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Reconstructing Architectural Environment from the Perspective Image

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Abstract

The perspective representation of architectural objects can be used for illustrative purposes, technical documentation and research. An inverse process, namely reconstruction of such objects on the basis of their single perspective image may prove difficult. The aim of the hereby study is to determine the requirements which the perspective image should meet for restitution purposes, as well as developing an effective method of the reconstruction of architectural objects on the basis of their perspective mapping. Our considerations were constrained to linear perspective as it is the most popular form of perspective presentation. It was stressed that the crucial point of linear perspective restitution is the determination of its base elements; a main point, a horizon line, a ground line and the distance of the station point from the picture plane, which define the method of the perspective representation. The reconstruction attempt was based on geometrical rules and relations occurring between the points of the given 3D object and their perspective 2D mappings. Due to the fact that straight lines are very common in every urban environment, algorithms were developed, with changeable base elements of perspective to draw linear perspective image of any straight line passing through two points of the given object. On the basis of these algorithms the equations were formulated for calculation of the 3D location of the object characteristic points presented in the perspective 2D image, which determined the edge 3D model. Our method of restitution can be useful for reconstruction of different forms of perspective presentation; technical drawings, paintings, photographs and sketches, as well as it can be applied for improving or finding missing building contour in the perspective image. The study shows that retrieving some information about a spatial structure of the architectural object from the single perspective image is not always easy, although it is possible in some cases.

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1. Introduction

The history of perspective began in fifteenth century, with the term considered at the beginning as the practical method of representation of the captured scene by an artist. The first to try describing perspective by geometry rules was Filippo Brunelleschi. However, only creation of descriptive geometry as a branch of mathematics by Gaspard Monge in seventeenth century enabled further development of the theory of perspective as the method of projection. Perspective was and still is a perfect method and a tool to present 3D architectural environment from a specific viewpoint. It enables representation of the spatial forms defined by their metric properties given usually by their plan and elevation drawings.

Restitution of the architectural forms from their perspective images is a reverse process to the perspective projection. It is very useful for retrieving geometric properties of the represented objects and it finds plenty of applications for inventory process and in supplementing dimensions of inaccessible parts of buildings. Restitution was pioneered by mathematician J.H. Lambert in eighteen century. Since that time several methods of reconstruction of 3D objects from their perspective images have been proposed. They vary from descriptive methods to photogrammetry methods. We review the known methods in section 2.

Due to the fact that every perspective representation is submitted to geometrical rules and relations geometrical knowledge is essential in any reconstruction attempt, which we stress in section 3.

In this paper, we present a new approach to the direct and accurate 3D reconstruction of the architectural forms from their single perspective 2D image. We constrain our considerations to the reconstruction of linear perspective, which is the most popular way of perspective representation. The method of reconstruction develop by us is a combination of the descriptive way of reconstruction with the computer aid. We describe our method in section 4 and present our results in section 5. Additionally, we discuss different requirements of the perspective images for the restitution purpose. Section 6 concludes.

2. Existing work and our attempt

Much work has been done in the field of the reconstruction of the architectural environment depicted in 2D perspective onto a flat surface. The overview of the earliest reconstruction methods is given in [1]. Most of the research is concerned with recovering a 3D structure from a set of perspective views [2,3]. The reconstruction of perspective based on a single view is the most challenging process. A lot of attempts have been made, however. Most researches concentrate on so-called parallel perspective where some geometric properties occurring in the 2D image are preserved in the 3D object [4]. The proposed methods of reconstruction are usually associated with the optimization process [5,6,7]. Some attempts use cubic corner to recover 3D polyhedral objects [4].

Compared to other reconstruction methods that use information about points, for computer vision and the CAD system, it was more convenient for us to use information about lines which apply very often in architectural forms. Due to this fact we develop analytical algorithms for drawing perspective images of the straight lines passing through two points of the free 3D form given in space. Next, on the basis of these algorithms we develop formulas for reconstructing these lines; that is for calculation of the position of lines in space on the base on their perspective 2D image. Our attempt is similar to that presented for cylindrical panorama reconstruction [8,9].

3. Perspective as geometrical representation

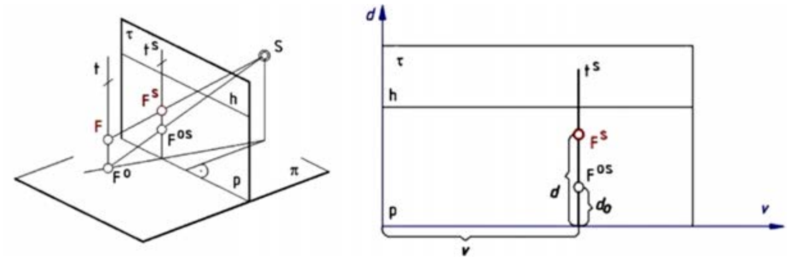
According to its descriptive geometry definition, perspective is a central projection from the real point onto a projection plane and it is submitted to projective geometry rules. The linear perspective system creates the illusion of depth onto a two dimensional plane by the use of the so-called ‘vanishing points’ to which all parallel lines converge at the level of horizon, which is the eye level. The base elements which define linear perspective are: picture plane, station point, the depth of sight, the horizon line, and the ground line. According to projective geometry rules, invariants of perspective projection are: incidence, collinearity of three non-coinciding points, cross ratio of quadruple of points, division of line segment parallel to the projection plane.

Geometric restitution of perspective is an inverse process of perspective projection; that is reconstructing three-dimensional models; their real shape, size and position in space on the basis of their two-dimensional image. The reconstruction process is not easy as during projection onto a flat surface many of the clues about three dimensional nature of the presented forms are lost. However, the information about real models lies encoded in their distortion occurring in the 2D image. Due to this fact retrieving this information and completely recovering a 3D structure requires some geometrical knowledge about the theory of projection.

4. Reconstruction

4.1. Linear perspective algorithms

Let us consider classical linear perspective onto a projection plane τ, from a viewpoint S and with a base plane $\pi \perp \tau$. The perspective image of any point F is a pair of two points (F^S, F^{OS}), see Fig.1a), 1b).



a) b)

Fig. 1. A perspective image (F^S, F^{OS}) of a point F: (a) construction; (b) mapping on the projection plane τ.

The point F^S is a central projection of F onto τ from S whereas F^{OS} is a central projection of F^O (orthogonal projection of F onto π base plane) onto τ. Both points F^S and F^{OS} are included in the vertical line t^S being a projection of t from S onto τ. The point F^S is a main projection whereas F^{OS} is a supplemental projection enabling restitution.

Let us consider the straight line t^S and its central projection ${}^St^S$ from S onto π, see Fig.2.

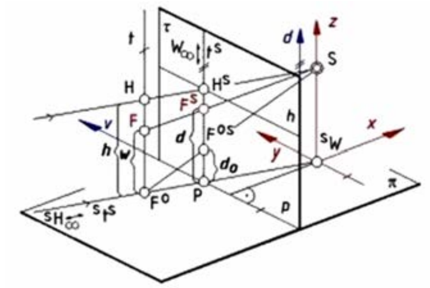


Fig. 2. Central projection of the line t onto τ and the line t^S onto τ with characteristic points included in them.

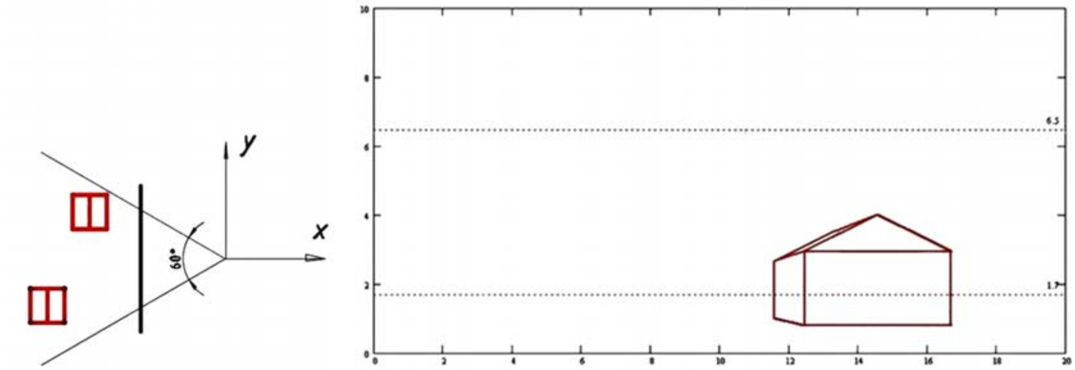
We can state that cross ratio of quadruple of collinear points (F^{OS}, P, W_∞, H^S) included in t^S is preserved during this projection, which can be written as follows:

$$\frac{F^{OS}P}{W_\infty P} : \frac{F^{OS}H^S}{W_\infty H^S} = \frac{F^O P}{{}^S W\, P} : \frac{F^{O\,S}H_\infty}{{}^S W\, {}^S H_\infty} \Leftrightarrow \frac{F^{OS}P}{F^{OS}\;\; H^S} = \frac{F^O P}{{}^S W\, P} \tag{1}$$

Similarly, considering the perspective projection of the line t from point S onto τ we can state that cross ratio of quadruple of collinear points (F^O, H, F, W_∞) is invariant.

$$\frac{F^O H}{FH} : \frac{F^O W_\infty}{FW_\infty} = \frac{F^{OS} H^S}{F^S\ H^S} : \frac{F^{O\,S} W_\infty}{F^S W_\infty} \Leftrightarrow \frac{F^O H}{FH} = \frac{F^{OS} H^S}{F^S H^S} \tag{2}$$

For the restitution purpose we place a spatial Cartesian coordinate system of axis x, y, z and a Cartesian coordinate system of axis v, d as shown in Fig.2. The equations (1) and (2) permit a creation of analytical algorithms for drawing a perspective image of a segment of line passing through two different points determined by their coordinates in coordinate system of axis x, y, z. The line is drawn as a plot of function $d(v)$ in Cartesian coordinate system of axis d, v placed as in Fig.1b and Fig.2. Let us not describe the algorithms in detail but show their example use for drawing the perspective edge image of a simple object (Fig.3a and Fig.3b). Due to the fact that the base elements of perspective are changeable in the algorithms we can obtain perspective images of objects from different viewpoints. The correctness of the algorithms has been checked in the Mathcad software, however they can be implemented in any drawing package.



a) b)

Fig. 3. Drawing perspective by Mathcad : (a) location of an object towards τ; (b) result- plot $d(v)$.

4.2. Reconstruction formulas

Reconstruction of perspective is a reverse process of perspective projection. Therefore, we derive formulas for calculating the 3D location of the characteristic points of figures on the basis of their perspective 2D image by transformation of the algorithms for perspective creation.

The calculation of the spatial location of any point F determined on the projection plane τ by its main projection $F^S(v, d)$ and supplemental projection $F^{OS}(v, do)$ shown in Fig.1b and Fig.2 can be established by means of the following parameters (Fig.4) :

$$w(v, d_o, d) = \frac{h \cdot (d - d_0)}{h - d_0} \tag{3}$$

$$k(v, d_o, d) = \frac{h \cdot r_k(v, d_0, d)}{h - d_0}, \tag{4}$$

where $k(v, d_o, d)$ it is a distance between points F^o and S^o and r_k is a distance between points T and S^o.

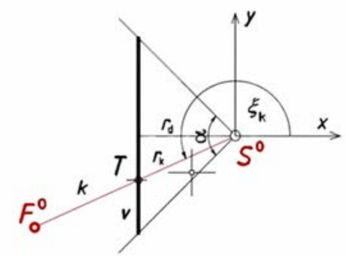
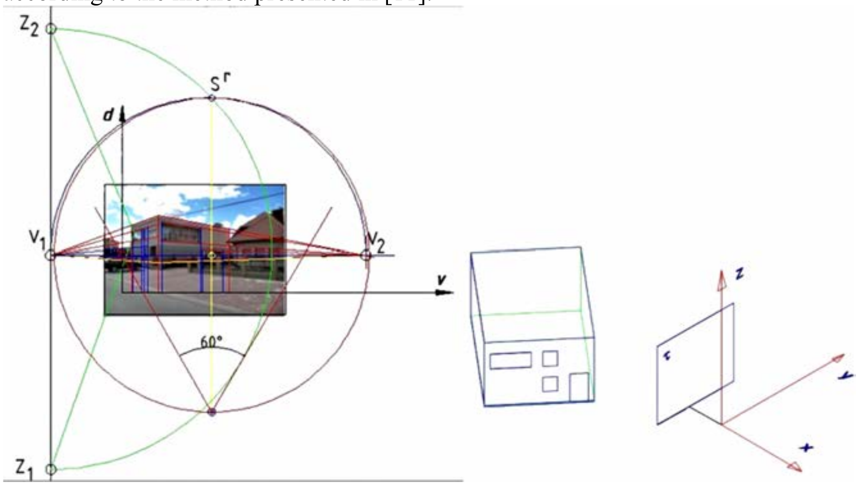


Fig. 4. Parameters defining the position of point F^o towards τ on a base plane *xy*.

The above parameters are calculated by the program for a given values of v, d_o, d and for the established base elements of perspective. The parameter $w(v, d_o, d)$ determines the coordinate z whereas on the basis of $k(v, d_o, d)$ and v polar coordinates for given point F^o are calculated.

4.3. Application of restitution formulas for reconstruction of a simple building given in a photo

The first step in our restitution is determination of the method of projection presented in the picture. It is evident that we deal with two-point perspective, see Fig.5a. Therefore, we establish base elements of perspective in a descriptive way according to the method presented in [11].



a) b)

Fig. 5. Reconstruction process: (a) establishing base elements of perspective; (b) location of the building model towards a virtual projection plane τ and the Cartesian coordinate system of axis x, y, z.

The base for our restitution is the perspective image of the horizontal rectangle forming a bottom of the building. The intersection points of the straight lines containing its parallel sides determine vanishing points V_1 and V_2, which in turn establish a horizon line h. Determination of other base elements of perspective on the basis of the single photo requires some empirical knowledge about the building or some assumptions which compensate lack of additional photos. Here, the clue is a square element of the window. Therefore, we establish two vanishing points Z_1 and Z_2 of two diagonals of the square element of the window. These pairs of points establish two circles intersection, of which gives a position of eye after rotation. We construct a circle of depth and locate the ground line parallely to the horizon line and beneath the ground contour of the presented building. We measure the distance between the horizon line and the ground line as well as the radius of the circle of depth, which are necessary to use in our formulas. Next, we place the orthogonal coordinate system v, d as in Fig.4a, and establish v, d_o and d for every characteristic point of the building. Finally, we calculate the position of points in space in 3D coordinate system of axis x, y, z, which defines the shape of the building (Fig.5b). If any additional measure of building is known, it can be scaled the model and achieve its real size.

In order to verify the correctness of the method we have realize the restitution of some elements of the same building on the basis of the second different photograph. Finally, we scaled both the model achieved in the first restitution and some elements of the building achieved in the second restitution assuming the real size of the square element of the window.

above parameters are calculated by the program for a given values of v, d_o, d and for the established base elements of perspective. The parameter $w(v, d_o, d)$ determines the coordinate z whereas on the basis of $k(v, d_o, d)$ and v polar coordinates for given point F^o are calculated.

5. Results and Discussions

The above example of reconstruction of a simple building given on the perspective image shows that our method of reconstruction works well. We have checked performance of this method in the case of three simple architectural building photographs. The results received were similar as far as accuracy is concerned. The measure of angle between any two horizontal and mutually perpendicular straight lines was 90-92 degree in reconstructed models. The difference in length between any two horizontal or vertical straight lines supposed to be equal was 15 mm.

Due to this fact we can state that our method of reconstruction is accurate. However, the application of this method depends on both the aim of restitution and the kind of perspective image being used. In the case of an accurate perspective image with known base elements we can apply formulas directly and achieve an accurate 3D edge model. In the case of reconstruction of objects from the paintings or sketches, first it is necessary to estimate their geometric content, next establish base elements of perspective in a descriptive away, and finally apply formulas. A lot of painters used an underlying drawing to construct a correct painting, however, no painting has the precision of photographic mapping [10]. Moreover, a lot of artists manipulated perspective composing pictures as a combination of views from different viewing positions [11]. Therefore, in the case of paintings drawn from several viewpoints the base elements of perspective should be established for different objects separately and then reconstruction is much more laborious. On the other hand, the use of the descriptive method of establishing base elements of perspective enables the application of different constructions dependently on preliminary assumptions.

There are also other basis requirements for the perspective image used in our restitution. First of all, it should be clear what kind of perspective is applied in the picture. The image should have a sufficient depth dependently on amount of details which are to be reconstructed. Perspective images with a slightly exaggerated perspective and with a big angle of view are the best for reconstruction purposes.

6. Conclusions

In the hereby paper, we focus on reconstruction of the architectural objects from a single perspective image. It has been proposed simple algorithms with changeable base elements of perspective to draw the perspective image. On the basis of these algorithms we derive formulas for calculating the space location of the characteristic points of objects presented in the perspective 2D image, which determines 3D edge models. The presented method of reconstruction is a conjunction of the descriptive method of reconstruction and computer aid, thereby it appears to be universal. The algorithms for drawing the perspective image can be useful for improving or finding the missing building contour in the perspective image. Due to the fact that the base elements of perspective can be changeable in the algorithms, they can be applied in the case of the single viewpoint perspective as well as perspective from multiple station points. Therefore, it can prove useful for reconstruction of various forms of perspective presentation technical drawings, paintings, photographs and sketches.

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