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Statistical detection of defects in radiographic images using an adaptive parametric model

Rémi Cogranne *, Florent Retraint [1]

ICD - LM2S - Université de Technologie de Troyes - UMR STMR CNRS, 12, rue Marie Curie, CS 42060, 10004 Troyes cedex, France

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A B S T R A C T

In this paper, a new methodology is presented for detecting anomalies from radiographic images. This methodology exploits a statistical model adapted to the content of radiographic images together with the hypothesis testing theory. The main contributions are the following. First, by using a generic model of radiographies based on the acquisition pipeline, the whole non-destructive testing process is entirely automated and does not require any prior information on the inspected object. Second, by casting the problem of defects detection within the framework of testing theory, the statistical properties of the proposed test are analytically established. This particularly permits the guaranteeing of a prescribed false-alarm probability and allows us to show that the proposed test has a bounded loss of power compared to the optimal test which knows the content of inspected object. Experimental results show the sharpness of the established results and the relevance of the proposed approach.

1. Introduction

During the past decades X-ray or gamma radiography inspection has been widely used in non-destructive testing processes. It is based on the fact that high energy photons have the ability to pass through inspected object which allows the imaging of its internal structure. In most of the Quantitative Non-Destructive Testing (QNDT) applications, a voxel-by-voxel reconstruction is not necessary because the goal of the inspection is to detect an anomaly or a defect. Usually, the detection process based on radiographies relies on human experts to perform manual interpretation of acquired images. However, this process might be subjective, labour intensive, and sometimes biased. Therefore there is a wide need for computer-aided systems or for fully automatic methods. However, depending on the inspected object geometry and its internal structure the detection may be made difficult due to the non-anomalous background.

1.1. State of the art

The prior methods for detection of internal defects using radiographies can be divided into three categories [21,41]: (1) generic methods that do not require any priori knowledge, (2) methods that require a ground truth or a reference, and (3) computerized methods based on statistical signal and image processing. The methodology proposed in the present paper belongs to this last group.

The first category includes defect detection methods which do not require any prior model of object structure. Such approaches typically involve image processing tools for enhancement (field flattening, contrast enhancement, edge detection, etc.) see [9,28,39] and the references therein, together with pattern recognition [6,36] methods. More recently, state-of-the-art image processing methods, such as multi-resolution representation [54], sparse dictionary learning [37] and variational methods [32], have

* Corresponding author. Tel.: +33 325759672.
E-mail address: remi.cogranne@utt.fr (R. Cogranne).
URL: http://lm2s.utt.fr/fr/membres/cogrannr.html (R. Cogranne).

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been applied for automatic defect detection. Similarly, classification methods have been used for automatic recognition of defect, mainly with the help of supervised machine learning [11,58,61]. These methods rely on the assumption that common properties can define all kinds of anomalies and distinguish them from any non-anomalous background [26,40,41]. 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. The methods from the second group are based on an available ground truth: a reference radiography used as a model [41]. If a sufficient difference is measured by comparing this ground truth with radiographies, it is then assumed that the inspected object is defective [12,53]. This approach is efficient but is very sensitive to experimental conditions, such as object position and projection angles. Moreover a ground truth is not always available in practice. Finally, most of the computerized methods rely on the reconstruction of the inspected object from a (large) set of radiographies. However, when a limited number of radiographies are available for inspection, a full voxel-by-voxel reconstruction is impossible, see [3, Chap. 15], and [48], and the use of prior information on the non-anomalous background is necessary. Two main approaches have been proposed to introduce statistical prior knowledge: Bayesian and non-Bayesian approaches.

For a more detailed review on methods for automatic defect detection, the reader is referred to [13,35,41].

1.2. Motivation of this work

The methodology proposed in the present paper belongs to the category of non-Bayesian statistical methods for anomaly detection. Let us briefly recall the relative advantages and drawbacks of Bayesian and non-Bayesian approaches in order to emphasize the contribution of the proposed methodology. The most commonly found methods in the literature belongs to the Bayesian approach [24]. In fact, Bayesian statistical approach offers an efficient (with minimal expected risk) and rather simple solution for the detection problem. However it assumes that (1) occurrence of an anomaly is a random event with known prior probability and, (2) the non-anomalous background and the anomaly are random and drawn from apriori known distributions. These apriori knowledges on the inspected objected and potential anomalies are not always available; this may compromise the application of Bayesian approaches.

In such a situation, a more convenient modelling of radiographies can be obtained by representing the expected non-anomalous background as a linear combination of basis functions. This modelling particularly makes possible the use of non-Bayesian hypothesis testing theory. In fact, such hypothesis testing methods allow the introducing of "nuisance parameters" which have no interest for the considered QNDT but which must be taken into account because their impact may be non-negligible. In the considered anomaly detection problem, this is especially relevant because the non-anomalous background has no interest while it may hide the anomaly and, hence, may prevent their detection.

To remove, or reject, the nuisance parameters, the main idea is to split the space of observations into two subspaces: one containing all the nuisance parameters and the other one completely free from these nuisance parameters. Of course, the main difficulty here is to have a model which is accurate enough to represent the content of any radiography, while leaving the anomalies into the background-free subspace, to preserve a high detection performance. Examples of such a non-anomalous background representation and rejection can be found in [30,58] but this approach has seldom been used together with hypothesis testing theory [21]. Some other approaches have been proposed to allow the subtraction of background such as the simple field-flattening operation [9] and the image processing methods for denoising [35,46]. The main drawback of these methods is that they do no allow the establishing of neither the decision threshold which guarantee a given false-alarm probability nor the missed-detection probability (or detection power).

Similarly, several Bayesian approaches have been proposed. Those methods require that the apriori distribution of Background is known, so the problem of its rejection is trivial. Hence, the problem reduces to test the presence of signal in noise in the framework of binary [49] or multiple hypothesis testing theory [24].

On the contrary, a linear model of non-anomalous background has been used to provide a test with known statistical properties in [21]. Unfortunately, this test is based on a geometrical model, or on a Computer-Aided Design (CAD) model, of the inspected object which may not always be available. Moreover, a precise calibration process is required to match the observed radiography with the geometrical model. Hence, this method is compromised when the inspected object geometry or acquisition conditions may slightly change.

In our previous work, this methodology, using hypothesis testing theory with the use of a linear model of background, allows us to address the problem of hidden data detection [14,15]. It has also been shown, for that detection problem, that the use of a precise model [16,17] allows the obtaining of a statistical test with better performance. The main difference is that, is the context of anomaly detection, no information is available of the potential anomaly (shape, size, position, etc.) while, for hidden data detection, the alternative hypothesis is well described statistically.

1.3. Contribution of this paper

This paper proposes a novel methodology for automatic detection of anomalies from a few radiographies. An original model of radiographies is proposed based on a study of the whole radiography acquisition process [47,57]. This model is used for background subtraction/rejection. Then, a statistical test with analytically established properties is proposed. The main contributions are the following:

1. By modelling the whole acquisition process, the proposed methodology does not require any prior knowledge on the inspected object and, hence, is entirely automated; this also allows the application of the