Generating an Anamorphic Image on a Curved Surface Utilizing Robotic Fabrication Process

Marko Jovanovic¹, Vesna Stojakovic², Bojan Tepavcevic³, Dejan Mitov⁴, Ivana Bajsanski⁵
¹,²,³,⁴,⁵Faculty of Technical Sciences, University of Novi Sad
¹,²,³,⁴,⁵{markojovanovic|vesna100|tepavcevicb|dejan_mitov|ivana_b}@uns.ac.rs

The integration of industrial robots in the creative art industry has increased in recent years. Implementing both brick stacking robotic fabrication, following a curved wall, and generating an image viewed from a single point, by rotating the bricks around their centres, has yet to be studied. The goal of this research is to develop a functional, parametric working model and a workflow that ensure easy manipulation and control of the desired outcome via parameters. This paper shows a workflow for the automatic generation of anamorphic structures on a curved wall by utilizing modular brick-like elements. As a result, a code for the robot controller and the position of the structure during fabrication are provided.

Keywords: anamorphosis, brick lying, robotic fabrication, generative design

INTRODUCTION
In the last decade, the implementation of industrial robots as fabrication tools has presented itself as being productive, effective and manageable (Keating 2013; Braumann 2013). Therefore, it is important to consider fabrication type in the early design stages. This is due to the multipurpose nature of the industrial robot, which is the primary fabrication tool used for a specific purpose. Robotic arms function by moving its parts via joints, and the robots are defined as having specific degrees of freedom, usually 3 to 6. By utilizing a gripping or suction tool, a robot can utilize a specific modular element, such as a brick-like module (Yu Nam et al. 2009; Bärtschi et al. 2010; Bonwetsch et al. 2007), and follow a computational model to assemble a structure resembling the original (Rakovic et al. 2014; Vomhof et al. 2014).

The integration of industrial robots in the creative art industry has increased in recent years. Design works generated by utilizing a robotic arm have become part of performance art [1]. As a tool for fabricating artwork, industrial robots have been used for generating paintings with an element of randomness (Aguilar & Lipson 2008; Alkhodairy & Patel 2014). Regarding studies examining the utilization of anamorphosis, with shapes on freeform surfaces, recent studies have been published on projecting vector-based shapes (Di Paola et al 2015). In addition, research regarding the generation of anamorphic sculptures have discussed the question of elevating ideas from a 2D image to a 3D sculpture (Manal 2015). Furthermore, in 2006, Gramazio and Kohler utilized a raster image as a guideline for brick rotation following a planar surface in the Gantenbein Vineyard Façade in Switzerland.

However, implementing both brick-stacking robotic fabrication, following a curved wall, and generating an image viewed from a single point, by ro-
tating the bricks around their centres, has yet to be studied. The goal of this research is to develop a functional, parametric working model and a workflow that ensure easy manipulation and control of the desired outcome via parameters. As a result, a code for the robot controller and the position of the structure during fabrication are provided.

**METHODOLOGY**

This research’s starting point is the early implementation of robotic fabrication and its insight into the design process. Here, it is the robotic arm that is utilized to place brick-like elements in the form of a curved surface. Additionally the bricks are rotated around their central axis in order to form an anamorphic raster image that can be input and this image is user defined. Hence the end result has to comply with the necessities and requirements this fabrication type dictates, which is a code for the robot controller - a set of instructions that a robot follows and executes.

The main parameters used for defining the anamorphic sculpture are: the input surface, to which the brick-like elements are stacked, the size of the bricks, the minimal distance between the bricks, their maximum and minimal rotations, the height and position of the viewer’s eye point, the position, orientation and height of the desired image plane (the plane where the image is formed) and the grayscale image used as a guide. In this research, a custom-scripted component for the Grasshopper programming language is used to generate the missing code for the robot’s RAPID programming language. Once the parameters are set, a single text file is generated and prepared to be implemented into a code for the robot controller. The workflow is explained in the following section.
ANAMORPHIC IMAGE ON A CURVED BRICK STRUCTURE

In order to fabricate the desired anamorphic image as a curved brick-like structure, the workflow is divided into three phases. The first phase explains the initial brick setup following a curved surface and the eye position for the generation of the anamorphic image. Based on the eye position, the second phase rotates the bricks around their central axis in order to procure adequate anamorphic image generation, where the bricks are viewed as pixels. Lastly, the structure is then used to extract the necessary data and transcribe it into a code for the industrial arm to follow. All the phases are explained in greater detail in the following subsections.

The Initial Brick Setup

The first phase is the surface reference and parameters setup for the desired outcome. This phase starts by generating and referencing a single surface in the Grasshopper programming environment. Here, an extruded curved shaped is chosen. Once the parameters for the brick-like elements are set, including the length, width and height, the surface is trimmed, if necessary, to address the brick-fitting tessellation accordingly (Figure 1a).

The lower horizontal edges of the tessellated elements are taken and edge centre points are chosen for the position of the brick-like elements to come (Figure 1b). They are defined as $C_1, C_2... C_n$, where $n$ is the total number of bricks in the tessellated surface. Afterwards, the eye-point position, defined as $E_p$, has to be set, meaning the place where the viewer needs to be in order to see the anamorphic image as a planar image. Next, the image plane, defined as $\alpha$, needs to be set, meaning the position, the orientation in reference to the eye point and the size. The setup is visible in Figure 2.

Finally, a grayscale image is chosen and input as a guideline for the brick rotation, which is explained in the following subsection.

Brick Rotation for the Anamorphic Setup

The brick rotation is carried out in a twofold process. The first rotation is done in accordance with the eye point. The brick-like element centre points, $C_1, C_2... C_n$, are evaluated according to the surface they follow and normal vectors, defined as $n_n$, are extracted as a result (Figure 3a). By connecting these points to the eye-point position, $E_p$, another set of vectors is generated, $e_n$ (Figure 3b). The angles between these two sets of vectors are then compared to the maximum brick rotation angles, set at around 45 degrees. This corresponds to the borderline rota-

Figure 3
a) The first set of vector, normal surface vectors; b) The second set of vectors, connecting the brick positions to the eye point.
tion angle, while keeping in mind the stability of the entire structure, as one brick lays on top of the two below. The values are then remapped as to atone for the corrections. This step is necessary since this is a central and not an orthogonal projection and mapping process.

The second rotation is carried out in accordance with the image chosen for the anamorphosis. The algorithm references the gray-scale image as a guideline for the brick rotation in reference to the eye point. The algorithm starts by utilizing the $e_n$ set of vectors to generate the lines connecting $C_1$, $C_2$, ..., $C_n$ and $E_p$, respectively. These lines intersect the image plane and produce a set of points, defined as $I_1$, $I_2$, ..., $I_n$, as a result. The points have coordinates in the Cartesian coordinate system. These coordinates cannot be utilized as a reference for the two-dimensional gray-scale image in this form. Therefore, the image plane is reparametrized, meaning its domain is set as a function of percentage in reference to the two main surface directions, U and V, ranging from 0 to 1 and not according to its actual size. The intersecting points are evaluated according to the image plane, and a set of UV coordinate points is generated. By changing the size of the image plane, the resulting points are not impacted domain-wise. The main reason for generating a UV set of coordinates is to adequately align them to the two-dimensional planar gray-scale image, where the domain is also set from 0 to 1. The aligned points on the gray-scale image reference the colour values which are then remapped to the desired minimum and maximum rotation values for the brick-like elements. These values depend on the desired end result, the eye-point position and the initial surface chosen as a guideline and they are empirically determined. Finally, those values are used on the previously rotated bricks to generate the desired image. After the bricks are rotated into place and the anamorphic image visibility is checked in the 3D environment, it is necessary to prepare the code for the robot controller.

**Generating the Code for the Robot Controller**

The code for the robot controller consists of two parts: the 'target' of the bricks in the final anamorphic structure and the stacking process. The first part of the code, the 'target', refers to the position and orientation of the bricks in the anamorphic structure. They are extracted from the Grasshopper environment by using a custom script that references the bricks and generates a code that the robot can interpret. The stacking process is written in Robot Studio, a software for the offline robotic programming and robotic arm control. The stacking consists of two functions or processes: picking up the brick from a desired position and then placing it in the previously defined targets defined previously. The final phase implies taking the generated code for the robot controller, derived from the input parameters previously described, and using it in RobotStudio software for controlling the industrial robot. Robot Studio then utilizes the centre points and orientation of the bricks from the 'target' code. The robot picks up the brick from a single position in its vicinity and places it in the respective points in an iterative manner. In tribute to Alvar Aalto, who used bricks and masonry as material, along with curved lines, for the purposes of generating an anamorphic sculpture, his portrait is chosen.

**RESULTS AND DISCUSSION**

First, a desired input surface needs to be generated and an image for the anamorphosis chosen. In order to generate an anamorphic structure that is visible from a single viewpoint, its position has to first correspond to the size and position of the surface guideline. Given the narrow field of clear vision in the human visual cone, around 30 degrees, the eye point has to be positioned so that the visual cone completely encloses the input surface. Otherwise, the entirety of the structure is not visible and, hence, the anamorphosis of the image is lost. In addition, the image plane has to be enclosed by the cone as well, or the image will spread beyond the borders of the input surface.
Once these parameters are set, attention must turn to the choice of brick-like elements. Utilizing a brick with edges of three different lengths, in this case 70mm length, 30mm width and 19mm height, proves to be inadequate, as can be seen in Figure 4.

The bricks cannot rotate fully to atone for the eye-point position correction angle due to the loss of stability and the support under each brick: hence, the bricks cannot be rotated to adequately suit the image. In addition, the bricks in the front can obscure the bricks in the back and produce inaccurate results. The rest of the wall can occlude bricks depending on the wall's curvature. Therefore, the visibility of the bricks varies, and the image is simulated differently. However, if the change of the curvature is subtle, these variations will not influence the image's readability.

In order to mitigate this, we used bricks with edges of only two different lengths (a square brick), which avoids the rotation issues and, thus, the stability issues as well, without impacting the appearance of the anamorphic image. The number of bricks is also an important factor. A smaller number of bricks gives anamorphic structures lower resolution and, hence, smaller resemblance to the desired image and vice versa.

Since the bricks form a non-smooth structure, the overhanging parts of the bricks cast a shadow on the rest of the structure, which can mitigate the final image's appearance. In order to avoid these issues, two nonadjacent, vertical sides of the bricks are coloured black, while the rest is left white. With an increased number of bricks and the difference in colour, the end result (Figure 5) seems much more realistic than the one in Figure 4b. Even though the structure is anamorphic, it offers a different experi-
ence while moving from one side to the other, not honouring the viewpoint (Figure 6).

The limitation of using this workflow are exhibited in the distortion and appearance change due to the use of elongated brick shapes, the lack of supporting area and the instability given the large angle rotations. Also, a lower number of bricks will produce inadequate results in terms of similarity, between the anamorphic structure and the desired image. Finally, the surface design and the position of the eye point can cause the viewing directions to become tangent to the surface generating a smeared appearance of the image, as seen in the Figure 6c.

Regarding the robotic fabrication application aspect of this research, the size of the robot and the working area it can service, limit the size of the structure; hence, they must be taken into account at the start of the workflow.

CONCLUSION

In this paper, a workflow for automatic generation of anamorphic structures is shown: a curved wall generated by modular brick-like elements. As opposed to the previous approaches when generating anamorphic structures, the fabrication process is automated by utilizing an industrial robot. Furthermore, the surface, the image is generated on, is curved. The main characteristic of this structure, is that the end result has a different appearance in reference to the viewing. The result can be applied in fabricating various wall panels, where the expected result is a different appearance depending on the viewing angle. The control can be achieved by changing the parameters, (brick size, viewpoint and image plane), alongside a desired raster image, generating a computational working model.

This model can be used for further refinement, utilizing the aforementioned parameters, with an instant result in viewport. Furthermore, the model is used as a base for generating a code for the robotic fabrication process. By manipulating a set of parameters in the above-mentioned workflow, the design process is much more fluent and straightforward, with a clear path from the design phase to the fabrication phase. Limitations of this workflow are the restrictions in brick shape, robot working area and the influence of the wall curvature on the visibility of the bricks.

Future work will focus on fabricating the designated structure and comparing the results in real-life conditions with the ones generated here. Also, the workflow can use an upgrade in the area of utilizing elongated brick shapes, with the similar results as seen here.
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