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Preliminary Study on Digital Images for Automated Identification of Structural Damages by Edge Detection

構造物の輪郭抽出による被害状況自動抽出のためのディジタル画像に関する基礎的研究

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This paper carries out a preliminary study on utilizing observation cameras to meet the demand for the quickness in evaluating urban earthquake disaster. The key issue is the examination of the high-accuracy and high-speed in measuring displacement by means of image analysis. The properties of the pixel data taken for buildings and building edges are quantitatively analyzed in this paper. The applicability of GIS to set a window for image analysis is proposed to reduce the computation cost. Also an experimental evaluation of sub-pixel edge detector is performed.

Key Words: *structural damages, digital image analysis, edge detection, GIS*

1. Introduction

There is a continuous need for the evaluation of urban earthquake disaster right after the occurrence of a large-scale earthquake. The primary importance of this evaluation is to achieve the quickness, i.e., the time to complete the estimation must be of the order of ten minutes. The target of this evaluation is buildings or structures which are located in hundred meters square or 1 kilometer square at most; it is enough if we can evaluate the structure damage at several levels, although the evaluation must be exclusive. Many methods to realize such quick evaluation have been proposed; for instance, methods which use satellite images, satellite remote sensing data, or aerial images are being studied. While some remarkable results are obtained, it is still difficult to meet the demand of the quickness in evaluating urban earthquake disaster.

The authors are proposing the utilization of remote observation cameras which are installed on the top of high-rise buildings or fire stations. Digital images of old RC buildings in a few hundred meters are taken by the cameras, and the quick evaluation of possible damages for the buildings and structures are made by means of image analysis. A major task to realize this method is the development of suitable image analysis from which the level of building damage can be evaluated. Displacement of RC buildings is used for this evaluation. That is, the image analysis calculates vertical or horizontal displacement including slant after an earthquake; the accuracy of calculating displacement is of the order of centimeter. The displacement is converted to floor deformation, which is a standard index for building damage, so that the damage level is evaluated. The reliability of the evaluation will be improved if a three dimensional displacement vector is calculated by integrating the results of the image analysis of several digital images taken by observation cameras which are distributed in an urban area.

Table 1 Outline of urban earthquake disaster evaluation system

target area	a few hundred meter square (maximum a kilometer square)
target	RC buildings
analysis	displacement due to earthquake accuracy is order of a few centimeter so that relative deformation can be measured
key issues	accuracy of measuring displacement quickness of image analysis

The fundamental difficulties for the utilization of observation cameras are the achievement of accuracy and quickness in calculating displacement by means of image analysis; see Table 1. The displacement is measured for the edge of the building. Principally, it is not difficult to detect the building edge by suitable image analysis; the building edge in a digital image is a place at which pixel data are changed non-smoothly, and the detection of such an edge is a primary objective of image analysis. The pixel data of the digital image are strongly influenced by the weather and day/night conditions. To solve the first difficulty, therefore, the influence of the weather and day/night conditions on the pixel data needs to be analyzed. The second difficulty is more serious since the number of pixels must be large enough to detect the building edge with higher accuracy, while the larger number of pixels increases the scale of computation for image analysis. To solve this dilemma, the authors proposed using Geographical Information System (GIS) which stores 3D geometrical data for buildings and structures; the location of the building edges in a digital image can be calculated if the location and orientation of the camera is given together with its characteristics such as focal lengths and zooming ratio. The number of pixels used for the building edge detection is drastically reduced if a suitably small window is pre-set to the digital image so that image analysis is applied only to this window; the window must include the building edges within it.

The objective of this paper is to carry out the fundamental study of utilizing observation cameras for quick evaluation of urban earthquake disaster. The major concern is the examination of the accuracy and quickness in measuring displacement by means of image analysis. The content of this paper is as follows: The properties of the pixel data which are taken for buildings and building edges are quantitatively analyzed in Section 2. The applicability of GIS to set a window for image analysis is studied in Section 3. In section 4 experiments for edge detection which illustrates the needs for high-speed and high-accuracy sub-pixel edge detector is needed for the automated identification system.

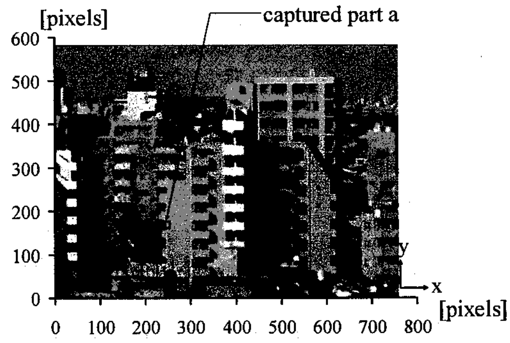
It should be mentioned that digital cameras which can be used for city observation range from a common CCD camera to a special device which is used for astronomy observation. There are various kinds of lens which are used in the digital camera, and, moreover, various kinds of CCD devices. The pixel data of the digital camera usually consist of RGB values the data length of which is 8 bit for each color. Even a common CCD camera has tens mega pixels, which means that a digital image is converted three matrices the dimension of which is a few thousand by a few thousand.

2. Accuracy of Building Edge Detection

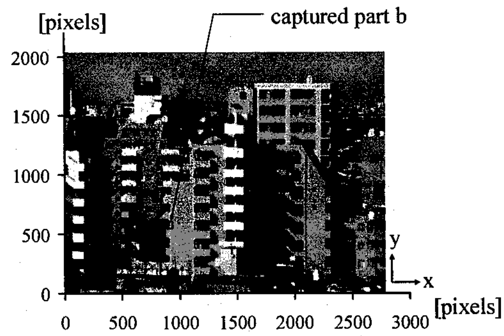
Table 2 Comparison of the camera specifications

	Cooled CCD camera	low-price product
	BITRAN BJ-40L	Cannon PowerShot A700
lens	NIKKOR f 24-85[mm]	f 5.8-34.8[mm]
pixel	580 × 772	2112 × 2816
scale	16 bit Gray scale	8 bit RGB

Digital images are taken for buildings under four weather and day/night conditions, namely, sunny, cloudy, and rainy days and a night. Two digital cameras are used, a cooled CCD camera for astronomy observation with low-noise CCD devices and a common CCD camera; see Table 2 for the characteristics of the two

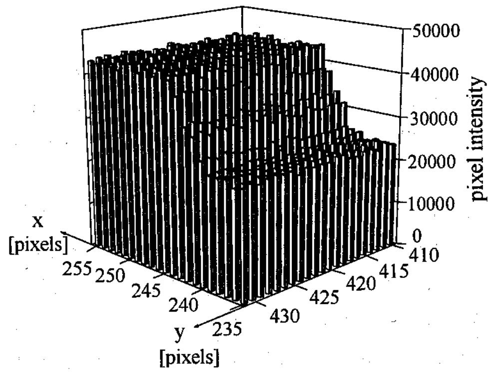


(a) image taken by cooled CCD camera

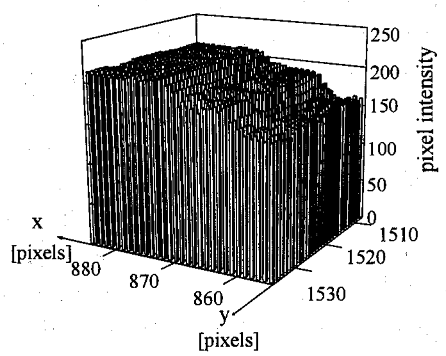


(b) image taken by common CCD camera (converted in gray-scale)

Fig.1 Examples of digital images



(a) captured part a in Fig. 1



(b) captured part b in Fig. 1

Fig.2 Two-dimensional distribution of the pixel data in gray-scale digital cameras. Examples of digital images are presented in Fig. 1. Since a cooled CCD camera has only gray-scale pixel data, RGB pixel data of the common CCD camera are converted to a gray-scale using the standard conversion formula:

$$(Gray\ Scale) = 0.3R + 0.59G + 0.11B\,. \qquad (1)$$

Here R, G and B are standing for red, green and blue respectively. The resolution of each pixel of the cooled CCD camera and the common CCD camera is 16 and 8 bit, respectively.

As a typical example, two-dimensional distribution of the pixel data in gray-scale for captured parts a and b in Fig. 1 are plotted in Fig. 2. In usual, pixel intensity changes non-smoothly across the building edge. The change, however, is not uniform along the building edge.

Fig.3 and Fig.4 respectively shows the mean and standard deviation of the pixel intensity along an edge in the digital images taken under different weather/light conditions. Also, digital images for each condition with some time shifts are taken to examine the stability of the image with respect to photo timing.

2.1 Pixel Data Change across Building Edge

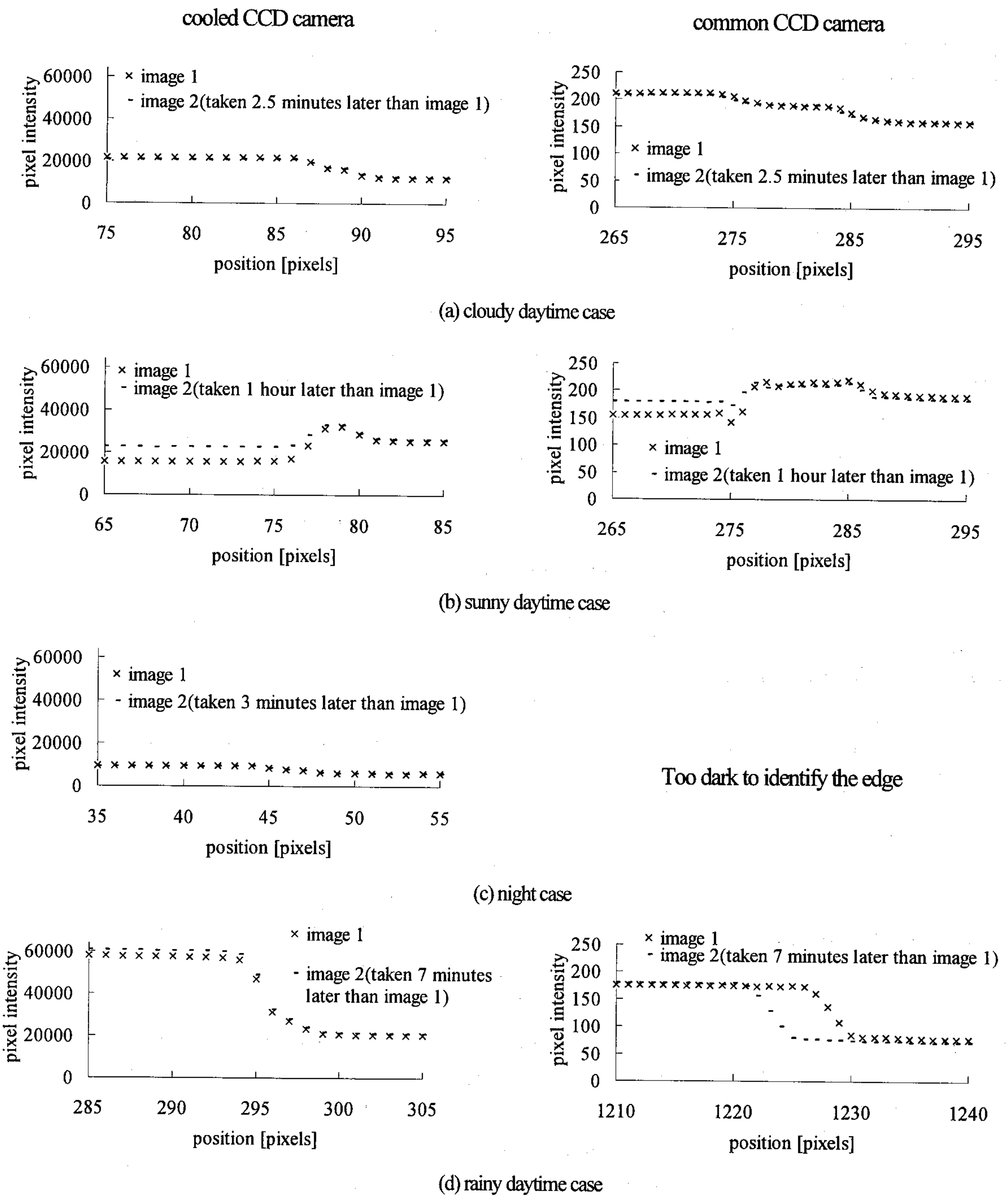


Fig.3 Pixel intensity of captured part

The width of the building edge must be taken into full consideration, in order to accurately measure the displacement by means of image analysis. When a digital image with 1,000 by 1,000 pixels is taken for a domain with the width and height of 50 [m], one pixel in the image corresponds to a 5 by 5 [cm] in the real world. Thus, the width of 5 pixels corresponds to the width of 25 [cm]. If the digital image is zoomed in and taken for the width and length of 10 [m], then, the width of 5 pixels corresponds to the width of 5 [cm].

It should be recalled that PIV[1] (Particle Image Velocimetry) uses statistical analysis in order to increase the accuracy in identifying the location of a particle. The spatial and statistical distribution of pixel data for a spherical object is used for this purpose. Similarly, if the statistical distribution of pixel data is obtained for the building edge, it is possible to identify the location of the edge in a sub-pixel scale even though this accuracy in the sub-pixel scale is guaranteed only in a statistical sense.

2.2 Influence of Photo Timing on Pixel Data

In Fig. 3, the mean value of the pixel data taken along the building edge is plotted for a digital image taken 1 hour later. There are some differences, mainly due to the change in the

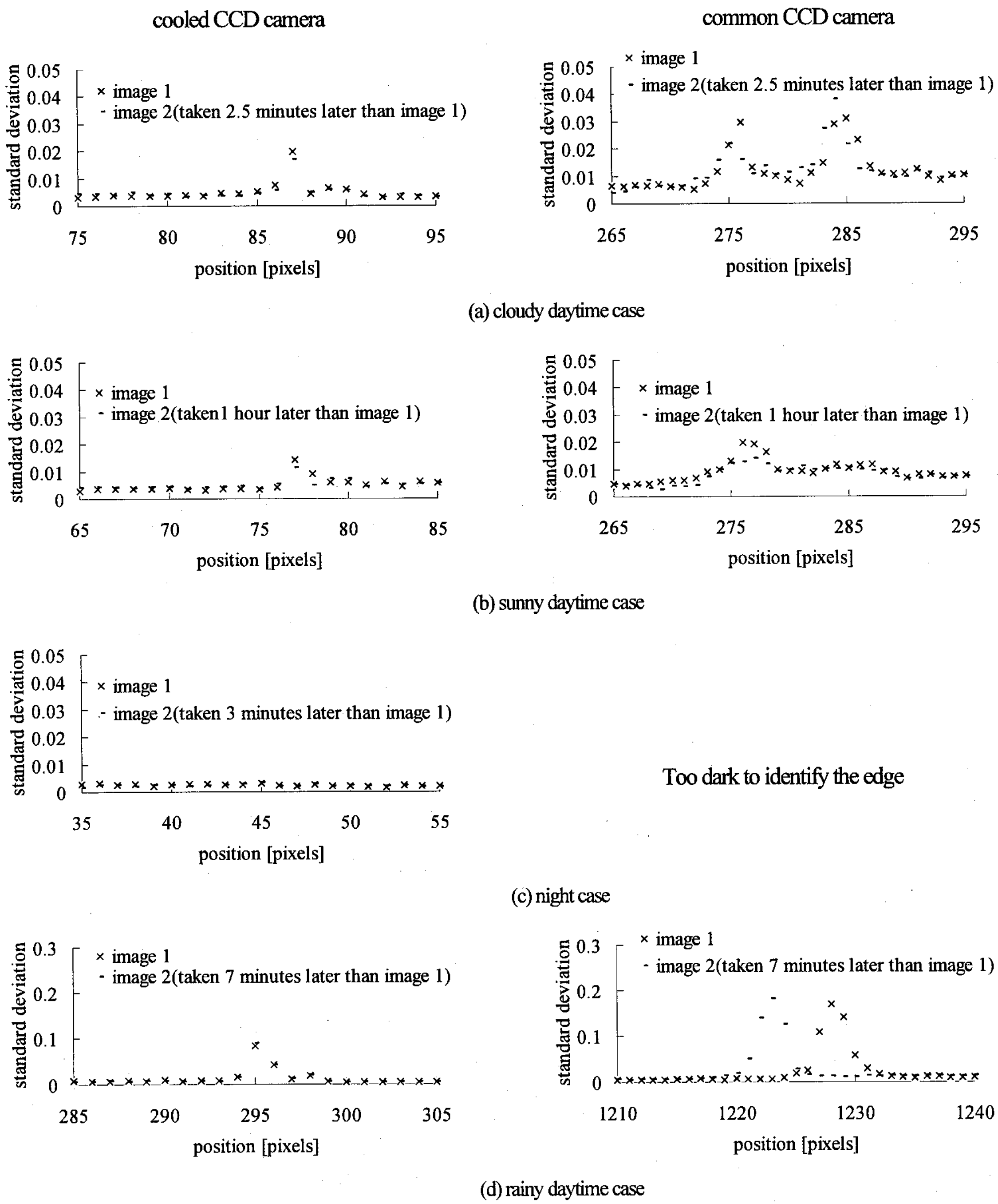


Fig. 4 Standard deviation corresponding to Fig. 3

daylight condition. For the cooled CCD camera, the pixel data are generally unchanged when an image is taken a few minuets later. Under the condition of a rainy day, however, the pixel data inside of the building part increases from 58,000 to 61,000 when a digital image is taken 7 minuets later.

For the common CCD camera, the pixel data are more sensitive to the photo timing; the camera has auto correction function of the pixel data, and hence the image is influenced by the daylight condition. Difference in pixel data would not be negligible if a digital image is taken more than 5 minutes later. It should be pointed out that there is a case where the building edge is shifted by 4 pixels when a digital image is taken 7 minutes later; this could be due to the unrecognized small movement of the camera.

2.3 Statistical Distribution of Pixel Data

Statistical distribution of the pixel data is measured in terms of the standard deviation of the data along the building edge. For the cooled CCD camera, the standard deviation inside the building part is less than 1% for all day/night conditions. The standard deviation within the building edge of 5 pixel width is slightly larger, and the value is around 2 to 5%. It is remarkable that the standard deviation does not increase even under the night condition.

For the common CCD camera, the standard deviation tends to be larger than that of the cooled CCD camera; it goes beyond 1% even inside the building which is assumed to be uniform. The dependence of the standard deviation on the weather and day/night conditions is greater, too. Still, the standard deviation of the pixel data is around 1%. This would not cause a serious problem in detecting the building edge to measure the displacement.

2.4 Choice of CCD Camera

As expected, the cooled CCD camera shows better performance under various weather and day/night conditions; the distribution of the pixel data is not significantly influenced by an object or a background, and the building edge can be detected more stably in the sense that the standard deviation of the pixel data is smaller. The common CCD camera can be used as an alternative of the cooled CCD camera, since its performance is substantially the same as the cooled CCD camera, in order to detect the building edge. However, some attention must be paid to the following two points in utilizing the common CCD camera: 1) the accuracy of taking the pixel data is less to some extent; and 2) some difficulties in taking stable images under the night condition; see Table 3.

Table 3 Comparison of the camera performance

	Cooled CCD camera	low-price product
edge	Approximately 5pixels	5∽10 pixels (depends on weather/sunlight)
error	Standard Deviation<1%	S.D.(≒or >) 1% (depends on weather/sunlight)

3. Utilization of GIS to find Analysis Window

As mentioned, the edge detection is a primary objective of image analysis to identify an object. The edge detection of image analysis is in general divided into two categories, namely, taking finite difference in the pixel data so that the edge is found where the finite difference becomes larger than a threshold, and computing the correlation with a given distribution of pixel data when some information of the target image is known. The use of finite difference is standard, since it only manipulates the pixel data. There are several formulae to accurately compute finite difference of the first or second order. Setting a suitable threshold for the computed finite difference needs some practice. The computation of the correlation is numerically efficient since it takes advantage of the information of the target image. However, choosing a suitable function for the target image requires some practice since the target image varies depending on various factors which include light conditions. This method also needs setting a threshold for the correlation.

While general methodologies are established for the edge detection, it requires some tune-up for the edge detection to identify the edge of a particular object; this tune-up will be know-how of establishing reliable image analysis. Tune-up of the edge detection needs practical study of trial-and-error approaches in which pixel data of actual images are analyzed.

The target of the present image analysis is the building edge; the background could be sky or another building, and building images might be overlapped with each other when buildings and structures are densely located. Some advanced techniques are needed for the detection of the building edge in such digital images. Hence, it is surely necessary to reduce the size of a pixel data which are used for such advanced image analysis.

Based on these considerations, the authors are searching a pre-setting of an analysis window for a digital image in which the building edge possibly appears, by taking advantage of GIS which stores three-dimensional configuration data for buildings and structures. Choosing a small size for the window, the computation needed for the advanced image analysis is drastically reduced. The 3D configuration data are being rapidly stored in GIS with the aid of aerial photo and laser scanning; for instance, several tens and hundreds of points are measured by laser scanning for each building. It is a straightforward task to construct a virtual structure model for each building using the 3D configuration data. However, the difficulty arises regarding to the development of a virtual digital image which mimics an actual digital image taken by observation cameras.

3.1 Virtual Digital Image

Development of a virtual digital image needs the location and orientation of an observation camera. At this moment, it is possible to automatically develop a virtual digital image for a given camera with known location and orientation. The improvement is needed to develop a virtual digital image which is closer to an actual digital image; the camera characteristics must be included in developing the virtual digital image.

An actual digital image changes depending on the focal length and the focal depth. The sharpness of the digital image is a key factor in order to accurately measure possible displacement of a target building after an earthquake. It would be necessary to detect the building edge for non-focused camera image.

3.2 Methodology of Developing Virtual Digital Image [2] [3]

The essence of developing a virtual digital image is the computation of the 2D location in a digital image for a 3D object. That is, a 2D vector in a digital image must be computed for a 3D vector of an actual point; the 2D vector is integer-valued, since it corresponds to the location of a pixel in which the target point appears.

The formulation of converting a 3D vector of an actual object to a 2D vector in a digital image is straightforward when an observation camera is given. The location and orientation of the camera are denoted by (C_X, C_Y, C_Z) and (n_X, n_Y, n_Z), respectively, and the vertical and horizontal direction of the camera are denoted by (h_X, h_Y, h_Z) and (u_X, u_Y, u_Z), respectively; the three vectors, (n_X, n_Y, n_Z), (h_X, h_Y, h_Z) and (u_X, u_Y, u_Z) are the unit vector which are mutually orthogonal; see Fig. 5. When magnification coefficients in the horizontal, vertical and axis directions of the camera are S_X, S_Y and S_Z, a 3D vector (X, Y, Z) is transformed to another 3D vector (x,y,z) in the local camera coordinates of (n_X, n_Y, n_Z), (h_X, h_Y, h_Z) and (u_X, u_Y, u_Z), as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} S_X & 0 & 0 \\ 0 & S_Y & 0 \\ 0 & 0 & S_Z \end{bmatrix} \begin{bmatrix} u_X & u_Y & u_Z \\ h_X & h_Y & h_Z \\ n_X & n_Y & n_Z \end{bmatrix} \left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} C_X \\ C_Y \\ C_Z \end{bmatrix} \right). \quad (2)$$

When a 2D vector (x, y) is converted to an integer vector, it gives the location of the point (X,Y,Z) in the digital image. The conversion needs a scale of one pixel.

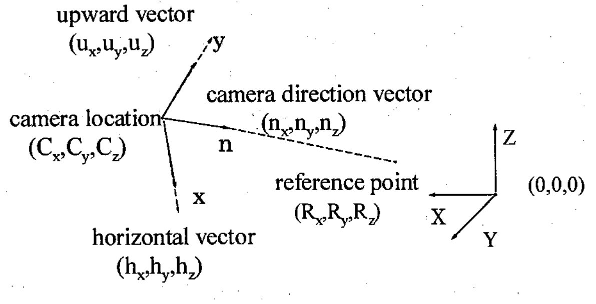
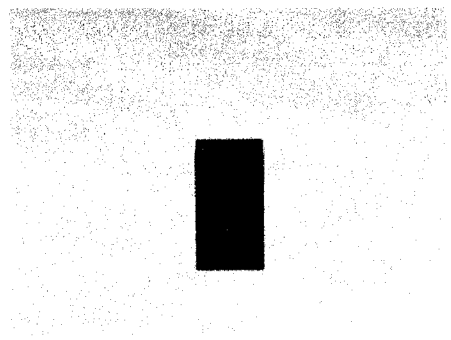


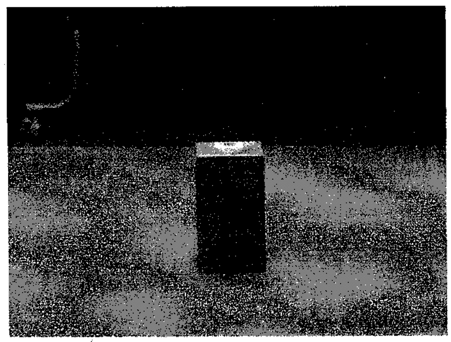
Fig.5 Viewing transformation

3.3 Example of Virtual Digital Images

Using the formulae shown above, several virtual digital images are developed for actual objects. Figure 6 shows a box put on a floor; a) is a virtual digital image and b) is an actual image. Since the location and orientation of the camera is precisely given, the virtual digital image is very close to the actual digital image. The difference in the box configuration is a few pixels.



(a)virtual digital image



(b) actual image

Fig. 6 Example of virtual digital image

4. Edge detection in sub-pixel scale

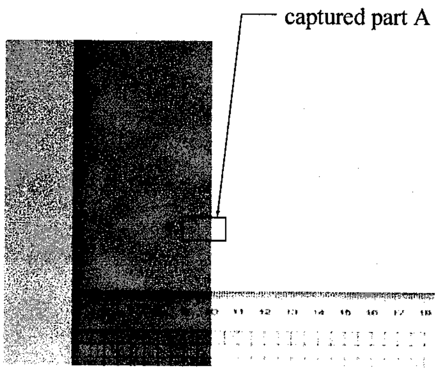
How and on what degree we can measure the shift of the building is the key issue in automated identification of structural damages. To realize it, a relative object in the digital images such as a line or a point with high accuracy position has to be identified, which makes edge detection in sub-pixel scale important. Automatic accurate edge detection requires low computational cost. Since the images taken by cooled CCD camera has the strong stability about the pixel intensity as shown in section 2, the simplest way to get the sub-pixel edge position is taking advantage of the mean value before and after the edge, then with the average of those two value the cross pixel position can be detected using linear approximation.

Two cases are taken into consideration to identify the edge in sub-pixel, indoor case and outdoor case. In the experiments, the cooled CCD camera used to take photos only moves in one direction step by step automatically on the automated optical stage.

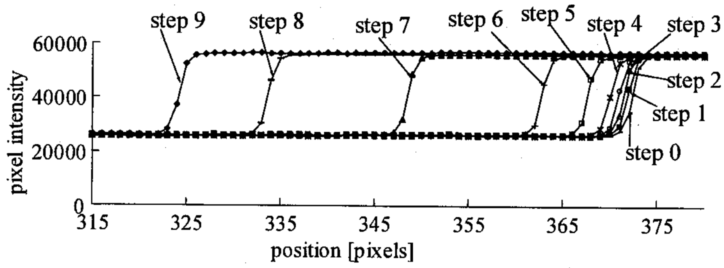
In digital images one pixel corresponds to different size, for example one pixel could correspond to 0.001cm in short distance photography or it can be 1km in aerial photography. In our experiments, the camera moving distance is within 1cm for indoor case, and from 1 cm to 15 cm for the outdoor case. For each step, 30 images are taken at the interval of 2 seconds by the cooled CCD camera automatically.

Fig. 7 shows the digital images and pixel intensity corresponding to the edge in the images. For indoor image, one pixel corresponds to 0.208 mm. And for outdoor image, one pixel corresponds to 35.59 mm. Table 3 and 4 show the comparison between observed edge shift and the shift of the camera. The maximum error is 0.256 pixels (0.053 mm) for indoor case and 0.473 pixels (16.821mm) for outdoor case.

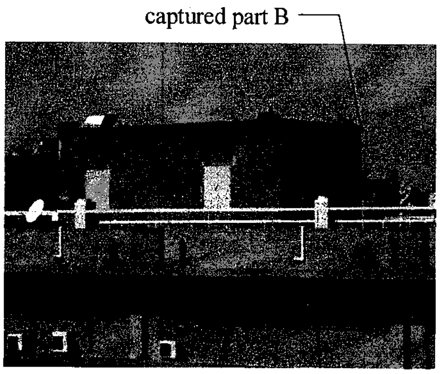
Since the high-speed and high accuracy of the edge detector is the key problem in proposed automated identification system. If we can detect the edge shift of the structure before and after earthquake with high accuracy, for example 0.1 pixels or perhaps 0.01pixels, the accurate displacement can be obtained and other analysis can be done based on that. Better algorithm will be studied in the future to improve the accuracy of the edge location.



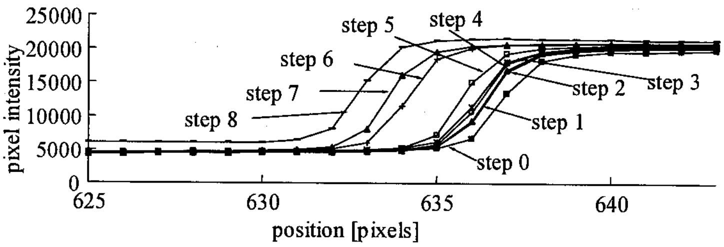
(a) indoor digital image



(b) pixel intensity of captured part A in (a)



(c) outdoor digital image



(d) pixel intensity of captured part B in (c)

Fig.7 Experiment of edge detection

Table3 Comparison of edge shift in sub-pixel scale of indoor case

camera shift (um)		200	300	500	1000	2000	5000	8000	10000
(a)corresponding edge shift (pixels)		-0.962	-1.442	-2.404	-4.808	-9.615	-24.038	-38.462	-48.077
(b)experimentally identified edge shift (pixels)		-0.967	-1.556	-2.373	-4.784	-9.677	-23.851	-38.717	-48.114
error =(b)-(a)	(pixels)	0.005	0.113	-0.031	-0.023	0.062	-0.187	0.256	0.038
	(mm)	0.001	0.024	-0.006	-0.005	0.013	-0.039	0.053	0.008

Table4 Comparison of edge shift in sub-pixel scale of outdoor case

camera shift (um)		10000	20000	30000	40000	50000	100000	120000	150000
(a)corresponding edge shift (pixels)		-0.281	-0.562	-0.843	-1.124	-1.405	-2.810	-3.372	-4.215
(b)experimentally identified edge shift (pixels)		-0.382	-0.398	-0.562	-0.651	-1.119	-2.645	-3.231	-4.053
error =(b)-(a)	(pixels)	-0.101	0.164	0.281	0.473	0.286	0.165	0.141	0.162
	(mm)	-3.590	5.832	9.992	16.821	10.165	5.876	5.013	5.754

5. Conclusions

This paper presented a preliminary study on digital images for automated identification of structural damage by edge detection. The properties of the digital images of the edge of the structure under different weather conditions are analyzed in listing the images taken by two kinds of CCD camera, low-noise cooled CCD camera and common CCD camera. The proposed consideration of pre-setting of an analysis window including the edge of the structure can drastically reduces amount of computation with a help of GIS data. Sub-pixel edge location is the key issue in the proposed method. Automated identification with high-speed and high-accuracy is needed.

Earthquake disaster always takes place in a very short time period. Since CCD images can be very easily collected, if information of structural damage can be extracted automatically and quickly from the images, it will help a lot to evaluate urban earthquake disaster quickly and to prevent risk of catastrophic failure.

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