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Statistical decision methods in the presence of linear nuisance parameters and despite imaging system heteroscedastic noise: Application to wheel surface inspection☆

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ABSTRACT

This paper proposes a novel method for fully automatic anomaly detection on objects inspected using an imaging system. In order to address the inspection of a wide range of objects and to allow the detection of any anomaly, an original adaptive linear parametric model is proposed; The great flexibility of this adaptive model offers highest accuracy for a wide range of complex surfaces while preserving detection of small defects. In addition, because the proposed original model remains linear it allows the application of the hypothesis testing theory to design a test whose statistical performances are analytically known. Another important novelty of this paper is that it takes into account the specific heteroscedastic noise of imaging systems. Indeed, in such systems, the noise level depends on the pixels' intensity which should be carefully taken into account for providing the proposed test with statistical properties. The proposed detection method is then applied for wheels surface inspection using an imaging system. Due to the nature of the wheels, the different elements are analyzed separately. Numerical results on a large set of real images show both the accuracy of the proposed adaptive model and the sharpness of the ensuing statistical test.

1. Introduction

During the past decades, automated visual inspection (AVI) systems have been broadly used for the inspection of a wide range of "objects" such as fabrics [1–3], nuclear fuel rods [4], steel [5–8] or even food [9] to cite few examples. The main role of a computer-vision system is to provide detailed description of the inspected product, from one or several images, in order to detect and classify the possible occurrence of any type of anomaly. Given a set of product specifications, any observation that deviates more than a prescribed value from what is standard, or normal, is considered as an anomaly. Furthermore, if the anomaly surpasses certain acceptance limits, which are usually defined by the customer, it is then referred to as a defect.

In general, the anomaly detection process is a –fully or partially– manual process conducted by operators, whose main role is to inspect each and every product manufactured along the fabrication line. A single operator might have to inspect thousands of manufactured products during the day. As a result, this manual process is usually subjective, labor intensive, and sometimes biased. Therefore, and in order to overcome these difficulties, there is a great need for fully automatic systems that are fast and sufficiently efficient, and which are used to replace, or to assist, the operators to control the presence of defects [10]. Such systems have to be reliable, and trustworthy, for the detection of various types of defects. However, depending on inspected objects geometry and their internal structure, the detection may be made difficult due to the non-anomalous "background".

1.1. State of the art

Prior methods for surface anomaly detection based upon images captured with an AVI system can be divided into three categories [1,4,11]: 1) Generic methods that are highly flexible as they are not based on any prior knowledge on inspected objects [5], 2) Specific methods that are based on ground truth or examples of a reference [11], and 3) Methods based on computer vision and image processing, see [12, Chapter 15] , that usually require prior information on the non-anomalous object.

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The first category includes anomaly detection methods that do not require any prior model of object's structure. Different types of filters [3,6], such as median filter or Gaussian filter, morphological operations [13], and histogram equalization [14], have been all applied for noise reduction, image enhancement, with the aim to improve the contrast between the anomaly and the non-anomalous background. These tools, followed by pattern recognition methods [15,16] or thresholding operations [7,8], illustrate the core architecture of this type of methods. First-order gradient filter followed by thresholding is one of the most commonly used approach in this category [6,8,17]. More recently, state-of-the-art image processing methods, such as multi-resolution representation [18], sparse dictionary learning [19] and variational methods [20], have all been applied for automatic anomaly detection. Similarly, classification methods have been used for automatic recognition of anomalies, mainly with the help of supervised machine learning [7,8,21,22,24]. These methods consist of separating the inspected image into regions of distinct statistical behavior [23], based on the assumption that common properties can define all kinds of anomalies and distinguish them from any non-anomalous background. The existence of such properties is doubtful in practice and these methods are thus often sensitive to the object and anomaly geometry and to the presence of noise.

In the second category, the detection methods are based on a ground truth: a reference image of the non-anomalous background used as a model [11,25]. The detection is thus straightforward as it is usually based on mere differences between the reference and the inspected image. If a significant difference is identified, the inspected image is classified as defective [14,26]. Usually, the reference image is created by averaging multiple anomaly-free images [27]. In an alternative approach, the reference image is estimated from the inspected image using a filter consisting of several masks [28]. This approach is efficient but is very sensitive to experimental conditions, such as object position, illumination and projection angles. Moreover an accurate ground truth may be difficult to obtain in practice.

Finally, methods from the third category make use of prior statistical information on the non-anomalous object. Two main approaches have been proposed to introduce statistical prior knowledge: Bayesian and non-Bayesian approaches. The Bayesian statistical approach allows the design of efficient and rather simple methods for anomaly detection. However those methods require 1) that the anomaly occurs with known prior probability and, 2) that the non-anomalous object is also random with known a priori distribution. Those requirements limit the application of Bayesian methods.

For a more detailed review on methods for automatic defects detection, the reader is referred to [5,11,29,30].

In the anomaly detection problem considered in the present paper, the non-anomalous background of the inspected surface has no interest in the detection process while it may hide the anomalies and, hence, may prevent their detection. In addition, we do not always have prior distributions to model both the inspected surface and the occurrence of anomalies. In such situations, it is more convenient to represent the expected non-anomalous background as a linear combination of basis functions, and to consider non-Bayesian hypothesis testing methods for anomaly detection.

As a result, the method proposed in present paper belongs to the third category, and, specifically, to non-Bayesian approaches. It is based on some knowledge on the inspected surface and uses it to design a broad method for rejecting the non-anomalous part of this inspected surface. This allows to meet the practical constraints of the industrial process, such as speed and reliability, while using geometric knowledge on the inspected object which is easily available at the manufacturing stage.

1.2. Contribution of this work

In this paper, it is proposed to design a non-Bayesian method based on an adaptive model of the non-anomalous part of the inspected surface, also referred to as the "background". This original adaptive model is interesting as it allows the inspection of a large range of surfaces, with different geometries, without prior information or Computer-Aided Design (CAD) models of the inspected object; this extends the application of the proposed methodology to various quality inspection domains. In addition, the use of this model with an heteroscedastic statistical noise model of digital images prevents the need to calibrate the imaging system. Eventually, the proposed model is accurate enough to allow the detection of small defects that are hardly visible by naked eyes. The proposed method is then applied for wheels surface inspection to detect "appearance defects" that are located on the surface of the wheel. This specific application allows challenging the efficiency of the proposed methodology in several ways; indeed the surface of the wheel is rather complex to inspect and requires an accurate model, while as in most of industrial applications, the large number of wheels produced every day requires mastering precisely the properties of the statistical test.

Our prior works [31,32] also rely on a similar approach for hidden data detection; fundamental differences, however, are that in this paper no information of the potential anomaly (shape, size, position, etc.) is available and that the adaptive model is much more accurate which allows its use in a much wider range of applications.

The main contributions of the present paper are the following:

1. An adaptive statistical model is proposed to represent the imaged surface. This model only requires knowledge of inspected objects geometry making, thus, the anomaly detection system fully automatic and applicable to a wide range of surfaces.
2. The proposed model is accurate, to ensure high detection performance, and computationally simple, for real-time applications.
3. The heteroscedastic noise model is used to accurately describe the noise properties in raw images. Accordingly, for other types of images, the heteroscedastic model can be replaced with the appropriate model without having any effect on the detection accuracy.
4. The statistical properties of the method are explicitly provided. The detection threshold only depends on the false-alarm probability. Consequently, an operator can, for instance, prescribe a false-alarm probability easily and can know which type of anomalies can be detected with which probability.

Numerical results on extended data sets of wheel images from a wide range of wheel types show the relevance of the proposed adaptive statistical model and the sharpness of theoretical established results.

1.3. Organization of this paper

The present paper is organized as follows. Section 2 states the problem of anomaly detection. Section 3 details the proposed adaptive model of the inspected surface. This model is both simple, for a real-time application, and linear for a simple use within hypothesis testing theory. Section 4 presents the proposed statistical method for anomaly detection. It also establishes the statistical properties of the statistical test. Then, section 5 describes the different elements of the wheel and the approach used for their detection and localization, and presents the preparation of the wheel surface for inspection. Finally, Section 6 presents numerical results and Section 7 concludes the paper.