Hyperspectral camera technology for detection of fungal growth on building materials

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Abstract. Hyperspectral cameras are becoming more widely and frequently used as a valuable tool within different industries, from plant inspections to garbage sorting and used in the food and medical industry. However, the building industry has yet to embrace this technology, even though there are many potential benefits for application e.g., in building investigations. With a hyperspectral camera, it is possible to achieve a better colour characteristic than with an ordinary camera, allowing minor variations in the reflected colour spectra to be identified. As the growth of different fungal species reflects different colours, the current study investigates, if a hyperspectral camera can be used for detection of fungal growth on building materials.
A hyperspectral camera was used on a series of gypsum board samples, to test if fungal growth of three different species could be detected, and if fungal growth not yet visible to the human eye could be detected. The results showed that it was possible, with use of hyperspectral imaging, to detect fungal growth on the surface of the samples, and to distinguish between the three different fungal species. Also, it was possible to detect the early stages fungal growth before they were visible to the human eye.

1. Introduction

Hyperspectral imaging is a technology which is becoming more frequently used, in a broad range of industries, such as agriculture, medical and food industry and as a tool for optimizing garbage sorting [1–5]. The building industry is yet to embrace this technology, even though it has many potential benefits, e.g., as a tool for identification of fungal growth on building materials. This could aid buildings investigators in the field to optimize sampling on surfaces with suspected fungal growth.

Fungal growth in buildings is known to cause various health issues to the building occupants [6,7]. Thus, fungal growth in buildings, that affects the indoor environment, should be removed. However, this requires thorough knowledge of the extent of the fungal growth in order to best design a plan for remediation. Since the fungal growth often is hidden within construction cavities, destructive investigations of the constructions are usually necessary. Moreover, the fungal growth is often not visible on the surface. Today the most common tools for detecting fungal growth on surfaces is microscopy, culturing, or enzyme-based methods. However, the only method that makes it possible to gain a comprehensive overview of the extent of the fungal growth on a given surface, is direct microscopy on a material sample of the surface in question. This requires destructive sampling, where a piece of the surface is taken back to the laboratory for direct microscopy. Alternatively extensive sampling by cultivation and microscopy of tape samples will be necessary. In some cases, e.g., in the case of fungal growth on the surface of a concrete deck, it is impractical to conduct destructive sampling of the surface, making it difficult to conduct representative sampling.

Applying the technology of hyperspectral imaging as a tool for detection of fungal growth on building materials, will allow for on-site investigations of the extent of fungal growth on a given surface in the field. Thus, it can potentially reduce the cost of laboratory analysis, and give a faster and more accurate detection of the extent of fungal growth when conducting building investigations.

The scope of this study is twofold: to investigate if hyperspectral imaging can be used to identify fungal growth of three different fungal species on gypsum boards, and to investigate if the fungal growth can be identified early in the growth process, before it is visible to the human eye.

2. Methods

In the following, the method for preparing the test samples, collecting hyperspectral imaging data, and evaluation of the imaging data is described. Each of these steps was carried out as a laboratory study, hence no on-site field tests were performed.

2.1. Preparing of the test samples

In total 7 pieces of 90 x 90 mm samples of gypsum boards were cut out and sterilized. The samples were placed in sterile petri dishes (14 cm in diameter) and 20 ml of sterilized water was added on top of each gypsum board sample.

After the gypsum boards had absorbed the water, the surface of each specimen was inoculated with a fungal spore suspension. Two samples were inoculated with *Aspergillus niger* (black spored mould), two with *Penicillium rubens* (blue-green spored mould), and two with *Trichoderma viride* (light-green spored mould). One sample was left as a reference without inoculation (blind sample). The fungal suspension was spread evenly over the surface of the specimens, and the samples were incubated at 26 °C over a period of 7 days.

2.2. Collecting hyperspectral imaging data

The hyperspectral camera was set up in the laboratory, and initially calibrated. The hyperspectral camera used in study is a Specim IQ model. The camera has a wavelength band of 400-1000 nm. Thus, the wavelength band extends from visual to near infrared light.

To optimize the colour rendering (Ra-value), halogen spots were added to the test set-up in the laboratory to simulate daylight. Whereas daylight has an Ra-value of 100, halogen light has a Ra-value of 99. In comparison LED light will often have an Ra-value of 80-90.

The hyperspectral images were taken in the given order; 1. Blind sample, 2. *Aspergillus niger* samples, 3. *Penicillium rubens* samples and 4. *Trichoderma viride* samples. The first hyperspectral image was taken on day one after inoculation. Afterwards, a hyperspectral image was taken each day until seven days after the samples were inoculated.

On day four of the incubation process, visible fungal growth was observed on the surface of the samples with *Aspergillus niger*. For samples inoculated with *Penicillium rubens* and *Trichoderma viride*, visible fungal growth was detected on the surfaces on day six after inoculation. On day seven after inoculation, larger areas of fungal growth were visible on the surface of all samples.

2.3. Evaluating hyperspectral imaging data
The hyperspectral image data was analysed using the software IQ Studio, which was downloaded from the company webpage [8]

In IQ Studio, a model for fungal growth on the surface of the gypsum board samples was established, by creating a reflected colour spectrum identical to the specific fungal species growing on the surface of the gypsum boards, based on identification of a coloured pixel for the investigated fungal species on the images taken on day 7 (resembling fungal growth). Afterwards, the model was applied to the hyperspectral images from the earlier stage in the growth process i.e., before visible fungal growth had established. Regarding *Penicillium rubens* and *Trichoderma viride*, the initial stage of growth has a much different colour than the later stage, thus it was necessary to create a model for both early stage of growth and later stage of growth, for the two fungal species.

3. Results and discussion
On the pictures in figure 1-7, the growth of *Aspergillus niger* is visualized using hyperspectral imaging. The last picture of the series (figure 8) is the hyperspectral image of the blind samples taken on day seven. On the pictures in figure 9-16, the growth of *Penicillium rubens* is visualized using both the model for early stage of growth (figure 9-12) and the model for later stage of growth (figure 13-16).


Figure 1. Growth of Aspergillus niger on day one after inoculation.

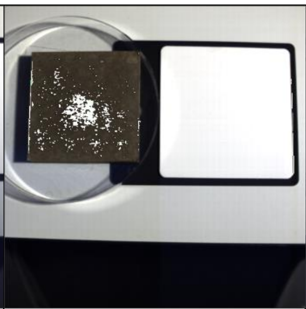
Figure 2. Growth of Aspergillus niger on day two after inoculation.

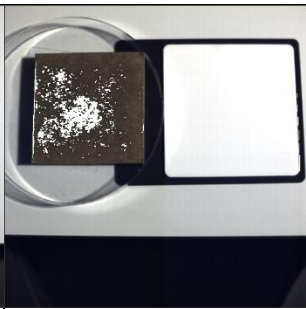
Figure 3. Growth of Aspergillus niger on day three after inoculation.

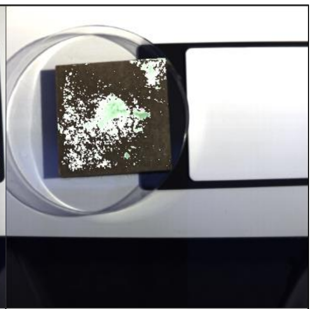
Figure 4. Growth of Aspergillus niger on day four after inoculation.

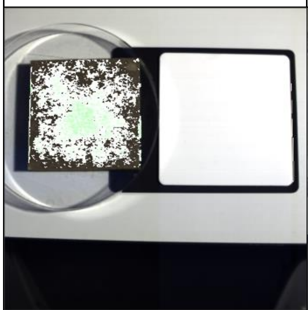
Figure 5. Growth of Aspergillus niger on day five after inoculation.

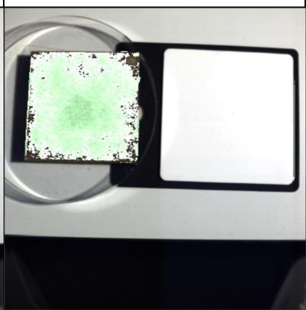
Figure 6. Growth of Aspergillus niger on day six after inoculation.

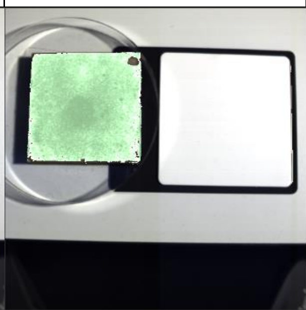
Figure 7. Growth of Aspergillus niger on day seven after inoculation.

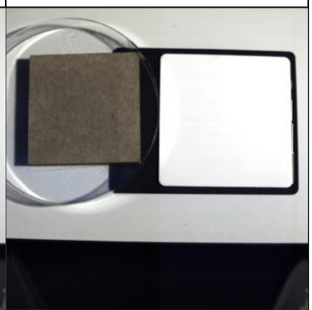
Figure 8. Blind sample on day seven after inoculation.

The results showed that it was possible by use of hyperspectral imaging to detect fungal growth of the three selected fungal species on the gypsum boards. Furthermore, the results showed that when applying the model for fungal growth of *Aspergillus niger* to the hyperspectral images from day two after inoculation, it was possible to detect the initial stage of growth before it was visible to the human eye on day four. This was also the case for *Penicillium rubens* and *Trichoderma viride*. However, their growth was only detected by the model on day five, 1 day before visible to the human eye. Applying the model for early stages of growth for *Penicillium rubens* and *Trichoderma viride*, the model was able to detect growth already from day three of the incubation period, 3 days before visible to the human eye.

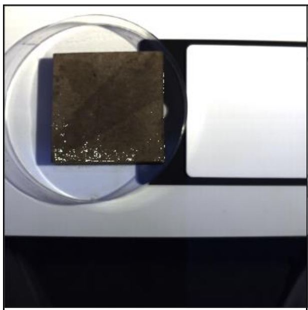	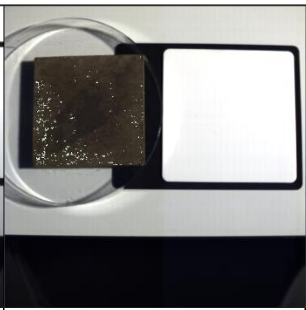	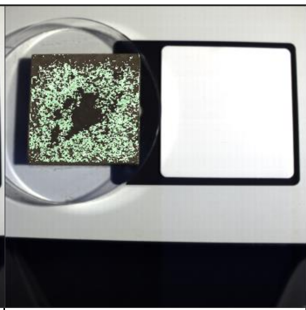	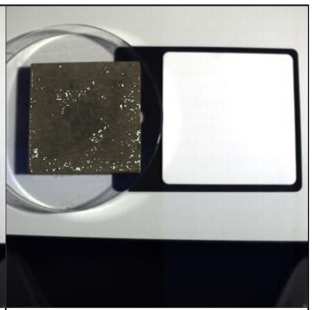
Figure 9. Penicillium rubens after day **two** after inoculation. Model for early growth.	Figure 10. Penicillium rubens after day three after inoculation. Model for early growth.	Figure 11. Penicillium rubens after day four after inoculation. Model for early growth.	Figure 12. Penicillium rubens after day five after inoculation. Model for early growth.
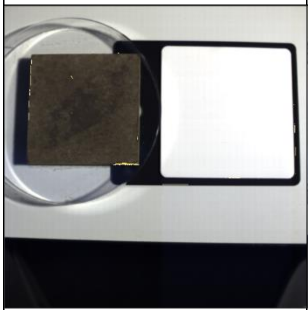	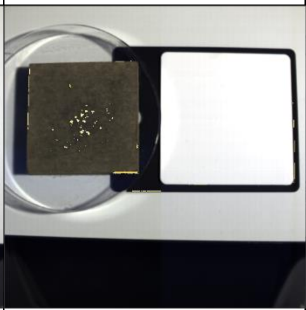	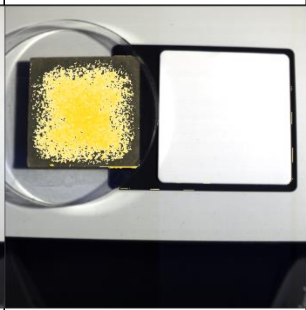	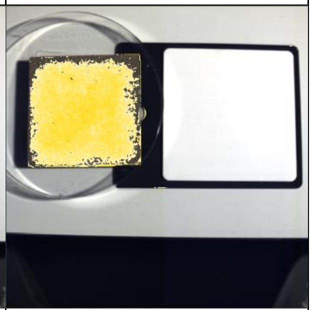
Figure 13. Penicillium rubens after day four after inoculation. Model for later stage growth.	Figure 14. Penicillium rubens after day five after inoculation. Model for later stage growth.	Figure 15. Penicillium rubens after day six after inoculation. Model for later stage growth.	Figure 16. Penicillium rubens after day seven after inoculation. Model for later stage growth.

No fungal growth was detected in any of the hyperspectral images of the blind sample. Microscopy on the surface of the blind sample also showed no fungal growth on the surface, indicating that the sample was not contaminated during the incubation process. As the models created in IQ Studio did not detect fungal growth on the surface of the blind sample, the technology (hyperspectral imaging) does not seem to be fooled by natural differences in the colour of the surface of the gypsum boards, which is essential in order to use the technology in the field. However, the surface of the gypsum board is fairly even coloured, and it would therefore be necessary to test the potential for use of hyperspectral imaging on surfaces with slightly larger colour variations, e.g., plywood or concrete. As a next step, we are therefore currently investigating if a discolouring of the surface of the gypsum boards, (e.g. by adding dirt) perceived by the human eye as similar to fungal growth, can be mistaken for such when using hyperspectral imaging.

When applying the model for *Aspergillus niger* to the hyperspectral images of samples with growth of *Penicillium rubens* and *Trichoderma viride,* the model did not detect any growth on the surfaces. The same was the case when applying the model for *Penicillium rubens* and *Trichoderma viride* to the hyperspectral images of samples with growth of *Aspergillus niger*. However, when applying the model of *Penicillium rubens* to the hyperspectral images of the samples with growth of *Trichoderma viride*, the model detected growth on the surfaces. The same was the case when applying the model for *Trichoderma viride* to the hyperspectral images of the samples with growth of *Penicillium rubens.* This indicates that the technology has difficulties distinguishing between growth of green spored moulds but has no trouble distinguishing between growth of black and green spored moulds. This is not necessarily a problem when conducting building investigations if the technology will be used as a tool in combination with sampling. However, it is important to keep this in mind when using the technology both in laboratory setting and in the field.

In the current study, we did not validate the results by microscopy on the samples during the early stages of growth. However, this could give valuable information for comparison of the results to the currently commercially used sampling methods. Hence, we are now also performing studies where sampling on the surfaces with both an enzyme-based technology and microscopy is conducted continuously throughout the incubation period, for validation of these results against the developed models for hyperspectral imaging.

Moreover, as a next step, studies of mixed fungal growth, and dried fungal growth, on a given surface should be considered, since most surfaces with fungal growth in buildings will have a mixture of species growing within the same area. Moreover, the growth will often be inactive (dried out), since moisture criteria for growth only periodically will be present. These factors can possibly affect the reflected colour spectra from the growth, and should therefore be investigated thoroughly, prior to conducting case studies outside the laboratory.

Furthermore, an application for the hyperspectral camera, that combines models of different fungal species, should be considered, so that it is possible, with a single image, to immediately detect a wide range of fungal species growing on the surface.

4. Conclusion

The study described in this paper reveals that fungal growth of *Aspergillus niger, Penicillium rubens,* and *Trichoderma viride* on the surfaces of gypsum boards can be detected by use of hyperspectral imaging. Further, the study shows that the technique of hyperspectral imaging can be used to detect early stages of fungal growth before it is visible to the human eye.

A number of factors, such as e.g. colour variation of material surfaces and mixed fungal growth, have been identified as potentially having a major influence on the use of hyperspectral imaging as a commercial tool for field use in building investigations, and thus require more detailed investigation. For these reasons, we conclude that there still is some way to go before the technique of hyperspectral imaging can be used as a commercial tool for detection of fungal growth on building materials. However, the initial studies described in this paper show that the technique has potential and that further research on the topic is relevant.

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