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RESEARCH

Cylindrical Mirror Anamorphosis and Urban-Architectural Ambience

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Abstract Cylindrical mirror surfaces fall into the group of reflecting surfaces that give a distorted image of an object. However, if the object is designed according to the laws of optical geometry, in a way that its mirror image is conceived in advance, then this is anamorphosis. The objective of the present study is to emphasise the potential of cylindrical mirror anamorphosis, in the context of change in the urban-architectural ambience. In this respect it is necessary to obtain a constructive, geometrically correct solution of the 3D model of cylindrical-mirror anamorphosis, whereby the mirror surface is a vertical rotating cylinder. This topic is the primary focus of the present research. In addition, the conditions for change in the anamorphic form were analysed, and its possible functions in architecture were identified. Various examples of existing buildings with cylindrical mirror elements, in respect of which it was possible to construct and apply these types of anamorphoses, were used. The method of constructive perspective and the laws of optical geometry were applied. Analyses were made on the basis of experiments and using AutoCAD 3D methods to analyse the mirror anamorphosis of a cube and octahedron.

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Introduction

Anamorphosis is a type of *projection form,* the meaning of which is understood only when observed from the viewpoint in respect to which it has been constructed, and in a wider sense, it is a form to which specific projections give more meaning. Cylindrical mirror (catoptric) anamorphoses are a subcategory of mirror anamorphoses, the identification of which requires a cylindrical mirror.

The objective of the present study is to identify the potential of mirror anamorphosis in the context of change in the urban-architectural ambience. The potentials for the application of its geometry are varied and numerous. A cylindrical mirror surface, as an existing architectural element (Fig. 1), can be the basis for multiple applications of the previously mentioned anamorphosis. Solutions may also be varied, but the success of the design of the anamorphosis depends, amongst other things, on its function.

Given that the hitherto published constructions of cylindrical mirror anamorphosis[1] relate to plane anamorphosis, the main objective of the present study is to obtain a constructive, geometrically correct solution for the 3D model of cylindrical mirror anamorphosis, whereby the mirror surface is a vertical rotating cylinder.

Jean-François Nicéron (1663: tab. 44, 45) was the first to describe, by way of geometrical methods, cylindrical mirror plane anamorphosis, which was popular during the 17th century. Later on, many authors published different constructive explanations of this phenomenon (Goddijn 1992; Füsslin and Hentze 1999; Leeman 1976), but due to the fact they were only approximate, they cannot be applied to 3D cylindrical mirror anamorphosis. Construction by means of a nephroid grid, with its flaw being a viewpoint that is positioned at infinity, is also not adequate, as section two of this paper demonstrates, when a 3D model is in question. The constructive solution of the 3D models of Jonty Hurwitz, the British artist, have not been published anywhere.[2] In this context, the aim of the present paper was to check all the constructions analysed in our study, in order to determine cube and octahedron mirror anamorphosis using an experimental method. In addition to the constructive perspective method, optical geometry laws were also applied.

[1] Beside cylindrical mirror anamorphosis in plane (Baltrušaitis 2004; Hamngren 1981; Hickin 1992; Hunt et al. 2000; Heeke 2003) “a general procedure for the construction of mirror anamorphoses” has also been published (De Comité 2010).

[2] In the interview Jonty Hurwitz explains that he used software to create 3D anamorphosis http://www.youtube.com/watch?v=KcTp5Q3-8Ng (accessed 15 August 2013). De Comité (2011: 33) used a chain of software and programming languages to make the spherical mirror anamorphosis and Soddu (2010: 39) designed the software for cylindrical mirror plane anamorphosis.

Fig. 1 Glass-clad façade with mirror effect, office building of the Imel Group, Bulevar dr Zorana Djindjića, Belgrade, Serbia. Photo: author

Fig. 2 Catacaustic of rays reflected from a vertical rotating cylinder—nephroid. Photo: author

Geometry of Nephroids and the Catacaustics Grid

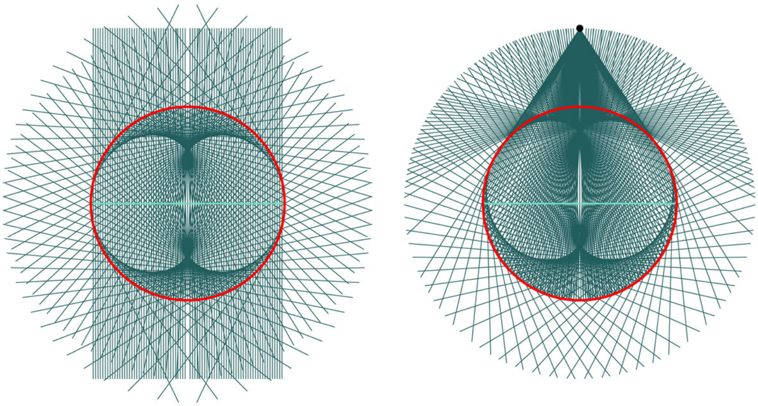
The caustic is a curve, which is an envelope of light rays obtained by their reflection or refraction on a curved surface or object. When this curve is an envelope of light rays from a finite or infinite *radiant point*,[3] which is obtained by their reflection from an established mirror surface, it is then known as a catacaustic (Fig. 2).

Only two types of base circle catacaustic (Fig. 3) of a cylindrical mirror can be applied to cylindrical mirror anamorphosis, when the mirror surface of a vertical rotating cylinder is convex:

(a) the position of the radiant point is at infinity (parallel rays) and the catacaustic curve is a nephroid;
(b) the position of the radiant point outside the circle is finite, and the catacaustic curve is an irregular nephroid.

In this situation, the reflection of rays is from the convex side of the curve, so it can be concluded that for a convex mirror, these curves are evolutes of reflected

[3] The point of illumination for a caustic. Wolfram Mathworld, http://mathworld.wolfram.com/Catacaustic.html (accessed 15 August 2013).



(a) **(b)**

Fig. 3 Catacaustic of a circle (section curves of a cylindrical i.e., spherical mirror). Catacaustic circle—the section curve of cylindrical i.e., spherical mirror exists in four shapes; two of which are shown. Drawing: author

curves. If, onto the arch of the circle (radius *r*) (base curve of a cylindrical mirror) a pencil of parallel rays falls, the envelope of reflected rays is a nephroid. For a concave mirror, the nephroid envelope is also a nephroid which, relative to the initial nephroid, is orthogonally oriented and inscribed in the base circle (Fig. 4a). A nephroid is an epicycloid[4] with two vertices. In respect to kinetic geometry, it is the trajectory of the circle point, the radius of which is *r*, which rolls around the fixed circle of a twofold larger radius (2*r*).

Using a nephroid grid, an anamorphosis of the base square of a cube was constructed, which occupied the same plane as its mirror image (Fig. 4b). As a consequence of parallel rays passing through an infinitely distant viewpoint, anamorphosis of the top square of the cube was constructed, according to the same principle, which also lies in the plane of its mirror image (Fig. 5). By connecting the anamorphoses of these two squares by the verticals, a cube anamorphosis could be obtained. However, a mirror image does not make an impression of a cube that is on the horizontal plane. An experimental effort to obtain cube anamorphosis by means of a nephroid curve grid showed the absence of the effect of perspective, by which the impression will have been given that the cube was on the horizontal plane.

Cylindrical Mirror Anamorphosis Obtained Using Methods of Optical Geometry

On the basis of the analyses conducted, the aim was to obtain cube anamorphosis, using the method of optical geometry, that is, by constructing its characteristic

[4] An epicycloid, the trajectory of the circle point, which without slipping rolls around the second circle, is the catacaustic curve that emanates as an envelope of rays reflected off the circle.

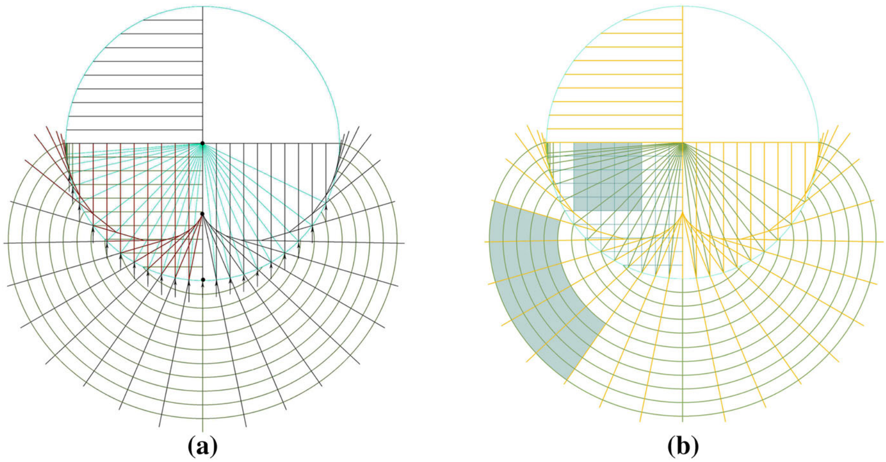


Fig. 4 **a** Construction of a catacaustic grid when the viewpoint is infinitely distant. Drawing: author. **b** Square anamorphosis by means of catacaustic grid. The first orthogonal projection: author

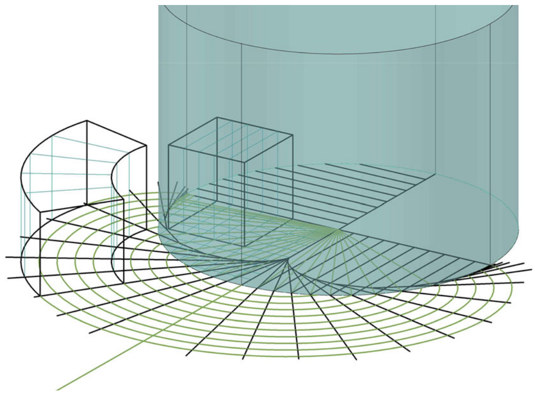


Fig. 5 Cube anamorphosis by means of a nephroid grid. Axonometric presentation: author

points. The idea was to construct every point in space by means of the three[5] basic principles of optical geometry, given that, by the construction of the anamorphosis of the cube's horizontal square, by means of the nephroid curves grid, no satisfactory solutions had been obtained.

Procedure for Constructing Point Anamorphosis

An imaginary-virtual image (an image in a mirror) is given as point A (Fig. 6). If, using the *law of the reflection,* the image in the mirror is obtained from the

[5] Geometrical optics is based on the four fundamental laws: *the law of rectilinear propagation of light; the law of the independence of light propagation; the law of light reflection; and the law of light refraction*, of which the former three relate to mirrors and are included in the experiment.

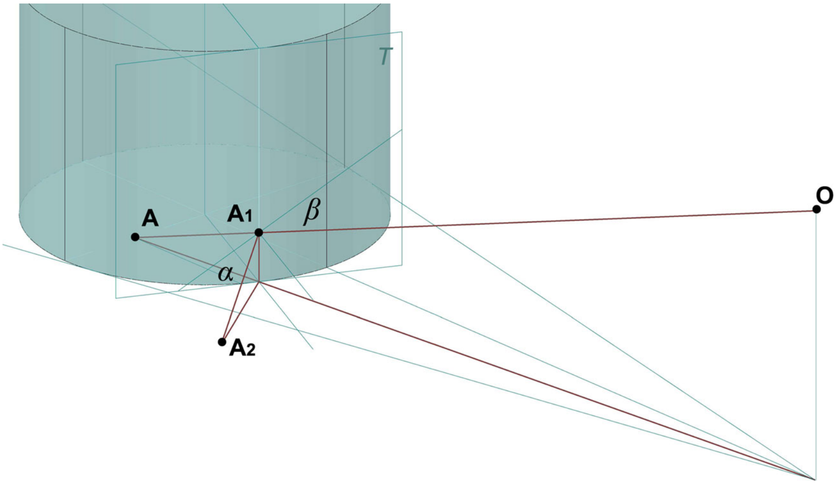


Fig. 6 Anamorphosis of point A when the mirror surface is a vertical rotating cylinder. Axonometric presentation: author

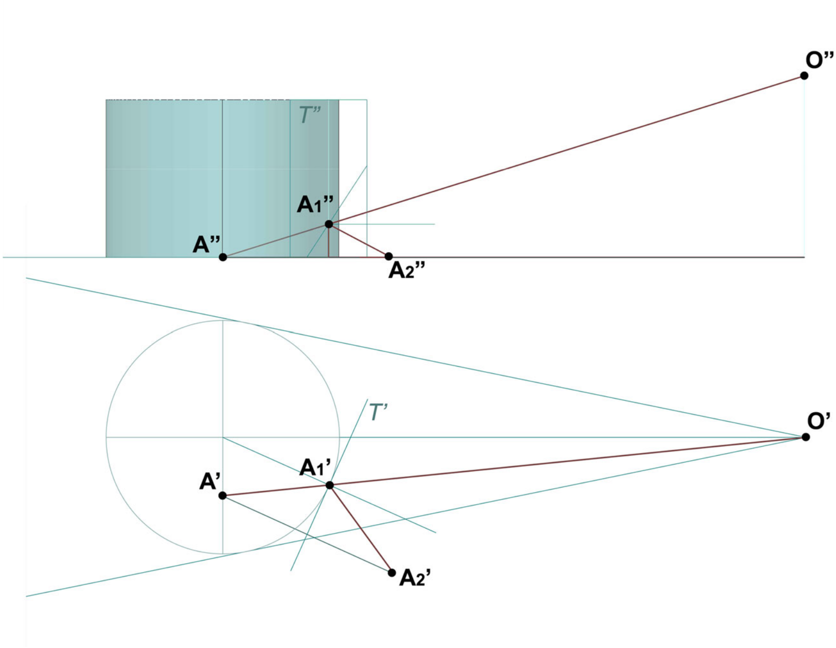


Fig. 7 Anamorphosis of point A in relation to the mirror surface of a vertical rotating cylinder. The first and the second orthogonal projection: author

intersection of virtual rays, which are geometrical extensions of the reflected rays, then the anamorphosis of point A (i.e., point A2), can be solved in a simple manner. Point A2 is equally distant from the tangent plane, as is its mirror image, point A, which can be clearly seen in the first orthogonal projection (Fig. 7). In order to

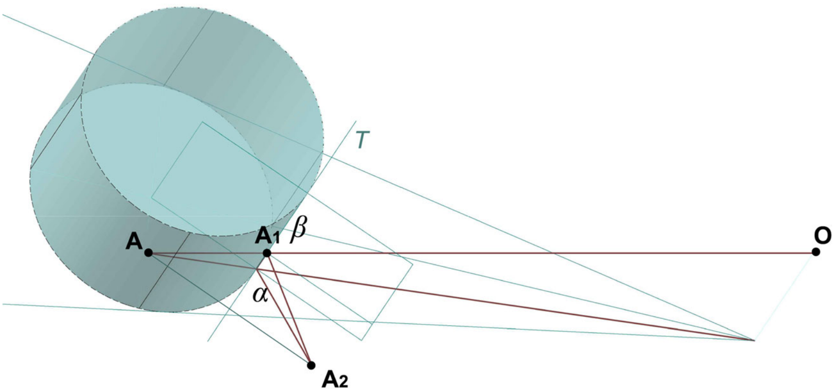


Fig. 8 Anamorphosis of point A in relation to the mirror surface of a vertical rotating cylinder, the true size of the plane of reflection. Oblique projection: author

obtain point A2, it is necessary that the mirror image of the required point is situated on the visual ray from the viewpoint O. The angle of incidence α, which covers the mentioned visual ray with the tangent plane (T) of the mirror, must be equal to the angle of reflection—angle β, so that the consequence of such a construction is a point in space—point A2. This can be seen best in the orthogonal projection of the *plane of reflection*[6] (Fig. 8), in which the visual ray reflects from the mirror. The point of intersection of the visual ray through the cylindrical surface of the mirror, point A1, is the point of reflection of the visual ray from point A2, and is also the cylindrical perspective of point A.

Procedure for Constructing an Anamorphosis of a Cube by Means of its Horizontal Sections

For the purpose of checking the anamorphoses of vertical directions, i.e., directions parallel to the axis of a cylindrical mirror, the determination of the anamorphoses of the points of a cube, which remain in the same horizontal plane, as do their mirror images, required that the horizontal squares of the cube were solved first (Figs. 9, 10).

In anamorphosis, they remain in the parallel planes, and the appearance of the anamorphoses of both the horizontal squares and of all the sectioned horizontal squares of the cube coincide (Fig. 11).

Reflection points on a cylindrical mirror, from the aspect of a perspective method, can be understood and constructed as intersections of view rays of the virtual object (cube) through the cylindrical image plane. In this respect, the image obtained is a cylindrical perspective of the cube (Fig. 12).

Approximation of the cube anamorphosis depends on the number of points chosen on the virtual cube (Fig. 13). A photograph of the 3D model realised (Fig. 14), which was obtained on the basis of an AutoCAD model, shows that the approximation was correct.

[6] It is determined by the view ray A, A1, O and A2.

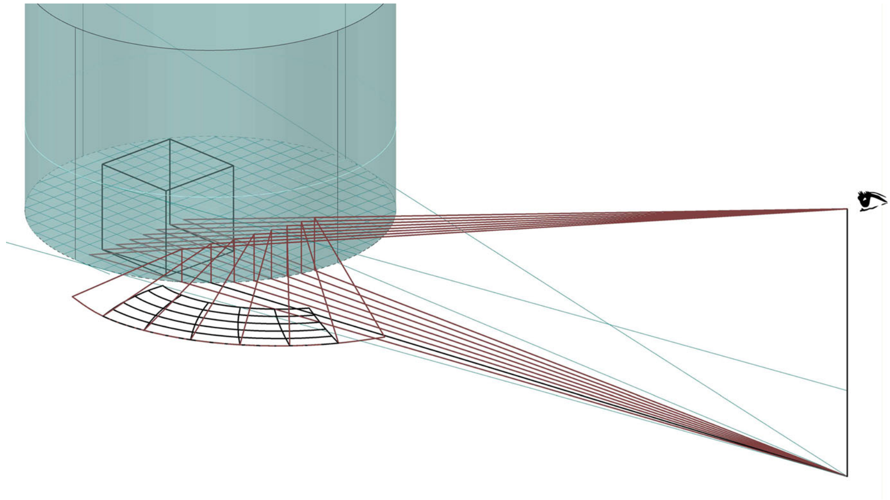


Fig. 9 Anamorphosis of the base square of a cube in respect to the mirror surface of a vertical rotating cylinder, with view rays, by which the anamorphosis of the cube edge was obtained. Axonometric presentation: author

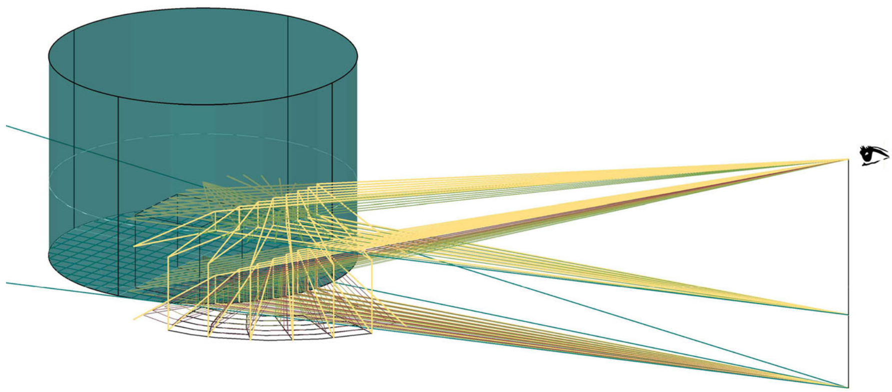


Fig. 10 View rays by which the grid points of the base square of the anamorphosis of the cube are defined, in respect to the mirror surface of a vertical rotating cylinder. Axonometric presentation: author

It was shown that the anamorphosis of a base square obtained in this way, diverges from the construction of a nephroid grid with parallel rays (Fig. 15). Anamorphoses of the directions parallel to the principal optical axis of the mirror[7] are not straight lines, as is the case in a nephroid—they coincide only for the directions that lie in the axial plane of the cylindrical mirror.

[7] The principal optical axis is a line that passes through *mirror vertex* T (the most convex, or most concave, point) and the centre of the curvature of the base circle S (Fig. 15).

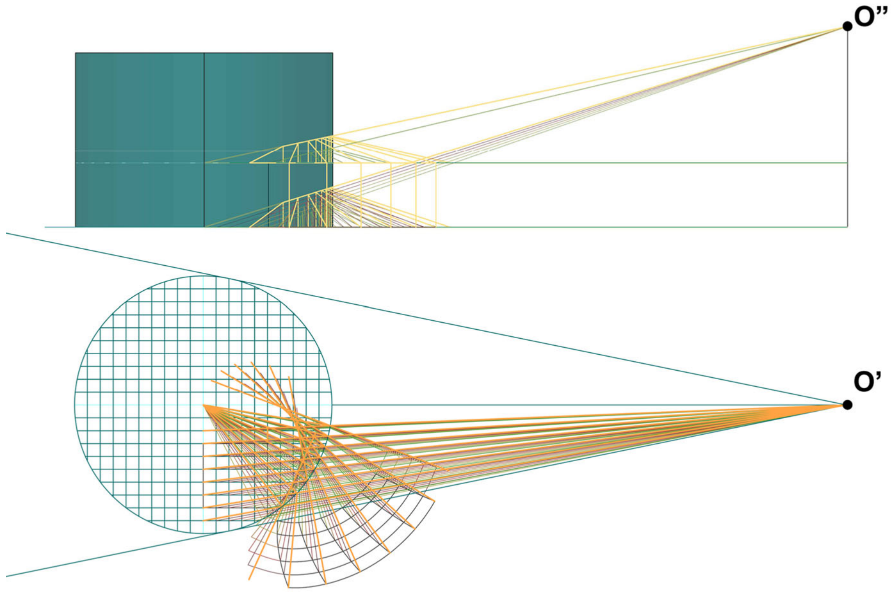


Fig. 11 View rays, by which grid points of the base square of the cube anamorphosis are defined in respect to the mirror surface of a vertical rotating cylinder. The first and the second orthogonal projection: author

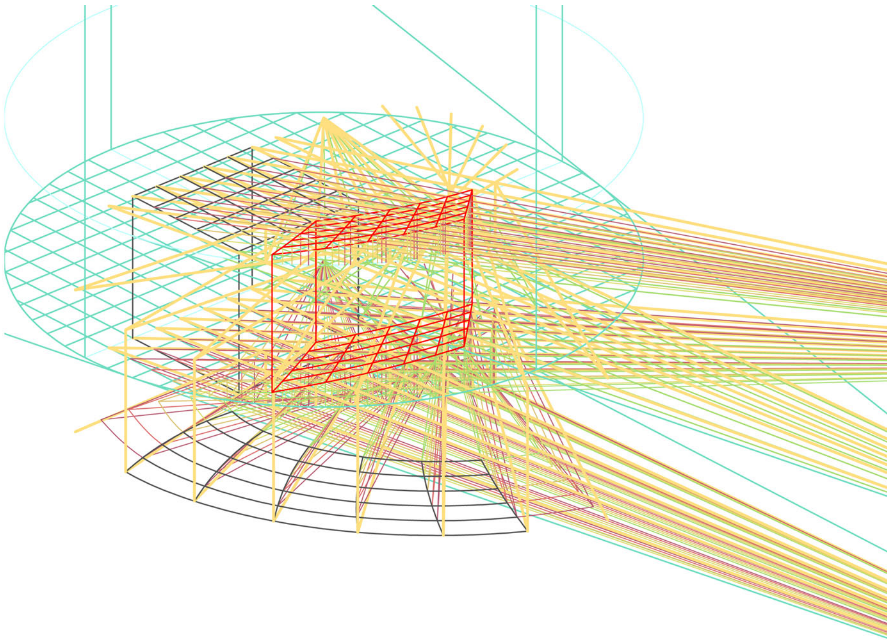


Fig. 12 Cylindrical perspective of a cube. Axonometric presentation: author

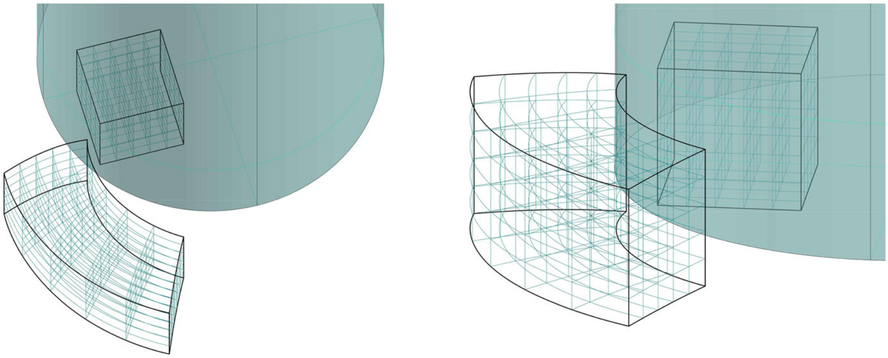


Fig. 13 Anamorphosis of a cube in relation to the mirror surface of a vertical rotating cylinder, AutoCAD 3D model. Axonometric presentations: author

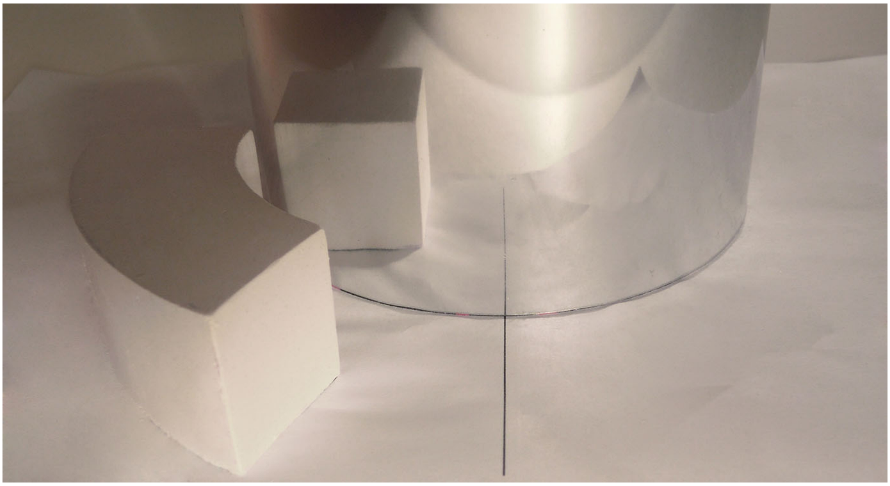


Fig. 14 The realised 3D model of a cube anamorphosis, in respect to the mirror surface of a vertical rotating cylinder. Photo: author

Construction of an Octahedron Anamorphosis Using Characteristic Sections

In order to confirm these constructions, one additional experiment was undertaken (Fig. 16). The octahedron ABCDEF was constructed, and inscribed into a cube, which was mounted in the same position as in the previous experiment.

For the previous construction, the cube edge was divided optimally into five parts, in order to obtain a 3D grid, for obtaining the octahedron anamorphosis. Accordingly, for this construction it was necessary to add another three mutually perpendicular planes, which were orthogonal to the faces of the cube, with a common point in its centre, the sections of which were the three axes of the octahedron (given that without these planes, the construction of the octahedron vertices would have been approximate).

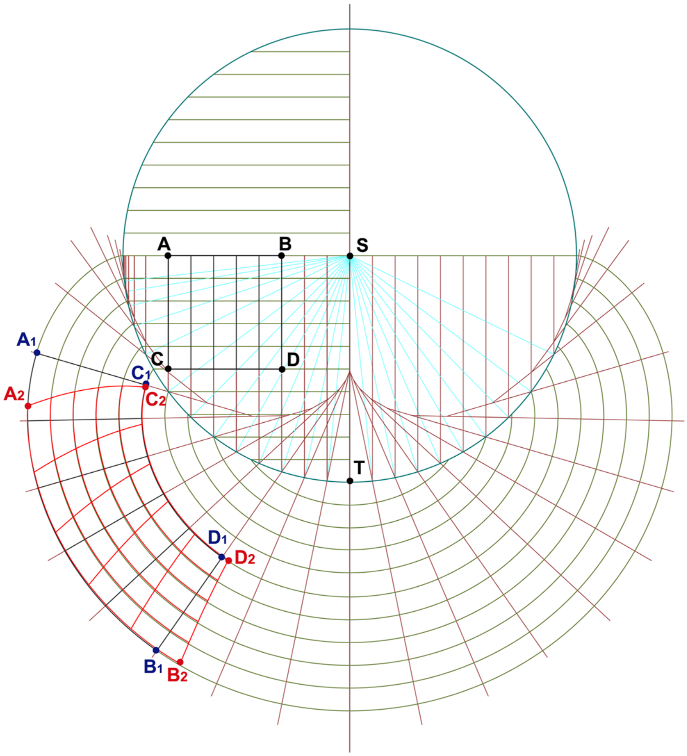


Fig. 15 Comparative analysis of a cylindrical anamorphosis of cube base squares, obtained by constructing a nephroid grid (A1, B1, C1, D1) and by constructing the points according to the principle of optical geometry (A2, B2, C2, D2). Orthogonal projection: author

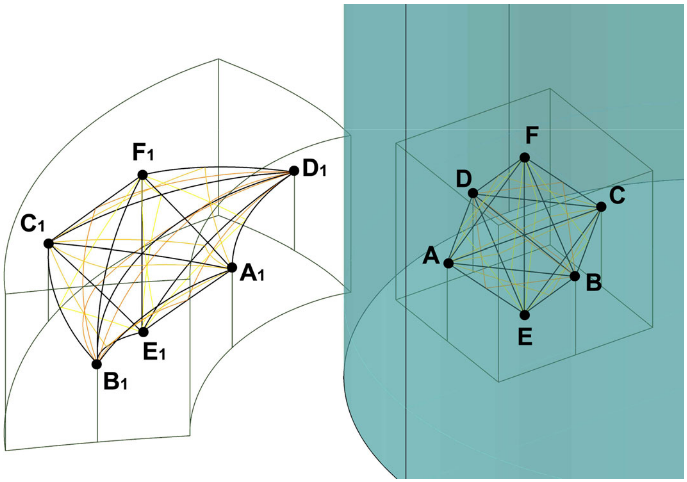


Fig. 16 Anamorphosis of an octahedron inscribed into a cube. Axonometric presentation: author

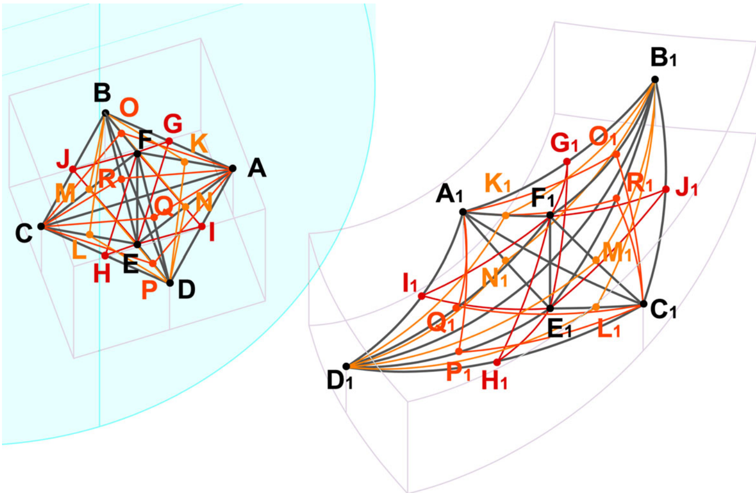


Fig. 17 Characteristic points by means of which the octahedron sections were determined. Axonometric presentation: author

An octahedron was constructed by means of characteristic sections (Fig. 17). In addition to the orthogonal trihedron with a common point in the centre of the octahedron, by means of which the anamorphoses of the edges and vertices of octahedron A1B1C1D1E1F1 were constructed, rhombs EFGH, EFIJ, BDKL, BDMN, ACOP, ACQR were also used, the edges of which were the heights of the equilateral triangles of the octahedron faces. On the basis of these nine planes and sections, the octahedron's anamorphosis was determined.

Change of Architectural-Urban Ambience by Means of Cylindrical Mirror Anamorphosis

Reflecting surfaces—both those that give the ideal and those that give a curved distorted image—are often used in modern urban-architectural practice. Both types of surfaces provide opportunities for the transformation of the urban-architectural ambience by means of anamorphosis. Cylindrical mirror surfaces fall into the group of reflecting surfaces which generate a distorted image, so that changes in urban-architectural ambience may be made in respect to existing cylindrical elements which create the effect of a mirror. These might include glass-clad façades, circular rotating doors, chrome pipes and chrome street columns.

An example of this type of reflective surface is found in the mirror-clad façade of the Cairns Botanic Gardens Visitors Centre (Cairns, Australia, Charles Wright Architects, 2011); an exceptional example of a form that offers multiple opportunities for the application of mirror anamorphosis. According to the design, the surrounding tree canopy is reflected onto the façade, but by means of

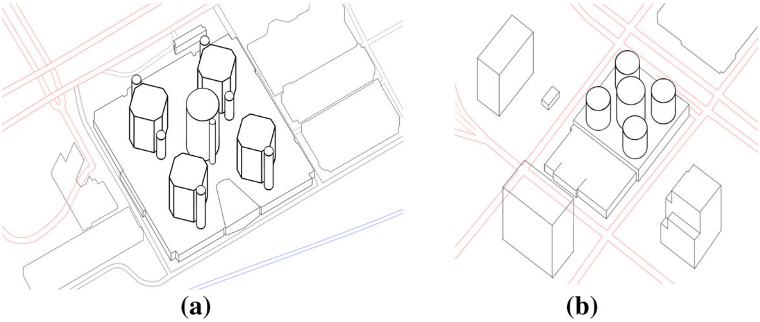


Fig. 18 Architectural form—military perspective. **a** GM Renaissance Centre, Jefferson Avenue, Beaubien, John Calvin Portman, Jr. Detroit, Michigan. Drawing: author. **b** Westin Bonaventure Hotel, Los Angeles. Drawing: author

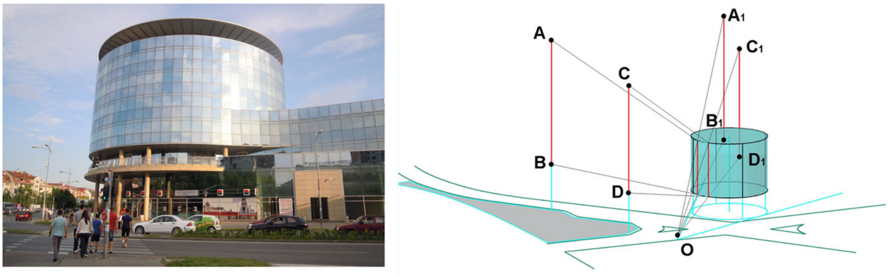
anamorphosis (which has the effect of surprise), it also has, in addition to camouflaging the structure, a marketing function. British artist Jonty Hurwitz has also used street columns as cylindrical mirrors for his 3D free-form anamorphosis.[8]

The GM Renaissance Centre in Jefferson Avenue, Beaubien (John Calvin Portman, Jr), is a dominant feature and one of the most recognisable structures in Detroit, Michigan, USA (Fig. 18a). The central building (the conference centre) is shaped as a rotating cylinder (diameter 57 m, roof height 222 m) and is symmetrically surrounded by four buildings that are situated on two orthogonal axes of symmetry. Depending on the position of the viewer of these four surrounding buildings, two are visible on the mirror-clad façade. The anamorphosis that is designed and positioned in the space between these buildings can be seen from a great distance. In this way, the panoramic image of this part of the town can be changed with a small amount of funds, offering the possibility of frequent transformations.

There is a similar composition in the structures of the Westin Bonaventure Hotel, a 112 m tall tower in Los Angeles (Fig. 18b), which has been designed by the same architect. This complex expands the geometrical possibilities of anamorphosis, given that the central cylindrical-shaped building in the complex is symmetrically surrounded by four cylindrical buildings of a smaller diameter and lower height. It is possible to achieve different forms of anamorphoses and their mirror images, in respect to a larger number of cylindrical mirrors.

However, designing anamorphosis in respect to a high-rise cylindrical structure, according to the ideal position of the viewer, may also permanently change the appearance of an urban-architectural solution. The Building of the Commercial Chamber of Vojvodina, is an example of applying a vertical rotating cylindrical façade shell (Fig. 19a). If, instead of the parking lot, which is located across the street, a structure of anamorphosis were to be built, part of its façade could be designed in respect of the ideal position of the viewer. Figure 19b shows the

[8] Hand anamorphosis, Rejuvenation, Copper and Chrome | 60 × 60 × 45 cm, 2008, http://www.jontyhurwitz.com/rejuvenation#e-8.



(a) (b)

Fig. 19 Analysis of the anamorphosis of a vertical line segment in the urban-architectural ambience. **a** Building of the Commercial Chamber of Vojvodina, Hajduk Veljkova, Novi Sad, Serbia. Photo: author. **b** Optimal position for the viewer and the mirror image (A1B1 and C1D1) of landmark verticals AB and CD that are situated in the parking lot contour. Axonometric presentation: author

axonometric presentation of one of the possible optimal positions of viewpoint (O), in respect to which the mirror image (A1B1 and C1D1) of landmark verticals AB and CD are constructed.

The application of anamorphosis does not necessarily imply construction only on the basis of the existing cylindrical mirror elements, but may be designed, in respect to some urban-architectural space, regarding both the anamorphosis and the mirror. When constructing an anamorphosis, the greatest influence on the appearance of the reflected structure itself is the position of the virtual structure (e.g. of the cube), in respect to the principal optical axis of the mirror (Fig. 20). Figure 20a reveals the difference in the form of anamorphosis (a1 and a2), when it is constructed dependent on the position of the viewpoint (O1 and O2), for the same position of the virtual object (c), in respect to the mirror. By changing the position of the viewpoint (O1, and O2) in respect to the object, with the same distance from the centre of the mirror base, only the principal optical axis is changed. If these constructed anamorphoses (a1 and a2) were placed in respect to the common position of viewpoint O (Fig. 20b) i.e., if their principal optical axes overlapped, two virtual cubes would appear in the mirror (c1 and c2). The distance of the viewer, i.e., the change of their position along the principal optical axis, does not markedly change the appearance of the anamorphosis of the horizontal directions perpendicular to the principal axis (Fig. 20c). The distance of the viewer from the mirror along the axis is doubled, and the height of the viewpoint is increased four times.

The appearance of anamorphosis also depends on the ratio between the size of the virtual object and that of the mirror diameter (Fig. 21a). The edge of cube c2 is 2.5 times longer than that of c1. Anamorphosis a2, of the cube c2, not only has a greater area than anamorphosis a1 of the cube c1, but its shape is also significantly altered. The size of the virtual object is bound by tangent planes (t1, t2) placed through viewpoint (O′) on the cylinder. Additionally, the shape, position and size of the anamorphosis is dependent on its virtual image, given that, in specific positions (Fig. 21b), anamorphosis may screen the virtual object, i.e., the image in the mirror. Point A of the virtual object is screened by the anamorphosis of the object.

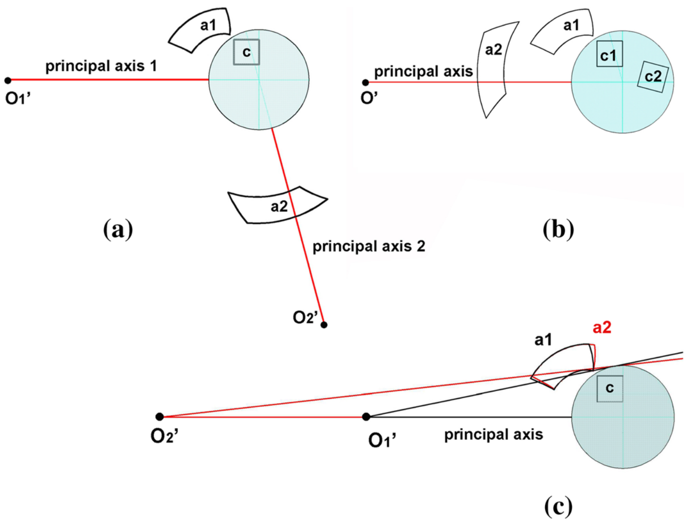


Fig. 20 Analysis of the form of anamorphosis. **a** The change of the form of anamorphosis (a1 and a2) when principal axis 1 is changed to principal axis 2, with the same distance of the viewer (O1′, O2′) from the centre of the mirror base, when the position of the virtual object (c) is not changed. Orthogonal projection: author. **b** Mirror image (c1 and c2) of anamorphoses (a1 and a2) when the position of the viewpoint (O′) i.e., the principal optical axis (pa), is not changed. Orthogonal projection: author. **c** The effect of viewpoint distance from the cylinder along the principal axis on the form of anamorphosis. Orthogonal projection: author

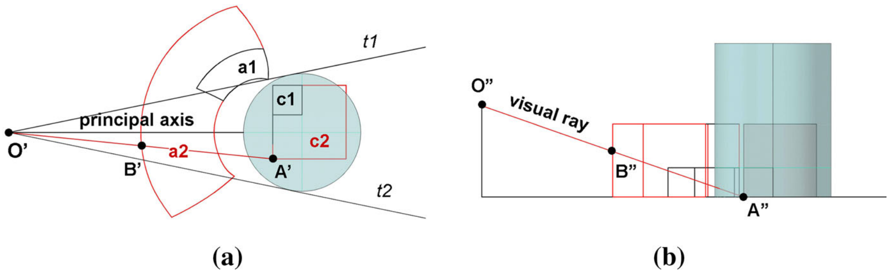


Fig. 21 Analysis of the change of size and form of the anamorphosis due to change in virtual object size. First and second orthogonal projection: author

With the aim of a more detailed analysis and visualisation, the computer application of an anamorphosis of two AutoCAD 3D models of a cube onto a photograph of a mirror, located in Tašmajdan Park, Belgrade, was performed (Fig. 22). The park benches, shaped like cube anamorphoses, in addition to having an aesthetic purpose, also have a utilitarian function that enhances urban design, distinction and attractiveness.

In addition to the functions of aesthetics, utility, marketing and communication, mirror anamorphosis may also include the function of energy efficiency. Sunlight rays, which are insufficiently utilised in the context of energy efficiency, when

Fig. 22 Anamorphosis as a utilitarian form. Conceptual design for Tašmajdan Park, Belgrade, Serbia by Marijana Paunović. Photomontage: author

reflected from a cylindrical mirror surface, produce a catacaustic effect.[9] If an anamorphosis were designed so as to absorb these sunrays more efficiently, its function would be multiple, and its surface would be dependent on this function. In this way, it would be able to accumulate light energy, and also emit it. Thus, it can be concluded that the position, appearance and size of an anamorphosis is determined, on one hand, by the ideal position of the viewer, and on the other, by the catacaustic effect of sunlight reflection.

Conclusion

A detailed analysis of the existing construction methods showed some flaws in applying the construction of plane anamorphoses to the creation of 3D models.

The experimental method and geometrical solving of the construction of a 3D model of catoptric anamorphosis, in respect to a mirror surface—vertical rotating cylinder—as well as on the basis of specific points, resulted in models of the cube and octahedron anamorphoses.

For the definition of anamorphosis, it is necessary to have both a virtual object, positioned between the tangent planes of a cylinder that contains a viewpoint, as well as specific points and sections of that virtual object.

For achieving free-form anamorphosis, it is practical to use the isohypse points of that free form, that is, its horizontal sections. In this respect, each isohypse has its

[9] The case study, conducted at the University of Applied Sciences in Germany, analyses in details, by simulation and experiments, catacaustic effects produced by the sunlight reflected from some curved façades. (Vollmer and Möllmann 2012).

anamorphosis, and their union is an anamorphosis of that free form. A form achieved in this way will play a significant role in the practical realisation of a model of anamorphosis.

Analysis of the change in the form of anamorphosis, in respect to the change of different parameters, led to the conclusion that the greatest influence on the appearance of the anamorphosis, in addition to the ratio between the mirror size and the virtual object, is the position of the principal optical axis.

Throughout this study, all of the examples indicated the various potential applications of anamorphosis, whereby its five functions are emphasised: aesthetic, utilitarian, marketing, communication and energy efficiency.

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