Super Resolution Hyperspectral Imaging based Automated Inspection of Nuclear Fuel Pellets

J. Zabalza, A. J. Parker, M. Bandala, P. Murray, S. Marshall, X. Ma, C. J. Taylor, and M. Joyce

***Abstract*— This work presents a new methodology for the automated inspection of nuclear fuel pellets based on Single Image Super Resolution (SISR) and Hyperspectral Imaging (HSI). HSI technology provides optical images in which the pixels contain comprehensive spectral information, normally hundreds of channels (wavelengths) covering the Visible Near InfraRed (VNIR) region in the electromagnetic spectrum. Therefore, the spectral information provided by HSI can be used for inspecting images of pellets pixel-wise. However, the spatial resolution in HSI is lower in comparison to conventional imaging, and SISR is proposed for enhancing the HSI images. Results showed how techniques such as Principal Component Analysis (PCA) can be applied to SR-HSI images to effectively exploit the HSI spatial-spectral content and generate maps for the automated detection of potential abnormalities on the surface of nuclear fuel pellets. While experiments used color chalk as analogues of PWR pellets, results with sintered UO_2 will be presented at the conference.**

***Index Terms*— Automated inspection, hyperspectral imaging, nuclear fuel pellet, principal component analysis, super resolution.**

I. Introduction

NUCLEAR fuel pellets are *the* power-generating component in nuclear power reactors, as such, their quality is paramount. Any defects can affect the performance and safety of the nuclear reactor; therefore, inspections must take place during fuel pellet production, ensuring the absence of any defects. However, these defects are usually small and difficult to identify by manual visual inspection. This is why machine vision and digital image processing has been recently proposed for an automated and efficient inspection of the pellets' surface.

Some machine vision methods have been proposed for inspecting nuclear fuel pellets, including approaches such as Neural Networks (NNs) defect detection based on image histograms [1], convolutional NNs for crack detection [2], or structured light with morphology and Gaussian mixture models for detecting general defects [3]. At the same time, there is research based on spectroscopy, where in [4] they used Raman mapping with Principal Component Analysis (PCA) to evidence structural/chemical inhomogeneities in the material.

Hyperspectral Imaging (HSI) captures images in hundreds of different wavelengths across the electromagnetic spectrum, normally covering the Visible Near InfraRed region (VNIR, 400-1000nm). Therefore, unlike conventional imaging, HSI can capture fine spectral details of the samples under study, detecting features invisible to the human eye, which can be extremely advantageous for the inspection of fuel pellets. However, the spatial resolution in HSI is limited, compromising the detection of small features.

In this work, HSI is introduced for pellet defect detection, where Single Image Super Resolution (SISR) is proposed as a pre-processing stage to enhance the spatial resolution in the HSI images, and PCA is used for processing the enhanced SR-HSI data, generating color maps in which the presence of potential abnormalities is highlighted.

II. Materials and Methods

Given similarities in geometry and surface finish, cylindrical pieces of chalk with ~10mm diameter were used as non-radioactive analogues of PWR pellets. These were manipulated to show chips, dents, contamination or impurities (represented by different colors). The experiments focused on inspecting the top face of a pellet analogue ("green chalk" pellet).

An HSI image of this pellet was captured by the VNIR E-series system from Headwall Photonics Inc. This system captures data across the range 400-1000nm in 373 different spectral channels. The image was captured via line-wise scanning at a distance of ~50cm, following a standard calibration procedure (light source and dark/white references).

The SISR technique implemented in the experiments is based on CNN [5], being applied individually to all channels in the hyperspectral image. Then, PCA was used to generate 3 color maps (first 3 components) highlighting potential abnormalities. Both techniques were implemented in MATLAB (on a PC with i7, 3.70GHz, 24GB RAM) requiring ~15s to obtain the SR-HSI image and <1s to generate the PCA color maps.

III. Results and Discussion

A comparison between the original HSI image and the one after SR is shown in Fig. 1, where a magnification factor of 4 was applied, i.e., each pixel in the original image was replaced by 4x4 pixels in the new SR-HSI image. This can be appreciated in the zoomed-in Region of Interest (RoI), where the pixilation effect in the original image is highly mitigated. After SISR, the spatial resolution is increased while preserving the spectral content, improving the ability to detect small features.

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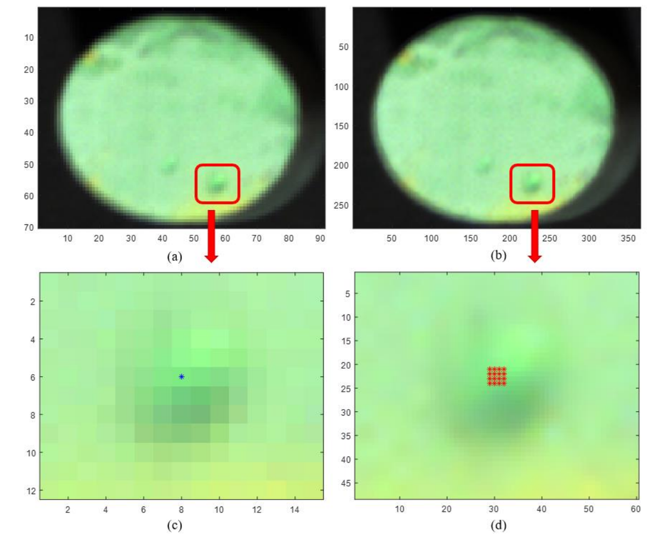

Fig. 1. SISR results: (a) original composite image of a pellet, (b) equivalent image after SR, (c) zoomed-in RoI in the original image, and (d) equivalent image after SR, where the original pixel highlighted in blue color is replaced by the 4x4 pixels highlighted in red color in the SR image.

Fig. 2 shows some spectral content from the SR-HSI image. The spectral information is shown in terms of reflectance intensity (normalized in the scale [0-1]) against the spectrum (VNIR region). Before the experiments, the pellet analogue was contaminated deliberately with yellow color chalk. The yellow coloring represents other material found in the pellet manufacture processes, e.g., steel used in the pelleting press, that are of a different color to that of UO_2 and may contaminate the pellets. This is a good example to show the capabilities of the HSI technology, where regardless of the intensity of the spectral responses, their shape can be evaluated to distinguish among different materials (in this case, represented by two different colors). Hence, potential impurities on the surface of the pellets could be detected through HSI.

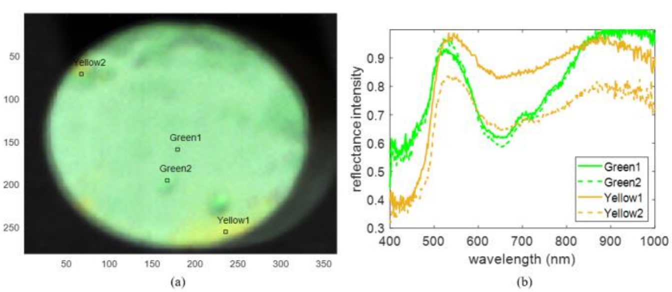

Fig. 2. Visualization of the spectral content from the HSI image of the pellet: (a) composite image, and (b) spectral responses from those locations highlighted in (a), in which the shape of the responses of yellow impurities is clearly different from the shape of the green color responses.

Finally, Fig. 3 shows the results obtained from PCA when applied to the SR-HSI image. PCA is able to process all information from spatial and spectral domains simultaneously, projecting the data to few components representative of the entire image, which can be plotted in the form of color maps. The main abnormalities were well captured by the 1st component, appearing in a dark yellow color different to the lighter yellow color present on most part of the pellet ("healthy") surface. Further details about these potential abnormalities can be found in the 2nd and 3rd components, where impurities were well captured by the 3rd component.

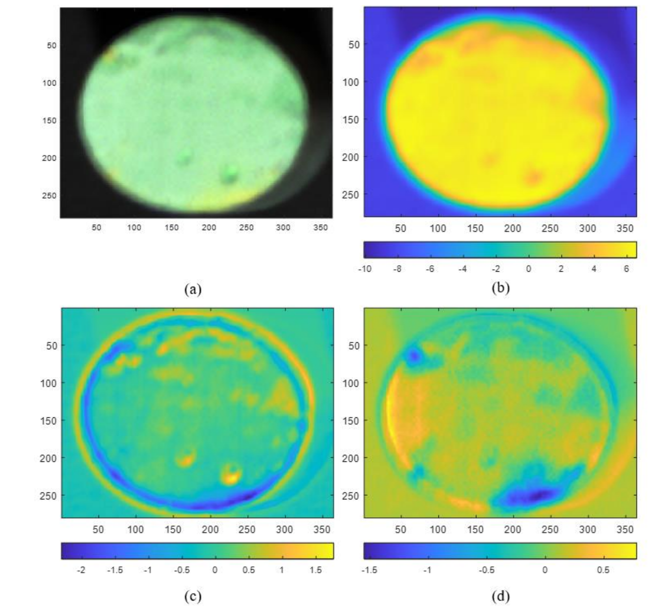

Fig. 3. PCA results applied to the SR-HSI image of the pellet: (a) composite image for reference (after SR), (b) 1st PCA component, (c) 2nd PCA component, and (d) 3rd PCA component from which potential abnormalities, surface consistency, and presence of impurities can be evaluated.

Techniques such as PCA are able to detect small differences across the surface of a pellet, highlighting the presence of potential abnormalities. However, in order to implement this techniques, predefined calibration would be required, which will be investigated in the future.

IV. Conclusion

This work investigated the use of HSI for automated inspection of nuclear fuel pellets, including SISR as pre-processing stage to enhance the spatial resolution of the HSI images for analysis while retaining their spectral information. PCA was used to generate color maps highlighting potential defects, impurities, and evaluating the consistency across the surface of the pellets. Results suggested that HSI is a promising technology for the inspection of nuclear fuel pellets.

Experiments evaluated color chalk pieces to simulate PWR pellets. Further work is ongoing to capture HSI data of real nuclear fuel pellets and repeat these experiments, where a comprehensive assessment with sintered UO_2 will be presented at the conference.

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