A Semi-Automatic Terrain Measurement System for Earthwork Control*

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ABSTRACT: Less time-consuming and high accuracy DTM production is required for successful management of large scale earthwork construction because efficient control of earthwork requires repeated measurement of cut-and-fill terrain during execution. This paper describes a newly developed semi-automated measurement system for this purpose. Conventional measurement techniques are here replaced by operator-assisted stereo matching by computer. The basic algorithm is based on a sophisticated coarse-to-fine correlation, and the measurement system is implemented on general purpose image processing hardware linked to a newly developed earthwork management system. The paper also describes the outlines of the hardware and software configuration as well as matching precision and processing time.

INTRODUCTION

STEREO MATCHING TECHNIQUES have for a long time been studied as a powerful tool to speed up photogrammetric processing. Among many strategies proposed so far, we believe that area based correlation and some of its sophisticated versions are to be regarded as most practical and cost-effective in many major application fields.

One of the most challenging applications of stereo matching techniques in photogrammetry is quick measurement of cut-and-fill terrain for the construction management of large scale earthwork. Traditionally, aerial photogrammetry or conventional ground surveying have been employed for this purpose but, as these methods are quite time consuming, this causes delays in the fine control of the cut-and-fill work and requires replanning of the disposition of the construction equipment. It is therefore required to shorten the construction time and to improve the cost-benefit ratio of repeated measurement. Consequently, it is necessary to speed up the photogrammetric work and to shorten the feed-back time.

The Japan Society of Photogrammetry has, in cooperation with the Ministry of Construction, developed and just released an image processing system for semi-automatic DTM production from aerial photographs, which is particularly designed for the described problem. Operator measurement of terrain coordinates is here replaced by operator assisted stereo matching by computer. The basic matching algorithm is based on the so-called coarse-to-fine correlation. Terrain coordinates are measured in three steps of coarse-to-fine matching, an approach whose validity already has been established (Hattori *et al.*, 1986).

In connection with this development, the earthwork management system has been developed by the Ministry of Construction. It is intended to cover the comprehensive collection and analysis of data associated with earthwork, i.e., cut-and-fill work, soil quality maps, etc., and to re-plan the time schedule and machine disposition. These two systems form an integrated control system, but we will here only discuss the semi-automatic measurement system and describe an outline of the configuration of the hardware and software as well as system performance and matching precision.

* Presented paper, 16th Congress of the International Society for Photogrammetry and Remote Sensing, Kyoto, 1–10 July 1988, under the title "Stereo Matching Project in Japan."

HARDWARE CONFIGURATION

Figure 1 shows the configuration of the system hardware, the components being general purpose devices for image processing. Since several stereo models are usually required to cover the entire construction area, a gigantic peripheral memory is needed to store image data, and so the system is provided with an optical disc unit. Each device is outlined as follows:

AD CONVERTER (IMAGE SCANNER)

This is an image AD converter (Topcon Co.) with a comparator function, recently developed to meet the requirements for high speed conversion and high positional accuracy (Figure 2). The film is placed on a carrier sandwiched between two glass plates at a marked position. Every 8.97-mm by 6.58-mm portion of the film (called sub-image) is illuminated and its image is focused on an area CCD sensor with a pixel size of 11.5 by 13.5 μm. The 780 by 488 output gray values are temporarily stored in a frame memory, and then transferred to the optical disc memory together with the center point coordinates of the sub-image, which are measured by linear encoders provided along the x and y axes of the carrier. The carrier then moves to the next digitizing position.

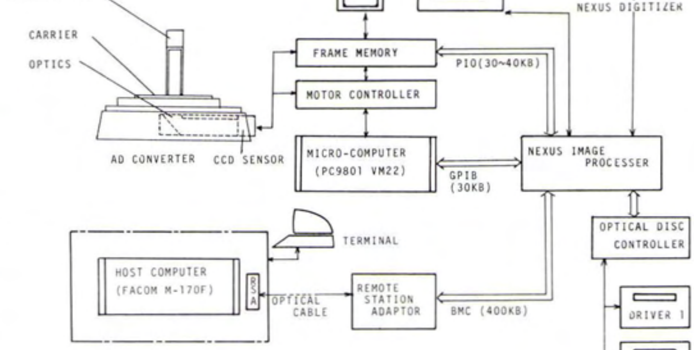

FIG. 1. Hardware configuration.

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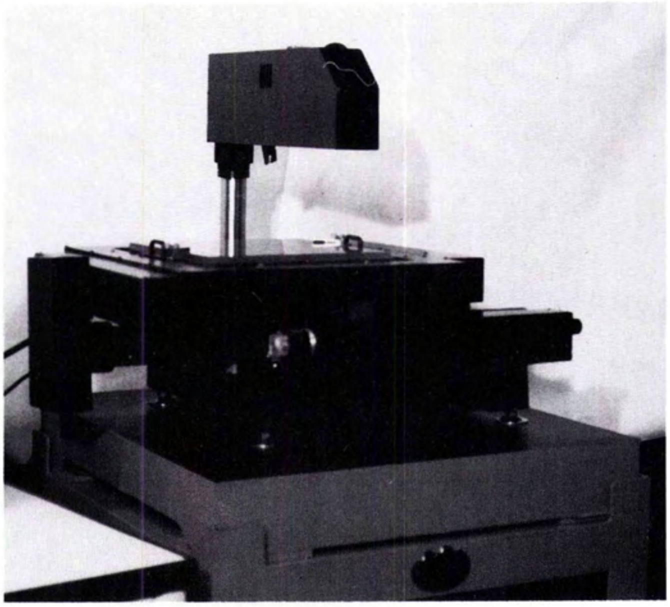

FIG. 2. Topcon AD converter.

TABLE 1. PERFORMANCES OF TOPCON AD CONVERTER

Items	Data
maximum film size	230 × 230 mm
size of a field view	8.97 × 6.58 mm
pixel size	11.5 × 13.5 μm
accuracy	less than 3 μm in x and y
axial orthogonality	less than 10″
driving velocity of carrier	20 mm/sec
driving mode	manual or programmed
weight	60 kg
output format	8 bit binary (0–3D)
controller	micro comp. (PC 9800)

The drive of the carrier is controlled by a micro computer, and the scanning is monitored on a black-and-white TV monitor. Point-by-point coordinate measurement is also possible by pointing with the cursor on a particular position on the screen. Output gray values are calibrated to a Kodak gray scale. Basic specifications for this instrument are listed in Table 1.

IMAGE PROCESSOR

The NEXUS 6510 image processor (Kashiwagi Research Co.) features four image memories of 512 by 480 bytes each, and many useful hardware provisions such as graphics display functions and cursor controlled coordinate measurement functions through the graphic digitizer table. They are used for the organization of the interactive system.

OPTICAL DISC UNIT

The unit, DU15 (Matsushita Electronics Co.), has two drives to cope with the handling of a stereo pair. The drives are controlled by an optical disc controller, NEXUS 68151. The memory volume of each disc is 1.2 GB, enough to store as much data as 2.5 sheets of digitized photographs. The time to transfer data from the NEXUS memory to the optical disc (write mode) is approximately 13 seconds per sub-image, while the time for data transfer in the reversed direction (read mode) is roughly one second.

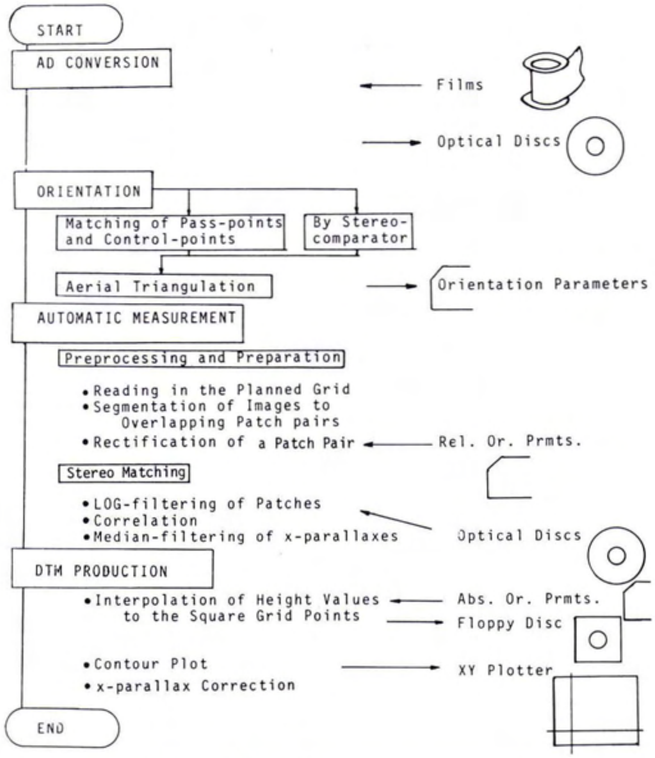

FIG. 3. Flow of the semi-automatic measurement.

HOST COMPUTER

All calculation tasks are executed by a FACOM M170-F (16 MB memory), which is connected to the NEXUS through a BMC interface (400 KB/sec).

PROCESSING FLOW OF AUTOMATIC MEASUREMENT

Figure 3 shows a flow diagram of the digital measurement consisting of five parts: AD conversion of photographs, relative and absolute orientation, stereo matching, DTM production, and x-parallax correction. The operator runs the program by selecting menues in succession. Each item is illustrated in the following with an example of a typical earthwork area (43 ha). The area is here covered by two models consisting of three 1:5,000-scale photographs.

AD CONVERSION OF PHOTOGRAPHS

Areas to be digitized are designated by measuring coordinates of paper prints on the graphic digitizer table. Digitized images are stored in optical discs in a sub-image mode.

RELATIVE AND ABSOLUTE ORIENTATION

The system has two alternative options for choosing the coordinating orientation points. The first is the conventional procedure using a stereo comparator, where the orientation parameters are typed in manually. The other is a method to find pass points and control points in the digitized images using least-squares correlation (Gruen, 1985; Hattori, 1987; Kometani, 1987). In the case of the latter method, the operator selects matchable point pairs on the screen and designates approximate positions by the cursor. A 31-by 31-pixel window is normally employed, but it can be changed according to image or terrain conditions. To ensure convergence, three steps of coarse-to-fine correlation are used (for details see Hattori (1987)).

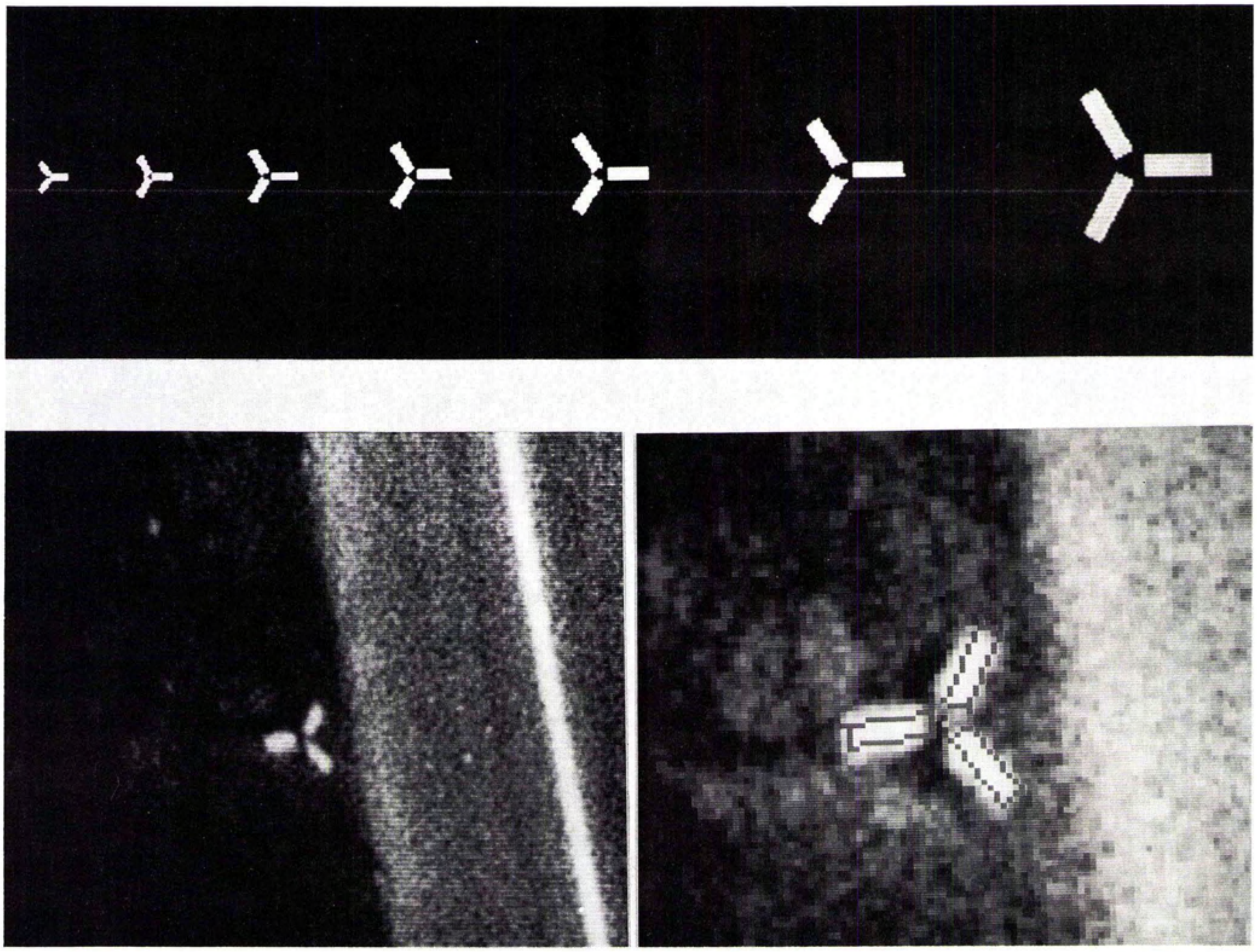

FIG. 4. Identification of ground control points. (upper) Automatically generated templates. (lower left) Original image. (lower right) Superposition of a matched template.

The matching of control points is performed in the same way, except for the following two factors (see Figure 4):

- Standard templates are prepared in advance; and
- search windows, including targets, are converted to binary form to remove noise (because the templates are given as binary images).

STEREO MATCHING

Preprocessing and Preparation. At the stage of ground planning a basic planned grid is defined to cover the entire construction area. The operator defines the area by filling grid squares on the screen, as seen in Figure 5. The normal grid width used is 20 by 20 m.

Sub-images are merged and divided automatically to 1,024- by 1,024-pixel patches. They are processing units of matching and overlap each other. The operator selects patches which are to be matched (see Figure 6).

Each patch pair is rectified by rearranging pixel arrays along epipolar lines. The new pixel size is 50 by 50 μm. The rectified images are then stored in optical or magnetic disc files.

Stereo Matching. The outlines of stereo matching are described in the section on the Stereo Matching Algorithm (for details see Hattori (1986)).

Matching is executed for every patch pair independently. If

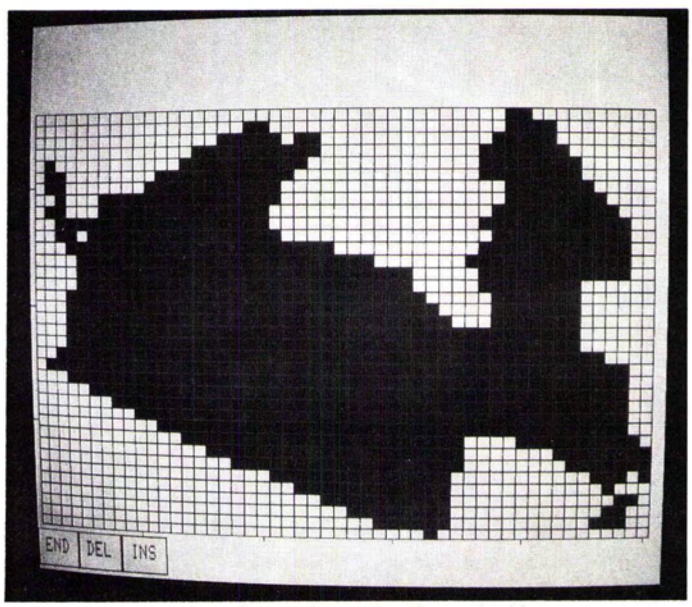

FIG. 5. Screen input of a planned grid.

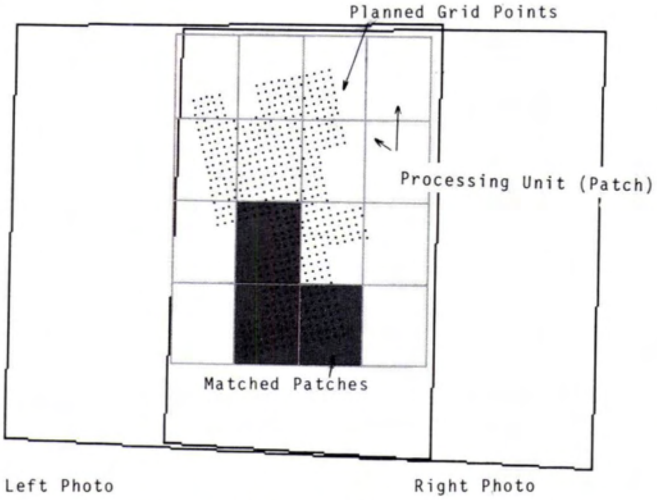

FIG. 6. Patch allocation. A pair of images and patches is displayed on the screen. An operator daubs patches which should be matched.

necessary, the right patch is shifted automatically in the x direction in order to come into the correct position. This is done by referring to the average ground height of a neighboring patch that already has been matched.

DTM PRODUCTION

Matched points will not make a regular grid in the ground coordinate system, as will be seen in the section on the Stereo Matching Algorithm. Terrain data are interpolated to any regular grid by the simple weighted mean approach, because the density of matched points is very high (about 2-m spacing on the ground with 1:5,000-scale photographs and the 50- by 50-μm pixel patches used).

Figure 7 shows an example of a contour map of the earthwork area. It was plotted from the planned-grid-based DTM (20- by 20-m width), which was obtained by interpolating matched terrain data. Terrain data were obtained by matching the rectified (50- by 50-μm pixel) images.

X-PARALLAX CORRECTION

In many applications, matching errors of 2 to 3 m in height may appear at some occlusions, e.g., both sides of buildings. However, as far as earth volume evaluation is concerned, these errors have little effect, but in case the operator wants to get more precise DTMs, false matchings can be interactively corrected on the screen.

STEREO MATCHING ALGORITHM

Because each step of the algorithm consists of identical processes, there will be no references to the step numbers.

LOG FILTERING OF PATCHES

Correlation degradation occurs mainly from perspective distortion due to terrain relief. For suppressing this effect, the coarse-to-fine approach is useful. Besides, narrowly band-limited images should preferably be used, as band limitation keeps the distortion effect on a low and constant level (see Hattori (1986)).

In this system a pair of patches is filtered with the Laplacian of Gaussian (LOG) filters of three different scales. The LOG filter is the most narrow band-pass that can be realized without a "wind-up" effect. The peak frequencies of the filter are 1/4, 1/2, and 1 rad/pixel for three steps.

The filtered images are reduced by resampling at every four and two pixels for the first and second steps. It is assured by the sampling theorem that no information is lost.

GRID POINTS ALLOCATION AND CORRELATION

First of all, the corresponding square grids (Grid A) with eight-pixel spacing are set on both patches, assuming that the terrain is flat. Then the right conjugates to the left patch points are searched for. Second, the same search is done from the right to the left (so called two-way search). Thus, two independent x-parallax sets are obtained. The correlation window size is 15 by 15 pixels (four octaves). The search range is ±3 pixels, which

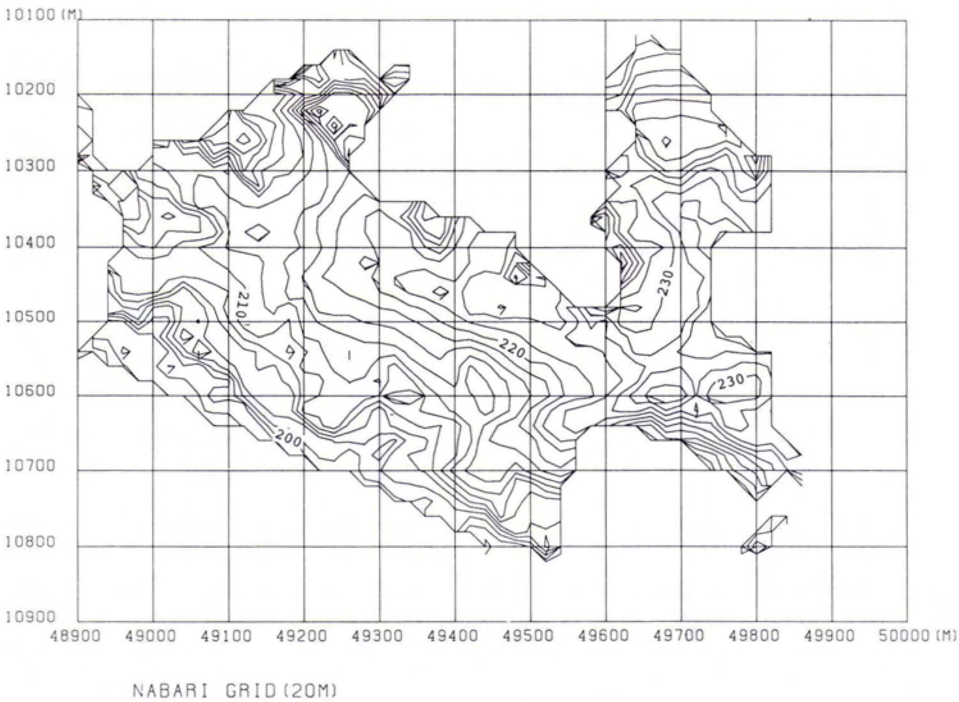

FIG. 7. Example of a contour map output. The contour interval is 2 m. The grid spacing is 100 m. Contours are plotted from DTM data associated with the planned grid (20-m spacing).

is approximately one principal wavelength of the LOG filter. If the search goes beyond this range, the possibility for a correlation peak to occur at a neighboring (false) position increases.

Median-Filtering of X-Parallaxes

x-parallaxes obtained by correlation usually include high frequency components and some gross errors. Gross errors tend to occur at the borders of occlusions. Because these errors have a negative effect on the following procedures, median-filtering with a 3 by 3 window is applied to the respective parallax sets. The median filter removes isolated gross errors and random errors but retains abrupt changes of the x-parallaxes, e.g., at steep cliffs.

X-Parallax Elimination from the Patch Pair

A new grid (Grid B) is set on the XY model datum in such a way that it has equal spacing in the X direction of the model coordinate system as in the y direction of the image coordinate system. The height values of the new grid points are evaluated as a simple mean value of the grid heights of the two surface lines which are obtained by connecting two kinds of matched points obtained by the two-way search, respectively (see Figure 8).

As long as only correlation is used for matching, it is impossible to know if each point pair is correctly matched. Hence, the geometrical consistency of the x-parallax arrays is checked line by line after the median filtering. Geometrical consistency means that point arrays on the ground must occur in the same order in both the left and right image. If an inconsistency appears, a gross error is assumed. However, such points are actually used anyway, without special treatment when interpolating Grid B, because preliminary experiments show that, by averaging the two-way search results, remaining gross errors are reduced to a moderate level.

Next, the pixel arrays of both patches are rearranged to eliminate x-parallaxes and to reform the grids to new square grids (Grid C) in both image planes. Note that the reformed grid lines, after this process, are no longer straight lines in the Y-direction on the model datum.

Coarse-to-Fine Convergence and X-Parallax Output

The four above processes are repeated in every step. Grid C becomes Grid A at the beginning of the following step and the density of the grid points are doubled in x and y. After the completion of the three steps, 97 by 121 grid points have been identified. Points on the patch boundary are regarded as less reliable, which reduces the number of points to 88 by 112.

Figures 9(a), 9(b), and 9(c) show LOG-filtered images and identified matched points in Grid B in each step. Each image is 1,024 by 1,024 pixels in size.

SYSTEM PERFORMANCE

The system performance should be assessed from the viewpoints of total consumed time, precision, reliability, and man

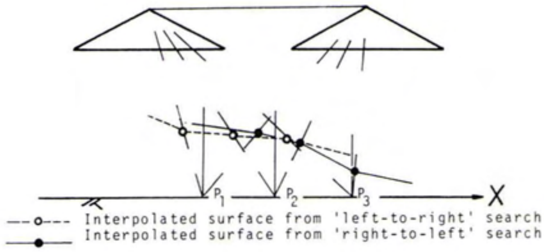

FIG. 8. Schematic diagram for the two-way search. ○ is a matched points by the "left-to-right" search. ● is by the "right-to-left" search. P_1, P_2, P_3 are model grid points with equal spacing.

ageability. We must confess that the first version of the system has some shortcomings in these respects.

Table 2 lists the processing time required for a typical case. The bottleneck is at LOG-filtering which is executed with a Fast Fourier Transformation (FFT). As many as eight FFTs of 1,024 by 1,024 pixels are needed to make six filtered images for a patch pair. We believe that this process needs to be implemented in a microprocessor.

A precision and reliability check was performed at a test site of about 120 by 120 m in area. The site was a portion of the earthwork area described earlier (see Figure 10). Conventional ground surveying, using a distance meter and conventional photogrammetry (Planicomp C-100), was performed at the same time as measurements with the semi-automatic system were made. In the ground surveying case, terrain points were collected at approximately every 3 m in a random mode. Using conventional photogrammetry, the heights of square grid points were measured with an interval of 2.5 m. In the semi-automatic measurement case, image data were rectified with 20 by 20 μm pixels, and matched terrain data were interpolated to the same grid as above. Figures 11(a), 11(b), and 11(c) show the respective contour maps. No corrections were made in Figure 11(c).

Large errors in the stereo matching occurred only in forest areas and at one particular building. The maximum error at bare ground was within one pixel except in occlusions at steep slopes, where errors of at most three pixels arose and the terrain was reproduced a little too smooth. However, the overall accuracy is to be considered good enough for earth volume evaluation, as areas where such errors occur are few compared to the total work area.

Concerning forest areas, errors may occur if vegetation is sparse, as solitary trees create noise which make correct matching impossible. On the other hand, if vegetation is dense, matching will be performed at tree top level, which is different from the custom of manual plotting where the operator traces the ground.

Fortunately for earthwork management, DTMs of bare ground

TABLE 2. CONSUMED TIME FOR A TYPICAL CASE. 10 × 11 SUB-IMAGES COVER THE ONE SIDE OF A MODEL IMAGE PAIR.

Items	Processing Unit	Time
AD Conversion	10×11 sub-images	ca. 30min. (with 2 verify-check)
Merging and Transfer	10×11 sub-images	ca. 40 min.
Rectification	1 patch	6.3 min. in CPU
Matching	1 patch	
• LOG Filtering		13.3 min. in CPU
• Correlation		3.6 min. in CPU
DTM Production	6 patches (62×49 grid points)	4.5 min. in CPU

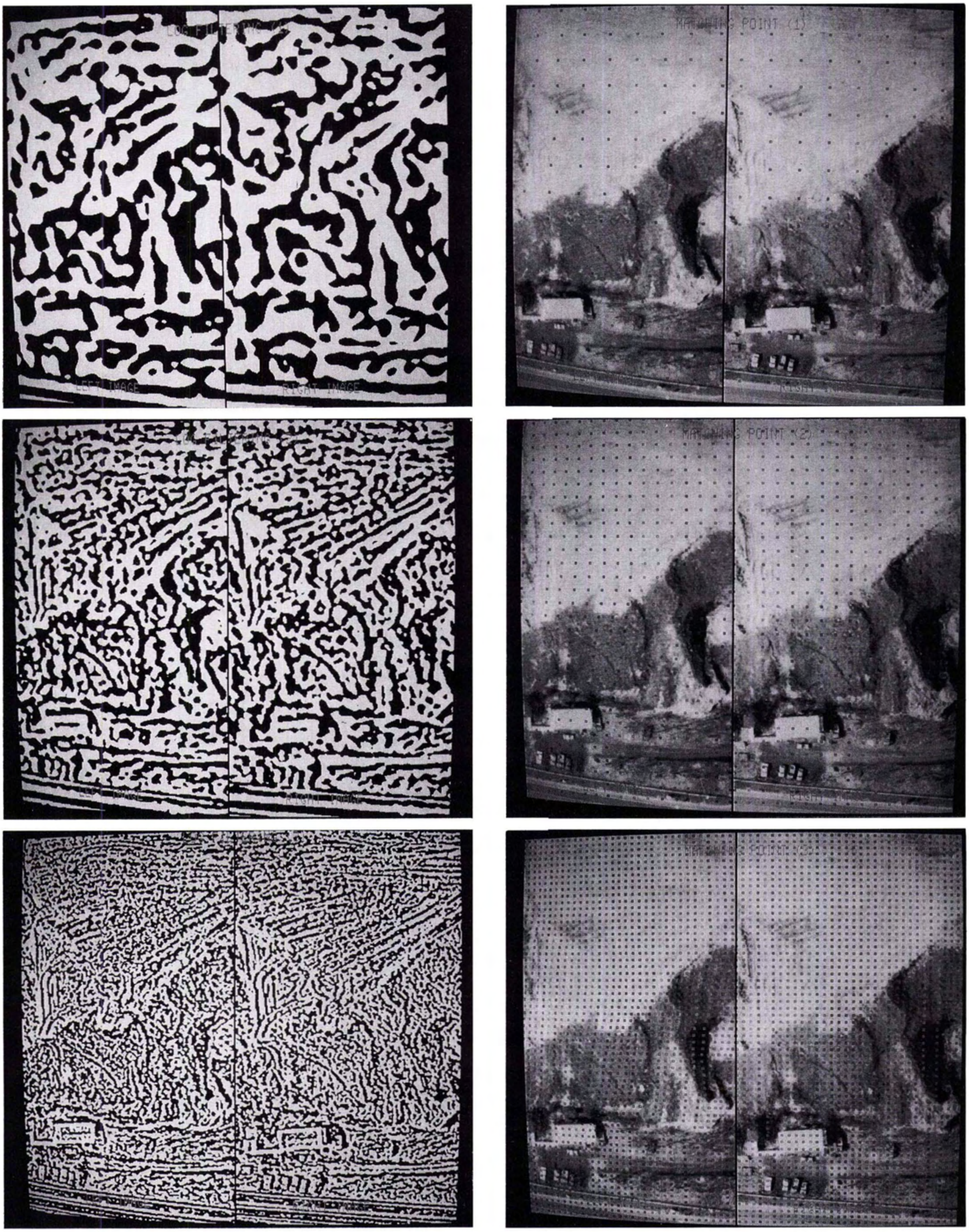

FIG. 9. An example of the LOG-filtered images and matched points in three steps. (a) First step, the principal frequency of the LOG filter, ω_p = 1/4 rad/pixel. (b) Second step, ω_p = 1/2 rad/pixel. (c) Third step, ω_p = 1 rad/pixel.

FIG. 10. Test site for matching precision check.

are generally required. The reliability of the measurement can there be considered very high. However, if the measurement field is extended to other objects, serious matching errors may occur. In that case, we may need AI based strategies.

As seen in Figure 11, the precision of the semi-automatic system is the same as that of conventional photogrammetry, while the measurement time for one point of the former is about 10 to 20 times faster than of the latter, if orientation is done. On the other hand, semi-automatic measurement is more expensive than conventional photogrammetry, mainly because of the expensive image processing hardware. However, the cost of hardware is expected to decrease in the near future.

CONCLUSION

This semi-automatic measurement system is the first realization in Japan intended for the task of earthwork management. The basic matching method is area correlation. Preliminary tests show that the matching precision is sufficient for that task.

We are now improving the system, especially in the areas of processing speed and manageability, to make it applicable also for the measurement of areas other than cut-and-fill terrain, in particular, areas where speed and automation are of primary interest and high accuracy is secondary. In this respect, we expect automatic or semi-automatic map production from satellite imagery to be one of the more promising and straightforward applications.

ACKNOWLEDGMENTS

We should like to acknowledge our collaborators, Mr. Y. Kometani, Mr. K. Uda, and Mr. O. Uchida, for their burdensome computer programming and research work.

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(Received 16 August 1988; revised and accepted 6 December 1988)

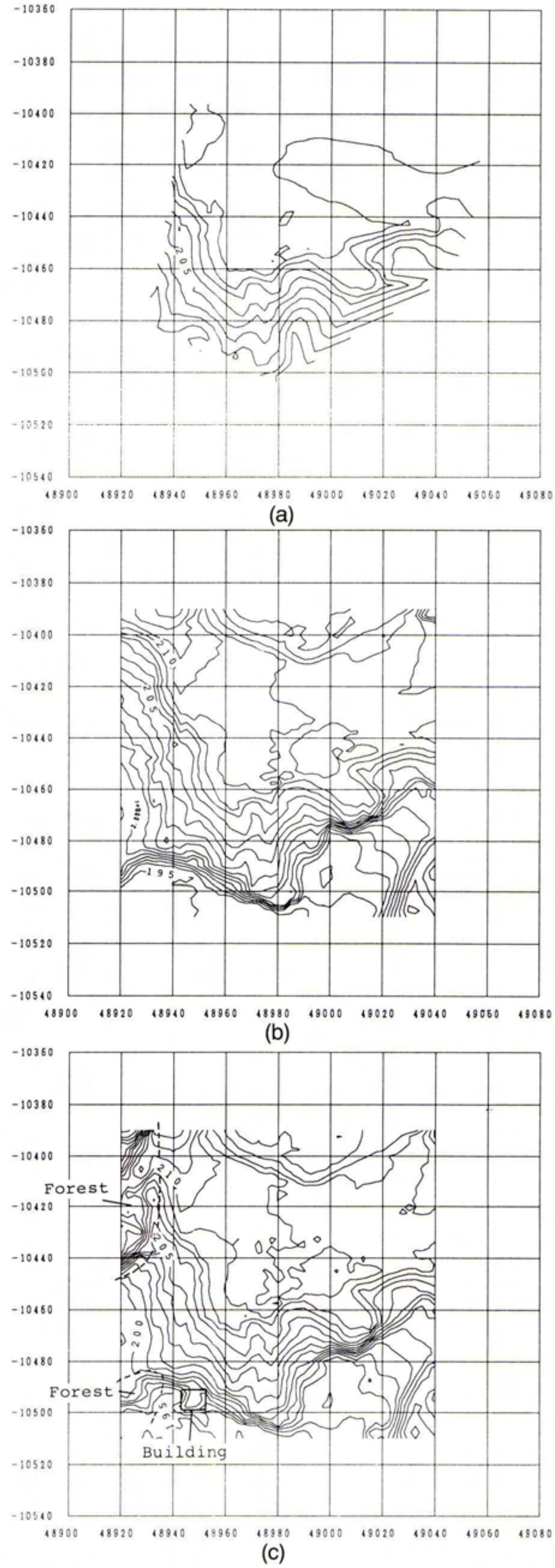

FIG. 11. Contour maps from three-kinds of measurements of the test site. The contour interval is 1 m. (a) Ground surveying in a random mode. (b) Photogrammetry with Planicomp C-100 in a grid mode of 2.5-m spacing. (c) Automatic measurement. Matched terrain data are interpolated to the same grid as (b).