

SPATIALLY RESOLVED DETERMINATION OF SOIL LAYER THICKNESS ON SURFACES OF 3D PARTS BY MEASURING THE FLUORESCENCE INTENSITY

André Boye^{1*}, Hannes Köhler², Roman Murcek², Enrico Fuchs²,
Marc Mauermann¹, Jens-Peter Majschak^{1,2}

¹Fraunhofer IVV, Branch Lab for Processing Machinery and Packaging Technology AVV Dresden,
Heidelberger Str. 20, 01189 Dresden, Germany

²Technische Universität Dresden, Faculty of Mechanical Science and Engineering, Institute of Processing
Machines and Mobile Machines, Bergstr. 120, 01069 Dresden, Germany

*e-mail: andre.boye@avv.fraunhofer.de

Abstract

The spatially resolved measurement of the soil layer thickness on surfaces is a precondition for quantitative cleanability tests of 3D parts which are important for the investigation, optimization and validation of spray cleaning systems.

In this paper a photogrammetric analysis method is investigated which uses the luminescence intensity as an amount for the layer thickness of a luminescent test soil. The luminescence signal is emitted by a tracer that is admixed to the layer substance and excited with a UV lamp. By using 3d parts various factors influence the measured brightness from which it shall be concluded on the layer thickness. In this paper the influences of these parameters are determined and subsequently they are mathematically described.

An experimental set up in which each parameter can be varied independently from the others was built to survey these parameters. The influence of the tracer was also regarded - water-soluble fluorescein and non-water-soluble zinc sulfide crystals were investigated. Afterwards the mathematical descriptions were combined in one formula. With that and a calibration it was possible to compute the layer thickness out of the measured local brightness and the corresponding parameters by the knowledge of geometrical data.

This procedure was verified in an experimental environment and checked for its suitability. Finally the method was tested for the application to curved surfaces.

Key words: Surface hygiene, Cleanability, Soil, Layer thickness, Cleaning test, Fluorescence.

1. Introduction

Nowadays, food processing machines are often delivered with automated cleaning systems because of the repeatability and the possibility to verify them. For open systems there doesn't exist any large-scale cleanability test but only wetting tests based on the VDMA [1]. These wetting tests make only the decision whether an area is reached of the cleaning fluid or not. They say nothing about the locally existing cleaning efficiency which is important to know for the assessment of cleaning systems. Because of this, the whole food sector is interested in having a standardized industrial cleanability test. In this context, recent researches have shown that a defined soiling of complex parts or machines isn't realizable. So, the measurement of the distribution of the soil layer thickness is a precondition for the development of a quantitative cleanability test. Such a measuring method has to be non-destructive, contactless and applicable for large-scale devices. With these demands, only a photogrammetric method seems useful. Thereby, researches have been done by [2] and [3] in regard to the characterization of liquid falling films. Furthermore [4], [5] and [6] investigated the time-resolved cleanability of small 2D surfaces where the residual soil was calculated by the detected fluorescent brightness of the excited soil. Hereby, it was shown for a test soil consisting of starch and zinc sulfide crystals that the fluorescence intensity depends on the layer thickness. Based on these investigations a new photogrammetric method was developed for determining the distribution of the soil layer surface mass on 3D parts. A precondition for this was to identify the several influencing parameters and bring them together in one separate equation.

2. Materials and Methods

Detection Principle

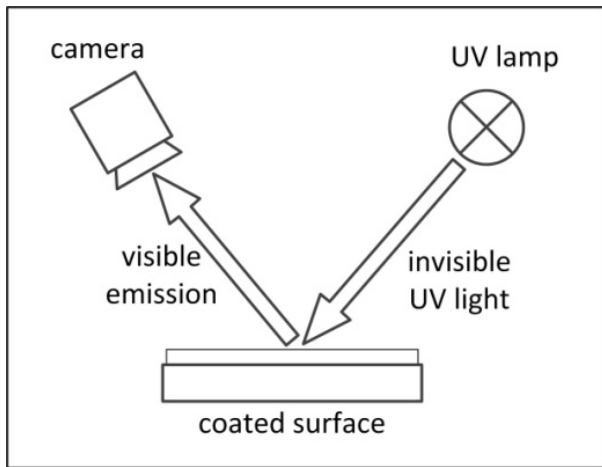


Figure 1. Principle for the detection of fluorescent layers

In Figure 1 the basic principle of soil detection is shown. The luminescent layer is excited by a constant radiation of an UV lamp. As a result, it emits visible light which is detected by a CCD camera. The measured intensity is converted into an equivalent grey-scale value by the camera. Thereby, scientific studies have been shown that the intensity depends on the layer thickness [6, 7, 8, and 9]. Unfortunately, for 3D treatments there are more influencing parameters which have to be considered. So, these several effects on the detected intensity have to be determined for giving good estimations for the layer thickness.

Test Rig

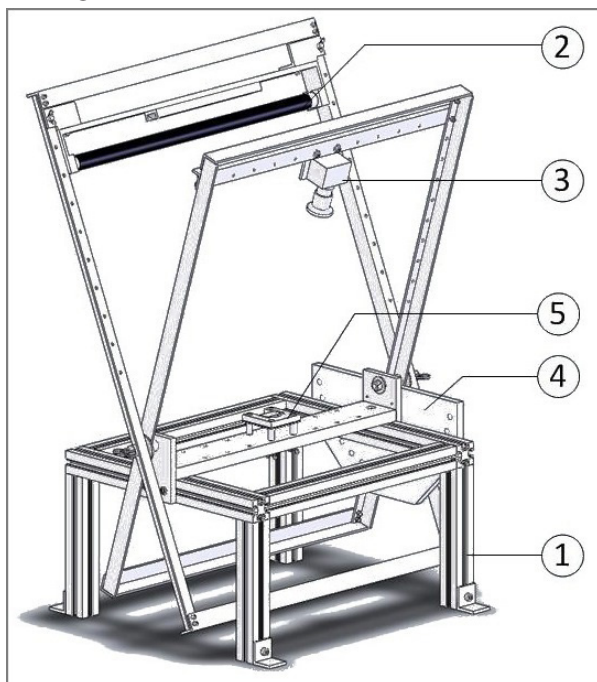


Figure 2. Test rig: 1 – base frame, 2 – UV lamp, 3 – camera, 4 – angle plate, 5 – sample holder

The test rig (Figure 2) consists of a *base frame* (1) with two wings on which the *UV lamp* (2, Phillips TLD 18W Blacklight blue) and the *camera* (3, Matrix Vision mvBlueCOUGAR-X) are installed. Both wings can be clamped in defined positions with the *angle plate* (4). In the middle, there is the *sample holder* (5) on which the samples (soiled stainless steel plates in the dimension 20 x 40 mm²) or a UV sensor (Ahlborn Radiation probe FLA 623 x) can be fixed.

Sample Preparation

To gain reliable results, it is important to provide a defined and even coating on the samples. For that, two different methods were used depending on the used coating substance. First one, a starch-fluorescein soil matrix was prepared and applied like described in [6].

On the other hand, a model soil consisting of xanthan (0.5% w/v, dissolved in distilled water) and zinc sulfide crystals (3% w/v) was used. It was applied to the sample surfaces by using a very fine spray which was spread evenly on the surface. The layer thickness was varied by spraying multiple times over the test coupons.

For both coating methods the resulting layer thickness was unknown. Because of that, the test coupons were weighed before and after the coating. Thus, the surface mass could be determined which is direct connected to the soil layer thickness.

The used plates consisted of untreated stainless steel.

3. Results and Discussion

All regarded several effects were investigated and evaluated for both tracers (fluorescein and zinc sulfide crystals).

Effect of Soil Layer Thickness

The soil layer thickness is the command variable of the presented investigations but an adequate method for compared measurements was missing. So, in this paper the surface mass was used instead due to its direct proportional relation to the layer thickness. This replacement is valid for a constant density and a homogeneous layer. By using the described soiling method these requirements were fulfilled for the small test coupons.

In Figure 3, the results for the grey value depending on the surface mass are shown.

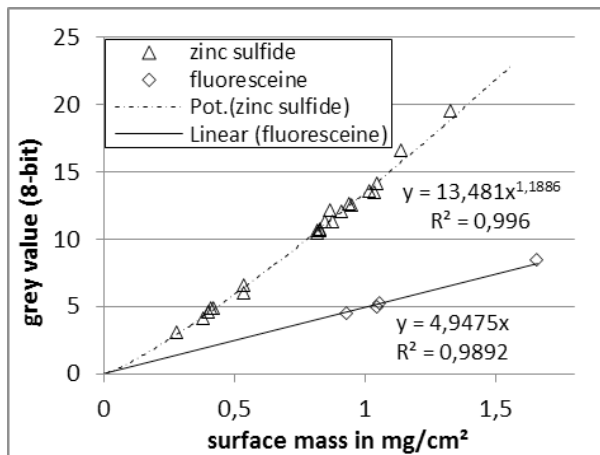


Figure 3. Influence of the surface mass on the measured grey value

For fluorescein, an expected linear dependency between surface mass and grey value was detected. This comes along with findings by other authors [4, 6]. In contrast to that, the zinc sulfide tracer showed a light exponential behavior. A possible reason for this phenomenon could be the interference of the spectrums for excitation and emission. In this case, proximate zinc sulfide crystals excite each other and if there are more luminescent particles (thick soil layer), the basic brightness of the whole layer is much higher and finally there is a secondary exciting source. The reduction of the emitted intensity due to the Beer-Lambert law should not have to be regarded because of the very thin layers in the μm -range.

Effect of Lamp Position

The positioning of the lamp has a high impact on the detected fluorescence intensity. Thereby, this main influence can be divided in the two factors *distance between lamp and surface* and *angle of incidence onto the surface*. For the investigations the lamp distance was varied between 100 mm and 500 mm and the UV intensity onto the surface was measured by the UV sensor.

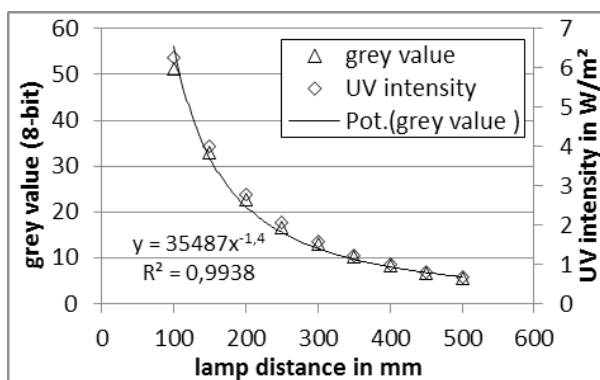


Figure 4. Influence of the lamp distance on the UV intensity and the grey value

The tests (Figure 4) showed a non-linear effect of the lamp distance on the UV intensity (measured by the UV sensor) and in the same way on the grey value (detected by the camera). In this case, it was possible to approximate this relation by an exponential function with a negative exponent.

Furthermore, it was established that the effect of the lamp distance is independent of the angle of incidence. Every angle setting results in the same calculated exponent for the approximated function. Additionally, the different tracers - fluorescein and zinc sulfide crystals - showed also identical behavior.

In the diagrams of Figure 5 and Figure 6 the influence of the angle of incidence is pointed out. This parameter was adjusted between 0° (orthogonal to the surface) and 80° . Unfortunately, both used tracers showed different and very complex behaviors.

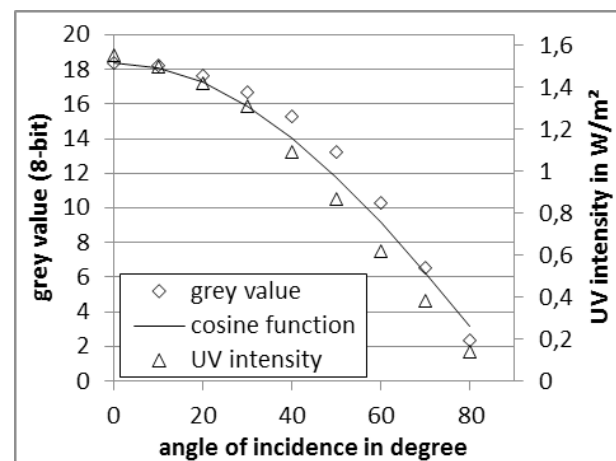


Figure 5. Influence of the angle of incidence on the UV intensity and the grey value for fluorescein

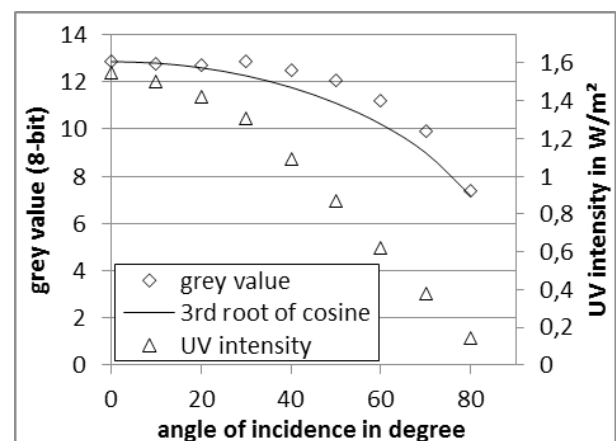


Figure 6. Influence of the angle of incidence on the UV intensity and the grey value for zinc sulfide crystals

For the water-soluble fluorescein (Figure 5) a cosine function could be chosen for an adequate approximation of lamp angle effects. The usage of the cosine function is justified by trigonometrically relations by calculating the projected surface. This one is equal to the sample surface for 0° and 0 for 90° .

The higher decreased UV intensity for increasing angles compared to the detected grey value is based on the characteristic of the UV sensor which should be used normally for orthogonal measurements.

For the zinc sulfide tracer (Figure 6), the cosine doesn't give a good approximation because the tracer shows a constant light emission from 0° to 30°. This phenomenon is explainable with the shape and relatively big size of the non-soluble luminescent particles for which it is assumed that they jut out from the soil layer surface. By using different angles of light incidence, there are only different areas of the single particles which are excited by the UV light. The size of these areas is the same. This is running up to the limit of about 30°. Above this value the shadows due to neighboring crystals raise up and the excitation rate of each particle decrease.

Finally, an approximation consisting of the third root of the cosine was chosen because it fitted reasonably well and a better physical model wasn't found.

Effect of Camera Position

The three parameters *distance of the camera*, *camera angle* and *sample shift out of the camera axis* were investigated to determine the effects of the camera position.

The camera distance was varied between 100 mm and 420 mm for different camera angles. Thereby, a nearly constant grey value was detected by the camera. So, it was pointed out that the distance of the camera to the surface hasn't to be considered for the tested range of distances.

The influence of the camera angle was investigated between 0° and 80°. The tracers showed a very different behavior for this (Figure 7 and Figure 8) but for both tracers the detected relations were independent from camera distance.

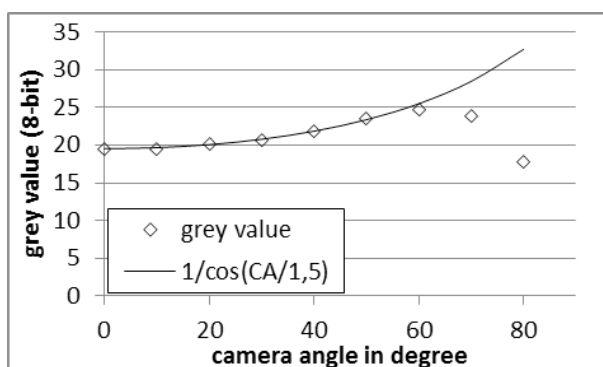


Figure 7. Influence of the camera angle on the grey value for fluorescein

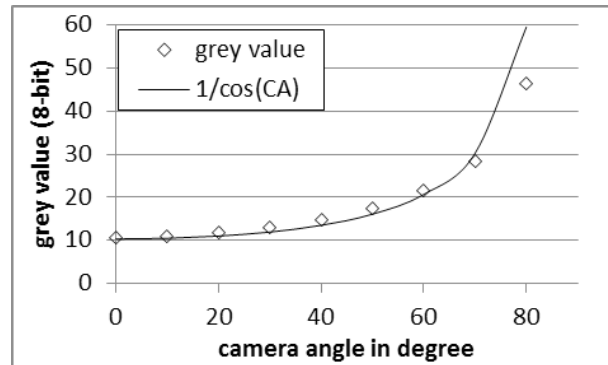


Figure 8. Influence of the camera angle (CA) on the grey value for zinc sulfide crystals

In contrast to the zinc sulfide tracer, the curve of fluorescein shows only a slight increase at the beginning with a rapid downfall at the end (Figure 7). The slight increase can be explained by the higher detected layer thickness due to angles of view not equal to 0°. For the heavy decrease of the curve over 60° it can be assumed that it depends on total reflections into the soil layer. This thesis is also confirmed by the knowledge about general critical angles for the existing of total reflection which are between 40° and 60° on the border from solid or fluid substrates to air. The detected physical phenomenon also shows that there must be refraction of the rays going out of the soil into the air. Because of this and for giving an adequate approximation of the fluorescein curve, it is important to consider the refraction angle. In this case, it was calculated relatively by knowing that at the critical point of 60° an angle of 90° was obtained (total reflection). Thus, the measured grey values can be approximated by the inverse cosine function between 0° and 60° of the angle of view.

For the zinc sulfide tracer (Figure 8), a highly non-linear increase of the grey value was noticed by raising the camera angle. An inverse cosine function leads to a good approximation which can also be explained with the projected surface and its trigonometrically relations to the sample surface. In detail, every luminescent particle of the soil can be assumed as a single light source which emits in all directions. So, if the angle of view increases and consequently the projected surface decreases, the luminous intensity per area raises up. In other words, if the projected surface decreases, you see the same amount of luminescent particles in a smaller section. The presented estimation works quite good for angles until 70°. For higher angles, the shadows of neighboring particles become a significant influence.

The influences due to the shift of the samples out of the camera middle axis could be considered by a camera calibration step involving vignetting corrections etc. After this there was no further effect of this parameter detectable.

Model for Determination the Surface Mass

The obtained single parameters have to be fitted in one main model for determining the surface mass for plane surfaces.

In a first step the several effects were combined by multiplication to receive the grey value GV . This seemed applicable because no combined effects were found out in the presented investigations.

$$GV = GV_0 * E_{SW} * E_{LP} * E_{CA}$$

In this formula, GV_0 means the reference grey value which depends on the soil layer characteristics, the UV lamp power and the camera settings which are used for calibrating the system. The other factors are the surface mass (E_{SW}), lamp position (E_{LP}) and camera angle (E_{CA}) which are determined by measuring their single effects like described before. The insertion of the factor of surface mass leads to:

$$GV_{zinc\ sulfide} = GV_0 * \left(\frac{SW}{SW_0}\right)^{1,15} * E_{LP} * E_{CA}$$

$$GV_{fluorescein} = GV_0 * \frac{SW}{SW_0} * E_{LP} * E_{CA}$$

Thereby, SW stands for soil weight (surface mass) and the index 0 for the calibration step. To obtain the resulting soil layer thickness, the equations have only to be transformed to SW and with knowledge about the density of the soil layer, it can be calculated.

The main schedule for measuring the layer thickness is summarized in Figure 9.

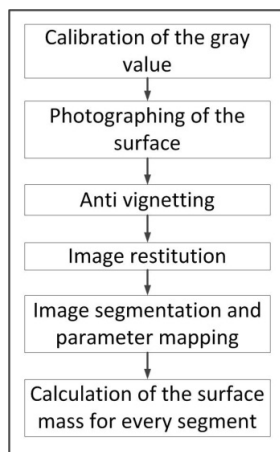


Figure 9. Schedule for the measurement of the surface mass spreading

Verification on plane Surfaces

The verification on plane surfaces was firstly done in the developed test rig with the test soil containing zinc sulfide crystals. Therefore, a mosaic consisting of a huge number of the standard sample plates with different soil weights was used instead of only one single sample. For this test, the average failure was 9%.

A secondary verification was done in a real cleaning test rig. This was the washing cabin of the Fraunhofer AVV which is described by [10]. For determining the real soil weight, the small standard test coupons were also used but clamped onto a plate (500 mm x 500 mm). The received curve comparing the real and the detected/ calculated soil weight is shown on Figure 10. These investigations led to the same result as seen before. The average failure was nearly 9% which is quite good considering the very thin layers.

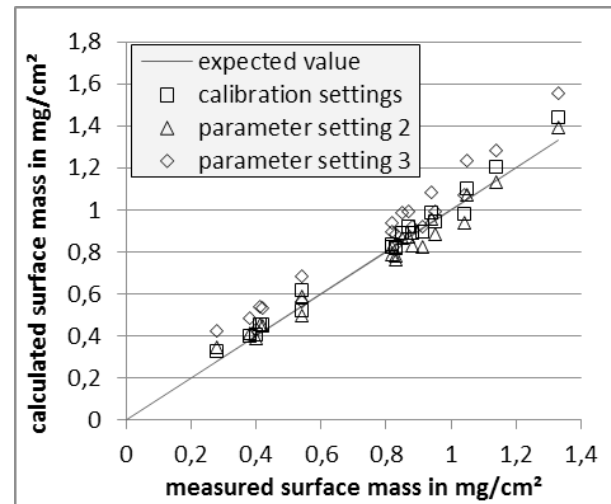


Figure 10. Verification of the method in a real cleaning test rig

4. Conclusions

- This paper shows that it is possible to detect the layer thickness of luminescent soils if the geometrical data is available. Furthermore, the present work provides a schedule for using the new method including how to do the calibration step. Thereby, an average failure of 9% with closely distributed test results was achieved by verification of the approach in the developed test rig and in an industry-related washing cabin.
- In this context, the single effects of the several influencing parameters could be quantified pointed out and combined in one model for calculating the surface mass with an optical system.
- As an outlook, current investigations with convex shapes seem to show that the presented method can also be used for such curved surfaces by knowing the surface normals of every point. Maybe, a critical point in the future can be reflections in concave devices or inner edges.
- With this paper, a further step is done towards a currently missing quantitative industrial cleanliness test.

Acknowledgement

Supported by:



on the basis of a decision
by the German Bundestag

5. References

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