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Characterization of Image Acquisition and Epipolar Geometry of Multiple Panoramas

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Abstract

Recently multiple panoramic images have emerged and received increasingly interest in applications of 3D scene visualization and reconstruction. Examples of such approaches and applications are discussed throughout the paper. Although many panoramic image acquisition models have been proposed in the literature, there is still a lack in studies about what principles are essential in the design/assessment of new/old panoramic image acquisition models in a formal way. Geometric studies such as epipolar geometry are well established for a pair of planar images. Compared to that, the computer vision literature still lacks work on pairs of panoramic images. There is a need to characterize and clarify their common natures and differences so that a more general form/framework or a better computational model can be further discovered or developed. This paper introduces some notions at an abstract level for characterizing the essential components of panoramic image acquisition models. Based on the result of this characterization, we develop a general computational model for describing the family of cylindrical panoramas. A classification within this family, and results of epipolar curve equations for different subclasses of this family are presented.

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Abstract. Recently multiple panoramic images have emerged and received increasingly interest in applications of 3D scene visualization and reconstruction. Examples of such approaches and applications are discussed throughout the paper. Although many panoramic image acquisition models have been proposed in the literature, there is still a lack in studies about what principles are essential in the design/assessment of new/old panoramic image acquisition models in a formal way. Geometric studies such as epipolar geometry are well established for a pair of planar images. Compared to that, the computer vision literature still lacks work on pairs of panoramic images. There is a need to characterize and clarify their common natures and differences so that a more general form/framework or a better computational model can be further discovered or developed. This paper introduces some notions at an abstract level for characterizing the essential components of panoramic image acquisition models. Based on the result of this characterization, we develop a general computational model for describing the family of cylindrical panoramas. A classification within this family, and results of epipolar curve equations for different subclasses of this family are presented.

1 Introduction

Traditionally, a 360° full-view panorama can be acquired by rotating a camera with respect to a fixed rotation center and taking images consecutively at equidistant angles. More recently, panoramic images acquired with respect to a single rotation axis or multiple rotation axes have emerged and received increasingly interests in applications of 3D scene visualization, reconstruction and navigation. Examples of these approaches and their applications are discussed throughout the paper.

An *image acquisition model* defines image-acquiring components (i.e. logical units) and their usages in the image acquisition process for a particular application. Conceptually, the closer the relation between the data acquired and the outcome expected in the application, the simpler the processes involved as well as the better the performance. QuicktimeVR [3] serves as a good example. For being able to design, analyze and assess an image acquisition model, we need to establish the building-blocks (basic components) which construct the architecture of image acquisition models. However there are still lacks of the studies about what principles are essential in the design and assessment of an image acquisition model in a formal way.

Geometric studies such as epipolar geometry are well established for pairs of planar images [4, 9, 11, 13, 26]. Compared to that, the computer vision literature still lacks work on pairs of panoramic images. Due to differences in geometry between the planar and the panoramic image models, geometric properties for planar images may not necessarily be true for panoramic images.

Since many different panoramic image models have been proposed and used in various applications, there is a need to characterize them and clarify their differences so that better understanding of them and related properties can be achieved. By observing the common characteristics among them, a more general form/framework or a better computational model may be further discovered or developed.

In this paper we introduce some notions at an abstract level for characterizing the essential components of panoramic image acquisition models. The formal definitions of the notions are given followed by an exploration of relationships among the components. Various examples are provided for demonstrating the flexibility and compactness in characterizing different types of panoramic image acquisition models. Although this paper focuses on panoramic images, the notions introduced are in fact general enough for describing a wide range of image acquisition models for 3D scene visualization and reconstruction applications.

This paper is organized as follows. Brief reviews of related literatures regarding panoramic images and their applications are provided in Section 2. In Section 3 we introduce some basic/general components/notions for the design, analysis and assessment of image acquisition models. A family of cylindrical panoramic images, as a case study, is then studied. The computational model, classification and epipolar curve equations of the family are presented in Section 4. Observations, important issues, and proposals for future directions are then summarized in the conclusions.

2 Brief Reviews

A well-known and typical example for 3D scene visualization using a single-focal-point panorama is QuickTimeVR [3] from Apple Inc. Using multiple single-focal-point panoramas to reconstruct a 3D scene, S.B. Kang and R. Szeliski discussed different methods and their performance in [12]. Other similar works can be found in [6, 14, 15, 24]. The direct merit of this omnidirectional reconstruction of a surrounding 3D scene is by-passing a complicated and erroneous[1] process of multiple merging operations for depth-maps which would be required if multiple planar images would be used instead.

The family of cataoptrical panoramas [2, 5, 16, 23, 27] provide real-time and highly portable imaging capabilities at affordable cost. The applications include robot navigation, teleportation, 3D scene reconstructions, etc.. In the latter case,

[1] Various sources of the errors, such as inexact estimation of relative poses between cameras, may cause serious degradation to the resulting quality.

the epipolar geometry coincides with image columns if the two panoramic camcorders are specially arranged such that the optical axes are co-axis and each acquired panoramic image is warped onto a cylinder. The drawbacks of this type of panoramic image include low resolution; inefficient usage of the image (e.g. the self-occluded and mirror-occluded area of the image); and potentially inaccurate image acquisition along the peripheral of the spherical mirror (e.g. spherical aberration or distortion).

S. Peleg and *M. Beh-Ezra* [17] described a model using circular projections[2] for stereo panoramic image generation, which allows the left and right eye perceptions of panoramic images. These left and right images are approximated with respect to the views from the inner circle of their cylindrical model. *H-Y. Shum* and *L-W. He* [20] proposed a concentric model in which novel views within an inner circle and between the inner and outer circles were approximated by the circular projections in normal direction (the same as in [17]) and in tangential direction. Besides, using the concentric model of panoramic images H-Y. Shum and R. Szeliski [22] show that epipolar geometry consists of horizontal lines if two panoramic images form a symmetric pair (see Def. 8).

H. Ishiguro et al. first proposed an image acquisition model that is able to produce multiple panoramas by a single swiveling of a pinhole-projection camera, where each panorama is associated with multiple focal points. The model was created for the 3D reconstruction of an indoor environment. Their approach reported in 1992 in [10] already details essential features of the multi-perspective panoramic image acquisition model. The modifications or extensions of their model have been discussed in other papers such as [7, 17, 18, 20–22, 25].

3 Image Acquisition Characterizations

In this section we introduce some notions at an abstract level for characterizing the essential components of panoramic image acquisition models. The formal definitions are given and various examples of the existing panoramic image acquisition models are provided.

Definition 1. *A* focal set $\mathcal{F}$ *is a non-empty (finite) set of focal points in 3D Euclidean space. A focal point, an element of* $\mathcal{F}$*, can be represented as a 3-vector in* $\mathbb{R}^3$.

Definition 2. *A* receptor set $\mathcal{S}$ *is a non-empty infinite or finite set of receptors (photon-sensing elements) in 3D Euclidean space. A receptor, an element of* $\mathcal{S}$*, can be characterized geometrically as a 3-vector in* $\mathbb{R}^3$.

In practice, a focal set $\mathcal{F}$ contains a finite number of focal points, but a receptor set $\mathcal{S}$ may either have an infinite or finite number of receptors depending on the type of photon-sensing device used. For instance, radiational film (negative) is regarded as containing infinitely many photon-sensing elements; and the

[2] See the following sections for further explanations.

CCD chip in a digital camera contains only a finite number of photon-sensing elements.

It is convenient to express a collection of points by a supporting geometric primitive such as a straight line, curve, plane, quadratic surface etc. where all of the points lie on. For examples, the single-center panoramic model (e.g. QuickTimeVR) consists of a single focal point (i.e. the cardinality of the focal set is equal to 1 or formally $\#(\mathcal{F}) = 1$) and a set of receptors lie on a cylindrical or spherical surface. The multi-center image model consists of a set of focal points on various geometrical forms, such as on a vertical straight line, a 2D circular path, a disk, or a cylinder etc., and a set of receptors which are incident with a cylindrical, cubic or spherical surface.

A single light ray with respect to a point in 3D space at one moment of time can be described by seven parameters, that is, three parameters describing the point's location, two parameters describing the ray's emitting angle, one parameter describing the wavelength of the light in the visible spectrum, and one parameter describing the time. A function taking these seven parameters as inputs and outputting a measure of the intensity is called *plenoptical function* [1]. All possible light rays in a specified 3D space and time interval form a *light field*, denoted as $\mathcal{L}$.

The association between focal points in $\mathcal{F}$ and receptors in $\mathcal{S}$ determines a particular proper subset of the light field $\mathcal{L}$. For instance, a complete bipartite set of focal and receptor sets is defined as

$$\mathcal{B}_{\mathcal{F}\times\mathcal{S}} = \{(p,q) : p \in \mathcal{F} \text{ and } q \in \mathcal{S}\},$$

where each element (p,q) specifies a light ray passing through the point p and striking on point q. Note that a complete bipartite set of focal and receptor sets is a proper subset of the light field (i.e. $\mathcal{B}_{\mathcal{F}\times\mathcal{S}} \subset \mathcal{L}$).

Definition 3. *A focal-to-receptor association rule defines an association between a focal point and a receptor, where a receptor is said to be associated with a focal point if and only if any light ray which is incident with the receptor passes through that focal point.*

Each image acquisition model has it's own association rule for the focal and receptor sets. Sometimes, a single rule is not enough to specify complicate associating conditions between the two sets, thus a list of association rules is required. A pair of elements satisfies a list of association rules if and only if the pair satisfies any of the individual association rule.

Definition 4. *A projection-ray set $\mathcal{U}$ is a non-empty subset of the complete bipartite set of focal and receptor sets (i.e. $\mathcal{U} \subseteq \mathcal{B}_{\mathcal{F}\times\mathcal{S}} \subset \mathcal{L}$), which satisfies the following conditions:*

1. *It holds $(p,q) \in \mathcal{U}$ if and only if (p,q) satisfies a (list of) pre-defined association rule(s);*
2. *For every $p \in \mathcal{F}$, there is at least a $q \in \mathcal{S}$ such that $(p,q) \in \mathcal{U}$;*

3. *For every $q \in \mathcal{S}$, there is at least a $p \in \mathcal{F}$ such that $(p, q) \in \mathcal{U}$.*

For example, the projection-ray set $\mathcal{U}$ of the traditional single-center panoramic image acquisition model is the complete bipartite set of focal and receptor sets, because there is only a single focal point and every receptor defines a unique projection-ray through the focal point. Moreover, the projection-ray set in this case is a proper subset of the *pencil*[3] of rays at that focal point.

The projection-ray set $\mathcal{U}$ of a multi-perspective panoramic image acquisition model [8, 17, 21] is a subset of the complete bipartite set of focal and receptor sets and can be characterized formally as follows. The focal points in $\mathcal{F}$ are an ordered finite sequence, $p_1, p_2, \ldots, p_n$, which all lie on a 1D circular path in 3D space. The set of receptors form a uniform (orthogonal) 2D grid and lie on a 2D cylindrical surface that is co-axial to the circular path of the focal points. The number of columns of the grid is equal to n. The association rules determining whether (p, q) belongs to the projection-ray set $\mathcal{U}$ are as follows:

1. All $q \in \mathcal{S}$ which belong to the same column must be assigned to an unique $p_i \in \mathcal{F}$.
2. There is an ordered one-to-one mapping between the focal points $p_i \in \mathcal{F}$ and the columns of the grid. In other words, the columns of the grid, either counterclockwise or clockwise, may be indexed as $c_1, c_2, \ldots, c_n$ such that every $q \in c_i$ is mapped to $p_i, i \in [1..n]$.

Definition 5. *A reflector set $\mathcal{R}$ is a set of reflectors' surface equations, usually a set of first or second order continuous and differentiable surfaces in 3D space.*

A reflector set, e.g. a set of mirror(s), is used to characterize how light rays can be captured indirectly by the receptors. For instance, a hyperbolic mirror is used in conjunction with the pinhole projection model for acquiring a wide visual field of a scene (e.g. 360° panorama). Similarly, with the orthographic projection model, the parabolic mirror is adopted. Such type of image acquisition model allows that all the reflected projection rays intersect at the focus of the hyperboloid [2, 23], which possess a simple computational model for supporting possible applications.

Let $\mathcal{P}(\mathcal{R})$ denote the power set of the reflector set. Define a geometrical transformation T as follows:

$$T : \mathcal{U} \times \mathcal{P}(\mathcal{R}) \rightarrow \mathcal{A}, \\ ((p, q), s) \mapsto (p', q'),$$

where $\mathcal{A}$ is a non-empty subset of the light felid. The element of $\mathcal{A}$, a light ray, is represented by a pair of points, denoted as (p', q'), specifying its location and the orientation. The transformation T is a function which transforms a projection ray with respect to an element of $\mathcal{P}(\mathcal{R})$ to a reflected ray.

[3] The set of all rays passing through one point in space is called a *pencil*.

Definition 6. *A reflected-ray set $\mathcal{V}$ is a non-empty set of light rays, which is a subset of the light field. Formally,*

$$\mathcal{V} = \{T((p,q),s) : (p,q) \in \mathcal{U}\},$$

where s is one particular element of the power set of a reflector set (i.e. $s \in \mathcal{P}(\mathcal{R})$).

Note that, when a transformation of a projection-ray set takes place, only one element of $\mathcal{P}(\mathcal{R})$ is used. In particular, as $\emptyset \in \mathcal{P}(\mathcal{R})$ is chosen, the resulting reflected-ray set is identical to the original projection-ray set. When the number of elements of the chosen s is more than one, the transformation behaves like ray-tracing.

A single projection-ray set (or a reflected-ray set - we omit to repeat this in the following) is referred to as a set of light rays defined by an image acquisition model at a moment of time and a specific location. Two factors are added to characterize multiple projection-ray sets. The temporal factor describes the acquisition time, and the spatial factor describes the pose of the model. A collection of (or multiple) projection-ray sets is denoted as $\{\mathcal{U}_{t,\rho}\}$, where t and ρ indicating time and pose, respectively. Multiple images, i.e. a collection of projection-ray sets acquired at different times or poses $\{\mathcal{U}_{t,\rho}\}$, are a subset of the light field.

Some applications [3, 20] use only a single projection-ray set to approximate a complete light field in a restricted viewing zone and some [22, 24] require multiple images in order to perform special tasks such as depth from stereo. Regardless of the time factor, to acquire a complete light field of a medium-to-large scale space is already known to be very difficult, or say, almost impossible to achieve based on the technology available to date. Usually, a few sampled projection-ray sets are acquired for approximating a complete light field. Due to the nature of scene complexity, the selection of a set of optimal projection-ray samples become an important factor to determine the quality of the approximation of a complete light field of a 3D scene.

4 Epipolar Geometry

This section presents the results of epipolar geometry study in the family of cylindrical panoramas which are well-known and widely used in 3D scene visualization and reconstruction applications. Based on the result of the image acquisition characterizations, we develop a general model for describing this family. The classifications of the family are provided. The results of epipolar curve equations for each class in the family are presented. The definition of an epipolar curve in general is given as follows.

Definition 7. *For every projection ray $(p,q) \in \mathcal{U}$, there is a non-empty set $\mathcal{E} \subseteq \mathcal{S}'$ such that for every $q' \in \mathcal{E}$ the associated projection ray $(p',q') \in \mathcal{U}'$ must intersect[4] with (p,q). The set $\mathcal{E}$ defines an epipolar line (either a curve or a straight line) of q.*

[4] This implies two properties (i.e. coplanarity and visibility) hold: (p,q) and (p',q') are coplanar and q' must lies on the projection rays that are visible to p.

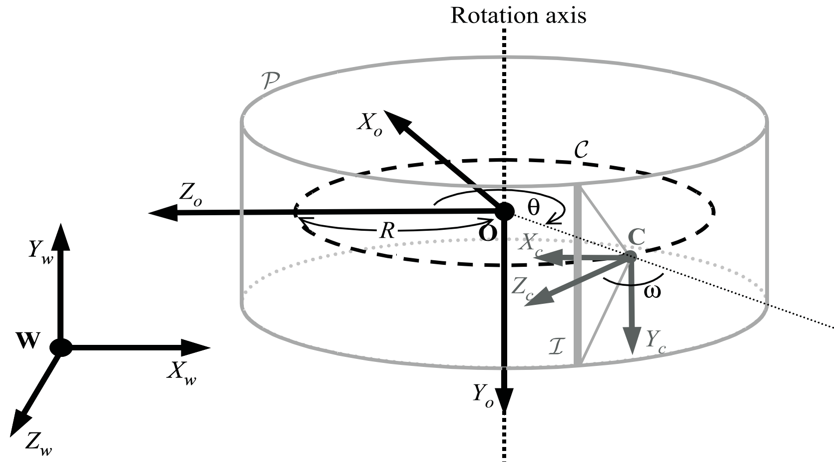

Fig. 1. A general image acquisition model of the cylindrical panorama family. The figure illustrates the geometrical model and the notations. Three coordinate systems used in the text include: a slit camera coordinate system (originated at **C**); an associated turning-rig coordinate system (originated at **O**); and the world coordinate system (originated at **W**).

The definition is generally true for any pair of images. The actual epipolar curve equation to each class is discussed in the following subsections. The derivations are omitted and readers who are interested in are referred to [8].

4.1 Computational Model and Classifications

A general computational model of the cylindrical panorama family is presented and depicted in Figure 1. A slit camera [19] is considered here for some practical reasons such as availability, flexibility etc. A slit camera can be characterized geometrically by a single focal point **C** (the effective focal length is denoted as f) and a 1D linear receptor $\mathcal{I}$. The distance between the slit camera's focal point and the rotation axis, denoted as R, remains constant during a single panoramic image acquisition process. The angular increment of every subsequent rotation is constant in size resulting in uniformly spaced viewing angles. Each slit image contributes to one column of a panoramic image $\mathcal{P}$of resolution $H_{\mathcal{P}} \times W_{\mathcal{P}}$.

An angle, ω, is defined by the angle between the normal vector of the focal circle at the associated focal point and the optical axis of the slit camera for more flexibility in generating different viewing-angled panoramic images, which has been reported being useful in various applications [17, 20–22].

Our classification within the family of cylindrical panoramic images is summarized as follows: a set of panoramic images all acquired with respect to one single focal point which is exactly on the rotation axis, i.e. $R = 0$, is referred to as *single-center panoramic images* [3, 14, 15]. A set of panoramic images all acquired with respect to the same rotation axis but $R > 0$ and possibly different focal points (on this axis) are referred to as *concentric panoramas* [17, 21, 22]. A collection of panoramic images acquired with respect to different rotation axes and $R > 0$ is referred to as *polycentric panoramas* [8].

4.2 A Single-center Panoramic Pair

Without loss of generality, for a pair of single-center panoramas, the orientations and positions of their turning-rig coordinate systems with respect to the world coordinate system (cf. Fig. 1) can be defined as $\mathbf{R}_{wo} = \mathbf{R}_{wo'} = \mathbf{I}_{3\times 3}$ and $\mathbf{T}_{wo} = (0,0,0)^{\mathrm{T}}$ and $\mathbf{T}_{wo'} = (t_x, t_y, t_z)^{\mathrm{T}}$, respectively. Each associated focal circle degenerates into a single point, thus $R = R' = 0$. We also have that $\omega = \omega' = 0$. The epipolar curve equation is described as follows.

Let (x, y) and $(x'y')$ be a pair of corresponding image points in a pair of single-center panoramas, respectively. Given x and y, we have

$$y' = y \cdot h \cdot (t_z \sin\theta' - t_x \cos\theta'), \text{ where } \ h = \left(\frac{f'}{f\,(t_z \sin\theta - t_x \cos\theta)} \right).$$

Here, $\theta = (2\pi x)/(W_{\mathcal{P}})$, $\theta' = (2\pi x')/(W_{\mathcal{P}'})$.

4.3 A Concentric Panoramic Pair

Let (x, y) and $(x'y')$ be a pair of corresponding image points in a pair of concentric panoramas. Given x and y, we have

$$y' = y \cdot \left(\frac{f'}{f}\right) \cdot \left(\frac{R' \sin\omega' - R \sin(\theta' - \theta + \omega')}{-R\sin\omega - R'\sin(\theta' - \theta - \omega)} \right),$$

where $\theta = (2\pi x)/(W_{\mathcal{P}})$ and $\theta' = (2\pi x')/(W_{\mathcal{P}'})$. Note that we have a translation vector $\mathbf{T}_{oo'} = (0, t_y, 0)^{\mathrm{T}}$ (i.e. $t_x = 0$ and $t_z = 0$) in this case describing a shift along the rotation axis.

4.4 A Symmetric Concentric Panoramic Pair

Definition 8. *Two concentric panoramic images are called a symmetric pair* [17, 22] *if* $f = f'$, $R = R'$, $t_y = 0$ *and, most importantly,* $\omega' = (2\pi - \omega)$.

For a symmetric pair of concentric panoramic images it holds that epipolar curves coincide with image rows, which can be shown by

$$y' = y \left(\frac{R\sin(2\pi - \omega) - R\sin(\theta' - \theta + 2\pi - \omega)}{-R\sin\omega - R\sin(\theta' - \theta - \omega)} \right) = y \left(\frac{-\sin\omega - \sin(\theta' - \theta - \omega)}{-\sin\omega - \sin(\theta' - \theta - \omega)} \right) = y,$$

where $\theta = (2\pi x)/(W_{\mathcal{P}})$ and $\theta' = (2\pi x')/(W_{\mathcal{P}'})$.

4.5 A Horizontally-aligned Polycentric Panoramic Pair

Without loss of generality, for a pair of horizontally-aligned polycentric panoramas[5], the orientations and positions of their turning-rig coordinate systems with respect to the world coordinate system (cf. Fig. 1) can be defined as $\mathbf{R}_{wo} = \mathbf{R}_{wo'} = \mathbf{I}_{3\times3}$ and $\mathbf{T}_{wo} = (0,0,0)^{\mathrm{T}}$ and $\mathbf{T}_{wo'} = (t_x, 0, t_z)^{\mathrm{T}}$, respectively. Thus, we have $\mathbf{R}_{oo'} = \mathbf{I}_{3\times3}$ and $\mathbf{T}_{oo'} = (t_x, 0, t_z)^{\mathrm{T}}$.

Let (x, y) and $(x'y')$ be a pair of corresponding image points in a pair of horizontally-aligned polycentric panoramas. Given x and y, we have

$$y' = y \cdot \left(\frac{f'}{f}\right) \cdot \left(\frac{R' \sin\omega' - R\sin(\delta' - \theta) - t_x \cos\delta' + t_z \sin\delta'}{-R\sin\omega + R'\sin(\delta - \theta') - t_x \cos\delta + t_z \sin\delta}\right),$$

where $\delta = (\theta + \omega)$, $\delta' = (\theta' + \omega')$. The more complicate epipolar curve equation for an arbitrary polycentric pair can be found in [8].

5 Conclusion

This paper characterized the image acquisition and epipolar geometry of multiple panoramic images. Existing approaches using multiple panoramic images are briefly reviewed. The emphasis has been placed on demonstrating the flexibility and compactness in characterizing different types acquisition models and associated epipolar geometry of multiple panoramic images.

A family of cylindrical panoramic images, which serves for a wide range of applications, has been particularly studied. A general computational model of this family is proposed and used in computing epipolar curve of each class in the family.

In future we will look further into the relationship between applications and various panoramic image acquisition models such that the capabilities, limitations as well as the evaluation criteria of image acquisition models can be analyzed and further characterized.

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[5] Both associated rotation axes are parallel and are located at the same height with respect to the world coordinate system.

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