New generation of high-resolution panoramic lenses

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New Generation of High-Resolution Panoramic Lenses

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ABSTRACT

During the last few years, innovative optical design strategies to generate and control image mapping have been successful in producing high-resolution digital imagers. This success has, in turn, increased the interest in the high-resolution camera and absolute measurement with high-resolution wide-angle lenses. This new generation of panoramic lenses includes catadioptric panoramic lenses, panoramic annular lenses, visible/IR fisheye lenses, anamorphic wide-angle attachments, and visible/IR panomorph lenses. Given that a wide-angle lens images a large field of view on a limited number of pixels, a systematic pixel-to-angle mapping will help the efficient use of each pixel in the field of view. In this study, the various relevant tradeoffs will be detailed and the advantages and disadvantages of panoramic lenses will be discussed. Of particular concern in the optical design of a panoramic imager is the uniformity of the image quality; because two hemispherical images can be stitched together digitally to form a complete 360-degrees X 360-degrees image, the performance of the lens at 90 degrees (preferably more than 90 degrees) is just as important as at the centre. Lateral colour, edge compression (distortion) and severe drop-off of the relative illumination can also present significant image defects and may cause seams in the immersive image. Finally, we will present various current scenarios where a high-resolution panoramic imager will be most advantageous.

Keywords: wide-angle lens, panoramic, panomorph, immersive, anamorphic.

1. INTRODUCTION

Photography was invented by Daguerre in 1837, and at that time the main photographic objective was that the lens should cover a wide-angle field of view with a relatively high aperture[1]. However, these requirements were only satisfied after many years of development. Today, panoramic lens designers are facing the same challenge but with a different goal -- to efficiently control the image mapping to produce high performance digital imagers.

This paper will describe the most recent development in high-resolution panoramic imagers. A brief outline is given of the more significant types of wide-angle lens that have been developed since the invention of photography some 175 years ago. The most recent lenses will be studied, including their applications in automotive vehicles, projection devices, security and defence, to name a few. Design challenges will also be discussed.

2. FROM REVERSE TELEPHOTO TO THE MODERN PANORAMIC LENS

2.1 The reversed telephoto & wide-angle lens

Adding a large negative meniscus element mounted on the head of a compact positive component will create a system with a long back focal distance and a short focal length, which is namely a reversed telephoto. In the past, these types of lenses were very popular, since any lens used with a 35 mm camera had to have a back focal length of at least 35-40 mm to clear the rocking mirror on the camera. Consequently, any lens with a focal length of less than approximately 40 mm is a reversed telephoto type. Fortunately, this type is favourable for a wide-angle field of view. Wide-angle lenses are generally considered to be lenses with a field of view greater than 60 degrees.

However, for angles larger than 100 degrees, the barrel distortion becomes difficult to correct. With an extended field of view, the reversed telephoto lens will cover a hemispherical field -- we will call such lens a fisheye lens. This lens is

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not really an extension of a wide-angle lens. The fisheye lens has inherent large distortion, but this distortion should not be considered an aberration but rather the result of the projection of a hemispheric field on a circle, which is not possible *without* distortion.

2.2 Sky lens and fisheye

The classical example of a fisheye lens "type" of image formation is an actual fish eye under water[2-3]. Robert W. Wood described in his book, *Physical Optics* (1911), a water-filled pinhole camera that was capable of simulating a fish's view of the world (Figure 1A). Bond added a hemispheric lens with a pupil at the centre of the curvature in place of the water (Figure 1B). In 1924, Hill developed his Sky lens by adding a diverging meniscus lens (Figure 1C) before the hemispheric lens to improve the field curvature (thereby reducing the Peztval sum). This lens was a first prototype of the modern fisheye lenses (Figure 1D) which was patented by Schultz (1932) and Merté (1935). Some 40 years later, the now famous afocal wide-angle door viewer was patented[4].

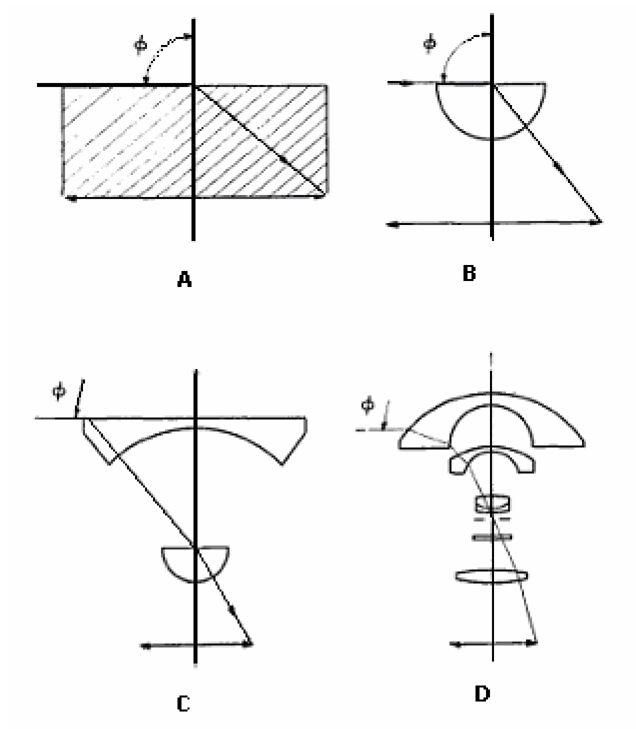


Figure 1 A-D: Development of fisheye lens[2]

At that time a severe drawback was encountered when the fisheye was facing up or down, because in these positions the subject of interest might have appeared at the edge (large angle) of the field where the barrel distortion is very large. We will see later in this paper how the modern high-resolution lens design can now control this distortion, to improve the field coverage of a panoramic lens and solve this historical concern.

2.3 Flat cylinder perspective

Motivated by the need to record a distortion-free panoramic image, the flat cylinder perspective was born[5]. The panoramic feature is different from the fisheye in that there is no longer imaging of a hemispheric field onto a circle, but instead a 360^o cylindrical field of view imaged onto a two-dimensional annular format (Figure 2). This kind of image will still suffer from severe image deformation. The annular image produced by such a geometrical transformation will not produce (theoretically) radial distortion (cylinder height); however, the horizontal (circle circumference) direction will suffer from compression, from the edge to the centre of the image plane.

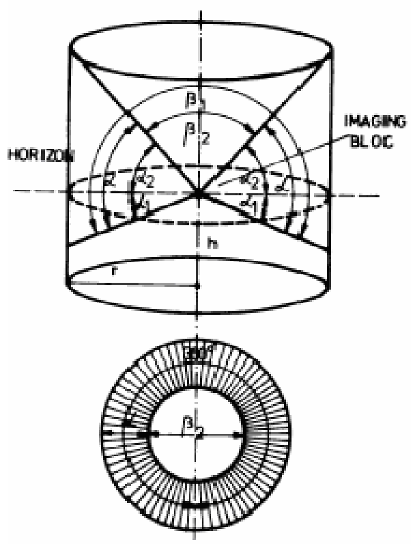


Figure 2: Flat cylinder perspective

There are many known panoramic viewing optical arrangements that use this cylinder perspective. In particular, Greguss' patent[6] was one of the most promising approaches. Figure 3, which shows a block arrangement, is a copy of an actual drawing included in the patent. Rather than a fisheye, the panoramic block field-of-view is centred around a plane which is orthogonal to the optical axis at the expense of the on-axial imagery. This configuration allows a limited field-of-view in the radial direction (vertical in the field), where the imagery is relatively good to a first-order approximation. Thus we can expect an object space mapping onto the image plane based on a linear f-theta relationship. The main disadvantages are the limited dimension of the annular image on the sensor and the blind zones above and below the device. From an optical design point of view, it is difficult to achieve the very low f-number required for low light levels or IR applications.

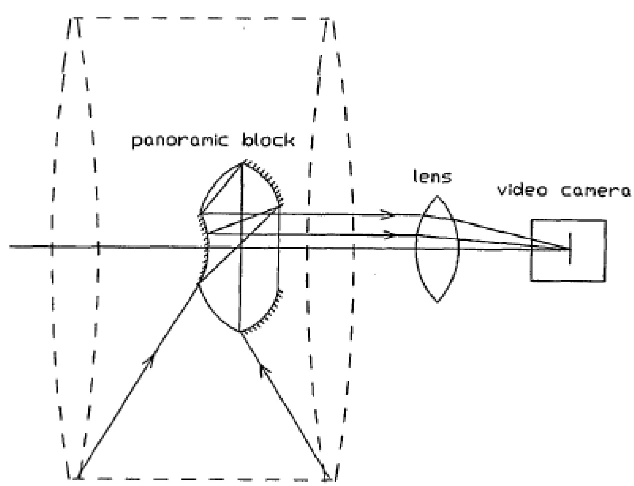


Figure 3: Optical arrangement proposed by Greguss

Another approach to getting a flat cylinder perspective is to rotate a conventional camera around the vertical axis. This technique requires several frames (with proper synchronization) for the camera to complete a full rotation. This method is useful and widely used today in the production of high-quality panoramic photography. The technique is time consuming because it requires a long time for the image acquisition and extensive image processing to stitch all the images together.

2.4 Multi-lens and wide-angle catadioptric lens

Ideally, the goal in panoramic imaging is to be able to capture the entire scene in a single image from a single camera. This ideal imaging system would allow more than one hemisphere to be visible, similar to some insects' vision system[7]. In reality, this can be achieved by using a multi-lens system with individual consecutive fields-of-view, totally covering a hemisphere[8] (Figure 4). One of the major problems with this concept is the very complex image processing required, particularly on a moving platform.

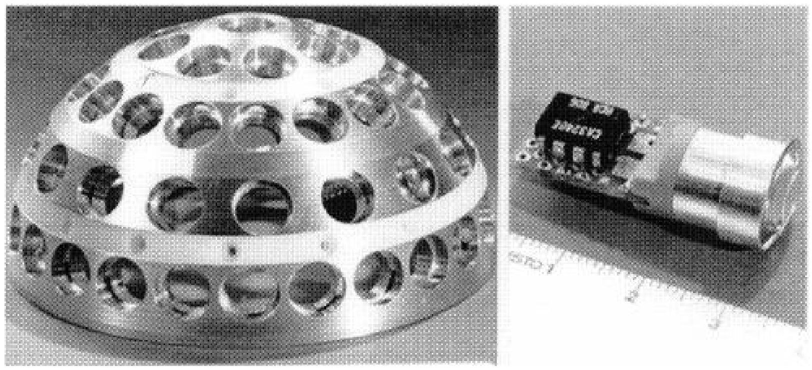


Figure 4: Hemispheric alerting demonstrator, working in the NIR, developed by TNO-FEL

Reflective optics offer an alternative to panoramic imaging. A standard camera placed below a convex mirror will image a large field-of-view, the properties of which will depend on the shape of the reflective surface[9]. This approach has been used predominantly for producing panoramic TV displays. The projected images are captured by another equivalent optical arrangement (the reversibility property of light). For such an arrangement, the surface shape is not important as long as the projection mirror and the acquisition mirror are equivalent.

Systems with spherical and conical mirrors have been used to capture wide-angle images for robotics and machine vision devices. The mirror shape design is important and can provide a global image on the sensor, which presents a polar image with elevation and azimuth linearly distributed to radius and angle respectively[9]. However, the imager using a front mirror exhibits a number of constraints. The position and alignment of the camera are important for the acquisition of undistorted images. Regions above and below the camera cannot be imaged. The assembly is quite fragile; you have to maintain the camera beneath the reflective surface with tiny arms (with the potential for shadow). Finally, the light captured by the reflective surface is dependent on the radial angle.

Recently Kweon *et al*[10] have developed a wide-angle catadioptric lens with a rectilinear projection scheme. The lens was designed for a miniature camera with a 1/3'' colour CCD sensor (70 lp/mm) video graphics. For an application that requires a field-of-view of less than 180 degrees, a wide-angle rectilinear lens can be an interesting solution. Rectilinear means that straight lines will appear as straight on the sensor. The wide-angle lens will respect the relation between the pixel (r) and the angle (θ) as $r = f \tan \theta$ as a standard camera lens. Again, the field-of-view is not a full hemisphere. The field-of-view of Kweon's imager is limited to 151 degrees, and the distortion is less than 1%. The f-number is limited to 4.5, as the authors were not able to lower the f/number. Figure 5 shows a photograph of the catadioptric lens and a sample video image.

Figure 5: Photograph of the lens with the camera on a pole (left sample image).

2.5 IR panoramic lens

Imaging infrared systems operating in the long range wavelength infrared (LWIR, 8-12 um) band detect the heat emissions of objects rather than reflected visible light, and are therefore able to image in darkness, dust and smoke. This kind of imager has long been used to extend the useful range of operation conditions from those of visible sensor systems. IR imaging also provides a thermal signature of different target types, which facilitates better classification beyond the limits set by a camera's spatial resolution.

Among others, the advantages of panoramic IR imagers include increased area coverage with fewer cameras, instantaneous full horizon detection, and location and tracking of multiple targets simultaneously. However, typical fields of view of LWIR imagers run from very narrow sub-degree fields-of-view, which are useful for high-resolution detection (long range), to 40-50 degree fields-of-view commonly used for wider angle surveillance applications.

A few IR panaromic imagers have been developed during the last few decades. The Automatic Panoramic Thermal Imaging Sensor (APTIS) is an IR panoramic imager designed to be used with a sensor network[11]. The APTIS design features automatic detection, location and tracking of multiple targets. The system is a catadioptric configuration designed to match the resolution of 640X480 pixels. However, as discussed by Gutin[11], designing a compact IR panoramic catadioptric optics with low aberration and high numerical aperture presents a real challenge.

In addition, a design study has been done comparing different types of panoramic IR concepts. In particular, Powel[12-13] designed different types of IR imagers for a 3-5 um band. He identified two serious candidates for his application. The first one was a conventional fisheye lens followed by some relay optics, and the second was a panoramic shell arrangement. The panoramic shell arrangement is similar to the panoramic block, with minor differences. The main advantages of all refractive solutions were the small diameter and the fact that there was no blind zone in the field-of-view.

In a recent application, DRS & ORA[14] have studied the optical design of a fast panoramic lens imaging system for the full 3-12 um band. They concluded that a refractive design solution is the most compact and practical means of achieving a panoramic field-of-view in the IR. Nonetheless, a catadioptric design using a highly curved reflective component in front of a refractive design is undesirable from the point of view of fabrication and packaging, and offers no advantage over a more conventional all-refractive solution due to the diameter and the complexity of the refractive components required to correct the mirror aberrations.

2.6 Distortion-control lens & panomorph lens

Panoramic imaging is of growing importance in many applications. While primarily valued for its ability to image a very large field-of-view (180° X 360°), other characteristics, such as its ability to reduce the number of sensors, are also important benefits of panoramic imaging. Modern panoramic lenses are able to add a distortion control which is considered a major enhancement in panoramic vision[15]. Specifically, the panoramic imager can be designed to increase the number of pixels in the zones of interest using a distortion control approach, which is a process patented by ImmerVision. The main benefit of the ImmerVision patent is that it is based on a custom-designed approach, simply because the panoramic lens application should be designed to meet real and very specific needs. By including specific distortion during the optical design stage, ImmerVision can produce a very unique and more efficient panoramic lens.

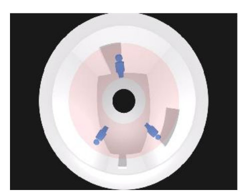
The Panomorph lens[16] uses this distortion control approach and an anamorphic image mapping to provide a unique full hemispheric field coverage. In contrast to other types of panoramic imagers that suffer from blind zone (catadioptric cameras), low-image numerical aperture and high distortion, the Panomorph lens uses distortion as a design parameter, in order to provide a high-resolution coverage where it is needed. It also features an anamorphic image mapping of the full hemispheric field, which produces an ellipse image footprint rather than a circle (or annular footprint) as do all other types of panoramic imagers. This feature provides an immediate 30% gain in pixels used on the sensor (the ellipse footprint matches the 4:3 ratio of a standard CCD or CMOS imager). The combination of distortion control and anamorphic design provides an important gain in resolution, and an advantage over all other types of panoramic imagers.

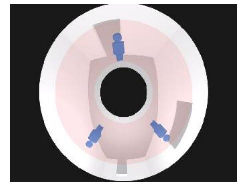
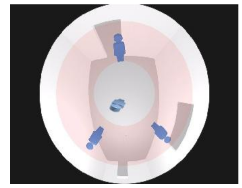
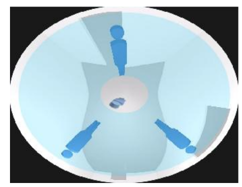
The following table summarizes how the modern distortion corrected lens has a real benefit over other types of panoramic imagers (at least 180 degrees field-of-view). As comparison matrix we used:

- percentage of sensor surface used to image the field-of-view (FOV)
- percentage of the pixels of the sensor used to image the zone of interest
- blind zone
- compactness

The zone of interest is defined as 20° to 60° calculated under the horizon (0 degrees corresponds to a horizon), which is 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 provide the sensor footprint to visualize a particular indoor scene. Mirror, PAL and fisheye panoramic imagers use less than 60% of the sensor areas to image the FOV. Using anamorphic design, the panomorph lens uses up to 80% of the sensor, which is 30% more than any other panoramic imager on the market. The modern imager panomorph lens offers important advantages over other type of panoramic technologies.

Table 1: Sensor comparaison matrix

	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	

Modern development also includes a new design approach to correct for fisheye distortion for a motor vehicle vision system application[17], where the image distortion (rectilinear or F-tanθ) is less than one percent for about eighty percent of the image. This is achieved by adding a complex aspheric element near the image plane, or in front of the lens assembly. Another way to correct distortion is used by Theia Technolgies[18]. This different approach includes a wide-angle lens stage and a relay lens stage. The wide-angle lens images the wide field-of-view in a distorted intermediate image plane, which is then re-imaged by the relay to the sensor. The distortion caused by the relay lens compensates for the distortion caused by the wide-angle lens. The final image presents a less-distorted or non-distorted image. As with the imager presented in Figure 5, the field-of-view is not a full hemisphere due to theoretical limitations of the rectilinear correction.

3. DESIGN AND TEST CHALLENGE

New panoramic and immersive digital imaging developments have generated increased interest in high performance camera lenses. In this section, we will discuss some design challenges when designing modern panoramic imagers.

3.1 Resolution, f/number and lens dimension

To maximize the panoramic picture, the image quality of the imaging system should be limited by the sensor resolution. The resolution (minimum resolvable object) of a panoramic lens should match or be smaller than the sensor pixel size. In addition, the performance of the lens at the edge (90 degrees) is just as important as it is at the centre of the image in order to allow two hemispherical images to be stitched together to form a complete 360-degree X 360-degree image. Consequently, the image quality should be as uniform as possible.

In catadioptric panoramic imagers, front reflector aberrations may significantly compromise the image resolution at high aperture settings, which typically are reduced by imaging at a low-image numerical aperture (high f/number). It is well known in optics and photography that at small aperture settings, any lens operates in near-pinhole mode, and this approach reduces aberrations but also comes with a significant loss of light. Higher image quality is easy to achieve with large mirrors placed at long distances from the camera. In other words, larger catadioptric panoramic cameras have lower aberrations and produce better images, at the expense of the overall larger size of the optics. However, a complex multi-element refractive group would correct the large aberrations generated by the front mirror. The mirror shape would also present fabrication challenges.

High apertures (low f/number or fast optics) are required in low-light imaging conditions and thermal imaging. In low light levels, large apertures translate into higher light throughput. In thermal imaging, sensitivity considerations demand a low f/number of about f/1.0 (or even f/0.8).

High aperture is also required from a resolution point of view. As mentioned above, the lens resolution should match the sensor pixel size. However, the pixel size tends to be smaller and smaller with the development of mega-pixel sensors. At some point, the pixel size will match the diffraction limit of a perfect lens. In other word, the lens should be diffraction limited (mostly perfect, no aberration) in order to be used with the high-resolution sensor. The diffraction limit is proportional to the wave length and f/number. In the visible, the diffraction spot size is about 1 X f/number (in um), so if the f/number is 2.0, then the diffraction spot size will be 2 um ($2X10^{-3}$ mm) and 4.0 um if f/4. The pixel size of a 1.2 MPx – 1/3'' sensor is about 3.8 um!

The diffraction effect can also affect the size of an optical system. For example, diffraction spot size in the LWIR (Long Wave IR, 8-12 um) is about 20 X f/number. With an f/1 lens, the diffraction spot size will be about 20 um. Consequently, the focal plane array for the LWIR is very large compared to the visible, and the lenses are also bigger. Getting a compact solution for an IR system is a major concern. Refractive design solution is actually the most compact and practical means of achieving a panoramic infrared system operating over the LWIR band[14].

Due to the large field angles, the aberration most difficult to correct is lateral colour. Because the front element in a refractive design is large (see Figure 1D), it is important to select economical and available glasses for these elements. Generally a common crown is used in the visible band (N-Bk7 or B270). The chromatic aberration of the chief ray can best be corrected by the use of exotic glass in the front group, with limited success[19]. A more useful technique seems to be the addition of a small negative achromat in front of the stop to correct the lateral colour.

3.2 Relative illumination

It is known that for off-axis image points, even when there is no vignetting, the illumination is lower than it is for the image point on the axis. This effect is known as the "cosine fourth law" which can reduce the illumination by $\cos^4\theta$, where θ is the field-of-view angle. This effect can be dramatic for panoramic imaging systems, but this is not the case. The panoramic lens construction is such that the apparent size of the pupil increases for off-axis points. Additionally, the large amount of barrel distortion keeps the angle in the image space smaller than one would expect from the corresponding field angle in the object space. At the extreme end, certain panoramic lens make use of these principles to increase the off-axis illumination.

3.3 Pupil aberration

A major problem in the design process of a panoramic lens is proper consideration of pupil aberration. At large field angles, the location of the entrance and exit pupils may be substantially different to the paraxial prediction. For example: In wide-angle optical lenses, as one moves off axis, it is usually necessary for the entrance pupil to move from the interior of the lens towards the front-lens vertex, if the incoming rays are to get into the optical system. The entrance pupil may also increase in size and may move off axis and tilt. This change in size can compensate for the loss of illumination due to natural cosine fourth law.

One consequence of this pupil shift with the off-axis angle is the potential for ray-tracing failures during the optimization process. The software iteration routine used to find the appropriate starting point for a chief ray to pass through the centre of the aperture stop becomes unreliable. As a result, the ray trace cannot be performed reliably.

One potential solution is to reverse the lens and trace through the object space from the focal plane. However, it is not possible from an analysis standpoint to optimize the lens for its intended use, in order to optimize criteria like spot size in the sensor plane. Recently, Spencer proposed a method designed to make this easier[14]. It consists of a strategy to set up the lens with several zoom positions, each corresponding to a single different zoomed field-of-view with a variable entrance pupil position. This method gives a very stable convergence of the merit function during the optimization, thus avoiding ray-trace failure. A simpler approach is to include a fixed pupil shift in the optical design. The pupil shift helps achieve better stability during the optimization process.

4. CURRENT APPLICATIONS

Panoramic imagers offer a real 360-degree coverage of the surrounding area, valuable for a variety of surveillance, security and defence applications, including force protection, port security, perimeter security, site surveillance, border control, airport security, maritime operations, search and rescue, intrusion detection, and various others. Adding automatic detection, location, and tracking of targets ensures maximum protection, increases the protection system reliability and user confidence, and at the same time reduces the personnel workload.

The advantages of panoramic imagers with high-image resolution include increased area coverage with a limited number of cameras, instantaneous detection, and location and tracking of multiple targets simultaneously. Adding incremental capabilities such as a visible, NIR or IR panomorph lens-based imager to an existing surveillance video system can provide improvements in operational efficiency and effectiveness[16].

An IR panoramic system can also be used for driving ground vehicles in darkness or conditions of limited visibility, since it provides a field of view similar to that of the human eye and is therefore intuitively more user-friendly. Mounted on top of a vehicle it can be used to see events in darkness and the activity all around the vehicle, including people and other life forms, objects, and activities. It can also be used to see around ships to detect threats or to follow activities in progress.

In an automotive application, the benefits of panoramic technology might include "intelligent" airbag deployment, blind spot detection, automated or assisted parking, back-up warning systems, pedestrian detection, and lane departure warnings -- all accomplished with the use of a very limited number of sensors. For example: A single panoramic sensor flush-mounted on the front of a vehicle could provide all the information necessary for adaptive cruise control, pedestrian detection, lane-departure alerts and even lane following. A second panoramic sensor mounted on the back of the vehicle could provide all the information necessary for parking assistance, assisted overtaking of another vehicle (by allowing a view of the other side of the road from a point of view different than the left rear-view mirror), back view, and others.

5. CONCLUSION

We have discussed the current developments in panoramic imager design by providing an historical perspective from the reversed telephoto to the new controlled-distortion lenses such as the panomorph lens. Rectilinear correction is popular, but it limits the field-of-view coverage to under 180 degrees. Catadioptric design offers an attractive solution but with limited f/number and blind zone capability. Modern lenses which provide a distortion control approach and an anamorphic design are considered a major enhancement in panoramic vision[15]. ImmerVision recently received Frost & Sullivan's 2007 North American Technology Innovation of the Year Award in the field of Panoramic Imaging for developing a revolutionary panomorph technology. We have examined and determined that a refractive lens is still the most compact, low-cost, robust lens to survive in various civil and military applications, both in visible and IR waveband. We have presented various current scenarios where a high-resolution panoramic imager will be most advantageous.

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