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Mobile microscope: A new concept for hand-held microscopes with image stabilization

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Abstract— **In this paper, we propose the concept of a "mobile microscope". This is a hand-held microscope that can be used for observation in various places. Because microscopes which have a small observable area and are vulnerable to vibrations, images from hand-held microscopes are usually blurred. We propose a method of stabilizing images from a microscope which are affected by shaking, and we use the method to realize a mobile microscope. The method is based on high-speed visual feedback with an inclined image sensor for measuring the 3D movements of the microscope. We developed a prototype microscope system, without a built-in actuator, by employing this method. Experimental results showed that images from the hand-held microscope could be stabilized by our method.**

I. INTRODUCTION

Small, hand-held microscopes containing an objective lens, an image sensor, and a source of illumination are now commercially available [1]. However, those microscopes are not ideally suited for hand-held observations because the images tend to be blurred by shaking. The observable area of such microscopes is small and is too difficult to be aligned with a target by hand. This issue becomes even more pronounced when the magnification rises, and if the microscope is not secured on a stage, observation is practically impossible.

Here we propose a "mobile microscope" that stabilizes images by measuring vibrations of the microscope due to hand shaking and by controlling the focal plane position dynamically to cancel out the vibrations. With this microscope, various targets within the reachable range of a user's hand could be clearly observed, as shown in Fig. 1. In addition, the versatility of the mobile microscope is extremely high. For example, it should be possible to readily perform on-site observation of the surfaces of large objects such as buildings which cannot be placed on stages, as well as the inside of complex machines (for example, jet engines), to improve the reliability and efficiency of examination.

In a mobile microscope, it is necessary to stabilize vibrations of the microscope body. Therefore, it is first necessary to measure and cancel out the movements of the microscope.

The microscope has six degrees of freedom: translations in three dimensions and rotations around each axis. Because the working distance of the microscope is small and rotations are normally smaller than translations, the rotations around two axes orthogonal to the optical axis can be disregarded. The rotation around the optical axis is small and can be cancelled easily. Therefore, it is only translations in three dimensions (x and y shifts on the image plane and focusing in the z direction) that cause blurring and shaking of the images.

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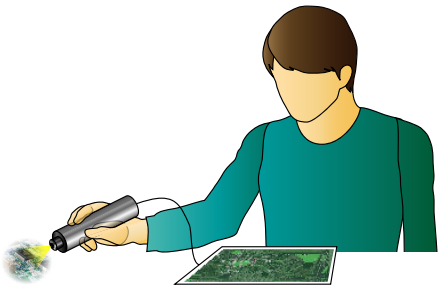

Fig. 1. A conceptual image of the mobile microscope.

Blur-correction technologies for camera shake have been studied [2] [3]. However, because such blur-correction technologies are designed for cameras with a large depth of field, correction of shifts in the focusing direction is not considered. These technologies are not suitable because they lack the focus correction needed for a mobile microscope, which has a very shallow depth of field.

We measured the speed of vibrations due to hand shaking in a preliminary experiment to be about 6 mm/s. On this basis, some requirements are as follows. The observation area should be kept fixed with an accuracy of micrometer order for stability of the image. Therefore, the frequency of the image sensor should be several thousand hertz. Thus, we propose a microscope image stabilization method based on high-speed visual feedback, in which the microscope's position is measured from captured images by a high-speed vision system having an inclined sensor. This technique is an extension of the concept known as micro visual feedback (MVF) [4], which is a control technique based on high-speed visual feedback using microscope images.

The effectiveness of our proposed technique was shown by constructing a prototype system and conducting image stabilization experiments.

We also developed an object finding and tracking application of the mobile microscope, showing that the mobile microscope is capable of various functions.

II. IMAGE STABILIZATION METHOD

Our image stabilization method involves controlling the microscope's focal plane. The difference between the microscope's observed position and the target position is made zero using a feedback system. Displacements of the microscope

are measured from images acquired by the installed high-speed vision system. As a result, the target area is always projected on the sensor of the microscope, and stable images can be acquired.

First, it is necessary to perform three-dimensional displacement measurement of the microscope from the acquired images, which is explained below. Because the mobile microscope needs to be compact, we decided to use only one high-speed vision system for displacement measurement. The observed object is assumed to be on a plane perpendicular to the optical axis.

One high-speed vision system provides only one image at a time. With a sensor which is perpendicular to the optical axis, information about movements parallel to the sensor can be obtained from one image. However, information about movement along the optical axis cannot be obtained. Therefore, information about how far away the microscope is from the object in the optical axis direction is necessary. To determine the three-dimensional displacements of the microscope from one image, the sensor was inclined with respect to the optical axis of the microscope. Thus, the microscope displacement in the optical axis direction can be determined from the position of an in-focus area in the image. In addition, the displacements in the directions perpendicular to the optical axis can be measured within the in-focus area.

Carpenter [5] proposed and Scheimpflug [6] formulated the idea of inclining the optical system with respect to the optical axis. More recently, Ishii [7] proposed a system with an inclined sensor that measures the three-dimensional structure of objects. In our research, however, it is necessary to detect the displacements in two directions perpendicular to the optical axis at the same time; our work differs from Ishii's in this respect.

A. Displacement Measurement in Optical Axis Direction

If an object which is perpendicular to the optical axis is observed with the microscope, a limited area on the inclined sensor is in focus but other areas are not, as shown in Fig. 2. Therefore, the displacement of the microscope in the optical axis direction can be determined from the position of the in-focus area in the image. The position of the in-focus area is detected with a high-pass filter.

Consider the situation where the inclined sensor intersects an image at the center of the sensor, as shown in Fig. 3. The z axis and the ζ axis are taken as shown in the figure. Let θ be the angle from the optical axis to the sensor, let d be the distance between each pixel, and let M be the optical magnification.

A zonal part (red part in figure) near the center of the image obtained with the sensor is in focus, as shown in the upper right of Fig. 3. A z movement of the microscope in the opposite direction along the optical axis makes the image approach the lens, as shown in the lower part of Fig. 3. At this time, the in-focus zonal part on the image shifts by distance l from the center of the image in the direction of $-\zeta$. Let ζ be the position at which the sensor and the image

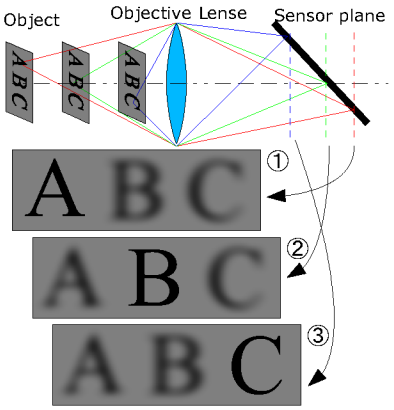

Fig. 2. Displacement of the microscope along the optical axis direction causes an in-focus area to move.

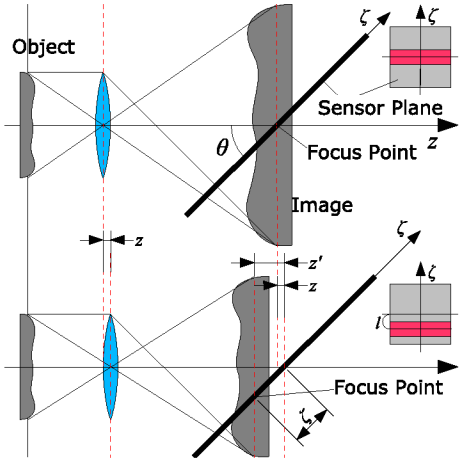

Fig. 3. The position of the in-focus area gives the displacement in the optical axis direction.

intersect, and let z' be the displacement of the image in the direction of the optical axis. Then we obtain the following equations:

$$\zeta = ld \tag{1}$$

$$\zeta = -\frac{z'}{\cos\theta} \tag{2}$$

$$z' = M^2 z \tag{3}$$

$$\Rightarrow z = \frac{-ld\cos\theta}{M^2}. \tag{4}$$

B. Displacement Measurement on Images

Displacements in the directions perpendicular to the optical axis are measured using template matching[8] on the in-focus part.

First, an image of the target is saved as a template. Next, images from the microscope are each matched with the template, yielding the 2D-coordinates of the target position in the image.

The matching score employs correlations between an image and the template. Let T be the template matrix, whose

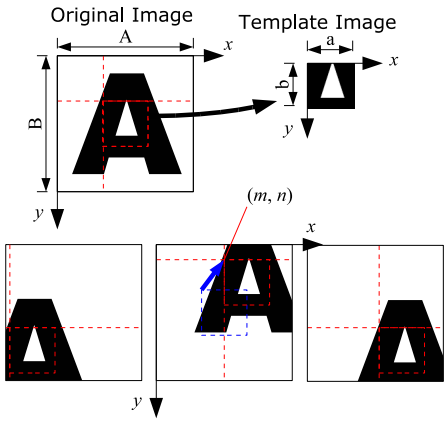

Fig. 4. Template matching.

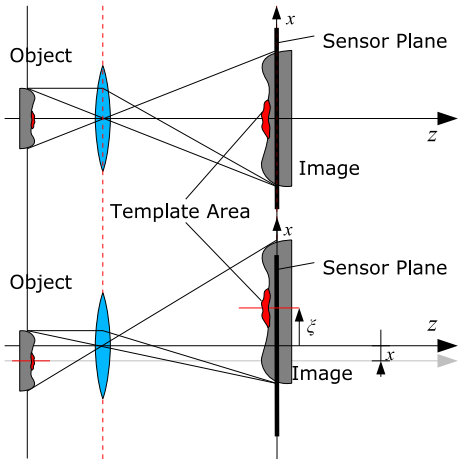

Fig. 5. The matching point gives the displacements.

size is $a \times b$, and let I be the image matrix, whose size is $A \times B$, as shown in Fig. 4. The score N indicating the degree of match between the position (x, y) in I and the position $(0, 0)$ in T is

$$N(x,y) = \sum_{i=1}^{a} \sum_{i=1}^{b} I(x+i, y+j)T(i,j). \tag{5}$$

Suppose that $N(m, n)$ is the highest score in N. Let d be the distance between each pixel, let M be the optical magnification, and let ξ be the position on the sensor which corresponds to (m, n) in I, as shown in Fig. 5. Then, the displacement x of the microscope in the x axis direction is given by the following equation:

$$\xi = -md \tag{6}$$

$$\xi = Mx \tag{7}$$

$$\Rightarrow x = \frac{-md}{M}. \tag{8}$$

Likewise, the displacement in the y axis direction is given by the following equation:

$$y = \frac{-nd}{M}. \tag{9}$$

Thus, the position where the template matched provides the displacements of the microscope in the directions perpendicular to the optical axis.

C. Image Stabilization by Displacement Measurement in Three Directions

A combination of the above-mentioned microscope displacement measurements enables image stabilization. The image stabilization for fixing the observation point consists of two stages, described in turn below.

1) First Stage: Focusing : First, the amount of displacement of the microscope in the optical axis direction is determined. Then, the microscope is controlled to cancel this displacement. As a result, the center of the acquisition image can be kept in focus.

2) Second Stage: Fixing of observation point : The displacements of the microscope in the directions perpendicular to the optical axis are determined by template matching, as described above. Then, the microscope is controlled to cancel out these displacements. As a result, the observation point is kept on the part of the object from which the template is acquired, and the image is kept in focus.

The second stage must start after the first stage. Moreover, focusing control is needed during the second stage, as well as control for fixing the observation point. This is because a good template of the center of an image provided by focusing facilitates the control required for fixing the observation point.

III. System for Evaluation

We constructed a prototype system for evaluating the image stabilization method (Fig. 6). Techniques for directly controlling the microscope field of view are still under investigation in our laboratory. Therefore, the prototype microscope contained no built-in actuator for control; instead, a movable stage on which the observation object was fixed was controlled by an external actuator. In the evaluation system, images were stabilized by maintaining the relative position of the microscope and the object using the external actuator.

In future, we plan to provide an internal actuator in the mobile microscope. For example lens shift system of hand-held cameras is applicable to the actuator for the mobile microscope. Rapid Liquid Lens [9] will be also applicable.

A. Configuration

The microscope part shown in Fig. 7 included a 2.7x objective lens, a halogen epi-illumination unit, a high-speed vision system, and a CCD image sensor. The specifications of the high-speed image sensor are shown in TABLE II. It was inclined to the optical axis by 70 degrees and was conjugate with the CCD image sensor without inclination.

The raw image obtained by the high-speed image sensor (Profile Imager [10] made by Hamamatsu Photonics) was sent to an image-processing computer, which determined the

In the directions perpendicular to the optical axis	
pixel size	$d < Mx = 7.3 \times 2.7 \approx 20$ [μm]
frame rate	$f > \frac{6\times10^3}{7.3} \approx 818$ [fps]
In the optical-axis direction	
pixel size	$d < \frac{M^2 z}{\cos\theta} = \frac{3\times2.7^2}{cos70} \approx 64$ [μm]
frame rate	$f > \frac{6\times10^3}{3} = 2000$ [fps]

TABLE I

REQUIRED SPECIFICATIONS OF VISION SYSTEM.

displacements in the optical axis direction and the directions perpendicular to the optical axis. Information about these displacements was sent to a control computer through a shared memory. The control computer calculated the target position from the displacement information of the microscope and the current position of the stage and sent a control voltage signal, converted from the target position, to a proportional-integral-derivative (PID) position control machine. Then, the stage was moved to the target position by controlling the servo driver.

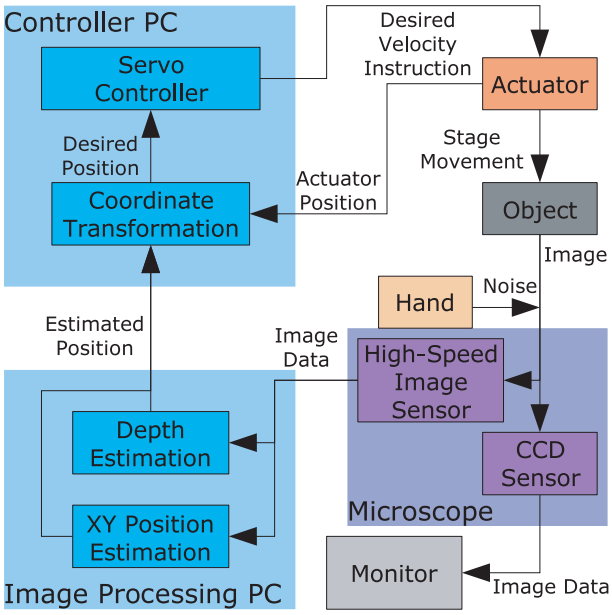

Fig. 6. Configuration of evaluation system.

B. The Need for High-speed Vision

The optical magnification of the microscope was 2.7 times in this system, and the inclination to the optical axis of the sensor was 70 degrees. As described above, the measured speed of the vibrations of a shaking hand was about 6 mm/s. Image stabilization suppressed vibration of image to 2 pixels ($\pm$7.3μm) in the directions perpendicular to the optical axis, and half of the depth of field ($\pm$3μm) in the optical axis direction.

Combining the above conditions and eqs. 4, 8, and 9 gives the required specifications of the vision system, as shown in TABLE I.

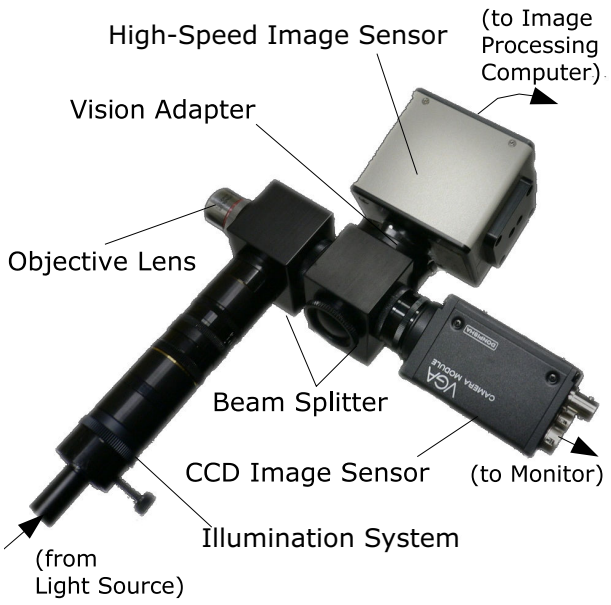

Fig. 7. Microscope body.

sensor size	13.0 $\times$ 14.3 mm
pixel size	20 $\times$ 20 μm
array size	320 $\times$ 64 (full: 512 $\times$ 512)
frame rate	2000 fps
resolution	8 bits

TABLE II

ACTUAL SPECIFICATIONS OF THE HIGH-SPEED IMAGE SENSOR.

Therefore, we used the high-speed image sensor which fulfills the requirements shown in TABLE II and the image processing computer shown in TABLE III.

C. Application: Object Tracking

To show the versatility of the mobile microscope, we provided a function for recognizing and tracking an object, in addition to the basic image stabilization function. This function can be applied to surface scanning to find damage etc. A part brighter than a threshold is recognized as a target. Once the target is recognized, the system is controlled to keep the target at the center of the field of view.

IV. EXPERIMENTS

A. Image Stabilization Experiment

We conducted an experiment to verify the effectiveness of the image stabilization method. We observed the head

OS	Microsoft WindowsXP
CPU	Intel Xeon
CPU clock	2.8GHz
Memory	1.0GByte

TABLE III

SPECIFICATIONS OF THE IMAGE PROCESSING COMPUTER.

of a metal screw with the hand-held mobile microscope. Stabilized images acquired by the system are shown in Fig. 8.

Part (i) of Fig. 8 shows images acquired when stabilization was turned off. They are not in focus or they are blurred. Part (ii) of Fig. 8 shows images acquired when stabilization was on. They are in focus and fixed on the same area.

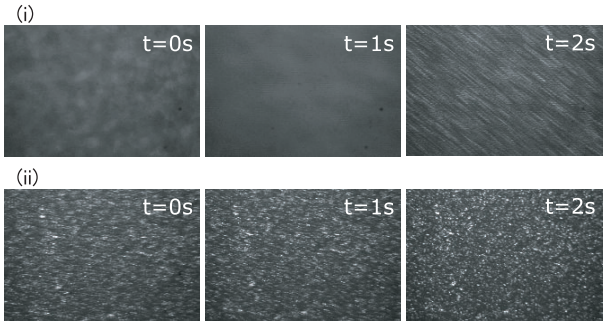

Fig. 8. Results of the image stabilization experiment: (i) image stabilization off, (ii) image stabilization on.

B. Tracking Experiment

We conducted another experiment to verify the object finding and tracking function. We observed the head of a metal screw with the hand-held mobile microscope, similarly to the image stabilization experiment described above. In addition, a small piece of metal (a few millimeters in diameter) was attached to the surface of the screw head. The metal piece was observed to be brighter than the surrounding area. After the focusing function and the tracking function were turned on, we manually moved the microscope back and forth in directions perpendicular to the optical axis to scan the surface. Once the metal piece was observed, the stage moved as shown in Fig. 9 and the metal piece was tracked as shown in Fig. 9.

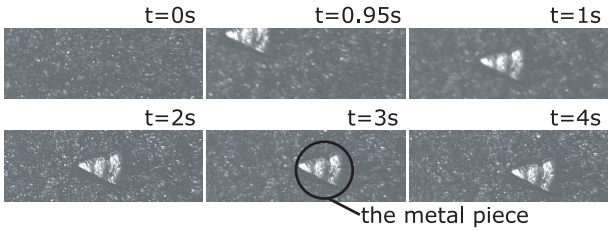

Fig. 9. Results of the tracking experiment: Sequential photographs.

V. CONCONCLUSIONS

We proposed the concept of a "mobile microscope". This is a hand-held microscope that can be used for observation in various places. Our goal was to develop a system that measures displacements of the microscope and controls the focal plane to cancel out the displacement with a built-in actuator.

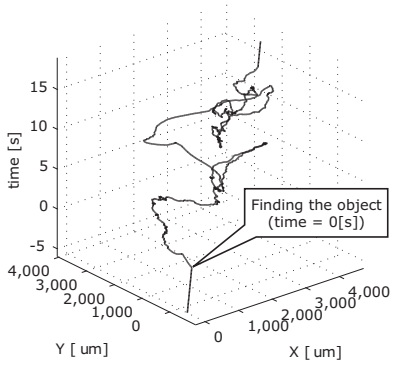

Fig. 10. Results of the tracking experiment: Stage position.

We developed an image stabilization method for the microscope. The method is based on visual feedback, in which the microscope's position is measured from images acquired by a high-speed vision system having an inclined sensor. A displacement measurement method required by the image stabilizations method was also developed.

We developed a prototype microscope system employing the method. In the prototype, image stabilization was achieved by moving a stage with an external actuator, rather than with a built-in actuator. Experimental results showed that images from the hand-held microscope could be stabilized by the method. Moreover, we developed an object finding and tracking application for the mobile microscope. Experimental results of this application demonstrated the versatility of the mobile microscope.

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