Novel Hemispheric Image Formation: Concepts & Applications

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ABSTRACT

Panoramic and hemispheric lens technologies represent new and exciting opportunities in both imaging and projection systems. Such lenses offer intriguing applications for the transportation/automotive industry, in the protection of civilian and military areas, business. In this paper we describe a new optical design technique that provides a greater degree of freedom in producing a variety of hemispheric spatial light distribution areas. This innovative optical design strategy, of generating and controlling image mapping, has been successful in producing high-resolution imaging and projection systems. This success has subsequently generated increased interest in the high-resolution camera/projector and the concept of absolute measurement with high-resolution wide-angle lenses. The new technique described in this paper uses optimization techniques to improve the performance of a customized wide-angle lens optical system for a specific application. By adding a custom angle-to-pixel ratio at the optical design stage, this customized optical system provides ideal image coverage while reducing and optimizing signal processing. This novel image formation technique requires the development of new algorithms in order to view the panoramic image on a display without any residual distortion.
Keywords: Panoramic, panomorph, hemispheric, image forming, rendering.

1. INTRODUCTION

Natural or artificial vision systems process the images collected with the system's "eyes" or cameras to capture information required for navigation, surveillance, tracking, recognition and other tasks. Since the way images are captured determines the degree of difficulty in performing a task, and since most systems have to cope with limited resources, the image mapping on the system's sensor should be designed to optimize the image resolution and processing related to particular tasks. Different ways of sampling light, i.e., through different camera lenses, may be more or less powerful with respect to specific competencies. This seems intuitively evident in view of the variety of eye designs in the biological world.

Over the last several years, ImmerVision's research team has focused on the imaging process and the development of a new type of panoramic imager that is optimized to provide superior image mapping with respect to specific applications. We have shown that for surveillance scenarios[1], as an example, the camera system can be improved by increasing the resolution in the zone of interest as it relates to the system's overall capabilities and costs. This first application demonstrates a new way of constructing powerful imaging devices which, compared to conventional cameras, are better suited to particular tasks in various wide-angle vision applications, thus leading to a new camera technology.

2. HARDWARE: PANOMORPH LENS CONCEPT

Panoramic imaging is of growing importance in many applications. While primarily valued for its ability to image a very large field-of-view (180^o X 360^o), other characteristics, such as the ability to reduce the number of sensors, are equally important benefits of panoramic imaging. In addition, ImmerVision's "panomorph" lenses offer distortion control, which is considered a major enhancement to panoramic vision[2]. Specifically, the panoramic imager, equipped with a panomorph lens, can be designed to increase the number of pixels in the zones of interest using a patented distortion-control process. The main advantage of the ImmerVision patent is that it is based on a custom-design approach, simply because panoramic lens applications need to be designed to meet real and very specific needs. By integrating specific distortion control during the optical design stage, ImmerVision technology can produce a unique and highly efficient panoramic lens.

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The panomorph lens provides a full hemispheric field-of-view. In contrast with other types of panoramic imagers that suffer from blind zone (catadioptric cameras), low-image numerical aperture and high distortion, the panomorph lens is designed to use distortion as a design parameter, with the effect of producing a high-resolution coverage where needed, i.e., in the zone of interest.

In the design of an efficient panoramic lens, the coverage area is divided into different zones. A specific resolution requirement as well as a particular field of view is defined for each individual zone. Figure 1 shows a typical surveillance scenario.

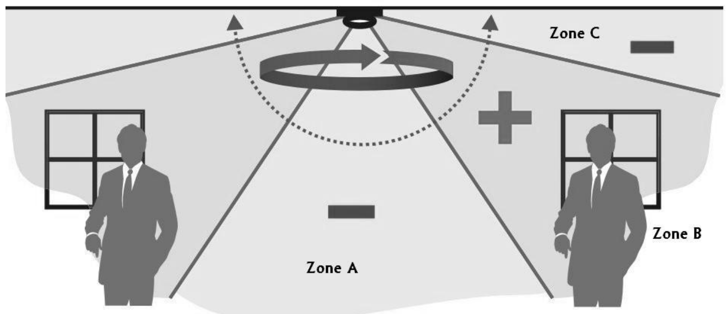


Figure 1: Specific security zones.

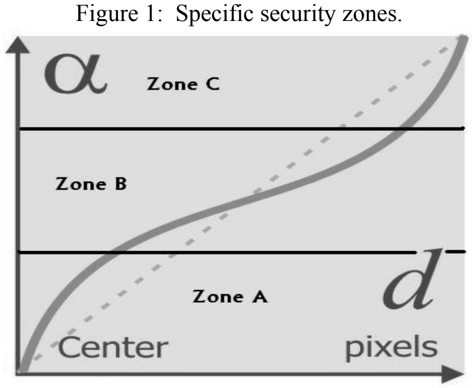


Figure 2: The ideal FOV (α) vs. the position (d) on the sensor for the scenario presented in Figure 1.

For this particular scenario, the panoramic coverage area is divided into five adjacent and continuous zones. Zones B and C are symmetrical with the vertical axis. The five adjacent zones, while still providing full hemispheric coverage together, each feature a different resolution requirement, as the most significant objects are in Zone B. (Zone B in a surveillance application enables facial recognition and identification.) An object in Zone B is also more distant from the camera than an object in Zone A. This means that the relative angular resolution (pixels/degree) in Zones A and B should be different.

For example: A human face in Zone B (located at 60 degrees from the vertical axis) will subtend an angle by half the amount that it would in Zone A (above the camera). To get the same number of pixels per face in both Zones A and B, the pixels/degree in Zone B must be twice the pixels/degree in Zone A. This means that the number of pixels required on the sensor to image Zone B is twice the number of pixels required to image Zone A.

It is difficult to evaluate the exact resolution as a function of the sensor, because this would depend on the resolution chosen for the zone of interest. However, if we define i zones (1 to n) where each zone covers an angle (θ_i) with a number of pixels (N_i) we can describe the resolution (R_i) for each zone:

$$R_i = \frac{N_i}{\theta_i}, \tag{1}$$

with the following limit conditions:

$$\sum_{i=1}^{n} N_i = \sum_{i=1}^{n} R_i \cdot \theta_i = \#\, pixels \; . \tag{2}$$

and

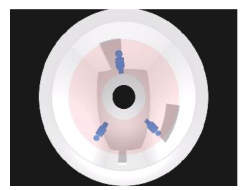
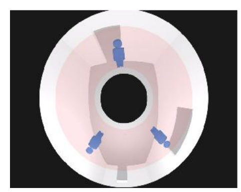
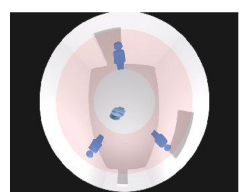
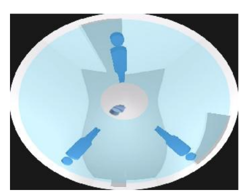
$$\sum_{i=1}^{n} \theta_i = \theta_{\max} \; , \tag{3}$$

showing that if you increase the resolution in the i zone, the result is less resolution in the other zones. In the next section we will see some examples of this.

Table 1 summarizes how the modern distortion-corrected panomorph lens offers a real benefit over other types of panoramic imagers (with at least 180 degrees field-of-view). As a comparison matrix we used the following:

The zone of interest is defined as 20° to 60° calculated under the horizon (0 degrees being the horizon), representing a typical zone of interest for a surveillance application. This comparison table is valid for any number of pixels on the sensor. The last column has been added to show the sensor footprint in viewing an interior scenario. As you can see, mirror, PAL and fisheye panoramic imagers use less than 60% of the sensor areas to image the FOV. In comparison, using anamorphic design, the panomorph lens uses up to 80% of the sensor to image the FOV, which is 30% more than any other panoramic imager on the market.

Table 1: Panoramic image formation comparison

	Sensor surface used	Pixels used in the zone of interest	Blind zone	Compactness	Sensor Footprint
Mirror Imager	57%	18%	Yes	No	
PAL (Panoramic Annular Lens)	51%	28%	Yes	Yes	
Fisheye Lens	59%	29%	No	Yes	
Panomorph Lens	**79%**	**50%**	No	Yes	

3. SOFTWARE: FROM PANORAMIC PICTURE TO STANDARD VISUALIZATION

To be effective, the panoramic video-viewing library corrects image distortion from cameras equipped with a panomorph lens for display and control of one or more standard views, such as a PTZ (Figure 3) in real time. The viewing library allows simultaneous display of as many views as desired from one or more cameras (Figure 4).

Figure 3: Real-time distortion-free display (left: original image produced by the panomorph lens).

Figure 4: Four PTZ views (left), and two strips to display a 360° total camera surround in one single view (right).

Consequently, the viewing process must unwrap the image in real time in order to provide views that reproduce real world proportions and geometrical information. The algorithms can be customized and adapted for each specific application, which is then related to human vision (display) or artificial vision (analytic function).

The viewing process can be decomposed into three main steps:
- the definition of the panomorph geometrical model (PGM) associated to each custom panomorph lens application;
- the projection of the recorded image onto the PGM to provide a discretized mapping based on the recorded pixel position on the sensor;
- finally, the rendering, which uses well-known standard rendering techniques.

3.1 Panomorph Geometrical Model (PGM)

The image produced by each panomorph lens is unique to its application. The image mapping can be defined by a unique 3D geometrical model (Panomorph Geometrical Model, or PGM), which reproduces the panomorph lens design characteristics.

The PGM is a geometric representation (surface) of the relative magnification of the lens as a function of the angles, expressed in spherical or polar coordinates (R, θ, ϕ). In other words, if the surface is represented by vector R, the length of the vector is proportional to the lens magnification (resolution) in the direction defined by the polar angles. This model depends on lens parameters such as the anamorphic ratio, the field of view, as well as position, size, and the magnification in the zones of interest.

The PGM is a mathematical transformation of the image footprint I(u,v) into a surface S(R,θ,ϕ) representation using spherical coordinates:

$$I(u,v) \rightarrow S(R,\theta,\phi), \quad (4)$$

3.1.1 Anamorphic ratio

The anamorphic ratio is used only as a scale factor, which is function of the angle ϕ (Figure 5) This angle defines the azimuth direction of the recorded image taken by the panomorph lens.

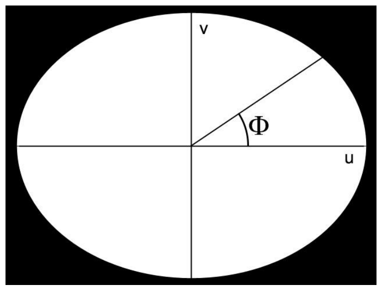


Figure 5 : Panomorph elliptical footprint I(u,v); scaling defined with ϕ angle.

3.1.2 Field of view

The field of view, or FOV, determines the angular limit (theta) of the PGM. The FOV of the panomorph lens is about 180 degrees and can be more or less, depending on the application. Figure 6 shows two schematic PGMs with 180 degree and 250 degree FOVs respectively.

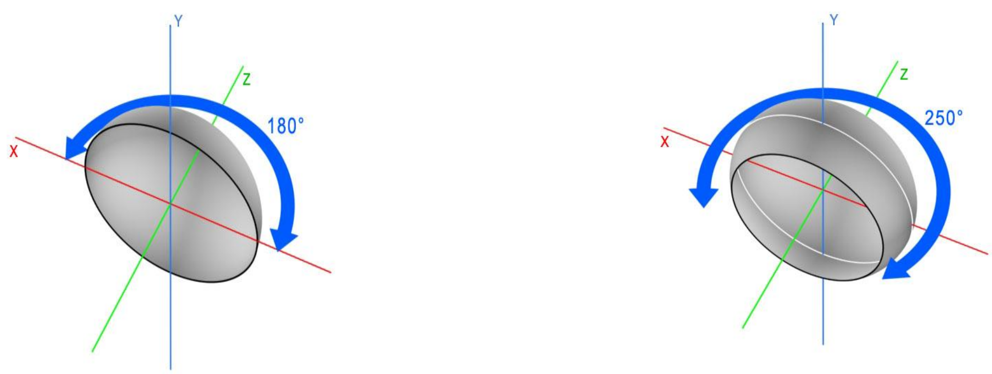


Figure 6: PGM with 180 and 250 degree FOVs respectively.

3.1.3 Distortion

The panomorph lens uses distortion as a design parameter, in order to provide high-resolution coverage in a specific zone of interest. In other words, the FOV can be divided into different zones, each with a defined resolution, which all respect the equation 1 to 3. The characteristic of each zone is defined by its specific angular extension and relative resolution.

To illustrate the impact of the distortion profile on the PGM, we will study two examples. In these examples, the FOV is 180 degrees wide, the zone of interest is 30 degrees wide, and the resolution is two times greater in the zone of interest than it is in the rest of the FOV (2:1). From one example to another, only the position of the zone of interest changes .

Example 1:

The first example is based on the design of a front view camera (Figure 7). In this case, the zone of interest is the central part of the image, even though the entire 180-degree FOV is still recorded. A panomorph lens with this feature can be used on a cell phone (for video conferencing) or on an ATM surveillance camera.

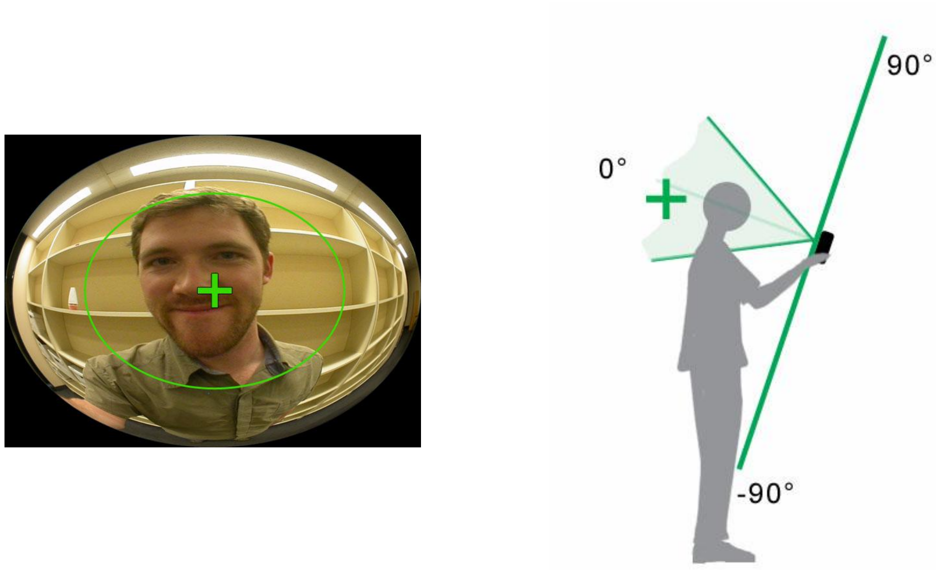


Figure 7: Panomorph lens for a front-view camera.

The panomorph lens resolution in the central zone is twice that of the resolution in the periphery. Figure 8 shows the image footprint with the proper resolution for each zone. On the left of Figure 8, we have a Cartesian plot of the resolution as a function of the view angle (defined from the centre). We note that a transition zone exists between the central and the periphery areas. Theoretically, this transition can be very small, but as the panomorph lens is a real product, this transition can extend over 10 degrees.

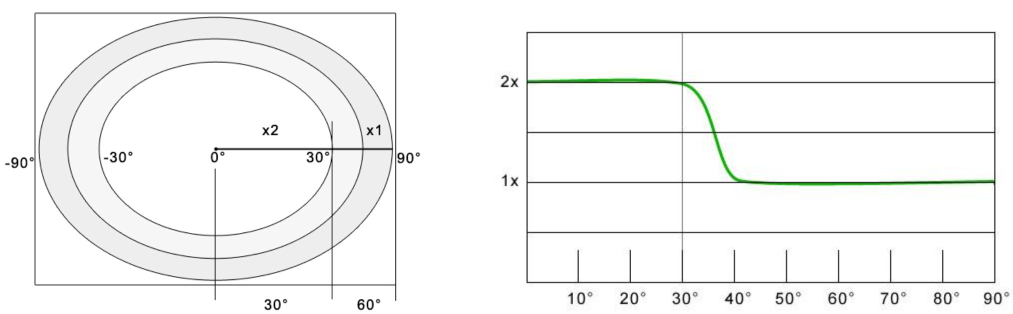


Figure 8: Image footprint (left) and resolution graph for the front-view panomorph lens.

As defined, the PGM in the polar coordinate space represents the resolution of the panomorph lens, or a surface in space where the spatial resolution is constant in terms of azimuthal (θ) direction. Mathematically, it means that the Cartesian graph (Figure 8, right side) is transposed into the spherical coordinate plane. Figure 9 shows the 3D PGM representation.

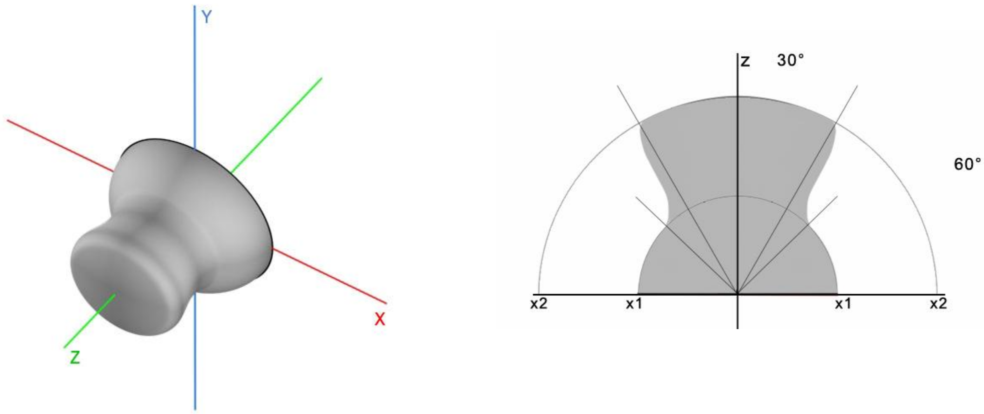


Figure 9: 3D PGM (left), 2D view in Y-Z plane.

Example 2:

The second example demonstrates a panomorph lens optimized for video conferencing, where the zone of interest is not in the centre but on the edge of the field of view. Figures 10, 11 and 12 show the image footprint, the resolution and the corresponding PGM respectively.

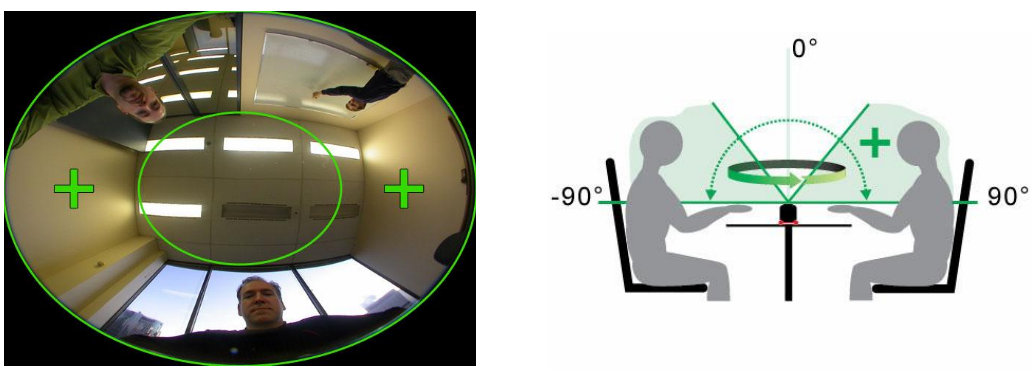


Figure 10: Panomorph lens for video conferencing.

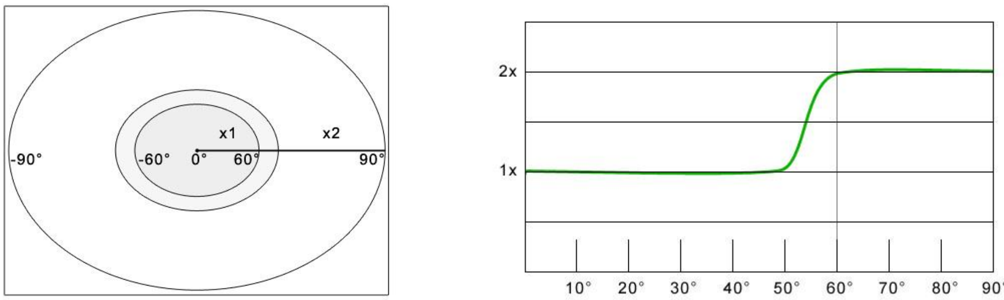


Figure 11: Image footprint (left) and resolution graph (right) for the video-conferencing panomorph lens.

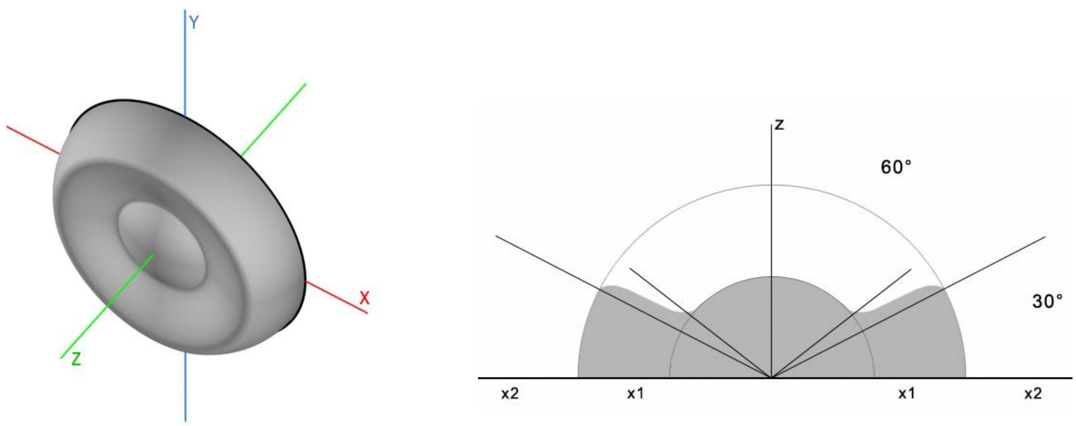


Figure 12: 3D PGM (left), 2D view in Y-Z plane (right).

3.1.4 Sensor resolution

A panomorph lens can be used with any sensor format (VGA, XGA, etc.) as long as the lens performance matches the Nyquist frequency of the sensor. The number of pixels will have an impact on the discretization of the model for the PGM. Up until now, the PGM has been defined by a continuous mathematical surface, however, on sensor we have a finite number of pixels.

The continuous PGM will be sampled by the pixels. The number of pixels required to map the entire surface of the PGM is equal to the number of pixels on the sensor. Figure 13 shows a 2D sampling of the PGM using only 22 elements. You should note that the pixel dimension is constant over the entire PGM, and the pixels are always perpendicular to the direction of regard (direction of the vector R). With a higher number of pixels, the discrete PGM will be closer to the continuous PGM, as shown in Figure 14.

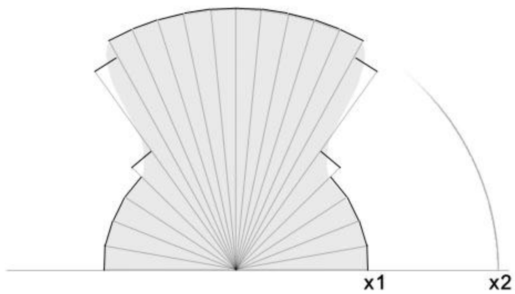


Figure 13: Discrete PGM with 22-unit (pixels) sample

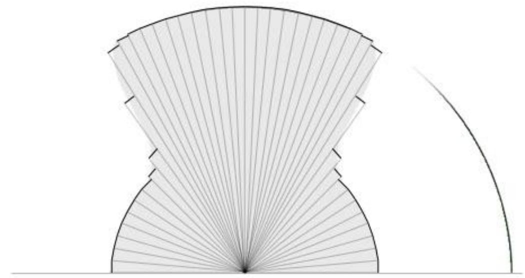


Figure 14: Discrete PGM with 44-unit (pixels) sample

3.2 Projection of the panomorph image onto the PGM

The image I (u,v) from the panomorph lens is projected onto the PGM, as shown in Figures 13 and 14. The final result is a discrete surface.   The PGM is mapped with the panomorph image and can then be viewed using any classical 3D visualization techniques.

Each pixel of the panomorph image is projected onto a discrete element of the PGM. The pixel position in the 3D space (on the surface) represents the real object position in the recorded scene. The projection uses the adapted azimuthal projection technique[4] with anamorphosis and distortion parameters added.

3.3 Standard rendering of the PGM

The final goal is to visualize the recorded scene without distortion. The PGM can be used to achieve this goal using a standard algorithm[3]. A virtual camera is placed at the central position (0,0,0). Viewing the scene with this virtual camera requires first selecting the angle (θ,ϕ) of viewing direction. Figure 15 shows two cameras pointing in two different directions. The camera pointed at the centre of the PGM will show a total of four elements (1D, 16 elements in 2D). The camera pointed at the edge of the PGM will show only two elements. This is the distortion effect. The resolution is twice in the centre than it is on the edge. A zoom can also be applied to change the Δθ and provide virtual functionalities.

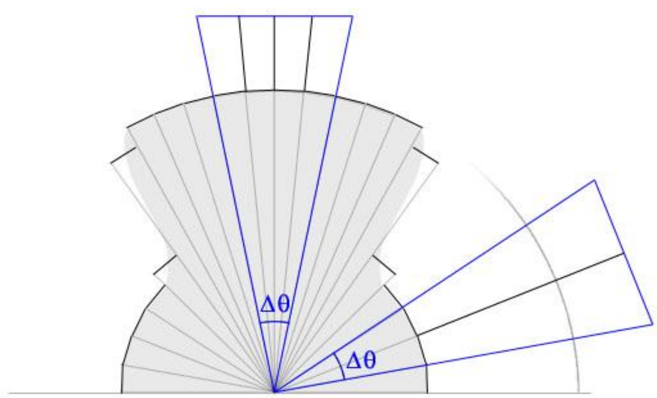


Figure 15: Virtual camera at the centre of the mapped PGM

The following Figure 16 shows the final projection on a 2D plane of each virtual view. This 2D view can be sent to a display monitor.

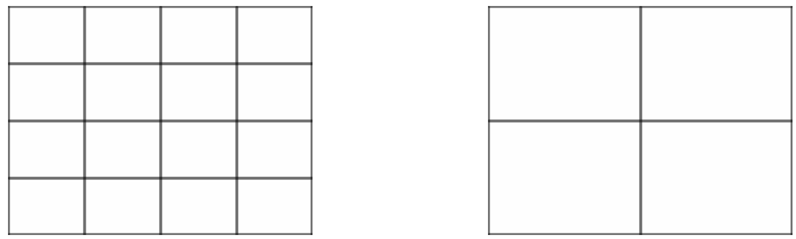


Figure 16: Viewing pixel as a function of the pointing direction of the virtual camera (left = centre, right =edge).

4. CONCLUSION

Panomorph lens development has led to a new type of panoramic imager that can be customized to enhance any panoramic imager application. The design features full hemispheric coverage, better use of sensor areas and increased resolution in the zone of interest. During the last decade, the ImmerVision research team has developed a custom viewing process perfectly adapted to the panomorph lens. The viewing process is composed of three steps. The first step is the definition of the panomorph geometrical model (PGM) associated with each custom panomorph lens application. The second step is the projection of the recorded image onto the PGM to provide a discretized mapping based on the recorded pixel position on the sensor. The third is a final rendering based on an azimuthal projection technique. The algorithms developed over the years have been optimized for use on small CPU and memory, enabling embedded processing. The algorithms are available thru a SDK running on Linux and Windows operating systems, and can be ported to many processors and systems.

REFERENCES

1. Thibault S. Enhanced Surveillance System Based on Panomorph Panoramic Lenses. *Proc SPIE* Vol. 6540, paper 65400E, 2007.
2. Thibault S. Distortion Control Offers Optical System Design a New Degree of Freedom. *Photonics Spectra* May 2005, pp. 80-82.
3. Radu HORAUD Olivier MONGA , Vision par Ordinateur - Outils fondamentaux, ,Ed. Hermès, 1995
4. Weisstein, Eric W. "Azimuthal Equidistant Projection." From *MathWorld*--A Wolfram Web Resource. http://mathworld.wolfram.com/AzimuthalEquidistantProjection.html