# Automatic Hard Disk Drive Slider Bar Auditing with Spatial Light Modulator based Imaging System

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### Abstract

In Hard Disk Drive (HDD) slider fabrication process, the slider bar auditing is required to verify if the slider bars in the tray are sorted correctly as indicated by the serial numbers printed on sliders. In this paper, we present a machine vision system for automated reading of the serial numbers. Since the sizes of slider bars are very small, an imaging system (CCD camera) with high magnification lens is usually exploited to acquire the slide bar images. For such high magnification vision system, an autofocus module is indispensable. Unlike conventional autofocus modules which perform using mechanical zoom lens, we develop an autofocus module based on Spatial Light Modulator (SLM) where the SLM will act as phase mask filter for focus adjustment. The key contribution of our work is that we perform non-mechanical autofocus approach by adjusting the pixel-based phase mask pattern sending through the SLM. The main advantage of our system is that there is no macro-mechanical movement part involved in Z-axis focus adjustment. We propose a machine vision algorithm that consists of 3 major steps including coarse localization of slider bar, Autofocus and optical character recognition (OCR). To our best knowledge, our developed system is the first system that uses the SLM based autofocus in machine vision for HDD slider manufacturing. From the experiment, our system can accomplish the task with very high accuracy. By using our system, we can improve the machine vision applications by replacing conventional mechanical zoom lens based autofocus modules that generally cause machine vibrations and increasing maintenance costs related to mechanical movement issues.

Keywords: Autofocusing, HDD Slider Bar, Slider Bar Auditing, Spatial Light Modulator

# 1. Introduction

In HDD manufacturing, several complicated sub processes are required. As the HDD components are very small, it is very difficult to totally handle the production by human operator. Incorporating computerized automation, especially machine vision system, is indispensable for HDD manufacturing.



Figure 1. Slider bar auditing process.

In this paper, we concern in developing a machine vision system to improve the process of HDD slider (HDD read/write head) fabrication. Particularly, the task we want to tackle is slider bar auditing.

Generally, in slider fabrication process, first the wafer consisting of many sliders will be cut into several row bars and put into a tray as shown in Figure 1. Each row bar consists of an amount number of sliders connecting in a row-wise manner. The serial numbers printed on sliders of the bar are used to identify different slider bars during the manufacturing process. It is very important to have the bars placed in their order especially for part traceability. The slider bar auditing process is brought out here to verify if the slider bars in the tray are sorted correctly. Specifically speaking, the input of our proposed system is a tray of slider bars while the output is the corresponding bar ID numbers.

Since the sizes of slider bars are very small, an imaging system (CCD camera) with high magnification lens is usually exploited to acquire the slide bar images. As we feed slider bars in front of the camera, some acquired images may not be in focus, i.e., blurry images. The major cause of this effect is due to the variations in distances between bars and lens according to some mechanical tolerance. If the variations are larger than the depth-offield (DOF) of imaging system, the acquired images will be blurry. To solve the problem, an autofocus module must be indispensably included into the machine vision system.

Conventionally, a mechanical zoom lens is integrated to the imaging system to accomplish the autofocus task. The zoom lens usually consists of multiple optical elements and requires on-axis movement between the elements to adjust the focal distance. The main disadvantage of using mechanical zoom lenses lies in the complication that we need to control the moving parts of the lenses either manually or automatically in which it may take some time to complete the adjustment process as well as design and maintenance issues related to the mechanical movement.

To get around the problem of mechanical zoom lens, in this work, we present an improved machine vision system for slider bar auditing process. The key novelty of the system lies in the use of autofocus module based on a SLM. The SLM placed between lens and camera will act as filter (phase mask) for imaging focus adjustment. Unlike a system with mechanical zoom lens based autofocus, the focal length can be varied by manipulating the phase mask pattern sending through the SLM. Therefore, replacing many parts (as required in mechanical based systems) with active optical components that stay stationary could decrease the time required for adjusting the focal length and maintenance issues.

The remainders of this paper are organized as follows. We present some related works in section 2. The overview of our proposed system is explained in section 4. Detail of SLM based focus adjustment is presented in section 3. Machine vision algorithm used is presented in section 5. The experimental result is reported in section 6. Finally, the conclusion is drawn in section 7.

### 2. Related Work

There are some works related to ours in the sense that they involve machine vision systems that are accompanying with microscope or high magnification lens.

In the work of Subramanian et al.<sup>1</sup>, the authors proposed a system for monitoring the seedling development in plant phenotype studies. A part of the system that is related to ours is the mechanical based autofocus module. The normalized variance was used as the focus measure. To speed up the focus searching, the authors proposed a method based on the idea that the focus measure function was modeled as two lines corresponding to the increasing side and the decreasing side of the focus measure curve.

Vision modules necessary for Microsystems were proposed in the work of Bilen et al.<sup>2</sup>. As the major module, the authors presented a mechanical based autofocusing on microscope that moved along the z axis in a range of 1,750  $\mu$ m with 5  $\mu$ m steps. A focus searching based on Fibonacci search was proposed and the normalized variance was used as focus measure.

In the work of Bell et al.<sup>3</sup>, the authors proposed a system for multi-modal cell analysis. This requires the system to be able to re-localize the identical cells in different stains on the slide. Similar to<sup>1,2</sup>, a mechanical based autofocus was proposed in which Sum-Modulus-Difference (SMD) was used as the focus measure. The focus position was found by acquiring the images at different z positions of microscope stage adjustment in the prior known range (upper and lower limits). The idea of using two levels of autofocus, i.e., coarse autofocus and fine autofocus, was proposed to speed up the searching in which the steps of z increments for these levels were different. An automated system for recognizing pollen grains under microscope was proposed in the work of Allen et al<sup>4</sup>. A microscope with two objective lenses was used to acquire the pollen grain images. The first one was the lower magnification lens to capture large angle field of view in order to autofocus and localize pollen grains in a quick manner. The second one was the high magnification lens to acquire the specific area of pollen grains on the slide. The autofocus module was carried out along Z movement with a step of 0.6  $\mu$ m. For the images acquired by the lower magnification lens, the standard deviation was used as the focus measure. Meanwhile, for the images acquired by the high magnification lens, the maximum gradient squared was used as the focus measure.

Several works on autofocusing were proposed. In the work of Allegro et al.<sup>5</sup>, the authors presented a passive autofocusing technique for micro-assembly under a motorized microscope. The key idea of this approach is to determine and to identify the focal planes. A comprehensive study of different autofocusing algorithms on a large set of microscope images was presented in the work of Sun et al<sup>6</sup>. The authors also proposed guidelines for selecting the optimal focus algorithm under different circumstances.

To the best of our knowledge, there is no existing work similar to ours proposed in the area of machine vision for HDD slider bar manufacturing. Some commercial systems with restrict information are available, e.g, Xyratex (http://www.xyratex.com/products/polaris). However, there are some works, in the area of machine vision for HDD manufacturing, described as follows.

In the work of Chang et al.<sup>7</sup>, the authors proposed an image processing algorithm deployed in robotic vision guided system for alignment of flex cable assembly (FCA) onto disk drive actuator comb of head suspension assembly (HSA). The key idea of algorithm lies in how to precisely detect the fiducial target marked on the flex cable solder pad in which two different detectors are proposed, i.e., shape finder based detection and edge finder based detection.

In the work of Withayachumnankul et al.<sup>8</sup>, the authors proposed an image processing algorithm for detecting hairline cracks on the surface of PZT actuators in HDD. The algorithm consists of three major stages

including the step of ROI extraction, the step of crack region enhancement and the step of irrelevant feature elimination. The proposed algorithm could detect several variations of cracks with high accuracy.

In the work of Mak et al.<sup>9</sup>, the authors proposed a Bayesian Network based approach accompanied to automated optical inspection (AOI) of the solder jet bond (SJB) joint in the Head Gimbal Assembly (HGA) process. For image processing part, an algorithm was proposed to extract eight different key features (e.g., size, length, shape) of solder joints for further use in decision inference by a TAN-BN Probabilistic Classifier using GeNIe/SMILE (a library of C++ classes implementing Bayesian Networks). The proposed system yielded 91.5\% accuracy when testing with 660 production parts.

In Doo Hee Han's<sup>17</sup> work, the authors proposed zoom lens set by applying aspheric lens to improve the spherical and distortional aberration. For our purpose, we can reduce both parameters by using programmed SLM and also if the system is modified we just re-program the SLM. Moreover, our purposed is convenient and flexible to use.

# 3. Adaptive Focal Length Imaging System Using SLM

To adjust the focal length, we follow the idea similar to the works presented in<sup>10,11</sup> in which an SLM is placed between lens and CCD camera as shown in Figure 4. The focal length can be adjusted by changing phase mask pattern sent through SLM. Simply speaking, we can consider that a phase mask pattern is varied according to the distance between object and lens, i.e., z. As shown in figure 3 (b), supposed that the object is at the distance z, and we send the proper phase mask corresponding to the correct distance, i.e.,  $P_{(z_i)}$ , the image of object will be in focus. On the other hand, in Figure 3 (c), if the object is at the distance  $z_2$  but the phase mask is still  $P_{(z_1)}$ , the acquired image will be blurred. Accordingly, if we adjust the correct phase mask to  $P_{(z_i)}$ , then the image of object at the distance  $z_2$  is now in focus. That is, the proper adjustment of SLMbased phase mask pattern is equivalent to adjusting the

moving elements of an equivalent zoom lens so that the

object of interest is in focus.

(1)



Figure 2. Generalized optical system.

Theoretically, the adjustment of focal length of our proposed imaging system can be described as follows. Our imaging system is based on a generalized optical system<sup>12</sup> as shown in Figure 2, in which we consider all elements of imaging system as a black box that consists of two different planes, i.e, the plane of entrance pupil and the plane of exit pupil. In similar manner to the work of Ferran et al.<sup>13</sup>, the intensity pattern  $f_i(u, v)$  in the observation plane at the distance  $z_1$  from the exit pupil can be explained by

$$f_{i}(u,v) = f_{\sigma}(u,v)^{*} |h(u,v)|^{2}$$
<sup>(1)</sup>

Where  $f_g(u,v)$  is the intensity of object image. The operator \* is 2D-convolution. The complex amplitude of the point spread function (PSF), h(u,v), of the system can be represented by

$$h(u,v) \propto \frac{1}{\lambda z_i} \int E(x,y) dx dy$$
 (2)  
Where

$$E(x, y) = e^{ikA_s(x^2 + y^2)^2} e^{i\frac{k\Delta z}{2z_i^2}(x^2 + y^2)} e^{-i\frac{2\pi}{\lambda z_i}(ux + vy)} e^{-i(2\pi)(ux + vy)} e^{-i(2\pi)(ux + vy)}$$
(3)

The first exponential term in equation 2 corresponds to the spherical aberration at the exit pupil. While the second exponential term corresponds to the de-focus according to the effect that the observation image plane (at  $z_i$ ) is not located at the same position of the paraxial image plane (at z') and,  $\Delta z = z_i - z'$ . Note that the paraxial image plane is the location that the focused image of a point source is formed for aberration-free imaging system.

To make the object image in focus, we incorporate the SLM into the imaging system. The phase mask pattern sent to the SLM is used to modify the wave front passing through the imaging system in such a way that the optical rays converge to the required focal point. Specifically, we add the phase mask, as expressed by the term  $e^{ikP(x,y)}$ , at the exit pupil of the imaging system. That is, from equation 2, the PSF is now represented by

$$h(u,v) \propto \frac{1}{\lambda z_i} \int e^{ikP(x,y)} E(x,y) dx dy$$
(4)

The term  $e^{ikP(x,y)}$  is used to cancel out the effect of spherical aberration and to compensate the effect of de-focus that is equivalent to focal-length adjustment. Mathematically, the P(x, y) is defined by the following equation.

$$P(x,y) = -A_s(x^2 + y^2)^2 - A_d(x^2 + y^2)$$
(5)

Where  $A_s$  and  $A_d$  are constants (units in  $\lambda$ ) corresponding to the effects of spherical aberration and defocus, respectively. The value  $A_s$  can be estimated from the optical system configuration by using some commercial software for optical system design (e.g. Zemax.). The value  $A_d$  of can be calculated by the following equation

$$A_d = \frac{\mathsf{V}z}{8F_{\#}^2} \tag{6}$$

$$F_{\#} = \frac{R}{2a} \tag{7}$$

Where  $F_e$  is F-number. *R* is the distance between the exit pupil and the detector plane. The notation *a* is the semi-diameter of exit pupil.



**Figure 3.** Examples of adaptive focal length imaging system using SLM, (a) The images acquired with the normal (without SLM) optical system at various object locations (b) the phase mask patterns at the SLM (c) The images acquired with our adaptive focal length systems.

For the purpose of demonstration of the above idea, we show preliminary results of focal length adjustment on a proof-of-concept system with single thin lens in Figure 3. In the example, we acquire the images of the object at several positions from -2 mm to 2 mm in a step of 0.5 mm. Here the position at 0 mm means that the object is in focus if we capture the image without enabling the additional active components (the SLM and polarizers). The top row (a) contains images obtained from the normal (without SLM) optical system at different object distances. As we can observe, the contents of images are totally out of focus when the object move further away from  $\pm 0.5$ mm. At each varied location of the object, we create and send the phase mask patterns to the SLM as shown in the second row (b). Then we acquire the images that are shown in the last row (c). As we can discern from the results, the acquired images are almost identical no matter where the object is located.

# 4. System Overview

The key idea for designing our system is to solve the disadvantage of mechanical zoom lens based autofocus by using active optics based imaging<sup>10,11</sup>. Specifically, we use a SLM to act as a phase mask that can modify the optical ray in the same manner as adjusting lens position for focusing. The focus position (i.e., focal length) can be varied by manipulating the pixel-based phase mask pattern sending through the SLM.



**Figure 4.** The system components, (a) CCD camera sensor, (b) and (d) polarizers, (c) SLM, (e) 4X lens, (f) red LED coaxial light source, and (g) object (slider bars on tray).

The hardware configuration of our slider bar auditing system is shown in figure 4 in which it consists of (i) Y-axis robot, (ii) imaging part, and (iii) computer. The imaging part consists of CCD Camera, 4X Macro lens, red color coaxial light source, SLM and a pair of polarizers. These imaging components are mounted together within a single platform. This platform is controlled by the robot to move horizontally for acquiring different slider bars on the tray.





From software perspective, the system consists of 4 major stages to accomplish the auditing process of each slider bar. These major steps can be shown as the flowchart in Figure 5. First, the robot controls the imaging part to stay in front of a slider bar in tray. Then, an image without focus adjustment is acquired.



**Figure 6.** Example of input image with fiducial marker and ROI consisting of slider bar's serial number.

An example of acquired image can be shown in Figure 6. Next, for the coarse localization step, the system will detect a fiducial (cross mark) on the slider bar in the image.

The detection is based on Normalized Cross Correlation (NCC) template matching due to its capability to deal with blur image. For the autofocus step, we perform a fine focus adjustment by analyzing images in the region of interest (ROI) that its position is relative to the detected fiducial. We use Image Variance as focus measure. For focusing algorithm, an algorithm based on golden search method is used. The detail of this step is explained in section 5. The focus position adjustment according to the result of focusing algorithm is performed by sending a pixel-based phase mask pattern through the SLM. This pattern is varied according to the resulting position returned from the focusing algorithm. The detail of focus adjustment with SLM is explained in section 5.2. At the end of fine focus adjustment, the final acquired image will be sharp enough for reading the slider bar serial number. Finally, the OCR module is applied to this final image to obtain the resulting ID numbers. The above processing steps will be repeated for auditing the remaining slider bars on the tray.

### 5. Machine Vision Algorithm

In this section, we will explain in details about two major software modules, i.e., *Coarse localization of slider bars* module and *Autofocus* module. For the *OCR* module, we use an off-the-shelf library in which we feed the image region consisting of slider bar serial numbers as the input of library. Specifically, this image region is found after we apply the *Coarse localization of slider bars* step and the *Autofocus* step.

#### 5.1 Coarse Localization of Slider Bar

In this step, the algorithm will find the location of slider bar so that the image region consisting of serial number can be extracted from the input image Figure 6. To achieve this step, the cross mark as indicated in the figure is used as fiducial. We store a reference image of cross mark extracted from a training image. Then, to search for the cross mark location in the input image, a fiducial detection based on template matching is applied.

However, the input image at this step could be blurred as the autofocus is not carried out yet. Therefore we decide to use NCC based template matching as it is robust to image blur. Mathematically speaking, the NCC measure between the template image (reference cross mark) w of size  $L \times K$  and the input image f at the pixel (i, j) can be explained by the following equation

$$NCC(i, j) = \frac{\sum_{x=0}^{L-1} \sum_{y=0}^{K-1} [w(x, y) - \overline{w}] [f(x+i, y+j) - \overline{f}(i, j)]}{\left[\sum_{x=0}^{L-1} \sum_{y=0}^{K-1} (w(x, y) - \overline{w})^2\right]^{\frac{1}{2}} \left[\sum_{x=0}^{L-1} \sum_{y=0}^{K-1} (f(x+i, y+j) - \overline{f}(i, j))^2\right]^{\frac{1}{2}}}$$
(8)

Where  $\overline{w}$  is the average intensity of template image w and  $\overline{f}(i, j)$  is the average intensity of input image f in the region coincident with w.

From the pixel position that the NCC score is maximum, the ROI, as shown in Figure 6, is established for the steps of autofocus and OCR.

#### 5.2 Autofocusing

As the image content inside the ROI obtained from the previous step may be blurred, applying OCR to the ROI is prone to erroneous. To resolve the problem, the autofocus module is applied to acquire the best focused image. Unlike conventional auto-focusing on mechanical zoom lens, our system carries out the autofocus on SLM based imaging system. However, the ideas from mechanical based focusing can be applied with some modification.

Briefly speaking, the key idea of autofocusing can be explained as follows. We acquire multiple images at different focal distances. A quantitative measure, referred to as focus measure, will be calculated from each acquired image. To minimize the number of acquired images, a search on focus measured values is exploited. The best focused image is the image that corresponds to the maximum value.



**Figure 7.** Focus measure curve: plot of image variances computed in the serial number ROI at several distances.

In this work, we use image variance, shown in equation 9, as the focus measure. An example of the values of image variance computed inside the ROI at several distances from the actual focus position (distance =0.00 mm.) can be shown in Figure 7. As it can be seen from the graph, the computed value at the focus position corresponds to the maximum.

$$F_{\rm var} = \frac{1}{N-1} \sum_{x} \sum_{y} (I(x, y) - \mu)^2$$

Where I(x, y) is the intensity of pixel (x, y), N is the number of pixels in the image I and  $\mu$  is the averaged intensity.

(9)

For the search algorithm, we exploit the Golden Section method<sup>14</sup> in which it is typically used for finding the maximum or minimum of a unimodal function. Note that a unimodal function is the function that contains only one minimum or maximum on considered interval.

The pseudo-code for our golden section search based focusing algorithm can be shown in Algorithm 1. At the beginning,  $b_l$  and  $b_u$  are initialized with the extreme values in the range of working distance (i.e., distance between lens and object) plus some offset value according to mechanical tolerance.

At each iteration (Lines 5-19), the values of  $b_l$  and  $b_u$ will be updated in such a way that the range  $/b_u - b_l/$  is narrowed down. These values are updated by two different conditions according to the current values  $F_{\text{var}}(z_l)$  and  $F_{\text{var}}(z_u)$  as expressed in (Lines 12-14) or in (Lines 16-18).

#### Algorithm 1 Golden Section Search based Autofocus

The procedure Focus Measure called in Lines 7 and 10 is to probe the focus position of SLM based imaging system. That is, we generate the phase mask pattern according to equation 5 with the value of  $z_l$  or  $z_u$  as explained in section 3 and send it to the SLM. Then the procedure will acquire the image and compute the focus measure (Image Variance) as in equation 9. The computed values are stored in  $F_{var}(z_l)$  and  $F_{var}(z_u)$ . The iterations are repeated until the range  $/b_u - b_l$  is less than the value of converged range condition ( $\dot{O}$ ). After the iteration is terminated, the output of focused position  $z^*$  is the last value of either or depending on the larger values of  $F_{var}(z_l)$  and  $F_{var}(z_u)$ . This part corresponds to the codes in (Lines 21-25).

### 6. Experiment

#### 6.1 Setup and Implementation

The details of hardware components of our system can be listed as follows. For the Y-axis robot, we use IAI actuator. For the imaging part, we used the SLM token from a commercial SONY video projector model: VPL-CS1 in which the resolution is 800 x 600 pixels. The model of lens is Moritex MML6X in which we remove some optic pieces such that it works like 4X macro lens. For the CCD camera, we use Basler acA1300-30gm to acquire images at the resolution 1296 x 966 pixels. The computer we use to control the overall system is Intel Core i5, 2.76 GHz, RAM 4GB with MS Windows 7.

For the purpose of maximizing the phase modulation while minimizing the amplitude modulation, we calibrate the SLM by using the similar procedure to the one proposed in<sup>15</sup> in which we found that the orientations of the first and the second polarizers are about 200° and 260°, respectively.

For the software part, we develop a program in NI LabVIEW. To generate the phase mask pattern according to a focal length value, we follow the similar approach as presented in<sup>13</sup>. That is, after we know the target focal length value, we generate the phase mask pattern according to equation 5. Then we send the phase mask pattern to the SLM as we display the pattern to LCD video projector. For the OCR step, we use the OCR module of NI Vision in which we train the module with the sample characters extracted from a set of training slider bar images. For other parts of software module, the program works as the explanation stated in section 4.

Algorithm 1 Golden Section Search based Autofocus
<b>Input:</b> $b_u$ = Upper bound of focus distance range
<b>Input:</b> $b_l$ = Lower bound of focus distance range
Input: $\epsilon$ = Converged range condition
Output: $z^*$ = Focused position
1: $K = 0.618$
2: $z_l = b_u - K * (b_u - b_l)$
3: $z_u = b_l + K * (b_u - b_l)$
4: while $ b_u - b_l  \ge \epsilon$ do
5: // Calculate the focus measure from the image
6: <i>II captured at the focus distance</i> $z_l$
7: $F_{var}(z_l) \leftarrow FocusMeasure(z_l)$
8: // Calculate the focus measure from the image
9: <i>II captured at the focus distance</i> $z_u$
10: $F_{var}(z_u) \leftarrow FocusMeasure(z_u)$
11: if $F_{\text{var}}(z_l) \leqslant F_{\text{var}}(z_u)$ then
12: $b_l = z_l$
13: $z_l = z_u$
14: $z_u = b_l + K * (b_u - b_l)$
15: else
16: $b_u = z_u$
17: $z_u = z_l$
18: $z_l = b_u - K * (b_u - b_l)$
19: end if
20: end while
21: if $F_{\text{var}}(z_l) \leq F_{\text{var}}(z_u)$ then
$22:  z^* = z_u$
23: else
$24:  z^* = z_l$
25: end If



Figure 8. Sample objects (a tray of slider bars) used in the experiment.

The sample objects used in this experiment are slider bars residing in a tray as shown in figure 8. An example of acquired image by our system is shown in Figure 6.

#### 6.2 Results

We test our slider auditing system with 54 test slider bar images. Our system can correctly read (by OCR) all ID numbers of slider bars.

Some qualitative results on each step of our machine

vision algorithm can be shown in Figure 9. The sample results on the step of Coarse localization of slider bar (section 5.1) can be depicted in Figure 9 (a). The rectangles drawn on the input images are the positions of detected fiducial cross marks. Note that, although some input images are blurred, our system can correctly detect the markers. In Figure 9 (b), we show the results of the step of Autofocus by using SLM (section Autofocus) on the same test images in Figure 9 (a) (after coarse localization of slider bars). Finally, the results of OCR in the ROI of



**Figure 9.** Example of images focusing and OCR reading, (a) The coarse localization of slider bar (b) The focused images by using SLM (c) The OCR results reading by software.

serial numbers are shown in Figure 9 (c).

For the speed of our system, we can report as follows. The time for the robot to move between bar to bar is about 1 seconds. The processing time of our vision algorithm (coarse localization, Autofocus using SLM, OCR) is about 1.5 seconds per image. Totally, the units per hour (UPH) of our system (excluding the time for tray loading by human operator) is about 1,440 slider bars.

The key advantage of our system is the use of autofocusing without any mechanical moving part. This could resolve several issues of mechanical based autofocus, especially on the vibration that occurs during the focus adjustment in which it may disturb the inspecting operation.

The current major drawback of our system is that the intensities of acquired images will significantly decrease as the phase mask on SLM could block some of lights passing through the camera. However, this problem could be mitigated by automatically adjusting exposure times of the camera.

# 7. Conclusion

In this paper, we present an automatic system for auditing HDD slider bars. The system can read the serial numbers of slider bars residing in a tray. These serial numbers are necessary for auditing in several sub-processes of HDD slider fabrication. The key advantage of our system is that we use a non-mechanical autofocus approach in which our imaging system can adjust the focal length of image acquisition by changing the pixel-based phase mask pattern sending to a SLM.

The current system still has some drawbacks that some possible future works can be listed as follows. First, we should explore another focus measure that could be robust to intensity drop due to the images are acquired behind the SLM based phase mask. Second, we could extend our current imaging system into the Extended Depth Of Field (EDOF) approach<sup>13,16</sup> in which we could capture only one image and then with some post processing the image will be in focus.

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