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The body can be viewed from the next page.

An Accurate 3-D Morphology Recovery Using Binocular Parallax and Its Application to Morphological Analysis of Metal Powders*



Akira Miyajima
Senior Researcher, Mechanical Processing, Instrumentation & Control Research Center, Technical Res. Div.

Osamu Furukimi
Dr. Eng., Senior Researcher, New Materials Research Center, Technical Res. Div.

Fumio Saito
FA Sec. II, Factory Automation Engineering Dept., Kawasaki Steel Systems R & D Corp.

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1 Introduction

Human beings perceive the depth of an object by utilizing binocular parallax; similarly, an original object is reproducible in a three-dimensional morphology by using a pair of images taken from binocular angles. That is, a three-dimensional surface image projected onto a pair of two-dimensional planes contain information on the surface morphology of the object, and a three-dimensional morphology can be reproduced by detecting positional difference by parallax.

The usefulness of this technique has been appreciated in such a case as in preparing terrain shapes from aerial photographs, and this technique has made progress as a result of various research studies. There have been many reports[1)] in recent years on the application of this technique to optical recognition in the robot-vision field.

The technique of three-dimensional morphological recovery by binocular parallax is superior in its simplicity to other techniques for direct measuring of morphology, i.e., its ease of processing at high speed and its economy because special devices are unnecessary. However, the reproductional accuracy of three-dimensional morphology cannot yet be said sufficient. For the recovery of three-dimensional morphology, a searching and matching process for identifying and calculating the correspondence between a pair of images is necessary, and the main cause of the low accuracy is in this searching process. There is a technique for recovering three-dimensional structures without using the correspondence between images;[2)] in this case, it is necessary to express features that describe the whole object, and the technique cannot be applied to objects with undetermined morphological features.

The generally-adopted optical matching techniques to search for correspondence between two images can be broadly divided into the area-based method and the feature-based method, the latter being superior in speed and accuracy if the images have identifiably clear features. In robot vision, images with relatively clear boundaries for objects are often processed, and the use of the feature-based method is predominant; for example, triangulation geometry is used as the basis for extracting edge information.[3)]

For the observation of material surfaces and sections

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under an electron microscope by the material industry, however, the three-dimensional recovery accuracy is decreased by the existence of texture, amorphousness and smoothness if edge information is used. Therefore, it is necessary to adopt the areabased method or a combination of the area-based and feature-based methods, and not the feature-based method.

Application of the three-dimensional morphological recovery technique by binocular parallax in the material industry has been reported for the quantitative measurement of fine, three-dimensional structures mainly involving the analysis of fracture surfaces; this includes the measurement of facet fracture surfaces, dimple fracture surfaces, corrosion pits and stretch zones in steel materials,[4] and analysis of the geometrical shape of crack propagation in ceramics. The three-dimensional morphological recovery techniques used in these examples are still in the trial stage, and the accuracy obtained is not sufficient for general-purpose use.

In this report, it is demonstrated by a numerical simulation and an image-processing experiment that high-accuracy and general-purpose-oriented three-dimensional morphological recovery is possible by considering the size of the areas searched for and the deformation of images by parallax when correspondence between two images is sought by the area-based method. A program including the algorithm for processing such three-dimensional morphological recovery was developed for use in the morphological analysis of materials, and the results of its application for the morphological analysis of metal powders are described.

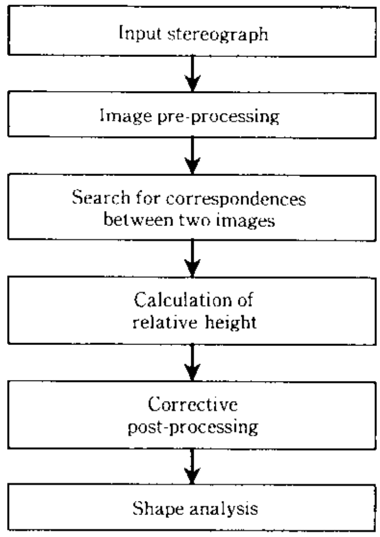

Fig. 1 Image processing flow for three-dimensional (3-D) analysis using binocular parallax

2 Three-Dimensional Morphological Recovery Technique by Binocular Parallax

The flowchart of general image processing for three-dimensional morphological recovery is shown in **Fig. 1**. The pre-processing section depends on the image input method used; in the case of camera input, it involves image processing such as positioning a pair of images, correcting the gray level and removing noise.

In the section for searching correspondence between two images, a displacement caused by tilting is detected by checking the two-dimensional gray level pattern on the reference image against the gray level pattern on the tilted image. Unlike the feature-based method where a corresondence between a pair of images is searched by extracting features of images such as of edges, the area-based method separates reference image into small areas and searches for small area in correspondence between a pair of tited images in each small area.

If a displacement of a small area is known, the relative height can be calculated from the known tilt angle; the original morphology can then be recovered by detecting the difference between the tilted image and the whole reference image.

When searching for correspondence between the two images, there are cases where portions corresponding to the reference image and tilted image do not exist in a region where the morphology changes abruptly; this is called "unmatching." Furthermore, there are cases of portions different from the original portions due to a distortion of the gray level pattern and for other reasons regarded as correspondence between two images, although there are other more valid corresponding portions; this is called "mismatching." When unmatching and mismatching occur, an abnormal pattern is produced in the relative height; this in turn causes errors in the recovered morphology. Both are error factors that inevitably occur in the recovery techniques by binocular parallax. To minimize mismatching, it is necessary to increase the accuracy of searching for correspondence between two images by evolving a processing algorithm. After mismatching and unmatching have occurred, it is also necessary to take some corrective actions.

Strictly, the calculated relative height is a sequence of discrete points in three-dimensional coordinates of the surface morphology; conversion to a birdseye view or a contour map is necessary to make the calculated relative height visible, and three-dimensional feature-extraction processing such as by calculating the surface area with a surface generation technique is conducted for a three-dimensional morphological analysis.

The most recent three-dimensional morphological recovery processing by binocular parallax is usually conducted by digital image processing, in consideration of the flexibility and ease of processing, and of the errors caused by discretely treating image information in each stage of processing.

3 Examination by Numerical Simulation

3.1 Morphological Model

Unmatching is an unavoidable cause of error when correspondence between two images does not exist, and additional steps such as smoothing as post-processing are necessary. The purpose of this study is to recover high-accuracy, three-dimensional morphology by substantially reducing mismatching. This was done by examining the techniques needed to improve the accuracy over conventional techniques in searching for correspondence between two images, and in calculating the relative height.

In the numerical simulation, the improved accuracy was verified by using a linear profile, i.e., the surface shape of one section with a three-dimensional morphology. **Figure 2** shows simulated profile A of a surface shape, and profile B obtained by rotating profile A by 8° clockwise. The profiles are sine curves, and no unmatched portions are formed with this rotation. The gray level pattern used for the optical matching process cannot express morphology directly; it can be considered that it expresses mainly the matrix pattern of a three-dimensional surface. In the simulation, each point on the surface of profile A was incorporated into a model with a gray level expressed by gray level pattern C. In gray level pattern C of Fig. 2, numerical values are obtained by a trigonometric function and random sampling numbers. When profile A is rotated through 8° clockwise, gray level pattern C of the surface changes to pattern D according to Eq.(1):

$$\left.\begin{aligned} x_d &= x_c \cos\theta - y_c \sin\theta \\ G_d &= G_c \end{aligned}\right\} \cdots\cdots\cdots\cdots\cdots (1)$$

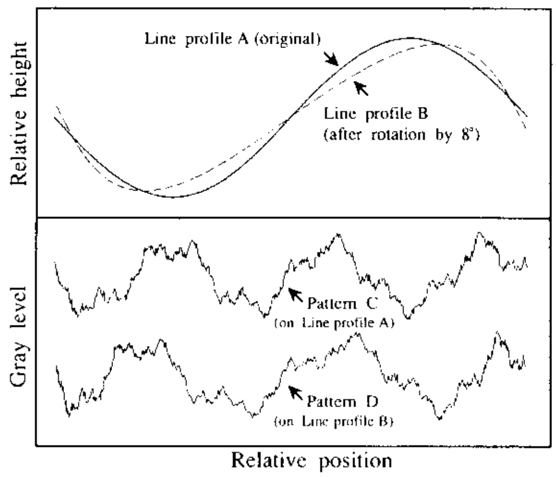

Fig. 2 Deformation of gray level pattern by line profile rotation

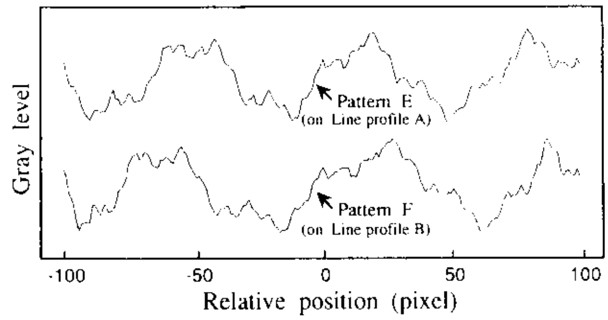

Fig. 3 Effect of quantization and discretization of gray level pattern

where x_d and G_d are the x-coordinate and gray level of gray level pattern D, x_c and y_c are the x-coordinate and y-coordinate of profile A, and G_c is the gray level of the surface at coordinates (x_c, y_c). θ is the tilt angle, and is $-8°$ in this case. The modification of the gray level pattern by rotation depends on the position on profile A, and the gray level is preserved.

To take into consideration errors in image input corresponding to the digitization of an image, sampling and quantization of patterns C and D were conducted, and pattern D was processed by interpolation to correspond to the discrete x-coordinate of pattern C. After this processing, patterns C and D become patterns E and F, respectively, as shown in **Fig. 3**. Patterns E and F are each composed of 200 points equally spaced in the x-axis direction, and each point corresponds to a pixel having a gray level value in the y-axis direction.

With the three-dimensional morphological recovery technique by binocular parallax, patterns E and F of the surface gray level and tilt angle θ are known, and the profile can be determined by using these known values.

3.2 Search for Correspondence between Two Images

With the area-based method, small areas are defined on the reference image, and by scanning the search area on the tilted image, a small area on the tilted image having a gray level pattern with the highest degree of correspondence is regarded as the matching portion. This is called template matching, and methods utilizing the sequential similarity detection algorithm (SSDA), modified SSDA,[5] cross-correlation computation, etc., are used to evaluate the degree of correspondence. To search for correspondence in images with little difference in gray level pattern, the cross-correlation computation method,[6] which is simple and has a relatively high accuracy, is generally adopted. The correlation coefficient value R_n in an n-th small area within the search area is defined by Eq.(2):

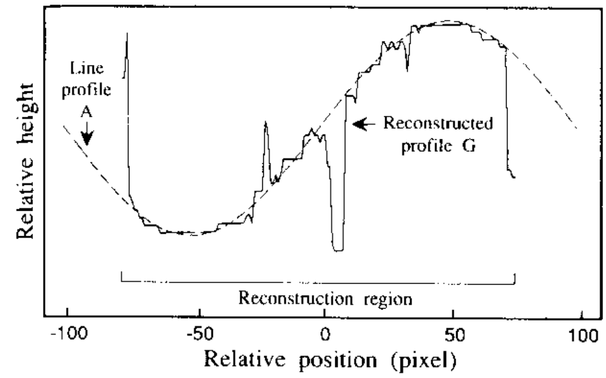

Fig. 4 Profile reconstruction by conventional method

$$R_n = \frac{\sum_{i,j} (G_{ij} - \bar{G})(g_{nij} = \bar{g}_n)}{\sqrt{\sum_{i,j} (G_{ij} - \bar{G})^2 \sum_{i,j} (g_{nij} - \bar{g}_n)^2}} \quad \cdots\cdots(2)$$

where G_{ij}: Gray level value of each pixel in the small reference area

$\bar{G}$: Average gray level value of the small reference area

g_{nij}: Gray level value of each pixel of the n-th small area within the search area

$\bar{g}_n$: Average gray level value of the n-th small area within the search area

$\sum$: Sum for pixel (i,j) of the correspondence between the two small areas

Figure 4 shows reconstructed profile G and original profile A when the small-area size (small line size in the simulation) is 15 pixels and the search-area size is 47 pixels by the generally-employed cross-correlation computation method. The height was calculated by using Eq.(3).

$$h_i = (x_i \cos\theta - x_i - d_i)/\sin\theta \quad \cdots\cdots\cdots\cdots(3)$$

where h_i is the height of x_i in profile A, and d_i is the positional difference between patterns E and F in the x-axis direction at x_i obtained after searching for correspondence between the two images.

Although patterns E and F have a similar shape, it is apparent that there is not only a positional difference in the x-axis direction, but also partial expansion and reduction in the x-axis direction. For this reason, when the degree of correspondence is evaluated in areas of the same size for the reference image and tilted image, errors are large even if the cross-correlation computation method is adopted.

The reason why errors are especially large at both ends of profile G in Fig. 4 is that, as derived from Eq. (1), the long distance from the rotation center and the large height result in a large profile deformation and a high degree of reduction. When the correlation coefficient distribution within the search area during the search for correspondence at both ends of profile G is analyzed, it is found that multiple peaks exist, and that other similar portions have higher correlation coefficients or the correlation coefficient distribution by scanning is flattened, with the result that errors are produced.

Reconstructed profile G, which has a stepped contour, generates errors in the height direction. This is because the positional difference during the search for correspondence is due to discrete values with one pixel as the smallest unit, and because at $\theta = -8°$, a change in one unit of d_1 has an effect equivalent to 7.2 pixels on height h_i; that is, the minimum resolution in the height direction is about 7.2 pixels.

3.3 Technique for Improving Accuracy during the Search for Correspondence between Two Images

In the conventional area-based method where the small area on the reference image and the small area in the search area on the tilted image are made the same in size, mismatching as in Fig. 4 occurs because image deformation by tilting is not considered. When the deformation is similar with each other, there is a method for extracting corresponding morphology by using normalized central moment around the principal axis as an invariant.[7] When the deformation is due to tilting, similar figures are not generated, and the deformation becomes such that expansion and reduction occur only in the X-axis direction.

In general when the small area contains high-frequency gray level elements, the smaller the size, the higher the matching accuracy. In the case of low-frequency elements, the larger the size, the higher the accuracy. Therefore, the authors have developed a dynamic-region-partitioning technique for dynamically determining the small-area size depending on the gray-level change rate within the area, and ascertained that this technique is very effective for improving the search accuracy for correspondence and for shortening the processing time.[8] This dynamic-region-partioning technique was adopted to determine the small-area size. Gray level change e was evaluated by the following equation:

$$e = \frac{1}{N} \sum_{i,j} (g_{ij} - \bar{g})^2 \quad \cdots\cdots\cdots\cdots\cdots\cdots(4)$$

where g_{ij}: Gray level value of each pixel in the small area on the reference image

$\bar{g}$: Average gray level value within the small area on the reference image

N: Number of pixels in the small area on the reference image

Furthermore, the authors developed a technique for changing the size of the small area on the tilted image that is being searched for in order to cope with the expansion and reduction of the gray level pattern within the search area. With this technique, the small area on the tilted image is gradually changed from a small to large size relative to the small area on the reference image, and the degree of correspondence is calculated by scanning the search area for each small-area size. The portion determined for the small-area size on the tilted image with the highest degree of correspondence is regarded as a match between the two images.

When a difference in the small-area size on the reference image occurs with a size change in the small area within the search area, the gray level of the small area on the tilted image can be interpolated as being suitable for the discrete position in the x-direction on the reference image. The degree of correspondence is then evaluated according to the modified SSDA method in consideration of its high speed. Sufficient accuracy can be obtained even with the modified SSDA method because of the algorithm that was developed to consider expansion and reduction.

Figure 5 shows profile H reconstructed by using this new technique and original profile A. It is apparent that the morphological recovery accuracy has been substantially improved when compared with profile G reconstructed by the conventional cross-correlation computation method, using the same small-area size for the reference image and tilted image. The error in the height direction is within 2.4% of the maximum height. This is because this technique not only can cope with the expansion and reduction of the gray level pattern, but also can reduce the unit of positional difference d_i to 1/2 pixel, with the result that the unit of change in height h_i is held to as little as about 3.6 pixels.

In Fig. 5, the dynamic-region-partioning technique has not been used, and the small-area size was fixed at 15 pixels on the reference image and at 47 pixels on the tilted image to observe the effect of expansion and reduction of the small-area size within the search area during the search for correspondence between the two images.

The results of the numeric simulation reveal for the case shown in Fig. 5 that the small-area size on the tilted image with the highest degree of correspondence changes smoothly between 10 and 22 pixels relative to the positional difference in the x-axis direction. The fact that, with a morphology that changes smoothly like profile A, the deformation and partial expansion and reduction of gray level pattern by projection are smooth demonstrates that the selection range of the small-area size on the tilted image during the search for correspondence between the two images is close to the optimum small-area size selected last time. Therefore, it was possible to narrow the selection range of the small-area size and to increase the processing speed.

In **Fig. 6**, this technique has been applied to a profile that changes abruptly. The same processing algorithm as that in Fig. 5 was used, with the small-area size on the reference image fixed at 9 pixels and the search-area size at 41 pixels. While relatively large errors occur in the abrupt-change portions, the average error in height is 3.2% and is low compared with the conventional cross-correlation computation method. This is because, near the abrupt-change portions, the degree of change in deformation by tilting is high, and expanded and reduced portions coexist in the small area, with the result that the evaluation of the degree of correspondence as an area is inaccurate. To solve this problem, an abrupt change in shape can be coped with by reducing the small-area size; however, this increases the possibility of mismatching for low-frequency elements.

In the case shown in Fig. 6, the change in the small-area size on the tilted image with the highest degree of correspondence ranged from 5 to 15 pixels relative to the 9 pixels of the small-area size of the reference image, while the optimum small-area size in the abrupt-change portions changed suddenly. In those portions that show great change over a small area, therefore, the optimum small-area size selected last time has no validity, and it is necessary to set a wide selection range for

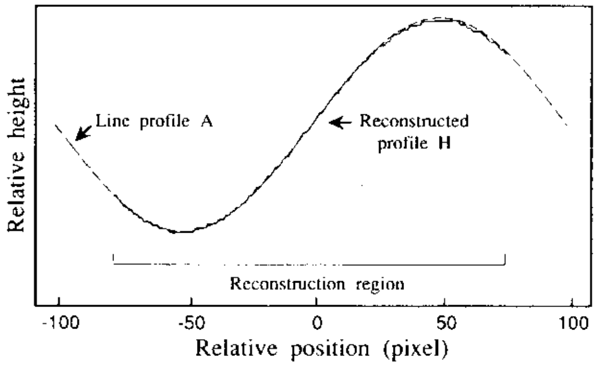

Fig. 5 Profile reconstruction by newly developed method in the case of "smooth" reference profile

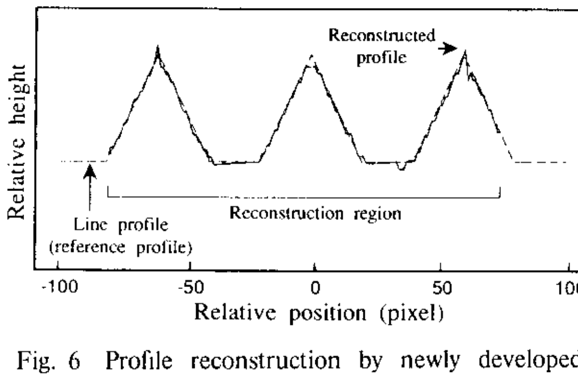

Fig. 6 Profile reconstruction by newly developed method in the case of "sharp" reference profile

the small-area size on the tilted image. However, because the small-area size is set at a relatively low value to cope with a sudden change in shape, the selection range is narrower than that of the larger small-area size.

It is apparent from the foregoing that, by making the small-area size on the tilted image variable, the morphological recovery accuracy is very high for a relatively smooth morphology, and that the processing speed can be increased. When the morphology has an abrupt change, the errors can be minimized by setting the small-area size at a low value, although mismatching may occur in the abrupt-change portions.

In actual images, the optimum small-area size on the reference image is determined by evaluating the gray level change rate with the dynamic-region-partitioning technique, while the matching small-area size within the search area on the tilted image is changed to adapt to the above-determined small-area size. Therefore, mismatching can be substantially reduced compared with the conventional method. Even for an abrupt-change morphology, in which mismatching is likely to occur, it is easy to improve accuracy by such a measure as partially reducing the small-area size on the reference image, because if attention is paid to the change in optimum small-area size on the tilted image, those portions with great change correspond to the abrupt-change portions.

The resolution of the present technique for calculating the relative height is twice that of the conventional techniques, enabling a three-dimensional morphology to be recovered with high accuracy.

There is also a technique for increasing accuracy by avoiding unmatching portions in the search for correspondence between two images or suppressing the effect of errors in an area with a constant gray level and few features,[9] and a technique for shortening the computation time by conducting hierarchical optical matching in a pyramid structure.[10] Although these methods have not been incorporated in the present processing algorithm, both can be used in combination with the present technique because they do not conflict with the principle.

4 Morphological Analysis of Metal Powder Particles

4.1 Purpose of the Morphological Analysis

The morphology of a metal powder is closely related to the powder, molding and sintering characteristics. A more direct and higher-accuracy quantitative determination of three-dimensional morphology is required than the conventional quantitative determination in two dimensions can offer. There is a technique for directly observing the profile under a laser microscope, in addition to the three-dimensional morphological recovery technique by binocular parallax. However, problems accompanying the processing of digitized information, and the selection of feature parameters for a three-dimensional morphology related to material characteristics are common.

The purpose of the present experiment is to evaluate the application to spheroidized and non-spheroidized water-atomized iron powders of the algorithm that was developed for three-dimensional morphological recovery, and to find a feature parameter for the three-dimensional morphology as that represents the degree of spheroidizing and is not affected by different observation conditions such as the magnification of an electron microscope.

4.2 Image Processing Environment for the Morphological Analysis

The "Dr. IMAGE" image processing system developed at Kawasaki Steel was used. With Dr. IMAGE, scanning electron microscopic (SEM) images can be input directly or through a removable disk as digital images. However, a procedure that involves taking photographs and inputting photographs from a CCD camera installed on a macro-stand was adopted here to verify the general applicability of the present method.

The algorithm for three-dimensional morphological recovery by binocular parallax was programmed in C-language, and the image processing library and image processor of Dr. IMAGE permit high-speed processing on a workstation. Prototype operation menus that would operate the developed program were prepared for the menu of Dr. IMAGE by using the built-in user-defined application function. **Figure 7** shows an example of a prototype menu that sets the processing conditions for the experiment.

The program is executed on a workstation by the image processor of Dr. IMAGE, and processing of the

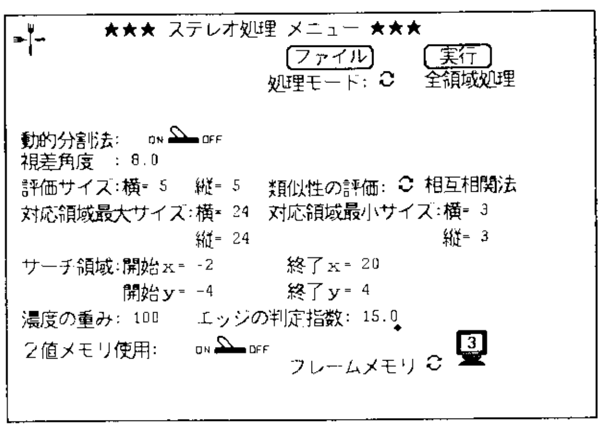

Fig. 7 Prototype menu of stereo vision programs on Sun workstation

image and the morphological profile are displayed on a color monitor. Numerical data obtained during processing is stored in the analysis file of Dr. IMAGE, while image data is stored in the image file on a magnetic disk unit and an optical disk unit so that they can be used again for comparative evaluation and preparation of the experimental report.

4.3 Image Input and Pre-processing

Spheriodized and non-spheroidized water-atomized iron powders were used as samples for image input, and multiple photographic sets of reference images of one particle by SEM and of tilted images obtained by rotating the reference image through 8° were prepared for both types of powder.

Accurate positioning of the reference image and tilted image is necessary to conduct the search for correspondence between two images with high accuracy when inputting each pair of SEM photographs from the TV camera. In this experiment, they were positioned manually, an image recorded beforehand being displayed in red, and the corresponding image being input by the camera being displayed in blue. These images were superimposed on the monitor and observed with spectacles having a left-hand red lens and a right-hand blue lens. In this manner the position that ensures an appropriate stereoscopic view could be found by moving and rotating the image being input while stereoscopically observing it.

Images input from the CCD camera to Dr. IMAGE are digitized to obtain a reference image and a tilted image each composed of 512 pixels by 432 pixels, one each pixel having a gray level of 256 grades. Through digitization, the gray level pattern of each image is accuracy quantified; while correspondence of the measuring positions between images is apparently lost, it is within the practical range.

In the numerical simulation model described in the previous section, the gray level is adjusted even if the image is tilted. In the case of camera input of photographs, however, the gray level usually changes due to the difference in photographic density during the printing of photographs and change in the illustration during camera input. Furthermore, dust that is created during printing appears on the input image as noise, and can cause mismatching. Therefore, after inputting the reference and tilted images, the gray level is adjusted to normalize the two images.

Next, processing to extract only the area for measurement from the whole image is done to shorten the processing time necessary for the search for correspondence between the two images. Attention is paid to the difference in gray level and smoothness between the object for measurement and the background, the necessary area being extracted by using the binarization, morphological function, and inter-image computational functions of Dr. IMAGE.

4.4 Search for Correspondence between Two Images and the Calculation of Height

Recovering the morphology over the entire area of the extracted image and the linear profile of the image for measurement were both carried out in searching for correspondence between two images. In the latter process, the ability to cut the image for measurement at constant intervals and at any position were added.

In the search for correspondence between two images in the linear profile case, ideally, only a single corresponding pixel line of the reference image and tilted image is sufficient for the matching process. However, to allow for positional movement and rotation between the two images during input, the degree of correspondence was evaluated in terms of a small-area search. For this reason, the same algorithm was basically adopted for recovery of the surface profile over the entire surface and for recovery of the linear profile.

Since most of the processing time is spent in searching for correspondence between two images, and recovery of the linear profile is quicker than recovery of the surface profile, the surface profile and linear profile were used appropriately depending on the three-dimensional feature parameter to be found.

The dynamic-region-partitioning technique was employed to determine the small-area size on the reference image during the search for correspondence between two images; with the initial small-area size set at 24 x 24 pixels, the small-area size was adjusted to gradually decrease to 3 x 3 pixels depending on the gray level change rate within the area.

Figure 8 shows a linear profile before correction that was obtained by cutting the sample shown in **Photo 1** along the line indicated. It was ascertained that this profile was in good agreement with the visual profile observed with a stereoscope. The portion where the profile drops suddenly in Fig. 8 shows an abrupt-change portion that was also stereoscopically observed. It is possible that unmatching could occur here.

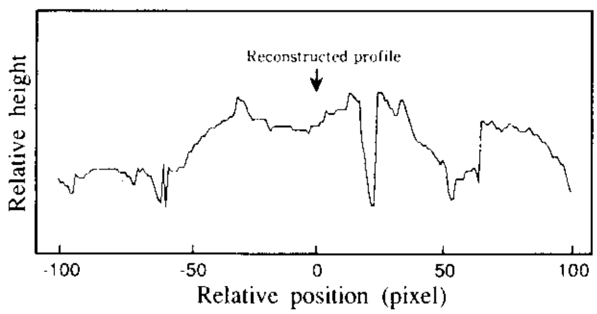

Fig. 8 Profile reconstruction of water-atomized iron powder

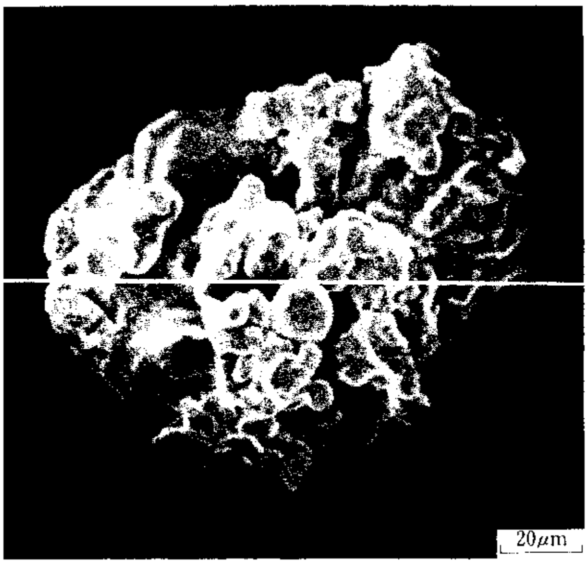

Photo 1 Water-atomized iron powder and "line profile" position (white line)

4.5 Correction and Indication of Errors

In actual images, mismatching occurs due to such error factors as nonuniform printing of photographs. If the angular change in morphology is great, and a portion disappears from a two-dimensional projected surface after rotation through 8° or newly appears, then unmatching occurs as shown in Fig. 8.

To correct such unmatching and mismatching, a method was adopted by which the height surrounding the portion to be corrected is averaged and is regarded as the correction height. If any other surrounding portions are to be corrected, they are excluded from the object for averaging.

When the degree of correspondence is evaluated by using the cross-correlation computation, there is a method for automatically determining points to be corrected; for example, portions whose correlation coefficient is lower than the threshold level set beforehand are included in the object for correction. A similar threshold level for automatic determination can also be set with the SSDA method. However, the numerical simulation model shows that when the degree of deformation of the gray level pattern by tilting is high, the correlation coefficients and SSDA values deteriorate even in portions with correct matching. Consequently, the recovered morphology may worsen under the conventional automatic correction method. In this experiment, therefore, the range for automatic correction was narrowed, and automatic correction was combined with an effective manual correction method. Manual correction can shorten the computing time and improve reliability[11] by combining the general judgment of human vision with the local vision of the computer by digital image processing.

The extraction of surfaces is necessary for determining the feature parameter of morphology from discrete information on the relative height after correction. Strictly, such processing as the preparation of surface maps and the coordination of plane patches and quadratic-surface patches[12] is done, and the feature parameter of morphology is calculated after the surface information has thus been established.

In this experiment, a surface generation technique by triangular elements that makes it simple and easy to extract a surface was adopted to suit the feature parameter of the morphologies being used. **Photo 2** shows a birds-eye view of the surface profile prepared after obtaining discrete relative height groups by the processing the whole surface of the measured object shown in Photo 1, covering these relative height groups with triangular elements, and then correcting for hidden surfaces. The incident angle for the birds-eye view can be freely changed, and shading and ray-tracing are also possible.

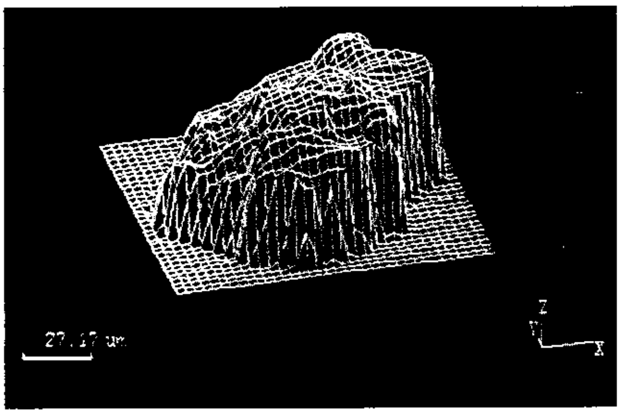

Photo 2 Birds-eye view of iron powder shown in Photo 1

4.6 Results of the Three-Dimensional Morphological Analysis and Discussion

Morphology analyses of particles range from a simple calculation of the aspect ratio to higher-level methods for extracting feature factors by using a Fourier analysis, delta analysis, and fractal analysis.[13] A method for extracting the morphological features of mineral-resource particles prepared by using different comminution devices[14] and that of ceramic powder by using the linear technique with Fourier transformation[15] have been reported. In this experiment, the purpose has been to determine easy and simple feature parameters that permit a quantitative expression of the degree of spheroidizing of water-atomized iron powders; therefore, the feature parameter found by the linear profile method that is characterized by its short processing time was desirable.

The ratio of curve length l to projected length l_0 of the linear profile, l/l_0, expresses the degree of morphological change, and indicates a quantity equivalent to the degree of complexity when the linear profile cuts a particle. Spheroidized powders have a smoother morphology than non-spheroidized powders and should, therefore, have lower l/l_0 values.

Ratio l/l_0 was compared between the linear profile group recovered from images of spheroidized powders and that recovered from images of non-spheroidized powders. However, no significant difference in l/l_0 value was observed between the sheroidized and non-spheroidized powders under different magnification with an electron microscope. This might have been due to errors ascribable to the algorithm used to search for correspondence and to the digital processing in which samples with different magnifications were treated by limited discrete numerical values.

Next, an investigation was made into the relationship between data sampling intervals within the same image and the l/l_0 ratio, which is little affected by a difference in the magnification of an electron microscope nor by discretization by digital processing. Attention was paid to the change in the l/l_0 value due to the difference in interval of pixels sampled, using a pixel that is a discrete quantity in the x-axis direction as the unit. **Photo 3** (a) shows spheroidized powder, the relationship between its sampling interval and l/l_0 value being shown in **Fig. 9** (a). Each point is the average value of l/l_0 calculated from the linear profile in five places. In Fig. 9, the x-axis is expressed by the step size, i.e., a quantity that is the sampling interval converted into length. When the fractal dimension shown in Eq. (5) is used as a quantity for evaluating the change, $1 - D$ is equivalent to the gradient of the approximate linear equation in Fig. 9 (a), and the D-value is 1.076.

$$l/l_0 = \eta^{1-D} \cdots\cdots (5)$$

where η: Step size (μm)
D: Fractal dimension

Similarly, in the linear profile of the non-spheroidized sample in Photo 3 (b), the D-value is 1.137 from the graph shown in Fig. 9 (b), which is high compared with the figure for the spheroidized powder.

The l/l_0 value decreases when the step size increases, because the effect of high-frequency elements decreases with increasing step size. However, the higher the degree of complexity of the linear profile, the larger is this decrease. The D-value is a quantity that expresses the degree of complexity of the linear profile; the higher the D-value, the more complex the profile will be.

When the same analysis was made by increasing the number of powder samples measured, the D-value for

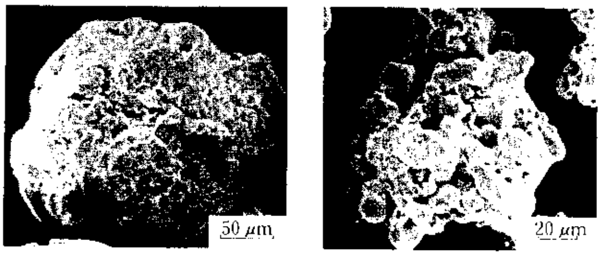

Photo 3 Water-atomized iron powders (digital images from SEM micrographs)

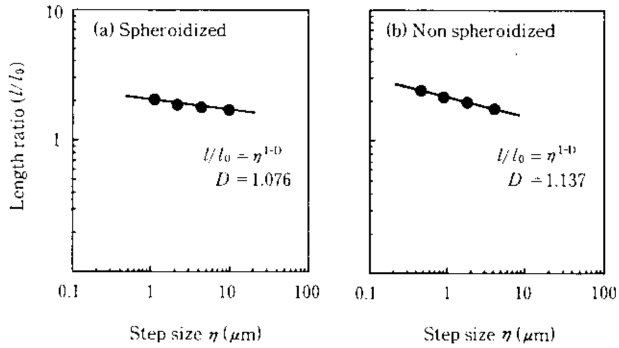

Fig. 9 Relation between length ratio and step size of water-atomized iron powders

the spheroidized powders was between 1.076 and 1.103, and that for the non-spheroidized powders ranged from 1.105 to 1.142. Therefore, in the present experiment, it was possible to discriminate between spheroidized powders and non-spheroidized powders if the threshold level was set between 1.103 and 1.105. The D-value is a feature parameter corresponding to the degree of complexity of the morphology, and can be calculated within the same image, while not being affected by the difference in magnification of the input images nor by the difference in other observation conditions. Therefore, it is possible that a threshold level using the D-value is an invariable quantity, even if the number of measured samples were to be further increased.

Furthermore, changes in the D-value are quantitatively in agreement with changes in the degree of complexity from stereoscopic observations, and a change in D-value not only enables us to judge whether a powders is spheroidized or non-spheroidized, but also may enable the degree of spheroidizing to be quantitatively expressed.

5 Conclusions

By paying attention to the change due to tilting and the gray level change rate within an area in the matching process by binocular parallax according to the area-based method for a pair of images, the authors developed an algorithm for changing the area size and verified a new technique by conducting a numeric simulation and an image-processing experiment. The results obtained are as follows:

(1) In the search for correspondence between two images, i.e., the reference image and tilted image, a technique that involves changing the small-area size within the search area can cope with the deformation induced by tilting better than the conventional techniques that involves evaluating the degree of correspondence over the same small-area size. This new technique ensures a high accuracy for the recovery of a three-dimensional morphology.

(2) This method of changing the small-area size within the search area can calculate the degree of correspondnce up to the center of two neighbour pixels in the search for correspondence between two images; therefore, the resolution of the new technique in the calculation of relative height is twice that of the conventional techniques.

(3) The following results were obtained by applying this new technique for a morphological analysis of spheroidized and non-spheroidized water-atomized iron powders:

(a) Whether the powder is spheroidized or not can be judged by using the fractal dimension without allowing for different observation conditions such as magnification. Furthermore, it may be possible to quantitatively express the degree of spheroidizing.

(b) The developed technique, which ensures higher accuracy than the conventional techniques can recover a three-dimensional morphology at a level of accuracy suitable for practical application, even with objects having relatively intense irregularity such as that in a non-spheroidized powder.

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