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Multi-task single lens for automotive vision applications

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ABSTRACT

The increasing trend to use vision sensors in transportation is driven both by legislation and consumer demands for higher safety and better driving experiences. Awareness of what surrounds an automotive vehicle can directly affect the safe driving and maneuvering of that vehicle. Consequently, panoramic 360° field-of-view (FoW) imaging is becoming an industry prerequisite. However, to obtain a complete view of the area around a vehicle, several sensor systems are necessary. This paper explains how panomorph optics can satisfy the needs of various vision applications with only one sensor or panomorph lens configuration.

A panomorph lens is a hemispheric wide-angle anamorphic lens with enhanced resolution in a predefined zone of interest. Because panomorph lenses feature an optimal pixel-per-degree relationship, the resulting vision systems provide ideal area coverage, which in turn reduces and maximizes the processing. Here we present how panomorph technology is one of the most promising ways to integrate many automotive vision applications (processing/viewing) onto one single camera module. For example: a single panomorph sensor on the front of a vehicle could provide all the information necessary for assistance in crash avoidance, lane tracking, early warning alerts, parking aids, road sign and pedestrian detection, as well as various video monitoring views for difficult areas such as blind spots.

Keywords: wide-angle lens, panoramic, panomorph, immersive, hemispheric, anamorphic, 360° vision systems, vision sensors, automotive vehicles, field of view, transportation, driver assistance systems, lane tracking, blind spot, pedestrian detection, road sign detection, parking assistance

1 INTRODUCTION

The increasing trend to use vision sensors in transportation is driven both by legislation and consumer demands for higher safety and better driving experiences. Awareness of what surrounds an automotive vehicle can directly affect the safe driving and maneuvering of that vehicle. Indeed, video and vision processing have become the fastest growing technologies deployed in automotive manufacturing. Increased integration of electronic components and the declining prices of electronics in general are the primary enablers of this trend. Lane keeping, driver monitoring, night vision and parking assistance are just a few of the applications "driving" the need for improved vehicle imaging systems. Many of the new applications using video imagers are for advanced safety systems, used to assist the driver in vehicle management or to autonomously control occupant safety systems.

With such a wide variety of system objectives and requirements, it is important that we examine how an enhanced vision system, equipped with an enhanced resolution wide-angle lens, can solve current vehicle vision application challenges while allowing integration with less sensor requirements.

There are two major objectives of this paper:

- The first is to present various needs related to computer vision-based applications (analytics) and viewing applications.
- The second is to present the novel *panomorph technology concept* patented by ImmerVision, explain how it compares to fisheye vision sensor systems, and show how it can be used to integrate many applications with only one vision sensor (case study).

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2 VARIOUS AUTOMOTIVE APPLICATIONS: VARIOUS NEEDS

In recent years, considerable efforts have been made to develop driver support systems which enhance safety by reducing accidents[1]. As an example:

- Lane detection vision systems can determine the lateral position of a vehicle and warn the driver in the event of an imminent lane departure. They can also help prevent collisions with other vehicles or fixed objects, or from literally driving off the road.
- Front-view detection is useful in preventing accidents by detecting objects such as vehicles, pedestrians and cyclists, and by piloting the cruise control using road-sign detection and forward vehicle tracking.
- Monitoring the vehicle's blind spots is useful before the driver changes lanes.

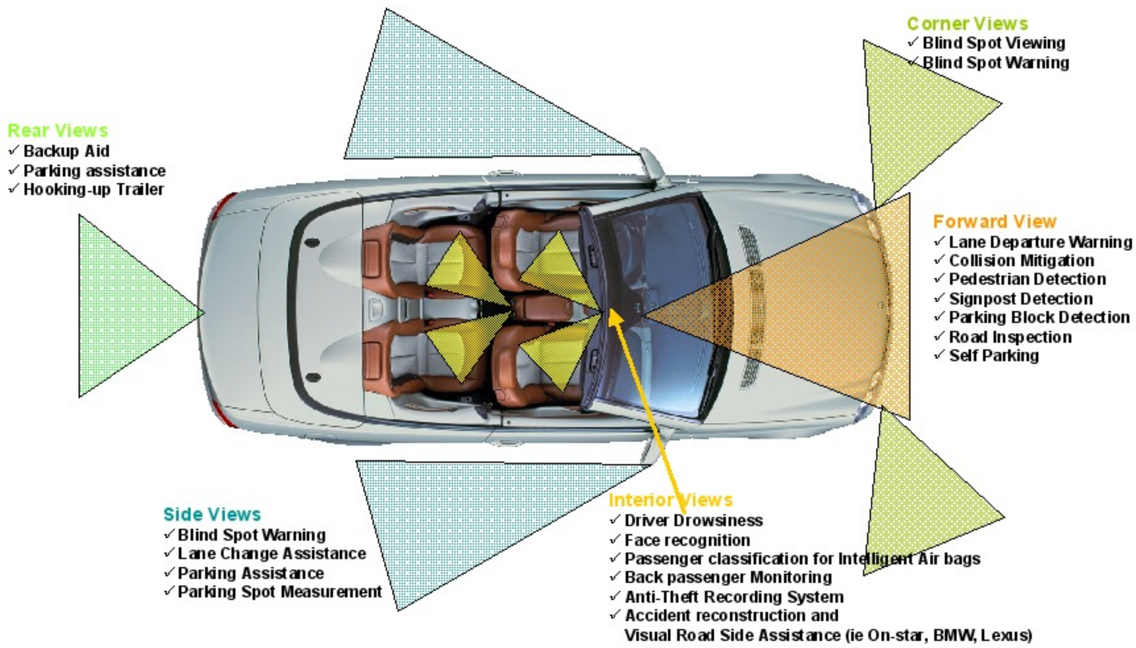


Table 1 and Figure 1 show a non-exhaustive list of information/applications that can be provided or required in respect to view zones.

Table 1: Developing the market for advanced sensor ability and safety

View area	Information provided / Applications
Rear view	Back-up aids Parking aids Blind spots Lane change assistance Hooking up trailer Lane departure warning
Forward view	Adaptive cruise control Lane departure warning Collision warning (cars and pedestrians) Blind spots Parking aids Road sign detection (speed limits, etc.) Pedestrian detection

	Self parking Road inspection
Interior view	Passenger classification for airbag system Driver drowsiness Rear view (back seat, children) Face recognition Visual roadside assistance Anti-theft/recording system
Side view	Parking aids Blind spots Lane change assistance Collision warning (cars and pedestrians)

Each application has different needs in terms of sensor position, orientation, resolution and coverage. Usually, to complete each functionality listed below, many sensors are required. In this paper, the authors explain how to realize the same applications with fewer cameras and less sensors, using panomorph technology.

2.1 Computer vision-based applications

2.1.1 Lane departure and lane curvature recognition

The lane departure warning system (LDWS) is designed to warn a driver when the vehicle begins to move out of its lane (unless the appropriate turn signal is activated) on freeways and arterial roads. The LDWS needs lane curvature information and the vehicle's position on the road as input. This starts with lane detection via a camera lens. The objective is to detect and track the line separating the lanes on the road to evaluate the trajectory of the vehicle and the road curvature.

Depending on the approach, the algorithm can use a front or rear camera. Regarding the field-of-view of these cameras, Takahashi[2] explains that a wide-angle lens has two main advantages over a narrow-angle lens: One, it is easier to detect lane marks because the camera can see the lane mark just under the vehicle; and two, there are many recognition clues due to the fact that the camera can search widely in a lateral direction.

Regarding the image resolution requirement, Takahashi[2] further notes that this type of application needs enough resolution to detect the gap between two lines -- for example the lines down the middle of a highway. He then demonstrates that the projective view of a wide-angle camera can accelerate image processing on a vehicle-embedded system (by using less processing power). After vehicle trajectory and road curvature detection information is collected, it can be sent to the driver, to the adaptive cruise control system (ACCS), or to the vehicle stability control system, which maintains lane position by applying gentle brake pressure.

2.1.2 Collision warning using vehicle detection

Collision warning applications regroup different functionalities such as “stop and go” ACCS -- forward collision warnings and intersection collision warnings using vehicle-detection algorithms. The goal is to detect an imminent collision and to warn the driver, the ACCS or the auto brake system. This type of algorithm uses pictures from a camera to detect, classify and localize a potential obstacle.

For an intersection collision warning (a situation during which obstacles can come from any direction around the vehicle), a wide-angle sensor is required. After the detection step, the picture of the potential obstacle is then extracted from the wide-angle picture. According to Zhang[3], the obstacle classification requires a 40*40 pixel image of an obstacle from which the detection system can provide a minimum of 10*10 pixel images. Zhang then reformats the images as a 40*40 picture. One can deduce that the required resolution for the classification algorithm is 40*40 pixels, even if the classification algorithm works with a 10*10 image. After classification, the system can evaluate the position and speed of the potential obstacle and use other radar/lidar sensor information to obtain distance information (sensor fusion). This information can then be sent to the ACCS or for viewing on an on-board driver information display.

2.1.3 Road sign detection and recognition

In the future, being able to recognize traffic signs will be increasingly important for vehicle safety systems. Such systems could assist drivers with signs they failed to notice *en route*. Specifically, speed-limit sign recognition could inform drivers about the current speed limit, and alert the driver if the vehicle is being driven faster than the posted speed limit.
In futuristic scenarios, autonomous vehicles would *have* to be controlled by automatic road-sign recognition. As there is a preponderance of traffic signs for speed limits, directions, warnings, upcoming traffic lights, etc., this will become an essential feature. Road-sign detection and recognition systems can inform the driver or the ACCS about current speed limit restrictions, dangers or potential interdictions. In addition, the localization of road signs changes, depending on type of sign, regional driving laws, and whether the signs are permanent or temporary. For example: a road sign can be mounted on poles situated on street corners, hung from horizontal poles or be on wires strung over the roadway, before, at or after the actual intersection. The many variations around the road sign's possible location require a large field-of-view (FoV) camera sensor for effective detection.
After detection, the target road sign image is extracted from the wide-angle picture. The resolution in pixels of the sign depends on the distance from the sensor (camera). Alefs[4] explains that a road-sign detection and recognition system needs at least a 12 pixels-wide road sign for detection. Indeed, the system is able to detect 85% of objects which are12 pixels wide or more, and 95% of objects 24 pixels wide or more at a low false alarm rate. After successful detection, the information can then be sent to the ACCS or for viewing on an on-board driver information display.

The computer vision applications listed above offer active assistance to the driver. All of them are interconnected to ensure that the best decision is made possible. As described, they have several different requirements in terms of sensor field-of-view, resolution and image rectification, and projection. In this paper, the authors will explain how one single wide-angle sensor can be used to meet each application's needs.

2.2 Driver viewing applications: A new way to avoid blind zones

A vehicle's blind zones are the areas surrounding the vehicle where the driver can not see what, if anything, resides in that defined space (the blind zone). The size of the blind zone depends on the vehicle design (driver position, windows and mirror positions).

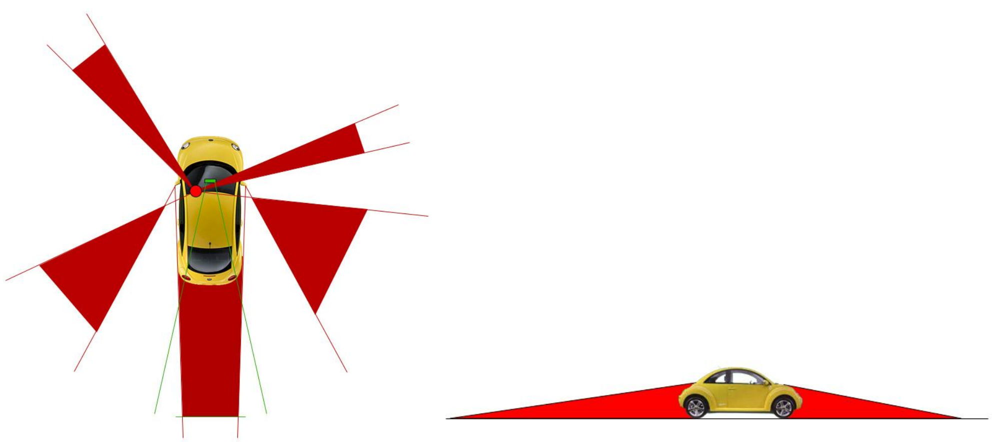


Figure 2: Blind zones for a standard left-hand side driver's car

For many years now, flat mirrors have helped drivers reduce blind zones. In the 80s, custom shape mirrors and wide angle Fresnel lenses further improved blind zone coverage. More recently, cameras and on-board displays appeared, providing another point of view for the driver. The most famous application to date is the rearview camera, which assists drivers with challenging parking. The on-board display shows the video produced by the rear camera, and effectively helps the driver overcome the rear blind zone.

Blind zone reduction is necessary for reducing injuries, especially in the case of vulnerable objects/items/elements (pedestrians, bicycles). Hughes[5] explains that some legislation has been proposed by several governments (Europe, Japan and USA) that requires the diminution of blind zones using a mirror or camera device. To drastically reduce the blind zones without increasing the number of sensors and mirrors, wide-angle lenses must be considered as a serious option.

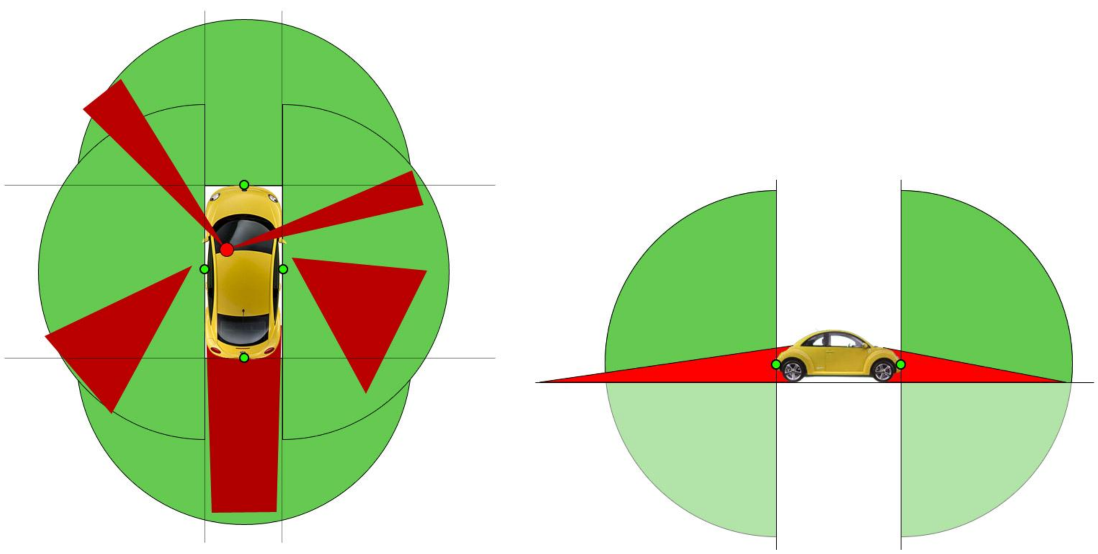


Figure 3: Blind zone avoidance using four (4) wide-angle lenses

Several manufacturers, including Honda, Mitsubishi and Fujitsu, provide on-board systems which use multi-camera systems (four or five cameras) located all around the vehicle (see reference on companies' web sites). These systems provide different types of viewing, depending on the driver's needs, and successfully eliminate most of the blind zones.

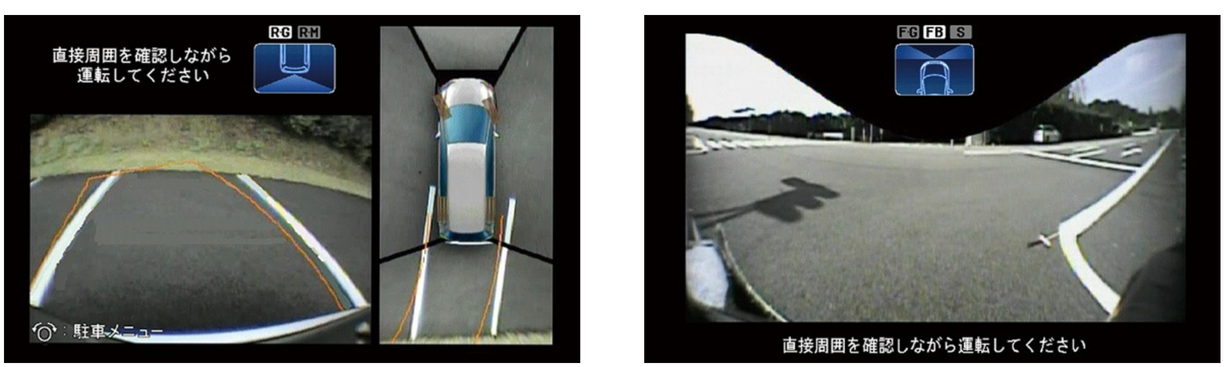


Figure 4: Honda's multi-camera viewing system

Figure 5: Fujitsu's multi-camera viewing system

In the next section, the authors will explain how the panomorph lens may provide the ideal solution to the modern driver's viewing requirements. We will also explain how to use the panomorph lens' key features to avoid blind zones, and we will demonstrate how just one panomorph sensor can provide a variety of different views.

3 THE CONCEPT OF PANOMORPH TECHNOLOGY

Many lenses with a camera sensor (CMOS or CCD) are naturally suited to provide surround-monitoring of vehicles. However, due to the camera's large field-of-view (FoV), any virtual view generated electronically and pointed in a specific direction suffers from low resolution[1]. Consequently, to get a high-resolution surround image, a high-resolution sensor is required, which leads back to the issue of cost.
Panomorph lenses, on the other hand, can control distortion. This alone is considered a major enhancement in panoramic vision[6]. By using a distortion-control approach and anamorphic image mapping, both patented by ImmerVision, panomorph lenses provide a unique full hemispheric field coverage. In contrast to other types of panoramic imagers that suffer from blind zones (catadioptric cameras), low-image numerical aperture and high distortion -- the panomorph lens uses distortion as a design parameter, to provide a higher-resolution coverage where needed.

Panomorph lenses also feature an anamorphic image mapping of the full hemispheric field, resulting in an ellipse-image footprint rather than the circle or annular footprint that other types of panoramic imagers produce. This feature provides an *immediate* 30% gain in pixels on the sensor (the ellipse footprint matches the ratio of a CCD or CMOS imager). This combination of distortion control and anamorphic design provides an important gain in resolution pixel/degree in the zones of interest, and an advantage over all other types of panoramic imagers. Finally, the main benefit of panomorph optics is its custom-design approach, meaning that the panoramic lens and the image projection software can be customized to meet real and very specific needs in visible or infra-red applications[7].

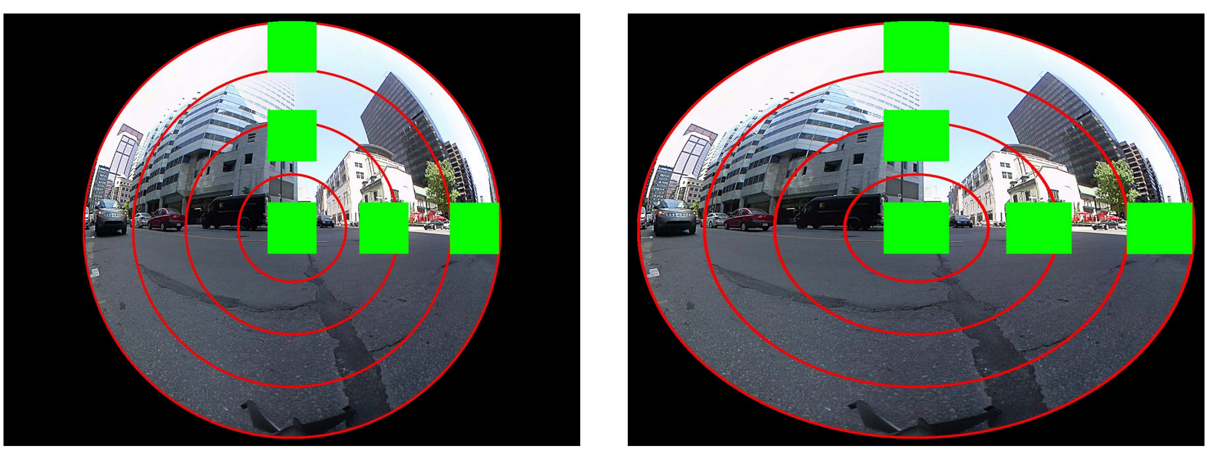


Figure 6a and 6b: Images taken with a fisheye lens (6a, left) and with a panomorph lens (6b, right).
Green boxes represent equivalent areas.

Figure 6 shows the front-view image from a car in a parking lot, produced by a fisheye lens (6a) with equidistance projection (perfect linear [f-theta] mapping) and the same image produced by a panomorph lens (6b). The green boxes show the relative dimension of an object in the field. The elliptical footprint on the right produces an anamorphic correction, and the panomorph lens provides increased resolution along the long axis of the sensor.

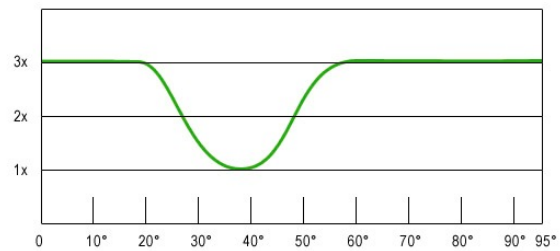


Figure 7: Associated pixels/degrees distortion curves

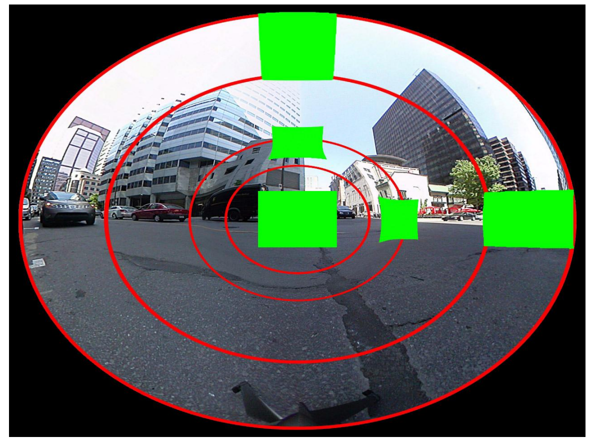


Figure 8: Increased resolution with a panomorph lens

Figure 7 shows the same image taken by a panomorph lens with increased resolution in the center and along the border. Figure 8 shows the resolution ratio of the lens (pixels ratio/degrees). The resolution along the border is three times higher than in the center. Where the resolution is higher, the camera is able to see for a longer distance. The viewing algorithms embed the proper resolution curve/algorithms to correct the distortion (please refer to section 4.4). This custom image mapping is the resolution distribution required for a typical application. As another reference, we refer readers to a published case study[8] for a panoramic imaging security scenario.

4 A CASE STUDY: FOUR APPLICATIONS – ONE LENS DESIGN

Consider the simplified situation of a camera flush-mounted on the front of a vehicle. The goal of this section is to determine the appropriate parameters of the panomorph lens and the projection (un-warping) algorithms which correspond to the application requirements.

Lens and algorithm parameters to be determined:

- Field-of-view (FoV) of the application
- Lens distortion, anamorphosis ratio and resolution
- Lens mathematical model and calibration
- Software projection type, treatment and performance

Applications requirements:

- Lane departure and lane curvature recognition:
    - Large FoV: Larger than 180° to increase the robustness of line tracking
    - Projection algorithms to rectify the image and provide a straight line for recognition
- Collision warning using vehicle detection:
    - Large FoV to detect oncoming vehicles from all sides of a road intersection
    - 2-meter vehicle width must cover 10 to 40 pixels wide

- Road sign detection and recognition:
  - Large FoV to detect road signs at different locations
  - 0.5-meter sign width must cover 12 to 24 pixels wide
- Blind zone avoidance:
  - Large FoV: Larger than 180° to avoid blind zones
  - Projection algorithms to rectify the image and provide a user-friendly view to the driver

4.1 Field-of-view (FoV) of the application

Each application listed above needs a large field-of-view (FoV), so a wide-angle lens is required. Depending on the tolerances in the lens position, a FoV of up to 190° is required to guarantee a full hemispheric FoV. There are different types of wide-angle lenses, as the author has explained in a previous paper[9]. Mirror imager and PAL are not studied due to inappropriate fit-form-function factors (i.e. the blind zone in the middle of the FoV). In this case study, the authors will consider only fisheye and panomorph lenses, and will demonstrate the benefits of the panomorph lens utilization.

4.2 Lens distortion, anamorphosis and resolution

Fisheye lenses have a radial distortion across the hemispherical field-of-view (FoV). The radial distortion of the fisheye lens depends on the design itself, and introduces some variation in the resolution (pixels/degrees) over the entire FoV. This variation can be quantified as a departure from the ideal theoretical fisheye lens, which has a theoretical linear (f-theta) mapping. According to Kumler and Bauer[11], different types of fisheye lenses have different performances regarding the departure of perfect linear (f-theta) mapping, which can go up to 16%, especially along the border (20 last degrees). The panomorph lens uses distortion as a design parameter, in order to provide high-resolution coverage in a specific zone of interest. For this academic exercise, we will consider the "theoretically perfect" fisheye lens with 190° FoV and 0% departure (linear resolution), and a panomorph lens with 190° FoV and an adapted resolution (distortion).

Fisheye lenses produce a circular footprint on the sensor. Fisheye lenses don't have any anamorphosis. Panomorph lenses produce an elliptical footprint on the sensor. The anamorphic design of the panomorph lens provides a customizable coverage of the sensor. Depending on the mechanical and assembly tolerances, the panomorph lens is designed to ensure that the footprint fits into the sensor, using small border merges. For this academic exercise, we will choose a 4/3 sensor and the border merges will be negligible.
A panomorph lens can be used with any sensor format (VGA, XGA, SXGA etc.) as long as the lens performance matches the Nyquist frequency of the sensor. For this academic exercise, we chose a 1.2 mega pixel sensor (1280 x 960 pixels) called a target sensor.

A collision warning application needs to have at least 10 pixels to define a two-meter wide object (vehicle). As defined by Thibault[12], a fisheye lens is 5.04 pixels/degree on the targeted sensor (1280*960) over the entire FoV.

(1) $$\alpha = \frac{Size_p}{\mathrm{Re}s_{P/\circ}}$$

Where $Size_p$ is the object size on the sensor in pixels, and $\mathrm{Re}s_{P/\circ}$ is the resolution of the system lens-sensor in pixels/degree: A 10-pixel object represents a α=1.98° FoV and a 40-pixel object represents a α=7.9 FoV.

(2) $$d = \frac{Size_m}{Tan(\alpha)}$$

Where $Size_m$ is the object size in meters: A 10-pixel object is d=57.8 meters from the car. This means that a two-meter wide object will illuminate 10 pixels or more when the objects are within 57.8 meters.

With a panomorph lens, we can customize the distortion mapping to provide better resolution where required. Based on Figure 9 (used only for indicative purposes), we define three zones of interest in the horizontal plane. The first area of interest in which we would like to increase resolution is the forward view. The second and third areas are to the right of the left-corner views (see Figure 7 for suggested distortion curve).

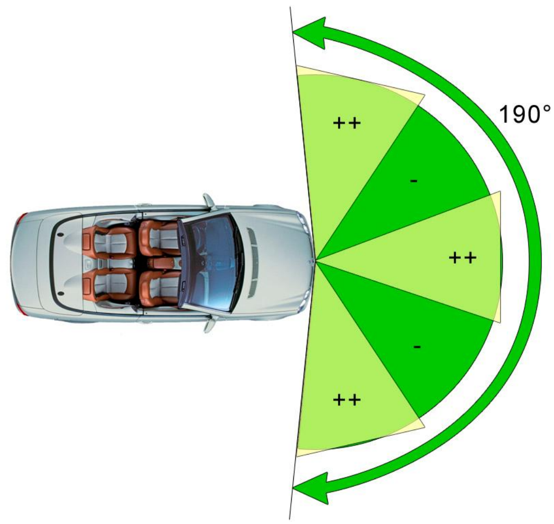


Figure 9: Augmented-resolution areas of interest for a panomorph front view lens.

For a collision warning application, there is a need to see farther on both sides when crossing an intersection. One needs also to see farther right in the middle, to detect a vehicle in the same lane. Figure 9 shows the resulting areas of interest over the entire FoV. As defined by Thibault[12], the resolution of this type of lens is 8.42 pixels/degree on the targeted sensor within the zone of interest. Using formulas (1) and (2), a 10-pixel object would be 97 meters from the car, a 70% increase compared to a theoretical fisheye lens within the same area of interest.

The safe distance between two vehicles is based on the driver's reaction time; some governments have determined that this reaction time is at least the distance travelled during two seconds. We can deduce the following formula:

$$ds_{meter} = 0.56 \times V_{km/h}$$

Table 2: Safe distance between two vehicles at conventional speed limits

Speed	50 km/h	70 km/h	90 km/h	110 km/h	130 km/h
Safe distance	28 m	39 m	50 m	62 m	73 m

Considering this, the panomorph lens is a serous option, because it can provide enough resolution for a collision warning application during different traffic conditions (city driving to highway driving).

Road sign detection and recognition applications need to have at least 12 pixels to define road signs of widths from one (1) meter up to 1.5 meters[13].

With a fisheye lens, using formulas (1) and (2):

- For a one-meter wide road sign, a 12-pixel object is 24 meters from the car and a 24-pixel object is 12 meters from the car.
- For a 1.5-meter wide road sign, a 12-pixel object is 36 meters from the car and a 24-pixel object is 18 meters from the car.

With a panomorph lens, using formulas (1) and (2):

- For a one-meter wide road sign, a 12-pixel object is 40 meters from the car and a 24-pixel object is 21 meters from the car.
- For a 1.5-meter wide road sign, a 12-pixel object is 60 meters from the car and a 24-pixel object is 30 meters from the car.

Again, because of the specific panomorph resolution pattern suggested in this case study, panomorph optics will increase the distance in its areas of interest (++ areas on Figure 9) by a factor of 70% compared to a theoretical fisheye lens.

For a lane departure warning system, the painted lines are right in the zone of interest of the suggested panomorph lens as in Figure 9. This distortion pattern improves the resolution of the road line in front of the car to provide the best image quality for detection. Also, a specific viewing function will be suggested in order to simplify processing (see section 4.4).

For side views (blind spot monitoring), a higher resolution image will significantly enhance the viewing of far-away objects and vehicles on the periphery of the optical area.

4.3 Lens mathematical model and calibration

The panomorph geometrical model (PGM)[9] and lens calibration is required when the targeted application needs a projection algorithm to compute a special view. This will be explored in more detail in the next section.

Lens calibration might be required when:

- localization or measurement of targets on the panomorph image have to be determined;
- different sensors need to be stitched/integrated into one logical image;
- other types of sensors (radar, ultrasounds, etc) must be fused into a panomorph video feed;
- 3D reconstruction and/or camera localization (X,Y,Z spatial coordinates) is needed when using multi-camera imaging;
- 3D reconstruction and object measurement is needed when using only one camera combined with car displacement data.

Ramalingam[10] explains in his thesis how to calibrate and reconstruct a 3D scene using a unified camera calibration model. This model encloses different camera types as pinhole cameras and omni-directional cameras, up to non-parametric mapping cameras. The panomorph lens calibration model can be customized to the unified model, relying on its pixel projection mapping. For example, the lens suggested in this case study cumulates polynomial radial distortions with an anamorphic ratio. This theory is described further by the authors in a previous paper[9].

All algorithms using a camera calibration function easily with the panomorph lens calibration model -- such as image stitching or fusion, motion estimation, camera position estimation or 3D reconstruction. Figure 13 is an example where this type of calibration is required. Indeed, to stitch four panomorph camera images and provide a fused view, we need to know the position of each panomorph camera in the real world. As a camera can move from its initial position, a dynamic calibration is required, using intrinsic and extrinsic camera parameters. When a panomorph lens design provides the theoretical intrinsic parameters, a self-calibration algorithm fine-tunes the intrinsic parameters and computes the extrinsic parameters using interest-point matching. Again, for this type of application the panomorph lens can improve the results by increasing the resolution along the border, where interest-point geometry is known (for example: a car's geometry).

4.4 Software projection types, manipulations and performances

For collision warning and road sign detection and recognition, the size of the object is not big enough to be influenced by the distortion of the lens. A projection algorithm is not necessary. For lane departure and lane curvature recognition, however, the projection algorithm is important in reducing the CPU load. Indeed, using a PGM model of the lens, we can create a projection table (LUT) that transforms the panomorph picture into a picture dedicated to lane departure and lane curvature recognition algorithms.

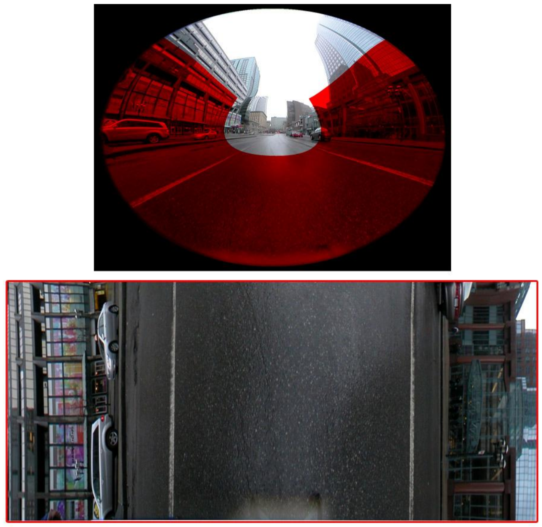


Figure 10: Lane departure custom projection rendering

The goal of this projection is to provide a straight line to simplify the line recognition algorithm and reduce the car-embedded computation. The pixels used to create the projected view are highlighted on the panomorph view.

For blind zone coverage there are many types of viewing possible with a panomorph lens (for example, to avoid a blind zone at a garage entrance created by vehicles parked on the street side).

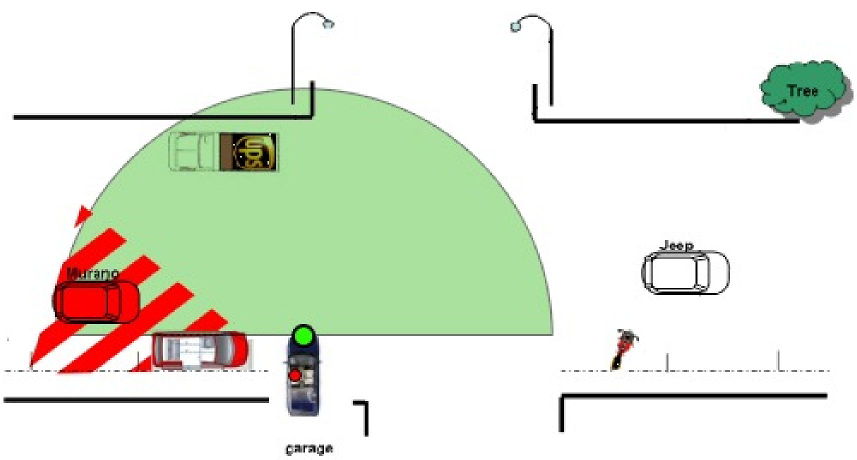
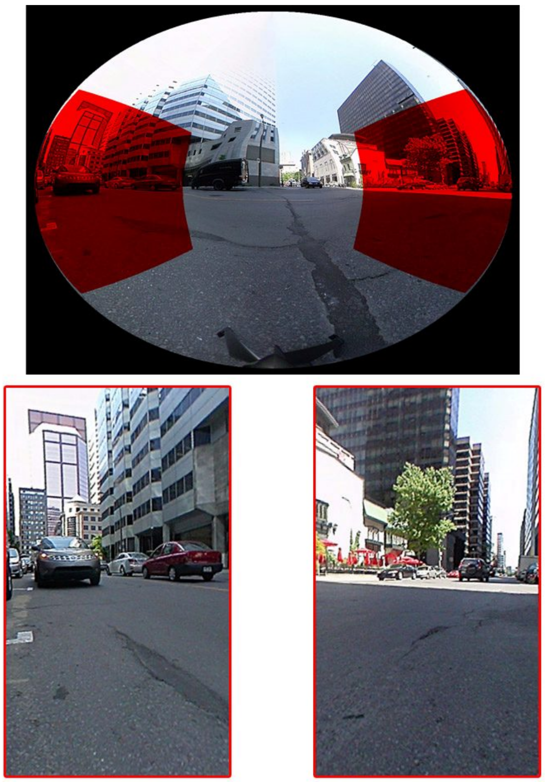


Figure 11: Panomorph coverage of a blind zone created by a parked vehicle

Using the PGM, different software projection types can be created, depending on OEM requirements. The two following figures show ways to display a view of the intersection to the driver while avoiding the blind zone created by a parked vehicle. This type of projection is simply a pixel displacement that has been computed during the calibration phase on a production chain. This can be hard coded in a lookup table in the camera module. No special CPU horse power is required.

Figures 12 and 13 show ways to avoid a blind zone. The driver can see everything in the blind zone using his/her on-board display. The panomorph lens design suggested in this paper increases the resolution of objects along the border and right in the middle. Where the resolution is higher, the camera is able to see for a longer distance. The panomorph distortion is optimized for this type of application. The driver is able to see far down each side of the street.



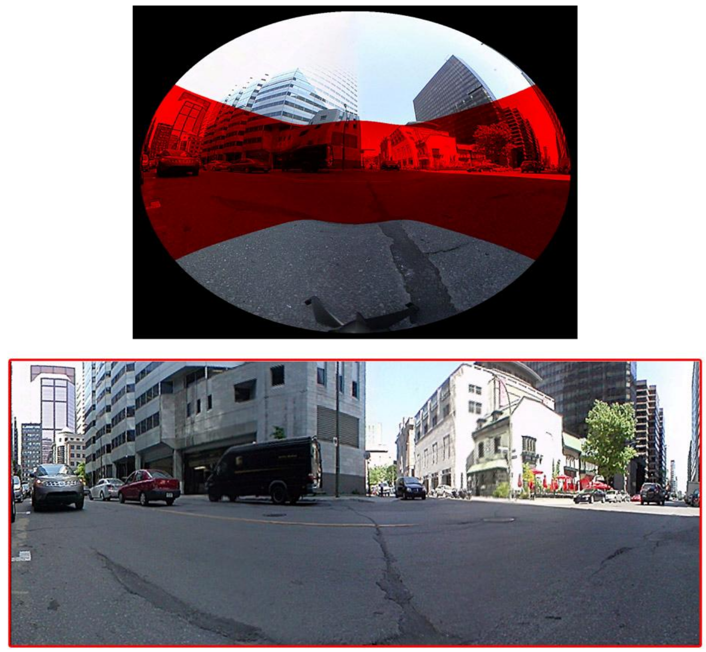


Figure 13: 190° strip integrating full intersection

Figure 12: Two views rendering either side of the intersection

In Figures 12 and 13, the topmost image is the panomorph picture with certain areas highlighted. The lower ones show the projections as processed from the pixels in these areas.

There are no limitations in terms of projection ability, although the scope for real applications requires imagination and, ultimately, driver understanding. For example, one could mount four (4) panomorph lenses all around the vehicle to provide a complete view for parking assistance (Figure 13) with the added benefits of panomorph technology's augmented resolution.

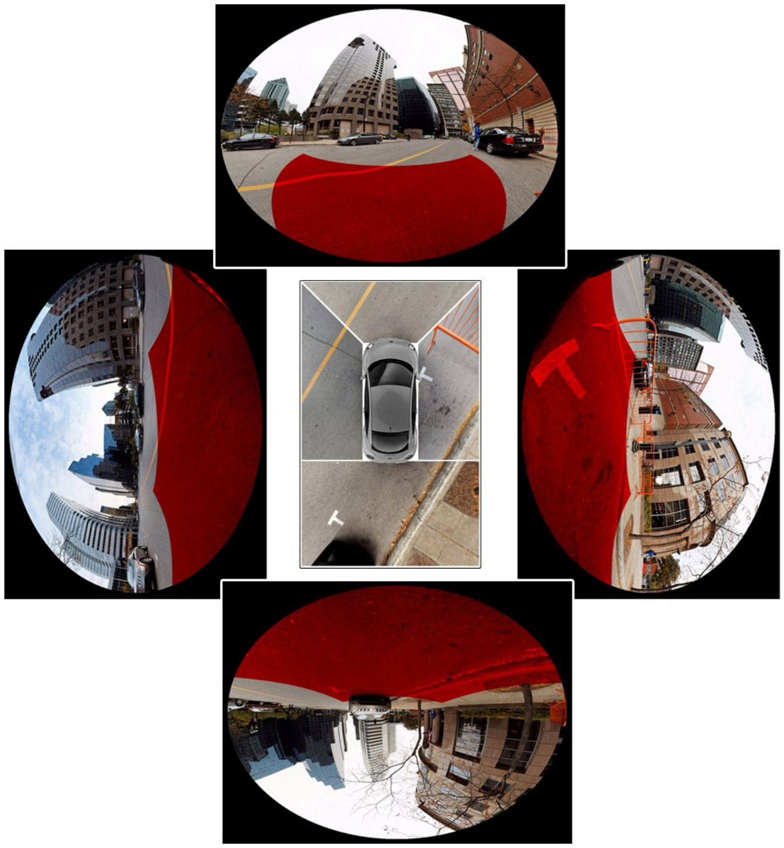


Figure 13: View of area surrounding vehicle using four (4) panomorph lenses.

5. CONCLUSION AND OPPORTUNITIES

This paper presents a variety of viewing needs related to specific automotive applications, now and into the future. Computer vision-based applications (analytics) will require various resolution factors (pixel per degree) in various areas of a vehicle's field-of-view (FoV), depending on the position of the objects to be analyzed, as well as distance and size. Viewing application requirements, on the other hand, will focus on the clarity and quality of the images to be displayed to the driver. We also saw that the objects to be detected, analyzed and viewed can literally be everywhere around the vehicle. We demonstrated that a novel panomorph technology (optics and software) performs significantly better than other traditional panoramic vision systems in fulfilling various needs relating to automotive applications. In conclusion, the novel pixel-optimization characteristic of panomorph optics allows the integration of many applications with the use of fewer vision sensors.

Finally, we demonstrated in the case study that, because of the specific panomorph resolution pattern suggested in this case, panomorph optics can increase the distance by a factor of 70% compared to a fisheye lens. It can also reduce computation time, while at the same time achieving high recognition performance. All of these benefits will bring a total cost reduction to the automotive industry for the various systems that require vision sensing.

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