360° Vision System: Opportunities in Transportation

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ABSTRACT

Panoramic technologies are experiencing new and exciting opportunities in the transportation industry. The advantages of panoramic imagers are numerous, including (but not limited to) increased area coverage with fewer cameras, simultaneous imaging of multiple targets, instantaneous full-horizon detection, and easier integration of various applications into the same imager. This paper details our work on panomorph optics and its potential for transportation industry applications. The novel panomorph* lens is a new type of high-resolution panoramic imager perfectly suited to this industry, as the panomorph lens uses optimization techniques to improve the performance of customized optical systems for specific applications. By adding a custom angle-to-pixel relationship at the optical design stage, the system provides ideal image coverage to reduce and optimize the processing. The optics can be customized for visible, near infra-red (NIR) or infra-red (IR) wavebands. The panomorph lens is designed to optimize the cost per pixel as well, which is particularly important in IR wavebands.   We discuss the use of the 360-degree vision system to enhance on-board collision avoidance systems, intelligent cruise controls and parking assistance.   In conclusion, 360-degree panoramic vision systems have the potential to enable safer highways and, subsequently, to significantly reduce the number of related casualties.

Keywords: wide-angle lens, panoramic, panomorph, immersive, anamorphic, 360 vision systems, vision sensors, automotive, transportation.

* Panomorph lens: A very large anamorphic angle with enhanced resolution through optical distortion.

1.   INTRODUCTION

Automotive and general transportation applications are one of the largest vision-sensor market segments and one of the fastest growing ones. The trend to use increasingly more sensors in cars is driven both by legislation and consumer demands for higher safety and better driving experiences.   Automotive vision systems are among the many new and emerging applications.

Automotive safety systems are now moving from passive to active safety systems. Passive safety systems are designed to protect the car's occupants against injury, or reduce the severity of the injury in the event of an accident.   Seat belts and air bags are examples of passive safety features. Today, passive systems are being complemented by active safety systems designed to help avoid collisions. Blind-spot monitoring and adaptive cruise control features are examples of active safety systems.

Intelligent imaging systems for automotive applications will play a crucial role in the near future. In real-time events where complex environments need to be quickly interpreted, visual signals are still desirable because they are rich in the information required to understand the surrounding environment. Consequently, imaging systems used in conjunction with other types of RADAR and LIDAR sensors are becoming an increasingly important information source for many automotive applications.

Almost every active safety system under current development integrates a camera sensor, and all major suppliers are currently working on a camera-based sensing technology. However, integrating imaging sensors into cars has suffered from serious delays because high-speed displays and compact, low-cost signal processing units and memories have not been previously available. Also, earlier generation camera sensors did not perform sufficiently well and did not match the stringent automotive industry's needs. Today, with the availability of the newly developed automotive camera sensor, automotive OEMs can create revolutionary safety and comfort features for the car of tomorrow.

The main drawback of the current technology (which offers a broad range of active safety features) is often the cost. The real question then, is how can we improve the efficient use of vision systems in the automotive industry? In other words, how we can optimize these various sensor types, not only for high-end models or as expensive "add on" options, but to allow the adoption of these safety features for all applicable car models.

This paper presents a new type of panoramic lens (panomorph) -- specifically 360-degree vision-based technology -- for vision-based systems that already use cameras and panoramic lenses for remote sensing in the transportation industry. The advantages are numerous, including increased area coverage with fewer cameras, simultaneous imaging of multiple targets, and instantaneous full-horizon detection.

2. 360^{O} VISION SYSTEM IN AUTOMOTIVE SAFETY

Over the years it has been confirmed that there is limited space in a car for sensors to be installed, and limited in-car computing power that can support sophisticated data processing and analysis. Consequently, any chosen sensor must be able to provide essential information for as many functions as possible. We believe that these issues are key to implementing panoramic imagers into integrated intelligent sensors.

Panoramic imaging sensors can also contribute greatly to the perception of the world around the driver. For a complete vision of the area around the car, several sensor systems are necessary; however, a 360^{o} visual sensor is probably one of the most promising ways to fuse many sensors into one. As an example, a single panoramic sensor, flush mounted on the front of a vehicle, could provide all necessary information required for crash avoidance, early warning alerts and various video monitoring views.

As another example, an intelligent airbag system might combine seat-specific weight sensors with a stereo 2D overhead camera. Complex software is required to correlate the data from each sensor, and it may take additional devices to discriminate between a 70-lb. box and a 70-lb. child. The alternative is to build a consolidated system around a few or even a single panoramic optical sensor that can recognize and size (range) the object in the vehicle. Combining both ranging and recognition in a single, dedicated, small panoramic sensor will result in a practical imaging system that could potentially reduce the number of sensors required in the car. The same imaging sensor could also be used as a back-seat view camera (for child safety). In fact, a rear, interior and forward-view panoramic camera can handle a large number of applications simultaneously. The next section will provide the functional requirements of a panoramic vision system useful for various types of applications.

3. HEMISPHERIC LENS REQUIREMENTS FOR AUTOMOTIVE SENSORS

3.1 Technical requirements for automotive cameras

Automotive imaging sensors should comply with several requirements in order to meet the automotive market demands:

- The imaging sensor must have a very high sensitivity (low f-number) over a wide spectrum -- typically from the visible to the NIR.
- The image quality is limited by the pixel size, which means that the optical lens resolution will be equal or better than the resolution of the detector (CCD or CMOS).
- All these optical features should work over a broad temperature range, from –40^{o}C to +85^{o}C (+ 105^{o}), and be resistant to road vibration.
- The vision system must be compact and designed for cost optimization.
- The imager sensor must integrate many internal features (ADC, anti-blurring, etc.), must be easily programmable, and use common video formats.
- The lens should be customized for the benefit of its specific applications.

- Any un-warping (panoramic distortion management algorithms) software must be light in both memory usage and processing power consumption.

Automotive Tier1 and Tier2 are now designing “custom” products, which are perfectly designed and optimized from both a software and hardware point of view. With modern technologies, this modeling approach play an even more critical part in imager development. Simulation programs can help identify the trade-offs between various design alternatives.

3.2 Monitoring around a vehicle

In order to develop an intelligent vehicle, we need to “sense” the surrounding environment. A perception of the complete surroundings includes events taking place in the front, back, and sides of the car, which should be the basis of an effective driver assistance system. This driver support system, which can warn the driver of a possible collision, would allow the driver to take timely action to avoid or at least reduce the impact of a collision. Finally, we also need to observe ground objects, traffic signs over vehicles, and the landscape of the road. These facts imply an hemispheric view.

In recent years, considerable efforts have been made to develop driver support systems to enhance safety by reducing accidents[9]. As an example, lane detection vision systems help to determine the lateral position of the vehicle and warn the driver in the case of lane departure. This can also help to prevent collisions with other vehicles or fixed objects, or from running off the road. Front-view detection is useful in preventing accidents due to the sudden braking of another vehicle, detecting non-motorized objects such as pedestrians and bicyclists, who are harder to detect than vehicles and more vulnerable. Monitoring the side of the vehicle’s blind spots is useful when the driver intends to change lanes. Table 1 and Figure 1 show a non-exhaustive list of information that can be provided or required in respect to view zones.

Table 1: Developing the market for advanced sensoring and safety

View area	**Information provided**
Rear view	Back-up aids Parking aids Blind spots Lane change assistance
Forward view	Adaptive cruise control Lane departure warning Collision warning (cars and pedestrians) Blind spots Parking aids Road sign detection (speed limits, etc.)
Interior view	Air bags Driver drowsiness Rear view (back seat, children) Face recognition
Side view	Parking aids Blind spots Lane change assistance Collision warning (cars and pedestrians)

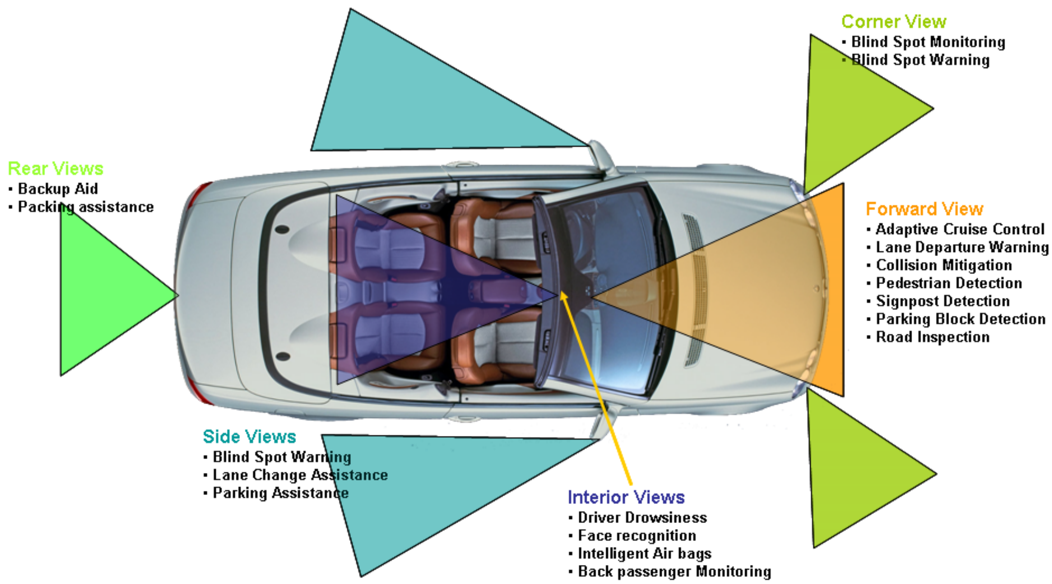

Figure 1: Applications of cameras

4. PANORAMIC VISION SYSTEMS

Wide field-of-view and a high frame rate are necessary for real-time tasks of the new generation of intelligent vehicles, mobile robots and surveillance systems[6]. Providing real-time visual-surroundings information to drivers is very helpful for driver safety and is necessary for the actualization of an autonomous intelligent vehicle. This section describes five ways of acquiring those surrounding images.

4.1 Conventional camera

Since a conventional camera has a limited field-of-view, the only way to have a larger field-of-view with a conventional camera is to rotate the camera to scan the scene through a slit or acquire multiple views with overlaps and then stitch all the views on a cylinder. However, this approach uses a larger number of images, takes a lot of processing time[7] and is not appropriate for real-time vision systems.

4.2 Cluster of cameras

Another method is to use a cluster of cameras to cover a wide field-of-view. This approach is more robust than in the previous method, but multiple camera sensors are needed and complicated calibration and heavy image processing are required[8].

4.3 Panoramic annular lens (PAL) & catadioptric lens

Panoramic annular lenses and catadioptric lenses such as Omni Cameras[9] are feasible because they provide a wide-scene view using a single camera. However, PAL cameras have blind zones in the center which provide only a cylindrical panoramic field-of-view. They also need extensive custom calibrations. The limited field-of-view in the vertical axis limits the height of the captured image. Thus, it is difficult to monitor all objects with great height (such as a traffic sign positioned above the vehicle or landmarks). 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 then presents a polar image with the elevation and azimuth linearly distributed to the radius and angle respectively[10]. However, the front-mirror imager has 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.

4.4 Fisheye lens

Another alternative for acquiring a wide field-of-view image using a single camera is with a fisheye camera. The fisheye lens has an inherently large distortion, and this distortion is not an aberration but rather the result of the projection of a hemispheric field on a circle, which is not possible *without* distortion.

Recently, Li[7] reported on a spherical image sensor based on the use of two fisheye lenses. To monitor the entire surrounding environment, he built a prototype of a full-view spherical image sensor. The field-of-view was divided into two hemispherical views. Each hemispherical view was imaged by a fisheye lens Both hemispherical views were then fused by a mirror to acquire them on a single image plane. Figure 2 shows a sketch of the prototype built by Li. As described in his paper, the system was far from the ideal spherical image sensor. To get a real spherical image (homogenous resolution and single view point) with these components, a redesign of the fisheye lens is required.

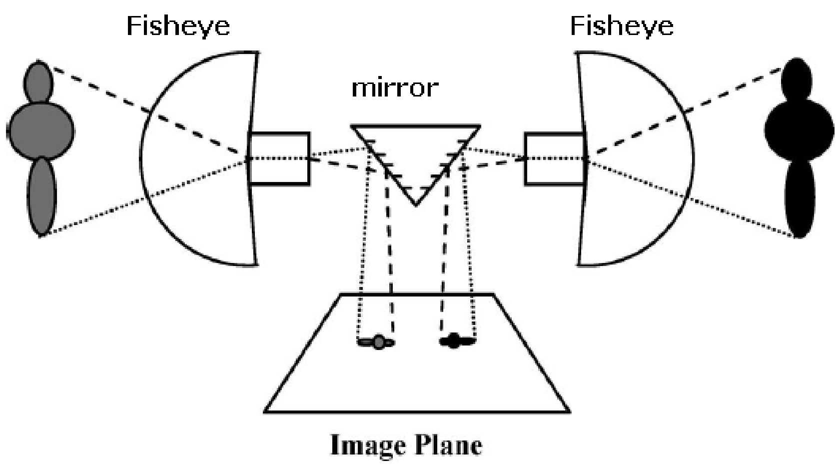

Figure 2: Sketch of the spherical image sensor protoype[7].

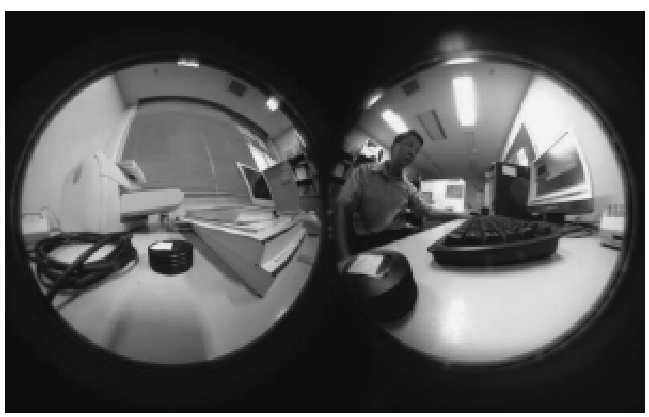

Figure 3 : Full-view spherical image acquired by the spherical image sensor shown in Figure 2[7].

The main drawback when using a fisheye is the poor resolution if you are not using a very high-resolution sensor. Li presented a dual system that used less than 50% of the sensor surface areas. Figure 3 shows the image produced by the spherical image sensor -- a large fraction of the image plane is not used, which is a real cost issue for the automotive industry.

4.5 Panomorph lens

Many of the above lenses used with a camera sensor (CMOS or CCD) are naturally suited to provide surround-monitoring of vehicles. However, due to the large field-of-view of the camera, any virtual view generated electronically and facing any specified direction becomes low in resolution[9]. Consequently, to get a high-resolution surround image, a high resolution sensor is required, leading back to a cost issue. This begs the following question: How can we improve the use of standard imagers in the automotive industry to get an efficient surround-monitoring of vehicles? The panomorph lens may be the answer..

Panomorph lenses are able to control distortion, which is considered a major enhancement in panoramic vision[11]. Specifically, the panoramic imager can be designed to increase the number of pixels in the zones of interest using a distortion-control approach, a process patented by ImmerVision. The main benefit of panomorph optics is that it is based on a custom-designed approach, simply because the panoramic lens application can be designed to meet real and very specific needs, particularly within the transportation industry. By including specific distortion during the optical design stage, ImmerVision can produce a very unique and a cost effective panoramic lens. Moreover, the panomorph lens can be used with any of the standard video format sensors already developed for automotive applications.

The panomorph lens uses only refractive lenses made with glass or plastic, which is perfectly suitable for high volume production. The lens can be very compact and robust. Consequently, the panomorph lens image quality, size, cost, reliability and integrity make it suitable for a safety-critical automotive application.

The panomorph lens[6] uses a distortion-control approach and anamorphic image mapping to provide a unique full hemispheric field coverage. In contrast to other types of panoramic imagers, which suffer from blind zones (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 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 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.

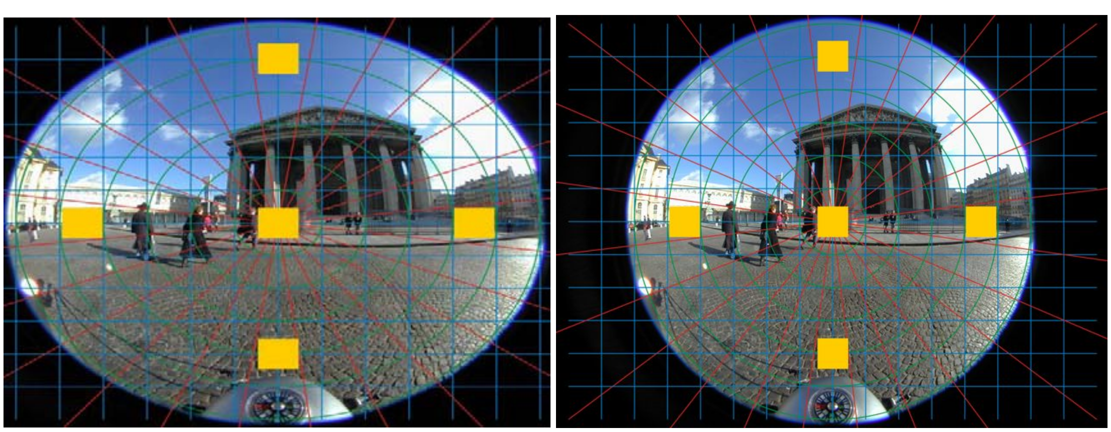

Figure 4: Images taken with a panomorph lens (left) and a fisheye lens (right). Yellow boxes represent equivalent areas.

Figure 5: Increased resolution with a panomorph lens.

Figure 4 shows a front view image in a parking lot, taken by a fisheye lens and a panomorph lens with equidistance projection (linear with FOV angle). The yellow boxes show the relative dimension of an object in the field. By providing an anamorphic correction (elliptical footprint), the panomorph lens also provides a gain in resolution along the long axis of the sensor. Figure 5 shows the same image taken by a panomorph lens with increased resolution on the border. The resolution on the border is double the center resolution. Where the resolution is higher, the camera is able to see at a longer distance. This custom image mapping is the resolution distribution required for a typical application. As another reference, we refer readers to another publication[6] of the author, which discusses a case study for a security panoramic imaging scenario.

5. LENS CONFIGURATION: A CASE STUDY

Because we want to optimize the use of each pixel on the sensor, proper design configuration is very important to determine the exact image mapping. Consider the simplified situation of a camera flush-mounted on the front of a vehicle. Based on Figure 1 (used only for indicative purposes), we can define three zones of interest in the horizontal plane. The first is the forward view, the second and third ones are to the right of the left corner views (see Figure 6). According to a specific need and only for this academic exercise, it may be a requirement that the resolution in these three zones should be the same. Additionally, the full field-of-view must be 190 degrees to cover all the zones and for each zone to cover 38 degrees (1/5 of the full field-of-view).

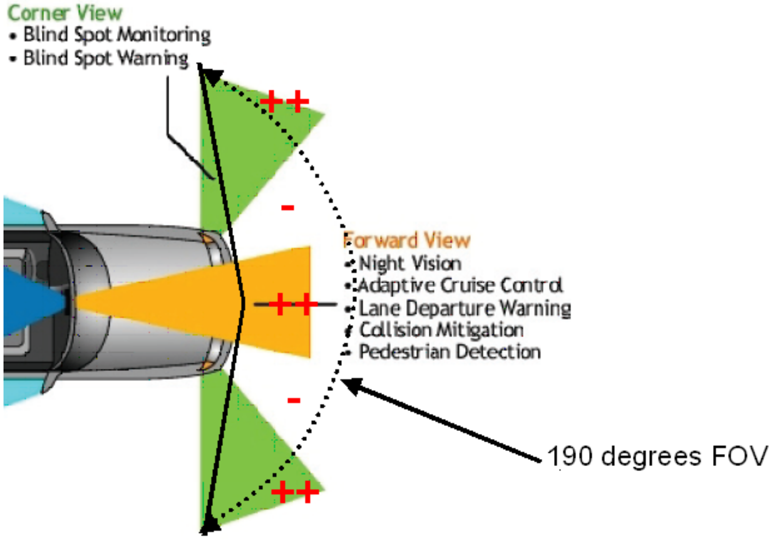

Figure 6: Front-view hemispheric zones of interest.

Using a standard fisheye lens on a VGA sensor (640X480 pixels) to fulfill these requirements, the resolution will be:

$$R_{fisheye} = \frac{480\,pixels}{190\deg} = 2.52\,pixels/\deg$$

The fisheye will provide a constant resolution over the entire field-of-view.

With a panomorph lens, we can manage the resolution or the image mapping in such a way that the resolution for each zone will be the same, and we can decrease the resolution in the inter-zone (between the forward and side views). This approach will provide a much better resolution. The panomorph lens includes an anamorphic correction, hence the 190 degree field-of-view will be spread not only over 480 pixels but on the longer axis, and will use 640 pixels (30% more). If we consider that the inter-zone also covers 38 degrees and that the resolution can be reduced by a factor two in this zone, the new resolution of the panomorph lens is:

$$R_{Panomorph} = \frac{160\,pixels}{38\deg} = 4.21\,pixels/\deg$$

For the calculation, we considered that 160 pixels are required to image each zone of interest and 80 pixels are required for each inter-zone, for a total of 640 pixels. The resolution of the panomorph lens is 170% higher than the resolution of the fisheye lens in the zones of interest. For the inter-zones, the resolution is only 10% smaller.

This example shows how a custom-design panomorph lens can provide a higher resolution where required, while still providing full hemispheric views. It is also possible to have a lower resolution in the inter-zones. The actual ImmerVision security lens has a 350% ratio between the inter-zone and the zone of interest. The resolution can also be variable for each zone. For example, the forward view can have a higher resolution than the corner views. The panomorph lens can be designed specifically for an application’s precise requirements.

6. CONCLUSION & OTHER OPPORTUNITIES

In this paper, we propose the use of a panomorph lens for efficient auto vision systems. With the panomorph lens, we can acquire a full hemispheric image with the use of a single standard camera sensor. The panomorph lens uses the distortion control approach and anamorphic image mapping to provide a unique full hemispheric field coverage. In contrast to other types of panoramic imagers, which suffer from blind zones (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 needed.

Based on a real front-view scenario, a standard automotive camera module equipped with a well designed panomorph lens provides an increase of 170% in resolution compared to any other type of panoramic lens used with the same sensor.

The panomorph lens has no moving parts, can be used with any standard camera sensor, is as small as a digital camera lens, can use either glass or plastic optical material and provides both visible and NIR images. Consequently, a refractive panomorph lens is well suited to fulfill the strict requirements for camera lenses in the automotive industry. Furthermore, when using plastic optical elements, the lens can be manufactured in volume, by using moulding techniques to reduce material costs.

In conclusion, a panoramic imaging sensor contributes most to our perception of the world. Several sensor systems are necessary to obtain a complete vision of the environment around a vehicle, a robot, an airplane, or a security vehicle;

however, a 360° visual sensor using panomorph lenses is probably one of the most promising ways to fuse many sensors into one, and thus reduce risk and cost.

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