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Feature Referenced Tip Localization in Robotic Nano Manipulation

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***Abstract*— One of the prerequisite conditions for making a successful manipulation is that the relative position between the AFM tip and the objects can be sensed and controlled accurately. While this prerequisite is grandly hampered by the PZT nonlinearity and thermal drift. Although the PZT nonlinearity can be compensated to a certain extent through mounting a position sensor on the PZT scanner, this method leads to a higher system noise and a higher cost. In addition, this method can not handle the positioning error caused by thermal drift due to the lack of sensing ability to the displacement between the AFM tip and the sample stage. This paper propose a newly developed strategy to solve these problems. Its pivotal idea is the tip position is localized based on the sensing information to sample features, not PZT driving voltage or sensor signal. In this way, the positioning error aroused from PZT nonlinearity and thermal drift can be effectively suppressed. Experimental results demonstrate the advantage and effectiveness of the proposed method.**

***Index Terms*— Thermal drift, PZT nonlinearity, Local scan, Nanoassembly.**

I. INTRODUCTION

The ultimate goal of nanotechnology is to fabricate systems and devices at nanoscale with unprecedented properties that traditional technologies cannot achieve. The critical needs to approach this goal are technologies that can observe objects at nanoscale, manipulate nano-objects with high accuracy and efficiency. The advent of Atomic Force Microscopy (AFM) [1] provides such a promising approach that meets the requisites. Taking advantage of its probe based imaging in observing objects with ultra high resolution and precision, AFM has the potential as a nanomanipulation tool to assemble devices at nanoscale.

In the past ten years, building nanostructures using AFM in air even in biological conditions has been successfully demonstrated for the study of energy transport [2], nano-device properties [3], ligand-receptor binding force [4] and so on, through which some new phenomenon is discovered and a deeper understanding to the biological mechanisms at nanoscale is obtained. As AFM is originally developed for imaging and characterization of surface, there are challenging problems when using it for nanomanipulation. Although these challenges have been solved to a certain extent after more than a decade's efforts by researchers worldwide [5][6][7][8], we are still afflicted with the lack of the abilities to locate the probe accurately relative to the objects or other objects being moved. This problem is mainly caused by two issues: PZT nonlinearity and thermal drift, which are the staple roadblocks hindering the efficiency and effectiveness of AFM based nanomanipulation currently.

PZT nonlinearity is mainly due to the hysteresis and creep characteristics of Piezo material. There are two common used methods to handle this problem: one is model based compensation, another is sensor based close-loop control. As for the model based compensation, different groups develop different methods, such as the inverse model method [9], iterative control approach [10], Preisach model [11] and so on. While the performance of these methods strongly depend on the parameter quality, obtaining reliable parameter value proved to be a difficult task especially for the common AFM user. Furthermore, poor robustness of model based compensation makes accurate positioning extremely hard in arbitrary manipulation condition. Thus researchers began to pursue close-loop method for getting highly reliable and robust compensation effect. Both Veeco company in USA and PI company in Germany commercialized PZT scanners with three-axis close-loop based on optic or capacitance principle respectively. Closed loop control can offer better compensation, but is a more expensive option and leads to a higher noise level. Moreover, the position sensor in use today can not compensate the positioning errors aroused from thermal drift. Fig. 1 shows the schematic diagram of sensor based close-loop control for PZT nonlinearity compensation. From this picture we can see, since the position sensor is mounted on the AFM scanner, only the displacement relative to the scanner central-axis can be sensed, that is, accurate positioning can only be guaranteed in the tip coordinate. The relative position between the tip and substrate can not be sensed, thus the positioning error aroused from thermal drift is still a challenging problem in AFM based nanomanipulation.

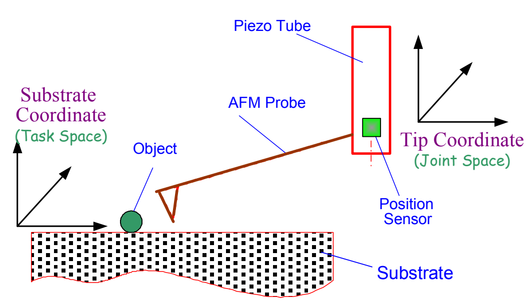

Fig. 1. Schematic diagram of traditional sensor based close-loop control for PZT nonlinearity compensation.

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The thermal drift is caused by many factors such as the contraction and expansion of the mechanical system due to temperature variety, humidity change and so on [12]. The traditional way to overcome these problems is running image scan first for a couple hours in a confined environment before manipulation, which is inconvenient and inefficient. Currently, due to lack of the physical sensor to detect the displacement between AFM tip and the substrate, there is no way to compensate the thermal drift in close-loop manner. It has to be handled through model based estimation and compensation, such as a Kalman filter is developed in [13] and a neural network is suggested in [14]. However, these methods are model based compensation, whether the compensation is successful or not lies on the degree of the model's accuracy, it is not easy and also takes time to obtain the accurate model parameters. Thus thermal drift is still a stumbling block in AFM based nanomanipulation.

This paper proposes a new method to eliminate the positioning errors aroused from PZT nonlinearity and thermal drift simultaneously without needing a position sensor. Its key idea is that the tip position is localized not based on the PZT driving signal, but the features of the sample surface. Here the feature to the AFM tip can be likened as landmark to a mobile robot in a pre-known environment. In this way, not only can the spatial error aroused from the PZT nonlinearity be greatly suppressed, but the influence from thermal drift be get rid of due to the servo function of the referenced feature to the thermal drift. The experimental results demonstrate the advantage and effectiveness of the proposed method.

II. Graphical Explanation to the Method

To make the idea more clearly, a graphical explanation is drawn as shown in Fig. 2. S delegates the starting point, and T delegates the target destination. A mobile robot starts from S and needs arrive destination T. For distance based navigation method, the robot has to have a high quality distance sensor which can measure the displacement accurately, through which the robot can locate and navigate itself to the destination. Obviously, this method has a higher request on the sensor performance. For feature referenced navigation method, the robot localizes itself with the feature as coordinate reference. As shown in Fig. 2, since the location and the relative locations of the features are pre-known, the robot can navigates itself to the destination with the feature as guidance. In this way, the request on the sensor performance can be lowered to an curtain extent.

The process for AFM tip localization is similar with above description. Due to the PZT nonlinearity and thermal drift, it is difficult to locate the tip position based on the actuator driving signal or the sensing information from the sensor mounted on the AFM scanner. As nanomanipulation is carried out on the sample surface with pre-known morphology, the sample features can be selected as coordinate references to localize and navigate the AFM tips.

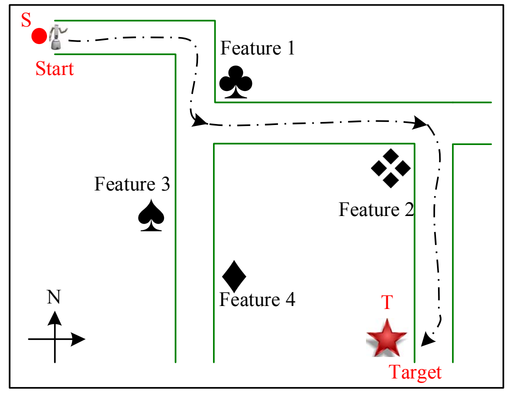


Fig. 2. A graphical explanation to the feature referenced tip localization

III. Reference Feature Selecting and Map Building

Since the feature is sensed through the 'touching' information of local scan [8], the minutia of feature may be lost due to the fast scan speed. Thus, the feature selected for localization reference should have distinct character and high signal-to-noise ratio, which make features be sensed easier under the condition of losing minutia. After the referenced feature are selected, a map is built to describe their relative locations. To make our point more clear, an example of selecting nanoparticle as reference feature is used to explain the map building strategy. Fig. 3a shows several nanoparticles with diameter 350nm are randomly deposited in the polycarbonate surface. From this picture we can see, the height signal of nano-particles has distinct character and high signal-to-noise ration. After they are selected as reference features, their topological relation can be expressed as shown in Fig. 3b. To make these relations easy be expressed in computer, two adjacency matrixes, whose elements delegate the relative location between any two feature reference, are built as following:

$$\delta = \begin{bmatrix} 0 & w_{12} & w_{13} & w_{14} & w_{15} \\ w_{12} & 0 & w_{23} & w_{24} & w_{25} \\ w_{13} & w_{23} & 0 & w_{34} & w_{35} \\ w_{14} & w_{24} & w_{34} & 0 & w_{45} \\ w_{15} & w_{25} & w_{35} & w_{45} & 0 \end{bmatrix}$$

$$\theta = \begin{bmatrix} 0 & \gamma_{12} & \gamma_{13} & \gamma_{14} & \gamma_{15} \\ \gamma_{21} & 0 & \gamma_{23} & \gamma_{4} & \gamma_{25} \\ \gamma_{31} & \gamma_{32} & 0 & \gamma_{34} & \gamma_{35} \\ \gamma_{41} & \gamma_{42} & \gamma_{43} & 0 & \gamma_{45} \\ \gamma_{51} & \gamma_{52} & \gamma_{53} & \gamma_{54} & 0 \end{bmatrix}$$

Here w_{ij} and γ_{ij} means the relative distance (unit: μm) and azimuth angel (unit: radian, range from -π to π) between feature i and j respectively. The inset of Fig. 3b shows the definition of azimuth angel (the angle between the vector direction and the horizontal line). Through these two matrixes, the relative location between any two features can be uniquely determined.

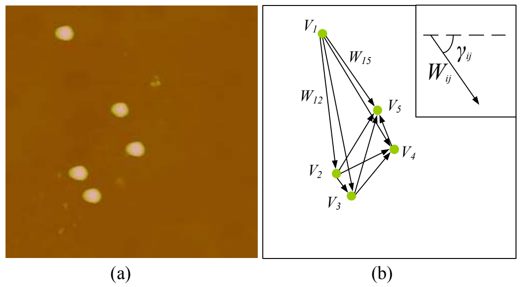


Fig. 3. Landmark based map building

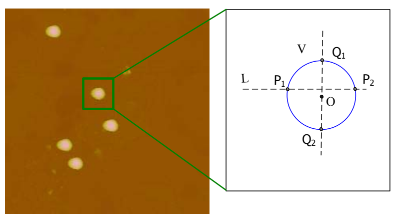


Fig. 4. Local scan based feature sensing

IV. Feature Sensing and Identifying

The prerequisite of tip localization is that the reference feature can be sensed and identified first. Here a local scan strategy is developed to approach this goal. Local scan does not scan the whole local area line by line, but just scan several lines following an optimized scan pattern, through which the nominal position of feature can be sensed. For example, if the nano-particle is selected as reference feature, its nominal position can be determined by two scanning lines. As shown in Fig. 4, the first scanning line forms two intersections with the boundary of the particles such as P_1 and P_2, then the second scanning line goes through the midpoint between P_1 and P_2, and perpendicular to the first scanning line. The second scanning line V also forms two intersections with the boundary of the particle, Q_1 and Q_2. The nominal center of the nanoparticle is located at the midpoint between Q_1 and Q_2. Due to the PZT nonlinearity and thermal drift, the nominal position does not delegate the true position of nanoparticle. The mapping relationship of the sensed nanoparticle to the map needs to be further determined.

Since several reference features may have the same geometry (such as nanoparticles have the same height and radius). It is difficult to find out in the map which feature is the sensed one. An additional speculation is needed to further identify the mapping relationship of the sensed feature to the map. The feature nominal position gives help to solve this problem. Considering the nonlinear character of PZT, although the output displacement is not unique to some certain input voltage, but it falls into a certain range. As shown in Fig. 5, for a input voltage V_{input}, although the actual displacement P_v of PZT scanner can not be determined, it falls into the so called unsure band range from

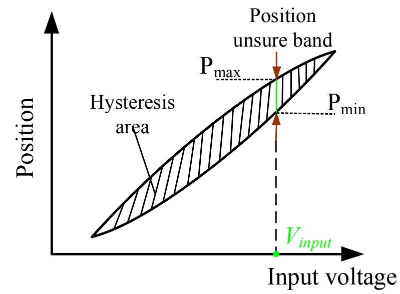


Fig. 5. The nonlinear voltage-displacement character of PZT scanner

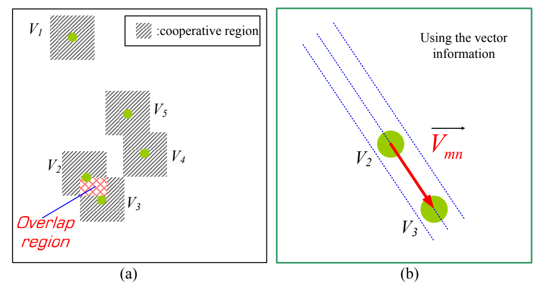


Fig. 6. Local scan based feature identifying. (a) Each feature is assumed to have a cooperative region as the dark area shows. (b) Vector information between two features obtained through local scan.

P_{vmin} to P_{vmax}. Combining this property with the sensed feature nominal position , the mapping relationship can be deduced through the following process. Firstly, each feature is assumed to have an cooperative region based on the unsure band, for example, if P^i is the position of reference feature i, then the corresponding cooperative region is determined by the range of $[P^i_{min}, P^i_{max}]$ as the dark area shown in Fig. 6a. P^i_{min} and P^i_{max} are the minimum and maximum displacement value of the unsure band corresponding to position P^i, and can be determined through experiments. If P_{nom}, which is the nominal position of the feature sensed by local scan, uniquely belongs to a cooperative region, it can be inferred that the feature sensed by local scan is the one corresponding to this cooperative region. Else if P_{nom} belongs to one or more cooperative regions, for example, P_{nom} falls into the overlap region of feature V_2 and V_3 as shown in Fig. 6a, it will be difficult to recognize which one is the sensed feature due to the same geometry of V_2 and V_3. Then an additional local scan is performed to get the vector information of these two features, such as the vector $\overrightarrow{V_{mn}}$ shown in Fig. 6b. The corresponding feature i and j should satisfy the following equation:

$$\min\{\mu(\|\overrightarrow{V_{mn}}\| - w_{ij}) + (1-\mu)(\arg\overrightarrow{V_{mn}} - \gamma_{ij})\} \quad (1)$$

Here μ is the adjustable coefficient to balance the weight between distance error and azimuth error. w_{ij} and γ_{ij} are the elements in the adjacency matrixes of the map.

V. Feature Referenced Tip localization

Even the mapping relationship of the sensed feature to the map is determined, there is still a problem to locate the tip in arbitrary position. As shown in Fig. 7a, the coordinate reference is not continuous in a feature based coordinate, which means only in the point with a reference feature the tip position can be sensed accurately. How to locate the tip in an arbitrary position? such as point B shown at the horizontal axis in Fig. 7a. The following strategy gives solution to this problem: since the accurate position of the identified feature is pre-known, the tip can be localized once its relative distance to the feature is measured. Fig. 7b show the schematic diagram of this method. The solid circles delegate feature reference, the straight lines generated by local scan acts as metrological ruler. Once the relative distance to the feature is determined, the tip can be located through simple vector calculation.

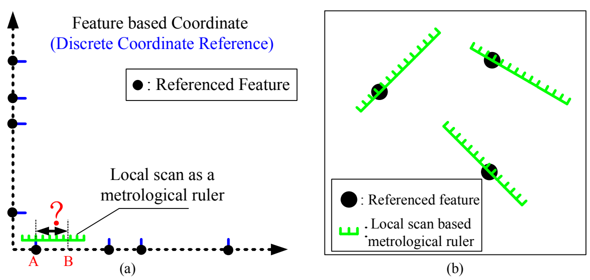


Fig. 7. (a) The coordinate reference is discrete in a feature based coordinate. (b) Local scan as a metrological ruler

To let local scan act as a metrological ruler, the distance between any two points at the scan pattern should be pre-known. While this prerequisite is hindered by the nonlinearity of PZT scanner. Fortunately, the pre-determined local scan pattern makes the compensation of PZT nonlinearity feasible. Several documents address different compensation method for the case that the motion behavior of PZT scanner is pre-designed [15]-[17]. Here we propose a patented PZT linear method. As shown in Fig. 8a, when a linear waveform voltage is applied to the PZT scanner, a nonlinear displacement is generated. It is difficult to determine the relative distance without accurate PZT voltage displacement relationship. While, a linear displacement can be generated through applying an nonlinear waveform voltage to the PZT scanner as shown in Fig. 8b. The detail about this linearization method can be found in [18]. The advantage of this method is that the waveform generation equation has been normalized. Voltage waveform corresponding to any desired scan pattern with linear displacement can be obtained without further calibration. By applying this nonlinear voltage waveform, the displacement from current tip position to the feature can be measured through recording the time interval in between during local scan.

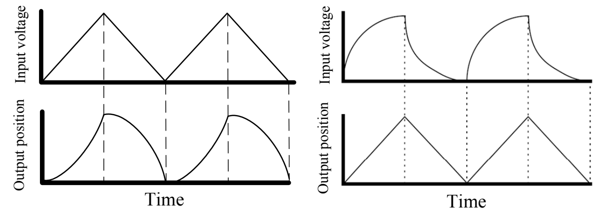


Fig. 8. The relationship between the input voltage and the output displacement of PZT scanner. (a) A linear input results in a nonlinear output. (b) A corrected nonlinear input results in a linear output.

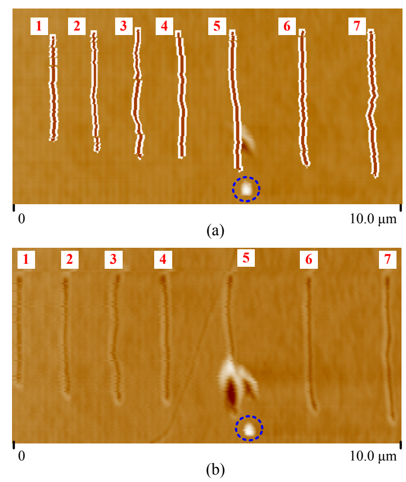


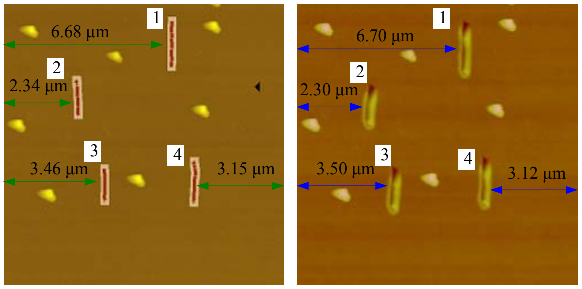
Fig. 9. Tip localization experiment without using feature referenced method: (a) Target position displayed in the interface, (b) Real position in nano-environment through a new image scan.

VI. Experimental Results and Discussion

The experiments were performed in an ambient condition. The experimental system is mainly consists of a Bioscope AFM (Vecco Inc., Santa Barbara, CA) with a scanner which has a maximum XY scan range of $90\mu m \times 90\mu m$ and a Z range of $5\mu m$, and some peripheral devices including a haptic device (Phantom, Sensable Company, Woburn, MA), a Multifunction Data Acquisition (DAQ) cards NI PCI-6036E (National Instruments) and three computers.

A. PZT Nonlinearity Compensation

During manipulation with nano robotic system, the meaningful aim of realizing accurate probe positioning is to enable the probe position displayed on the visual interface to be consistent with that in real nano-environment, that is, when the symbol representing the probe's position moves to a predefined point on the visual interface, the probe should also move to the corresponding point in the real nano-environment. Here we use the inscribing method to record the tip position in the real nano-environment. That is, after the tip is moved to the target position, the probe is pushed down and inscribing on the sample surface. Through comparing the target position in the interface with the position in the real nano-environment, the compensation effect to PZT nonlinearity can be proved.



(a) (b)

Fig. 10. Tip localization experiment under the assistance of feature referenced method, scan size: $10\mu m \times 10\mu m$. (a) Target position displayed in the interface, (b) Real position in nano-environment obtained from a new image scan.

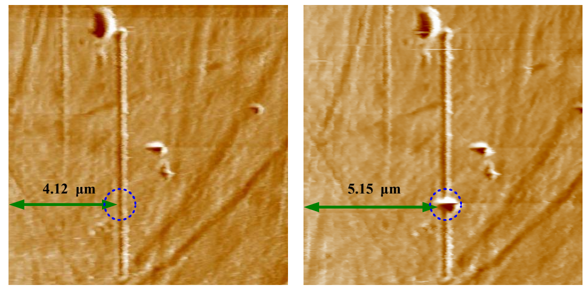
Fig. 9 shows the experimental result without using feature referenced tip localization method. Fig. 9a is the real time display on the visual interface. Fig. 9b is the inscribing result obtained from a new image scan. The labeled number shows the corresponding relation of the inscribing lines between the visual display and the true result. The white point in the figure is the positioning symbol. Obviously, the visual display can not match the true inscribing results, which means there are seriously positioning errors due to the PZT nonlinearity.

Fig. 10 shows the experimental result under the assistance of feature referenced tip localization method. As shown in Fig. 10a, several latex particles (with diameter 350nm) randomly deposited on the polycarbonate surface, which are selected as the artificial feature in feature referenced tip localization. During the interval of manipulation, the tip keeps local scan to sense these reference features. Once the feature is sensed and identified, the tip position can be uniquely determined by using the feature as the coordinate reference. Fig. 10b shows the inscribing result obtained from a new image scan. The measurement lines show that the PZT nonlinearity can be greatly depressed with the feature referenced tip localization method.

B. Thermal Drift Compensation

Thermal drift due to the expansion or contraction of mechanical systems is another stumbling block in AFM based robotic nanomanipulation, which makes the accurate tip positioning extremely hard since there are no available close-loop method that can deal with this issue.

As shown in Fig. 11a, a nano-hollow needs to be punched at the circle point of the snick line. For distance based positioning method, even the PZT nonlinearity can be compensated very well, the task can not be finished successfully if there is a displacement between the tip scanner and the sample stage. While this problem can be solved by the feature referenced method. To demonstrate the effectiveness of the proposed method, we manually generate a randomly displacement between the tip scanner and the sample stage through moving the sample stage right towards a curtain distance. In feature referenced tip localization method, the feature of snick with curtain depth is selected as reference to localize the tip position. The local scan result for feature sensing is shown as in Fig. 12. After the feature position is sensed by the first scan line (black), the tip makes another scan following the topography of the first scan, and punches a hole at where the feature is sensed. Fig. 11b shows the final result, through which we can see the positioning error aroused from the random drift can be get rid of well with the paper proposed method.



(a) (b)

Fig. 11. Landmark based localization under the condition of huge drift, scan size: $10\mu m \times 10\mu m$. (a) Before manipulation. (b) After Manipulation.

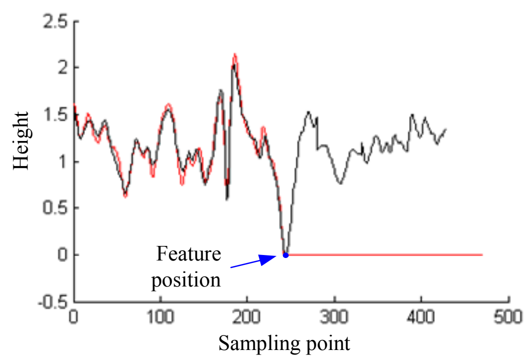


Fig. 12. Local scan result for sensing the feature. The valley point delegates the target position.

C. Discussion

Fig. 10 shows that tiny mismatch exists between the visual display and the true manipulation result. This may be caused by several possible reasons: Firstly, the nanoparticles may not be perfect circles, the true center can not be exactly located through the local scan method proposed in section IV, which will result in a position error in the visual display interface. Secondly, the exactly distance between any two points obtained by metrological local scan may not be true, since it is calculated through a mathematic equation, further calibration process is still needed to make this measurement higher accuracy. Thirdly, low density of features in the sample surface and the relative bigger size also render this mismatch. High feature density means more coordinate reference, sharp size of feature means lower measure uncertainties. Both of them will increase the positioning accuracy.

VII. Conclusion

Nonlinearity of PZT scanner and thermal drift are the main bottlenecks for locating the tip accurately in AFM based nanomanipulation. In this paper, a feature referenced tip localization method has been proposed to solve this problem. By using the feature selected from sample surface as coordinate reference, the tip position is not retrieved from the voltage-displacement relationship of PZT scanner any more, thus the positioning error aroused from PZT nonlinearity can be greatly suppressed. In addition, since the tip is localized through measuring the relative distance to the features set in the sample surface, the tip-displacement has nothing to do the tip localization, thus the positioning error aroused from thermal drift can also be get rid of. This proposed method has great potential application since it can be used for majority of AFM systems in use today without needing a position sensor.

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