Panoramic cameras for 3D computation

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Abstract   *In this paper, we review design and principles of existing panoramic cameras. Panoramic cameras which enable 3D computation in reasonable time for real time applications are emphasized. We classify panoramic cameras w.r.t. their construction, field of view, and existence of a single projective center. Using this classification we state a utility of the central catadioptric panoramic cameras. We show from which mirrors and conventional cameras can be constructed and expose that they are the only ones for which the epipolar geometry can be simply generalized.*

1   Introduction

A wide field of view eases the search for correspondences as corresponding points do not so often disappear from the field of view and helps to stabilize ego-motion estimation algorithms so that the rotation of the camera can be well distinguished from its translation [6]. As the panoramic cameras see a large part of the scene around them in each image, they can provide more complete reconstructions from fewer images.

Ideal omnidirectional cameras would provide images covering the whole view-sphere and therefore they would be image sensors with no self-occlusion. However, ideal omnidirectional cameras are difficult to realize because a part of the scene is often occluded by an image sensor. Recently, a number of panoramic cameras appeared. They do not cover the whole view-sphere but most of it.

In Section 2, we review design and principles of existing panoramic cameras. We put more emphasis to panoramic cameras which enable 3D computation in reasonable time for real time applications. We classify panoramic cameras w.r.t. their construction, field of view, and existence of a single projective center, in Section 3. Using this classification, we state a utility of the central catadioptric panoramic cameras. We show from which mirrors and cameras can be constructed and expose that they are the only ones for which the epipolar geometry can be simply generalized, see Section 4.

Similar survey oriented more for applications was given by Yagi [48].

2   Overview of existing panoramic cameras

We give an overview of various principles used to obtain panoramic images which appeared in literature. Panoramic images can be either createrd by using panoramic cameras or by mosaicing together many regular images. We shall concentrate on approaches leading to 3D computation. More stress is given to real time sensors.

2.1   Mosaic based cameras

Panoramic images can be created from conventional images by mosaicing. The QTVR system[1] allows to create panoramic images by stitching together conventional images taken by a rotating camera. Peleg et. al [38] presented a method for creating mosaics from images acquired by a freely moving camera[2]. Similarly, the mosaicing method proposed by Shum and Szelisky [41, 46] does not require controlled motions or constraints on how the images are taken as long as there is no strong motion parallax. These approaches are for visualization only, no 3D structure is computed.

Ishiguro et. al [26] proposed omnidirectional stereo camera. They used a standard camera which rotates on a circular path with non-zero radius. Optical axes in each position intersect in the center of the circle. The depth of an object is estimated from its projections in two images taken at different position of the camera circular path, see Figure 1. Capturing of a full panoramic stereo image takes approximately 10 minutes, which is useless for real time applications. Peleg and Ben-Ezra [37] presented a mosaicing vision system for creating stereo panoramic images. However, stereo images are created without computation of 3D structure, the depth effects are created only in viewer's brain.

2.2   Cameras with rotating parts

To speed up the acquisition of panoramic images, Benosman et al. [4, 5] use a line-scan camera rotating around a vertical axis. Two line-scan sensors have the same rotation axis and they are arranged one on the top of the other, see Figure 2. Each column contains 1024 pixels and the number of columns depends on the elementary rotation angle.

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[1]http://www.qtvrworld.com/
[2]Panoramic images can also be produced by Spin Panorama software http://www.videobrush.com/ using the camera moving on a circle.
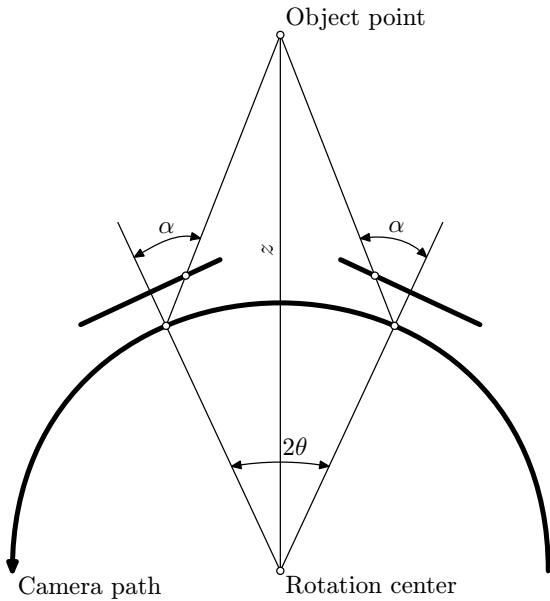
Figure 1: The depth z of an object point can be estimated by measuring of angles θ and α.
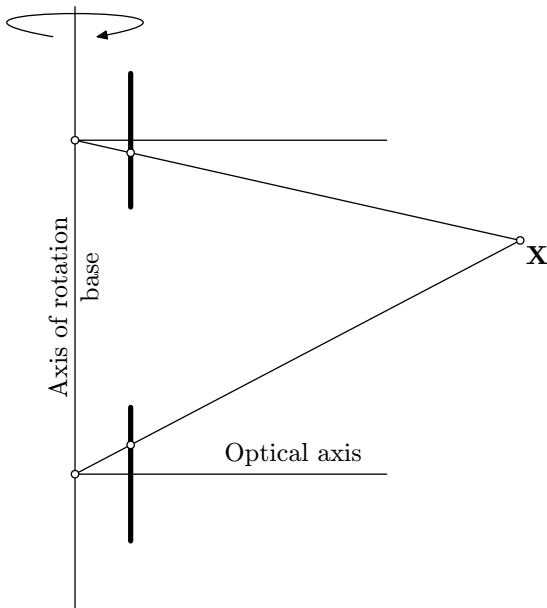

Figure 2: Two line-scan sensors have the same rotation axis and they are arranged one on the top of the other

A similar system was described by Murray in [28] who used panoramic images to measure depth. In [39], Petty et al. investigated a rotating stereoscopic imaging system consisting of two line-scan cameras.

Even though the capturing time is significantly reduced, those sensors are still not suitable for real time imaging.

2.3 Cameras with a single lens

"Fish-eye" lenses provide wide angle of view and can directly be used for panoramic cimaging. A panoramic imaging system using a fish-eye lens was described by Hall et al. in [22]. A different example of an imaging system using

wide-angle lens was presented in [35] where the panoramic camera was used to find targets in the scene. Fleck [14] and Basu et al. [3] studied imaging models of fish-eye lenses suitable for panoramic imaging. Shah and Aggarwal [40] extended the conventional camera model by including additional lens distortions. A camera with a wide-angle lens can be calibrated and then used for 3D computations when the standard camera model is extended employing distortion parameters [47]. However, such cameras are not full panoramic cameras due to limited field of view.

Greguss [20, 21] proposed a special optics to get a cylindrical projection directly without any image transformation. This optics is based on an annular lens with mirror surfaces, see Figure 3.
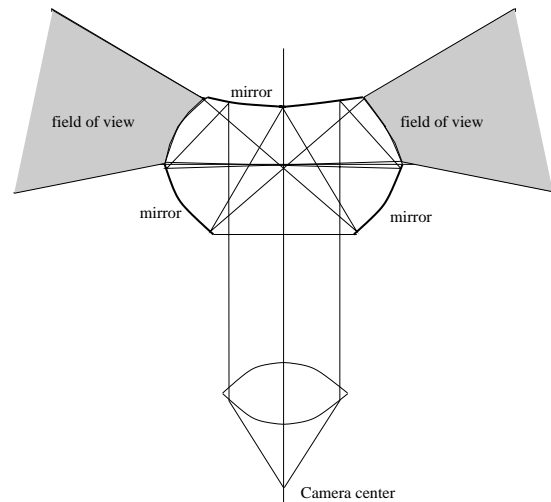

Figure 3: An annular lens is combined with mirror surfaces.

2.4 Cameras with a single mirror

In 1970's, Charles [11] designed a mirror system for the Single Lens Reflex camera. He proposed a darkroom process to transform a panoramic image into a cylindrical projection. Later, he designed a mirror so that the tripod holding the mirror was not seen in the image [10]. Various approaches how to get panoramic images using different types of mirrors were described by Hamit [23]. Chahl and Srinivasan [9] designed a convex mirror to optimize the quality of imaging. They derived a family of surfaces which preserve a linear relationship between the angle of incidence of light onto the surface and the angle of reflection into the conventional camera. Nayar et al. [31] presented several prototypes of panoramic cameras using a parabolic mirror in combination with an orthographic cameras. Geb [15] proposed a panoramic camera with a spherical mirror for navigating a mobile vehicle by a teleoperator. Recently, Hicks and Bajcsy [25] presented a family of reflective surfaces which provide a large field of view while preserving the geometry of a plane perpendicular to the mirror symmetry axis.

Chahl and Srinivasan [8] used a conical mirror with a standard camera and they proposed method for range estimation based on measuring of image deformations. The procedure is based on known motion of the panoramic sensor and on

a measure of image deformations that occurs along each azimuthal direction as a fraction of the deformation that would have occurred if the object was at a known, standard distance from the sensor. This algorithm estimates the range profile with the accuracy of 10% for ranges exceeding 100 times the separation of the sensor position (baseline).

Yagi et al. [49] used a conical mirror for a mobile vehicle navigation. They found corresponding vertical edges in panoramic images taken from different viewpoints and from their azimuthal shift the depth of the edges can be estimated. An acoustic sensor is then employed to detect whether there is a surface between the edges or not. The algorithm is used for creating of an environmental map or for navigation of the robot if the map is known.

Similarly, Yamazawa et al. [50] detected obstacles using a panoramic sensor with a hyperbolic mirror. They assumed that a robot moves within man-made environment and that the floor is almost flat and horizontal. They estimated a motion of the robot by establishing correspondence of features in consecutive transformed images. The input panoramic image is transformed to a perspective image with the center of the projection fixed in the focal point of the mirror and with the optical axis perpendicular to the floor. The apparent size of features on the floor is constant in this transformed images under assumption of flatitude of the floor. Location of a feature can be calculated form its projection to the transformed image. A robot motion is estimated from the displacement of the features. Moreover, unmatched features are recognized as unknown obstacles.

Svoboda et. al [44] used a hyperbolic mirror imaged by a conventional camera to obtain a panoramic camera with a single viewpoint and presented an epipolar geometry for the hyperbolic cameras. The epipolar plane π intersects the mir-
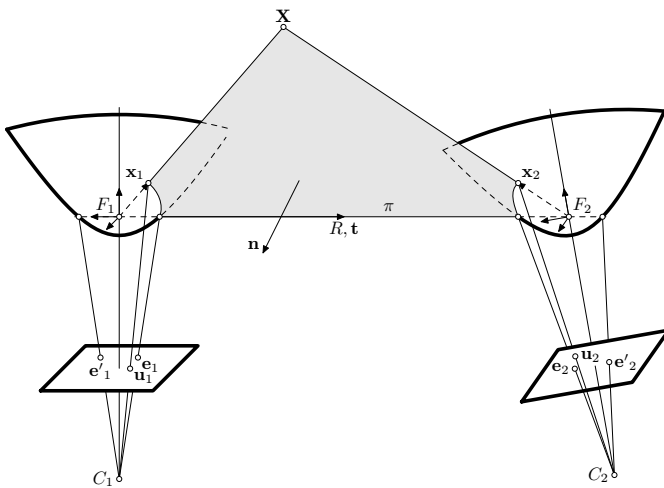

Figure 4: The epipolar geometry of two central panoramic catadioptric cameras with hyperbolic mirrors.

rors in intersection conics which are projected by a central projection into conics in the image planes. To each point $\mathbf{u}_1$ in one image, an epipolar conic is uniquely assigned in the other image, see Figure 4. Expressed algebraically, it brings us the *fundamental constraint* on the corresponding points in

two panoramic images

$$\mathbf{u}_2^T A \, \mathbf{u}_2 = 0 \,.$$

In a general situation, matrix A is a nonlinear function of the camera motion, of the point $\mathbf{u}_1$, and of the calibration parameters of a central panoramic catadioptric camera. This work was further extended for a panoramic camera with a parabolic mirror with an orthographic camera [36, 43]. Svoboda et al. also showed that the motion of these panoramic cameras can be estimated from coordinates of corresponding points [43, 45].

Similar epipolar geometry but for a special arrangement of panoramic was proposed by Chaen et al. [7] and by Gluckman et al. [17]. Their panoramic cameras are coaxially placed one above the other. The epipolar geometry is then considerably simplified and allows real-time computation. The epipolar lines are radial lines and become parallel when images are projected onto a cylindrical surface.

Gluckman and Nayar [18] estimated egomotion of a panoramic camera with parabolic mirror using optical flow. They re-projected optical flow to a sphere and then applied a standard algorithm developed for spherical optical flow.

An ubiquitous vision system was proposed in [34, 33]. This system comprises several panoramic cameras with convex mirror. This system enables viewers to observe a remote dynamic scene from any viewing perspective at any time instant. It can by typically used for monitoring of human activities.

2.5 Cameras with multiple mirrors

Nalwa [29] proposed a panoramic camera consisting of four-sided spire and four conventional cameras. His sensor is not usable for 3D computation.

Two planar mirrors placed in front of a conventional camera were used to compute depth by Arnspang et al. [1], Gosthasby et al. [19], and most recently by Gluckman et al. [16]. One camera with two planar mirrors is equivalent to two-cameras stereo, see Figure 5, but with a number of merits [16]. The point is reflected by mirrors and it is imaged twice in the camera. The system has two effective viewpoints and thus 3D information can be recovered.

A similar idea of two mirrors with one camera was proposed by Nene and Nayar [32]. They showed that the stereo system built from two mirrors and one camera can be constructed from any combinations camera-mirror preserving the single effective viewpoint. Real experiments with combinations perspective camera – planar mirrors and orthographic camera – parabolic mirrors were presented.

A double-lobed mirror and a conventional camera were used by Southwell et al. [42]. The mirror comprises two convex lobes with a conic profile. The field of view is over a hemisphere. At most elevations a point in environment is reflected in both lobes and is thus represented twice on the imaging plane of the camera. Since the object is effectively imaged from two different positions in space, the essence of binocular imaginery is present and depth can be recovered.

Kawanishi et al. proposed an omnidirectional sensor covering almost the whole view-sphere [27] consisting from two
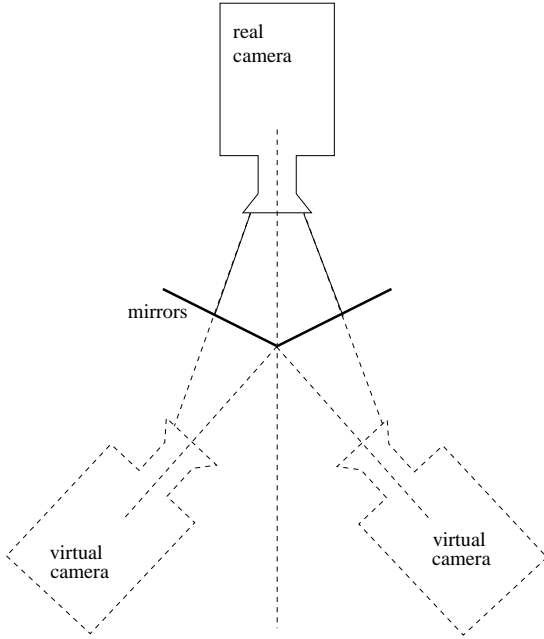
Figure 5: System with two planar mirrors and one camera can be viewed as a system with two cameras.

catadioptric panoramic cameras. One camera is constructed from six cameras and a hexagonal pyramidal mirrors. The panoramic camera preserves single effective viewpoint if it is carefully assembled. Stereo views are acquired by symmetrically connecting two such cameras. This complex system has two effective viewpoints and depth can be estimated. This camera offers high resolution of panoramic images however, it requires very complicated calibration and need a special hardware.

Nayar et al. [30] introduced a folded catadioptric camera that uses two mirrors and a special optics allowing for a very compact design. It was shown the the folded cameras with two conic mirrors are geometrically equivalent to cameras with one conic mirror.

3 Classification of existing cameras and comparison of their principles

With respect to whether the rays intersect or not, cameras can be classified as *central* (*Ce*) and *non-central* (*Nc*). We say that the camera is *central* or has a *single viewpoint* or a *projection center* if all rays intersect in a single point.

With respect to the field of view, cameras can be classified as *directional* (*Dr*), *panoramic* (*Pa*), and *omnidirectional* (*Od*). We say that the camera is *omnidirectional* if it has a complete field of view and its image covers the whole view-sphere. We say that the camera is *directional* if its field of view is a proper subset of a hemisphere on the view-sphere. For a directional camera, there exist a plane which does not contain any ray, hence the camera is pointed into the direction given by the normal of that plane. We say that the camera is *panoramic* if its field of view contains at least one great circle on the view-sphere. A panorama is seen around that great circle.

With respect to the construction, cameras can be classified as *dioptric* (*Di*) and *catadioptric* (*Ca*). The dioptric cameras use only lenses. The catadioptric cameras use at least one mirror but may also use lenses.

The most common cameras will be called conventional. We say that the camera is *conventional* if it is a central directional dioptric camera, in other words it is a pinhole camera which has the field of view contained in a hemisphere.

Table in Figure 6 compares the cameras described in Section 2 with respect to the classification of cameras defined above. It can be concluded that only the cameras with a single mirror provide a single viewpoint. The camera from [30] is not an exception because it is designed to be equivalent to a camera with one mirror. Cameras with more than one single effective viewpoint [1, 16, 19, 32] is based on cameras with the single viewpoint. Mirrors are arranged before appropriate camera enabling stereo computation.

The table also compares the approaches with respect to the number of conventional images needed to create a single panoramic image and with respect to the resolution of the final panoramic image.

It can be concluded that mosaic based cameras are characterized by no single viewpoint, long acquisition time, and high resolution. The exception is the system by Ishiguro [26]. The camera moves on a circular path and the optical axis in each position of the camera intersects the center of this circular path. They are therefore suitable for getting high quality panoramic images for visualization but they are not useful for an acquisition of dynamic scenes or for a computing a scene reconstruction. A similar situation holds for the cameras with rotating parts with that exception that the images are captured faster, though still not in real time.

Cameras with wide-angle lenses have no single viewpoint, are real-time, and have low resolution. The exception is the camera from [40], which has a single effective viewpoint but that is not a panoramic camera, only a directional one. Wide-angle lens cameras are suitable for fast panoramic image acquisition and processing, e.g. obstacle detection or mobile robot localization but are not suitable for doing a scene reconstruction. A similar situation holds for the cameras with multiple mirrors.

Cameras with a single mirror are real-time and provide low-resolution images. Only cameras with conic mirrors have a single viewpoint as it will be explained in the next section. These cameras are useful for low resolution dynamic scene reconstruction and ego-motion estimation. They are the only cameras for which epipolar geometry can be simply generalized.

4 Central panoramic catadioptric camera

Figure 7 depicts geometry of light rays for the catadioptric cameras consisting of conventional perspective cameras and curved conic mirrors. The rays pass through a camera center C and then reflect from a mirror. The reflected rays may, see Figure 7(b, c, d), but do not have to, see Figure 7(a), intersect in a single point F.

If they do intersect, the projection of a space point into the

Principle	Camera	Type[1]	3D[2]	Imgs[3]	Res[4]
Mosaics	QTVR	*NcPaDiC*	No	many	high
	VideoBrush, [38]	*NcPaDiC*	No	many	high
	Omnidirectional stereo, [26]	*CePaDiC*	Yes	many	high
Rotating parts	Line-scan cameras [4, 28, 39]	*NcPa—C*	Yes	many	high
Wide-angle lenses	Fish-eye [3, 22]	*NcPaDiC*	No	1	low
	Wide-angle lens [40]	*CeDrDiC*	Yes	1	low
	A special lens [20]	*NcPaCdC*	No	1	low
Multiple mirrors	Multiple planar mirrors with multiple cameras [27]	*CePaCdC*	Yes	a few	medium
	Two planar mirrors with one camera [1, 16, 19]	*CeDrCdC**	Yes	1	low
	Multiple conic mirrors with one camera [30]	*CePaCdC*	Yes	1	low
	Two conic mirrors with one camera (stereo) [32]	*CePaCdC**	Yes	1	low
Single mirror	Mirror for SLR camera [10]	*NcPaCdC*	No	1	low
	Convex mirror with constant angular gain [9]	*NcPaCdC*	No	1	low
	Parabolic mirror [31]	*CePaCdC*	Yes	1	low
	Hyperbolic mirror [44, 50]	*CePaCdC*	Yes	1	low
	Special mirror preserving plane geometry [25]	*NcPaCdC*	No	1	low

Figure 6: The comparison of the existing cameras. An asterisk * notes more than one effective viewpoint. These cameras are based on panoramic cameras with single viewpoint. [1]**Type** stands for the camera type, (*C*) Camera, (*Nc*) Non-central, (*Ce*) Central, (*Cd*) Catadioptric, (*Di*) Dioptric, (*Od*) Omnidirectional, (*Pa*) Panoramic, (*Dr*) Directional. [2]**3D** shows whether the 3D computation was conducted with the sensor. [3]**Imgs** gives the number of conventional images needed to create one panoramic image. [4]**Res** gives the resolution of the resulting panoramic image. The panoramic cameras with a single viewpoint are underlined.

image can be modeled by a composition of *two central projections*. The first one projects a space point onto the mirror, the second one projects the mirror point into the image. The geometry of multiple catadioptric cameras depends only on the first projection. The second projection is not so important as far as it is a one-to-one mapping. It can be seen as just an invertible image transform.

If the first projection is a central projection, the catadioptric camera has the same – perspective – mathematical model as any conventional perspective camera and all the theory developed for conventional cameras [13] can be used. Thus, the images from a central catadioptric camera can be directly used e.g. to reconstruct the scene or to estimate the camera displacement.

In 1637, René Descartes presented an analysis of the geometry of mirrors an lenses in *Discours de la Methode* [12]. He showed that refractive as well as reflective 'ovals' (conical lenses and mirrors) focus light into a single point if they are illuminated from other properly chosen point [24]. In computer vision, the characterization of curved mirrors preserving a single viewpoint was given by Baker and Nayar [2].

It can be shown [2] that the mirrors which preserve a single viewpoint are those and only those shown in Figure 8. All the shapes are rotationally symmetric quadrics: plane, sphere, cone, ellipsoid, paraboloid, or one sheet of a hyperboloid of two sheets. However, only two mirror shapes can be used to construct a central panoramic catadioptric camera.

Convex hyperbolic and convex parabolic mirror are the

only mirrors which can be combined with a conventional (central directional dioptric) camera to obtain a (one-mirror) central panoramic catadioptric camera.

Planar mirrors do not enlarge the field of view. Spherical and conical mirrors provide degenerate solutions of no practical use for panoramic imaging. For the sphere, the camera has to be inside of the mirror so that its center is in the center of the sphere. A conical mirror has the single viewpoint at its apex and only the rays which graze the cone enter the camera. An elliptic mirror cannot be used to make a panoramic camera because its field of view is smaller than a hemisphere due to the self-occlusion caused by the mirror if that is made large enough to reflect rays in angle larger than π. Parabolic and hyperbolic mirrors provide a single viewpoint as well as their field of view contains a great circle on the view-sphere.

5 Conclusions

We presented a survey of existing approaches for panoramic imaging. Panoramic cameras suitable for 3D computation in real time were pointed out. We proposed classification of panoramic cameras w.r.t. their construction, field of view, and existence of a single projective center. Panoramic cameras composed from a convex conic mirror and from a camera and having single effective viewpoint were emphasized. They capture whole panoramic images at any video rate and allow motion estimation and reconstruction of a scene. The disadvantage of low resolution is to be paid for these merits.
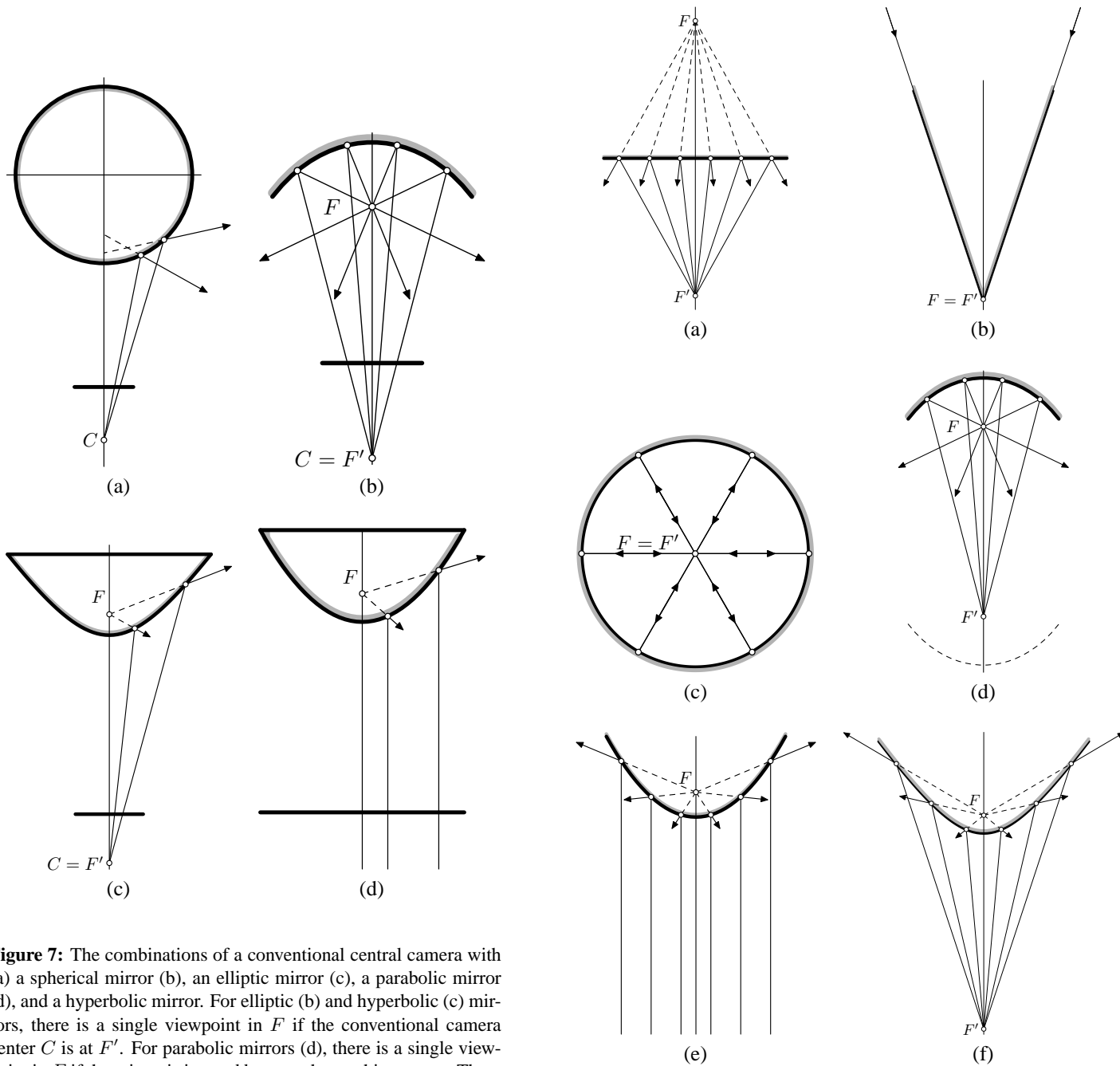
Figure 7: The combinations of a conventional central camera with (a) a spherical mirror (b), an elliptic mirror (c), a parabolic mirror (d), and a hyperbolic mirror. For elliptic (b) and hyperbolic (c) mirrors, there is a single viewpoint in F if the conventional camera center C is at F'. For parabolic mirrors (d), there is a single viewpoint in F if the mirror is imaged by an orthographic camera. There is no single viewpoint for a convex spherical mirror (a).

Figure 8: The mirrors which preserve a single viewpoint: (a) plane, (b) sphere, (c) cone, (d) ellipsoid, (e) paraboloid, (f) hyperboloid. The viewpoint is in F if the camera center is in F'.

The complete class of mirrors from which such cameras can be constructed was described.

Acknowledgment

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