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Dynamic deflectometry: A novel approach for the on-line reconstruction of specular freeform surfaces

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ABSTRACT

The dynamic inspection and reverse engineering of specular freeform surfaces is a challenge so far largely unsolved. Products produced in high quantities in industrial environments are still inspected manually which is labour intensive, expensive, monotonous and subjective. We propose a novel deflectometric hardware setup and methodology to overcome this shortfall. The reflection of a line laser from a moving specular surface is captured on a translucent screen. The resulting complex line provides detailed data about the surface gradients at the intersection of the laser light plane and the surface but cannot create correspondence between points of reflections and surface points. The latter is inherent in a traditional active light scanning setup whose data alone will, for specular surfaces, be subject to high levels of noise. We propose a novel method that by simulation of the reflection fuses the two data sets to allow digitalising moving specular surfaces with the high slope sensitivity of deflectometric methods.

1. Introduction

In today's highly demanding marketplace, quantitative analysis of goods during various stages of production is critical for ensuring that quality and productivity goals are being met by manufacturers. In many cases, modern machine vision technology provides a powerful approach for providing the reliable and stringent quality parameters that are required in real-time for closed loop control of the production. However, while vision based techniques for accurate measurement of 2D and 3D matte surfaces are relatively well developed, the inspection of specular (glossy) surfaces such as glass, metal or painted goods presents a more complicated problem. This is because they are themselves invisible to the observer and only a distorted version of the surroundings is visible in them. The dynamic inspection of such surfaces, when of any shape other than perfectly flat, can hardly be achieved using currently available machinery and methods.

Our research aims to help to close this gap. A novel system for the on-line reverse engineering of specular freeform surfaces is presented. It uses a line laser to scan a moving specular surface. The reflection of the surface is captured on a translucent screen that in turn is monitored by a CCD camera. The resulting line on the screen, that we have named specular signature, can take on highly complex shapes of virtually arbitrary nature but contains all the geometric information about the surface. Example signatures are shown in Figs. 6 and 10(d).

Its shape, more accurately its point-wise line centre position, is determined by the specular directions at the intersection of the surface and the laser light plane and hence by the surface normals. As any change in the surface normal will show double in the angle of reflection, even for small normal deviations a relatively large displacement of the signature will result. This makes the device very sensitive. Following the principle of deflectometry [1], two vectors on the surface can be used to compute the normal at that point. Here, these are the vector from the surface point to the centre of the employed line laser lens and the vector from the surface point to the point of reflection on the screen. However as a line laser is used, no correspondence can immediately be created between the single points of reflection and their respective origins on the surface. This problem is depicted in Fig. 1. It shows two identical signatures and two possible allocations of surface points to points of reflection along it. The two differing correspondences would result in entirely different surface normals.

We propose a methodology to create the true correspondence and successively compute the surface normals. This is achieved through fusing two datasets that are captured using two cameras. The proposed hardware setup is shown as a sketch and as a picture in Fig. 2. Camera 2 captures the specular signature whereas camera 1 monitors the Lambertian reflection of the laser line on the surface in a straight forward active light scanning (laser triangulation) process to produce a height map of the surface.

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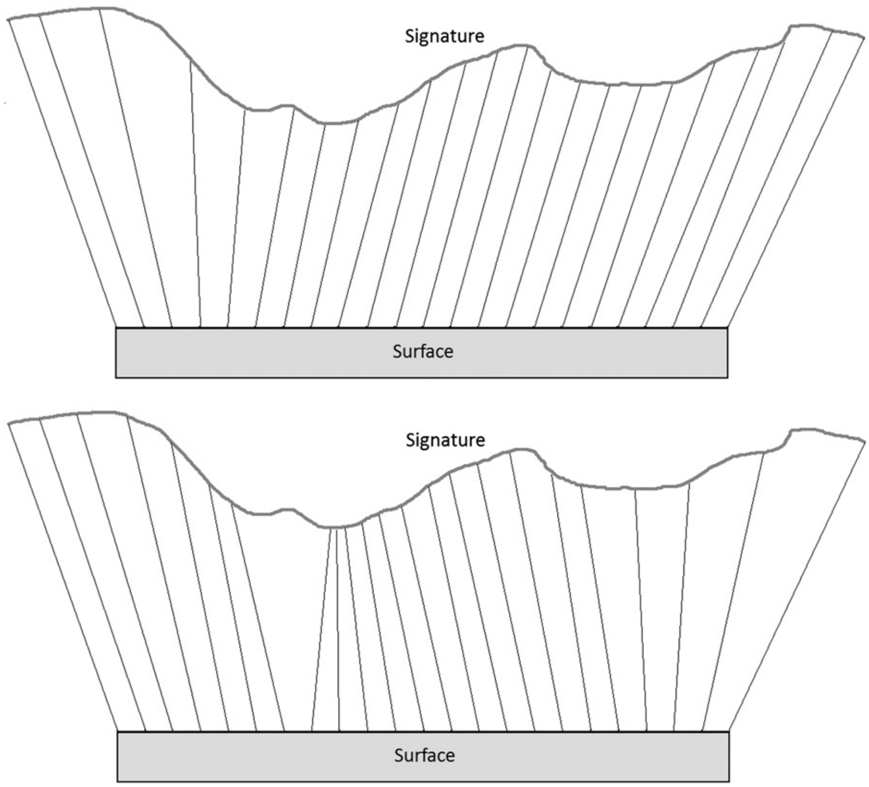

Fig. 1. Correspondence problem between surface points and associated points of reflection.

Due to the known problems of specular object inspection such as speckle noise or interreflections, this will however be very noisy. By low pass filtering however, a detail free, gross representation of the surface can be computed. From this in turn an equally detail free estimated specular signature, i.e. the signature that is to be expected from the resulting height profile, can be simulated via ray tracing methods. We show that this closely resembles the actual specular signature and only contains a lower level of detail.

The two signature sets are then merged and the sought after correspondence between surface points and points of reflection is created. With this at hand, surface normals can be computed using the accurate angular information of the actual signature. The result is an accurate surface bump map that can also be integrated to form an accurate height map. In this way, it is possible to digitalise specular objects in a fast and truly dynamic setup.

This paper will introduce this novel vision system and will outline its single steps of operation. These are shown in a flow chart in Fig. 3 and will be presented in the following. Section 3.1 will further introduce the principle and set it into context. Section 3.3 will describe the transformation of the Lambertian input image into the estimated signature as well as the merging of the signature sets and the re-triangulation of the surface normals. A crucial step is the extraction of the specular signature from the screen image. For this purpose we have developed a versatile line extraction algorithm that is described in Section 3.2 together with further possible methods of extraction. In Section 2 the current state of the art of both surface reconstruction and line extraction are presented.

A prototype demonstrator has been developed and assembled and extensive experimental results have been conducted. The results have been compared to ground truth data. This is presented in Section 4. For the experimental validation we use ceramic tiles as an example application as they are known to be very difficult to inspect [2] and are often used as a means to verify research results [3,4]. This is because of their variance in specularity, colour and reflectivity as well as the high quality demands put upon them. The presented method will however be directly applicable to a wide range of specular surfaces.

2. Related work

2.1. Surface reconstruction

Decades of research have resulted in a wide range of systems for the qualitative and quantitative inspection of Lambertian objects, both static and dynamic. Capabilities range from defect detection to surface reconstruction. Techniques include photometric stereo, passive stereo and laser triangulation/active light scanning methods. Photometric stereo is traditionally limited to static specimens although setups can be found that take all measurements virtually instantly [5] and dynamic photometric stereo setups also exist [6]. Research has also aimed to extend these techniques for the use on specular surfaces. In shape from shading the number of light sources has been increased [7,8] to provide at least three non-specular measurements for every surface point. In a similar manner, it has been proposed to increase the number of cameras in passive (binocular) stereo setups [9]. Specularity detection through colour or polarisation [10] has also been applied to both methods. These efforts however are still limited to the occurrence of minor specularities on primarily Lambertian objects and cannot work on fully specular ones. The same is true for active light scanning. While it probably is the most popular technique for Lambertian on-line inspection, speckle noise and interreflections permit an immediate transfer to specular objects. Both these problems have been tackled, for example through spacetime analysis [11] or identification of interreflections through colour [12] or polarisation [13] but so