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Thermal pattern generation for infrared deflectometry

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Abstract

Operating in the visible spectrum, the method of deflectometry provides reliable surface-slope measurements. We present the extension of the method to the thermal infrared (IR) spectrum, thus enabling the deflectometric inspection of rough surfaces and objects made of transparent and non-specular materials. Since affordable technologies to create code patterns in the thermal IR do not exist, we propose a novel method to produce large-scale dynamic thermal patterns with the help of a powerful laser. In addition, we adapted coded pattern techniques to our setup and present the results of deflectometric measurements.

Key words: deflectometry, surface-slope-measurement, thermal-infrared, laser.

Introduction

Non-destructive, no-contact inspection methods play an important role in industrial quality assurance. Among the variety of different methods, deflectometry is especially suited for specular or at least partially specular surfaces. The common methods such as stereo vision or structured lighting suffer from the lack of a Lambertian reflection while deflectometry requires at least some specular reflection to function.

Another feature that distinguishes deflectometry from the other methods of topological metrology is the direct access to the surface-slope instead of a 3D-point position. This makes the measurement particularly sensitive to changes in the surface incline, for example those induced by dents or defects in the paintwork. Moreover, a deflectometric inspection resembles the human perception of specular surfaces enabling thus the objective evaluation of e.g., aesthetic defects.

The necessity of a visible reflection restricts deflectometry primarily to polished or lacquered surfaces. However, this restriction does not apply to the long wave infrared (LWIR) spectrum. Surfaces amenable to deflectometric inspection in LWIR spectrum are often difficult for thermography applications due to their reflectivity such as bare metal surfaces.

First experiments with deflectometry in the thermal infrared spectrum have been conducted by Horbach et al. in [1]. They used a mechanically driven static stripe pattern to imitate a deflectometric code sequence. More recently, Sarosi et al. [2] investigated the applicability of one-shot deflectometry for the inspection of sheet metal. In [3] we demonstrated the benefit of thermal infrared deflectometry for the surface inspection of transparent materials. While all previous work relied on static patterns for position encoding, in this paper we present a new method to generate dynamic thermal patterns and acquire a complete deflectometric code sequence in the LWIR spectrum.

This paper starts with a brief introduction to the deflectometric measurement principle. After that we describe the optical effects specific the LWIR spectrum. Finally, we introduce our setup and conclude with the examples of measurements.

Deflectometry

A basic setup for the deflectometry consists of a camera and a display device used as a pattern generator, usually in the form of a monitor or a digital projector. The deflectometry exploits the fact that even slight changes in the surface slope create visible distortions in the reflected patterns. To obtain a quantitative measurement

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the display device shows a sequence of code patterns that uniquely encode every screen position on the device. After the camera observes the reflection of this sequence on the surface under inspection the decoding of the sequence yields a mapping between the camera pixels and the image points on the display device. Applying the law of reflection allows one to deduce the beam path between the camera and the display device (Fig. 1). The assumption of a nearly planar surface helps identify defects and locally reconstruct the regions of interest. Given the knowledge of the geometry of the setup, obtained from a prior calibration, it is possible to perform the global reconstruction from multiple measurements [4].

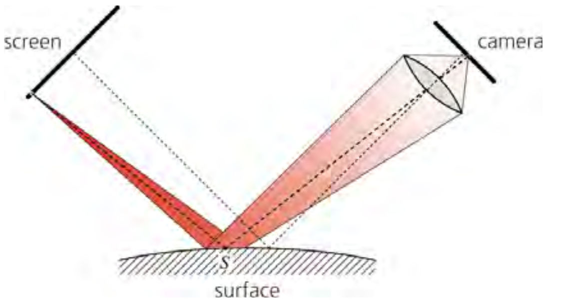

Fig. 1. Deflectometric principle: a camera observes the reflection of a screen on the surface under inspection. Changes in the surface incline lead to deviations of the beam path.

Optical properties in the IR spectrum

One reason to conduct deflectometry in the thermal IR spectrum is to exploit the different optical properties that many materials exhibit in this spectrum, most notably an increase in reflectivity. This effect is especially pronounced on metal surfaces (Fig. 2) and it benefits the deflectometric inspection of raw metal or machined metal parts. In the visible spectrum unpolished metals usually exhibit a dull reflection which blurs the image, whereas they demonstrate near mirror-like reflectivity in the LWIR spectrum [5].

Other materials which benefit from the change of the spectrum are transparent materials like glass or some plastics. Many effects in the visible spectrum such as multiple reflections or the visibility of the background behind the transparent object disturb the deflectometric measurement.

In the long wave infrared spectrum, however, many transparent materials appear opaque so that the predominant primary reflection enables a deflectometric measurement of the surface.

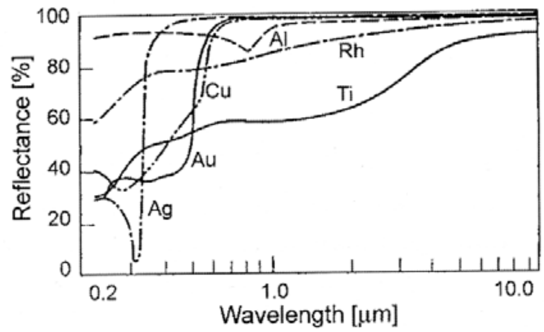

Fig. 2. Reflectance of metals for different wavelength. The reflectivity increases significantly towards the thermal infrared spectrum [5].

Light scattering on rough surfaces

Another beneficial effect for deflectometry is the connection between light scattering on rough surfaces and the wavelength of the incident light. It is known [6] that the amount of the specular reflection R on such surfaces increases with the wavelength λ. Expressions for the relation between reflectance and the root mean square roughness may be obtained by statistical treatment of the reflection of the electromagnetic radiation from a rough surface. Simplifying the full expression for a surface illuminated with a parallel beam of monochromatic light from Bennet et al. in [6], one finds:

$$\frac{R}{R_0} = e^{-(4\pi\sigma)^2/\lambda^2} + c\frac{\sigma^4}{\lambda^4}, \tag{1}$$

where R_0 is the specular reflectance of a perfectly smooth surface and σ denotes the root mean square roughness of the surface. The constant c combines, for simplification, the influence of the instrumental acceptance angle of the measurement and the root mean square slope of the profile of the surface. As can be seen from Eq. (1) the influence of σ decreases with increasing λ, which means that the specular reflection is obtained if the wavelength is significantly larger than the microstructure scale of the rough surface.

In the long wave infrared spectrum (8 - 14μm) a specular reflection is obtained for surfaces one order of magnitude more rough as compared to the visible spectrum (0.4 - 0.8μm) (Fig. 3). This effect allows for the application of the deflectometry even on surfaces which are, due to their roughness, non-specular in the visible light, but can be specular in the LWIR spectrum.

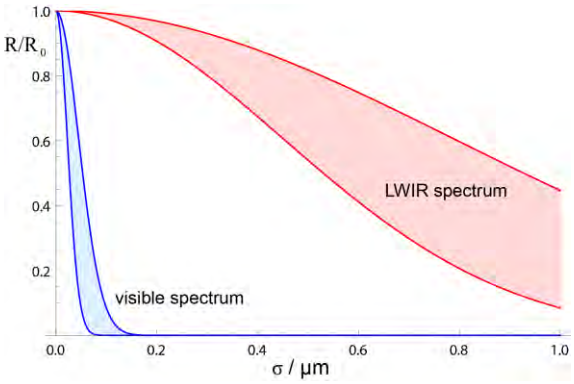

Fig. 3. The spectral range for a specular reflection in relationship to the root mean square roughness of the surface.

Dynamic thermal patterns

As described earlier, the basic components of a deflectometric setup are a camera and a display device. While the camera technology for infrared deflectometry is readily available, in form of thermal infrared cameras, there exists no appropriate display technology. The existing technology in this field is restricted to specialized military systems, designed to the test guided missiles and other thermal vision equipment [7]. Moreover, these image generators are directly coupled to the lens of the system under test and do not provide a display surface which would be necessary for a deflectometric setup.

Therefore, we developed a new method to create dynamic, large scale thermal patterns by using a powerful laser [8]. The basic idea is to create the patterns by using the laser beam to heat specific parts of a projection surface, which in turn serves as a display device. This allows us to create arbitrary two-dimensional patterns due to the high positioning speed of the laser beam. The temperature of an individual surface point here translates to the intensity of the corresponding image point in the pattern.

A general problem with the applications that involve heat transfer is the inertia of the process. Unlike conventional image display technologies for the visible spectrum, the switching times for thermal displays are limited by the time needed for to heat or cool down the display material. We assess the effect of the material thermal properties on the image formation by approximating this process with a model for irradiation on a semi-infinite solid to obtain an analytical solution [9, 10]. As we are only interested in the surface temperature of the solid we can simplify the equation for the increase in temperature T over time:

$$T(t) = 2 \cdot \frac{\alpha I \sqrt{\kappa}}{\lambda_{th}\sqrt{\pi}} \cdot \sqrt{t}\,, \qquad (2)$$

and for the cooling after an irradiation period t_L:

$$T(t) = 2 \cdot \frac{\alpha I \sqrt{\kappa}}{\lambda_{th}\sqrt{\pi}} \cdot \left(\sqrt{t} - \sqrt{t - t_L}\right), \qquad (3)$$

where I is the intensity of the irradiation, α the absorptivity of the surface, λ_{th} the thermal conductivity, and κ the thermal diffusity of the material. It is immediately evident that the dynamics of the both processes is governed by the same pre-factors and we cannot optimize the heating time without changing the cooling time equally. Additionally, from eq. (2) and (3) we can identify the previously mentioned properties as our relevant parameters when choosing the components for our setup. They impose constraints on the maximal possible refresh rate of the display.

Another difficulty is unintended thermal emission from the thermal display itself or its surroundings. As every electrical or mechanical device and even the human operator is a heat source, care has to be taken to avoid interference with the image acquisition. This is aggravated by fact that many materials are reflective for the thermal radiation - the reason we have chosen this spectrum - and therefore the materials and the positioning of the components for an infrared deflectometry setup have to be chosen carefully.

Pattern coding

The phase-shift and the binary coding are the most common techniques employed in deflectometric measurements. Both are time-multiplexing coding techniques, i.e. the code word is distributed over multiple images and thus over time. Given the short persistence of the thermal pattern it is not possible to create a full-sized code pattern of the size of our projection screen. When the laser has finished writing the pattern the greater part of it has already faded away (Fig. 6c). Therefore, we refrained from generating the whole pattern at one go and instead merged the video sequence of the writing process (Fig. 6d). This method is well-suited for binary images where we can obtain the merged image by applying a maximum-hold function to the image sequence. In this manner, binary coding techniques like gray-codes are easy to implement. Nevertheless, it is necessary to write several images for a complete code sequence.

The process of writing the image a line at a time suggests another way of position coding. Instead of using multiple images, the position is determined in a single pass of the writing process by observing the spot with the highest intensity in the reflection. As the position of the laser spot is known at each point in time we can use this information to encode the screen position. To speed this process up the camera captures per frame a whole written line instead of a single image point. By repeating this process in horizontal and vertical direction we can still encode every image point uniquely. This encoding technique, hereinafter referred to as *scancode* encoding, allows to encode the whole projection area in two passes.

Setup

We built a laboratory prototype for conducting infrared deflectometry with our method. The basic setup is similar to a setup for the visible spectrum with a camera which observes the distorted pattern of a display device on the surface under inspection (see Fig. 4). For our setup both components have been replaced with the equivalent components for the infrared spectrum.

For the image acquisition we use a thermal camera with a microbolometer sensor chip. The camera provides a resolution of 640 x 480 pixels and a temperature sensitivity of 30 mK NETD (*Noise Equivalent Temperature Difference*).

As even reflected laser radiation is able to damage the sensor chip the camera is equipped with a band elimination filter tuned to the laser wavelength.

Our aforementioned thermal infrared display device consists of a powerful laser and a projection surface.

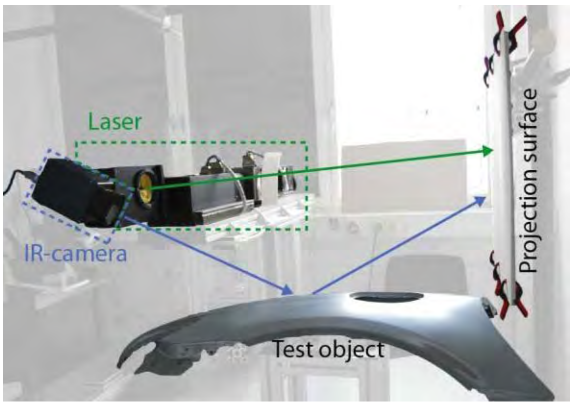

Fig. 4. Laboratory setup for the infrared deflectometry: a laser generates thermal patterns on a projection surface, while a camera observes the reflection in the surface under inspection.

We use a CO_2-laser with the maximum output power of 80 W and the wavelength of 10.6 µm. The mirror scanner positions the ray on the planar working area with the maximum dimensions of 1m x 1m and with a positioning speed of 10 m/s. The position, speed, and output power can be parametrized in a control program. The laser beam is first widened and then focused onto its working area. To avoid damage of the projection surface we set the focus point slightly behind the projection surface. This way we obtain a 4 mm wide beam for writing patterns and the beam energy is distributed more evenly.

For the projection screen a polyester fabric was chosen as material for two reasons. First, the plan for the future setup assumes that the projection surface is designed as conveyor belt. This enables us to write patterns continuously without having to wait for the material to cool down. Second, the material exhibits thermal properties that fit our application. It provides a low thermal conductivity, thus preventing fast diffusion of the thermal patterns. Additionally, the material has a rough surface structure. This structure is coarse enough to prevent specular reflections from other heat sources from overlaying the thermal emissions of the projection surface. The maximum temperature of the material should not exceed 100°C. We aim for a maximum temperature increase of 30°K for the thermal pattern so this is no practical restriction to our method.

Nevertheless, the thermal pattern fades away very quickly (see Fig. 5.) and it is necessary to compensate for that with an adapted pattern codification as mentioned before.

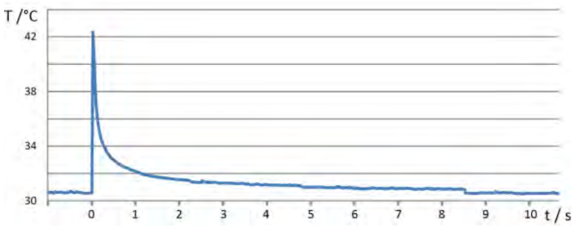

Fig. 5. Temperature profile of a surface point of the projection surface after laser irradiation (80 W output power, 2 m/s write speed).

Results

With our setup we conducted experiments on different metal surfaces, such as the car body panel in Fig. 6a. These surfaces are diffuse in the visible light, whereas the thermal infrared spectrum provides a specular reflection with much more contrast. We used the previously introduced scancode encoding and a pattern area with the dimensions of 400 mm x 400 mm.

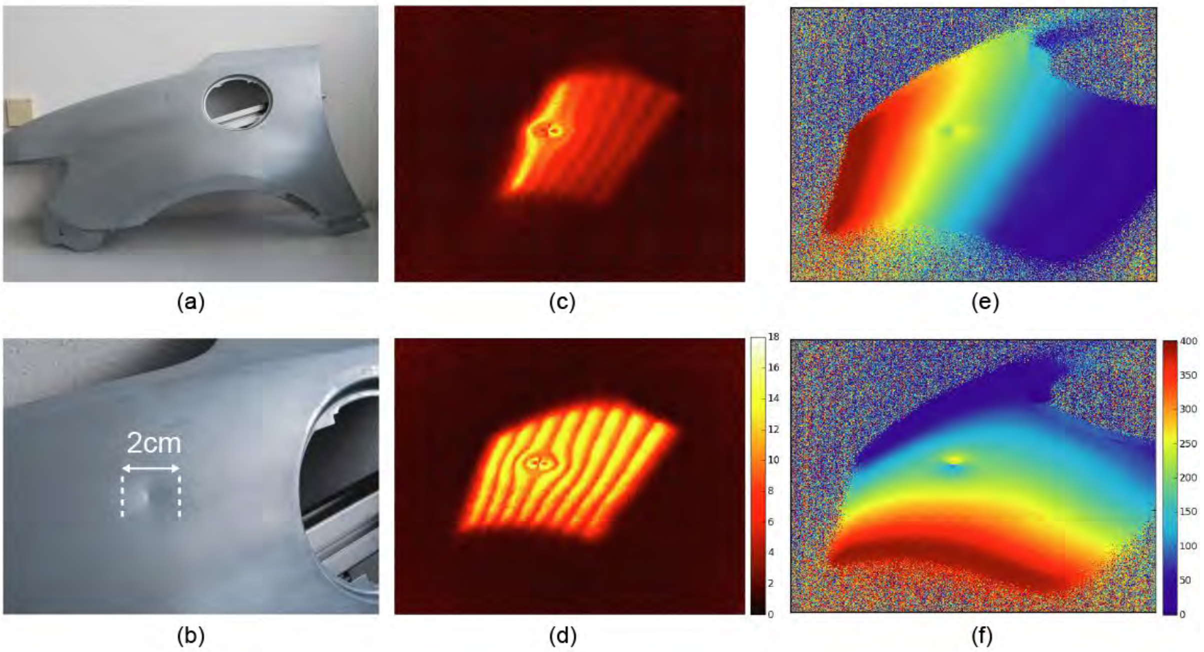

Fig. 6. Defect detection on a car body part: unpainted body panel (a) and a close up of a dent in the surface (b); (c) Single image while writing a gray code sequence and fused image (d) of a code image as measured temperature increase in Kelvin; Decoded scancode sequence in horizontal (e) and vertical (f) direction (the color indicates the reflected position from the display device in mm); In all images (c)-(f) the defect is clearly visible as a distortion in the code pattern or in the decoded positions.

The laser was configured to 80 W output power and a write speed of 2 m/s. This results in a 15°K increase in the surface temperature for the pattern, which gives us enough room to compensate for losses due to a low reflectivity of the surface. With a laser spot size of 4 mm it takes 20 seconds to write the entire pattern.

The sample parts exhibited defects and deformations up to 2 cm in lateral size (Fig. 6b). While these defects defy deflectometric inspection in the visible spectrum they are clearly visible in the thermal infrared. Fig. 6e and 6f show the result of a decoded scancode sequence representing lines and rows of the projection surface. These images show a mapping between the camera pixels and the screen positions as raw data of a deflectometric measurement. Scancode and adapted gray-code encoding yield virtually identical results, except that a gray-code sequence takes significantly longer to write.

The defects are already clearly visible in the raw data which proves the feasibility of a fully deflectometric measurement in the thermal infrared spectrum. Further processing would enable an automatic detection, classification or reconstruction of the defects.

Conclusion

We presented a new method for the dynamic generation of thermal patterns. It allows one for the first time to realize a full code sequence, necessary for deflectometric measurement in the thermal infrared spectrum. We demonstrated its applicability on practical samples by detecting defects on bare metal car body parts.

This new method enables the use of deflectometry for quality assurance in early stages of a production process. It allows for the deflectometric inspection of many unfinished surfaces which do not exhibit specular reflections in the visible spectrum.

Further development in this area will focus on different codification strategies and explore the applicability of different methods in the thermal infrared spectrum. Additionally, the established evaluation process for the deflectometric inspection in the visible spectrum has to be adapted for the thermal infrared spectrum. A geometric calibration for the setup is of particular interest as it is required for the reconstruction from deflectometric data.

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