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Precision micro-/nano-machining in a scanning electron microscope by run-to-run control based on image feedbacks

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ABSTRACT

This study aims to perform the micro-/nano-machining with an atomic force microscopy (AFM) tip in a scanning electron microscope (SEM) via run-to-run (R2R) controller and digital image feedbacks. The R2R is assisted by the technique of exponentially weighted moving average (EWMA). This "EWMA feedback" controller is a popular R2R control scheme, which primarily uses data from past process runs to adjust settings for the next run. On the other hand, the digital images are obtained by using the wavelet transform and binarization in order to recognize machining results, and then return feedback of the digital image information to the controller; finally obtain the next input data for the actuating controller to achieve the targeted machining precision. The experimental results for preliminary machining in micro-level indicate that the EWMA controller based on image feedbacks performs with satisfactory results at reducing the process variation, particularly at the first few production runs, thereby making it possible to further reduce the bias and bring the process output closer to its target as soon as the process begins to operate. It is seen that the proposed EWMA controller with digital image feedbacks is easy to implement and provides a good approximation to the optimal variable discount factor, which can reduce the error of the machining process from initial 40% without control to 0.7% with the proposed R2R. More importantly, such a reduction can be achieved at no loss of long-term stability. With sure precision of AFM, the aforementioned resulted micro-machining precision can easily be extended to nano-levels. Therefore, this study demonstrates a successful micro-/nano-machining operation in the environment of a SEM, by employing the designed R2R controller with digital image feedbacks.

1. Introduction

The purpose of this study is to conduct precision micro-/nano-machining by an AFM tip on sample material in a scanning electron microscope (SEM). In general, an SEM is used only for measuring micro-/nano-samples. SEM images are however in this study recorded in digital forms and then analyzed for generating feedback signals to perform precision micro-/nano-machining by atomic force microscopy (AFM) tip. This process is generally called "AFM lithography [1]," which provides an alternative means for precision nanoscale patterning. In this AFM lithography, the AFM is actuated in micro-precision by so-called "picomotors." Note that these picomotors are usually applied to optics experiments, since it can move objectives in nano-level distances with fast motions. In this way of actuation in nanoprecision, the positioning actuation parameters for the piezoelectric motors are tuned herein based on advanced auto-regression methods – the theories of run-to-run control. As results, the micro-/nano-machining in ultra-precision is expected to be achieved.

As mentioned above, a run-to-run (R2R) controller is designed with the assistance from the technique of so-called exponential weighted moving averages (EWMAs) as shown in Fig. 1a, which is probably the most frequently used process control method in the area of industrial engineering [2,3]. The run-to-run controller can be applied to chemical mechanical polishing as shown in Fig. 1b, which achieves well the job of thickness predictions of wafers with over-polishing time [4]. Another study [5] focuses on the design issues of applying the EWMA chart to end-of-line electrical test data and verifies the effectiveness of EWMA chart for detecting process shifts, if the weighing factor is appropriately chosen based on the derived correlation. Recognizing the merits of R2R control and its accompanying technique of EWMA, this study focuses on precise positioning control of the AFM tip driven by piezoelectric motors in a precision machining machine via the R2R control and EWMA. The discount factors for the R2R control is adopted, and how to

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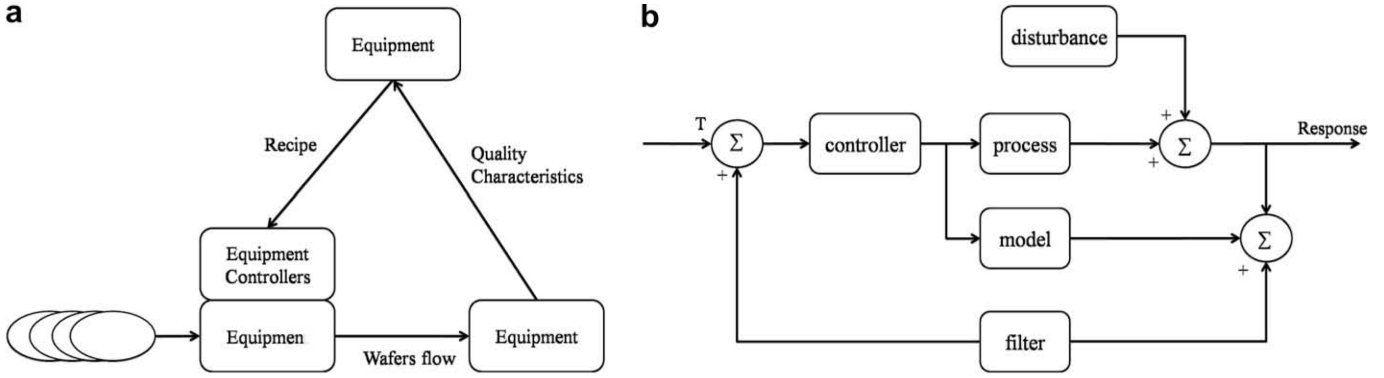

Fig. 1. (a) Framework of a run-to-run controller applied to semiconductor manufacturing. (b) An EWMA-based controller in simple structure of internal model controllers.

choose their values is discussed and determined in this study for the best performance of the micro-/nano-machining [6–8,11]. Experiments in micro-levels are first conducted to verify the predicted performance. With sure precision of AFM, the aforementioned resulted micro-machining precision can easily be extended to nano-levels.

2. System frameworks

This work develops a system to evaluate the performance of the AFM and its driving motors with the R2R feedback controller. This system includes a piezoelectric motor, actuators and the image capturing system. The flow chart of the system framework is shown in Fig. 2. The system is incorporated into the interior of the SEM. In addition, the run-to-run control is applied for the feedback system to control positioning of the actuation system precisely. There are three primary steps to achieve the target by using the feedback system. The three steps are (1) the usage of a typical SEM, (2) the adoption of piezoelectric motors for machining and (3) digital feedback image recognition.

2.1. Scanning electron microscope

In the machining process proposed by this study, the SEM is responsible for monitoring the machining results via providing digital image feedbacks. The SEM is responsible for observing surface stereoscopic structure and takes the digital pictures. The measured items include the surface shape of the sample made of Au coated on a glass substrate. In experiment, a SEM of type JSM-6300 is used. In early stages, this type of SEM generates analog data of image output, but it has capability to switch to output the digital image data. Therefore, we can monitor the images of the machining action on a SEM display in a real time fashion. The function of SEM is to provide the information of images for the designed controller to form the control effort. The feedback information is to monitor the machine action and capture the digital image of the machining results. Therefore, SEM plays a crucial role for this experiment system.

2.2. Piezoelectric motors for micro-/nano-machining

This study develops a system that is capable of performing three-dimensional machining under SEM with precisions in micro- and nano-scales. The proposed system is achieved by actuating two linear piezoelectricity motors and a precise three-dimensional platform supporting an AFM tip made of monolithic silicon. The platform is shown in Fig. 3a. Fig. 3b shows the photo of the platform. Part A of Fig. 3a is the moving platform along x–y direction, part B is the moving platform along z direction, and part C is the linear piezoelectric motors, which are produced by New Focus company [9] and also named as "picomotor." Finally, part D is the rotational piezoelectric motor, part E is the AFM tip holder, and part F is the sample stage. The picomotor can move objectives

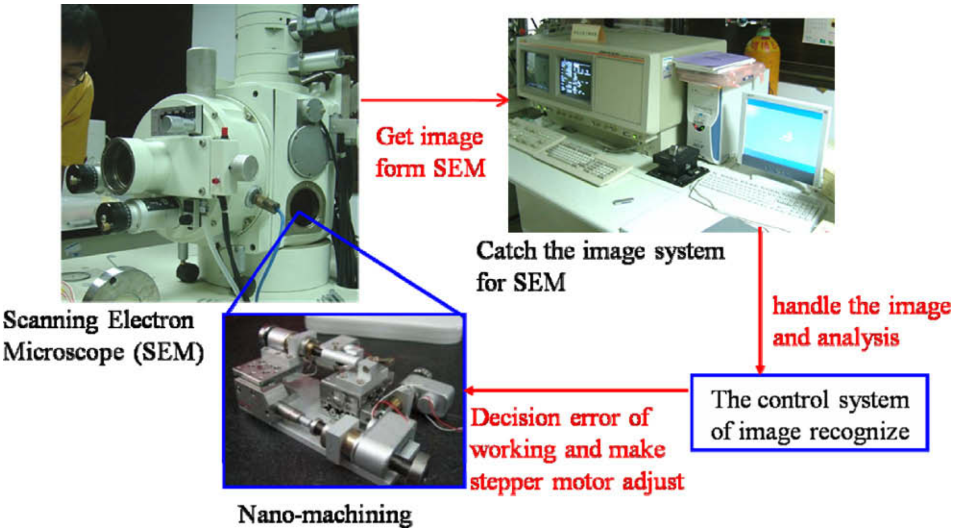

Fig. 2. Operation of the proposed system.

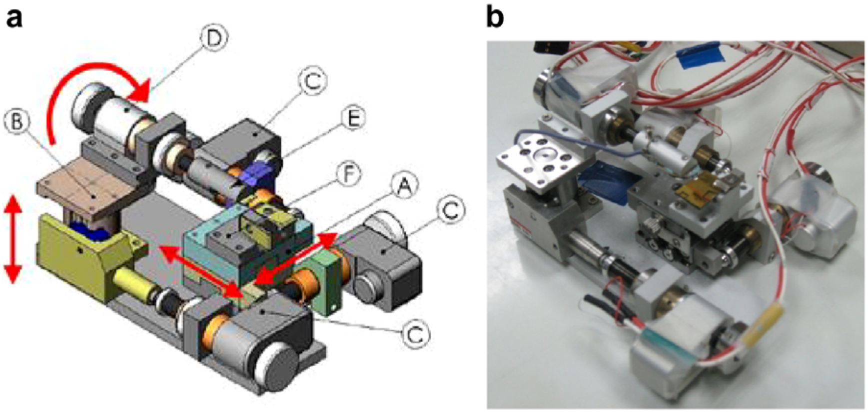

Fig. 3. (a) The positioning platform for AFM tip. (b) Photo of the platform.

in very small steps, as small as 30 nm. The picomotor controller can be used to control the motions of the motors in three directions. On the other hand, the AFM tip is made of silicon with BS-Tap300Al named from Budgetsensors Company [10]. The picomotor clips the tip and positioning the tip to perform carving on the sample, which is made of gold coated on a glass substrate. Fig. 4a shows the assembly of the tip with the positioning platform. Fig. 4b shows a micro-photo of the AFM tip.

2.3. Digital feedback image recognition

To provide the feedback signals for the run-to-run control scheme, an image recognition process is established in this study and then used for capturing the carving errors by the AFM tip. The error is identified by the digital images obtained from the SEM after carving or machining and subsequent analysis. Afterward, the aforementioned developed R2R control technique is adopted to determine the compensating steps of the picomotors. The process of image recognition is shown in Fig. 5.

A typical SEM image with carved marks is shown in Fig. 6a, while Fig. 6b shown a typical cross-section carving profile. When the SEM image is attained, two particular regions of interest (ROI) [11] are selected. ROI 1 contains scaling information of the captured digital image, while ROI 2 covers actual carving information, as shown in Fig. 5. In ROI 1, the template matching approach is used to identify and then disregard the scale in terms of number and units (0–9, μ, n, m). On the other hand, the binarized image in ROI 2 is extracted from the carved line. Then dilation and erosion operations are performed to remove noise and fillings in the small gaps between the adjacent parallel lines. Afterward, a line mask whose length is half of preset length of one horizontal or vertical carved line is used in both horizontal and vertical directions, respectively, to detect the carved lines. Fig. 7a and b shows the preprocessing results of image recognition for vertical and horizontal lines, respectively. Fig. 8 shows the results of binarized and dilation via the previously established recognition program.

2.4. Compensation by run-to-run control

The method of R2R control has been widely used for the manufacturing process, especially in the semiconductor industry. The model of the operation function for R2R theory is applied to eliminate drift effects and variability of the process. In this study, by removing the scaling information and detected line segments, we can calculate the actual lengths of the line segments in μm or nm. The single EWMA controller which is based on the R2R control is employed to perform precision positioning of the nano-machining platform. Considering the micro-/nano-machining process of this study, we formed a simple linear function as follows [8]

$$Y_t = \alpha + \beta X_{t-1} + \varepsilon_t, \tag{1}$$

where Y is the error value between the actual nick length and the target length T, X is the input step quantity, t is a sampling instant, "$t-1$" denotes previous time instant, and the random variable ε_t represents the random variation of the system. In addition, the parameter α is the working error of the system and the parameter β is the gain of working step quantity with actual moving distance.

To obtain the stochastic working model, the regression analysis or the response surface method is often used. The stochastic model becomes

$$\hat{Y}_t = a + bX_{t-1}, \tag{2}$$

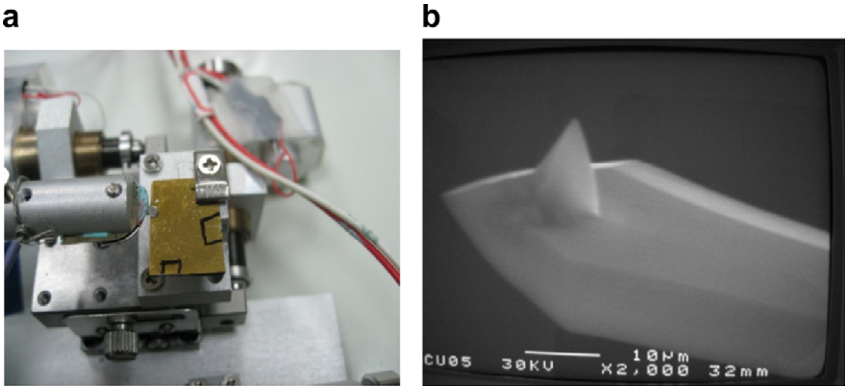

Fig. 4. (a) Assembly of the tip with the positioning platform. (b) AFM monolithic-silicon-based tip.

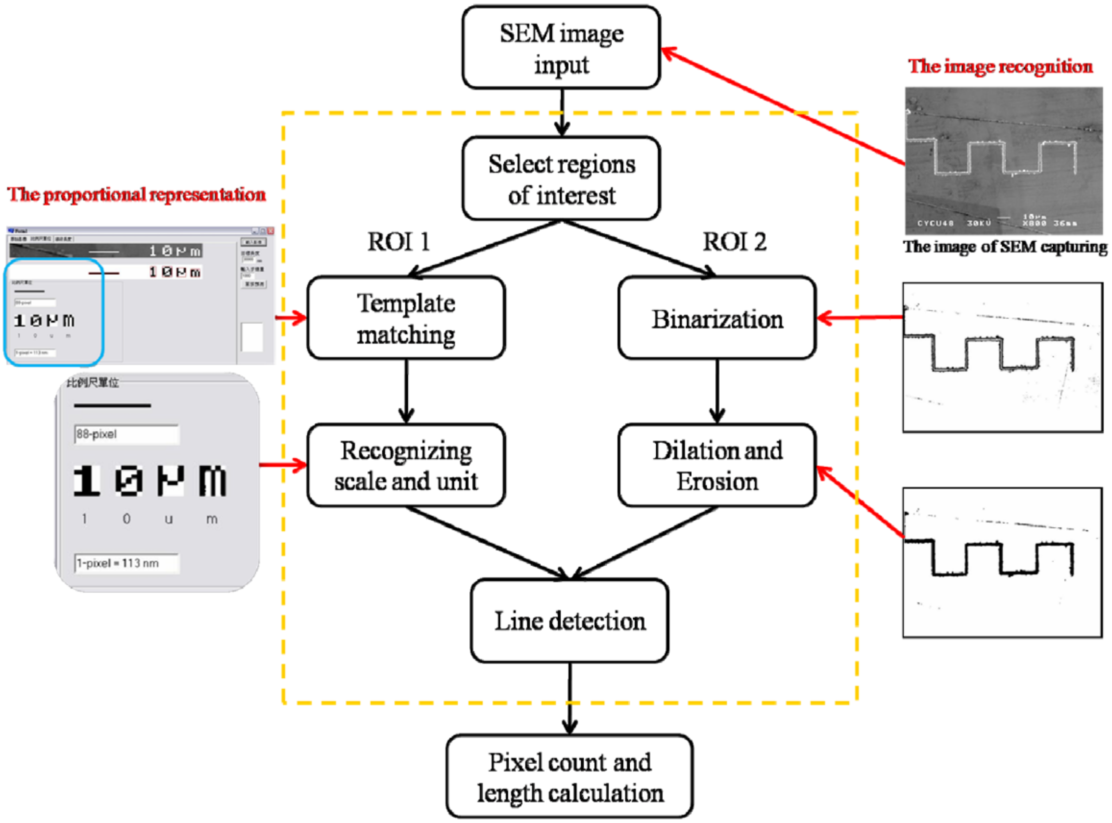

Fig. 5. Process chart of image recognition.

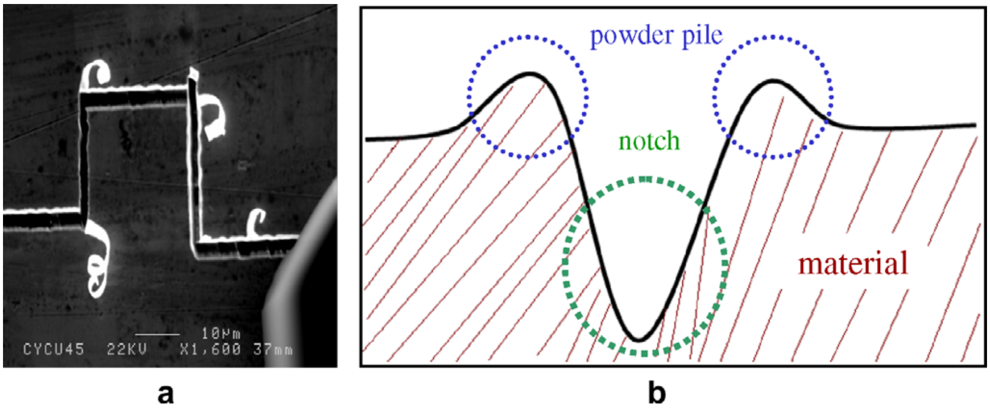

Fig. 6. (a) A typical SEM image with carved marks and (b) a typical cross-section carving profile.

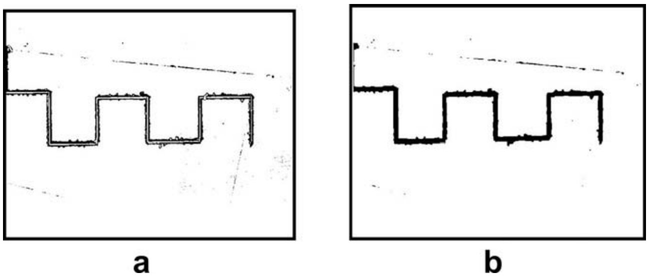

Fig. 7. Preprocessing results of image recognition of vertical and horizontal lines: (a) image binarization; (b) image after performing dilation and erosion (a).

where parameters a and b are the estimates of α and β in the original linear Eq. (1), respectively. Therefore, the system is able to establish a controller with the minimum mean square error as follows:

$$X_t = -\frac{a}{b}. \tag{3}$$

At $t = 0$, the nick length of the nano-machining deviates the target length T by the error

$$\Gamma_0 = \alpha + \left(\frac{\beta}{b}\right)(-a), \tag{4}$$

where Γ_0 is the original deviation to be eliminated by driving the AFM tip to approach the target length and reduce the output variation. Therefore, the system must adjust the input set systematically.

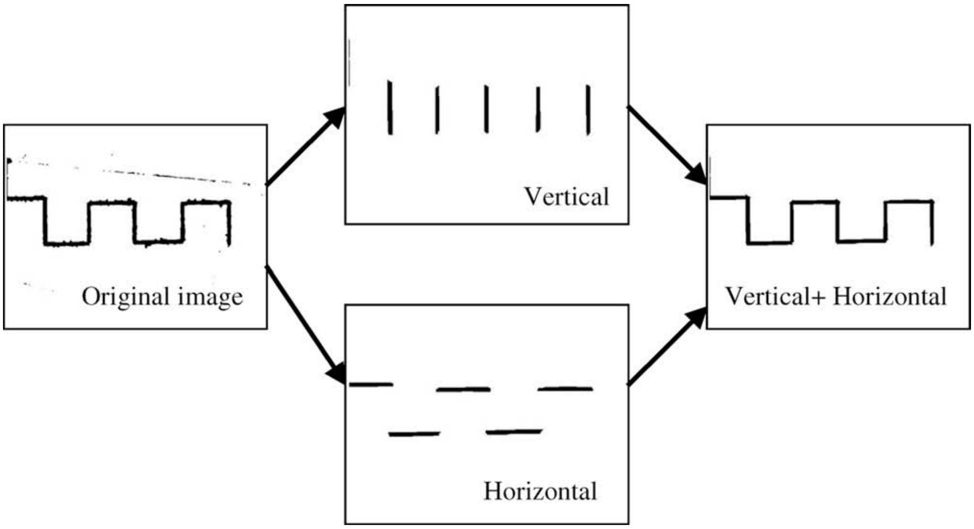

Fig. 8. Vertical and horizontal line detections.

The idea of run-to-run controller adopted herein is to utilize the single EWMA method, where the parameter α of the stochastic model is adjusted continuously. Moreover, by modifying the working input data, the expected working value would approach the target value. However, we need to consider the case when the system obtains the following intercept value

$$a^* = \frac{b}{\beta}(\alpha). \tag{5}$$

Since the model in Eq. (2) does not establish the disturbance effect on the working model, the system makes use of EWMA controller to adjust the parameter of the working model as follows,

$$a_t = \lambda(Y_t - bX_{t-1}) + (1-\lambda)a_{t-1}, (0 < \lambda \leqslant 1) \tag{6}$$

$$X_t = -\frac{a_t}{b}, \tag{7}$$

where $a_0 = a$, and λ is called the "discount factor." Based on Eq. (5), one would obtain the last measure value for next control run. If the information of the further past time is considered, one would give the average of logarithm specific gravity for each several last measure value, thus

$$a_t = \lambda[(Y_t - bX_{t-1}) + (1-\lambda)(Y_{t-1} - bX_{t-2}) + (1-\lambda)^2(Y_{t-2} - bX_{t-3}) + \ldots]. \tag{8}$$

3. Experimental results and discussion

The R2R controller is designed based on image feedbacks to perform square-craving for validation in this section. Experiments in micro-levels are first conducted in this study to verify the predicted performance. With sure precision provided by AFM, the aforementioned resulted micro-machining precision can easily be extended to nano-levels. There are three directions, upward, downward and leftward, considered in this study to carve the lines, which are recognized by subsequently-developed image processing techniques for three directions. Therefore, the machining process was controlled by three controllers. The discount factor in the R2R control is the tuning parameter toward the convergence of the target and become the next input value. Thus, in this study several values of the discount factor are considered and the best of which leads to the highest precision of the machining system is determined. The equipments of feedback system are described in the Section 2. We have prepared the equipments in the following procedures: (1) open SEM vacuum cavity; (2) set the nano-machine in the SEM vacuum cavity; (3) close the vacuum cavity and start the pump vacuum; (4) put in the picomotors for the nano-machining with the picomotor controller and (5) then operate the SEM and the picomotor controller. Once the equipments of the feedback system are prepared for experiment validation, and then the procedures of this experiment are started as in the following steps. The action flow chart of the main experiment operation is shown in Fig. 10. Firstly, we adjust the position of tip and sample, while making sure the tip is able to carve a line on the sample. Moreover the line is cut deep enough for the SEM image. Adjustment of SEM and the positioning of the machine allow picture to focus only on the carving lines, when it is displayed on the SEM display. Secondly, we set a target carved sample of Au to the machine to form a square line with step length of 30,000 nm. Thus the initial input is set as 1000 steps of the picomotor controller. Thirdly, we use the SEM to take resulted pictures when the desired action of machine is completed. Fourthly, we use the developed image recognition techniques to identify the step lengths of the square in the digital image. Fifthly, we use the R2R control based on the technique of EWMA in order to obtain the estimated value of the next input step and compensate the error of the machine process. Finally, the previous steps of experimental procedures are repeated until the desired craving value is reached in the micrometer scale.

Based on the method developed in Section 2.4, the control parameters for R2R control are set as $\alpha = -1000$, $\beta = 28$, $\varepsilon_t = 1$–500, $b = 30$ based a number of simulation trials. The output target

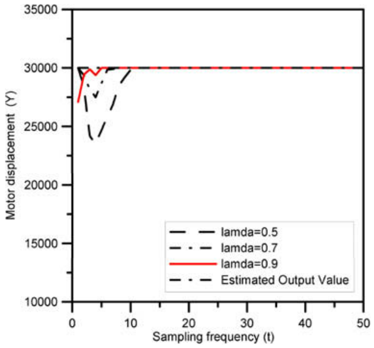

Fig. 9. Simulation results with different discount factors (0.5, 0.7, and 0.9).

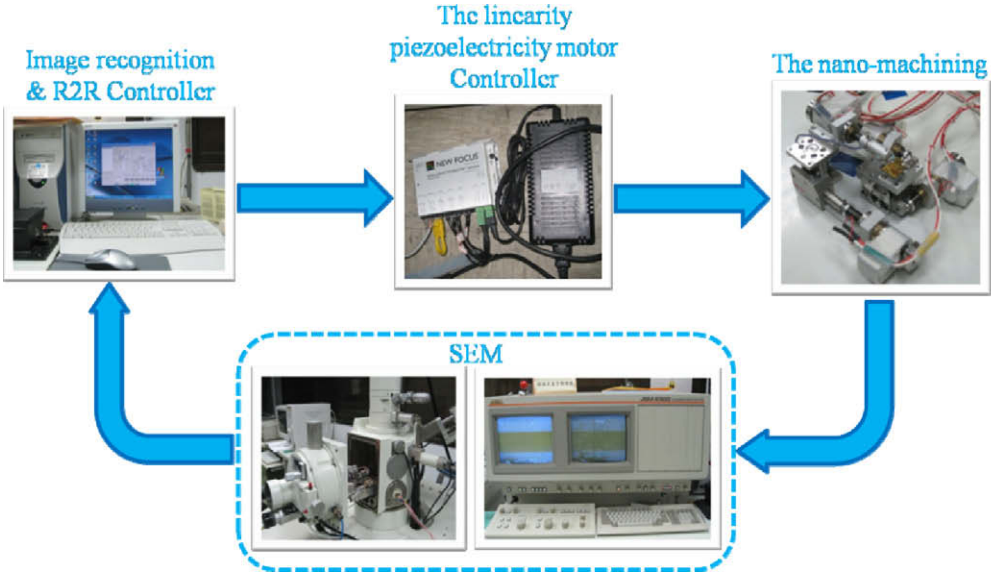

Fig. 10. The action flow chart of experiment operation.

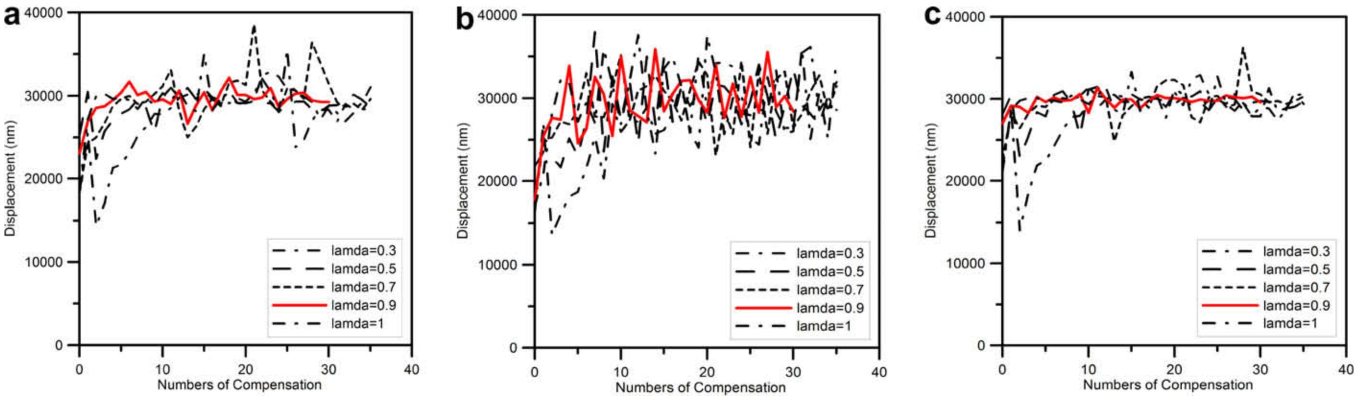

Fig. 11. Experimental data of the AFM tip displacement along (a) upward (b) leftward and (c) downward directions.

is 30,000 nm with the initial input step being 1000 units, in order to simulate the case with the different discount factor $\lambda = (0.5, 0.7$ and $0.9)$. The simulation results are shown in Fig. 9, where it is seen that the discount value 0.9 helps achieve the targeted machined precision in the fastest way. Therefore, it is chosen as the optimal value for compensation in this work. Fig. 11a–c shows the experimental displacements in the upward, leftward and downward directions, respectively. A general comparison between three subfigures reveals that the worse positioning effect appear along leftward direction, in which the AFM is compressed while performing carving. It is also seen from subfigure (a) that the machining precisions for the cases with $\lambda = 0.3$, 0.5, 0.7 and 0.9 converge to 5 um, 2 um, 1 um and 500 nm, respectively, along upward direction. Also seen for $\lambda = 0.9$ is that one can reduce the error from initial 40% in no-feedback case to 0.7% with the designed R2R control. The result shows obviously again that the choice of 0.9, the highest value other than one, as the discount factor leads to the best control performance. It can conclusively stated that this indicates that the designed R2R controller makes possible to achieve much better machining precision as compared to without control, and further to improve the machining precision with better chosen parameters.

4. Conclusions

In this study, an R2R controller based on image feedbacks to perform precision positioning of an AFM tip in a SEM is proposed. Experiments in micro-levels are first conducted in this study to verify the predicted performance. With sure precision of AFM, the aforementioned resulted micro-machining precision can easily be extended to nano-levels. With varied discount factors used, it is found from experimental results that the choice of 0.9, the highest value, as the discount factor leads to the best machining precision – under 500 nm. On the other hand, it is proven that with the designed R2R controller applied to AFM tip in a SEM, one can reduce the error from initial 40% in no-feedback case to 0.7% with R2R control. Therefore, the proposed control method is effective in obtaining satisfactory machining precisions with timage feedbacks.

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References

[1] Z.J. Davis, G. Abadal, O. Hansen, X. Borise, N. Barniol, F. Perez-Murano, A. Boisen, AFM lithography of aluminum for fabrication of nanomechanical System, Ultramicroscopy 97 (1) (2003) 467–472.

[2] James Moyne, Enrique Del Castillo, Arnon Max Hurwitz, Run-to-Run Control in Semiconductor Manufacturing, CRC Press, Boca Raton, FL, 2000.

[3] Sheng-Tsaing Tseng, Arthur B. Yeh, Fugee Tsung, Yun-Yu Chan, A study of variable EWMA controller, IEEE Transactions on Semiconductor Manufacturing 16 (4) (2003).

[4] An-Zhi Su, Off-line Application of Run-to-Run Control for Chemical Mechanical Polishing, Master Thesis, Department of Chemical and Materials Engineering, Chang Gung University, 2003.

[5] Jr-Min Fan, Ruey-Shan Guo, Shi-Chung Chang, Jim-Huei Lee, Abnormal trend, detection of sequence-disordered data using EWMA method, in: IEEE/SEMI Advanced Semiconductor Manufacturing Conference, 1996.

[6] James V. Beck, Kenneth J. Arnold, Parameter Estimation in Engineering and Science, Wiley, New York, 1977.

[7] George E.P. Box, Time Series Analysis Forecasting and Control, Prentice Hall, Englewood Cliffs, NJ, 1994.

[8] Enrique Del Castillo, Statistical Process Adjustment for Quality Control, Wiley, New York, 2002.

[9] New Focus Company, <http://www.newfocus.com/>.

[10] Budget Sensors Company, <http://cerncourier.com/>.

[11] R.C. Gonzalez, R.E. Woods, Digital Image Processing, second ed., Prentice-Hall, 2002.