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Curve Detection from Images in Video-Based Navigation Methods

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Abstract—**This study investigates image-based navigation methods and algorithms for devices, with a focus on curve detection as a key step in object recognition. Image-based navigation relies on identifying objects in the environment and determining the device's position based on their coordinates. Roads were selected as the objects of interest, and their identification was explored through curve detection in images. Curve detection is a fundamental problem in computer vision, as curves represent object boundaries, contours, and trajectories, and play a critical role in shape analysis, cartography, and navigation systems. The study employs the Hessian matrix, constructed from second-order derivatives of pre-processed images, to analyze local curvature. By examining the eigenvalues of the Hessian matrix, local structures are classified, and pixels belonging to curves are identified with high precision. A curvature detection criterion based on the relative magnitudes of the eigenvalues is applied: if one eigenvalue is significantly larger than the other, the corresponding pixel is determined to lie on a curve. This approach enables accurate and robust identification of road structures in images, forming a reliable foundation for subsequent navigation and mapping applications.**

Keywords—curve; Hessian matrix; road detection; image processing; curvature;

I. Introduction

The research work is devoted to the study of image-based navigation methods and algorithms for devices. The basis of image-based navigation lies in the device's ability to recognize objects observed at a given moment and determine its own position based on the coordinates of these objects [1,2]. Objects may include various infrastructural elements such as bridges, buildings, roads, water reservoirs, power stations, as well as natural features such as cliffs, forests, rivers, and lakes. In this study, roads were selected as the objects of interest, and the problem of identifying them using different methods was addressed. One of these methods involves identifying roads in the form of curves from images. For this purpose, the problem of detecting curves from the acquired images is first considered.

Finding curves from an image is one of the important issues in computer vision and digital image processing [3]. Since curves represent the boundaries, contours and trajectories of objects on the image, their accurate detection plays the role of the main base in object recognition, shape analysis, cartography and navigation systems in the later stages. Modern approaches implement this process with both classical mathematical methods and based on artificial intelligence methods. Finding curves from the image is performed by going through several stages. The first of these stages is image processing. Image processing refers to the steps of transitioning from a color image to grayscale images, and then transitioning to black-and-white form with edge detection [4]. Finding curves from images is performed after edge detection, which is the final stage of processing. Edge detection only operates on black pixels in a black-and-white format.

II. Hessian Matrix

The detection of edges and curves in image processing is necessary for determining the shapes, boundaries and local features of objects. Although traditional approaches use first-order derivatives - gradient operators (Sobel, Prewitt, Canny, etc.) [5], these methods mainly detect edges and do not provide enough information about curvature. However, the Hessian matrix constructed from second-order derivatives allows more accurate analysis of local curvature features on the image [6].

By analyzing the eigenvalues of the Hessian matrix, it is possible to classify local image structures and determine curves with sub-pixel accuracy. This approach has been successfully applied in areas such as vascular imaging, fingerprint recognition, pathfinding from aerial images, and robot navigation [7].

The Hesse matrix provides information about the local curvature on the image. Its specific values show the direction of curvature and also its strength. The application of this approach can be used and is particularly useful in detecting edges, angles and curves from images.

III. Curvature Detection Criterion

The Hessian matrix H(x,y) is the matrix of second-order derivatives of a given pre-processed image I(x,y), and at a point (x,y) is defined as follows:

$$H(x,y) = \begin{bmatrix} I_{xx}(x,y) & I_{xy}(x,y) \\ I_{yx}(x,y) & I_{yy}(x,y) \end{bmatrix} \quad (1)$$

Where $I_{xx} = \frac{\partial^2 I}{\partial x^2}$ - second-order derivative in the x-direction,

$I_{yy} = \frac{\partial^2 I}{\partial y^2}$ - second-order derivative in the y-direction,

$I_{xy} = I_{yx} = \frac{\partial^2 I}{\partial x \partial y}$ - mixed derivatives.

The eigenvalues of the Hessian matrix (1) are the roots of the following quadratic equation:

$$\det(H - \lambda \mathbf{I}) = 0 \quad (2)$$

where H is the Hessian matrix, λ denotes its eigenvalues, and **I** is the identity matrix. Expanding (2):

$$\det \begin{bmatrix} I_{xx} - \lambda & I_{xy} \\ I_{xy} & I_{yy} - \lambda \end{bmatrix} = 0 \quad (3)$$

yields

$$(I_{xx} - \lambda)(I_{yy} - \lambda) - (I_{xy})^2 = 0$$

which simplifies to

$$\lambda^2 - (I_{xx} - I_{yy})\lambda + (I_{xx}I_{yy} - I_{xy}^2) = 0$$

Solving this quadratic equation, the eigenvalues are obtained as:

$$\Delta = (I_{xx} + I_{yy})^2 - 4(I_{xx}I_{yy} - I_{xy}^2)$$

$$\lambda_{1,2} = \frac{(I_{xx} + I_{yy}) \pm \sqrt{\Delta}}{2}$$

Based on the sign and magnitude of the eigenvalues obtained as described above, the presence of curvature at a given point (x,y) in the image can be determined. For a point (x,y) to lie on a curve, one of the two eigenvalues must be significantly larger than the other, i.e.,

$$|\lambda_1| \gg |\lambda_2| \quad (4)$$

If condition (4) holds for a given pixel, it indicates that there is significant curvature only in one direction at that point, and hence, the pixel lies on a curve.

IV. Result and Discussion

Thus, the eigenvalues are computed and compared for each pixel of the image. Pixels that satisfy condition (4) are classified as belonging to a curve, while pixels that do not meet the condition are considered part of the background or other structures. The proposed algorithm was applied to an image obtained using the Google Earth platform. The result of the program, implemented in C++, is shown in Fig. 1.

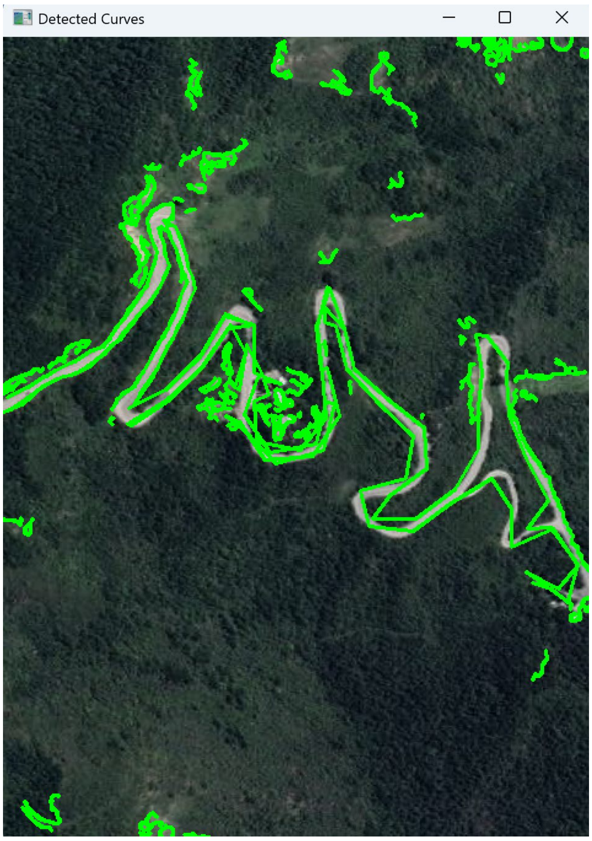

Figure 1. Description of the detected curve from the image

V. Conclusion

In this study, the Hessian matrix-based curve detection method was applied to video-based navigation systems. By analyzing the eigenvalues of the Hessian matrix, precise identification of roads, trajectories, and other linear structures was achieved in both images and individual frames of video sequences. The curvature criterion ensures that only pixels exhibiting significant curvature in a single direction are classified as part of a curve, while other pixels are considered background or irrelevant structures. This approach enables accurate real-time localization of the device relative to the detected curves, providing a reliable foundation for path planning, obstacle avoidance, and navigation decision-making.

The method demonstrates robustness under varying environmental conditions and lighting changes, which is critical for practical navigation applications. Overall, the Hessian matrix-based curve detection proves to be an effective and reliable tool for enhancing the accuracy and safety of video-based navigation systems, offering significant potential for future research and development in autonomous navigation and real-time guidance technologies.

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