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ROAD SEGMENTATION AND TRACKING BY MATHEMATICAL MORPHOLOGY

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S. BEUCHER, X. YU, M. BILODEAU

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S. BEUCHER, X. YU, M. BILODEAU

Centre de Morphologie Mathématique
Ecole des mines de Paris
35, rue Saint-Honoré
77305 FONTAINEBLEAU (France)

Abstract

A road segmentation technique based on morphological tools named watersheds and homotopy modification is presented. The watershed transform allows to define, starting from the initial image, a coarse marker of the road. This marker is produced by various methods. Among them, the morphological gradient regularization, and the hierarchical watershed of a simplified mosaic picture provide good results, slightly sensitive to noise. Many situations have been successfully tested and some examples of results are given.

Road segmentation may be improved by detecting the various traffic lanes. This improvement needs only a little change in the markers detection and do not require more sophisticated tools.

This technique is also well adapted to the problem of road tracking in a sequence of images. The previous road markers can be used to detect the actual road. This approach leads to a significant reduction in computation time.

Examples of road tracking and possible obstacle detection are presented on sequences of images.

INTRODUCTION

This paper presents some of the work done by the Centre de Morphologie Mathématique of Paris School of mines in the scope of the European PROMETHEUS project. Our contribution in this project is related to the use of vision sensors to provide assistance to the driver. Our main purpose is to elaborate image processing algorithms able to inform the driver about the position of the car on the road and about the occurrence of possible obstacles that could block the traffic.

The core of the process consists in automated road detection. This detection must be efficient for any kind of roads, motorways, highways or country roads and for any weather conditions. In fact, at this point of the project, all different weather conditions have not been tested yet. Because of the inability of video cameras to produce good pictures by night, we have restricted our investigations to daylight images.

This road detection is based on mathematical morphology tools and especially on a methodology of image segmentation called the watershed transformation. This technique will be shortly described in this paper. A more detailed presentation can be found in [1], [2], [9]. This approach enables the segmentation of the road in the scene as well as the detection of the traffic lanes. As a consequence of the segmentation, the free-running part of the road in front of the vehicle can be defined and therefore the regions of the scene containing possible obstacles.

The picture databases come from PSA, RENAULT. These pictures are black and white CCD camera images. The different image algorithms have been developed on morphological image processors at the CMM. At this stage of the project, no real-time treatment is available.

The first part of the paper briefly describes the segmentation tools. In the second part, some results for road and traffic lanes segmentation are presented. The use of the results for obstacle detection is also introduced. Finally, the application to road tracking in a sequence of images is described.

I) MORPHOLOGICAL IMAGE SEGMENTATION : AN OVERVIEW

I-1) Image segmentation

Image segmentation by mathematical morphology is based on two main tools. The first one, called the watershed transformation, produces a partition of the image into regions named catchment basins. In most cases, this transformation is applied on the gradient modulus image, in order to detect the homogeneous regions of the scene. Unfortunately, this results in an over-segmentation of the image. The second tool used in the segmentation process suppresses this over-segmentation. It consists in marking the regions to be segmented and in modifying the gradient image so that the watershed transform contains as many catchment basins as there are selected markers.

I-1-1) The watershed transformation

Let us give an intuitive definition of the watershed transform of a function g. Consider the graph of g as a topographic surface : the higher the value of g(x) at point x, the higher the altitude of the corresponding point in the graph. Suppose then that the minima of this topographic surface are pierced. If this surface is plunged in water, the water will flow through the holes and will progressively flood the topographic surface. While flooding, dams can be built on the surface at any point where waters coming from different minima may merge. At the end of the flooding process, the divide lines corresponding to the dams are the watershed lines of g and the various connected regions separated by the watershed lines are the catchment basins of g (Figure 1).

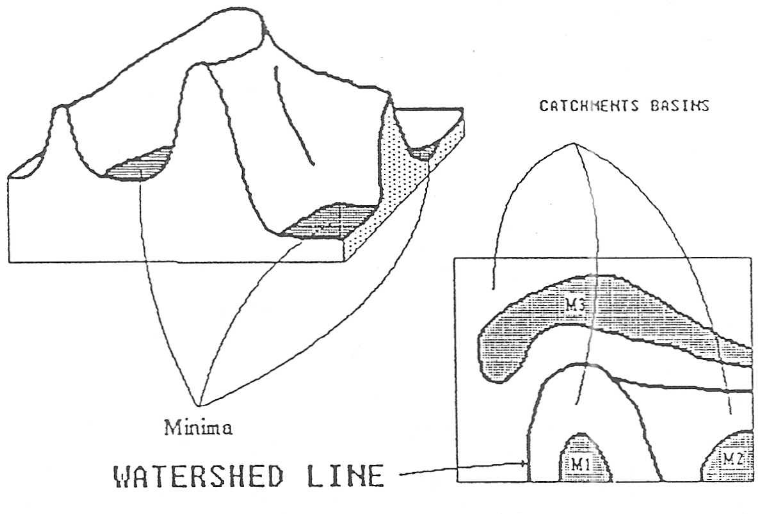

Figure 1 : *Regional minima, catchment basins and watershed lines.*

I-1-2) Watersheds of the gradient image

The watershed segmentation is based on the following assumption : any homogeneous grey-tone region in an image is characterized by a low contrast and hence a low gradient. Moreover, this homogeneous region corresponds to a minimum of the gradient function since the transition from a region to an adjacent one leads to an increase of the gradient modulus. Therefore, the homogeneous grey-tone regions in an image are the catchment basins of the gradient function. Let us denote by f the original grey-tone image. Very often, the gradient image used in the watershed transformation is the morphological gradient g of f defined as :

$$g(f) = (f \oplus H) - (f \ominus H)$$

where $(f \ominus H)$ is the erosion of f by an elementary hexagon H, and $(f \oplus H)$ is the dilation of f by H (the initial picture is supposed to be digitized on an hexagonal grid), [3] (Figure 2).

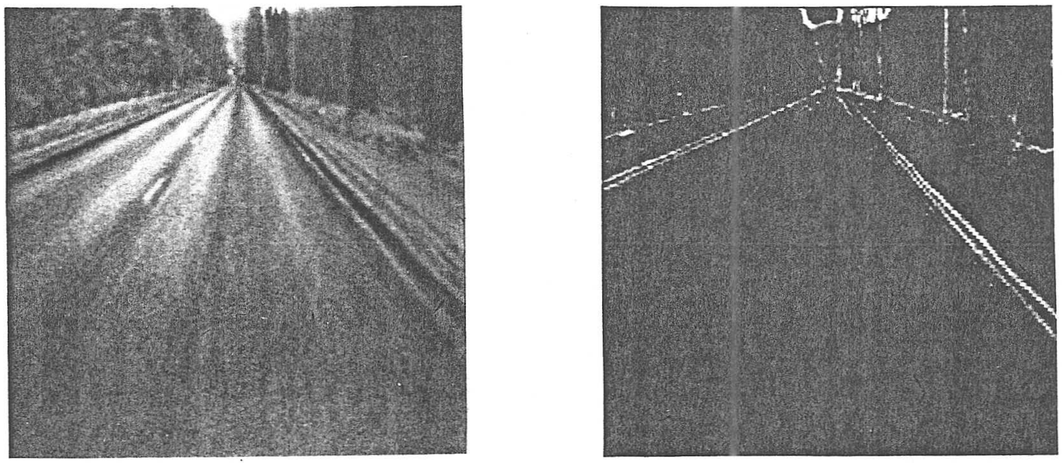

Figure 2 : *Original image and its morphological gradient*

I-2) Marker-controlled segmentation

As already mentioned, the use of the watershed transformation on the gradient image is unsatisfactory. Various factors, especially noise and grey-tone inhomogeneities, lead to a severe over-segmentation (Figure 3).

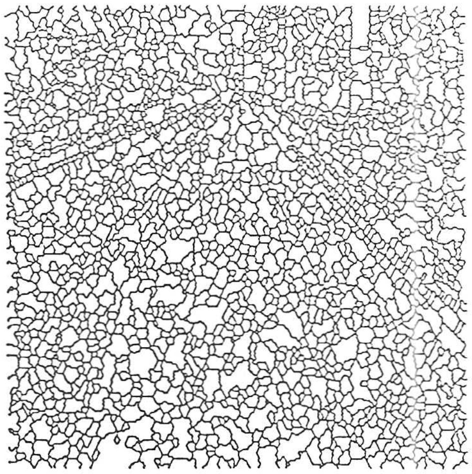

Figure 3 : *Watershed of the gradient image and over-segmentation*

In order to suppress this over-segmentation which comes from the fact that too many minima are used in the watershed transformation, we may impose that the topographic surface is flooded through a limited and previously chosen number of holes. In so doing, the regions to be extracted must be marked first, and the set of markers are then imposed as the new minima of the gradient. This is done by modifying the original morphological gradient function. This modification is performed with a geodesic image reconstruction (for more details, see [1]) (Figure 4).

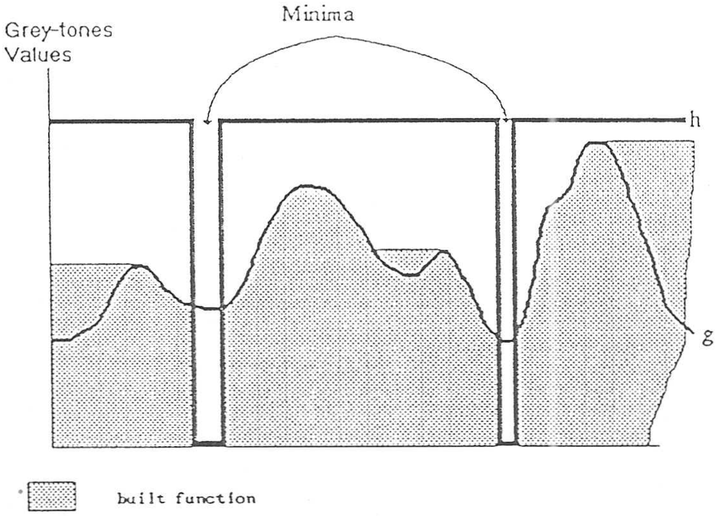

Figure 4 : *Reconstruction of a function by geodesic erosion*

As a result, the morphological approach of image segmentation is made of two successive steps : the first one consists in defining the markers of the regions to be segmented in the picture. The second one simply uses these markers to modify the gradient image. The watersheds of the modified image are then computed. To achieve marker selection, a lot of techniques depending on the case are available. Concerning road segmentation, we simply need, at least in the early steps of the process, two markers : a marker corresponding to the road and another one corresponding to the surroundings.

II) ROAD SEGMENTATION ALGORITHMS

II-1) Selection of markers

As said before, the main problem to be solved for a fair road segmentation is to find accurate markers of the road and of the surroundings. Many possibilities are available. One could, for instance, define these markers by setting some geometric template supposed to be a good representation of the road. The difficulty, in that case, lies in the fact that many configurations of the road may be encountered. So, a general template may be hard to define. Two solutions have been tested for the detection of the markers. Both use the current image of the road. The first solution consists in using a regularized morphological gradient in order to reduce the over-segmentation. The second solution starts from a simplification of the original image. This simplified image is used to extract homogeneous regions.

These two marking techniques are non-parametric. They are only based on the difference of contrast between the road and its border.

II-1-1) Segmentation using a regularized gradient

The regularized gradient g* of an image f is defined by :

$$g^* = \sup_i (u_i)$$

where u_i is given by :

$$u_i(f) = [(g_i(f) - ((g_i(f) \ominus H_{i+1}) \oplus H_{i+1})] \ominus H_{i-1}$$

with :

$$g_i(f) = (f \oplus H_i) - (f \ominus H_i)$$

H_i is an hexagon of size i.

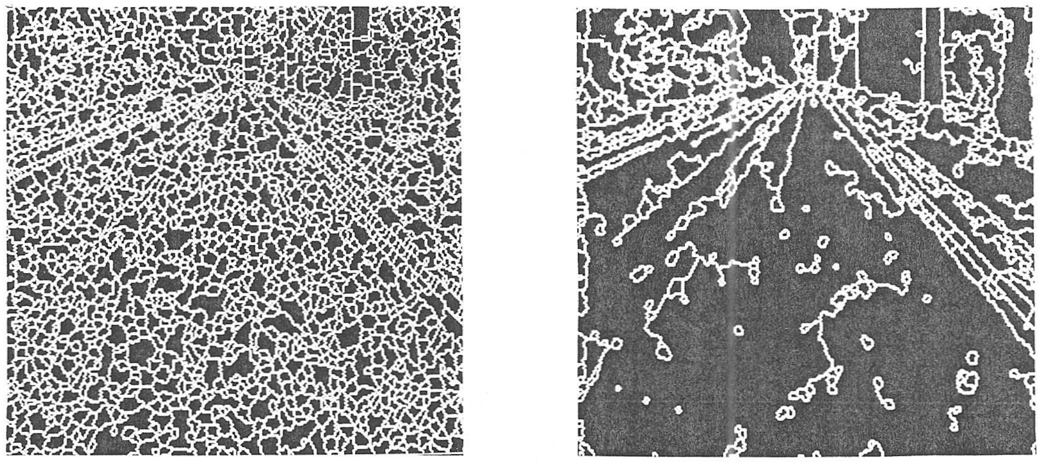

Figure 5 : *Watershed of the simple gradient (left) and the same transform applied to the regularized gradient (right)*

The watershed of g* (Figure 5) is less over-segmented than the watershed of g. So, this first segmentation can be used to extract a coarse marker of the road. This marker is obtained by a simple selection of the catchment basin of W(g*) located in the front of the scene (Figure 6). This marker is smoothed and an outer marker can be built by complementation and erosion. These two markers may be used as explained above to modify the original gradient and calculate the watershed. The final result of the segmentation (Figure 7) exhibits two regions corresponding to the two initial markers (road and surroundings).

Figure 6 : *Primitive marker of the road*

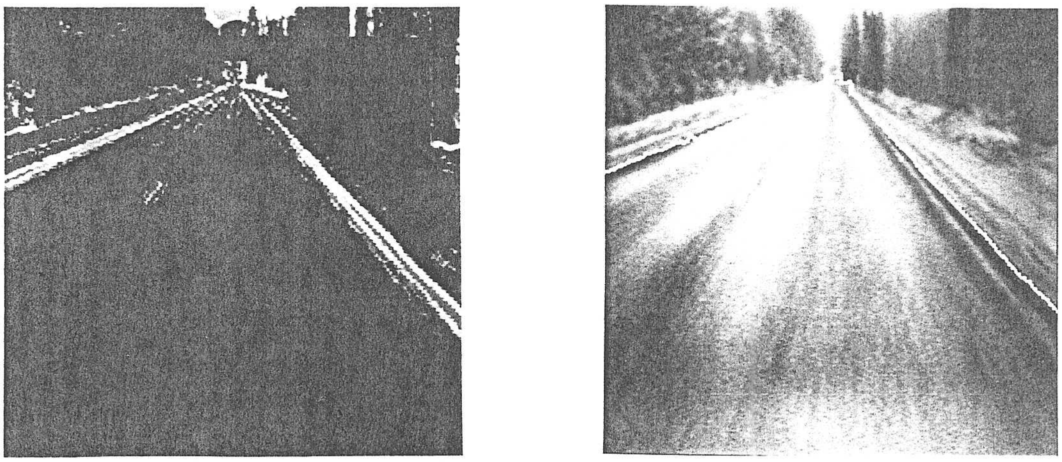

Figure 7 : *Selected markers and segmentation of the road*

II-1-2) Segmentation using a simplified image

In that case, the road marker is obtained by applying the watershed transform to a gradient image calculated from a simplified version of the initial picture. This simplified picture, also called mosaic image, is built by assigning to each catchment basin of the over-segmented watershed of the original gradient a grey value that is equal to the value taken by the less contrasted pixels inside this catchment basin (Figure 8). From this picture, a gradient can be defined. This gradient is equal to zero everywhere except on the watershed arcs of g where its value is $| f_i - f_j |$, f_i and f_j being respectively the grey values associated with the catchment basins on either side of the watershed arc. This gradient leads to the definition of a new image, its watershed pointing out the regions of the initial image surrounded by higher contrast edges (Figure 9). For a deeper presentation of this notion, see [1].

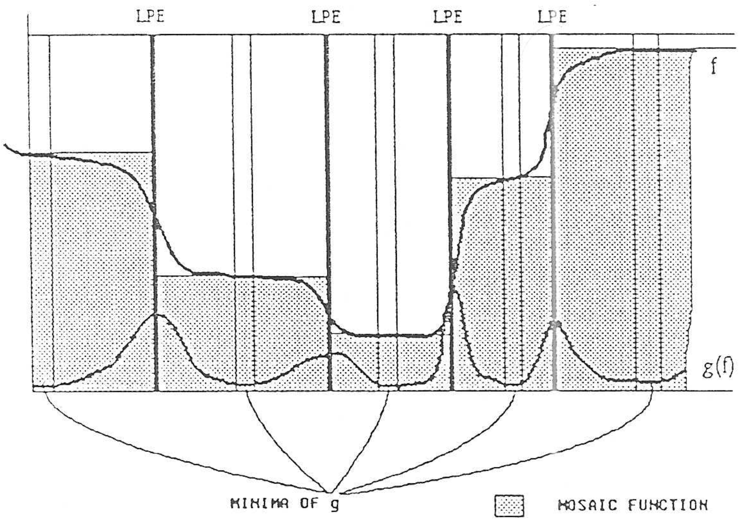

Figure 8 : *Principle of the construction of a simplified image*

Here also, the front catchment basin is extracted and used as marker of the road.

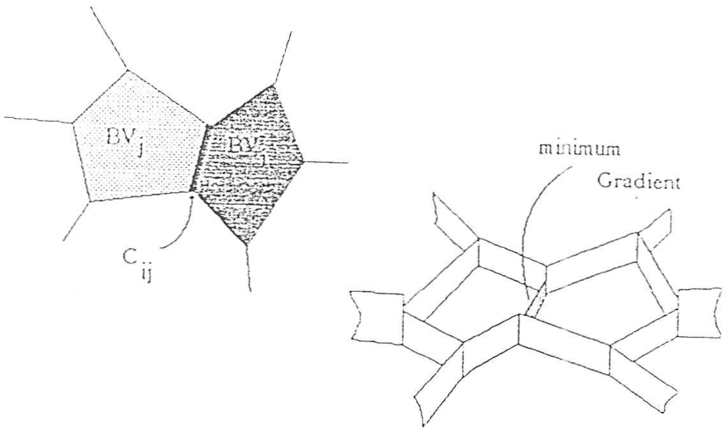

Figure 9 : *Mosaic image and its gradient graph*

II-2) Results

Figure 10 shows the markers obtained with the two methods. As already mentioned, we need two markers: an inner one and an outer one. The latter can be computed by complementation and erosion of the former one. This step is dangerous as we may impose an outer marker that covers the two regions to be segmented. We will come back to that problem when describing the road tracking techniques. In fact, we can show that (see [1], pages 246-248) the definition of an outer marker is not needed if we use watershed algorithms where the flooding is performed by the inner marker only and where adjacent catchment basins can be connected or not depending on the symmetry of the water flows coming from both sides of their common watershed arc (these algorithms are called waterfall algorithms). Moreover, the result obtained with this kind of algorithm is the same as the result of the hierarchical approach with a simplified image. This is the reason why the segmentation by means of the simplified image should be preferred because we do not need to introduce any hypothesis about the shape and size of the road. The only assumption is that the contrast between the road and the surroundings is greater that the contrast between the features inside the road. As a consequence, the better the contrast of the original picture, the better the results.

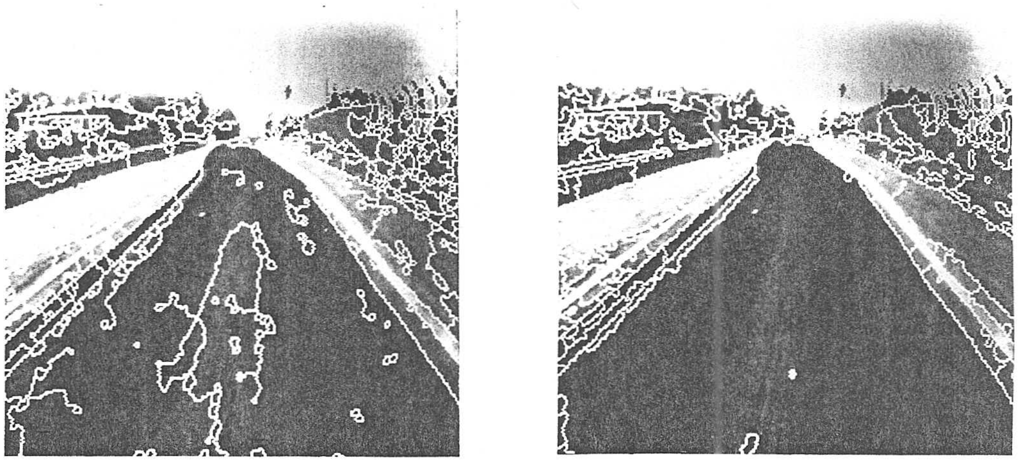

Figure 10 : *Markers obtained with the regularized gradient (left) and with the simplified image (right)*

Different techniques can be used to enhance the contrast of the initial image (notice for instance that the mosaic image is a higher contrasted version of the initial one). The best results are obtained when acting on the sensor itself. We can use CCD cameras with a good sensitivity to the infrared bandwidth. Good results could also be obtained by using colour cameras [4] because of the great difference in colour between the traffic lanes and the surroundings, especially for country roads.

III) OTHER APPLICATIONS

III-1) Traffic lanes detection

In the previous examples, the only criterion used for segmentation was the variation of the contrast between the regions to be extracted. That is why the function used in the watershed transformation was the gradient function. But it is also possible to apply this transformation to other functions corresponding to other criteria of segmentation. As an example, we can use the continuous or broken lines which may separate the traffic lanes. These lines are easily detected by a top-hat transform [3] :

$$TH(f) = f - (f)_{iH}$$

where $(f)_{iH} = (f \ominus iH) \oplus iH$.

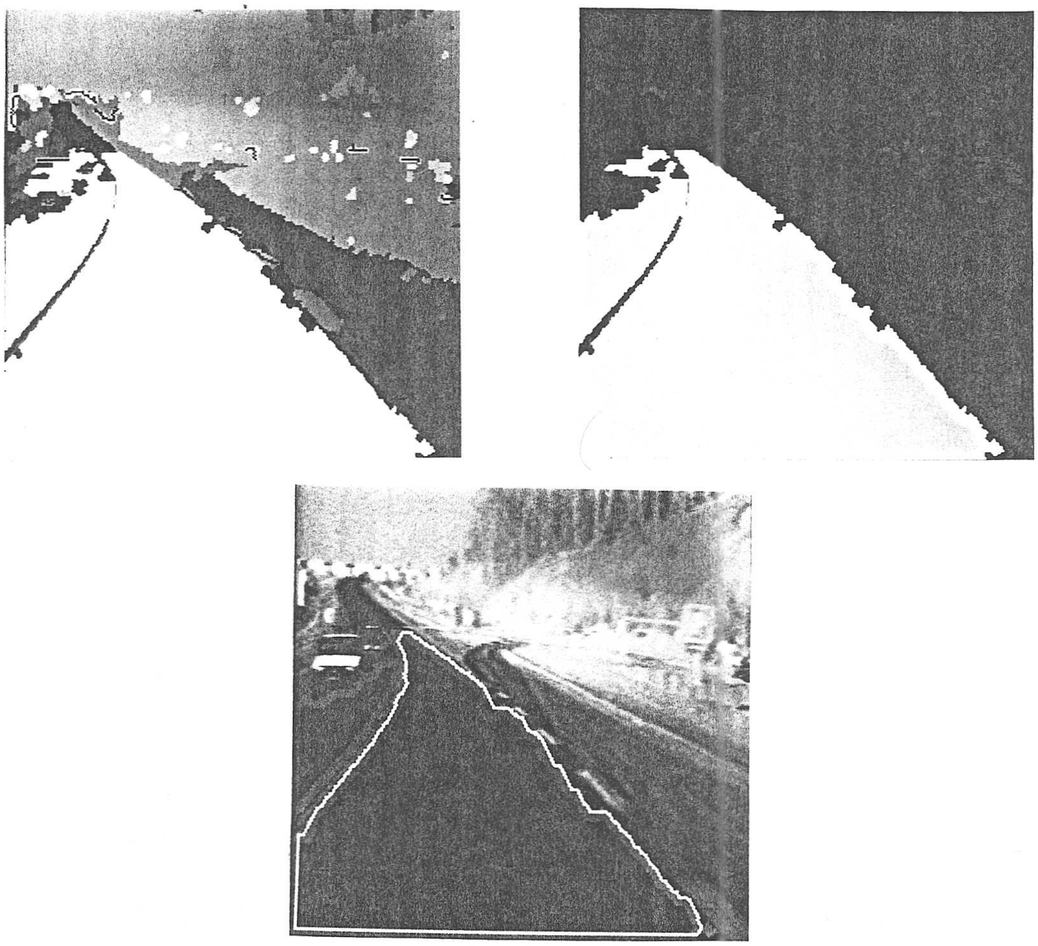

Figure 11 : *Lane by lane road segmentation*

White and elongated objects are extracted (Figure 11a). Among them, only those that are included in the primitive marker of the road are kept (Figure 11b) and used to cut this primitive road marker into its different traffic lanes (Figure 11c). This operation can be performed systematically for any kind of road because if no line exists on the road, no detection will be performed by the top-hat transform and then no deeper segmentation of the road marker either.

III-2) Obstacles detection

In order to introduce how to use the previous results to detect obstacles on the road, let us take an example.

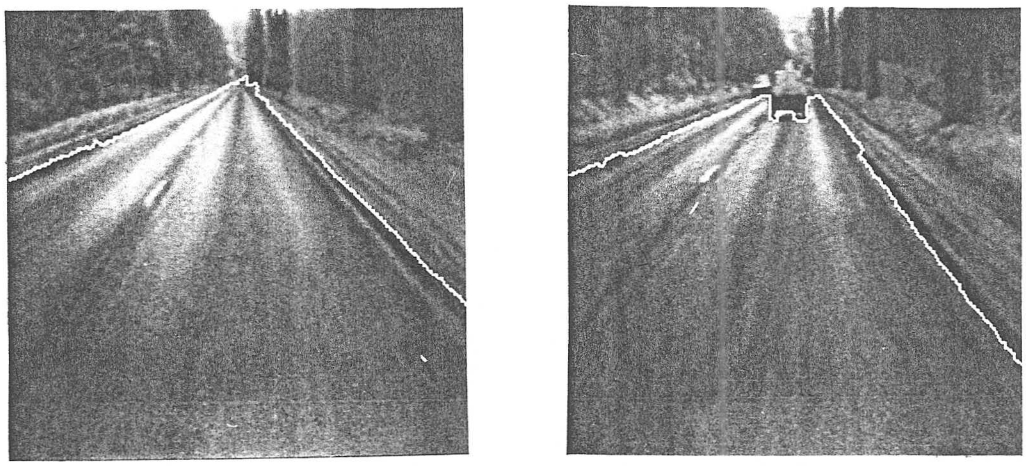

Figure 12 : *Road without obstacle (left) and obstacle-free zone (right)*

Figure 12 shows the same road taken at different times. In the left image, there is no obstacle and the road is segmented as far as we can see it. In the right image, there is an obstacle (another car) on the road, which hides a large part of it and leads to a reduced segmentation. In both images, the road segmentation delimits a zone without obstacle. This example illustrates our approach of the detection of possible obstacles: we do not evaluate where is the horizon point, neither how many obstacles there are, we simply try to delimit a zone in front of the car which corresponds to a obstacle-free region. This region is bounded by a zone containing possible obstacles. These obstacles may be real (other cars, pedestrians, bicycles, ...) or not (shadows, variations in grey levels on the road, ...) but at this point of the process, no classification is performed. Other cooperative techniques (stereoscopic vision, telemetry) should be used to separate the different kinds of obstacles.

III-3) Road tracking in a time sequence

The above processing can be extended for road tracking in a time sequence. The initialization process and the detection of the markers is performed as explained before on the first image: the watershed transform of the image gradient is made, then a mask of the road is extracted and is used to modify the gradient image. A watershed transformation is applied again to the modified gradient and produces the final segmentation containing as many regions as there are markers. The region in front of the car corresponds to the obstacle-free zone. These initial markers may be used to segment the next image in the sequence. The simplest approach consists in using the previous markers to modify the gradient of the next image. A watershed transform on this modified gradient produces the obstacle-free zone of the current image. The markers extracted from the segmentation of this current image are then considered as the new markers of the road and the surroundings. The previous step of the algorithm is run again for the next image of the sequence and so forth. This method has a great advantage: we do not need to build the markers set for each image of the sequence. This may reduce considerably the computation time of the process. But this technique has a major drawback: it assumes that the scene we see through the windscreen is more or less always the same. It does not take efficiently into account the information coming from the current image in the segmentation process since this segmentation is done on the current gradient modified by the markers of the preceding image. But in fact, the previous markers may often be poorly related to the current image of the road. If the road scene variations are too important because of shadows, bridges, obstacle coming laterally and so on, the markers of the previous image do not fit any more with those of the current image. Table 13 clearly illustrates this phenomenon when driving under a bridge. As a consequence, we may wrongly segment the road and produce a free-running zone smaller than it is because the outer marker is too important, or on the contrary, lose some obstacles on the road because the previous inner marker is too large and covers them.

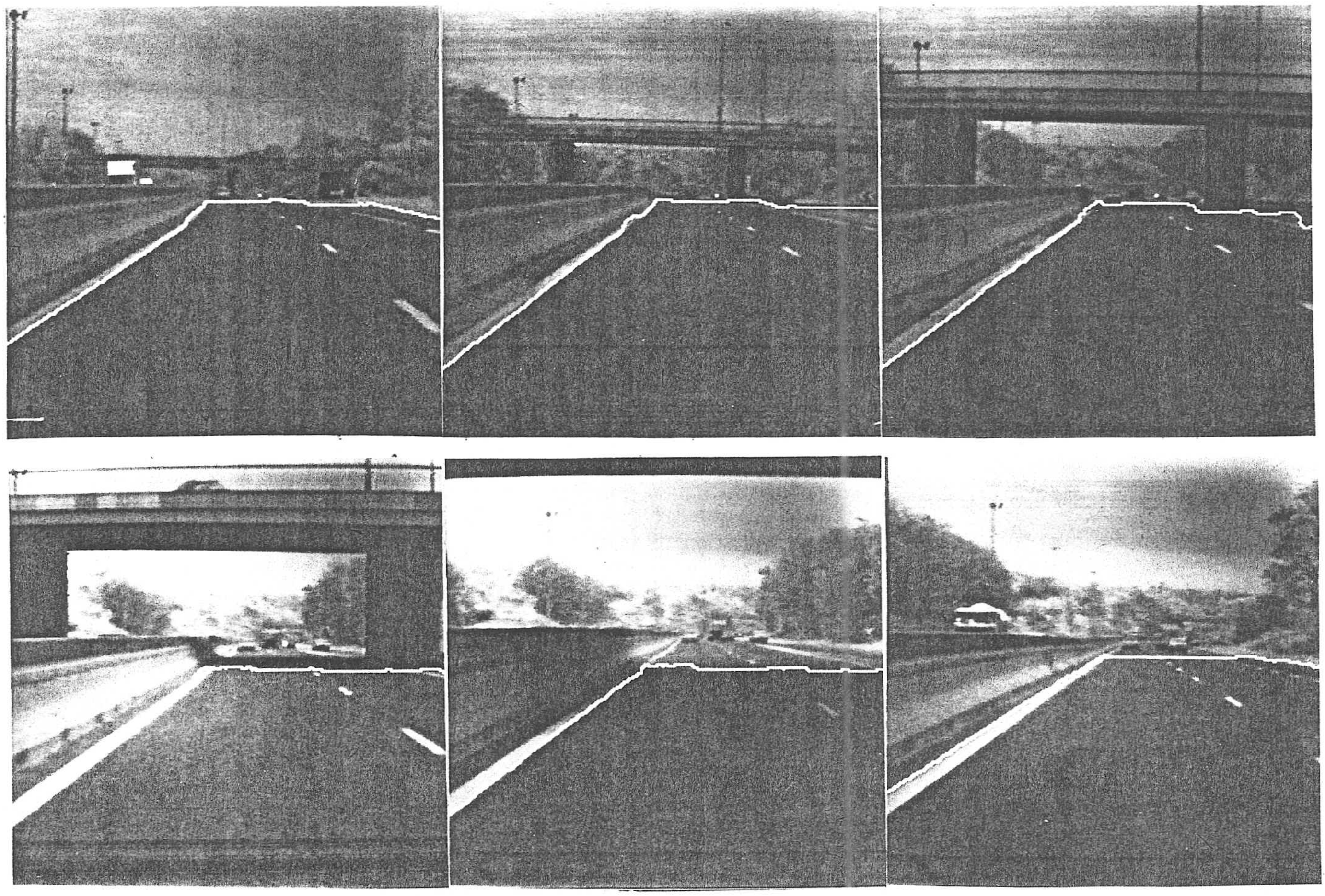

Table 13 : *Tracking the road while passing under a bridge*

This defect may be remedied if we merge the information coming from the previous image with that from the current one. The simplest way is to perform a complete road detection for each image of the sequence as described earlier and then to intersect the current markers with the previous ones. This complete road detection however nearly doubles the processing time since two watershed transformations have tot be made for each image.

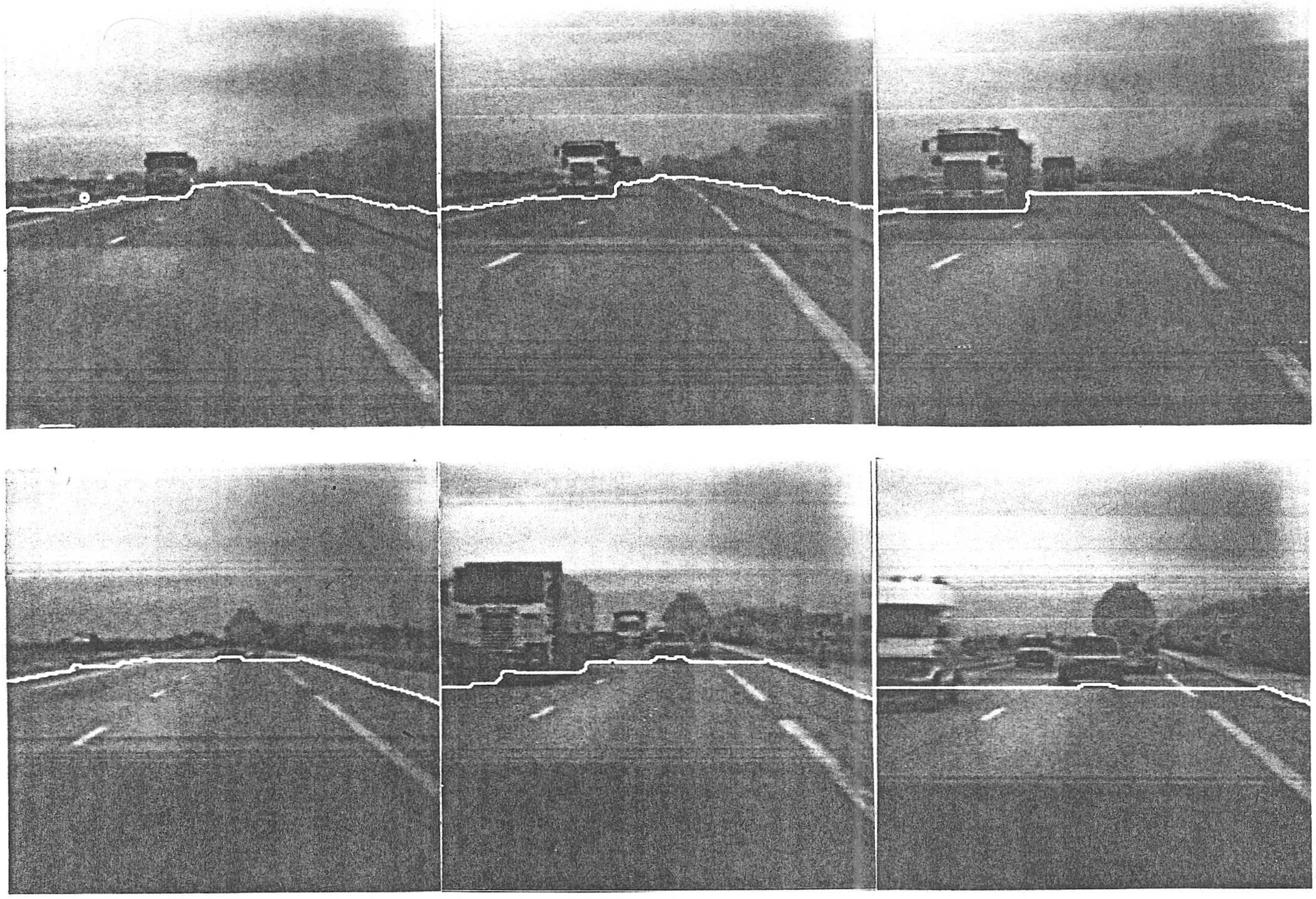

Figure 14 : *Obstacle detection and road tracking*

Other results of the processing of a time sequence are given on Figure 14. The first algorithm (road tracking without using the current markers) has been tested on ninety image sequences, with a time interval of 200 ms between the images. No real-time test exists yet. The entire process is emulated on a SUN 4/60 computer and takes about 7 seconds per image (10 minutes for the complete sequence). No measure is performed except the obstacle-free zone length that is calculated from the perspective distortion of the road. This parameter measures the distance between the car and a potential obstacle.

CONCLUSION

The use of the morphological techniques of image segmentation have proved to be efficient when applied to the problem of road detection and tracking. The algorithms described in this paper have been tested on a large database (more than one hundred scenes). The watershed transformation associated with image modification or simplification is an object-oriented segmentation method well suited to the road extraction.

Its main advantage are the complete control of connectivity problems (the result of the segmentation is always composed of a limited number of regions: the road or the traffic lanes and the surroundings) and the fact that the same algorithms can be applied to different images (gradient, distance function) so that a multi-criteria approach of the segmentation is not difficult. This approach leads to basic but efficient measurements and information: distance between the car and potential obstacles, nature of the road (with outlined traffic lanes or not). However, we do not try at this stage of the process to get more information about the nature of the potential obstacle. This is too complicated, too much time-consuming and in fact useless. Actually, this task must be done with the help of other sensors. A telemetric laser system could be directed towards the potential obstacle zone and its distance measurement compared with the value calculated from the image. A three-dimensional extension of the potential obstacle may also be obtained with a scanning telemeter [5] or alternatively by stereoscopic reconstruction [6].

The major problem raised by this approach is the problem of the computation time. As a matter of fact, the actual process is at least forty times slower than it should be if we want to achieve a real-time system. To increase the process speed, different solutions are available. The first one consists in optimizing the algorithms and especially the watershed transformation. Many efforts are currently being made in this direction [7]. The second one is to use hardware processors. The main drawback when using hardware processors is the loss of flexibility. Fortunately, most of the basic morphological operations can be wired on all-purpose morphological processors, combining high speeds of computation with a great versatility of use. Some of them are already designed [8].

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