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Q-EYE TUNNEL: A NOVEL INSPECTION SYSTEM BASED ON ARTIFICIAL VISION AND LIGHT PATTERN PROJECTIONS FOR DETECTING DEFECTS ON CAR BODIES

J. Ernesto Solanes (Universitat Politècnica de València, Spain), **Josep Tornero** (Universitat Politècnica de València, Spain), **Juan Carlos Villanueva** (Mercedes-Benz España S.A.U., Vitoria Plant, Spain)

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Abstract

Product quality control is one of the most important processes in manufacturing industries, with final products put through several inspections processes in order to satisfy client expectations. This is especially critical in the automotive industry.

Because of limitations in human detection, the automotive industry is still looking for systematic solutions. This paper describes the QEye-Tunnel installed in the Mercedes-Benz factory in Vitoria (Spain) for inspecting van vehicles based on a new generation of inspection systems using curved LED screens that project light patterns. The system is very powerful being able to detect defects not only in flat areas and in those with smooth slope changes, but in style lines (sudden surface slope changes), concavities, edges and corners, etc.

The algorithms implemented rely on two steps: a pre-processing step, performed during the scanning process, and a processing step where defects are detected. With regard to the pre-processing step, a new image fusion algorithm allows to reduce the effect of the diffuse light. Moreover, the algorithm enhances the contrast between pixels with low levels of intensity (indicating the presence of defects) and pixels with high levels of intensity (indicating the absence of defects), thus facilitating their detection in the following step.

As regards the processing step, a novel image processing is implemented, which allows defect detection in concave areas or those with abrupt changes in the surface such as handles, style lines, edges and corners, provided that the area is well lit. As far as we are aware, this is the first system dealing with the detection in those areas.

Introduction

Apart from quality assurance in the process, quality control is one of the most important processes in manufacturing industries, with end products undergoing final inspection to satisfy client expectations. This is especially critical in the automotive industry, where the finish process of the car is of the utmost importance, and the reason why most manufacturers have a dedicated quality control line in each of its mayor phases: raw plate or body in white, painting and final assembly.

Although the majority of production lines today are fully automated, the quality control process is still carried out using manual detection with subjective evaluation by operators, known as check-men (shown in Fig. 1). For instance, after a car body has been painted, these check-men inspect the car body based on the projection of the reflected light. Abnormal reflation is produced when a defect is present. Also they pass their hands over the car body, using special gloves, to detect defects of very small size.

Nowadays the quality level and the improvement ratios in the automotive industry are in endless improvement. On the other side the painting process is increasingly more complex and automated. The inspection requirement, even more so in a big volume unit like a van (more than 40 m2 of external surface per unit), is resource demanding (more than 4 blue collar workers per shift). The actual process, depending of the criticality of inspected zone, requires of a combination of special illumination, training, visual and touch abilities. These last aspects due to the human factor (fatigue, age, working place rotations, cognitive capacities, basic technic training, subjective factors, ergonomics, reflexes, complexity and difference of the quality standards for every zone) have a limited repeatability as compared other quality checkpoints of the production process.

The solutions in the market are no valid: they need robots moving scanners around the unit that needs. At least, 3 standard robots are required to cover all the surface of a medium-size car in the cycle time (high cost and space demanding in production line). Therefore, these systems are only valid for low volume production or for inspecting parts of the car body (only be applied to specific areas of the car).

Due to the above mentioned reasons and the possibility of collaborating with a partner with real experience in deflectometry and applied artificial vision and more importantly: passion and entrepreneurial capacity; we initiated in early 2015 a collaboration project between Mercedes Benz España S.A.U. and the Technical University of Valencia (Spain). The objective was to make the best cost effective innovative industrial solution in the world adapted to our specific case.

The first solution of this project was to put in value the state of the art in terms of computational speed power to limit the number of cameras and illumination screens which is one of the most important cost drivers. The idea is basic, if you have to scan a A3 page and you need to save money in the scanner you can buy a A4 scanner and do it in two parts assuring that you place the page properly.

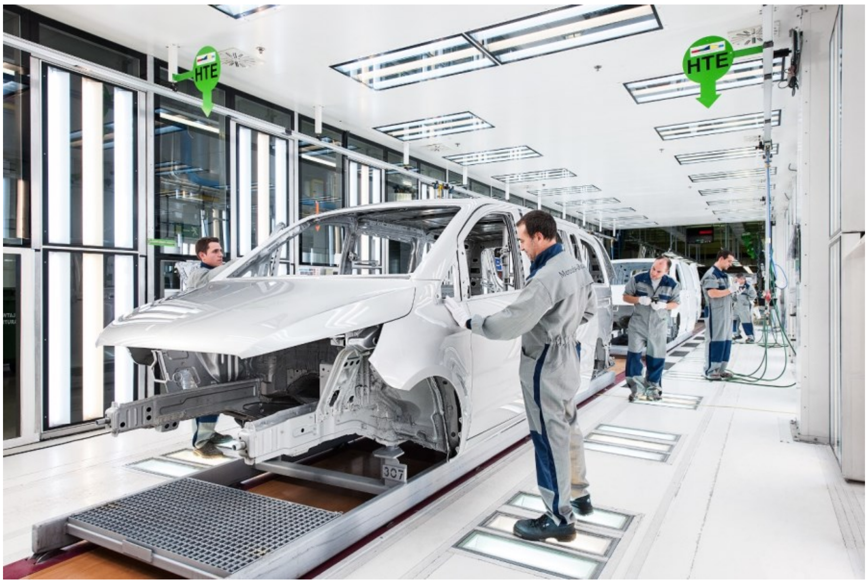

Figure 1. Check-men working on a production line, inspecting car body parts following the painting stage (image courtesy of Mercedes Benz España S.A.U., Vitoria Plant).

Industry 4.0 and the Q-EYE

The so called Industry 4.0 revolution is the result of the technological evolution applied to the cyber-physical and IT systems. In this case, we are applying the latest advances in LED matrix illumination screens combined with the best IT and artificial vision systems.

Before we arrived to this solution, we tried with LED-laser projectors, CDD and CMOS linear cameras, different image processing units, different processing algorithms, and so on…

It is also important to mention, that with the actual smart data philosophy, with advanced data analytics, the real power of this concept is to access and process the information of the precise location and characteristics of the defects. In this sense, we have developed a Business Warehouse (BW) with an integrated Business Intelligence (BI) dashboard in order to put in value the information of all these huge amount of data. It is also possible to track the control system performance. For these reason, we have defined some Key Performance Indicators (KPI) such as sensibility, reliability and precision.

The big data architecture approach of this project opens the door to speed up the root cause problem detection using multivariable analysis. With the actual inaccuracy and costly problem location data registered by hand with PDAs by the human controls, there is no enough quality and quantity of data to precisely carry out these correlations, for example between painting robot programs, trajectories and clouds of defects).

To complete this architecture and to introduce supervision loop from the control operator to the Q-Eye, the system server is integrated with our factory QES (Quality Execution System) in order to import the detected errors in the system. The Q-Eye System server receives the errors from the Q-Eye and as web server publishes them in HTML format in tablets for the paint shop workers.

They can decide if an error is due to be repaired at this moment, it is within the standard, it is a false detection, it is not detected, evaluate its criticality and the need of later rework. From this point is possible to automatically redirect it with the transport lines to the right destination (spot repair boxes, direct run, finish lines or second run preparation line).

Relevant defects are recorded in a quality record of the unit. At this level we are able to prevent any aspect going out of the area with any problem, manage field actions, feedbacks or claims. Also we have a visual digital record of the unit in the moment when it leaves the painting area.

The feedback of the control operator allows not only the possibility to track the efficiency and precision of the Q-Eye but also to open the door to introduce machine learning algorithms for the fine tuning of the inspection system.

Quality Standards

One important issue of the Q-Eye is to improve the standardization level of paint shop quality standards. In Mercedes Benz España S.A.U. these standards are well defined and harmonized among the different departments involved (field, intern QA Audit, production, processes, etc.).

The relevance of a given defect depends on the affected area and (in case many little defects occur one near the other) how many of them are in a defined area. To this task, we have defined more than 90 zones that map all the control area of the body. Every zone has its own defect standard threshold values. This concept helps us also to carry out different actions related with this subject and product variants.

In conclusion, due to this system, we have a more robust and error free quality control in the painting area.

High-availability and Degraded Operation

Every Critical production system must have a high availability operation architecture. In our Q-Eye the system is provided with duplicated central processor. So in case there is a miss function in this core hardware, takes only the time to re-patch the camera RJ connectors to the new computer.

In case one or more cameras are not working, the system can still work but with the information to the control worker of which areas are affected by this miss-function so the workaround of manually checking of these areas can be organized in order to assure that there is no vehicle area without check.

Previous existing systems

Despite different laboratory setups, a commercial and very successful system based on the ideas in [1] was developed and installed in Ford factories all around the world. This system, described in [2], [3], uses a moving structure made up of several light bars (fluorescent tubes at high-frequency) and a set of cameras in fixed positions around the stationary car body, and is able to detect defects of up to 0.4mm in diameter, speeding up and improving the quality of the manual inspection carried out until that point. Unfortunately, as with previous research, only flat surfaces and those with smooth slope changes are inspected, meaning that all style lines, edges and corners are excluded.

As mentioned before other commercial systems dealing with defect detection on painted car bodies use robots to inspect the entire area, such as in [4]. This system tries to cover as much area as possible by bringing vision and illumination close to the body surface. The main problem of these systems relates to cycle time production requirements, since it takes a long time to cover the entire surface of the car body and, as far as we are aware, it is still currently an industrial prototype.

In addition, some patents such as [5], [6], [7], [8], [9] can be found, proposing systems for the inspection and detection of defects on specular surfaces, none of which clarify or indicate how to overcome the problems of detecting defects in concavities, style lines, edges and corners, etc.

Description of the system

A novel automated vision inspection system based on deflectometry and image fusion techniques, the Q-Eye-Tunnel, has been installed in Mercedes-Benz' factory in Vitoria, Spain.

The system is very powerful being able to detect defects not only in flat areas and those with smooth slope changes, but in car body style lines (sudden surface slope changes), concavities, edges and corners, etc. This means that the system is able to detect defects in areas that are very difficult to inspect, such as handles for example, of course, assuming that the area is well illuminated.

Broadly speaking, this inspection system consists of two parts: an external fixed structure where a determined number of cameras are optimally placed in order to see the entire surface of the body to be analyzed, as well as a moving internal structure similar to a scanning machine which houses curved LED matrix screens known as 'sectors' which act as the light sources that project the illumination patterns over the body surface, as can be seen in Fig. 2. The number of cameras as well as the number and size of sectors depend on the car bodies to be analyzed by the system. In particular, the inspection system Q-Eye-Tunnel implemented at Mercedes-Benz in Vitoria comprises 23 monochrome cameras of 5MP working at 15 frame per second, and two sectors set 3 meters apart, with a resolution of 192 x 1344 each and a total route displacement of 2m moving at 0,267m/sec. of speed. With this setup, the scanning stage takes around 11s from start to finish.

Figure 2. Q-Eye-Tunnel installed at Mercedes-Benz plant in Vitoria (Spain).

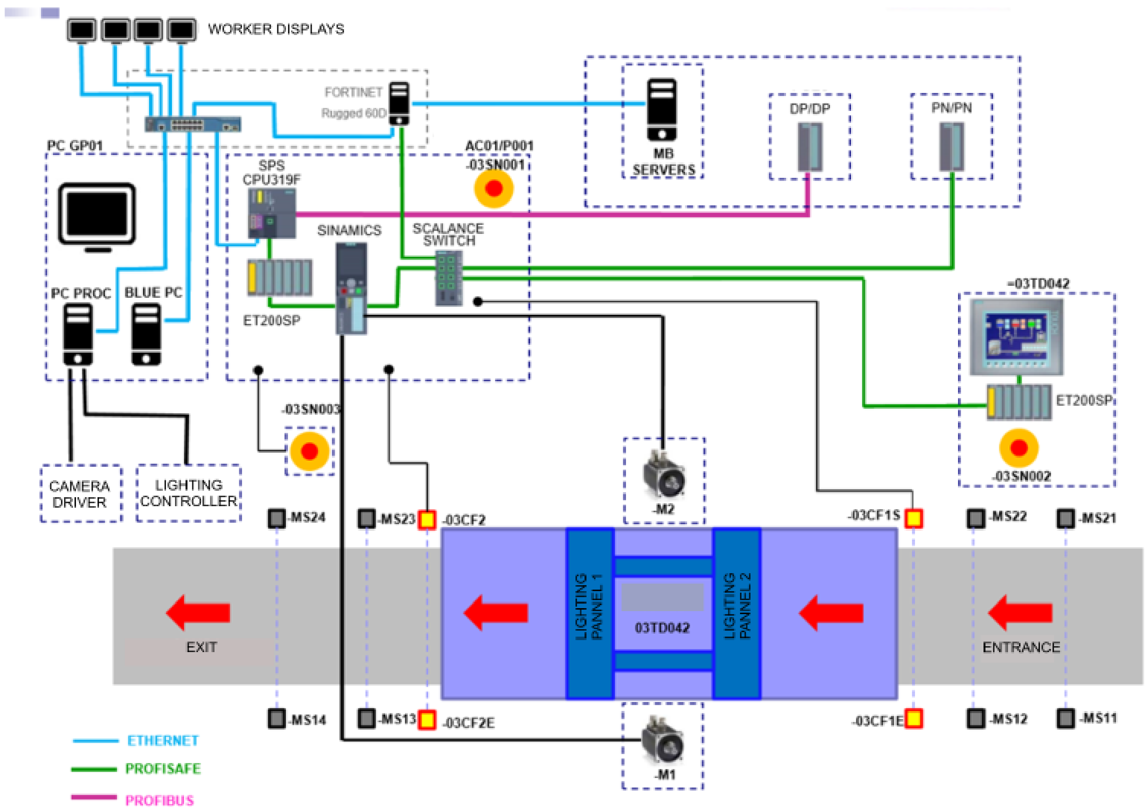

Figure 3. Hardware architecture and communication relationships.

Fig. 3 shows the elements of the hardware architecture as well as the communication relationships in the Q-Eye-Tunnel system.

A brief description of this system follows, excluding all industrial aspects and those related to the integration of the system. We have also omitted other aspects such as camera positions, intrinsic parameters, light patterns, etc., which are not deemed important in this paper.

The main components of the system are:

Low-level Controller (PLC)

This component, based on a PLC, controls the mechanical movement of the sectors and also monitors all production line stages, system security as well as visual and sound alarms. The PLC is connected using the PROFISAFE communication protocol, and to the PC-PROC using the TCP-IP protocol, through the use of a PROFISAFE-ETHERNET converter. The characteristics of each body as well as its position during the inspection process is indicated by this PLC to the PC PROC. The PLC waits for the starting signal from the PC PROC before sending back the ending signal when the scanning stage has finished.

Vision Industrial Controller (PC-PROC)

This element controls the program flow. It is an industrial vision computer from Matrox® named Supersight Solo, which is an entry-level configurable single-node high-performance computing (HPC) platform supporting two multi-core Intel® Xeon processors, third-party GPUs and Matrox® FPGA boards for demanding industrial imaging applications.

It is equipped with 6 GigE Card PCIe AdLink® GIE64+ with Power over Ethernet technology (PoE), and 4 ports for supporting 24 cameras. Moreover, it is equipped with 2 Gigabyte® GeForce GTX 1080 8GB GDDR5X Dual Link DVI-D HDMI 3X DisplayPort PCI-E graphic cards, which were used for the implementation of the computer vision algorithm and also to run the program which generates the patterns to be projected. This system communicates with the PLC and the BLUE PC using the TCP-IP communication protocol.

High-level Controller (BLUE-PC)

This is responsible for providing the inspection results to the production line workers, as well as acting as an interface between line workers and the PC-PROC on maintenance issues. It is an industrial PC-based system, which communicates with the several Worker Displays, Q-Eye-Server and PC-PROC systems using the TPC-IP communication protocol. The secure user authentication method is based in the corporate single sign on standard.

Workers' displays

Some screens controlled by thin PC clients are situated throughout the production line to display the results of the inspection. Workers use the information to locate the defects and act accordingly (fixing them when possible or marking them for later repair). Substituting such screens with lightweight augmented reality glasses is currently being considered, which would improve worker comfort and facilitate the identification and repair processes. Another possibility is to use laser marking of the defects over the vehicle.

Workers' tablets

Every worker involved in the process has a hand adapted tablet in order to receive the same information of the workers' displays and to give feedback to the system as previously mentioned. To improve the user experience and efficiency using this system, we have developed defects grouping functions.

Q-Eye-Servers

The results of each inspection as well as the system backups are stored on these servers. Communication with the BLUE-PC is through TCP-IP but using a FORTINET. Apart from serving as a data security system, it is also used to perform big-data analysis in order to identify problems in the painting process

According to Fig. 3, when a new body is ready to be introduced into the inspection system, the production line control systems inform the PLC accordingly and also provide all necessary body-related data (e.g. model, color, etc.). Only the necessary data is transmitted by the PLC to the PC-PROC which, while the body is being positioned correctly for inspection, loads all initialization parameters, such as thresholds, masks, light pattern, etc. Once the car body is in the inspection position (signal transmitted by the PLC to the PC-PROC), the PC PROC gives scanning permission to the PLC and activates the cameras. The 23 cameras begin to take images at 15fps and then sent to the PC-PROC while both sectors sweep the car body conrolled by the PLC. The PC-PROC computes the previously mentioned pre-processing step and at the same time waits for the PLC to send the scanning ending signal. With the end of the scanning, the PLC warns the PC-PROC and the latter stops the acquisition of images and proceeds to perform the post-processing step for all cameras. Meanwhile, the PLC allows the car body to leave the inspection system and, when a new body is ready, repeats the process. When the results of the inspection are obtained, the PC PROC sends them to the BLUE PC, which in turn sends them to the different display monitors so that workers can locate identified defects on the car body and see to their repair.

Description of the algorithms

Image processing is carried out based on a two-step algorithm: a new pre-processing step (image fusion algorithm), which is more robust when faced with environmental illumination pollution (or diffuse light) than, for example, and as is proved in this paper, the one used in [2], [3]; and subsequently, we present a new post-processing step to extract the image background using a local directional blurring in order to make it possible to detect defects on style lines, edges and corners.

In addition, a multi-level detection approach is presented enabling the detection of larger defects. The input at each additional level is the re-sized image background computed at a higher level. Since one defect can be detected at more than one level, a well-known clustering approach based on distance has been implemented.

As a consequence of all of that, a new image detection algorithm based on deflectometry techniques for detecting small defects on specular surfaces in general, and car body surfaces in particular, has been tested in production at the industry. This algorithm proves robustness in the face of varying surface properties and environmental light pollution, providing defect detection carried out not only on flat surfaces or those with smooth slope changes, but also on sudden slope changes such as style lines. In addition, the image processing meets the cycle time production requirements of car body production line manufacturers (less than 30s).

The algorithms are based on deflectrometry techniques and light patterns as follows:

- *Deflectometry-based detection on specular surfaces:* this technique has proven to be a reliable and accurate approach to accomplishing the task of detecting defects on car body surfaces [10]. In fact, this is what check-men do nowadays in manual inspections using their own eyes, analyzing the reflections on the car body reflected in the car body and looking for deformations. In the same way, as in the case with projection techniques, deflectometry is based on the projection of structured light patterns over a surface. When a triangulation method like fringe projection is used, the camera is focused on the surface onto which a light pattern is projected, as shown in Fig. 4. Thus, when a deformation (i.e. ding or dent) appears, the light rays are deviated, producing a sudden change in the shape of the pattern. Throughout the next sections, we will show how we can take advantage of these pattern changes in order to detect very small defects.

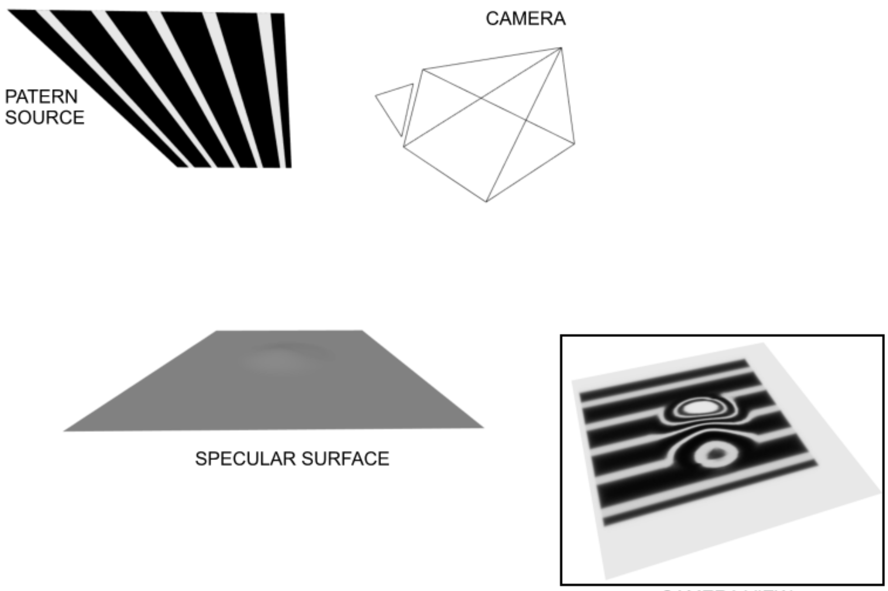

Figure 4. Light deformation of the projected pattern due to surface defects.

- *Light pattern reflection issues:* Since our approach is based on how the light pattern is reflected onto a surface, some issues regarding such reflection need to be considered.

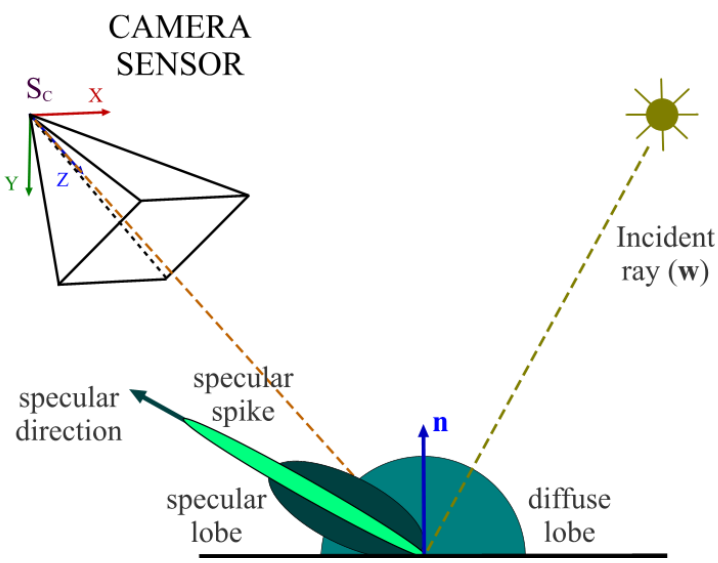

Figure 5. Reflectance model: diffuse lobe, specular lobe and a specular spike dependent on surface properties.

Fig. 5 shows a well-known surface reflection model proposed by [11]. In this model, the reflected light has three components: a specular spike, specular lobe, and diffuse lobe, where the diffuse lobe is the result of the internal reflection, while the specular spike and specular lobe are the result of the surface reflection. If the surface is perfectly specular, no diffuse lobe is observed, yet as the surface property changes from specular to non-specular, the specular spike rapidly diminishes and the diffuse lobe becomes stronger. Since the information regarding the surface structure is held mainly by the specular spike. In addition, it is very important to minimize the effect of the diffuse lobe. Moreover, the effect of the diffuse lobe is not always due to the surface's direct reflection properties, but can also be magnified due to environmental light pollution or even reflection on the surrounding structure.

- *Image fusion technique:* The goal of image fusion is to integrate complementary multi-sensor, multi-temporal and/or multi-view information into one new image containing information of a quality which cannot be achieved otherwise [12]. In this paper, the term image fusion refers to the process in which several images acquired by one single camera at different instants of time are merged forming a new image, enhancing information that is of interest in the purposes of defect detection.

Conlusion

In this paper, a new vision inspection system based on deflectometry techniques and reflecting a light pattern for detecting small defects on specular surfaces in general and on car body surfaces in particular, has been presented.

The algorithms implemented relies on two steps: a pre-processing step, performed during the scanning process, and a processing step where defects are detected.

With regard to the pre-processing step, it is implemented a new image fusion algorithm that allows us to reduce the effect of the diffuse light counterpart, thus leaving us with the interesting information contained in the specular lobe. Moreover, the algorithm enhances the contrast between pixels with low levels of intensity (indicating the presence of defects) and pixels with high levels of intensity (indicating the absence of defects), thus facilitating their detection in the following step.

As regards the processing step, a novel image processing is implemented, which allows defect detection in concave areas or those with abrupt changes in the surface such as handles, style lines, edges and corners, provided that the area is well lit. As far as we are aware, this is the first system dealing with the detection in those areas.

Finally, we can say that industrial Q-Eye-Tunnel inspection system installed at the Mercedes-Benz factory in Vitoria (Spain) is the most advanced inspection system available nowadays in the market.

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