Assessment of digital cameras for micro-structural sensing of low contrast surface features

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Abstract

Evaluation of three digital cameras are presented focusing on their capabilities and applicability in the detection of low-contrast surface features on the micrometer level. The key to a successful identification of surface flaws on micro-structured surfaces, such as silicon wafers is the ability to determine minor deviations in the reflectance of an object surface. Micro-topography of a surface, surface structure and surface roughness has a strong influence on the amount and direction of scattered light. Different portions of the surrounding illumination are reflected on different parts of an uneven surface, hence the resulting contrast-variation on the illuminated surface has a strong correlation to the surface structure itself.

In our work we discuss the possibilities of using either of the investigated cameras for the automated visual inspection of micro-structured surfaces. The cameras - two of them equipped with CCD and one with CMOS image sensors - are studied in an environment which is similar to standard surface appearance measurements, involving human observers. The specimens, featuring different surface structures are imaged in a well-controlled environment under varying illumination conditions. Experimental results of spatial resolution and contrast sensitivity are presented.

Keywords: surface quality, appearance, digital cameras, machine vision

1. Introduction

Engineers and industrialists increasingly recognize that the successful utilization of machine vision can provide solutions that will help them gain valuable insight into their manufacturing processes, optimize both product and process design, improve quality, reduce scrap, and improve product yield. A wide variety of vision inspection techniques are already in use for the determination of specific surface flaws in a range of industries, such as textiles, plastics, ceramics, machining, semiconductors, just to name a few. [1-6]

The rapid development of digital cameras and a continued reduction in computing costs may however provide a cost-effective alternative for automated surface inspection in a broad range of applications. Digital photography has gone through a considerable evolution during recent years, and as a consequence, high resolution cameras are nowadays available to anyone at an affordable price. A wide variety of different camera sensors and camera models are out on the market though. In this study we focus on three quite different digital cameras and their applicability for the detection of low-contrast surface features at the micrometer level.

2. Principle

2.1. Geometry of surface reflections

When a ray of incident light strikes the surface of a solid material three things can happen: it may be reflected, transmitted or absorbed by the material, and the reflected/transmitted light can be diffusely distributed in space or form a well directed beam. The distribution function that represents how much of the incident power coming from ($\phi_i, \theta_i$), see Fig. 1, is reflected in a certain direction ($\phi_r, \theta_r$) is called bidirectional reflectance distribution function (BRDF). [7] The physics behind the BRDF can be traced to the optical properties (refractive index) and roughness at different scales on the reflecting surface.

2.2. Surface reflection types

Considering the reflections that may occur at the surface we can differentiate two types of reflection, specular reflection and diffuse reflection. In case of specular reflection the incident light will immediately be reflected on the object surface in a way that the angle of reflection is equal and opposite to the angle of incidence. In the presence of diffuse reflection incident light rays, reflected from the surface are scattered in many directions. This is always the case whenever a beam of light rays strike a surface that is rough in comparison to the wavelength ($\lambda$) of the incident light.

Diffuse reflection can come from multiple surface reflections in a rough, faceted surface, as well as from edges, particles and microroughness at the top of the surface. The latter is referred to diffraction scattering from laterally small features (typically less than 25 $\lambda$ wide) and will add a veiling glare to a specular reflected beam. Subsurface interactions between the
light and the material itself is commonly responsible for spectral variation (i.e. the appearance of object colour), as the light that is not reflected at the surface penetrates into the material, undergoes multiple scattering and gets its spectral distribution modified by the absorption of the colourants.

Fig. 2 illustrates these reflection mechanisms, besides it also shows that even if the reflected light is scattered, the law of reflection applies to each individual ray, except for the diffraction scattering from laterally small features. It is the nature of the material, the wavelength of the incident light, and the scale of roughness of the illuminated surface which decides which mechanism will be the predominant one.

Intensity and spatial distribution of scattered light has a strong correlation with the surface structure. Light reflected from a microrough surface gets diffracted and scattered from the surface irregularities resulting in reflectance and transmittance distributions that are less peaked compared to that from a smooth surface. For this reason, at least in principle, it is possible to discriminate between sources of scattered light based on their respective effects on light scattering. Surface evaluation may therefore be optimized and limited to the detection of intensity variations, influenced by light scattering, caused by the surface detail of interest. [9]

Considering the fact that a rms surface roughness of 10 nm in the diffraction scatter region (surface spatial wavelengths of 0.5 – 15 µm) yields a 4% scatter loss [8] the technique of scatter detection by digital cameras can be sensitive to roughness levels of a few nm provided a camera contrast sensitivity of 0.5% can be achieved.

3. Experimental work

3.1. Cameras

Three digital camera models have been investigated in this study. The Philips PCVC740K TouCam Pro webcam and Fujifilm FinePix 6900Z are equipped with CCD sensors having 640x480 and 2048x1536 effective pixels respectively. The Canon 10D camera has a CMOS sensor with 3072x2048 effective pixels. Of particular interest in this study is the ability of the camera sensors to repeat their sensed intensity in a tight interval, proving that low contrast variations imaged from a test object come from the object and not from noise fluctuations of the sensor elements in the camera.

3.2. Experimental setup

For the assessment of the low contrast sensitivity we used well characterised paper samples. The digital camera under test was positioned at \( \theta_1=60^\circ \) angle of detection (see Fig. 3), and a well-controlled light-flux illuminated the sample from the opposite direction at \( \theta_2=45^\circ \). To achieve a constant, flicker-free illumination of the sample we used a point light source, a 3200K tungsten halogen capsule with a nominal power of 20W, operated from a well stabilised DC power supply.

The arrangement of the light source and the camera is based on the recommendations of the ISO 3664:2000 standard and the ASTM standards for color and appearance measurement. [10-12] In order to block any surrounding illumination and ensure a stable environment, the entire setup was surrounded by black absorbing surfaces. During the experiments sample illumination was varied by controlling the amount of electric current flowing through the filament of the lamp.

To record the actual illumination of the sample, a UDT Model 81 photometer was positioned in close vicinity of the camera in a baffled housing. Hence illuminance-detection was narrowed to the very central area of each inspected sample.

A stable geometry was preserved by adjusting exposure times and aperture settings remotely. The images were always taken by using the highest resolution available, and by using no image compression. Color information of the images was of no importance in this study, therefore 8-bit, respectively 12-bit grayscale images served as a basis of the evaluation.

3.3. Specimens and experimental method

The first objective was to measure the cameras response to small changes in the illumination, by using a uniform white paper as object. To further make the images uniform, the cameras were defocused, by setting the focus at infinity. Using the photometer data we raised the illumination level by 4\( \times 10^{-3} \) lux (appr. 0.25%) steps from 0.140 lux to 0.155 lux and at each step we took an image of the sample. Then we evaluated the acquired images by choosing and comparing the same pixels in each of the images.

At the second stage we focused the cameras on the centre of the paper surface and repeated the experiment, using the same steps in the illumination between 0.147 lux and 0.159 lux. The main difference between the first, defocused and the focused series was that during the second set of exposures tiny surface-structures were also represented in the images in the form of intensity-variation in the scattering pattern from micrometer-sized surface features.

Finally we imaged black printed paper specimens featuring both, highly gloss and uniformly matte surfaces to study the effects of different scattering properties on the most sensitive camera of the three, the Canon 10D.

3.4. Non-linearity of the cameras input/output

Human vision has a logarithmic perceptual response to luminance, and although CCD and CMOS sensors give a linear response to light intensity, cameras automatically “correct” the acquired images for the
nonlinearity of the eye to achieve the desirable visual experience.

While this gamma-correction is preferable for the human eye, it also implies that nonlinearity occurs between the illuminance-values recorded by the photometer and the camera sensors. Fig. 4 shows this nonlinearity between image brightness of the same pixel (recorded by the Fujifilm 6900Z with the exposure time and aperture settings held constant) and the measured illumination of the sample.

The diagram also shows that in case of small variations in illumination a linear approximation is a satisfactory estimate. However, in case of high-dynamic range scenes a linearization process prior to evaluation becomes necessary.

4. Results and Discussion

The spatial resolution obtainable on the sample is determined by the resolution of the camera sensors, the camera to sample distance and the focal length of the camera lens.

Due to the tilted geometry between the camera axis and the specimen, the highest resolution of the sample surface could be achieved in horizontal direction on the image sensors: 62 \( \mu \)m/pixel on both the Fujifilm 6900Z and the Philips webcam, and 40 \( \mu \)m/pixel on the Canon 10D. The smallest feature to be resolved on a surface is however not only a function of spatial resolution, but also the contrast sensitivity of the sensors, which we now will address.

4.1. White paper specimens

Fig 5. represents the experimental results on our white paper specimens. The diagrams show how each camera responded to the small changes in the general illumination of the sample. The vertical axis show the measured illumination, while the obtained brightness levels at the same pixels in the middle of each image are shown on the horizontal scales.

It is apparent that the contrast sensitivity of the inspected cameras differed markedly. On the defocused images the Philips camera required at least 3-4% increments in the absolute level of surface illumination in order to reliably detect any contrast difference. The construction restraints of the Fujifilm 6900Z camera (i.e. the limited number of images that were possible to take without physically removing the camera) did not allow us to evaluate a higher number of images. The Fujifilm 6900Z was capable of detecting appr. 1% increments in the illumination. The Canon 10D had undoubtedly the highest contrast sensitivity of the three inspected cameras and could successfully resolve 0.5% increments in the surface illuminance.

The comparison between the defocused and the focused image series showed that in case of focused images the cameras sensitivity to contrast variation was remarkably lower. The reasons were likely to be twofold. First, the increased dynamic range of the scene to be captured, as, because of the limited dynamic resolution, fine details in illumination variation could not be resolved by the camera sensors anymore. The other reason might have been veiling glare, when stray light bouncing off various points inside the lens and the cameras effectively suppress local contrast differences.

4.2. Black paper specimens

Due to their different surface microtopography these two specimens had diverse scattering properties – mostly specular reflection occurred on the glossy sample and diffuse reflection on the matte sample. Therefore the recorded illuminance was also different, even though absolute luminous intensity was the same for both samples. Since the photodetectors field of view was off the specular peak, approximately 50 percent lower illuminance was measured on the glossy sample than on the matte sample, which coincides well with the...
brightness levels, measured by the CMOS sensor. The results from the analyses are shown on Fig. 6.

![Fig. 6 Results of detected brightness under varying illumination conditions on a) matte and b) glossy surface](image)

Each step between two illumination levels on the vertical scales corresponds to a 0.5% increment in the luminous intensity, while the brightness levels indicate how much brightness a certain camera pixel recorded under such illumination conditions.

Our tests on the black paper specimens demonstrated how large impact different surface microtopography have on the cameras contrast threshold. In case of the glossy sample the threshold of the Canon 10D was surprisingly high – no significant brightness change was detected unless the illumination of the sample was raised by at least 5 percent. In case of the matte sample the sensitivity was slightly higher, however, the camera sensor still did not detect any significant changes as long as the changes in absolute illumination level remained under 2 percent.

6. Conclusion

We compared the contrast sensitivity of three digital cameras by imaging specimens featuring various surface microtopography. The investigation showed that each of the inspected cameras suffered from the drawbacks of their limited dynamic resolution. Dynamic range of the imaged surfaces had to be kept very low in order to be able to detect contrast changes extending to only a few percent of the general illumination. However, the reduction of dynamic range is usually not a viable alternative in real-life surface inspections. Therefore higher contrast sensitivity would be required to make a correct judgment of small intensity variations on an object surface.

Automatic gamma-correction of the Fujifilm 6900Z and the Philips cameras was an additional drawback, as equal steps in the illumination were resolved only at a certain part of the whole dynamic range. Similar surface features could therefore be detected at one end of the brightness scale, and missed at the other. Because of these concerns neither of these cameras are suitable for automatized surface inspection of demanding samples.

The relatively low contrast threshold of the Canon 10D camera, the 12-bit dynamic resolution, and the possibility to record images without any post-processing on the other hand suggests that it might a be suitable solution for the need of the industry inspection. The 40 µm/pixel resolution is certainly insufficient for the inspection of tiny microcomponents, however, spatial resolution can easily be improved, either by using higher magnification objectives, or simply moving the camera closer to the object. In case of static scenes even the camera’s limited dynamic range can be circumvented by taking two or more images of the same scene, using different exposure settings.

Therefore, as a direct continuation of this work a further series of tests will be conducted in order to investigate the highest obtainable dynamic resolutions of the Canon 10D camera.

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References