Monitoring surrounding areas of truck-trailer combinations

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Abstract. Drivers of trucks and buses have difficulties when to survey the surrounding area of their vehicles. In this paper we present a system that provides a bird's-eye view of the surrounding area of a truck-trailer combination to the driver. This view enables the driver to maneuver the vehicle easily in complicated environments. The system consists of four omnidirectional cameras mounted on a truck and trailer. The omnidirectional images are combined in such a way that a bird's-eye view image is generated. A magnetic sensor is used to measure the angle between the truck and the trailer and to stitch images acquired at the truck and at the trailer into a correct bird's-eye view image.

1 Introduction

Large vehicles like trucks and buses have large blind spots areas which lead not only to difficult maneuvering tasks but also to endangering pedestrians and bicyclists. There are two reasons why the blind are spots so large. First, the size of truck and trailer can reach up to 16 meters (see Figure 1), and thus the driver is not able to survey the back part of his vehicle. Secondly, the driver sits at about 2.5 meters above the ground and therefore he is not able to see the area in front and on the fellow side of the truck.

To reduce accidents with other road participants that are very close or next to the vehicle, the European Union passed a directive [2], that obliges new trucks to have a mirror or camera system that covers the blind spot area in the near surrounding of the truck. New trucks thus are equipped with many mirrors but they still do not cover the complete surrounding of the truck.

Omnidirectional cameras with a large field of view (close to 360°) are well suited for capturing the surrounding of vehicles. It is possible to cover the area with a small number of cameras. However, the raw omnidirectional images are not easy to understand due to their unusual projection geometry. They must be rectified and presented in a way that drivers can understand what they see. To achieve this, images are transformed and combined in such a way that a bird's-eye view image of the surrounding area of the vehicle is provided to the driver.

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Fig. 1. Mercedes-Benz Actros. The front omnidirectional cameras are mounted below the side mirrors. The back cameras are placed at the top of the trailer.

In this paper we will show how to transform and combine images from four omnidirectional cameras to provide a bird's-eye view of the surrounding area of a truck on a single display. To be able to compute a correct bird's eye image even when the truck turns, we use a magnetic sensor that measures the angle between truck and trailer.

The remainder of this paper is organized as follows: We first review previous work, then the projection of omnidirectional cameras is described in detail. In Section 4 the construction of the bird's-eye view system is explained. Finally, results are presented in Section 5.

2 Related Work

Optical systems can be split into two groups: dioptric and catadioptric. Dioptric systems use only lenses. The field of view of the practical dioptric cameras is limited to 180°.

Catadioptric systems, instead, use combinations of mirrors and lenses. Their field of view can be reach up to 360° and is easier to prescribe and design. Catadioptric systems can be further divided in two groups: single and non-single viewpoint systems. Single viewpoint catadioptric systems measure the intensity of light passing through a single point called the effective viewpoint [5]. The existence of the effective viewpoint is rewired if it is necessary to generate geometrically correct perspective images.

There are only six catadioptric systems with a single viewpoint [4]. Out of these six systems, only two systems enlarge the field of view and, thus, it makes

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sense to use them as omnidirectional cameras. If the shape of the mirror is a parabola, the projection to the image plane must be orthographic to ensure that the single viewpoint constraint is preserved. The only catadioptric system which consist of a standard pinhole camera and a mirror that enlarges the field of view has a hyperbolical mirror. Therefore, we use a catadioptric camera with a hyperbolical mirror in our bird's-eye view system.

Recently, Bertozzi *et al.* [11] introduced an obstacle detection system that is composed of two cameras with spherical lenses mounted on a heavy good vehicle. The cameras cover only the front of the vehicle and thus only obstacles in front of the truck are detected.

In [6] a system using omnidirectional cameras for traffic flow analysis is presented. Camera are deployed along the road. Thanks to the large field of view much smaller number of sensors is necessary compared to using conventional cameras. After receiving the omnidirectional images a flat plane transformation is performed and a car counting algorithm is applied.

In [7], a map of the surrounding area of a car is generated from catadioptric omnidirectional images obtained by using a hyperbolic mirror. The cameras are mounted on the side mirrors, and thus the views in front of the car overlap and can be used for stereo analysis. Due to the low resolution of the omnidirectional images in front of the car, the stereo estimation is too challenging to be reliable and useful.

In [8], an omnidirectional camera is placed above the roof of a car. This system detects and tracks vehicles. Because the cameras are placed too high above the car roof, the configuration is not suitable for general cars. Another camera configuration presented in their work consists of two omnidirectional cameras placed on the side mirrors. By using this configuration, only the side areas of the car are covered by the omnidirectional cameras and the area in front of the vehicle is not seen.

In our system, the position of the cameras is optimized such that every point on the ground plane is visible and the mounting position is selected so that it is suitable for car manufacturing and design.

3 Omnidirectional Cameras

The omnidirectional cameras mounted at the truck consist of hyperbolic formed mirrors and standard pinhole cameras; consequently the single viewpoint constraint is fulfilled. This ensures that valid perspective images can be generated from omnidirectional images.

A hyperboloid in 3D is given by

$$\frac{(Z-c)^2}{a^2} - \frac{X^2+Y^2}{b^2} = 1 \tag{1}$$

where $a > 0$ is the semimajor axis, $b > 0$ the semiminor axis of the hyperboloid and $c = \sqrt{a^2+b^2}$.

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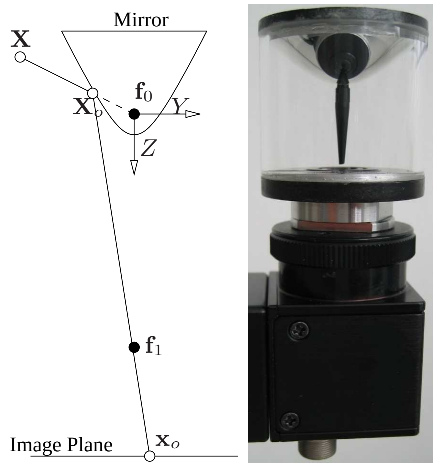

Fig. 2. The figure shows the omnidirectional projection. The point $\mathbf{X}$ is given in the coordinate system defined by the focal point $\mathbf{f}_0$ within the mirror. The z-axis points towards the image plane. $\mathbf{f}_1$ is the second focal point with coordinates $(0, 0, 2c)^T$. Right: Omnidirectional camera consisting of a hyperbolic mirror with a standard pinhole camera. The black needle in the middle avoids reflections on the glass cylinder [10].

The intersection $\mathbf{X}_0$ of a line $g = \mathbf{f}_0 + \lambda(\mathbf{X} - \mathbf{f}_0)$ with the hyperboloid leads to the following solutions (see Figure 2):

$$\lambda_{1,2} = \frac{b^2}{\pm a||\mathbf{X}|| + cZ} \tag{2}$$

with $||\mathbf{X}|| = \sqrt{X^2 + Y^2 + Z^2}$. The intersection with the mirror is given by λ_1 (see [9]), thus $\mathbf{X}_o = \lambda_1 \mathbf{X}$, if the origin of the coordinate system is placed in $\mathbf{f}_0$.

The point $\mathbf{X}_o$ is perspectively projected to the point $\mathbf{x}_o$, which is on the image plane. The optical center of this perspective projection is defined by the second focal point $f_1 = (0, 0, 2c)^T$ of the hyperboloid.

To apply the omnidirectional projection, the cameras must firstly be calibrated. The omnidirectional cameras are calibrated w.r.t. the vehicle coordinate system placed at the middle of the front of the truck. The calibration must be done once beforehand and kept fixed because the cameras are mounted in a fixed position.

The ideal mount position of the front cameras is close to the side mirrors and, for the cameras mounted at the back, it is on the roof edge of the trailer. It is obvious that the position of the back cameras is well suited for the task of obtaining a bird's-eye view image. The position of the front cameras is selected below the side mirror of the truck. Because of the side mirrors new blind spots would be generated if the camera were mounted at the top of the truck.

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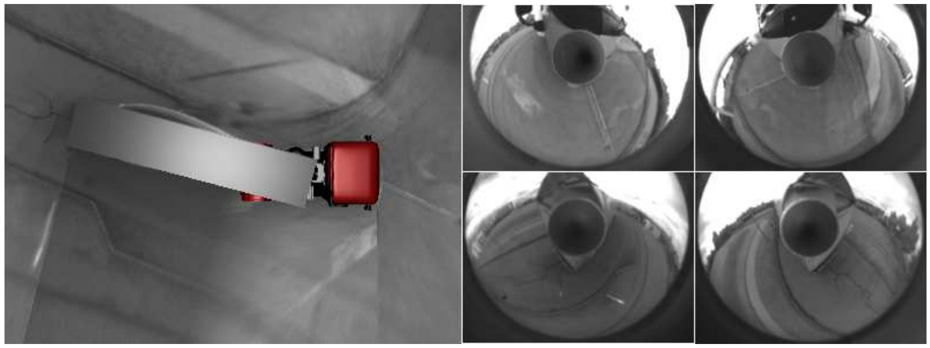

Fig. 3. Left: The bird's-eye view image. The kink angle between truck and trailer is $-14°$. Right: raw images from the omnidirectional cameras.

To obtain an optimal resolution, the hyperbolic formed mirrors are not centered in the cameras field of view. Instead, they are slightly shifted towards the top of the camera so that the region of interest on the ground plane is captured well (see Figure 3). The resolution is 752×480. The imager of the camera is CMOS.

4 The bird's-eye view construction

The bird's-eye view image is constructed in two steps (see Figure 4). First, a virtual perspective camera corresponding to the bird's eye is placed to a suitable point in space and pixels of the bird's-eye image are backprojected onto the ground plane. Secondly, the points on the ground plane are projected to one of the four omnidirectional cameras (see Section 4.1) and intensity values for them are constructed by an interpolation in the omnidirectional images. The explicit use of the virtual camera allows generating views suitable for current driving situation by placing the camera at arbitrary points in space.

Usually, we choose to place the projection plane of the virtual camera parallel to the ground plane and thus the resulting images are mere scaled versions of the ground plane.

4.1 Combine the images

The resulting bird's-eye view image is constructed in such a way that there are no new blind spots around the vehicle; consequently every point in the surrounding area of the vehicle is seen in the bird's-eye view image. For objects on the ground, it is obvious that they do not disappear. But this fact is not true for objects with non-zero height if the compound image was not constructed with care. A simple approach to stitch the images together is achieved by projecting $\mathbf{X}$ to the omnidirectional camera which is nearest to $\mathbf{X}$. In this case the part on the left-front side is taken by the camera on the driver side of the truck. The black lines

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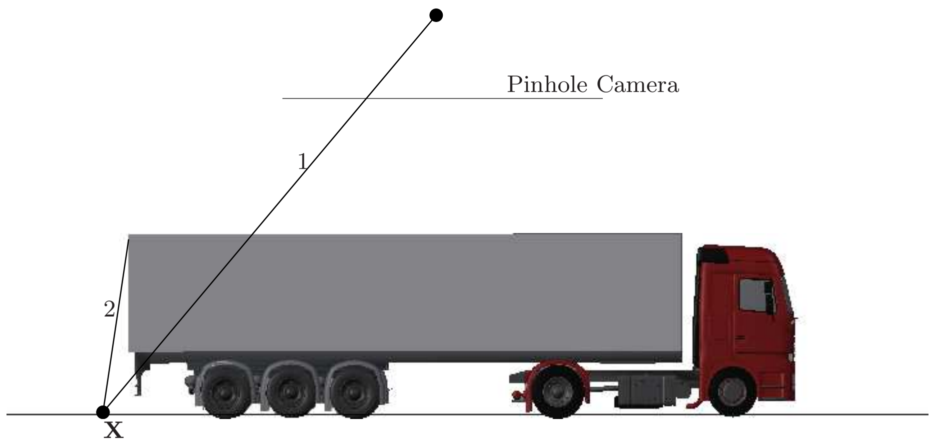

Fig. 4. The bird's-eye view system. First, pixels of the resulting virtual image are projected onto the ground plane and then they are projected to omnidirectional images where the pixel values are constructed by bilinear interpolation.

in Figure 5 shows a parting of the bird's-eye view according to this approach. The separating lines between the front and back cameras are chosen to be nearer to the front, due to the height of the cameras on the trailer.

This approach, however, leads to new blind spots in the surrounding area of the truck. Due to the flat world assumption objects with non-zero height are not fully seen in the resulting image. Figure 6 on the right hand side points out a person standing in the middle of the truck is not fully visible on the resulting bird's-eye view image.

On the left hand side in Figure 6, a division along the baseline of the front cameras is shown. The person in the middle is fully visible in the resulting image. The same fact is true for the omnidirectional cameras mounted at the back of the trailer and for the combination of the back and front cameras. We decided to choose a division along the baseline of the cameras for the front and back cameras, individually (see the red lines in Figure 5). However, it does not make sense to choose a separation along the baseline for the division of the back and front view, because the distance from the back to the front is very large and the sampling of the front area by the back cameras is too low to receive useful results.

A more detailed explanation of the construction of cameras mounted at a truck is given in [12].

4.2 Kink angle

The angle between the truck and trailer is measured contact-less by a sensor KMA 200 from NXP [3]. This sensor uses the anisotropic magnetoresistive (AMR) effect. This effect causes a change of the resistance of magnetic material

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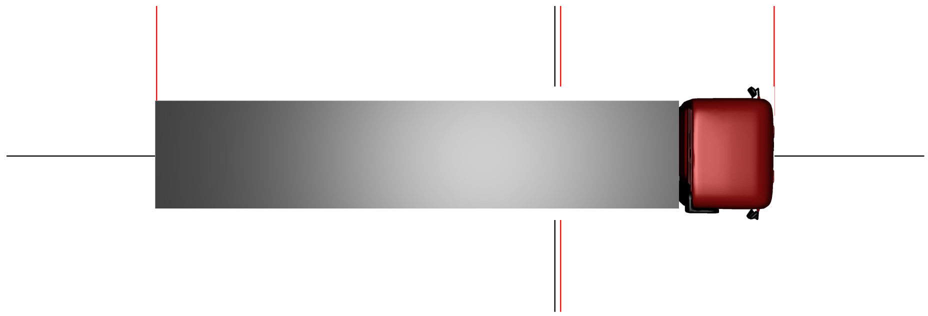

Fig. 5. Several subdivisions to construct bird's-eye view images. The black lines show the division into the cells of points closer to each camera than to any other camera with the exception of the the front and back camera separation line, which is set more to the front to the account for the height of the back cameras. The red lines show the subdivision that removes the most important blind spots. However, there is still a blind volume in the middle part between truck and trailer.

that depends only on the direction of a magnetic field and not on the strength of the field.

Thanks to this measurement method, the sensor is independent from the temperature and magnetic drift during life time. It is also independent from mechanical assembly tolerance and shifts caused by thermal stress. These features are very important for practical systems because the sensor is placed to outdoor conditions. Magnets are mounted at the trailer. The sensor is placed at the shaft of the truck.

The backprojected pixels from the pinhole are rotated according to the angle given by the measured angle $\mathbf{X}_{rot} = \mathtt{R}\mathbf{X}$ and then projected to the omnidirectional cameras, where $\mathtt{R}$ is the rotation matrix and $\mathbf{X}$ the backprojected point without rotation.

5 Results

The presented system works on a Mercedes-Benz Actros (see Figure 1). The truck is connected to a trailer, which is about 13 meters long. The truck is 2.49 meters wide and 3.85 meters high. The head of the driver is at about 2.80 meters above the ground plane. This causes that large parts in front of the truck are not seen by the driver. The parts behind the vehicle can also be hard to see, similarly to large areas on the right hand side. There are three mirrors on the passenger side and two mirrors on the drivers side. However, the mirrors do not cover the near surrounding area in front of the truck as well as some areas on the right and left hand side.

The bird's-eye view image is presented to the driver on a 8.5 inch display. This display is placed next to the steering wheel so that the driver is able to easily check the screen.

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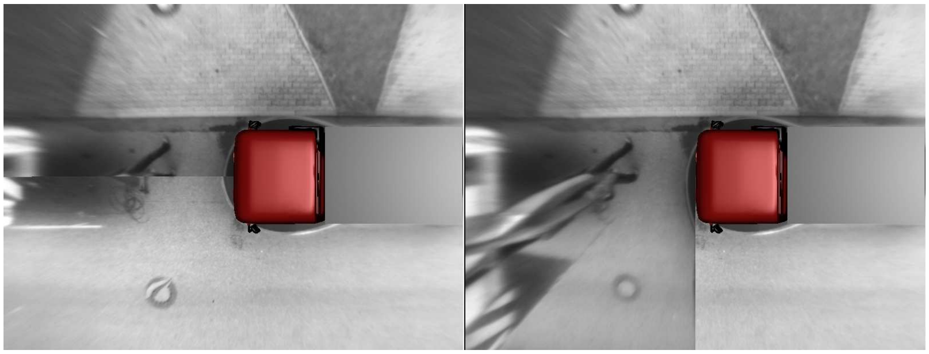

Fig. 6. Left: Bird's-eye view image of the front cameras with a symmetric subdivision along the line of lateral symmetry. The person in the middle of the truck is not fully visible in the resulting image. Right: A subdivision chosen in such a way that the person is always visible in the bird's-eye view image.

Figure 7 compares different approaches to combining images. The figure on the right hand side shows a combination that projects the point $\mathbf{X}$ to the nearest omnidirectional camera. In front of the truck this means that the left part is taken from the driver's camera and the right part from the camera on the passenger side. The Figure illustrates that there is a large blind volume - blind wedge - extending from the front of the truck. No point within the wedge can be seen in the compound image and thus is virtually invisible to the driver.

Figure 7 on the left hand side shows a splitting along the baseline of the cameras. It is illustrated that no point disappears from the compound image. As a point moves through the parting plane, its projection does not disappear, but it jumps along the separating line in the image. There is only a discontinuity in the projection.

A blind wedge also appears in the region between the truck and trailer. According to Figure 5, the parts in front of the red line are taken from the cameras mounted at the truck; parts behind the red line are taken from the cameras mounted at the trailer. Objects with non-zero height standing in the middle of the truck and trailer are within the blind wedge and thus are not seen by the driver. To avoid this blind wedge, we want to use a concept similar to line-scan cameras. For a point within the middle part of truck and trailer, we select the same point in some frames back, when it was at the level of the front cameras. Similar, if the vehicle drives backwards, we select the point when it was at the level of the trailer cameras. Thus, scan-lines at the level of the front cameras are placed in the middle part of truck and trailer. Consequently, the scan-line concept transmutes blind spots in space - blind wedge - to blind spots in time. If the truck is not driving, no scan-lines are used. This will be further investigated and explored elsewhere.

The resolution of the omnidirectional cameras is examined in Figure 8. The contours of a three-dimensional function is shown. This function consists of the

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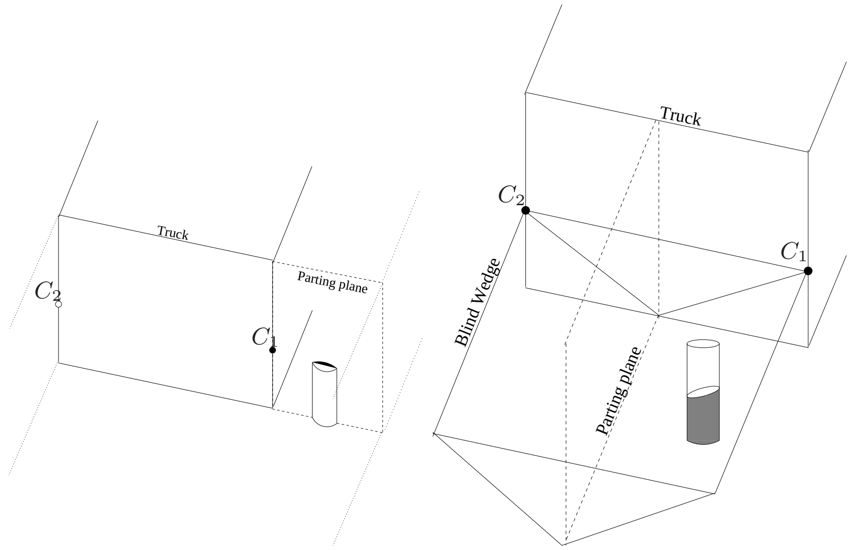

Fig. 7. Left: Splitting the space along the baseline of the cameras C_1 and C_2. Camera C_1 sees the black part of the cylinder and camera C_2 sees the white part. There is no blind spot. Right: Splitting plane along the line of lateral symmetry of the truck. Everything that is within the blind wedge is not seen in the compound image. Thus, the empty part of the cylinder is not seen on the display (See also Figure 6).

x and y world coordinate and the area covered by a backprojected pixel of a omnidirectional camera. Figure 8 shows that the lowest sampling is in the middle part between truck and trailer. But this area is well covered by the side mirrors of the truck. The cutouts are selected in such a way that the lowest sampling area is either in an area that is well covered by the mirrors or in a region that is directly visible from the driver's position.

6 Summary and Conclusions

We have presented a system that enables trucks, busses, and other large vehicle drivers to survey the surrounding area of their vehicle. Omnidirectional images are taken from four catadioptric cameras attached to the truck-trailer combination. The omnidirectional images are transformed and combined in such a way that a bird's-eye view image of the surrounding region of the vehicle is presented to the driver on a single display.

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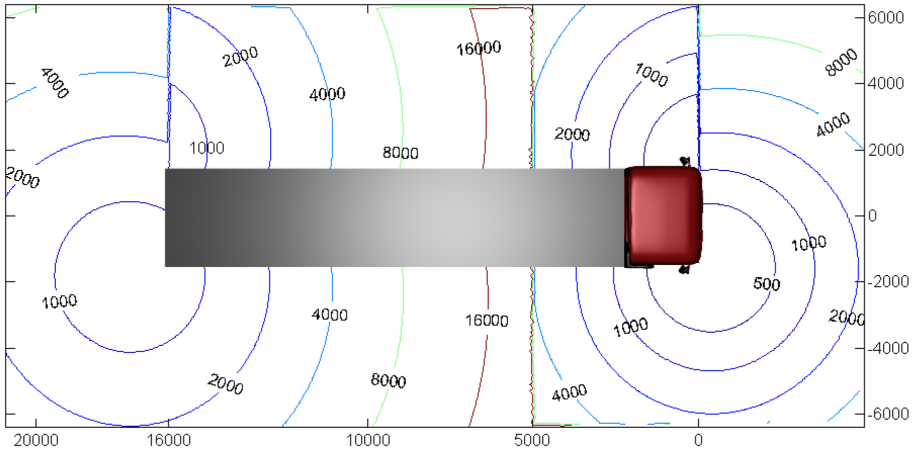

Fig. 8. The resolution of the bird's-eye view system. The Figure shows the contours of a three-dimensional function consisting of x,y coordinates and the area covered by backprojected pixel of the omnidirectional cameras. The values within the plot are the area covered by a backprojected pixel. All values are given in mm^2.

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