UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA
FACULTATEA DE AUTOMATICĂ ŞI CALCULATOARE

Eng. Tiberiu MARIȚA

PHD THESIS
(abstract)

CONTRIBUTIONS TO THE DEVELOPMENT OF AUTONOMOUS DRIVING SYSTEMS BASED ON COMPUTER VISION

Advisor
Prof. Dr. Eng. Iosif IGNAT

2008

CONTENTS

ABSTRACT

1. INTRODUCTION

The current work deals with a state-of-the-art domain of the science and technology in which increased efforts and resources are invested by the car manufacturers and scientific community: autonomous driving. In this context, the camera parameters calibration problem of far range and high accuracy stereovision systems is approached.

Monocular camera's calibration does not imply outstanding problems and can be done through general purpose calibration methods. The calibration of the stereovision systems requires in addition a very accurate estimation of the relative extrinsic parameters of the two cameras, which are essential for the stereo correlation process. Extensions of the general purpose calibration methods are allowing the estimation of these parameters with satisfactory precision for short range application (e.g. indoor robotics).

The calibration of the stereovision systems mounted in vehicles and used in driving assistance applications requires high accuracy methods. The estimated parameters should allow the 3D reconstruction of the environment with depth errors bellow 5% in arrange up to 50m in urban scenarios and up to 100 m in highway scenarios, in real traffic conditions (variable lighting, visibility and temperature, mechanical vibration and stress).

In this thesis a set of original calibration methods and a proper methodology is proposed, designed and implemented allowing a very accurate estimation of the stereo system parameters, with a very good reproducibility rate of the results and a high level of automation of the entire procedure. The stereo systems calibrated with the proposed methods are allowing the 3D reconstruction with a precision and depth range comparable with the laser and radar sensors but in addition are providing much 2D and 3D information about the environment. In the experiments performed, stereo systems for far range, highway configuration (16mm focal length, 300 mm baseline, VGA image resolution) were calibrated which have provided reliable 3D data in a depth range up to 120 m with depth estimation errors bellow 3%.

The current thesis is the result of the work performed in the fame of a series of research projects founded by Volkswagen AG in the 2001-2007 period. The propose of these projects was the development of a stereovision sensor which integrates specific driving assistance applications: camera calibration [Mar06], [Mar07], obstacles detection and classification Ned04g],[Ned07a],[Ned07b],[Ned07d], lane detection in structured environments, [Ned04f],[Ned07a], navigable channel detection in unstructured environments [Dăn06], [Ned07a] etc.

2. STRUCTURE AND CONTENT OF THE THESIS

The thesis begins with an introductive chapter that presents the motivations and the integration of the studied topic in the approached domain.

In Chapter 2 the camera model is synthesized along with the complete set of parameters which are describing its geometrical and optical properties (table 1). The model is then extended in Chapter 4 for a stereovision system mounted in a vehicle (fig. 1).

In Chapter 3 are revised the most relevant camera calibration methods found in the literature. General purpose methods applicable for monocular and stereo systems used in short range applications [Tsa87], [Wen92], [Hei97], [Zha99], [Bou07] or in automotive applications [Kam02], [Ern99], [Bro01]. [Web95b], [Cat04], [Mas04], [Col06], [Dan04], [Dan06] are presented.

Table 1. Complete set of parameters of a stereovision system mounted in a vehicle

Parameters group	Parameters type	Parameters set
Internal parameters of the stereo system	**Intrinsic parameters** (one set / camera)	Principal points: $\mathbf{PP}_L(x_{0L}, y_{0L})$, $\mathbf{PP}_R(x_{0R}, y_{0R})$ Focal distance: $\mathbf{f_L}(f_{XL}, f_{YL})$, $\mathbf{f_R}(f_{XR}, f_{YR})$ Distortion coefficients: - radial: (k_1^L, k_2^L), (k_1^R, k_2^R), - tangential: (p_1^L, p_2^L), (p_1^R, p_2^R)
	Relative extrinsic parameters (one set / stereo system)	$\begin{cases} \mathbf{T}_{rel} = \mathbf{R}_{CL}^T \cdot (\mathbf{T}_{CR} - \mathbf{T}_{CL}) \\ \mathbf{R}_{rel} = \mathbf{R}_{CL}^T \cdot \mathbf{R}_{CR} \end{cases}$
External parameters of the stereo system	**Absolute extrinsic parameters** (one set / camera)	*For individual cameras:* Translation vectors: $\mathbf{T}_{CL}$, $\mathbf{T}_{CR}$ Rotation matrices : $\mathbf{R}_{CL}$, $\mathbf{R}_{CR}$ or Rotation vectors: $\mathbf{r}_{CL}$, $\mathbf{r}_{CR}$ *For the stereo system (stereo-rig):* Translation vectors: $\mathbf{T}_{C\text{-}rig} = \mathbf{T}_{CL}$ Rotation matrices: $\mathbf{R}_{C\text{-}rig} = \mathbf{R}_{CL}$ or Rotation vectors: $\mathbf{r}_{C\text{-}rig} = \mathbf{r}_{CL}$

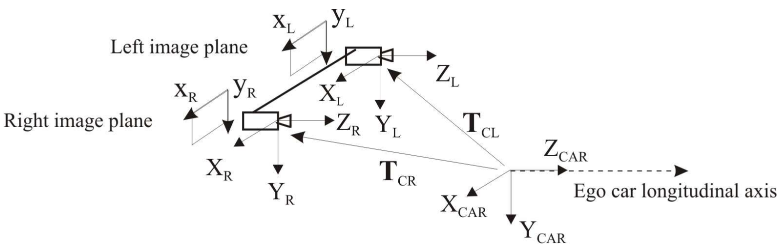


Fig. 1. Stereovision system model mounted in a vehicle.

In Chapter 4 a novel analysis of the influence of the camera parameters upon the stereo reconstruction process is presented. For this analysis, original algorithms were elaborated for simulating the 3D reconstruction errors and the epipolar errors induced by the drifts of the relevant camera parameters of the stereo system. Based on this analysis, the critical parameters (from the point of view of the accuracy) were identified. This analysis, along with the survey of the existing literature allowed the proper approach of the calibration problem for far range and high accuracy stereovision systems and the establishment of the best suited methodology and algorithms (fig. 2).

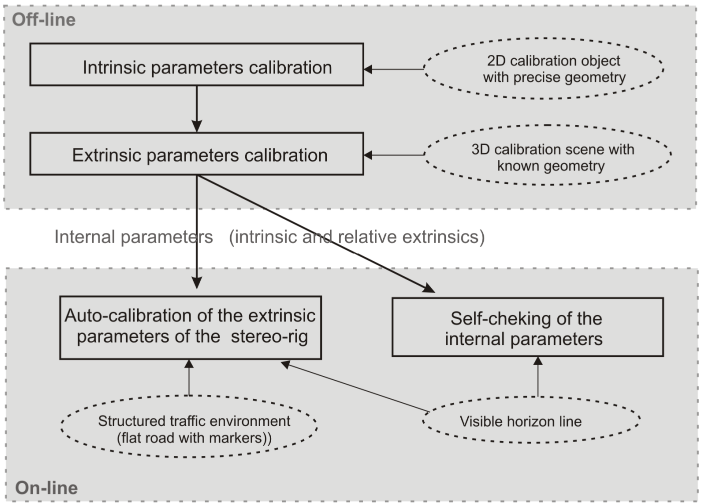


Fig. 2. Proposed calibration methodology for stereovision systems used in vehicles.

The proposed methodology involves the calibration of the critical parameters (internal parameters from table 1) by off-line methods which are using a dedicated calibration object or calibration scene with precisely measured dimensions. The less critical parameters (absolute extrinsic parameters) can be computed on-line in real traffic scenarios by using specific constraints.

In Chapter 5 the photogrametric calibration (which uses a calibration object or scene with known geometry) of the stereovision systems was approached.

First, an improved intrinsic parameters calibration method based on the Bouguet's algorithm (reference method in the literature) is proposed. The improvements are related to the automation of the calibration process:

- An automated and robust algorithm for detecting the 2D image projections of the control points (corners) from the chess board shaped calibration object;
- An automated algorithm for the 3D labeling of the detected control points;
- An algorithm for solving the correspondence problem between control points from the stereo images;
- A more efficient implementation of the stereo-optimization algorithm for the intrinsic and relative extrinsic parameters estimation based on Newton's method.

These improvements are allowing a significant reduction of the calibration's procedure duration and consequently the acquisition and processing of more views of the calibration object and consequently of the number of control points. This has the effect of increasing the accuracy of the estimated camera parameters. Due to its increased efficiency, the new method is much better suited for the calibration of the intrinsic parameters of the stereovision systems mounted in vehicles in comparison with the general purpose methods.

Secondly, an original method and methodology for the off-line extrinsic parameters calibration was developed. This method consists in:

- A robust algorithm for automated detection of the control points ("X"-shaped targets) through multiple validation steps;
- An algorithm for the detection of the "X"-shaped targets with sub-pixel accuracy;
- An algorithm for extrinsic parameters estimation based on the Newton's optimization method;
- An original calibration methodology used for the calibration of the stereovision systems mounted in vehicles.

The method can be used for the calibration of both monocular and binocular or multi-ocular stereo systems. The main advantage of this method over the existing general purpose ones is the high accuracy of the absolute and relative extrinsic parameters of the stereovision systems (the accuracy of the relative extrinsic parameters is crucial for far range stereovision systems).

Finally, a set of original methods for the off-line evaluation and validation of the calibration parameters' accuracy was developed. The validation methods are based on two types of stereo constraints: 3D reconstruction errors and epipolar drifts of a set of control points. Using these validation methods, it was demonstrated that, the camera parameters estimated with the proposed off-line calibration methods are leading to smaller 3D reconstruction and epipolar errors in comparison with other reference general purpose methods from the literature (e.g. Bouget's method – fig. 3).

In Chapter 6, the proposed methods for on line calibration and validation of the stereovision system's parameters are presented. These methods do not need a dedicated calibration object or scene with known geometry but instead they are based on some constrained specific to real traffic scenarios (flat road, longitudinal lane markings, visible horizon line etc.).

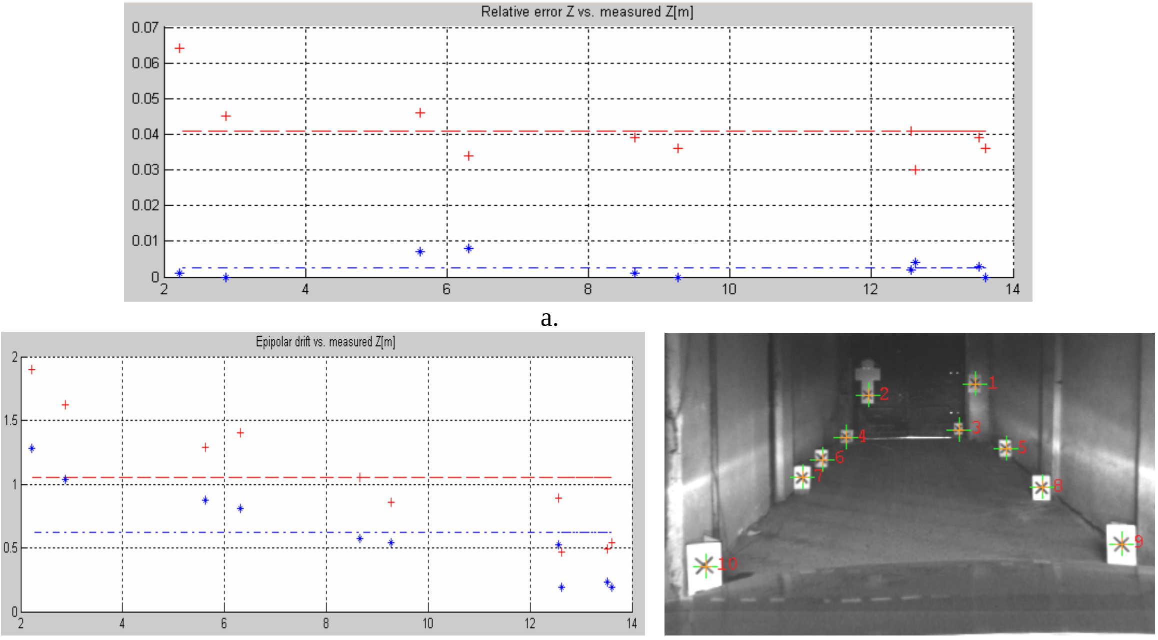


Fig. 3. a. Comparison between the relative depth errors obtained with the extrinsic parameters calibrated with the proposed method (blue) and Bouguet's stereo calibration method (red). b. Comparison between the epipolar drifts for the same two cases. C. The reference scenario with control points.

Firstly, an on-line method for the dynamic pitch angle estimation of the vehicle was developed. The method is based on the motion field estimation of the horizon line points and can be applied in highway or country road scenarios. The idea is not new in the literature, but some improvements were performed, consisting in:

- An original method for horizon line detection and matching in successive images;
- The usage (with improved results) of the motion field of relevant horizon features instead of the optical flow of the horizon line points for the camera motion estimation;
- The usage of the estimated dynamic pitch angle of the vehicle as prediction for the lane detection processing module (LD) [Ned04f] instead of using car sensors which are not standard and also not precise enough (fig. 4).
- An optimized implementation for real time processing (1 .. 2 ms / frame).

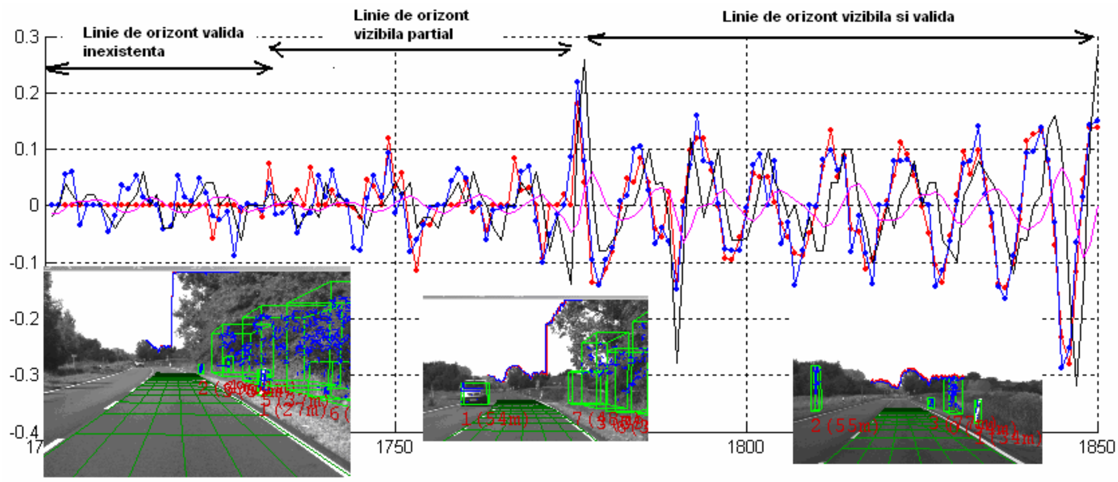
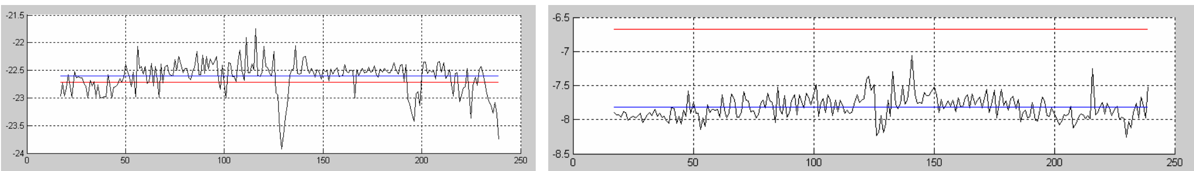


Fig. 4. Pitch angle variation [deg/frame] for a sequence of 150 images in a country road scenario: estimated value from horizon line (red), estimated value by LD module (blue), measured value from car sensors (black).

Secondly, an on-line method for estimating the absolute pitch and roll angles of a stereovision system relative to a road plane related coordinate system was proposed. The method can be applied for a general configuration stereo setup and requires the knowledge of the internal parameters (table 1), which can be calibrated off-line. The method is based on the estimation of the road plane parameters using the stereo correspondence of features (e.g. road markings edge points) from a flat road surface.

Finally, a novel method for the on-line self-checking of the calibration parameters was developed based on infinity points' constraints (e.g. horizon line features). The method is applicable in highway and country road scenarios with a visible horizon line and it measures a degree of the stereo system's *de-calibration* (principal point, focal length, relative rotation angles – which are the critical internal parameters of the stereo system). The *de-calibration* degree is measured as a difference between the "expected disparity" of the infinity points (which depends only upon the internal parameters) and the "measured disparity" (fig. 5). The "measured disparity" is computed by matching horizon line features in stereo image pairs. The method is entirely original through:

- The introduction of the "expected disparity" of infinity points and its mathematical computation formalism.
- Development of an original method for measuring the real "disparity" of infinity points from the horizon line
- Definition of a validation criteria of the parameters accuracy relative to the optical and geometrical configuration of the stereo system based on the "measured disparity" of the infinity points and along with the establishment of proper threshold values through simulations and experiments.
- Real time implementation of the method (1 ..5 ms / frame).



a. Horizontal disparity of points from infinity

b. Vertical disparity of points from infinity

Fig. 5. Average "measured disparity" of horizon points (black) for a sequence of 250 frames for a highway scenario. The average value of the measured disparity over the whole sequence is marked with blue while the "expected disparity" with red. The "disparity error" $\delta \mathbf{d}$ is below the threshold value $\|\mathbf{T}_d\| \approx 2.8 .. 4.3$ [pixels].

In Chapter 7 a brief description of the implementations of the calibration methods described in Chapters 5 and 6 is presented. The developed methods were integrated as modules in a framework application used for testing and integration of stereovision based algorithms for driving assistance systems (fig. 6).

3. CONCLUSIONS

In this thesis, the topic of the calibration for far range and high accuracy stereo vision systems used in vehicles was approached. An in-depth analysis of the requirements for these stereovision systems was performed from the point of view of the parameters accuracy. Reference general purpose calibration methods were improved to fit specific requirements while other new (original) methods were developed. All the methods were implemented and tested in many calibration experiments of several stereovision systems in different optical and geometrical configurations. The purpose of these experiments was to test, optimize and validated the proposed algorithms and to establish the proper calibration methodology, best suited for stereo systems mounted in vehicles and used for driving assistance applications.

Fig. 6. Snapshots of the implemented modules: a. Off-line intrinsic parameters calibration; b. On-line parameters self-checking; c. Off-line extrinsic parameters calibration and validation; d. On-line dynamic pitch angle estimation.

Over 10 experimental vehicles were equipped with stereo systems calibrated with the proposed methods presented in the current work. The accuracy of the estimated parameters of the stereovision systems was crucial for the proper 3D reconstruction and description of the driving environment). In table 2, some marginal conditions of the detection algorithms (e.g. obstacle detection, lane detection) working with the calibrated stereo systems are presented.

Table 2. Marginal conditions of the stereovision based detection algorithms

Stereo system parameters	**Highway configuration**	**Urban configuration**
Focal length	16 mm	6.5 mm
Horizontal field of view	34°	72°
Baseline	340 mm	340 mm
Image resolution	688 x 515 pixels	512 x 383 pixels
Detection algorithms' performance		
Stereo reconstruction engine	Software, edge based stereo	Hardware, dense stereo
Maximum 3D reconstruction depth	5 .. 120 m	0 .. 50 m
Maximum relative reconstruction errors (depth)	3%	5%
Maximum obstacles detection range	100 .. 120 m	40 m
Maximum lane detection range	80 m	30 m

SELECED REFERENCES

[Azi71] Y. I. Abdel-Aziz, H. M. Karara, Direct linear transformation into object space coordinates in close-range photogrammetry. *Proc. Symposium on Close-Range Photogrammetry*, Urbana, Illinois, 1971. p. 1-18.

[Bou07] J.Y. Bouguet, Camera Calibration Toolbox for Matlab, Computational Vision Group, California Institute of Technology, Pasadena, California, http://www.vision.caltech.edu/bouguetj/calib_doc/index.html

[Bou99] Jean-Yves Bouguet, *Visual methods for three-dimensional modeling*, Ph.D thesis, California Institute of Technology, Pasadena, California, 25 May 1999.

[Cat06] F.W. Cathey, D.J. Dailey, Mathematical Theory of Image Straightening with Applications to Camera Calibration, *Proceedings of the IEEE Intelligent Transportation Systems Conference (ITSC 2006)*, Toronto, Canada, September 17-20, 2006, pp. 1364-1369.

[Col06] J.M. Collado, C. Hilario, A. Escalera, J.M. Armingo, lSelf-calibration of an On-Board Stereo-vision System for Driver Assistance Systems, *Proceedings of IEEE Intelligent Vehicles Symposium*, (IV2006), June 13-15, 2006, Tokyo, Japan, pp. 156-162.

[Dan04] T. Dang, C. Hoffmann, Stereo calibration in vehicles, *Proceedings of IEEE Intelligent Vehicles Symposium*, (IV2004), June 14-17, 2004, Parma, Italy, pp.268-272.

[Dan06] T. Dang, C. Hoffmann, and C. Stiller, Self-calibration for Active Automotive Stereo Vision, *Proceedings of IEEE Intelligent Vehicles Symposium*, (IV2006) , June 13-15, 2006, Tokyo, Japan, pp.364-369.

[Dăn06] R. Dănescu, S. Sobol, S. Nedevschi, T. Graf, Stereovision-Based Side Lane and Guardrail Detection, *Proceedings of the IEEE Intelligent Transportation Systems Conference (ITSC 2006)*, Toronto, Canada, September 17-20, 2006, pp. 1156-1161.

[Dur96] Z. Duric, A. Rosenfeld , Image Sequence Stabilization in Real Time, *Academic Press Limited, Real-Time Imaging*, No.2, 1996, pp. 271–284.

[Hei97] J, Heikkilä, O. Silvén, A Four-step Camera Calibration Procedure with Implicit Image Correction, in *Proc. of IEEE Computer Vision and Pattern Recognition*, 1997, .pp. 1106-1112.

[Kam02] N. Kämpchen, , U. Franke, R. Ott, Stereo vision based pose estimation of parking lots using 3D vehicle models, *IEEE Intelligent Vehicle Symposium*, 2002, pp. 459- 464.

[Luo97] Q.-T. Luong and O. Faugeras. Self-calibration of a moving camera from point correspondences and fundamental matrices. *The International Journal of Computer Visio*n, 22(3):261–289, 1997.

[Mar06] **T. Mariţa**, F. Oniga, S. Nedevschi, T. Graf, R. Schmidt, Camera Calibration Method for Far Range Stereovision Sensors Used in Vehicles, *Proceedings of IEEE Intelligent Vehicles Symposium*, June 13-15, 2006, Tokyo, Japan, pp. 356-363.

[Mar07] **T. Mariţa**, F. Oniga, S. Nedevschi, T. Graf, Calibration Accuracy Assessment Methods for Stereovision Sensors Used in Vehicles, in *Proceedings of IEEE 3-rd International Conference on Intelligent Computer Communication and Processing* (ICCP2007), 6-8 Sept. 2007, Cluj-Napoca, Romania, pp. 111-118.

[Mas04] O. Masoud and N. Papanikolopoulos, Using Geometric Primitives to Calibrate Traffic Scenes, *Technical Report (TR 04-026), Department of Computer Science and Engineering*, University of Minnesota, Minneapolis, USA.

[Ned03c] S. Nedevschi, **T. Marita**, R. Danescu, D. Frentiu, F. Oniga, C. Pocol, C. Tomiuc, R. Schnell, Stereo-Camera Based Object Recognition System for Vehicle Application – 2 (SCABOR2): WP 4 - Final Report, *Technical Report*, Technical University Cluj-Napoca, September 2003.

[Ned04b] S. Nedevschi, **T. Marita**, R. Danescu, F. Oniga, C. Pocol, C. Tomiuc, R. Schnell, S. Sobol, C. Vancea, S. Mathe, Stereo-Camera Based Object Recognition System for Vehicle Application – 3 (SCABOR3): WP3 - Algorithm implementation, integration and testing, *Technical Report*, Technical University Cluj-Napoca, July 2004.

[Ned04d] S. Nedevschi, **T. Marita**, R. Danescu, F. Oniga, C. Pocol, C. Tomiuc, R. Schnell, S. Sobol, C. Vancea, S. Mathe, Stereo-Camera Based Object Recognition System for Vehicle Application - 3 (extension), *Technical Report*, Technical University Cluj-Napoca, Dec. 2004.

[Ned04f] S. Nedevschi, R..Schmidt, T. Graf, R. Danescu, D. Frentiu, **T. Marita**, F. Oniga, C. Pocol, 3D Lane Detection System Based on Stereovision, *IEEE Intelligent Transportation Systems Conference (ITSC)*, October 2004, Washington, USA, pp.161-166.

[Ned04g] S. Nedevschi, R. Danescu, D. Frentiu, **T. Marita**, F. Oniga, C. Pocol, R. Schmidt, T. Graf, High Accuracy Stereo Vision System for Far Distance Obstacle Detection, *IEEE Intelligent Vehicles Symposium,* (IV2004), June 2004, Parma, Italy, pp. 292-297.

[Ned05a] S. Nedevschi, **T. Marita**, R. Danescu, F. Oniga, C. Pocol, C. Tomiuc, S Sobol, C. Vancea, S. Bota, DEnse Stereo-Based Object Recognition system for automatic cruise control in urban traffic environments (DESBOR): WP1 - Study work and preliminary tool development, *Technical Report*, Technical University Cluj-Napoca, September 2005.

[Ned05d] S. Nedevschi, R. Danescu, **T. Marita**, F. Oniga, C. Pocol, Moving Camera Rotation Estimation Using Horizon Line Features' Motion Field, in *Procedeengs of 6-th International Carpathian Control Conference*, 24-26 May 2005, Lilafured-Miskolc, Hungary, pp.449-454.

[Ned06a] S. Nedevschi, C. Vancea, **T. Marita**, T. Graf, On-Line Calibration Method for Stereovision Systems Used in Vehicle Applications, *Proceedings of the IEEE Intelligent Transportation Systems Conference (ITSC 2006),* Toronto, Canada, September 17-20, 2006, pp. 957-962.

[Ned06d] S. Nedevschi, **T. Marita**, R. Danescu, F. Oniga, C. Pocol, C. Tomiuc, S Sobol, C. Vancea, S. Bota, DEnse Stereo-Based Object Recognition system for automatic cruise control in urban traffic environments (DESBOR): WP4 - Algorithm implementation and integration, *Technical Report*, Technical University Cluj-Napoca, October 2006.

[Ned07a] S. Nedevschi, **T. Marita**, R. Danescu, F. Oniga, C. Pocol, C. Tomiuc, S Sobol, C. Vancea, S. Bota, DEnse Stereo-Based Object Recognition system for automatic cruise control in urban traffic environments (DESBOR): WP5 - Optimization and validation, *Technical Report*, Technical University Cluj-Napoca, February 2007.

[Ned07b] S. Nedevschi, R. Danescu, **T. Marita**, F. Oniga, C. Pocol, S. Sobol, C. Tomiuc, C. Vancea, M.M. Meinecke, T. Graf, T. B. To, M.A. Obojski, A Sensor for Urban Driving Assistance Systems Based on Dense Stereovision, *Proceedings of 2007 IEEE Intelligent Vehicles Symposium*, (IV2007), Istanbul, Turkey, June 13-15, 2006, pp 276-283.

[Ned07c] S. Nedevschi, C. Vancea, **T. Marita**, T. Graf, On-Line Calibration Method for Stereovision Systems Used in Far Range Detection Vehicle Applications, *IEEE Transactions on Intelligent Transportation Systems*, vol.8, no. 4, pp. 651-660, 2007.

[Ned07d] S. Nedevschi, **T. Marita**, R. Danescu, F. Oniga, C. Pocol, C. Tomiuc, S Sobol, C. Vancea, S. Bota, R. Borca, M. Negru, S.Lazar, A. Vatavu, DEnse Stereo-based object detection , tracking and PEDestrian classification in traffic environments (DESPED): WP4, *Technical Report*, Technical University Cluj-Napoca February 2007.

[Tru98] Trucco E., Verri A, *Introductory techniques for 3D Computer Vision*, Prentice Hall, 1998.

[Tsa87] Tsai, R. Y., A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses, *IEEE Journal of Robotics and Automation* RA-3(4)/1987: p.323-344.

[Van06a] C. Vancea, S. Nedevschi, M. Negru, Ş. Mathe, Real-Time FPGA-based Image Rectification System, *Proceedings of First International Conference on Computer Vision Theory and Applications (VISAPP 2006)*, 25-28 February, 2006, Setubal, Portugal, vol. 1, pp. 93-100.

[Van06b] C. Vancea, S. Nedevschi, Analysis of different image rectification approaches for binocular stereovision systems, 1-2 September, Cluj-Napoca, Romania, 2006, pp. 135-140.

[Web95b] J.Weber, D. Koller, Q.-T. Luong and J. Malik, An integrated stereo-based approach to automatic vehicle guidance, *Fifth International Conference on Computer Vision, Boston 1995, Collision Avoidance and Automated Traffic Management Sensors*, Proc. SPIE 2592, 1995.

[Wen92] Weng, J., Cohen, P. & Herniou, M. Camera calibration with distortion models and accuracy evaluation. *IEEE Transactions on Pattern Analysis and Machine Intelligence PAMI,* 14(10): 965-980, 1992.

[Zha99] Z. Zhang. Flexible Camera Calibration By Viewing a Plane From Unknown Orientations. *International Conference on Computer Vision (ICCV'99)*, Corfu, Greece, September 1999, pp. 666-673.