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Applied algorithm in the liner inspection of solid rocket motors

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ABSTRACT

In rocket motors, the bonding between the solid propellant and thermal insulation is accomplished by a thin adhesive layer, known as liner. The liner application method involves a complex sequence of tasks, which includes in its final stage, the surface integrity inspection. Nowadays in Brazil, an expert carries out a thorough visual inspection to detect defects on the liner surface that may compromise the propellant interface bonding. Therefore, this paper proposes an algorithm that uses the photometric stereo technique and the *K*-nearest neighbor (KNN) classifier to assist the expert in the surface inspection. Photometric stereo allows the surface information recovery of the test images, while the KNN method enables image pixels classification into two classes: non-defect and defect. Tests performed on a computer vision based prototype validate the algorithm. The positive results suggest that the algorithm is feasible and when implemented in a real scenario, will be able to help the expert in detecting defective areas on the liner surface.

1. Introduction

Currently in Brazil, most rocket motors employ the solid propellant as the component responsible for generating thrust. During the manufacturing process of these motors, a thermal insulation material is used as an internal coating to protect the casing (motor case) from high temperatures produced by the combustion gases.

The bonding between the solid propellant and thermal insulation is accomplished by a thin adhesive layer, known as liner [1–4]. Fig. 1 shows the propellant/liner/insulation/casing interface representation of a typical solid rocket motor.

Throughout the lifetime of rocket motors, different load conditions, such as temperature fluctuations, vibration during transportation and acceleration during flight can cause geometric deformations or displacements of the propellant. A possible reason for these displacements is related to the bonding quality among the layers shown in Fig. 1 [4–6].

In Brazil, the liner application method involves a complex sequence of tasks, which includes in its final stage, the surface integrity inspection. Nowadays, an expert carries out a thorough visual inspection to detect defects on the liner surface.

The expert usually investigates two types of defects. The first is characterized by discontinuities (voids) on the liner surface. The second is based on the fact that there may be foreign objects (e.g., dust and fibers) dispersed on this surface. Given the nature of the manufacturing process, both defects have random physical characteristics. Their shapes and sizes may vary significantly hindering the visual inspection and compromising the bonding between the solid propellant and the insulation.

Such bonding must ensure that the entire unit is properly fixed during the storage, transportation, assembly and launch stages. The use of a rocket motor with defects on the liner surface may result in an uncontrolled gas generation and potentially in the rocket motor explosion, which can put lives at risk, cause financial losses and delays in technological/scientific projects.

According to statistical data, approximately one-third launch failures of solid rocket motors result from bonding problems in the propellant/liner/insulation/casing interface, making this process a critical point of inspection [7,8]. Hence, it is essential to correctly identify bonding defects and take preventive measures to minimize them.

Shearography [9–11] is a non-destructive inspection technique for the analysis of surface deformation in various types of materials. It identifies defects in an object by comparing the difference in the speckle patterns of images obtained before and after the object is deformed.

A limitation of the conventional shearography system is that it demands the inspected object to have a rough surface [12]. If the surface is specular (mirror-like surface), most of the light will be mirror-reflected resulting in an unsatisfactory speckle pattern for defect detection.

Several other non-destructive testing techniques have been used to assess the structural integrity of rocket motors after the final stage of

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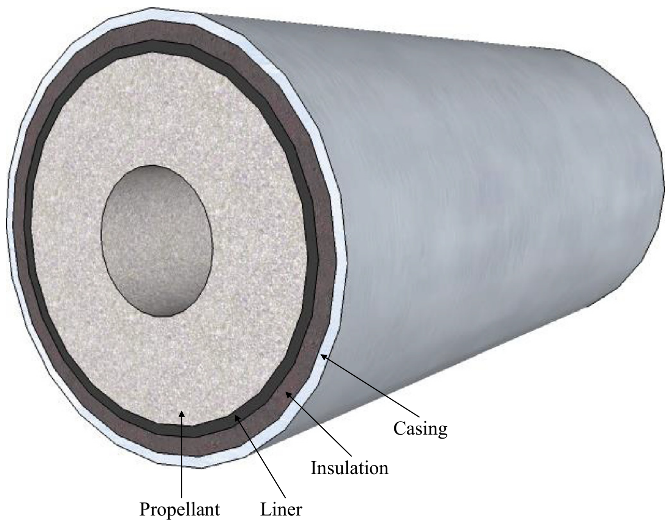

Fig. 1. Schematic model of a solid rocket motor.

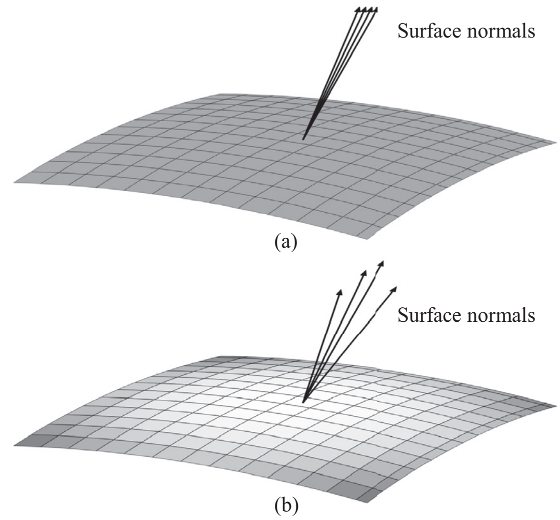

Fig. 2. Surface normals at a single point (a) without and (b) with specular reflection.

manufacture. Infrared thermography [7,13,14], finite element analysis [4,8,15–18] and digital image correlation [19–21] are widely used to evaluate interface debonding and strain in multilayer structures, and to detect displacements of solid propellant grains.

However, little research can be found on automated inspection of defects on the liner surface, before the loading of uncured propellant inside the casing. The main benefit of this activity is the quality improvement of the manufacturing process since it can avoid late identification of bonding defects. It should be noted that defect characterization after the rocket motor assembly, by techniques such as those just discussed, does not prevent the damage of the motor and the consequent financial losses for its rework.

Therefore, this paper proposes a computer vision based algorithm to assist the expert in detecting defective areas on the liner surface, before the loading of uncured propellant. The algorithm uses the photometric stereo technique [22] to minimize the specular reflection (highlights) generated by incident light on the insulation/liner surface, and the K-nearest neighbor (KNN) classifier [23] to detect defects on the liner surface.

Both techniques have some advantages over those mentioned earlier. Photometric stereo is an accepted technique for industrial inspection [24–27]. It can reveal defects on surfaces with varying degrees of specularity, as observed during testing with insulation/liner specimens.

In this paper, photometric stereo aims to recover surface information from test images, after removing their specular component. No additional filters are needed to improve the contrast between defective and nondefective areas because of the accuracy of the recovered surface information. This is a sufficient condition for the KNN classifier to be able to detect defects, with different shapes and sizes, on the liner surface.

Also, there is no need for speckle pattern comparisons or to apply stress to the test object. Moreover, photometric stereo allows the set up of a cost-effective hardware. Such algorithm features justify the choice of both techniques as a way of assisting the expert in the liner inspection and of increasing the reliability in the rocket motor manufacturing process.

The algorithm provides, primarily, resources for parameters setting, specular reflection treatment, and image color analysis. Its validation was achieved through experimental tests performed on a dedicated prototype.

The rest of this paper is organized as follows. Section 2 introduces the main concepts used in this work. Next, Section 3 presents two specimens of insulation coated with a thin liner overlay and the experimental setup. Section 4 describes the specular reflection treatment, the liner inspection algorithm, and the results. Finally, Section 5 synthesizes the conclusions of this work.

2. Theoretical background

2.1. Photometric stereo

The representation of three-dimensional surfaces by two-dimensional images relies on the effects of illumination, reflectance and relief properties of these surfaces. The appearance of an object can vary drastically depending on the lighting configuration, producing inaccurate results and making it difficult to correctly identify its characteristics, such as color and texture [28–30].

Among all methods which allow the recovery of three-dimensional shape information, photometric stereo, first introduced by Woodham [22] in 1980, aims to estimate the orientation and intensity (color) of surfaces from a few images of the same surface taken under different illumination directions but from the same point of view.

Considering that the image geometry remains unaltered, the correspondence between image pixels is known in advance. Thus, the intensity variation of these pixels results only from the surface orientation and the illumination direction. For a Lambertian or diffuse surface, image pixels intensities can be calculated by Eq. (1) [31,32]:

$$i(x, y) = \rho\lambda(\mathbf{n} \cdot \mathbf{l}) \tag{1}$$

where i represents the pixel intensity at coordinate (x, y), ρ is the albedo or surface reflection coefficient, λ is the light source strength, $\mathbf{n}$ is the unit normal vector, $\mathbf{l}$ is the unit illumination vector which points from the surface towards the light source, and "•" is the dot product symbol.

The normal vector indicates the surface orientation at a given point, while the albedo is the magnitude of this vector. The use of four images makes it possible to identify the presence or absence of specular reflection by comparing the variance among the recovered normal vectors [33–35].

Fig. 2(a) shows an example of a surface in which specular reflection at a single point (image pixel) is not significant, and therefore normal vectors do not exhibit expressive deviations. On the contrary, in Fig. 2(b), specular reflection is present for the corresponding pixel so that normal vectors have large variations.