# Vision systems applied in automotive quality processes: A systematic review.

**Vinicios da Silva Martins, Technologist.**
**Francisco Magalhães dos Santos Júnior, Eng., M. Sc.**
**Leonardo Mendes De Melo, Technologist.**
**Giovani Costa Silva, Technologist.**
**Gabriel Estevam Sousa, Technologist.**
**Pedro Henrique Birais, Eng., M. Sc.**
**Bruno Araujo de Sousa, Technologist, MBA.**
SENAI Institute of Technology – SENAI SP - School "Armando de Arruda Pereira".

**ABSTRACT**
The automotive industry produces millions of vehicles annually, making it a vital sector globally. Inspection processes, including visual checks and computer vision systems, ensure product quality and safety. Recent advances in machine learning and computer vision techniques have propelled the use of computer vision systems for automotive inspection. These systems enhance efficiency and production quality by detecting defects and anomalies missed by human operators. To gain a current understanding and identify relevant scientific research on automotive inspection using computer vision and machine learning, a systematic review titled "Computer Vision Systems Applied in Automotive Quality Processes" analyzed the Web of Science database. Initially, 220 articles were found, but after applying filters, 16 works were selected. The study employed semantic network analysis to identify inspection trends and examined patents and software records. This research aims to consolidate, organize, and update scientific knowledge in this field while assisting decision-making and serving as a reference for other researchers.

## INTRODUCTION

The automotive industry plays a vital role in the global economy by producing millions of vehicles annually. To meet the rigorous quality and safety standards demanded by consumers, a range of inspection processes are employed during manufacturing, ranging from visual inspections performed by human operators to the use of automated computer vision systems. In recent years, advancements in machine learning and artificial vision techniques have significantly propelled the utilization of these systems in automotive inspection.

Computer vision systems applied in automotive inspection possess the capability to detect defects and anomalies that may go unnoticed by human operators, resulting in substantial improvements in process efficiency and quality. Furthermore, these systems can process vast amounts of information in real-time, making them an effective solution for addressing challenges associated with large-scale production.

In this context, the present scientific article, entitled "Vision Systems Applied in Automotive Quality Processes: A Systematic Review," aims to conduct a comprehensive review of scientific works related to automotive inspection using computer vision systems and machine learning. The review was based on a search conducted in the Web of Science database, initially yielding 220 relevant articles. However, through the application of specific date and category filters, 98 more pertinent works were selected for analysis. In addition to the review of scientific literature, this study also sought to identify patents and software records related to automotive inspection, with the objective of obtaining a comprehensive understanding of trends and innovations in this field. Moreover, semantic network analyses were performed to identify patterns and relationships among the various concepts addressed in the reviewed works.

The results of this systematic review provide an overview of the most recent and relevant research in the area of automotive inspection using computer vision systems and machine learning. Understanding these trends and innovations can contribute to the enhancement of quality processes in the automotive industry, driving the adoption of computer vision technology and providing valuable insights for researchers and industry professionals.

## METHODOLOGY

### Definition of the topic of the article to be written:

The authors gathered for the purpose of discussing the technologies and solutions that are on the rise in the automotive industry. After a careful analysis, the research on "Vision systems applied in automotive quality processes: A systematic review" was defined as the central theme of the article This theme was chosen due to experiences and technical visits in automobile companies where the significant presence of manual services in the Brazilian industry was verified, mainly in the quality analysis process. It is believed that the use of dedicated software and algorithms for reliable control, through visual inspection, can identify, analyze, and point out components or situations that are outside the established models or standards.

**Definition of keywords:**

The keywords that will serve as a basis for searching and filtering relevant articles were selected. The keywords chosen were: "Automatic inspection", "Machine learning" and "Computer vision" "Automotive." These keywords are essential to direct the search for articles that address vision systems applied to automotive quality processes.

The first search was conducted for articles that fit the selected keywords. This platform was chosen due to its reliability and coverage in the academic area. The search resulted in a total of 220 articles that are presented at Figure 1 by different search areas.

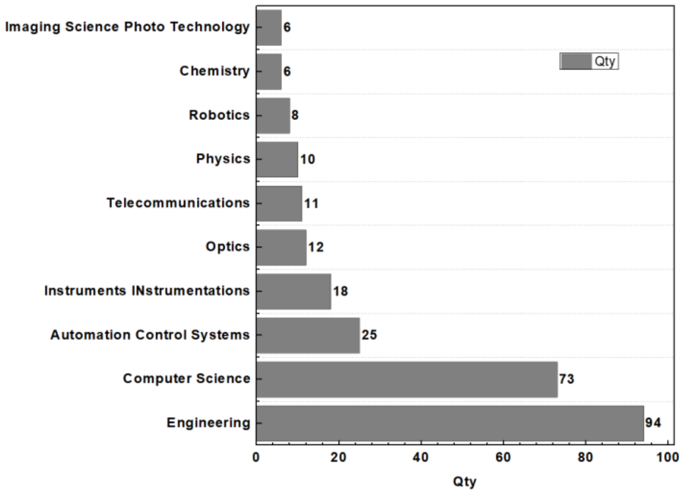


*Figure 1. First search result on Web of Science.*

**Filtering by date:**

To refine the search and obtain more recent and relevant articles, a date filter was applied, considering only articles published from 2012 onwards. With this criterion, the number of articles was reduced to 195.

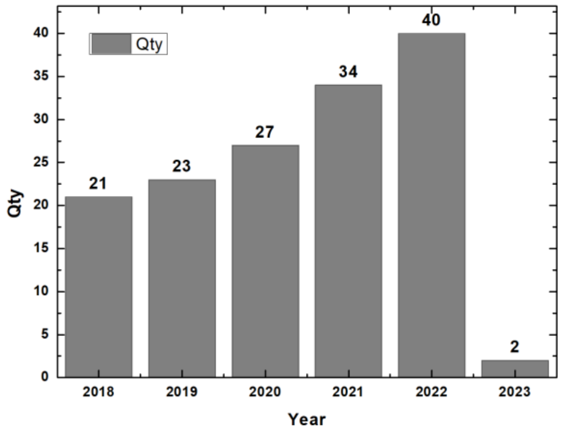


*Figure 2. Web of Science search result after adding date filter.*

**Filtering by category and area of study:**

Aiming to focus on the articles most relevant to the topic, more filters were applied related to the category and area of study of the articles. The categories that stood out the most were Electrical and Electronic Engineering, Computer Science and Artificial Intelligence, in addition to Systems Control and Automation. After this filtering, 147 articles remained. This result can be found on Figure 2 by search areas.

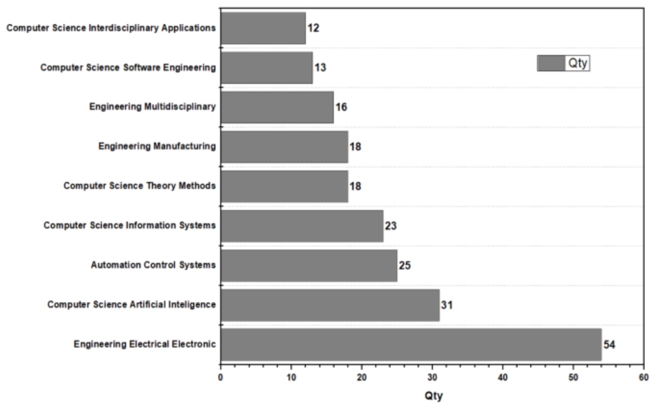


*Figure 3. Web of Science search result after adding category filter.*

**Filtering by regions and countries of origin:**

It was decided to exclude some articles from countries where research was not of great relevance and did not follow the topic to be addressed. To obtain a global perspective on the subject, filters related to the regions and countries of origin of the articles were added. This process aimed to ensure a diversity of sources and approaches. As a result, 116 articles were found (Figure 4).

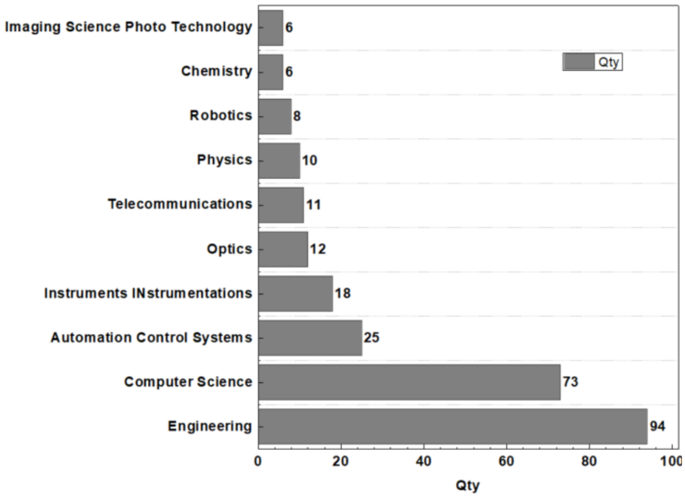


*Figure 4. Web of Science search result after adding country and region filter.*

**Reading of abstracts and selection of relevant articles:**

Based on the filters applied so far, the titles of the 116 articles were carefully read and analyzed. During this stage, some articles that were not related to the theme or that did not present applicable solutions in the automotive area were discarded. After this analysis, 98 articles remained.

**Choice of articles for the systematic review:**

The remaining 98 articles were selected as a source for the systematic review. These articles were considered relevant, as they presented information about vision systems that can be applied in the automotive area. There were 98 articles, the titles were read, and 60 articles were eliminated for not meeting the subject of our research. There were 38 lefts, 30 were divided into 4 people for each to curate and 8 were read together. From this, 16 potentially (Table 1) relevant articles were selected, divided into 10 with high relevance (green) and 6 with very high relevance (dark green). 6 highly relevant articles were read and 1 was eliminated at this stage. From these articles, information, concepts, and technologies relevant to the development of the article were extracted.

*Table 1.* Worksheet of selected or discarded items

| # | Title | Year |
|---|---|---|
| 1 | Development of a System for the Analysis of Surface Defects in Die-Cast Components Using Machine Vision [1] | 2022 |
| 2 | Image Processing-Based Classification of Asphalt Pavement Cracks Using Support Vector Machine Optimized by Artificial Bee Colony [2] | 2018 |
| 3 | Machine-learning-based Quality-level-estimation System for Inspecting Steel Microstructures[3] | 2021 |
| 4 | Automated defect inspection system for metal surfaces based on deep learning and data augmentation[4] | 2020 |
| 5 | Automatic crack detection for tunnel inspection using deep learning and heuristic image post-processing[5] | 2019 |
| 6 | Valve Detection for Autonomous Water Pipeline Inspection Platform[6] | 2022 |
| 7 | Machine learning system based on computer vision for the automatic inspection of magnetic particles in marine structures [7] | 2018 |
| 8 | External and internal quality inspection of aerospace components[8] | 2020 |
| 9 | Research on character correction method based on machine learning[9] | 2020 |
| 10 | Development Of Techniques to Determine Object Shifts for PCB Board Assembly Automatic Optical Inspection (AOI)[10] | 2018 |
| 11 | An integrated underwater structural multi-defects automatic identification and quantification framework for hydraulic tunnel via machine vision and deep learning[11] | 2022 |
| 12 | Enhance 3D point cloud accuracy through supervised machine learning for automated rolling stock maintenance: A railway sector case study[12] | 2018 |
| 13 | Automatic Damage Detection of Fasteners in Overhaul Processes | 2019 |
| 14 | Automatic optical inspection platform for real-time surface defects detection on plane optical components based on semantic segmentation [13] | 2021 |
| 15 | Visual inspection of steel surface defects based on domain adaptation and adaptive convolutional neural network [14] | 2021 |
| 16 | An Efficient and Accurate Object Detection Algorithm And Its Application[15] | 2020 |

## RESULTS

In this section, is present the resume of the top selected works, which represent significant advancements and relevant contributions in the field of study. These works have been carefully evaluated and chosen based on methodological described before, and potential impact on the scientific community. Through these abstracts, we highlight the main findings, methods employed, and conclusions drawn by the researchers.

### Machine-learning-based Quality-level-estimation System for Inspecting Steel Microstructures

The effectiveness of the proposed method was experimentally verified using 362 inspection images of alloy tool steel, SKD11. The experiment used a four-part cross-validation approach with a training-validation-testing ratio of 6.0:1.5:2.5. A comparative method without data expansion was also evaluated for independent verification[3]. As can be seen at Figure 5.

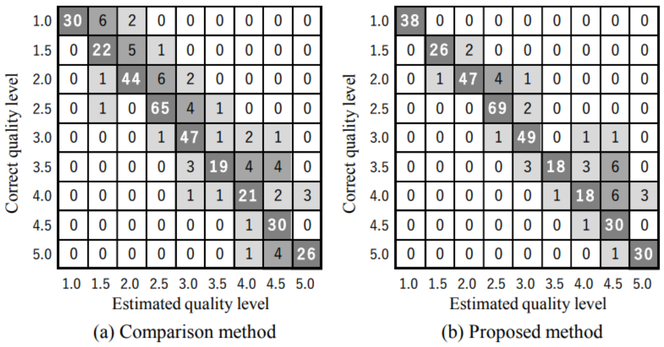


*Figure 5. Confusion Matrix* [3]

The estimation accuracy of the proposed method was compared to the comparative method. The confusion matrices in Figure 6 represent the quality level estimates for the test data. The proposed method showed a significant improvement in estimation accuracy, with a correct response rate of 90%, compared to 84% for the comparative method. This result indicates that data expansion improved performance. The proposed method achieved a correct response rate equal to that of a human inspector, which was considered the performance target for practical use[3].

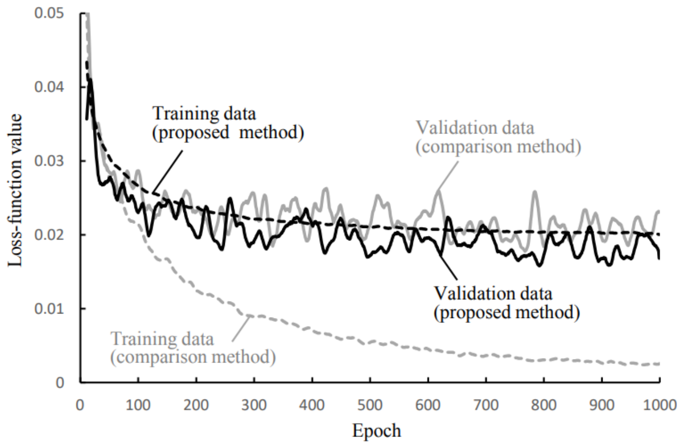


*Figure 6. Learning curves*[3].

The learning curve in Figure 6 illustrates the value of the loss function during training. The proposed method showed better generalization performance compared to the conventional method, as indicated by the lower loss value for the validation data. Although the loss value for the training data is generally smaller than the loss value for the validation data in general learning, the proposed method showed a significantly lower loss value for the validation data. This discrepancy can be attributed to dispersion of correct answer values caused by data expansion, suggesting the potential to further improve judgment accuracy by adjusting the distribution of variance of correct answer values[3].Overall, the experimental results confirmed the effectiveness of the proposed method, demonstrating an improvement in estimation accuracy and generalization performance compared to the comparative method[3].

The study proposed and experimentally evaluated an "automatic quality level estimation" system based on machine learning. Through data expansion, it was possible to avoid overfitting and achieve a judgment accuracy of 90%. This accuracy is considered equivalent to the visual judgment performance performed by an inspector. As future work, it is intended to implement this system in production sites to verify its applicability. Implementing the system will eliminate the influence of personal differences between inspectors and reduce inspection costs. In addition, the application of this system in the inspection of metals other than alloy tool steel verified in this study will be investigated, aiming to expand the scope of automation based on this system[3].

### Development of a System for the Analysis of Surface Defects in Die- Cast components Using machine vision

The developed system showed promising results in the studies conducted so far, demonstrating its applicability in the production line. The Deep Learning algorithms used show good stability in data processing and high compatibility with manual analysis of components, detecting about 95% of components with burrs or defects. However, it is important to point out that the number of components analyzed so far is too small to identify all possible errors. System performance will be better evaluated during deployment on the production line, as it is possible to enrich the case history of the Deep Learning software with weekly analyzes of approximately 21,000 components. Figure 7 illustrates how the software recognizes a burr on the peripheral surface of the part[1].

*Figure 7. Detection of the defect (burry) by means of the DL software*[1].

This work presents the development of a 2D/3D hybrid system for detecting surface defects in aluminum castings. The system uses custom and adaptive deep learning software to perform automatic error detection. Preliminary results are promising, demonstrating the system's ability to identify errors with a satisfactory accuracy rate. However, further testing and production line deployment is still needed for a more complete evaluation. The system also integrates other components such as cameras and measurement instruments for effective coordination. In the future, this combination method is expected to be widely used in the automotive industry for component quality control[1].

**Automated defect inspection system for metal surfaces based on deep learning and data augmentation.**

The project consists of a system for detecting defects in surfaces metallic. This system is made up of cameras located above the production line and pointed at the surface, which has its scanning area illuminated. This information is sent to a controller that processes the images and provides a diagnosis by the HMI (Figure 8) [4].

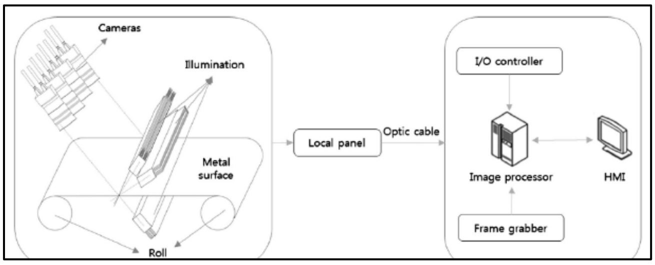


*Figure 8. System configuration of the proposed defect inspection for metal surface*[4].

The algorithm consists of two modules, one for data acquisition for learning and another module for defect classification. The secret of this system is to have a massive amount of data to minimize possible errors and condition to a standard, in this way, it is possible to monitor the deformations in the steel plate in real time and alert via HMI in case of nonconformities[4].

**Valve Detection for Autonomous Water Pipeline Inspection Platform**

The inspection of pipes for water distribution is done by robotic platforms that record the inside of the pipes, and with these recordings made by CCTV cameras (like security cameras) an analysis is made. However, platforms often find it difficult to bypass the 'butterfly valves'; this impasse ends up covering the recording at this stage or ends up suspending the operation of the robotic platform. In the current process, the inspection images are sent to the control center after the activities, so the operator needs to thoroughly analyze the recordings to understand what the obstacles were faced by the robotic platform, and this analysis can take hours to be done[6].

This article focuses on the automatic analysis of these recordings in real time, so that, in the first challenge encountered, the robotic platform can activate its control mechanism and divert the valves with precision. Thanks to computer vision and neural networks, it will be possible to locate these obstacles in advance and conduct an automatic generation of synthetic images to inhibit possible failures in capturing images. With edge computing, it is possible to control these robots remotely, so the inspection is done while the pipes are in operation[6].The results are experimental, and it is predicted that the inspection performance will remain the same as done manually[6].

Image of the vision system detecting the valves at Figure 9:

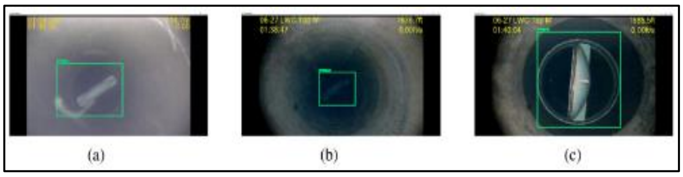


*Figure 9. Some of the valve testing sample results for our proposed model. (a) Valve test image-1 (b) Valve test image-2 (c) Valve test image-3*[6].

**Automatic crack detection for tunnel inspection using deep learning and heuristic image post- processing.**

Development of a vision system coupled to an articulated lifting platform to detect cracks or small quality variations in the tunnel structure[5].

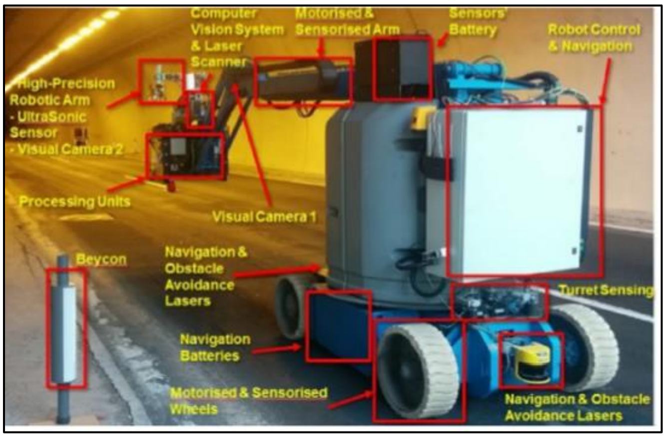


*Figure 10. The components of the ROBO-SPECT robotic plataform* [5].

This crack detection is done on an analysis of an RGB image pair. Only one image is selected, and an image filter, done by a heuristic post-processing engine, takes place to remove the noise. Soon after, the image is converted to gray and resized, so the Neural Network can visualize one pixel at a time and detect possible cracks or structural defects[5].

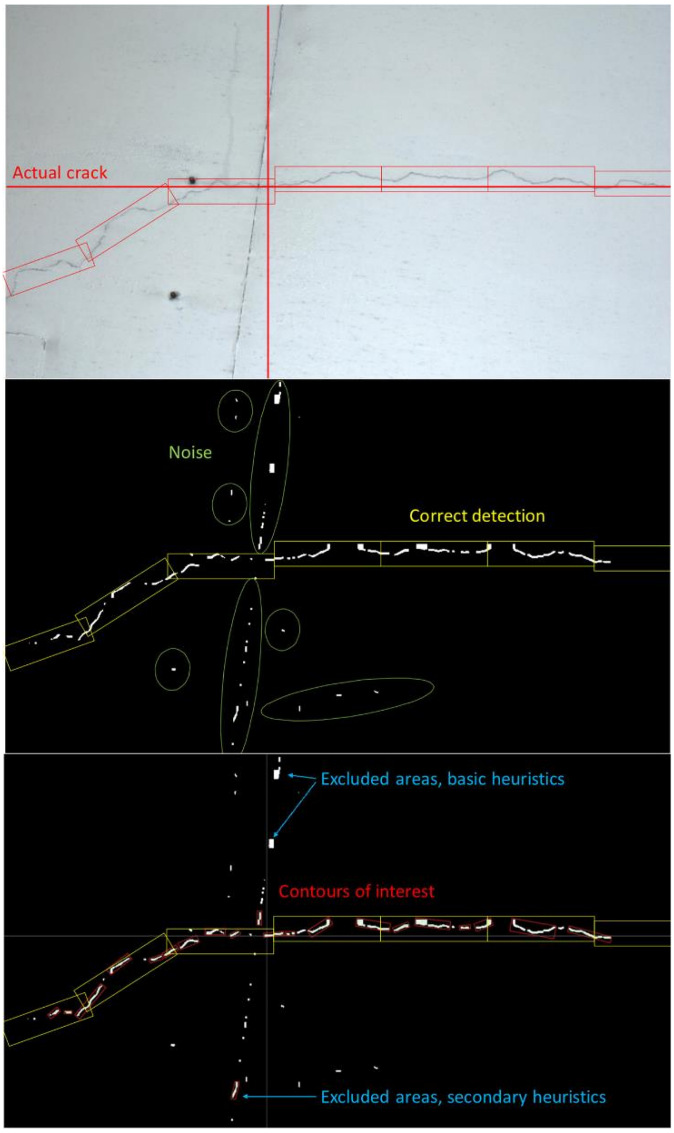


*Figure 11. Crack detection* [5].

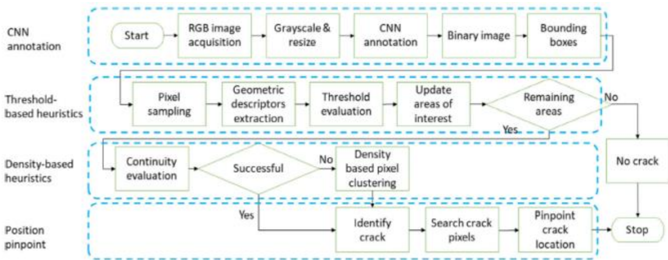


*Figure 12. Proposed methodology flowchart*[5].

The great challenge of the project was the wide variety of defects, such as types of deformations, cracks, disintegration of surfaces, discoloration of concrete, holes made by insect.

**Analysis and conclusion:**

After the reading and detailed analysis of the 98 selected articles, the main results, approaches, and solutions related to vision systems applied in automotive quality processes were identified. From this information, it was possible to draw grounded conclusions and elaborate a coherent synthesis of the results obtained in the systematic review. This analysis and conclusion will be presented at the end of the article.

## CONCLUSIONS

In the future, with the continuous evolution and integration of vision systems with artificial intelligence, it will be possible to make decisions in the production processes of automobile manufacturing without human interference. These advanced systems will be able to detect cracks, paint flaws, assembly errors and validate the required standards with accuracy and reliability.

However, despite the benefits and advances, it is necessary to recognize that the successful implementation of vision systems requires significant investments in infrastructure, training, and proper equipment maintenance. These challenges must be seen as opportunities for continuous improvement, seeking efficient and sustainable solutions. With this improved capability, vision systems will be able to take on an initiative-taking role, instructing managers on actions that must be taken to further improve the production process. These systems will be able to generate detailed reports, accurate diagnoses and even forecasts, providing valuable information for continuous optimization of automotive quality.

However, it is important to emphasize that, even with increasing automation, human supervision and the expertise of professionals will continue to be fundamental. Collaboration between humans and intelligent vision systems will enable a more efficient and effective production process, taking advantage of the best of both worlds.

In conclusion, vision systems are a promising technological solution that drives the automotive industry towards more efficient quality processes. Combined with artificial intelligence, these systems have the potential to make autonomous decisions, improving the efficiency and safety of manufactured vehicles. In addition, they provide and will provide increasingly detailed information and accurate diagnoses, driving strategic decision-making and continuously improving automotive production. This combination offers a promising future for production processes aligned with market demands.

## REFERENCES

[1] G. Cavaliere, Y. Borgianni, and E. Rampone, “Development of a System for the Analysis of Surface Defects in Die-Cast Components Using Machine Vision,” 2022, pp. 74–86. doi: 10.1007/978-3-031-14317-5_7.

[2] N. D. Hoang, Q. L. Nguyen, and D. T. Bui, “Image Processing-Based Classification of Asphalt Pavement Cracks Using Support Vector Machine Optimized by Artificial Bee Colony,” *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, vol. 32, no. 5, 2018, doi: 10.1061/(ASCE)CP.1943-5487.0000781.

[3] H. Nishiura *et al.*, “Machine-learning-based quality-level-estimation system for inspecting steel microstructures,” *Microscopy*, vol. 71, no. 4, pp. 214–221, 2022.

[4] J. P. Yun, W. C. Shin, G. Koo, M. S. Kim, C. Lee, and S. J. Lee, “Automated defect inspection system for metal surfaces based on deep learning and data augmentation,” *J Manuf Syst*, vol. 55, pp. 317–324, 2020, doi: 10.1016/j.jmsy.2020.03.009.

[5] E. Protopapadakis, A. Voulodimos, A. Doulamis, N. Doulamis, and T. Stathaki, “Automatic crack detection for tunnel inspection using deep learning and heuristic image post-processing,” *APPLIED INTELLIGENCE*, vol. 49, no. 7, pp. 2793–2806, 2019, doi: 10.1007/s10489-018-01396-y.

[6] R. Rayhana, Y. T. Jiao, Z. Bahrami, Z. Liu, A. Wu, and X. J. Kong, “Valve Detection for Autonomous Water Pipeline Inspection Platform,” *IEEE-ASME TRANSACTIONS ON MECHATRONICS*, vol. 27, no. 2, pp. 1070–1080, 2022, doi: 10.1109/TMECH.2021.3079409.

[7] P. J. Navarro-Lorente and I. J. Moreo-Lopez, “Machine learning system based on computer vision for the automatic inspection of magnetic particles in marine structures,” *Dyna (Medellin)*, vol. 93, no. 6, pp. 636–642, 2018, doi: 10.6036/8820.

[8] C. Beltrán-González, M. Bustreo, and A. Del Bue, “External and internal quality inspection of aerospace components,” in *2020 IEEE 7th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, IEEE, 2020, pp. 351–355.

[9] Y. Minglei, Z. Xingjie, and Z. Xiaoling, “Research on character correction method based on machine learning,” in *Proceedings - 2020 3rd World Conference on Mechanical Engineering and Intelligent Manufacturing, WCMEIM 2020*, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, pp. 136–142. doi: 10.1109/WCMEIM52463.2020.00035.

[10] R. Pramudita and F. I. Hariadi, “Development of techniques to determine object shifts for PCB board

assembly automatic optical inspection (AOI)," in *2018 International Symposium on Electronics and Smart Devices (ISESD)*, IEEE, 2018, pp. 1–4.

[11] Y. T. Li *et al.*, "An integrated underwater structural multi-defects automatic identification and quantification framework for hydraulic tunnel via machine vision and deep learning," *STRUCTURAL HEALTH MONITORING-AN INTERNATIONAL JOURNAL*, doi: 10.1177/14759217221122316.

[12] R. K. W. Vithanage, C. S. Harrison, and A. K. M. M. DeSilva, "Enhance 3D point cloud accuracy through supervised machine learning for automated rolling stock maintenance: A railway sector case study," in *2018 International Conference on Computing, Electronics & Communications Engineering (iCCECE)*, IEEE, 2018, pp. 242–246.

[13] J. Karangwa, L. H. Kong, D. R. Yi, and J. S. Zheng, "Automatic optical inspection platform for real-time surface defects detection on plane optical components based on semantic segmentation," *Appl Opt*, vol. 60, no. 19, pp. 5496–5506, 2021, doi: 10.1364/AO.424547.

[14] S. Y. Zhang, Q. J. Zhang, J. F. Gu, L. Su, K. Li, and M. Pecht, "Visual inspection of steel surface defects based on domain adaptation and adaptive convolutional neural network," *Mech Syst Signal Process*, vol. 153, 2021, doi: 10.1016/j.ymssp.2020.107541.

[15] L. Jiang and X. Li, "An efficient and accurate object detection algorithm and its application," in *2020 IEEE 5th Information Technology and Mechatronics Engineering Conference (ITOEC)*, IEEE, 2020, pp. 656–661.