Automatic Defect Detection on Specular Surfaces with resort to Computer Vision and Structured Lighting

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Abstract

Industrial production is facing considerable questions regarding flexibility in production volume and customization. This industrial revolution is resulting from the increasing data generation, and thus increasing the standards over quality control of the goods being produced and the processes responsible for making them. Surface inspection is one of the most commonly used processes in order to determine whether a product is within the specified quality boundaries and, due to the increasing computational power, there has been an increasing investment on the development of automated surface inspection systems. Within the surface inspection, the analysis of specular surfaces arises as one of the most challenging problems since the mirror-like behaviour may hide relevant information and thus interfering with the consequent inspection. After reviewing the current status of the solutions being proposed to tackle this matter, it came to the conclusion that most of them required and extensive amount of computational power, hardware and still presented a certain inflexibility with respect to the geometry that were able to inspect and with minimal detectable dimension. Hence the relevance of conceiving a solution that, utilizing considerably less computational power, was still able to inspect accurately several different geometries in an acceptable amount of time. The proposed prototype in this work resorts to structured lighting in order to apply a deflectometry principle and, consequently, study the interaction between the projected pattern and the surface. The implementation of this solution has been divided into two different stages, one laboratorial, one industrial where the solution was implemented in a real production line so that it was possible to validate the obtained results with the experience of specialized workers. There were inspected 124 surfaces making a total of 44640 captured and analysed images.

Keywords: Specular Surfaces, Deflectometry, Quality Control, Defect Detection

1. Introduction

Although quality management became popular in the 80's and 90's, 21st century enterprises in the era of Industry 4.0 are still struggling with the concept. Recent product recalls are notable examples of serious quality management issues that have led to substantial profit losses because of the increase in the costs of poor quality. Nowadays, the industrial sector is increasing largely in production volumes and in terms of the differentiation of offering products, all with the objective of ameliorating the relationship with their clients, partners and suppliers. This is reflected in the fact that service enterprises have multiple quality challenges in offering affordable care and innovation through service design [5]. However, over the last few years, due to the appearing of smart sensors, there has been seen an increase in the production capacity and analytics that has allowed the gathering of larger quantities of information regarding production processes and quality control of a product over its' manufacturing and easing also the decision making. In order to guarantee that a product keeps being competitive and economically sustainable, it's necessary to ensure a certain level of quality control in the manufacturing all-around. That being, it's expected that this new industrial era arises associated with another relevant concept, Zero Defect Manufacturing [4]. This philosophy focuses in assuring local, static and sequential solutions with the objective of detecting and correcting defects in early stages of the process and thus avoiding a freeze of the production line and allowing a quick and focused action on problematic stages [9].

1.1. Formulation of the problem

With respect to quality control in nowadays industrial context, human visual inspection remains to be the technique that is mostly used, being that's the one that still presents the most reliable results, is easy to conduct and doesn't require any specialized equipment to be conducted. However, the utilization of specialized workers to perform quality control tasks also present several disadvantages such as a high cost, subjectivity, monotony of tasks, difficulty in the documentation of results, among others [8]. Until the end of the 70's, the vast majority of inspection processes resorted to specialized workers but since then, with the increasing computational power of computers and the lowering of optical components prices, a generic investment on automatic inspection systems has been seen all over the industrial sector. This type of systems present several advantages when compared with human workers, being that they can work continuously, do not present any bias, present nearly perfect repeatability and, most important, allows an easy documentation of all the information gathered [3].

When it comes to automatically inspect a surface for defects, firstly, there is the need to understand that any captured image will be intrinsically dependent of the reflective properties of the object. The reflection of any object can be divided into two separate components, one diffuse (mate behaviour) and one specular (mirror-like behaviour), being that in most cases one will prevail with respect to the other.

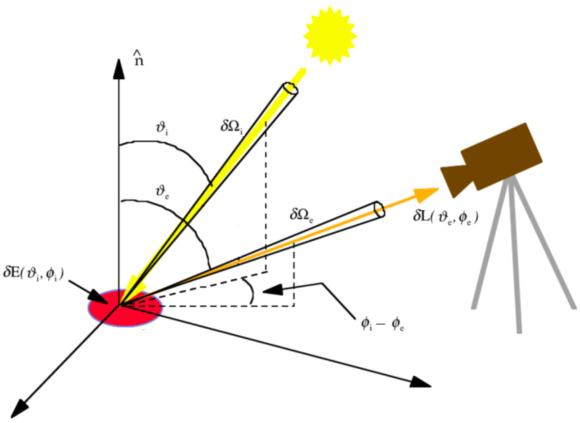


Figure 1: Schematics of the Bidirectional reflectance distribution function

In order to distinguish in a more rigorous way the difference between diffuse and specular reflections we can analysis the Bi-Directional Reflectance Function (BDRF)[2] and its' principle can be understood by analyzing figure 1, where it's possible to understand a diffuse behaviour is associated to a uniformly distributed reflection, while a specular surface is associated with a highly directional reflection. The BRDF describes the reflectance of the surface with respect to the directions of the incident and emitted light and goes by the following equation:

$$f_e(\omega_e, \omega_e) = \frac{dL_e(\omega_i)}{dE_i(\omega_i)} = \frac{dL_e(\omega_e)}{L_i(\omega_i)\cos(\theta_i)d\omega_i} \quad (1)$$

, where E corresponds to the irradiance (W/m^2), L to the radiance (W/$sr^1 m^2$), θ to the polar angle and ω to the azimuth angle. Being also that the i index references incoming light, while the index e references reflected light.[2]

The equation 1) states that the intensity of a captured image is related with the normal of the surface, the reflective properties and the illumination itself. The Lambertian surfaces(diffuse) describes a perfectly scattering of light: the incident light is uniformly emitted into all directions of a half-space, independent of the direction of incidence, while a specular would reflect light into exactly one direction, which is the reflection of the direction of incidence at the surface normal within the plane of incidence. Therefore, the specular behaviour of an object presents a challenging matter since it's mirror-like behaviour may hide relevant information while performing an automatic surface inspection and it demands that surrounding illumination is controlled in order to extract as much information as possible.

1.2. Structured light

In this work there were only considered option resorting to structured light as a solution for the illumination problem being that this genre of solution utilizes the principle of reflection to extract geometrical information regarding the inspected object. Structured light works by projecting a well-known pattern into the inspected surface so that it's possible to study the warp of that same pattern caused by the presence of defects enabling the perception of tri-dimensional information as it can be seen in figure 2[6].

Even though there are different structured light techniques, the one that is vastly more referenced in the literature and most used when working with specular surfaces is the one corresponding to the Deflectometry approach. Deflectometry is a non-interferometric technique whose principle is to obtain dimensional parameters based on the specular reflection of the inspected surface without having to resort to any contact. This technique presents the advantage that it can be implemented without resorting to a large amount of space or weight nor specialized object[1].

1.3. Objectives

The scope of this work is to conceive a prototype that is able of inspecting automatically specular surfaces with resort to structured light. What is expected of this system is that it's able of controlling effectively exterior factors in order to acquire

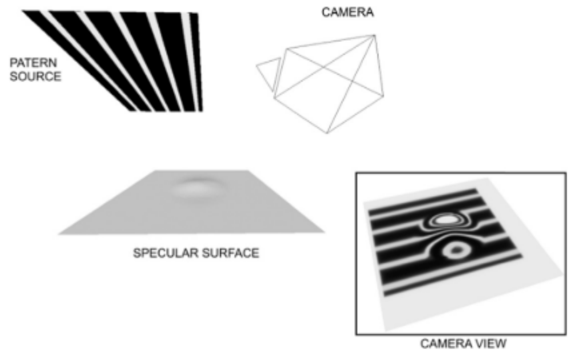


Figure 2: Schematics of the structured light

and process consistently images so that meaningful information can be transmitted to the working operators. By looking carefully at the problem, it's important to develop a dynamic solution that isn't confined to one static apparatus since this gives an additional flexibility to the system with respect to the inspection of various geometries. Noticing that the principal goal of the creation of this prototype is to help the inspection worker with their daily tasks and in order to do so, the main targets are the detection of defects with a minimal dimension of 0.2mm with a success rate of 85% in a wide range of surfaces with different colours and geometries. All of the work has been conducted in order to communicate all obtained information in a clear, unequivocal and fast manner

2. Methodology

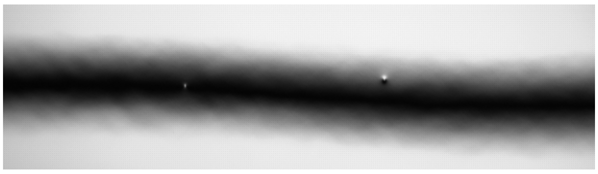
To propose a valid solution, firstly, it's necessary to understand which components and which principles are going to be used . To do so, it's necessary to divide the problem into two main parts: The illumination and the algorithm of detection. These are the cornerstones of this problem since the illumination is responsible for making the defects visible and the algorithm is responsible for detecting them.

2.1. Lighting system

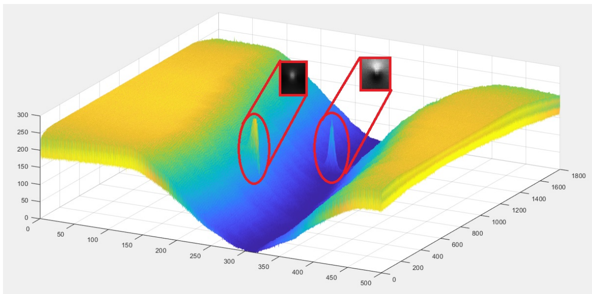
To detect defects in any surface is imperative that the acquisition system is able to visualize them and to make it possible, the illumination system must play a preponderant role. In this work and as it has been mentioned before, the goal of the illumination is to project a known pattern onto the surface so that is possible to study its warp thought its' reflection and, consequently, to extract meaningful information making the most of the specular properties of the surface [7].

Firstly, taking into consideration the specifications regarding robustness and flexibility, it was assumed that any inspected geometry had to be segmented into several locally planar areas so that all the results obtained could be replicated, independently of the shape of the object. That being, the illumination system had to be designed in a way that all lighting conditions could be mimiced for every single acquisition and making all acquired images as similar as possible between them. This principle allows to develop a robust algorithm that can be applied to every image regardless of the shape and the environment.

After trying to develop an illumination system based on shadow detection and deflectometry resorting to texture, the solution converged into an illumination system that applied a deflectometry technique with a dim intensity gradient. To implement this solution, a collimated LED backlight was used due to its' ideal mix of collimated and diffuse behaviour, high intensity and relatively uniform light projection. To apply the deflectometry technique, black stripes where added to the backlight in order to create the desired pattern. This system allowed to obtain consistently images similar to figure 3a. As it's possible to verify, this lighting interacts with the defect to generate a local intensity disturbance that can be identified on figure 3b



(a) Example of an image captured when the proposed illumination system is applied



(b) Representation of the overall image intensity with special emphasis on the two presented defects

2.2. Algorithm

The main objective of the implemented algorithm is to find local variations of luminous intensity in the image that should correspond to defects in the surface. To do so, there were obtained several images with resort to the previous lighting system and a study was conducted so that it was possible to understand and detect the corresponding light patterns that each type defect generated when interacted with the illumination. Looking at all the available defects it was possible to divide them into two separate groups, the ones that generated abrupt illumination variations and the ones that generated a gradual change in the intensity of the image.

Before attempting to detect any defect in the image, there was the need to make an pre-processing of the image in order to smooth out any unwanted defects and, for that purpose, gaussian and median filters are used with resort to diamond kernels with the objective of uniformizing equally the image in all directions. Then, a intensity stretching technique is applied to the image so that the 1% of the lower intensity pixels are saturated at the value 0, the 1% of pixels that presented the highest values are saturated at 255, while the remaining 98% are adjusted in a way to maintain the coherence of the image. This transformation is used to augment the range of intensity so that any present defect would cause a more denounced perturbation in the image.

The first block of the algorithm is responsible for detecting abrupt intensity variation and it was developed considering the variation of the gradients' magnitude in the overall image, being the the magnitude of the gradient is the norm of x and y gradients. Initially it's computed the magnitude of the gradient in all the image, followed by the application of a median filter with the objective of smoothing out the values without losing any information regarding the defected zones being that this filter preserves boundaries. After doing so, a binary image is generated with resort to the use of an overall threshold fixed at a relatively high value since the defected areas are associated those values.

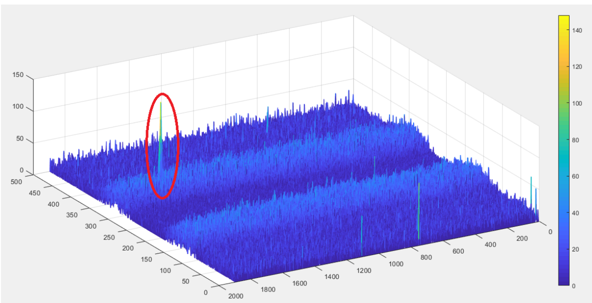


Figure 4: Example of the gradient distribution for an image with a defect signalized

As it can be seen in figure 3a, all the obtained images can be separated into 3 distinct areas. By analysing one specific column of the image, it's possible to understand that it resembles in a certain way a sinusoidal wave, being the two white areas the high peaks and the black area is a low peak, with two transition areas in between. Being this principle valid for all the existing column in the image, it's possible to understand that any present defect would mean the existence of a local maxima and a consequent local disturbance in the image. By trying to detect these local maxima in the overall image, it's possible to detect the previously mentioned defects that generate gradual intensity changes since they don't translate themselves as local change of intensity but don't translate into a significant change in the magnitude of the gradient. In order to detect the local maxima, it's studied the prominence of every column of the image being that disturbances caused by defect are in between two specified thresholds. Once applied the boundary threshold it's possible to obtain a binary image where all the pixels that present the value one corresponds to a defected area.

In a final stage, after applied these two block, it's applied the logical operation of conjunction to the two generated binary image in order to obtain an overall image where all the present defects are signalized and it's possible to extract their characteristics with resort to a blob analysis. Noticing that were also applied some morphological operation during the algorithm in order to enhance some characteristics of the binary images.

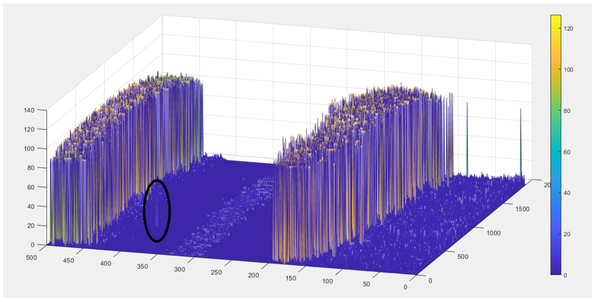


Figure 5: Example of the prominence distribution for an image with a defect signalized

3. Implementation

To validate the proposed system, several tests had to be conducted in order to understand the behaviour of the system with respect a wide range of external variables and, consequently, to conclude if the proposed solution' viability. The proposed solution was developed in a controlled and laboratorial environment where the influence of external agents was minimal, and all the information contained in the tested samples was previously known. Hence, pointing out that the major objective of this work was to develop an automatic surface inspection system, the proposed solution had to be implemented into several different contexts so that it was possible to state unequivocally that the presented results were valid independently of the circumstances of analysis and also being able to test the automatic component of the system.

The first concern regarding the implementation stage was to adapt the system to an arbitrary environment where the lighting condition would be varied and unpredictable since, to validate the solution, it would was necessary transpose and analyse it in different environments with the purpose of testing its' robustness to exterior interference.

Another aspect that must be validated in the implementation stage is the controlled acquisition of images for different positions with the same camera parameters, being that the validation of this aspect is intrinsically related with the overall flexibility of the system. Until this point, every image was acquired from a fixed position being the metallic plate doing them movement, however, to analyze a body with a considerable complex geometry, several sequential images from different perspectives must be taken making it compulsory that the system presents a controlled movement.

3.1. Static test

Throughout the laboratorial stage all tests were performed onto well known samples and all the parameters of experimental setup were configured in a way that the system was able to obtain images consistently. However, it's understandable that this system must perform in environments different from the one set up. Therefore, with the objective of validated the proposed solution, exists the need of transposing the setup into an industrial environment e verify if it still presents the desired consistency. To do so, a static test was conducted where several different parts were inspected locally.

In this stage of the work, and taking into consideration the validations mentioned previously, the configuration was transferred to manufacturing plant with the purpose of validating the functioning principle through the inspection of specialized workers and also for environmental conditions as similar as possible to industrial conditions where, after all, the system is supposed to be implemented. This allowed the analysis of larger and more complex geometry components. In order to analyze these new samples, the objects were placed in two frames and then the system was places over the surface has it is possible to see in figure 6 [Removed due to confidentiality reasons]. Evaluating the geometry of the new samples, it's possible to verify that they present both concave and convex curvature in their shape as opposite of the sample tested in the laboratory that only presented a light convex curve. This demonstrates the grand importance of testing the system for as much samples as possible.

Analyzing this stage of the implementation it's possible to verify that the obtained results allow to reach the conclusion that, in an industrial environment, it's possible to replicate the obtained laboratorial results. Nonetheless, with the results obtained from the image processing of the captured images, it's clear that the testing condition aren't optimal since some of the inspected surfaces presented unwanted dust particles that resulted in false positives. Overall, the conclusion of this test were positive since the inspection of a large range of colours and geometries were conducted with success.

Figure 6: Static test applied to blue metallic surface

3.2. Dynamics test

As mentioned before, the working principle of this solution consists in dividing the inspected surface in several locally planar sections and acquire sequentially the respective images, hence the need to approach the automatic matter of this work. Once validated the results obtained in the laboratory in an industrial context, a movement component must add to the working principle so that the system is able to scan an entire body regardless of its' size and shape. Consequently, associated with the capture of images from different perspectives, arises also the challenge of capturing images automatically with correspondence to the position of the system.

In order to analyse the whole object it's necessary that the system is able to move in order to obtain images of the surface from different positions and perspectives in certain way that, at the end of the inspection, there is an available bank of images that contain every single point of the surface at least once. During the trajectory planning it's crucial to ensure that the worker, when analyzing every individual image, can relate the index of the image if a certain point of the trajectory and that is process is as replicable as possible. To do so the system was coupled to a collaborative robotic arm that allows the planning of routes in a quick and intuitive way. Hence, the objective of this stage of the implementation stage is that, with one single command, the system is able to initialize a defined trajectory, acquire the images corresponding to the defined route points and that is able to process automatically those same images allowing the worker to extract meaningful information.

With respect to the acquiring of images and since these are acquired during the trajectory, there was the need to establish a certain communication with the robot and the camera in order to capture automatically an image in a precise position. Due to the characteristics of those two subsystems, it was used a I/O Digital connection to communicate between these to agents so that, when the robot was placed in a specified position, it would vary the digital flank and, consequently, trigger the acquisition of an image. To validate this step, a trajectory was planned by defining 60, equally spaced, route points that would correspond to an acquisition location. The objective of this test was to validate the repeatability of the robotic arm, the repeatability of the image acquisition and that all the acquired images were dully focused.

3.3. Industrial test

Until this point, it's wasn't possible to state any concrete conclusions regarding the industrial reliability of the system since only a reduced number of samples were tested and only relatively simple trajectories were defined. That being, to validate the overall solution, there was the need to implement the solution in an environment that enabled the systematic and consistent inspection of a wide range of objects, with a different set of colours, without requiring any adjustments between consequent inspection. To inspect systematically and repeatedly it's necessary to unsure the same exact condition for every analysis and to due so, in this stage of the implementation process it was conducted the installation of the proposed solution into an actual production line. This allows the operator to manipulate the processing time in a way that it's possible to pause the cycle and inspected the desired parts for the same exact amount of time and for the same stage of the production process.

During this manufacturing cycle all the objects produced are painted and inspected by specialized worker thus making the in between of these two stages the ideal location to conduct the automatic surface inspection. By doing so, the automatic inspection stage will be conducted right after the object leaves the painting stage and thus being less subjected of having dust particles resting on its' surface and, consequently, less subjected to false positives. Another relevant point it that, by conducting the automatic inspection process previously to the one conducted by the specialized worker, it's possible to compare both results and validate the robustness and reliability of the solution. Thus, the system accoupled to the robotic arm was implemented in a portico as it can be seen in image 7 [Removed due to confidentiality reasons]. This allows a free movement of the robot all over the inspected surface with relative ease. Concluding, it was programmed a trajectory with 360 route points making a total inspection area of 0.75 m^2 that was scanned in under two minutes

Figure 7: Proposed system implemented into a production line

4. Results & discussion

4.1. Process of results validation

To validate the obtained results, the experience of the workers was crucial. By placing the system in a stage previous to the visual inspection it was possible to analyze automatically the object and then transmit the results to the workers so that they could match that information with the defects present in the surface. In order to facilitate this process, the graphic interface present on figure 8 was developed so that it was possible to check, in real time, whether an acquired image had a defect or not. During the acquisition process, a marker was placed on the reference position of the acquisition in the interface and if that same marker was green it meant that the image was clear, but if the marker would turn out red, it meant that there was a defect detected in the image.

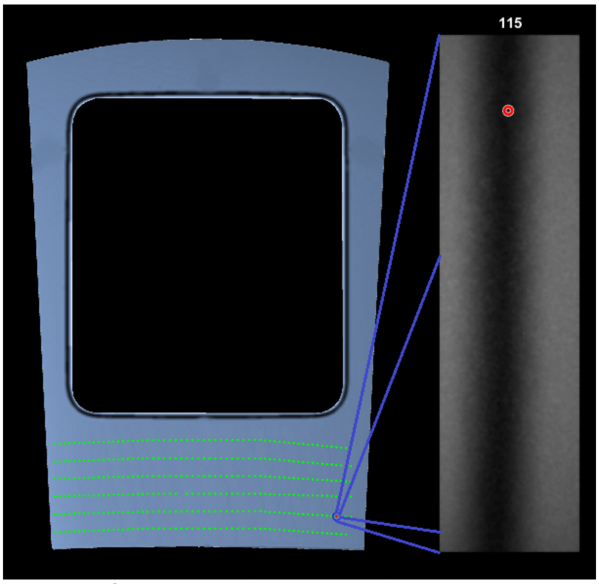


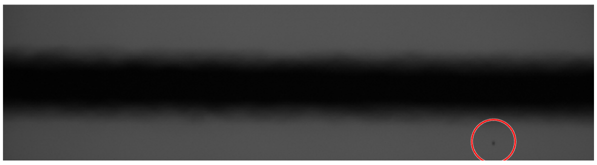
Figure 8: Graphical interface resulting from the automatic inspection

4.2. Results

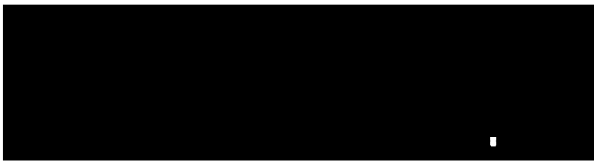
Analysing the obtained results, it's possible to verify that, in terms of acquisition and processing, there were inspected 124 surfaces making a total of 44640 captured images, being that each single one of them had an average processing time of 0.7047 seconds. Analysing also the obtained information regarding defects in table 1, it's possible to see that there 512 defects detected by the specialized workers while the system only detected 452, making an overall success rate of 88.28%, value that's over the initially defined 85%. In terms of percentages, it's also possible to see that dust contamination is the type of defect that comes up more frequently (71.29% of the overall defects) while, in the opposite direction, there weren't detected Runs in any of the 124 inspected surfaces, which is understandable since this is an extremely rare defect that's usually detected immediately.

4.2.1 Dust contamination

This type of defect represents the majority of the irregularities present and detected in this specific work. This is due to the fact that it arises, in most cases, associated with the deposit of unwanted dust particles that interact with the still drying paint and, consequently, forms a dent in the surface. The detection rate of this genre of defects is relatively high since dent usually interact greatly with the lighting pattern, making the defect fairly noticeable.



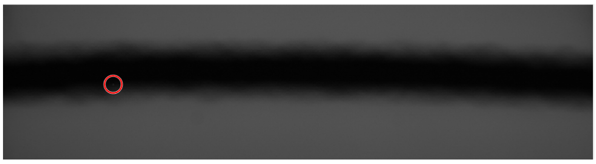
(a) Image corresponding to the detection of a Dust contamination



(b) Binary image resulting from the inspection of a Dust contamination

4.2.2 Craters

Craters show themselves most of the time associated with dings in the surface that, in the vast majority of the cases, are formed due to the collapse of bubble air that stay trapped in between that primary layer of paint and the outer layer. The relatively low detection rate associated with this type of defect comes associated with the fact that, in the majority of the cases, this defect is characterized by dim slopes that don't cause a significant disturbance in the projected light and, consequently, don't trigger any of the defined thresholds in the algorithm.

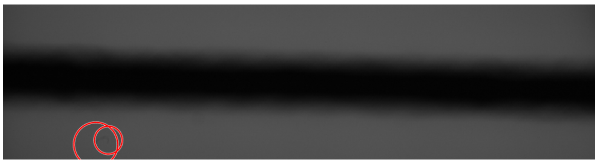


(a) Image corresponding to the detection of a Crater

(b) Binary image resulting from the inspection of a Crater

4.2.3 Fibers

With resemblance to dust contamination, defect associated with fibres come up when a particle of considerable dimensions deposits itself onto the surface while this one is still in a drying process. Also contained inside this category of defects are merely dust particles that deposit themselves onto the surface without interfering with the paint. This is due to the fact that this can indicate that the environment can be overly contaminated and could lead to the appearing of another sorts of defects.



(a) Image corresponding to the detection of a Fiber

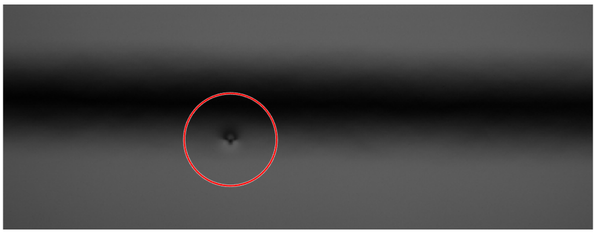
(b) Binary image resulting from the inspection of a Fiber

4.2.4 Pin-holes

The reason for the appearance pin-holes is related with the fact that solvents are very volatile and tend to rise once the outer layer of paint has been applied. With a thin coat this is not a problem since the solvents will evaporate, but if the coat is very thick, apart from a greater concentration of solvents, they will not have time to escape and will remain trapped inside the membrane forming bubbles in the surface. In some cases, these bubbles may actually break through the surface, causing the appearance of pin-holes.

Table 1: Table of overall results

Defects	Real defects	Detected defects	Success rate
Dust contamination	365	336	92.05%
Craters	70	38	54.29%
Fibers	41	40	93.03%
Pin-holes	37	36	97.30%
Solvent boil	2	2	100%
Runs	0	0	N/A%
Total	512	452	88.28%

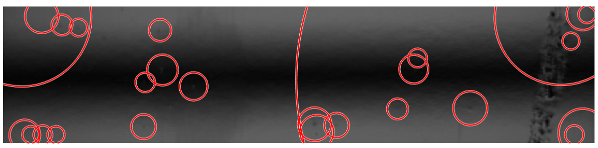


(a) Image corresponding to the detection of a Pin-hole

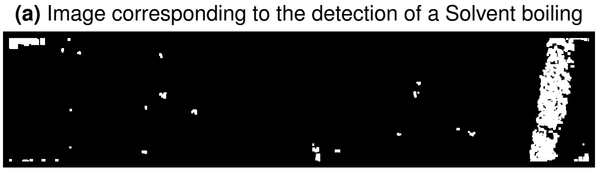
(b) Binary image resulting from the inspection of a Pin-hole

4.2.5 Solvent boiling

When applying the paint coating in high humidity condition, a small quantity of water vapour is absorbed into the paint structure and is then evaporated again in dry conditions(osmosis) like the ones generated inside the curing oven. This process is normal and does not harm a well-constructed finishing process. However, poor processing of the primers will leave water soluble substances (salts) behind as contaminants which lift the paint film into water blisters. Noticing in on the corresponding figure that this type of detect strongly damaged the surface.



(a) Image corresponding to the detection of a Solvent boiling



(b) Binary image resulting from the inspection of a Solvent boiling

4.3. Result discussion

The fact that the system was tested and implemented in an industrial environment allows to draw several conclusions regarding its' robustness. During these stages, the system was tested for several different colours of surfaces with different behaviours (solid and metallic) and, being the inspection order completely unknown, the systems' parameters had to set in a way that would the acquisition of valid images independently of the object that would arise. That being, and by analyzing the table 1 it's possible to verify that almost all types of defects were detected with an acceptable success rate with the exception of Craters. After a careful analysis of the images containing this type of defect, it was concluded that the grand majority of these would correspond to defects with an extremely dim slope that wouldn't meet any of the defined thresholds and, consequently, wouldn't show in the final binary image.

Although the viability of the system is highly connected to its' success rate, other matters arise when it's comes to discuss the performance of the overall system, being the most important one the time cycle that it takes for the system to inspect one whole surface since the solution loses all its' credibility if this time interval is too excessive. This time interval is highly connected with two factors, the trajectory and the processing of all images. When utilizing a GV1000 industrial computer and a UR10 collaborative robotic arm, it was possible to obtain an approximate time of 90 seconds regarding the trajectory and an average processing time of 253.66 per object (360 images).

5. Conclusions

The main goal of work was to develop a solution able of inspecting automatically specular surfaces with resort to structured light. To achieve this, a prototype was conceived, tested and implemented into a production line in order to validate the solution for static, dynamic, industrial environments and also for the largest number of different samples as possible. In this works there were inspected 124 samples of different colors making a total of 44640 images.

The most relevant considerations and findings are the following:

1. A principle of deflectometry was applied were

a known striped pattern was projected into the object and, consequently, a study of the deformation of that pattern was conduction in order to extrapolate topographic information regarding the object

2. In terms of hardware, a LED Collimated Backlight was utilized as the illumination system due to its ideal mix of collimated and diffuse emission. In terms of optical components, a GigE was implemented with a respective lens, since this optical system allows to establish a reliable connection with the processing unit and also allows to detect defects over the specified minimal dimension (0.2mm)

3. The proposed prototype was firstly tested in a laboratorial environment in order to validate the illumination and the proposed algorithm. Then, with the need of testing the behaviour of the system between consequent images, the system was coupled to a robotic arm and tested in a actual production line. This ensured the desired flexibility and robustness.

4. All of the acquired results were validated with specialized workers through a focus sheet. This validation ensured that all existing defects were present in the images and int the respective location

5. The systems presented a sucess rates over 85% for both solid and metallic surfaces and also for the vast majority of the defect presented. Noticing that the amount of metallic surfaces might not have been enough to strongly state the respective success rate

6. The presented system shows results above the defined success rate and utilizing much less resources when compared with other equivalent systems that resort to considerable apparatus that provide acceptable results but compromise in flexibility and overall cost. The amount of cameras is minimal and there virtually no restriction regarding the flexibility of the solution

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