

Fisheye optics for omnidirectional stereo camera

Performance evaluation for AGV applications

Aki Mäyrä, Mika Aikio, Kai Ojala

Intelligent Sensor Systems
VTT Technical Research Centre of Finland
Oulu, Finland
aki.mayra@vtt.fi

Szilárd Mandici, Andrei Vatavu, Sergiu Nedevschi

Department of Computer Science
Technical University of Cluj-Napoca
Cluj-Napoca, Romania

Abstract — Omnidirectional stereo cameras have been proposed to be applied as a safety sensor in automated guided vehicles. As a part of the EC-funded PAN-Robots project, a custom designed high performance omnidirectional stereo camera with fisheye objectives was designed and manufactured. This paper shows the results of the optical and environmental tests which were done for the fisheye objectives and for the omnidirectional stereo camera system.

Keywords — Omnidirectional imaging, fisheye lens, environment perception, automated vehicles, safety application, lens measurements

I. INTRODUCTION

Automated Guided Vehicles (AGVs) are devices which are used in transportation of raw materials and final products in manufacturing plants. AGVs can greatly enhance the productivity of factories as they are less prone to errors when compared to human operated vehicles such as forklifts [1][2]. Automated guided vehicles are equipped with several laser scanners which are used as a safety sensor which monitor the area around the AGV. An illustration of the field of view is shown in Fig. 1 where the laser scanner field of view has been highlighted as a semi-circle and two safety areas are marked as rectangles within the scan area. Laser scanners are highly reliable but they are only capable of detecting objects in a 2D plane around the AGV. This means that hanging or protruding objects cannot be seen by the laser scanner.

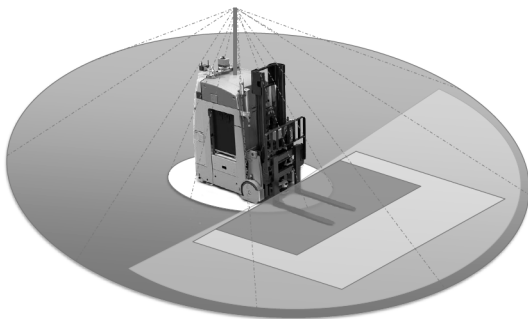


Fig. 1. Safety laser scanner field of view (semi-circle), safety areas (rectangles) and 3D omnidirectional stereo vision field of view (circle).

The PAN-Robots project [3], funded by the European Commission is a pan-European project which develops a new generation of green, flexible and safe AGVs and related infrastructure systems. Key technologies of the project, such as traffic control, obstacle avoidance, self-localization, mapping, and load handling technologies are reported in [4]-[15] and references therein.

As a part of the PAN-Robots project, a new on-board sensor system has been developed. It consists of laser scanners and an omnidirectional stereo camera. The hypothesis is that 3-dimensional data from stereo camera can be used to enhance the 2-dimensional safety sensor data received by the laser scanners [7]. Especially, it is expected that object classification will be improved when camera data is fused with laser scanner data.

One part of the novel on-board sensor system is the omnidirectional stereo camera [12][13]. The concept is based on a downwards looking, wide field of view, stereo camera which can monitor the area around the AGV. In Fig. 1 the field of view of the omnidirectional stereo camera has been highlighted in dashed lines which form a circular cone around the AGV.

At the beginning of this paper a brief introduction on the optical system design of the omnidirectional stereo camera will be given. In the second section, the optical and mechanical requirements already shown in [13] will be summarised. The third section will show the optical system and component designs which were chosen on the basis of these requirements. Section IV shows the results of optical performance measurements of the custom designed fisheye objectives. In order to find the best camera and lens pairs for the stereo sensor, a specific lens to camera coupling study was done. Results of this task are shown in section VI. In section VI the environmental test results of the objective lenses are shown. The last section summarises and concludes the main results of the performance evaluation of the omnidirectional optics developed for AGV applications.

II. REQUIREMENTS

A. Optical performance

Based on the calculations shown in [13] it was concluded that with a sensor range of 10 meters the PAN-Robots AGV can come to a full stop by soft braking before reaching both stationary objects and walking persons. Hard braking would suffice to stop before reaching a fast person running towards the AGV. Soft-braking in combination with fast persons is not addressed, since it is sufficient to avoid this kind of accident by hard-braking.

Based on the user requirements it was further derived that the sensor needs to detect objects as close to the PAN-Robots AGV as possible and thus the blind spot close to the AGV should be minimized. The blind spot is visualized in Fig. 1 as a white area around the AGV.

Objects with a height of 1 m should be detected at the very limit of the required measuring area. Objects that are larger than 10 cm must be distinguished and the depth resolution should be better than 25 cm. Depth resolution was required to be at least 3 % of the distance.

B. Environmental stability requirements

In addition the application sets requirements for the environmental stability and costs. The sensor was required to withstand AGV operation with respect to vibrations and cleanliness. There were no numerical specifications given for these requirements and unfortunately there are no valid standards which can be directly applied for AGV sensors. The selected approach was to test the designed objectives for vibration resistance and evaluate if the results would be sufficient for the application.

III. SYSTEM DESIGN

A. Hardware

The sensor specifications of the 3D stereo vision system were derived in [13]. In order to provide a complete safety area around the PAN-Robots AGV, it was proposed that the lenses and the cameras are mounted on the top of the AGV as shown in Fig. 2.

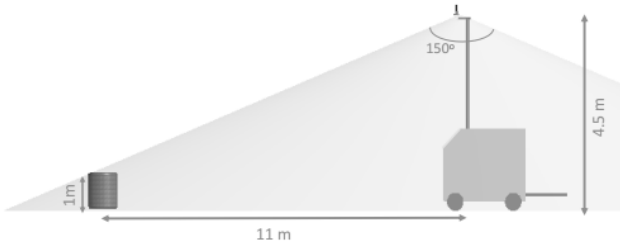


Fig. 2. Omnidirectional stereo camera measurement geometry.

In order to fulfill the selected measurement geometry, custom designed fisheye objectives were designed at VTT. The designed objectives have nine elements and with focal length of 4.5 mm they will provide very good image quality over the sensor for the 150 degree vertical field of view. The designed fisheye objectives have a light collection efficiency of F/1.2 which makes them suitable for dark factory conditions. One pair of objectives is used in one omnidirectional stereo camera sensor. The lens design was first introduced in [13].

Due to this mounting position, and due to the large field of view of the omnidirectional lenses, the vision system is able to monitor the AGV's environment in all directions. The vertical field of view processed by the top-mast mounted omnidirectional system is 150 degrees in the moving direction and 98 degrees across the moving direction as depicted in Fig. 3. In this manner, objects of 1 m height are completely visible up to 11 m in front and up to 4 m in lateral direction, starting from the axis of the system. It should be noted that due to the mounting geometry, there will be occluded areas around the AGV. These were discussed and visualized in [13].

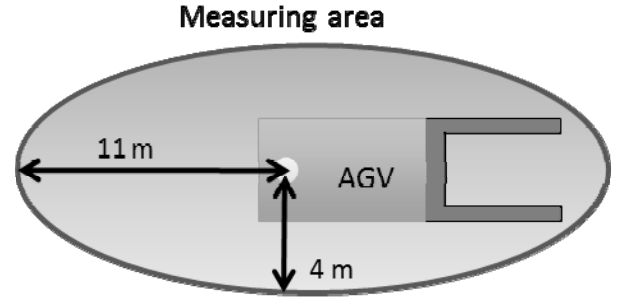


Fig. 3. Measurement area around the AGV.

B. Stereo vision based environment perception

The stereo vision system consists of a pair of fisheye lenses, two cameras and the data processing unit which tries to extract as much information from the input images as possible.

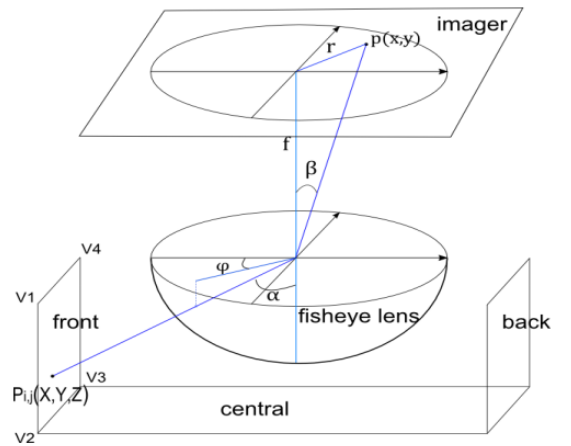


Fig. 4. The projection model of the fisheye lens. The front, central and back virtual imagers used for rectification [12].

After acquiring the original highly distorted fisheye images, there are a number of steps which are performed to represent the surrounding environment. The first step is the multi-channel rectification of the fisheye images. In order to perform the rectification, three virtual imagers are constructed as shown in Fig. 4.

For the rectification, the intrinsic and extrinsic camera parameters are obtained offline using the calibration procedure described in [12].

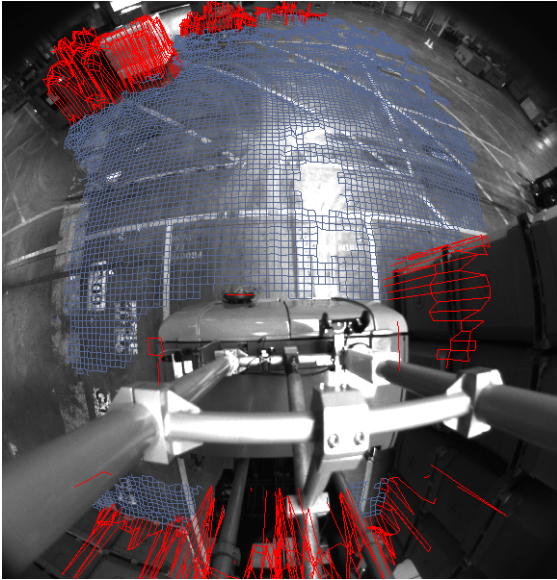


Fig. 5. Obtained DEM with classified cells (object cells at the top and bottom, road cell in the middle).

The resulting three rectified image pairs are processed using an SGM-based stereo reconstruction algorithm [22]. The obtained raw 3D points are processed using an intermediate environment representation in the form of a probabilistic Digital Elevation Map (DEM) [23]. The DEM is created taking into account the direct and inverse sensor models of the omnidirectional stereovision sensor. These model the sensor characteristics in a probabilistic manner and are determined through experiments. Apart from the actual height, in each DEM cell other pieces of information are present such as confidence, base height, histogram of heights, etc. After finding the heights, each cell is classified as corresponding either to the road surface or an object (Fig. 5).

The obtained DEM is further processed by extracting the individual 3D objects. There are currently two approaches for representing the objects. The first technique is based on grouping the DEM cells classified as obstacles and form 3D objects, while the second solution is based on extracting from each blob a free-form polygonal model [24]. The cuboidal models are used for defining the region of interest for the object classification, while the free-form polygons are used for an ICP-based object motion estimation. The resulting set of

obstacles is described by various properties such as the size, position, speed, heading angle, detection age or object type (pedestrian, AGV, large obstacle or small obstacle). Sample scene is shown in Fig. 6.

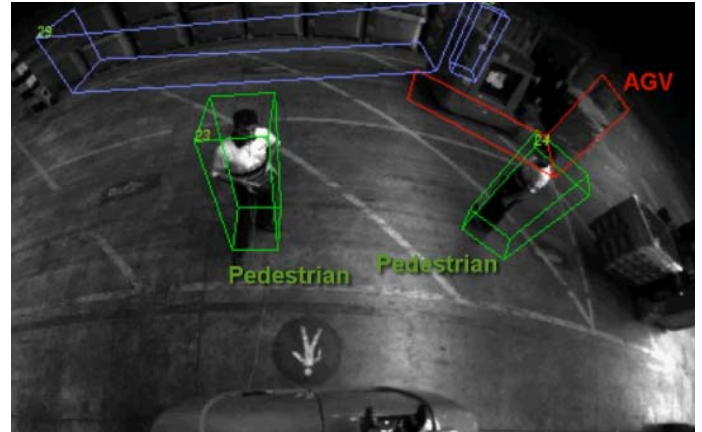


Fig. 6. The detected and classified objects.

IV. OPTICAL TESTS

A. MTF measurements

Fig. 7 shows the MTF-curves of the designed fisheye lens from the commercial Zemax software [16]. The MTF-curves measured for objective #1 are shown in Fig. 8. Measured values are shown for center fields up to 20 degrees only. No significant discrepancies were discovered in the MTF measurement, the contrast difference at 100-200 lp/mm is explained by the actual choice of focus during the measurement. The design target was to provide contrast of at least 10 % at 90 lp/mm spatial frequencies, which corresponds to the sensor Nyquist frequency. The measured MTF curve shows the contrast to be at least 30 % at this point. No significant differences were found between the four completed objectives. MTF curves were measured at the VTT laboratory by using the commercial Image Science test bench [17].

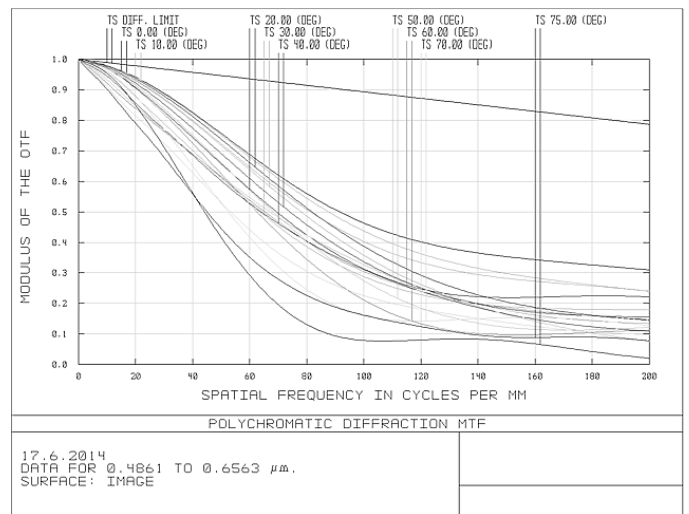


Fig. 7. Designed MTF curves.

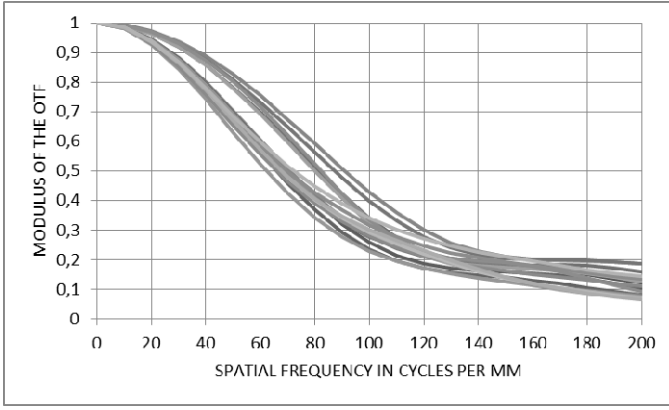


Fig. 8. Measured MTF values for center fields.

B. Test target measurements

The final test of the objectives was to resolve a 10 cm x 10 cm target at the distance of 11 meters. All four objectives were able to do this as designed, though the real world resolving power was determined to be roughly 2 cm at the distance of 11 meters. All objectives provided this resolution. The imaging system is limited by the image sensor of the 4 megapixel camera.

The evaluation scenario is shown in Fig. 9 where two targets are located on the right border of the image. A crop of this target is shown in the lower right. The spacing between the two black 10 cm x 10 cm blocks on the whiteboard is 2 cm. The four tested objectives performed identically, and thus the final evaluation criterion is achieved and the objectives were cleared for further integration.



Fig. 9. Test target measurement. Cropped 10 x 10 centimeter targets from the right side of the upper figure are shown in smaller figures.

V. SYSTEM ASSEMBLY

A. Lens to camera coupling

During the preliminary lens tests, it was reported that there were differences between different lens and camera combinations. Further studies confirmed that there were also differences which could be seen when the whole camera system was rotated around the optical axis. This effect could be seen on some cameras and with some cameras this effect was small. This led to an assumption that differences between different cameras were caused by tilted sensors in some cameras. For the selected camera model the sensor tilt tolerance about the axis perpendicular to the optical axis was not specified by the camera supplier.

Usually these minimal sensor tilts can be neglected but as the custom designed PAN-Robots fisheye lens [13] has an F-number as low as 1.2, sensor tilts can be seen as blurred image plane for certain fields. To overcome this property, the best camera and lens combinations were identified manually after which the cameras and lenses were fixed firmly together with spacer rings and additional mounting mechanics [13]. This was done after the best possible focus for the center field was found.

In order to obtain the best possible focus a semi-automated focusing tool was used. This tool makes it possible to select an area on the image field, such as focusing target or checkerboard, for which best possible focus depth is searched manually. The tool was found very useful because low F-number lenses are sensitive to focus adjustments and it is hard to identify the best possible focal depth by visual inspection only. Software was implemented in Labview and it was based on run-time edge detection and standard deviation calculation. The algorithm was partly based on example code which is openly available on NI sample programs [18]. The authors are aware that there are several options for autofocus algorithms and the choice was made due to its easy implementation.

B. Slanted edge sharpness measurements

In order to compare sharpness for different fields of different camera and lens pairs, the following set-up was used. Three measurement targets were placed in front of the camera so that three different fields could be mapped from one image. The measurement set-up is shown in Fig. 10.

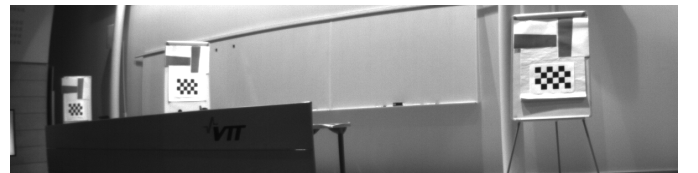


Fig. 10. Slanted edge and focus targets. The image has been cropped so that the center target is seen on the right side of image.

Targets were placed at 4,5 m distance in front of the camera so that the measurement geometry was similar to the PAN-Robots measurement geometry shown in Fig. 2. The camera

was placed on a rotating mount and a sample scene was imaged for four different orientations to have a comparable MTF value for four different camera fields. These orientations were 0, 90, 180 and 270 degrees about the optical axis, respectively. The camera orientation has been visualized in Fig. 11 where different orientations have been depicted together with a sample Imatest image. Shown results are for the second orientation of the M3L4 pair which is the second line in Table 1.

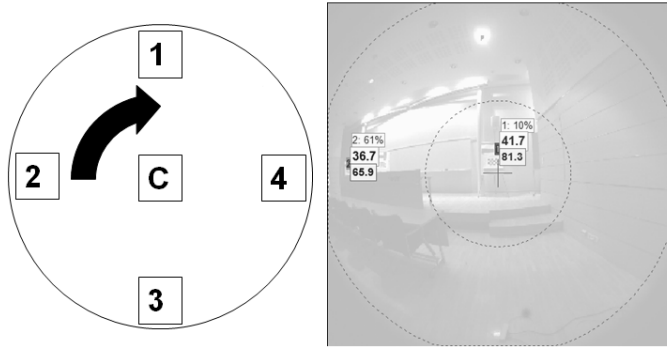


Fig. 11. Left: camera orientations and related fields. Right: sample Imatest [19] measurement for M3L4 pair for orientation 2. Figures on the right image show the distance from the center and line pair values for MTF 50% and 20% values.

Slanted edge targets and commercial Imatest software [19] were used to calculate the target sharpness for center and edge fields. These measurements are based on ISO the 12233 standard [20]. It should be noted here, that some measurements conditions, such as illumination, were not set according to the standard, thus the results can only be used for comparison of different camera and lens pairs and orientations. It should also be noted that these results cannot be directly compared with objective lens measurements as they show the MTF results for the camera and lens pair.

A sample of the measurements is shown in Table 1 where measured line pair values for 50 % and 20 % contrast for center and edge fields and for different lens orientations of two camera and lens pairs are shown [21]. These results show that for the used focus, the used camera and lens pair give comparable results and that there are no significant differences between different fields of the selected camera and lens combinations. The highest deviation can be seen for the first orientation of the first camera and lens pair. This means that for this orientation and focus the lens and camera pair draws sharper images at the center field and less sharp images on the edge, when compared with other orientations of the same pair.

VI. ENVIRONMENTAL TESTS

A. Vibration tests

In order to ensure the environmental stability of the sensor, vibration tests for the fisheye sensor were made at the VTT Expert Services facility at Espoo Finland. For the camera, environmental test results from the camera manufacturer were used.

TABLE I. MEASURED MTF FOR DIFFERENT CAMERA AND LENS PAIRS AND DIFFERENT ORIENTATIONS AND FIELDS [21]

Lens and camera pair	Line pairs for 50 % and 20 % contrast				
	field	center		edge	
	orientation	50 %	20 %	50 %	20 %
M3L4	1	47	101	26	40
	2	42	81	37	66
	3	50	84	39	73
	4	44	86	39	65
	average	45,8	88	35,3	61
M4L2	1	43	78	31	49
	2	44	78	33	54
	3	45	84	30	48
	4	49	94	31	47
	average	45,3	83,5	31,3	49,5

Vibration resistance was tested in two directions which were perpendicular and parallel to the optical axis as seen in Fig. 12. During the tests the objective was mounted on the PAN-Robots attachment plate which is normally used to mount the objective to the camera body. Resonances were measured with additional acceleration sensor glued onto the objective. A sample measurement can be seen in Fig. 13 where the measured accelerations of the test bench and acceleration of sensor glued on the objective are shown.

The frequency band was adjusted in order to keep the vibration parameters, like maximum force and velocity, within the limits of the shaking device. At the beginning of the tests, the objective was shaken for 5 minutes, and if the lens was ok, the shake was continued for 20 minutes. This was done for both mounting directions and for 5,5g, 20g and 28g rms accelerations. The used frequency bands were 10-200 Hz, 30-200 Hz and 50-200 Hz, respectively. After each session, the condition of the objective was visually inspected.

After the vibration tests the objective was installed to a machine vision camera and no performance degradation was seen in these tests. Because of these results, the vibration testing was considered successful, and the objective was cleared for AGV usage.

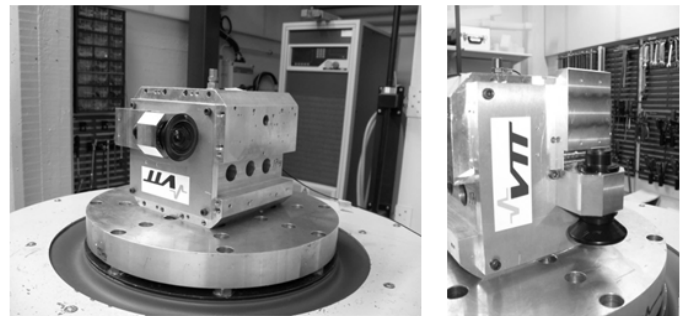


Fig. 12. Vibration testing with PAN-ROBOTS objective. Two tested orientations are shown.

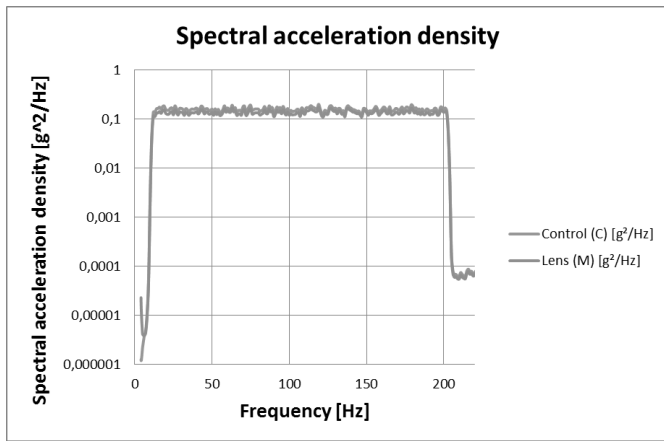


Fig. 13. Measured spectral acceleration densities for 5,5 g rms acceleration measurement.

VII. DISCUSSION

A validation process of the custom designed F/1.2 fisheye optics was described. First, the application specific requirements were summarized and system level design was presented. The optical validation results for the designed objective were shown and a method for manual coupling of high efficiency fisheye lenses to cameras was introduced. At the end of the paper, results from environmental vibration tests showed that the designed fisheye lens can withstand vibrations up to 28 g rms.

As a future work, the lens will be tested and validated in a real factory environment where measured performance will be compared to the expected values. A final evaluation will be performed at the demonstration event of the PAN-Robots project [3].

ACKNOWLEDGMENT

This paper is written within PAN-Robots project. PAN-Robots is funded by the European Commission, under the 7th Framework Programme Grant Agreement n. 314193. The partners of the consortium thank the European Commission for supporting the work of this project. The authors would also like to thank Ammons Engineering for releasing their autofocus sample code in Labview site [18].

REFERENCES

- [1] Eurostat, "Accidents at Work," in Health and safety at work in Europe 1999-2007. A statistical portrait, European Commission Employment, Social Affairs and Equal Opportunities, 2010, ch. 3, pp. 25.
- [2] L. Sabattini, V. Digani, C. Secchi, G. Cotena, D. Ronzoni, M. Foppoli and F. Oleari, "Technological roadmap to boost the introduction of AGVs in industrial applications," in Intelligent Computer Communication and Processing (ICCP), 2013 IEEE International Conference on, pp. 203-208, 2013.
- [3] <http://www.pan-robots.eu/>
- [4] M. Aikio, J.-T. Makinen and Bo Yang, "Omnidirectional camera," in Intelligent Computer Communication and Processing (ICCP), 2013 IEEE International Conference on, pp. 217-221, 2013.
- [5] A. Nagy, I. Szakats, T. Marita and S. Nedevschi, "Development of an omnidirectional stereo vision system," in Intelligent Computer Communication and Processing (ICCP), 2013 IEEE International Conference on, pp. 235-242, 2013.
- [6] M. Aikio, "Fast fish-eye objective for automated vehicle safety," Finnish Optics Days 2014, Turku, Finland, 2014.
- [7] E. Cardarelli, L. Sabattini, C. Secchi, and C. Fantuzzi, "Multisensor data fusion for obstacle detection in automated factory logistics," in IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, Sept 2014, pp. 221-226.
- [8] V. Digani, F. Caramaschi, L. Sabattini, C. Secchi, and C. Fantuzzi, "Obstacle avoidance for industrial AGVs," in Proceedings of the IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, sep. 2014, pp. 227 – 232.
- [9] F. Oleari, M. Magnani, D. Ronzoni, and L. Sabattini, "Industrial AGVs: Toward a pervasive diffusion in modern factory warehouses," in Proceedings of the IEEE International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, sep. 2014, pp. 233 – 238.
- [10] R. Varga, S. Nedevschi, "Vision-based autonomous load handling for automated guided vehicles," Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, sep. 2014, pp. 239 – 244.
- [11] M. Boehning, "Improving safety and efficiency of agvs at warehouse black spots," in Intelligent Computer Communication and Processing (ICCP), 2014 IEEE International Conference on, Sept 2014, pp. 245–249.
- [12] M. Drulea, I. Szakats, A. Vataavu, and S. Nedevschi, "Omnidirectional stereo vision using fisheye lenses," in Intelligent Computer Communication and Processing (ICCP), 2014 IEEE International Conference on, Sept 2014, pp. 251–258.
- [13] A. Mayra, M. Aikio, M. Kumpulainen, "Fisheye optics for omnidirectional perception," Intelligent Computer Communication and Processing (ICCP), 2014 IEEE International Conference on, Sept 2014, pp. 259-263.
- [14] P. Beinschob and C. Reinke, "Advances in 3d data acquisition, mapping and localization in modern large-scale warehouses," in Intelligent Computer Communication and Processing (ICCP), 2014 IEEE International Conference on, Sept 2014, pp. 265–271.
- [15] V. Digani, L. Sabattini, C. Secchi, and C. Fantuzzi, "Hierarchical traffic control for partially decentralized coordination of multi agv systems in industrial environments," in IEEE International Conference on Robotics and Automation (ICRA), 2014.
- [16] <https://www.zemax.com/>
- [17] <http://www.image-science.com/>
- [18] <http://www.ni.com/example/28506/en/>
- [19] www.imatest.com/
- [20] International Organization for Standardization: ISO 12233:2014
- [21] M. Aikio, A. Mäyrä, K. Ojala "MTF measurements of a fish-eye objective and objective sensor," Northern Optics, Lappeenranta, Finland, 2015, submitted.
- [22] Haller, I.; Nedevschi, S., "GPU optimization of the SGM stereo algorithm," Intelligent Computer Communication and Processing (ICCP), 2010 IEEE International Conference on , vol., no., pp.197,202, 26-28 Aug. 2010
- [23] S. Mandici, S. Nedevschi : "Aggregate Road Surface based Environment Representation using Digital Elevation Maps" Intelligent Computer Communication and Processing (ICCP), 2014 IEEE International Conference, Sept. 2014.
- [24] A. Vataavu, Sergiu Nedevschi, and Florin Oniga, "Real Time Object Delimiters Extraction for Environment Representation in Driving Scenarios", In Proc. of ICINCO-RA, Milano, Italy, 2009, pp 86-93.