Development of a simple device for the evaluation of the UV-C reflectivity of construction materials and coatings under application conditions.

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This work was completed based on a private initiative and follows the idea of other projects from „Makers“ to help protecting and improving public health in a collective effort during the COVID-19 pandemic.[1]

Introduction

In the situation of a pandemic it becomes evident that surfaces and objects which are touched or handled by multiple individuals can be a root cause for transmitting germs and spreading of an infection. To prevent a transmission of germs via surfaces it is common to apply disinfecting agents frequently in between uses of the objects. Providing those agents can be a cost factor, especially in peak times of a pandemic when supply is short. Also, they need to be constantly replenished and produce waste (e.g. disinfecting wipes and their containers).

Another way of routinely disinfecting „multi-user objects“ (e.g. shopping carts or baskets) during down-times (in between uses) could be the exposure to antimicrobial UV-C radiation. The advances in semiconductor development and large scale manufacturing make UV-C LEDs readily available at a low price.

UV-C Sterilization

For the efficient UV-C sterilization of a real life object a sufficient radiation dose will be required at all positions of the object that might be touched. As it is very hard to realize a 360° coverage of direct irradiation of a complex object one needs to apply smart engineering of the disinfecting chamber geometry and selection of the reflecting material.[2]

While one way to quantify the suitability of a sterilization chamber wall material or coating could be a well-defined and exactly measured reflectivity value in a simple UV-C source -> surface -> detector geometry, one might also choose a more pragmatic approach to allow or screen realistically occurring irradiation scenarios. As a matter of fact, a 100% direct reflection might not always cause the biggest effect in a real world scenario. People who do winter sports without sunglasses might become snow-blind, not because the slope is a mirror but because fresh snow is a highly efficient, diffuse reflector of sunlight. Turner and Parisi studied the UV reflectivity of metal surfaces and its biological impact using the Albedo, a unitless measure between 0 and 1.[3] While snow can be a perfect UV reflector with an Albedo close to 1, metal surfaces which would appear „shiny“ indicating a high reflectivity have an Albedo value of only 0.2-0.3.

Studying the antimicrobial effect of UV-C radiation using one UV source in an environment of objects to be disinfected (patient compartment of an ambulance) rather than one object in a dedicated sterilization chamber Lindsley et al. found a significant influence of the surface reflectivity.[4] The true efficiency of a reflective coating will be hard to quantify using a simple physical value in such a complex scenario. Consequently, we did not consider a well defined reflectivity scan geometry like in a Eulerean cradle mandatory for the characterization and identification of well-suited reflective materials or coatings for UV-C sterilization equipment.

Design of the UV-Reflectometer

For the purpose of evaluating the suitability of („wall“-) materials and coatings of UV-C sterilization equipment we developed a simple, cheap and 100% open source device using a UV-C LED module and a schottky diode based UV-C sensor module.

While the UV-C diodes are comparatively weak (compared to higher power UV tube lamps) and would require a longer irradiation time for efficient sterilization they are still commonly used in low-cost sterilization equipment and have the potential to allow a broad adaption of UV-C sterilization in every-day applications. The use of weak UV-C diodes in combination with a fully enclosed chamber and a safety mechanism which will switch on the UV-C diodes only if the test panels cover the openings of the chamber, this device is a cheap but safe solution for the purpose.

The UV-Reflectometer has a housing that was designed using the free 3D design platform TINKERCAD[5] and then 3D printed using a PRUSA i3 MK3S printer. The housing has a compartment for the UV source, UV sensor and test panels as well as a compartment for the circuit boards and control

unit. The geometry of the UV source, sensor and reflective panels allows for direct reflection from the UV source (lower panel) as well as indirect reflection (upper panel).
The principle of the device is to scan the UV intensity caused by reflection from different angels by tilting the sensor carrier over a total range of 200° covering the entire 180° hemisphere of the two reflecting panels plus 10° on both ends of the scan range.
Fig. 1 shows the geometry of the UV-Reflectometer chamber illustrating the path of the UV light from source to sensor.

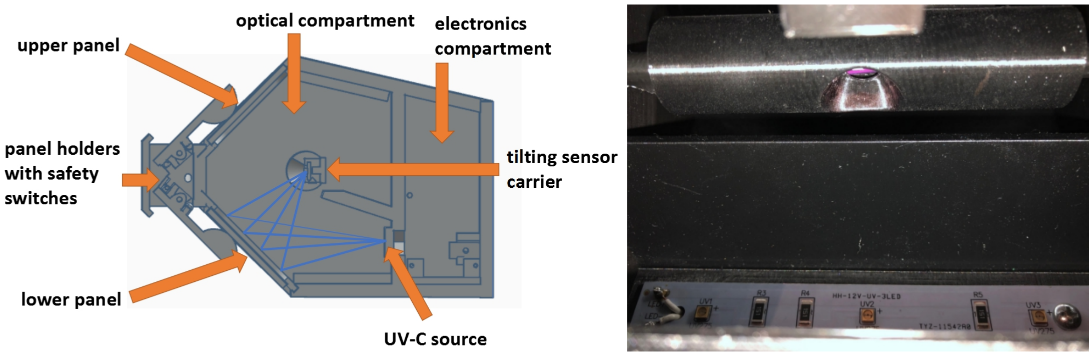

Fig. 1: UV-Reflectometer design indicating light paths at different angles (left) and view inside the optical compartment showing UV-C LEDs and sensor inside tilting carrier (right)

The UV-Reflectometer is designed for thin rectangular test panels of 70 mm x 100 mm. These are the dimensions of „hull cell panels“ which are used for the evaluation of electroplating baths[6] (--> inhomogeneous current density/coating properties) but are also commonly used as simple plating test substrates using a regular plating setup and leading to a homogeneous coating. In addition unplated panels dedicated for hull cell testing can be used or just any sheet metal cut to the same size.
The sensor carrier is tilted by a stepper motor located in the electronics department via a timing belt. The UV-C sensor is mounted on a board with an integrated amplification circuit. It was found that an additional 10x signal amplification provided by an OP in the electronics department improves the resolution of the scans. The reading of the (amplified) sensor signal, the control of the stepper motor driver, the relais switching the UV source as well as the microswitches for the panel safety mechanism and sensor tilt end stop are connected to an ARDUINO NANO microcontroller unit.
Firmware for the MCU was programmed in C+ and the software for data acquisition, plotting and analysis on a PC was developed using the open source platform SCILAB.[7]
The entire documentation on the construction of the device as well as the source codes for firmware and software are published in a GITHUB repository.[8]

The user interface and a typical UV-C reflectivity scan can be seen in Fig.2.
Connection of the UV-Reflectometer‘s MCU with the PC is provided automatically by a standard USB protocol. The software then allows to check the proper installation of the upper and lower test panel because an incorrect panel installation would keep the software from switching on the UV source and performing the reflectivity scan. This is a safety mechanism as only with installed test panels the entire optical department is closed with no UV radiation being able to exit and harm the operator.
After starting the measurement the software will start to record a full scan (0-200°) of background signal intensity with the UV source being turned off. In the example shown below (two unpolished Aluminium panels), the average background intensity over the entire scan range is 0.92 with a standard deviation of 0.62. While the device is not calibrated, it can be estimated (from typical values published for the sensitivity of the GUVA-S12SD sensor, additional amplification and A/D reading of the MCU) that the intensity values correspond roughly to a unit of 1 $\mu W/cm^2$. In the example it can be noted that the background signal is not angle-dependent and not significant considering the standard deviation (< 2σ) and can hence be considered „noise“.
After the background scan the UV source is being switched on and the actual UV reflectivity scan is performed. In Fig. 2 the graph depicted shows the UV scan results (intensity vs. angle) in blue. The

scan range of 0-100° corresponds to the reflection from the lower panel („direct“ reflection) and is highly angle-dependent. The maximum intensity of the entire scan is 122 (µW/cm^2).
In comparison, Hamzavi et al. quote a UV-C dose of 1 J/cm^2 as sufficient for the sterilization (3-log reduction of influenza activity) of face masks.[9] That means that effective sterilization through directly reflected UV-C light from the Aluminium panels evaluated here would take about 3 hours.

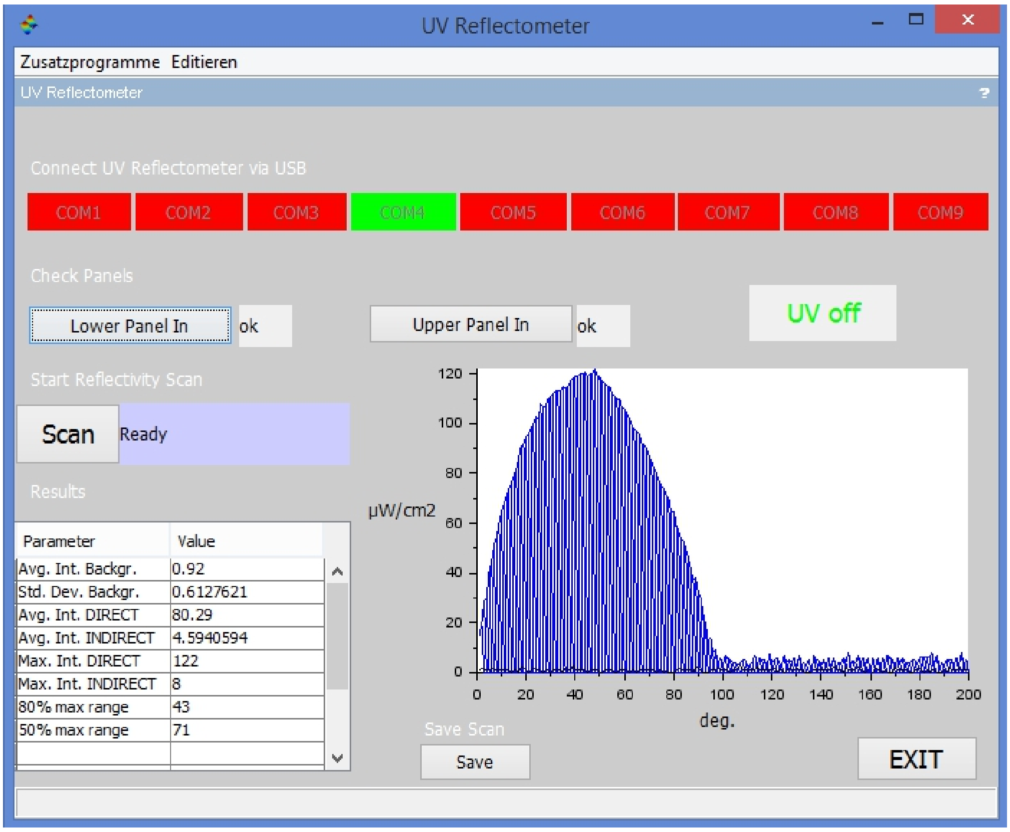

Fig.2: User Interface of the UV-Reflectometer showing results of a scan

Next to the maximum intensity value the results section of the user interface will also provide an angular range over which the intensity exceeds two distinct threshold values of 50% and 80% of the maximum intensity respectively. While those threshold values are chosen arbitrarily they could be a good parameter to be used for the construction and efficacy estimation of UV sterilization chambers: Considering a sterilization time of 3h for the highest intensity value one could derive that efficient sterilization is provided in 6h or lower within an angular range of 71 degrees („50% range“) of direct reflection from a blank aluminium panel in the given geometry.
The scan range of 101-200° representing indirect („diffuse“) reflection from the UV source is showing no clear angle dependent behaviour just like the background scan. The average signal intensity (4.6) while significantly above the background intensity is still comparatively low.

Comparing different sheet metal materials

In a small comparative study we characterized a few sheet metal types which were easily available in a hardware store using the UV-Reflectometer.[10]

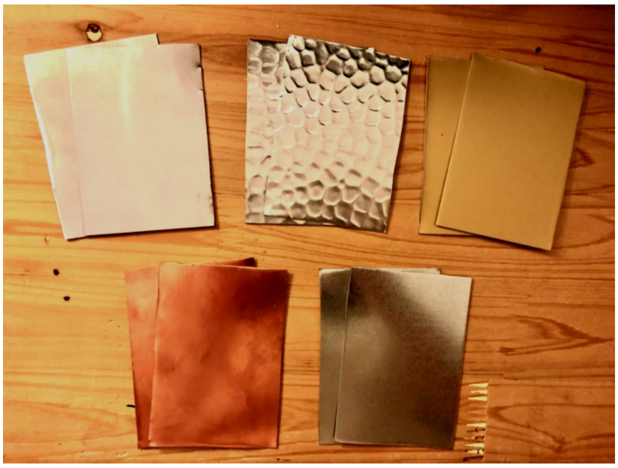

Fig.3: Test Panels: Blank Al, Textured Al, Anodized/coloured Al, Cu, galv. Steel

The results of the evaluation of the panels are shown in the table below.

	Al blank	Al textured	Al anod/gold	Cu	galv. Steel
Avg. Int. DIRECT	105.3	21.6	4.2	4.1	120.7
Avg. Int. INDIRECT	5.2	4.7	4.1	4.1	3.8
Max. Int. DIRECT	151	52	17	7	170
Max. Int. INDIRECT	10	16	14	8	11
50% max range	77	42	15	86	78

Tab. 1: UV-Reflectometer scan results from different pairs of panels

While this first evaluation of materials should only serve as proof of concept for the measurement principle of the device there are already some deductions possible based on the data acquired. The materials which appear silver and „shiny“ i.e. blank aluminium and zinc plated steel have the highest direct reflectivity. Copper panels, even though they appear glossy show very little direct reflectivity. The same applies to matte and coloured anodized Aluminium. An interesting comparison can be made between the blank and the textured aluminium panels which consist of basically the same material and surface appearance but with a macro-structure embossed in one case.

The absence of a flat, smooth reflective surface results in a significantly lower direct reflectivity (about 5x lower) compared to the flat, blank panel. The reflectivity is, however, still much higher (again about 5x) compared to matte, anodized panels. The fluctuations in intensity caused by the wavy texture can be seen in Fig. 4.

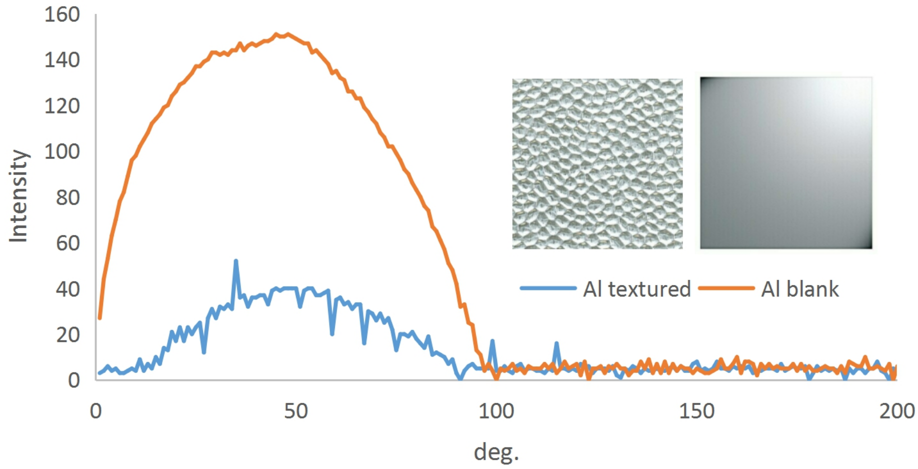

Fig.4: Reflectivity scan of a blank and a textured Al panel

While the direct reflection is lower for the textured aluminium panels it can be assumed that ideal combinations of reflective angles given by the ridges and dimples of the both panels result in some peaks of intensity even in the indirect reflection scan range exceeding the indirect reflection intensity of the blank panels.

Summary

It was found that the reflectivity of materials and coatings will have a big impact on the efficiency of UV-C sterilization equipment. A simple device could be built providing a practical way of evaluating UV-C reflectivity using standard test panels. This device and its software is based on open source platforms and the developed design and source code was made freely available. A first evaluation of different test panels could reveal that zinc plated steel panels have the highest direct reflectivity amongst the tested materials.

Outlook

The developed device can be used to optimize materials for the inside of UV-C sterilization equipment by optimizing texture and plating/polishing. It seems that a focus on a smooth-silvery surface possibly in combination with a dedicated macro-texture could have the highest potential for the application.

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Keywords

UV sterilization, UV reflectivity, UV-C LED, UV-C sensor, reflective material, reflective coating