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# In-situ high dynamic range inspection in Ebeam machine based on fringe projection profilometry

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**Abstract**

In recent years, additive manufacturing (AM), primarily metal AM developed rapidly. AM has advantages such as energy saving, less material consumption, efficient production, and so forth. In-situ inspection is an important practice during the AM process which can help to improve product quality and reduce material consumption.
This paper presents the development and implementation of a layer by layer in-situ optical inspection system embedded within a commercial Ebeam machine. The inspection system is based on fringe projection profimometry. The system is applied for testing of the powder bed surfaces before melting and the solidified metal surfaces post layer processing. A novel high dynamic measurement method for the solidified metal surfaces was investigated. An example of high dynamic range surface during a part build is used to demonstrate the system capability.

Key words: additive manufacturing; fringe projection; 3D measurement; high dynamic range measurement

## 1. Introduction

Additive manufacturing (AM) has been developed for many years because of its advantages in manufacturing internal features or complex structures. The fringe projection technique has advantages of full-field, high speed, high accuracy, low cost and large field of view. These advantages would appear to suit the requirements for the in-situ inspection of powder bed and printed parts. However, during metal AM process, metal powder would be solidified to metal surface whose reflection characteristics change from diffuse to shiny [1]. The solidified shiny surface and diffuse powder bed are measured simultaneously using fringe projection technology, which results in intensity saturation and data loss in shiny area from the captured images called high dynamic range measurement issues. Hence implementation of an effective in-situ measurement approach for assessment of powder delivery and resolidified shiny part quality is essential to improve manufacturing accuracy and to enhance product quality. Some researchers have conducted a series of studies on saturation issue. Zhang [2] presented a method to take a sequence of fringe images with different exposures which can select the brightest but unsaturated corresponding pixel to produce the final fringe pattern in their structure light projection system. This method requires taking multiple sets of pictures, which consumes time and slows down the measurement. Suresh [3] proposed an improved multi-exposure method which, after projecting binary sinusoidal patterns, captured two images during the projector's bright period and dark period, using different exposure times. It increased measurement speed but still needed additional fringe patterns to obtain absolute phase. Salahieh [4] presented a multi-polarisation fringe projection imaging technique to eliminate saturated points and combine the results in different exposures to measure both dark and shiny areas. This method requires the application of special polarizing cameras, as well as the addition of polarizing film in front of the projector lens, which increases the hardware cost and involves the distortion error of the extra lens. The above methods solved the issue of high dynamic measurement but still have some measurement limitations.

In this paper, a new method which is to solve high dynamic measurement issue in AM processing by using fringe projection profilometry is proposed. A machine learning algorithm is employed to classify and predict the sample under test (SUT) category and adaptive exposure parameters. After system calibration, the fringe projection system inspects solidified surface by adaptive exposure time during AM processing. Therefore, the fringe projection system realizes the intelligent detection capabilities of high-precision inspection, intelligent identification of the measured surface and in-situ high-speed measurement. The system is used in a commercial AM machine. The correct recognition rate of the inspection system was high. The results showed that the system had the ability to simultaneously measure both powder bed and metal surfaces.

## 2. Manufacturing process

The logic of manufacturing process as shown in figure 1 is that after process parameters are set, a layer of powder is dispensed from a powder hopper. Then the fringe projection system inspects the powder bed to assess if the surface is defect free enough to carry on with the process. If the result are good, the system will carry on building, namely powder fusion. Otherwise, the power delivery will be repeated until the surface is smooth enough. After the powder fusion, the fringe projection system will inspect the printed part to detect planar and out of plane error. If no problems are detected or the problem can be resolved the build will carry on, if a problem is detected i.e. the part build deviation is beyond a given threshold then the build is halted. Both of these two inspections need to finish measurement under 5 secs.

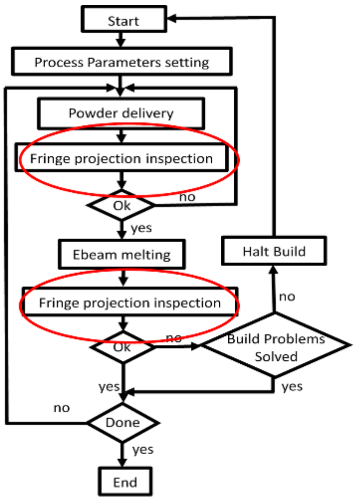



**Figure 1**. EBM Manufacture and inspection flow chart of additive manufacturing system

### *2.1. The principle of fringe projection technique*

The principle of fringe projection system which consists of a CCD camera and a projector is triangulation measurement. The measurement takes place after the geometrical relationship between the camera and the projector is established. The projector projects sinusoidal fringe patterns onto the sample surface, and the camera captures these deformed fringes. The absolute height value can be calculated from the phase map, with the geometrical relationship model as shown in equation 1. High-precision phase algorithms need to be investigated.

$$Z_r(x,y) = \sum_{n=0}^{N} a_n(x,y)\Delta\varphi(x,y)^n \tag{1}$$

The methods to obtain absolute phase information are generally divided into two categories, phase wrapping algorithms and phase unwrapping algorithms.Phase-shifting methods are widely used in optical metrology because of their speed and accuracy[5]. If a multi-step phase-shifting algorithm with a phase shift of $\delta_n$ is adopted, the intensity distributions for the ideal sinusoidal fringes can be described as,

$$I_n(x,y) = A(x,y) + B(x,y)\cos(\varphi + \delta_n), n = 1,2,3,\ldots,N \tag{2}$$

where $A(x,y)$ is the average intensity, $B(x,y)$ is the intensity modulation, and $\varphi(x,y)$ the phase need to be solved for. The surface with uniform reflectivity can be measured by using equation 2, and the high dynamic range surface in this paper can be measured by obtaining the rough powder and the shiny metal surface respectively.

The composite fringe pattern can be express as following,

$$I_{composite} = I_{c-metal} \times Mask + I_{c-powder} \times (\mathrm{U} - Mask) \tag{3}$$

where U is a matrix with one element, Mask is the effective pixels in the saturated region, $I_{c-metal}(x,y)$ is metal region intensity under 255 grey level with a suitable exposure time, $I_{c-powder}(x,y)$ is poweder region intensity under 255 grey level. Therefore, the wrapped phase and the unwrapped phase can be obtained by using the composite fringe patterns.

### *2.2. The principle of Support Vector Machine(SVM)*

We proposed a machine learning algorim to classify and predict SUT to solve saturation issue. Support Vector Machine(SVM) is a classical classification algorithm. SVM is a two-class classification model [6]. The basic model is a linear classifier with the largest interval defined in the feature space. The algorithm creates a line or a hyperplane which separates the data into classes [7]. When the different kernel functions are used for classification, SVM can become a nonlinear classifier. The classification principle of SVM is shown in figure 2. The separation hyperplane is $\vec{\omega}^{\mathrm{T}} \cdot \vec{x} + b = 0$, sample point is $(\vec{x_i}, y_i)$. Therefore, the distance from the hyperplane to the sample set is $\gamma_{\mathrm{i}} = y_i(\frac{\vec{\omega}^{\mathrm{T}}}{\|\vec{\omega}\|} \cdot \vec{x_i} + \frac{b}{\|\vec{\omega}\|})$. By maximizing the margin (2 $\gamma_{\mathrm{i}}$), the SVM model is used to solve the segmentation hyperplane problem. the optimal classification function can be expressed as equation 4,

$$f(\vec{x}) = \mathrm{sgn}(\vec{\omega}^* \cdot \vec{x} + b^*) = \mathrm{sgn}(\sum_{i=1}^{n} \alpha_i^* y_i (\vec{x}_i \vec{x}) + b^*) \tag{4}$$

where $\vec{\omega}^*$, $b^*$, $\alpha_i^*$ are the coefficients of the optimal hyperplane. Therefore, the sample data can be marked, one class is marked by 1 and the other is -1. For the linearly indivisible sample data, after the kernel function is determined, the optimization equation becomes:

$$L(\alpha) = -\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}\alpha_i\alpha_j y_i y_j K(x_i, x_j) + \sum_{i=1}^{N}\alpha_i \tag{5}$$

where $K(x_i, x_j)$ is the kernel function.

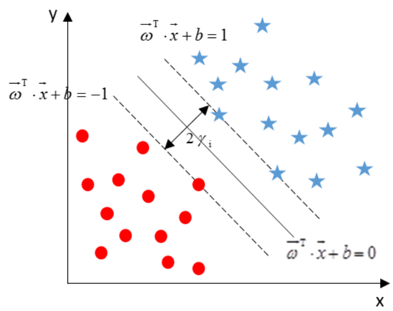



**Figure 2.** The classification principle of SVM - Support vectors delimiting the margin between classes

To achieve multiple classifications, the method of one-versus-rest (OVR) method is adopted in this paper. During the training, based on the categories, the samples were classified into one category successively which is labelled by 1, and the rest of samples into another class which is labelled by -1. In other words, if there are K categories in the sample set, K classifiers will be obtained after classification training. The unknown sample is classified into the category with the maximum classification function value as the shown in figure 3. Therefore, the SVM algorithm can achieve samples classification and predict the appropriate exposure parameters.

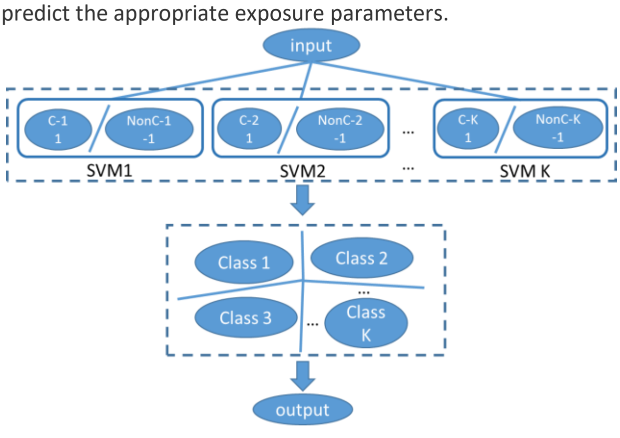



**Figure 3**. Schematic diagram of SVM multi-classification method

## 3. Training and testing

The process of printed surface inspection as shown in figure 4, after Ebeam melting, the projector projects fringe patterns on to surface with initial exposure time. The projected patterns include a set of sinosiodal patterns and a graylevel background intensity pattern. The sample surface is captured by the initial exposure time and projection intensity. Canny operator was used to separate the printed reflective surface and powder, and the unit overexposure pixel number in the reflective area was calculated as the input parameter 1, and the initial exposure time was the input parameter 2. The SVM classifier can predict printed surface in which class and its suitable exposure parameters based on these two input parameters. The system projects a set of fringe patterns and the camera captured them with predicted exposure time for the second measurement. At last, the results of the two measurements are merged to determine whether the measured surface is qualified.

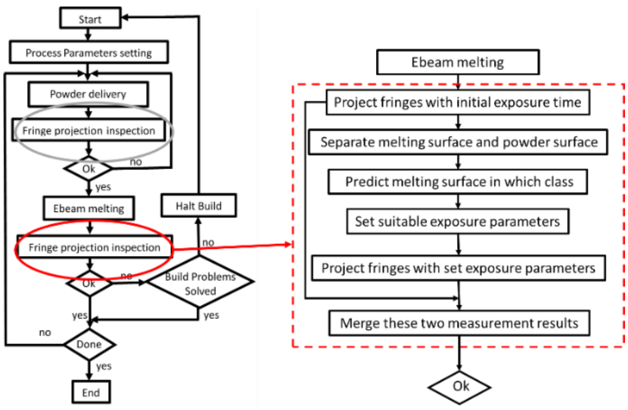



**Figure 4**. The process of shiny surface inspction.

In this paper, four types of manufactured surfaces as samples are classified and trained. According to the proposed classification method, four SVM classifiers can be obtained. According to the exposure time and saturated pixel number of each training surface sample, the scatter diagram is shown in figure 5.

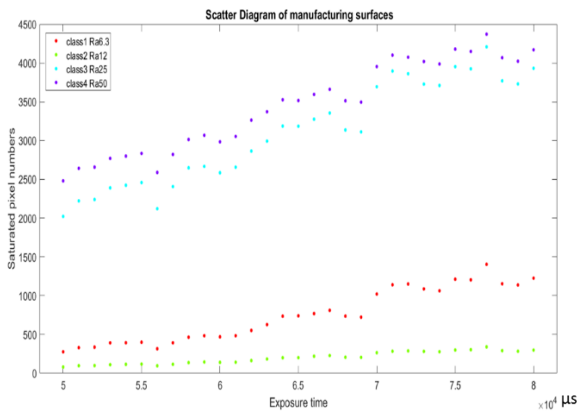



**Figure 5.** The scatter diagram of manufacturing surfaces

In order to verify the accuracy of the SVM classifier, the samples with different input parameters were classified and the results shown table 1. By comparing the predicted results with the actual classification labels, cross validation error of each training surface is 0.0887, 0.0565, 0.2016, and 0.1854 respectively. The correct prediction rate is 0.8629 (86%), and the false alarm rate is 0.0645.

**Table 1** The prediction results

| Class | Class1 | Class2 | Class3 | Class4 |
|---|---|---|---|---|
| Cross validation error | 0.0887 | 0.0565 | 0.2016 | 0.1854 |
| Precision rate | 0.8629 | | | |
| False alarm rate | 0.0645 | | | |

## 4. Experiment

As shown in figure 6, a full implementation of the inspection system was carried out on a commercial EBM machine. The position of the camera and projector outside of the vacuum build chamber with the viewing ports. The position of the projector and the camera were fixed with the angle between the optical axes of circa 30°. The camera model is evo12040MBGEB from SVS with a resolution of 3016x4016 pixels. The projector is an industrial digital projector (Light Crafter model 4500) with a resolution of 912x1140 micro mirror array.

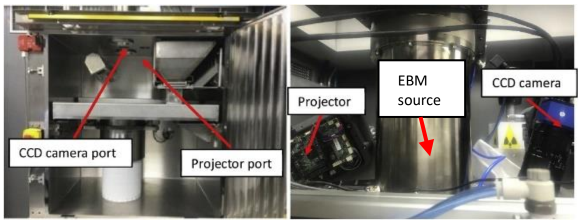
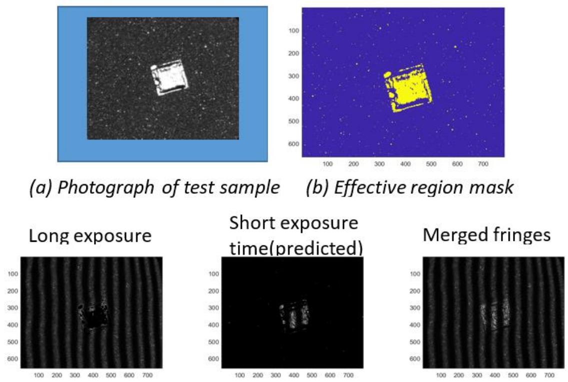



**Figure 6.** Prototype system with fringe projection system in a new EBM machine




*(c) Fringes with long exposure time and short exposure time and merged fringes*

**Figure 7.** The captured fringes with twice measurements and the merged fringes

The projector projected 12 sinusoidal fringe patterns with fringe number 81 80 72 and the background pattern with 240 grey level intensity onto the sample surface. The projected fringes were deformed by the shape of the surface and the intensity of the background pattern changed by the different reflective rates of the surface. The camera captured these deformed fringes and the texture background pattern with the long exposure time. The deformed fringe patterns were selected as the effective region by the corresponding mask as shown in figure 7(b). After SVM prediction, the sample surface belongs to training class4. Then, the corresponding exposure time of class4 was reset, the system took the second time measurement. The deformed fringe patterns with the low exposure time were cropped to select the effective area by the mask. Therefore, 12 unsaturated intensity patterns were merged by two measurements in figure 7(c). After the process of 4 steps phase-shifting and 3-frequency selection phase unwrapping, the merged absolute phase map can be obtained.

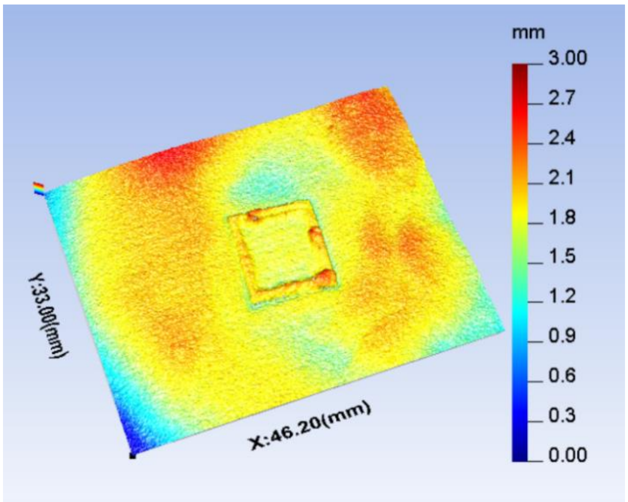



**Figure 8.** The measurement result of a manufacturing square

Figure 8 shows the measurement result with a high reflective feature and the powder bed with a low reflective rate was measured successfully simultaneously. And the whole process needs around 4 seconds with two measurements. The square built parts within the powder bed where edge thermal swelling which is shiny can be measured clearly. The threshold value would be set to determine the process halt or not according to the defect size.

**5. Conclusion**

In this paper, an in-situ monitoring technique was developed to facilitate inspection of the powder bed and printed surface of an EBM machine by using a fringe projection technique. After the electron beam melting the powder pool, the metal powder was solidified and the reflective characteristic of the surface changes from diffuse to highly reflective. It increased difficulty for the system to measure both diffuse powder and reflective metal surfaces. A novel intelligent fringe projection technique using SVM algorithm was proposed to measure high dynamic range surface. By training the exposure time and saturation pixel number of different surfaces, the SUT were classified and predicted by SVM classifier. Training error was evaluated, and the correct recognition rate was better than 86%, which indicated the proposed training method can effectively predict the measurement surface. The system has the capability for inspecting both powder bed and metal surface. The examples of melting edge swelling and powder bed during a real part build show the defects can be clear inspected, which offers improved manufacturing accuracy and control during the manufacturing process. The system has been developed on a commercial AM machine and control software integrated in the AM machine control. The measurement speed is around 2 secs for the powder bed inspection and less than 5 secs for the printed surface inspection during each measurement cycle, which did not incur extra time loss during manufacturing process. Compared with other methods, we achieved intelligent inspection and reduced measurement time during AM process.

**6. Acoknowledgements**

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