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COMPUTER VISION SYSTEM FOR AUTOMATIC EVALUATION OF IMAGES AND THICKNESS MEASUREMENT OF DRY FILM OF WIND TURBINE BLADE COATING

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Abstract. *The search for inexhaustible sources of energy has been caused the wind energy market to have a great expansion for 10 years. The blades are considered the main components in the design of a wind turbine and have the function of capturing wind energy and later converting it into rotational energy. The enormous structures that make up the blades make it difficult to manufacture and inspect, and this leads to the search for innovative methods capable of ensuring product quality. Several controls undergo visual inspection and manual measurement to validate items that are critical to the manufacturing process and product quality. Due to the still shy amount of work found in the literature using computer vision, and with the work found limited to inspections during the operation of small wind turbines, proposing corrective solutions for surface defects, this work proposes the application of an automatic inspection system for dimensional and quality control of wind turbine blades in a factory environment by means of computer vision and pattern recognition algorithms, applied to the evaluation of images captured during the dry paint thickness measurement process of the protective paint that guarantees the integrity of the blade surface for the life span for which it is sized.*

Keywords: *Computer Vision, pattern recognition, wind turbine blade, automatic evaluation.*

1. INTRODUCTION

Wind energy is an alternative for generating electricity, thus minimizing impacts on the environment and to society. It is considered by specialists as the cleanest, most natural, most available and most renewable energy source on the planet. The operation and performance of wind turbines are directly related to the regular manufacture and inspection of the blades (Denhofa *et al.*, 2019). Consequences of wind turbine blade failures include significant financial losses, unexpected downtime and environmental damage (Wang *et al.*, 2019). As defined by Winter and Segalovich (2018), the blades have the function of capturing wind energy and then converting it into rotational energy in the axis of the wind turbine. Therefore, the constructive shape of a blade directly influences the performance of the system, which can be considered the component that best represents a wind system. Wind turbine blades are hollow and made of glass or carbon fibers, connected to the main shaft through the hub. Some have controls integrated to their structure, responsible for controlling their aerodynamic profile.

Winter and Segalovich (2018) state that, during the design process, some important points must be taken into account: the resistance of the blades, their tendency to deflect under load, the natural frequency of vibration and its resistance to fatigue.

The huge structures that integrate the blades make their construction very difficult and, therefore, require an efficient quality control that guarantees capability in the manufacture of these components. Although the manufacture of a blade is a quite standardized process, most of it is done manually. After inspection of the components, the pressure shell and the suction shell of the blade are glued together. Once cured and the glass transition temperature is reached, the blade is removed from the mold, then sanded, painted and balanced. After the blade is tested, a group of 3 equal-weighted blades is formed. Each set of 3 aerodynamically compatible blades must be mounted on the same wind turbine (Pinho *et al.*, 2008).

Pinho *et al.* (2008) warn that the quality of a blade depends essentially on the people who manufacture it. Therefore, manufacturers must have well-refined process controls, since an undetected failure can lead to disastrous consequences. For example, a defective blade tip can be projected from a wind turbine in motion for up to 600 meters and cause serious accidents in the vicinity.

Computer vision techniques for extracting information during a production process in a factory environment can help in decisions during a dimensional and quality inspection, without relying exclusively on the continuous visual inspection by humans.

In this context, this work proposes the application of an automatic inspection system for the dimensional and quality control of wind turbine blades in a manufacturing environment through the application of computer vision and pattern recognition algorithms. These algorithms are applied to the evaluation of the images captured during the process of measurement of protective paint dry layer thickness, which ensures the integrity of the blade surface for the lifetime it is supposed to last. The need to measure dry film thickness is important in evaluating cost, quality and coating life. A coating that is too thick means excess material is being used, increasing costs. In addition, excess paint can result in paint not curing under the surface, making the coating brittle and likely to damage prematurely. A coating that is applied too thin can cause the surface to be unprotected, causing the premature failure of the entire system.The large dimensions of current wind blade projects make this paint thickness measurement gain volume in the production process and open the opportunity for the development of automatic systems that allow the measurement to be carried out reliably and with the shortest possible cycle time .

2. MEASURING COATING THICKNESS TECHNIQUES

One of the main requirements of wind blade paint and coating tests is the measurement and control of film thickness, which is a critical control of product quality. Ensuring that design specifications are met is important in any coating application method. Various ink film thickness measurement methods are available, and the choice of one depends on several factors, such as the environment where the measurement will be taken, the coated substrate, the condition of the coating (wet or dry) and the condition of the coated surface. A dry film is the coating of a surface that has been cured. The coating is usually a cured paint, varnish or powder. But it can be any substance applied to a substrate.

For Wenzler and Fletcher (1995), due to the many circumstances in which coatings and inks are used, no single method of measuring dry film thickness is universal. Some methods are destructive and are often used when non-destructive ones are not applicable, once these are limited to coating metals.

As for the techniques used to measure the thickness of the dry layer of paint or coating applied to a given product, whether metallic (magnetizable and non-magnetizable) or non-metallic, the applicable methods are described in NBR 10443:2008, ISO 19840:2012, ASTM D6132/97 and in device manufacturers manuals, and will be presented next.

2.1 Non-destructive methods

As the nomenclature indicates, the coating thickness is measured using methods which do not damage the coating or the substrate in any way.

2.1.1 Permanent-magnet method

Non-destructive test applicable to magnetizable metallic substrates and based on the principle that the force of attraction between the permanent magnet and the magnetizable substrate is inversely proportional to the distance between them. The instruments used in this test produce a static magnetic field as Figure 1.

2.1.2 Magnetic-induction method

Non-destructive test applicable to magnetizable metallic substrates. The instruments used in this test use an eletronic probe to generate a magnetic field with either a permanent magnet (with a Hall sensor) or an eletromagnetic induction coil). They produce a coating thickness measurement by measuring the change in magnetic field strenght within their probes due to the proximity of the magnetic substrat as Figure 2. The magnetic field strength is related to the coating

2.1.3 Eddy current method

Non-destructive test applicable to non-magnetizable metallic substrates. This method is based on energizing a coil by high-frequency alternating current, which induces eddy currents in the metallic substrate. These eddy currents create a

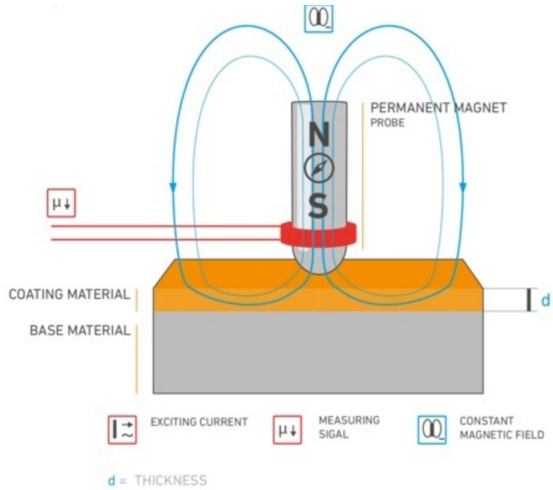

Figure 1: Magnetical measuring method (Fischer, 2021).

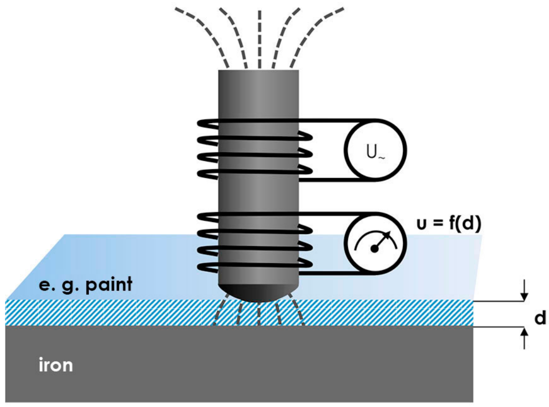

Figure 2: Probe according to the eddy current method (Phynix, 2021).

magnetic field opposite the initial field, thus modifying the electrical characteristics of the coil. The Instruments used in this measurement produce a varying high-frequency magnetic field. They measure the magnetic field produced by eddy currents caused by the probe in a conductive substrate. The magnetic field strength is related to the coating thickness as Figure 3.

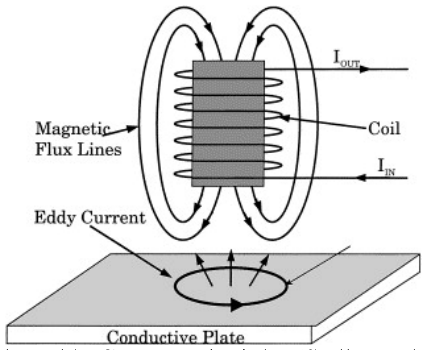

Figure 3: The Eddy Current principle. (Sadler and Ahn, 2001)

2.1.4 Ultrasonic gauge method

Per ASTM D 6132-97, this method uses ultrasonic equipment to accurately and non-destructively measure the dry film thickness of specific coatings on a substrate of different material. Measurements can be made on field structures, on commercially manufactured products, or on laboratory specimens. These types of gauges can accurately determine the dry film thickness of the organic coating on concrete substrates. For the application of this technique on other substrates, such as wood, cardboard, plastic and glass, the method needs to be proven effective before specifying the instrument for use as Figure 4.

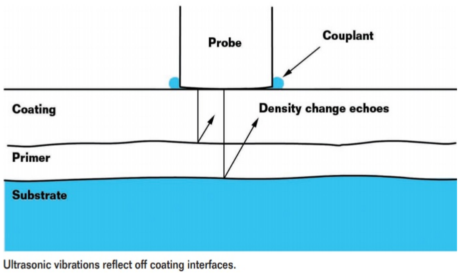

Figure 4: Ultrasonic vibrations reflect off coating interfaces. (Beamish, 2004)

2.1.5 Terahertz Wave method

The Figure 5 is a schematic diagram showing the surface reflection (S), interface reflection (R1), and the multiple reflection, which travels twice (round trip) across the topcoat (R2), in the case of normal incidence. The reflected wave becomes a sequence of pulses separated by a time difference Δt, which corresponds to the time required for the terahertz wave to travel once (round trip) across the topcoat. The topcoat thickness d can be obtained by Eq. 1, in which c is the speed of light ($300 \mu m/ps$) and n is the refractive index of the topcoat.

$$d = \frac{c\,\Delta t}{2n} \tag{1}$$

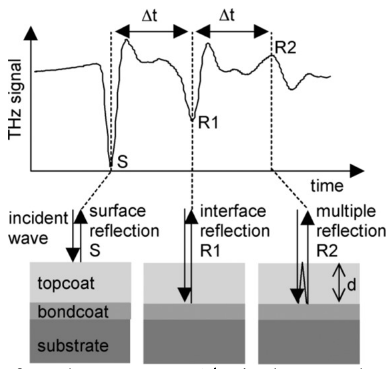

Figure 5: Schematic diagram of reflection of terahertz waves (Δt is the round-trip travel time across the topcoat). (Fukuchi *et al.*, 2014)

2.2 Destructive methods

As the nomenclature indicates, destructive methods of measuring dry film thickness result in damage to the coating or the substrate. Damage caused by carrying out destructive testing requires repairs to the coated coating on the protected surface. A simple destructive dry film measurement technique is to remove a sample of the coating and measure the thickness with a micrometer.

2.2.1 Dial depth clock method

This method is a destructive test applicable to metallic (magnetizable and non-magnetizable) and to non-metallic substrates. The test is based on the physical determination of the distance between the paint film surfaces and the substrate. The instrument used consists of a dial depth clock fixed on a support with fixed rods that allow the instrument to be supported on a base and the reading to be zeroed before measuring the painted surface. Then, the assembly is supported on the surface to be measured and the movable rod of the dial depth clock moves into the opening that was previously made in the coating, until the tip of the rod touches the substrate. Thus, the value displayed on the dial depth clock display corresponds to the thickness of the ink layer as Figure 6 .

2.2.2 V-Cut Method

This method is a destructive test applicable to metallic (magnetizable and non-magnetizable) and to non-metallic substrates. First, V-shaped cuts are made in the paint by using precision angled tools. Then, the cuts are observed by

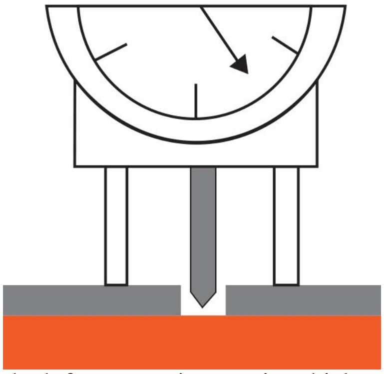

Figure 6: Dial depth clock for measuring coating thickness (Elcometer, 2021).

using an appropriate optical instrument, in order to determine the thickness of the paint laye as Figure 7.

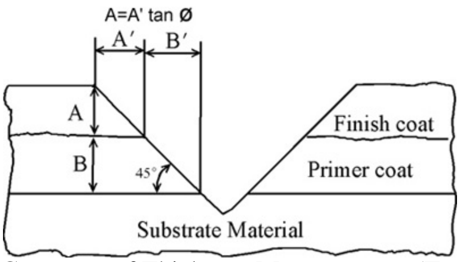

Figure 7: Geometry of Thickness Measurement. (Tooke, 1976)

2.2.3 The Coulometric method

The coulometric method involves removing an area of the coating by a process of anodic stripping. The weight of the metallic coating is then determined and the thickness is calculated based on mass per unit area as Figure 8. The main advantage of this method is for measuring electrically conductive coatings on a conductive substrate.

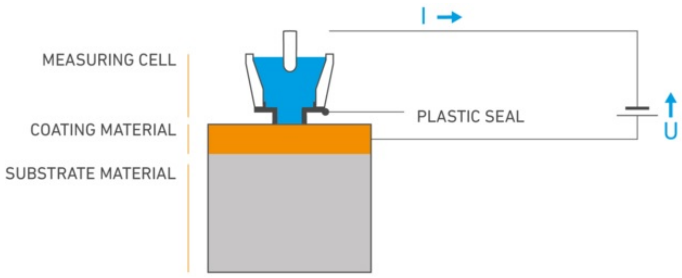

Figure 8: The coulometric method (Helmut, 2021).

2.2.4 The Saberg Drill Method

The Saberg Drill works on a similar principle to the V-Cut method, but instead of scoring a line, a conical hole is drilled through the coating to the substrate which minimises the damage to the coating. According to the work of Saberg (1980), the device for measuring the thickness of coatings comprises a rotatable drill, the cutting edge or edges of which are at a 45° angle to the axis of the drill. The drill is manually operated by means of a finger disc and guided and steadied during its operation in a through-going bore in a guide plate resting with an anti-slide surface on the coated surface, the thickness of whose coating is to be determined. The conical cut made by the drill is observed in a microscope, and the width of the circular band is noted on an in-built micrometer scale. Owing to the cutting angle being 45°, the said width is equal to the thickness of the coating (see Figure 9).

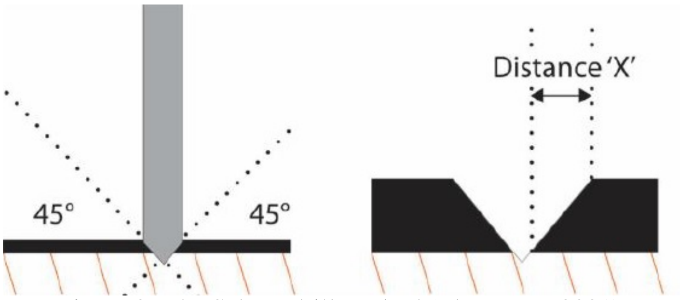

Figure 9: The Saberg drill method (Elcometer, 2021).

3. DIGITAL IMAGE PROCESSING METHODS FOR QUALITY INSPECTION

Computer vision is an excellent resource to obtain reliability and speed in quality inspections, as it is a promising sensing technology, applied to automation systems, as it tries to reproduce in machines one of the most complex senses. Computer Vision uses several Digital Image Processing (DIP) resources, aiming to prepare the input image in order to enable or facilitate the application of algorithms for the vision system itself. Such algorithms are responsible for analyzing the input image, in order to extract information or attributes and make a decision about its content. The PDI capabilities associated with Machine Learning tend to produce great results during quality inspection in the manufacture of wind blades.

Wei *et al.* (2019) present a laser scanning thermography technique as a form of non-destructive testing capable of detecting subsurface delamination in carbon fiber reinforced plastic (CFRP). The thermal response signal was processed using fast Fourier transform (FFT) and principal component analysis (PCA), and FFT amplitude and phase images and PCA image were formed. Defect signal noise ratios (SNRs) were calculated and used to assess the defect detection of different post-processing algorithms.

Concas and Jung (2019) investigate the behavior of a composite used in the manufacture of wind blades known as polyvinylchloride foam subject to combined tensile/twisting loads. Deformation analysis by digital image correlation is performed using eight cameras arranged to form a regular octagon, and image processing is performed by specific software.

Moreno Oliva *et al.* (2019) develop an optical contact instrument to measure the geometric shape of aerodynamic profiles in small wind turbine blades. The instrument uses the principle of triangulation, where a laser pattern of structured line is projected onto the surface of one face of the blade under test, a camera captures the image of the line and is processed to interpret the distorted shape of the projected line.

4. MATERIAL AND METHODS

Computer vision techniques for extracting information during a production process in a factory environment can help in decisions during a dimensional and quality inspection without relying exclusively on the continuous visual inspection of the human being.

Computer vision provides a large amount of information about the environment, thus, it is potentially one of the most powerful sources of information among all sensors that can be used in dimensional inspection. However, due to this large amount of data, extracting visual features for defect detection is not simple. Therefore, the problem of dimensional inspection using computer vision can be a great tool in quality control and have great relevance in the production of wind turbine blades.

Among the techniques that can be used to identify defects in wind turbine blades, computer vision stands out as an extremely effective tool and capable of overcoming the technological challenge for inspection purposes due to the large amount of information obtained. Such information is important for analyzing the real situation of the blades, which reduces possible defects that directly influence operating failures and accident rates.

Most of the dry coating thickness measurement techniques discussed above are not applicable to non-metallic substrates, and those that do apply have high cost and various operational limitations. Given these factors, the Saberg drill method was selected, due to its excellent cost-benefit ratio, for the development of an application using computer vision. With the method defined, three main steps were followed to carry out this work and defined below.

4.1 Preparation of specimen

A specimen was prepared in the form of a 500 mm x 500 mm rectangular plate. The rectangular plate was manufactured using a few layers of fiberglass fabric and epoxy resin. After impregnation and curing of the resin, the surface of the plate was sanded, cleaned and then coated. Three coats of polyurethane paint used to protect the edges of wind blades were applied, with an interval of 40 minutes between each coat, the first coat in red, the second in gray and the third in white. After the last coat, a time of 180 minutes was set aside for the coating to fully cure in order to ensure the application resistance, so that the protective layers would not peel off at the time of perforation.

4.2 Drilling of specimens and image capture

After the preparation and painting of the specimen, the saber drill method was used to perform the drilling in the coating. As already mentioned, the method consists of the execution of a conical-shaped hole, carried out through the coating until reaching the substrate. The device used consisted of an 8 mm diameter drill, with a 45° cutting angle, fixed to a disc that is manually operated with the aid of a recess in the disc surface for finger positioning. A plate with a through hole and a non-slip surface supported on the casing was used to guide and stabilize the hole. Due to limitations in the painting process, the hole in the coating was carried out from an initial spacing of 20 mm from the edge of the specimen, to minimize variations in thickness due to a possible greater deposition of the coating in this region. After drilling, the hole was cleaned with a jet of compressed air to remove coating burrs. The conical cut made by the drill was observed in a portable digital microscope from the manufacturer dnt which has a resolution of 5.0 megapixels and optical zoom with a magnification range from 10x to 500x. The microscope was positioned over the hole and the image was observed on the 3" LCD screen on the microscope body, then the focus and lighting were adjusted so that the image obtained the best possible framing for the hole made and the best observation condition of hole details. After adjustment, the image of the hole was captured. The same focus defined for the capture of the image of the hole was used to capture the image of a graduated scale with a resolution of 0.1 mm. The scale image was exported to the software provided by the microscope manufacturer, compatible with Windows, which allows measuring distances in images of objects magnified with a resolution of 0.001 mm. With the scale image displayed in the software, it was possible to calculate the magnitude of the amplification of the image to adjust the defined focus and illumination. With the image magnification value, it was performed the measurement of the circular band width between the inner and outer diameter of the image with the help of the existing resources in the software, as shown in Figure 10 below. Because the cutting angle is 45°, the width is equal to the coating thickness. The same measurement procedure was followed for all captured images and the results were compared with the automatic measurement and will be presented in the next section of this work.

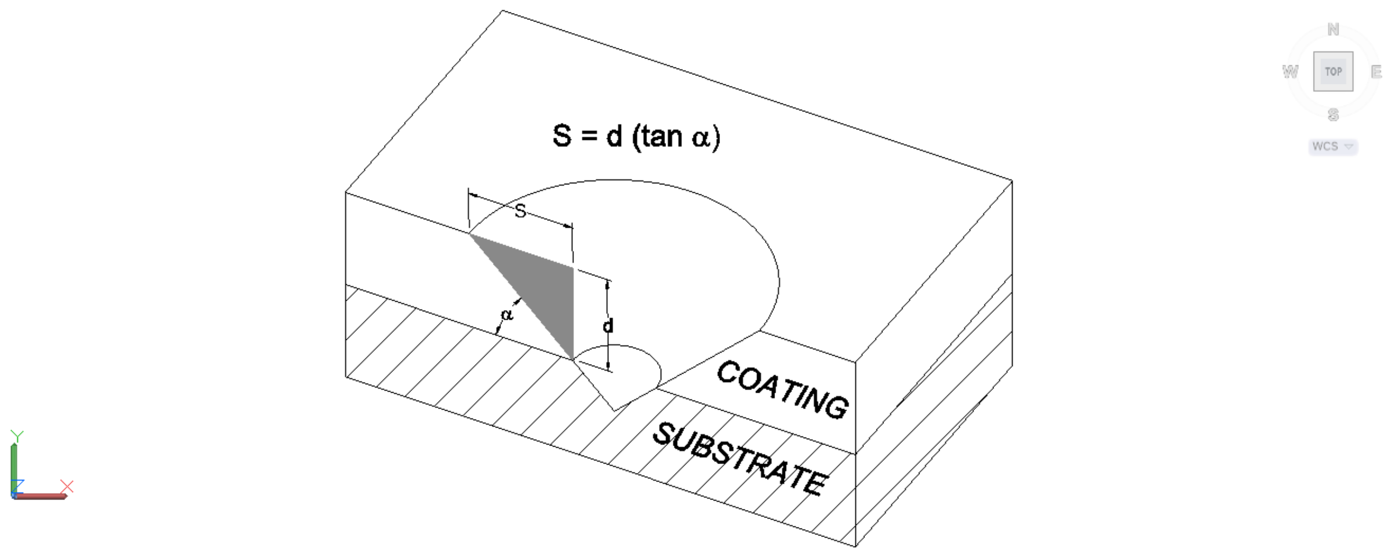

Figure 10: Section trasnversal hole

4.3 Development of computer vision system

The development of a system capable of automatically evaluating images and quantifying the applied coating thickness was motivated by the number of images that need to be evaluated in a single wind blade to ensure the protection of the entire surface. Thus, an image bank was formed using all measured images and was used in the development of the automatic assessment tool.

We used the programming language *Python* version 3.7 through the IDE *PyCharm* in order to implement an automatic evaluation through a computer vision system.

Initially, all images were resized to a width equal to 600 *pixels* and a height equal to 450 *pixels*. Images have been converted to grayscale. A Gaussian filter (low pass) of size 5×5 was applied in order to reduce the noise level of the images. The applied filter softened the image by attenuating the high frequencies, which correspond to abrupt transitions (noise), tending to minimize them and presenting the blurring effect of the image. With these smoothed images, the automatic calculation of an optimal threshold based on the images histogram was performed for further binarization.

After the image binarization, two border regions were found using the OpenCV library that has open source, mainly used to process images and videos to identify shapes, objects and text. For that, we used the cv2.findContours() function and the cv2.drawContours() function to draw borders on the images. The cv2.findContours() function discovers all shape boundary points in the image. The return of this function is a list of contour points. The cv2.drawContours() function draws a contour. In the case of this work, all boundary points are stored to represent the contour. Only the two largest contours are selected. These correspond to the region of interest.

After finding the contours, the distances between points (the closest) between the contours were calculated. With this, the average of the distances between points between the contours is calculated according to Figure 11. As the relation *pixel* $\times$ μm is already available, the equivalence is performed and the error related to manual measurement, using the corresponding software of the microscope, can be calculated.

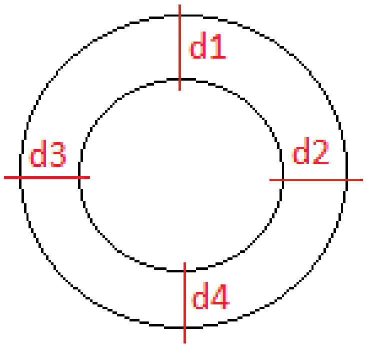

Figure 11: Average distance equals the average between d1, d2, d3 and d4.

5. RESULTS

In this section, we will report the application of an automatic inspection system for the dimensional and quality control of wind turbine blades in a manufacturing environment through the application of computer vision These algorithms are applied to the evaluation of the images captured during the process of measurement of protective paint dry layer thickness, which ensures the integrity of the blade surface for the lifetime it is supposed to last.

To make this essay less subjective, a system based on digital image processing techniques is known in this work. Libraries already consolidated in the python language were used for this purpose.

First, a low pass filter is applied to the image. Soon after, optimal thresholds according to each region are found in order to binarize the image. Then in all of the binary images contour values are detemined using opencv function cv2.contours(). The desired distance is the distance between the outermost green outline and the innermost red outline. Some contours performed by the automatic system are shown in Figure 12 and and the results for the 15 samples used in this work are shown in the table 1.

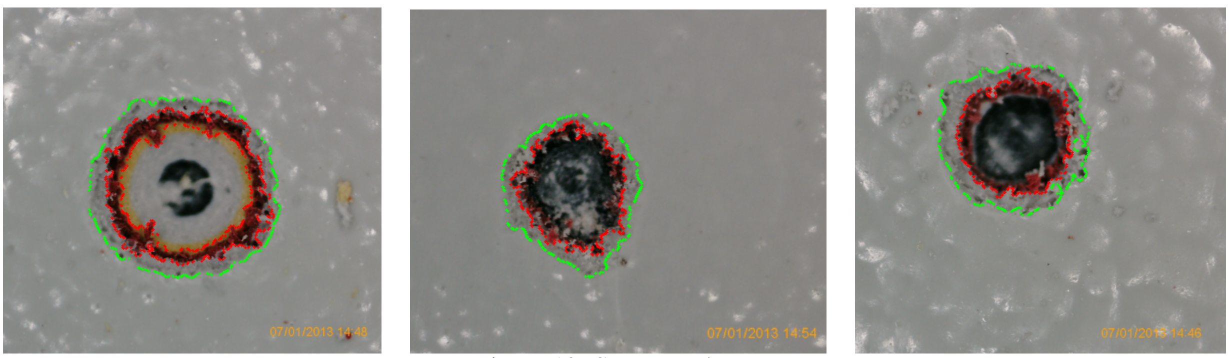

Figure 12: Segmented contours.

Table 1: Experimental results: error relative to manual measurement

Sample	Absolute error	Estimated percentage error	Processing time (s)
01	3.5μm	0.43%	0.8454
02	2.1μm	0.26%	0.8365
03	4.9μm	0.61%	0.8154
04	5.1μm	0.63%	0.8356
05	2.5μm	0.31%	0.8265
06	7.5μm	0.93%	0.8154
07	11.9μm	1.48%	0.8285
08	8.5μm	1.06%	0.8355
09	18.5μm	2.31%	0.8285
10	8.2μm	1.02%	0.8353
11	6.1μm	0.76%	0.8166
12	4.9μm	0.61%	0.8697
13	2.3μm	0.28%	0.8456
14	21.2μm	2.65%	0.8589
15	9.8 μm	1.22%	0.8549

6. CONCLUSIONS

The objective of this work is to propose a new method of analysis of dry film thickness, using digital image processing. Manual measurement of dry film thickness is a process entirely dependent on the reading made by the operator, in addition to being tiring and causing fatigue to the operator, thus, the results are prone to errors. The operator skill parameter has a great influence on the final measurement result, and can represent a great source of error. This error may result from deficiencies in the training of the observer to carry out the test and baggage individual operator that leads to different interpretations.

For this reason, it is important to develop a methodology that is not influenced by the operator observation and interpretation ability. In this context, a semi-automatic measurement approach is presented, based on concepts of Digital Image Processing, in order to minimize this important factor in the measurement process.

The method is tested using dry film thickness images, with the results obtained being very efficient for the tested images. In this way, it is hoped that this work will contribute to the progress of the analyses of dry film thickness images improving the operator's work tools in his analysis, contributing indirectly to the reduction of errors as a result of the observer's experience. The semi-automation of this system, using the proposed algorithm, obtains more accurate results and faster compared to the conventional procedure.

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8. RESPONSIBILITY NOTICE

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