres of gravity in top view of small and large marble pieces is calculated using Eq. (11).

$$\mathrm{S1} = 2(\mathrm{O1M}), \tag{11}$$

where S1: Distance between the centres of gravity in top view of the same type of marble pieces

$$\mathrm{O1M} = \frac{\sqrt{(\mathrm{A1}/2 + c + \mathrm{A2}/2)^2 + (\mathrm{A1}/2 - \mathrm{A2}/2)^2}}{\sqrt{2}}. \tag{12}$$

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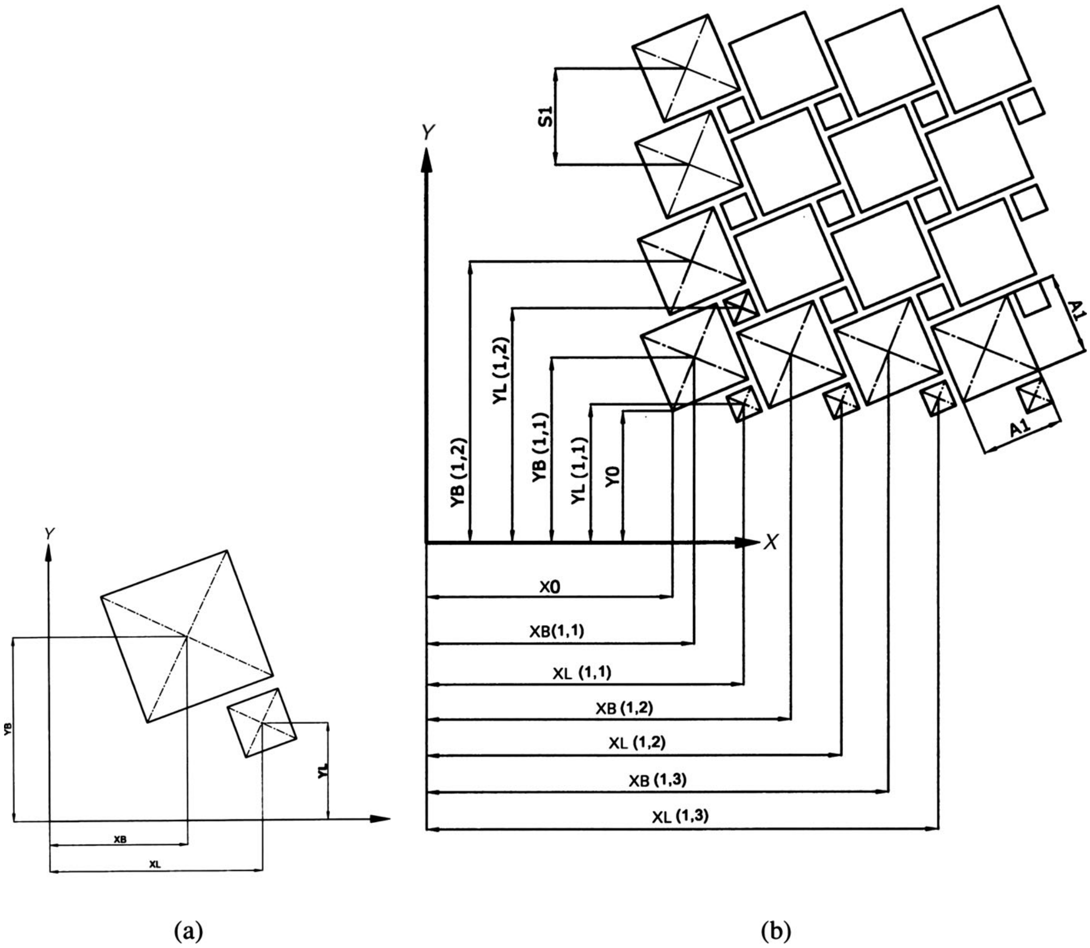

Fig. 8. Repeated marble configuration: (a) main pattern and (b) repeated pattern for a large configuration.

Centres of gravity in top view of marble pieces can be found using the following Equations. For large marble parts,

$$\mathrm{XB}(i,j) = \mathrm{X0} + \frac{\sqrt{2}}{2}\mathrm{A1}\cos(\beta+\alpha) + (j-1)\mathrm{S1}, \quad (13)$$

$$\mathrm{YB}(i,j) = \mathrm{Y0} + \frac{\sqrt{2}}{2}\mathrm{A1}\sin(\beta+\alpha) + (i-1)\mathrm{S1}, \quad (14)$$

For small marble parts,

$$\mathrm{XL}(i,j) = \mathrm{XB}(i,j) + \mathrm{S1}/2, \quad (15)$$

$$\mathrm{YL}(i,j) = \mathrm{YB}(i,j) - \mathrm{S1}/2, \quad (16)$$

where XB, YB are the x, y coordinates for the centre of gravity in top view of large marble pieces, XL, YL the x, y coordinates for the centre of gravity in top view of small marble pieces, S1, S2 the distance between same marble pieces in the configuration (mm), β the angle of corner of the large marble pieces (in degree), α the angle between horizontal axis and marble edge, X0, Y0 x and y distances between the origin and the corner point of a marble piece.

Using these equations, first, marble piece (in two different size) locations in a pattern are calculated (Fig. 8a). Then all coordinate locations of this pattern in a large configuration and the link angles of the robot arm are calculated (Fig. 8b). A computer program algorithm for this purpose has been created, shown in Fig. 9. In the algorithm, Robot link angle is calculated within a subroutine.

In the flowchart, q1L is the link1 angle of robot arm for small marble piece placement, q2L the link2 angle of robot arm for small marble piece placement, q1B the link1 angle of robot arm for large marble piece placement and q2B the link2 angle of robot arm for large marble piece placement.

4. Software for Patterning Automation of Mosaics and Experimental Procedure

In order to create mosaic patterning and configuration software named 'Software for Mosaic Tiling V2.0' (SMT V2.0) has been developed and applied successfully. This software makes use of a graphical user interface. The interface offers several alternative patterns and configurations for the users. After a desired patterning and configuration is selected, users enter various values such as marble piece size and number of pattern repetitions associated with the chosen pattern. The gap distance between marble pieces c is considered constant at 2.5 mm. Four screenshots from the software SMT V2.0 are shown in Fig. 10.

The required values for the mosaic pattern shown in Fig. 10b are marble sizes and the number of pieces in the horizontal and vertical directions. The required values for

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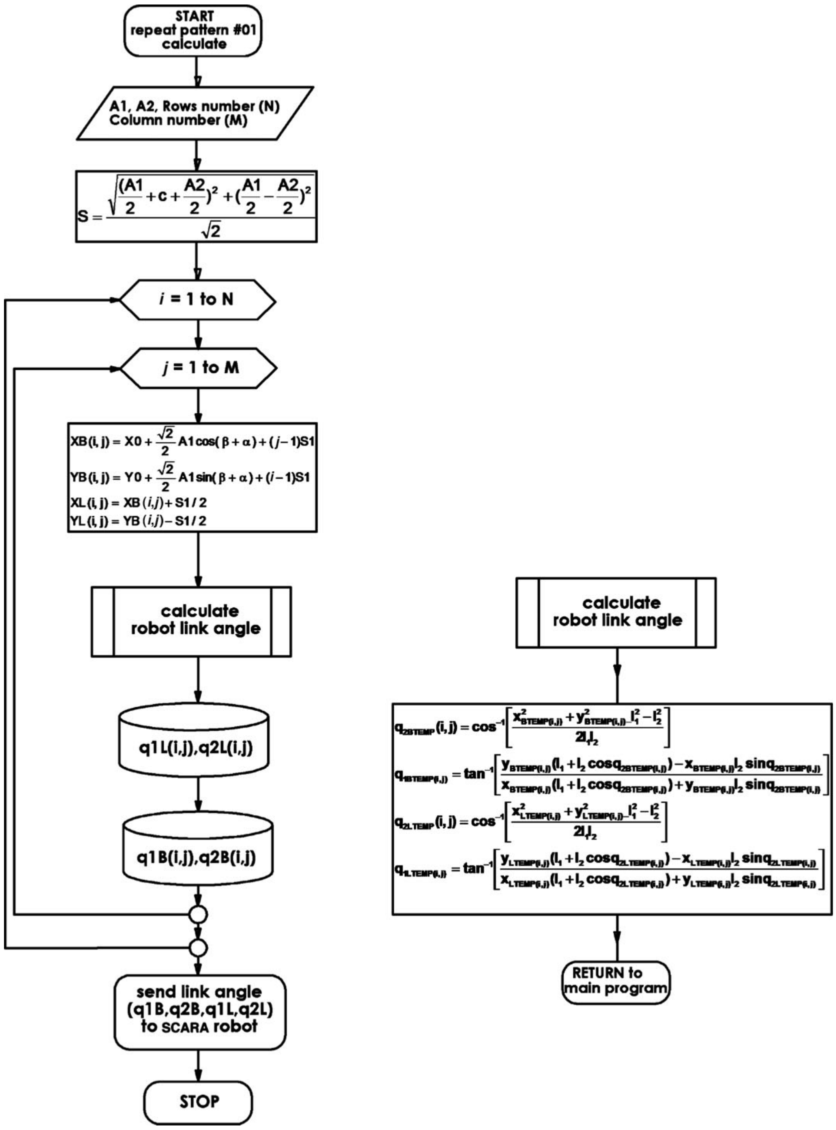

Fig. 9. Calculation of coordinate and link angle for repeatedly obtained configurations.

mosaics composed of two or three different shaped marble pieces (Fig. 10(c and d)) are the sizes for all marbles and the number of repetitions of the pattern in the vertical and horizontal directions. After data entry, the placement coordinates of the mosaic pieces and the link angles of the robot are calculated and mosaic tiling process starts.

The pick up and placement process using an end effector with multiple vacuum cups is shown in Fig. 11. Two different configurations with the same pattern have been obtained using marble pieces with two different sizes and two different colours. These configurations are shown in Fig. 12. A configuration obtained through pattern repetition with three different sized pieces is shown in Fig. 13.

5. Discussion

The current study furthers the previous marble mosaic tiling study[6] in the following areas:

- In the previous work mosaics could only be formed on a grid layout using identical pieces. The current study is able to create configurations using different types of pieces in a single mosaic (see Figs. 12 and 13).
- The current study adds a fourth axis of movement (rotation) and is able to work with a richer set of configurations (see Fig. 12).
- The current study explores gains in speed through the use of a novel end effector with multiple vacuum cups (see Fig. 11). Previous work could only place marbles into their coordinates one by one (See Fig. 1). Our tests with five vacuum cups did result in speeding up the tiling process by a factor of 5.

According to purpose of their usage marble pieces are grinded, polished and aged before they are used. To accelerate manufacturing, polishing process is applied only to one face of the marble pieces. Therefore, the other side of the marble pieces carries marks made by the cutter that are visible upon close examination. In this work, we assume that marble pieces will be placed into the tile charger with the correct sides facing up. The filling up of these tile chargers manually is another process that can benefit

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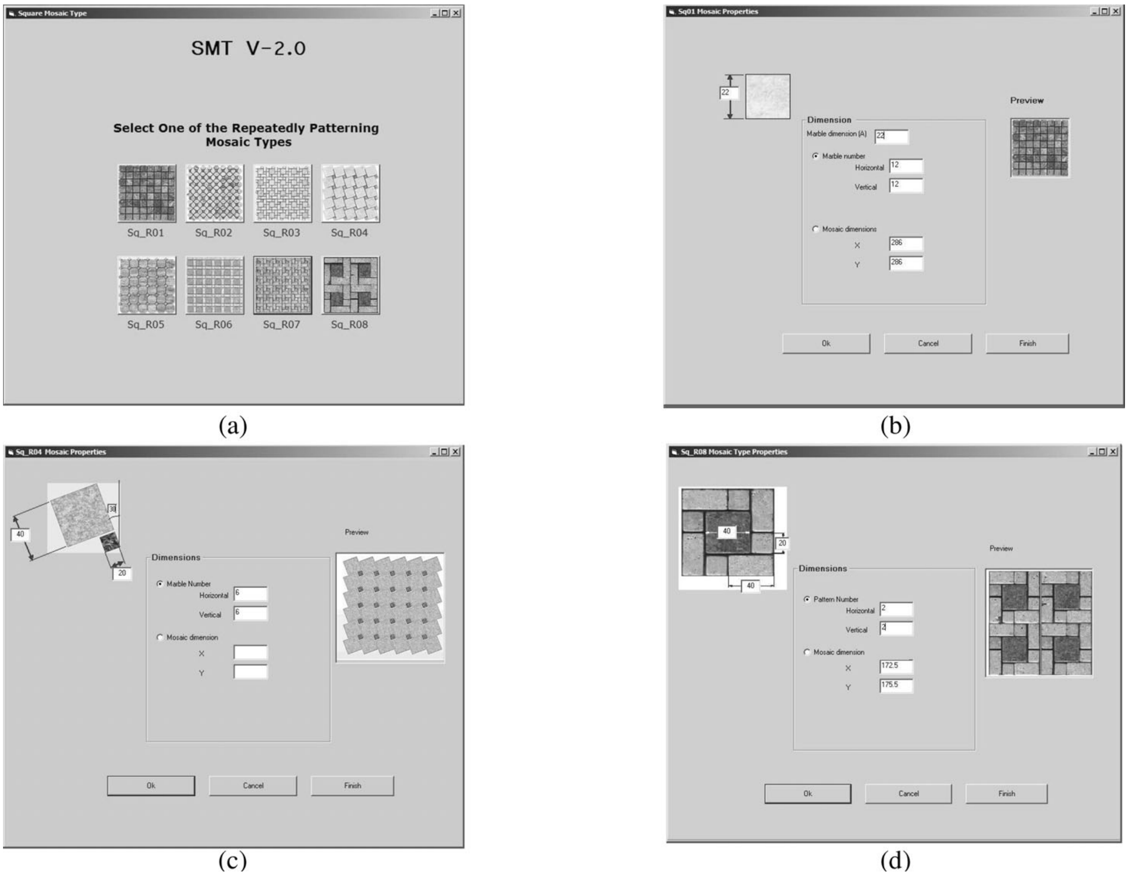

Fig. 10. Interface of the software SMT V2.0: (a) Screen shoot of mosaic types selection and (b, c, d) Screen shot of marble properties for various mosaic types.

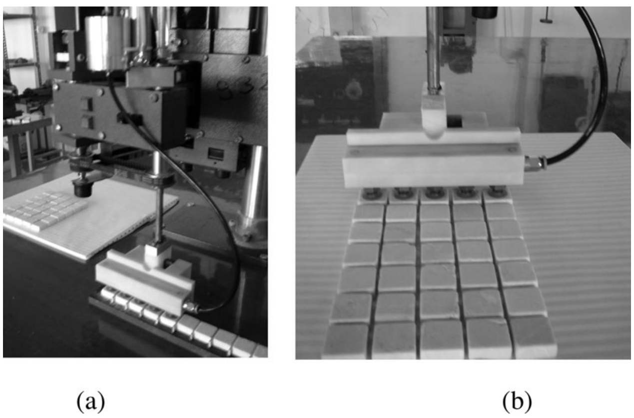

Fig. 11. Multi vacuum cups, during picking up and locating process.

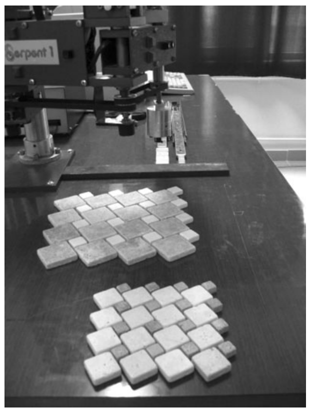

Fig. 12. Usage of marble pieces with two different sizes and two different colours.

from automation. The variable textures of natural marble and the disparity acceptable deformations of the aged marble parts make integrating an image processing system a challenging task that we intend to address in future work.

6. Conclusion

Inspite of all the technological developments in the marble industry, today mosaics are still prepared manually but this situation should be expected to change rapidly. Robotic systems are promising accelerated production, lower costs, elimination of human errors. Furthermore, automation introduces greater accuracy and flexibility in working with complex configurations. For example, moulds or drawn placement aids are not required in robotic systems. The computer assisted SCARA robot system with the SMT V2.0 software described in this paper illustrates how complex patterning that even includes rotations and multiple types of pieces can be automated. Furthermore, we have shown

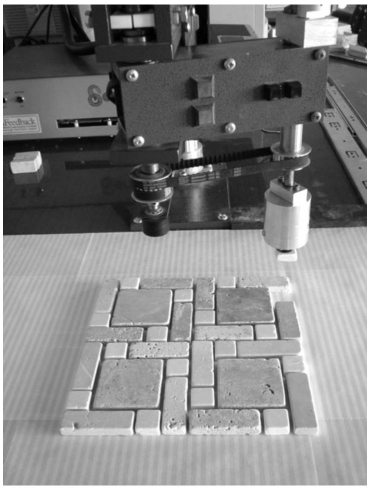

Fig. 13. Three different sized pieces.

how a novel end effector that simply uses multiple vacuum cups dramatically improves production speed in basic configurations.

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