High-speed Visual Measurement System of Pile Penetration and Rebound Movement for Construction

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ABSTRACT: A number of piles should be driven into the ground by a hammering process in order to make the ground under the structure safe and strong when construction companies build a high structure such as building and bridges. It is essential to determine whether piles are penetrated into the ground enough to support the weight of the structure since ground characteristics at different locations are different each other.

This paper proposes a high-speed real-time visual measurement approach for pile movement under hammering by combining a high-speed line-scan camera with a specially designed mark to recognize two-dimensional motion parameters, position and orientation, of a pile. A mark stacking white and black right-angled triangles is used for the measurement, and movement information for vertical distance, horizontal distance and rotational angle is determined simultaneously. Especially, a high-speed line-scan CCD camera whose line rate is greater than 10 KHz improves the measurement performance of dynamic characteristics of a pile at impact instant dramatically.

1. INTRODUCTION

Non-contacting visual measurement takes much attention since the measurement can be done safely without human intervention. It is possible to find many applications such as three-dimensional environments reconstruction and measurement of an object, posture determination of electronic components, and visual tracking of an object [1][2][3]. In most vision applications two-dimensional image sensors are used for the measurement but high-speed line cameras are adopted when dynamic motion of an object is considered since the measurement performance of two-dimensional image sensors – speed and accuracy - is constrained by image grabbing speed and imaging resolution of video cameras. Especially, blurring of images is happened and the size of image data is very huge in case of two-dimensional image sensors when the high-speed motion of an object is expected in images. So, in order to measure high-speed vibration characteristics of an object, there have been used two approaches using an acceleration sensor or a laser sensor.

Specifically, when a construction company builds a high structure, many piles should be driven into the ground by a hammer in order to make the ground under the structure safe and strong. Therefore, it is essential to determine whether a pile is penetrated into the ground enough to support the weight of the structure since ground characteristics at different locations are different each other. Normally, when the penetration depth of the pile for ten hammerings is less than 4 millimeters, the constructor finishes the pile driving process.

There have been proposed three approaches to measure the penetration and rebound movement of a pile. The first is a manual approach. After a worker attaches a white sheet on the pile, the worker draws a horizontal line slowly until a hammering process is finished. Then, the worker can obtain a graph for the vertical movement of the pile since the vertical motion of the pile changes the height of the white sheet during the hammering. The worker is, however, very dangerous since the hammering task is done over the head of the worker by using a hammer whose weight is greater than 7,000 Kg. The analysis of the movement is impossible since there is no quantitative data for the movement. The second way is to measure the movement characteristics by attaching an accelerator sensor on the pile. Since the accelerator sensor outputs acceleration information of an object, the distance of penetration and rebound movement of the pile is determined by integrating doubly the acceleration information. It requires a time-consuming process, however, to fix the acceleration sensor on the pile and the sensor data is noisy when horizontal vibration of the pile is included. The approach provides the data only for vertical movement of a pile. Another way to measure the distance of penetration and rebound movement of the pile is based on a speckle laser sensor [4] because the speckle laser sensor is effective to measure the vertical movement of an object. Distance information of vertical movement can be obtained from the sensor data directly. The measurement resolution is 0.25 millimeters while its sampling rate is 8 milliseconds. So, it is not easy to observe the details of dynamic characteristic of the pile movement at impact instant between the pile and the hammer since the rebound process takes a very short time less than 1 millisecond. Also, only one-dimensional measurement is possible.

In this paper, a high-speed real-time visual measurement system for pile penetration and rebound movement is proposed by combining a high-speed line-scan camera with a specially designed mark to recognize two-dimensional motion parameters – vertical movement, horizontal movement and rotational movement - of a pile. A simple mark stacking white and black right-angled triangles is used for the measurement, and two-dimensional motion parameters are acquired simultaneously. Especially, by adopting a line-scan CCD camera whose line rate is greater than 10 KHz, the measurement performance of dynamic characteristics of the pile at impact instant is improved dramatically comparing with other approaches. And, the measurement data for two-dimensional motion parameters shows successful applications of the proposed system for real construction field.

Section 2 introduces measurement principles and equations for two-dimensional motion parameters of a pile by using a proposed mark. Section 3 includes an edge-tracking algorithm while experimental results for a spring system and a real pile penetration system are shown in section 4. The paper is concluded in section 5.

2. MEASUREMENT EQUATIONS

For the measurement of two-dimensional motion parameters of a pile using a line-scan camera, a mark is developed by stacking white and black right-angled triangles repetitively as shown in Fig. 1. A line-scan CCD camera grabs a line image by scanning from the top to the bottom of the mark attached on the pile.

Referring Fig. 2, it is possible to determine the coordinates of intersection points between the lines in the mark and the scan line of the line-scan camera in image plane. Here,

H : Height of the mark,
W : Width of the mark,
{M} : Reference coordinate frame for measurement,
{T} : Transformed coordinate frame of *{M}*.

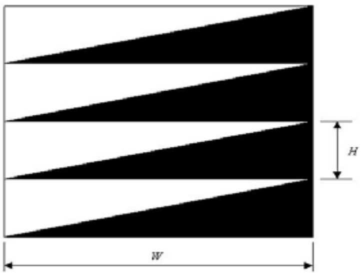

Figure 1. Proposed Mark for Measurement

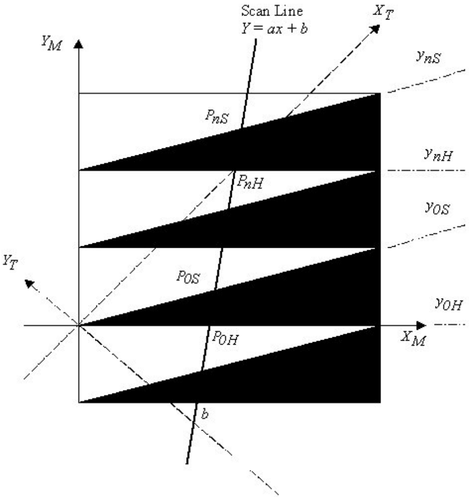

Figure 2. Used Coordinate Frames

{T} is used to overcome the singular case that the y-axis of *{M}* is parallel to the scan line of the line-scan camera. The line expressed by $y = ax + b$ in Fig. 2 represents the scan line of the line-scan

camera with respect to *{T}*. Then, if parameters of the line, *a* and *b*, are determined, the movement parameters for the mark can be calculated by using five intersection points between the mark and the scan line. When the rotational angle between two coordinate systems is set by 45 degrees as shown in Fig. 2, equations for the *n-th* horizontal and slanting line of the mark in *{T}* are expressed as follows, respectively.

$$y_{nH} = -x + n\sqrt{2}H$$

$$y_{nS} = -\frac{1}{W+H}((W-H)x + n\sqrt{2}WH)$$

Then, the coordinates of two intersection points between the scan line and the *n-th* black triangle of the mark in Fig. 2 is determined as follows.

$$P_{nH} = (\frac{n\sqrt{2}H - b}{a+1}, \frac{n\sqrt{2}aH + b}{a+1})$$

$$P_{nS} = (\frac{n\sqrt{2}WH - b(W+H)}{(a+1)W + (a-1)H}, \frac{n\sqrt{2}aWH + b(W-H)}{(a+1)W + (a-1)H})$$

Summing up, the ratio of the length of the *n(m)-th* white band of the mark with respect to the length of *n(m)-th* black band determines the line parameters, *a* and *b*, as follows.

$$a = \frac{(L_n - L_m)W + \{L_m - L_n + (L_m+1)(L_n+1)(n-m)\}H}{(L_m - L_n)W + \{L_m - L_n + (L_m+1)(L_n+1)(n-m)\}H}$$

$$b = \frac{\sqrt{2}WH\{m(L_m+1) - n(L_n+1)\}}{(L_m - L_n)W + \{L_m - L_n + (L_m+1)(L_n+1)(n-m)\}H}$$

Here,

$$L_n = \frac{D(P_{(n+1)H}, P_{nS})}{D(P_{nS}, P_{nH})} = \frac{(a+1)W + (a-1)H}{n(1-a)H - \sqrt{2}b} - 1,$$

$$L_m = \frac{D(P_{(m+1)H}, P_{mS})}{D(P_{mS}, P_{mH})} = \frac{(a+1)W + (a-1)H}{m(1-a)H - \sqrt{2}b} - 1.$$

The *D(P, Q)* is Euclidian distance between two points *P* and *Q* in a plane. Based on the above concept and equations, the following relationships to determine the motion parameters of the mark are derived by using the image of single line shown in Fig. 3. The five edge points in central area of the image are used. Let *n* = 0 for a slanting line representing the nearest upper white-to-black edge with respect to the center of the image. At first, it can be found

$$L_0 = \frac{D_{1H} - D_{0S}}{D_{0S} - D_{0H}} \text{ and } L_1 = \frac{D_{2H} - D_{1S}}{D_{1S} - D_{1H}}.$$

Then,

$$a = \frac{(L_1 - L_0)W + \{L_0 - L_1 + (L_0+1)(L_1+1)\}H}{(L_0 - L_1)W + \{L_0 - L_1 + (L_0+1)(L_1+1)\}H},$$

$$b = \frac{-\sqrt{2}WH(L_1+1)}{(L_0 - L_1)W + \{L_0 - L_1 + (L_0+1)(L_1+1)\}H}.$$

So, we can determine the coordinate of the center point of the line-scan camera image by referring Fig. 3 as follows.

$$P_C = RP_{1H} + (1-R)P_{0H}$$

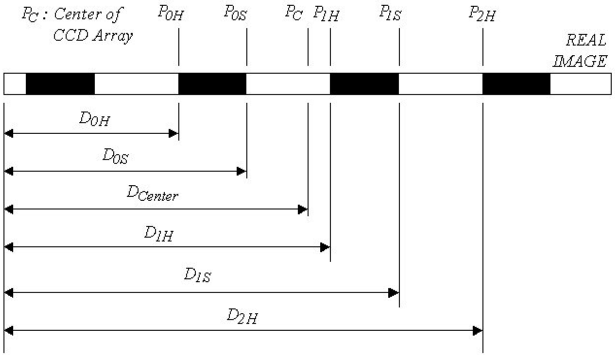

Figure 3. Distances in a Real Image

where

$$R = \frac{D_{1H} - D_{center}}{D_{1H} - D_{0H}}.$$

Consequently,

$$P_C = (\frac{-b + \sqrt{2}HR}{a+1}, \frac{b + \sqrt{2}aHR}{a+1})$$

since

$$P_{0H} = (\frac{-b}{a+1}, \frac{b}{a+1}) \text{ and}$$

$$P_{1H} = (\frac{-b + \sqrt{2}H}{a+1}, \frac{b + \sqrt{2}aH}{a+1}).$$

In order to endow the equations with the time, the initial coordinate of the center point and the coordinate of the center point at time t are described as follows.

$$P_{C0} = (\frac{-b_0 + \sqrt{2}HR_0}{a_0 + 1}, \frac{b_0 + \sqrt{2}a_0HR_0}{a_0 + 1})$$

$$P_{Ct} = (\frac{-b_t + \sqrt{2}HR_t}{a_t + 1}, \frac{b_t + \sqrt{2}a_tHR_t}{a_t + 1})$$

Finally, incremental linear movements of the center point of the line-scan image and incremental rotational movement of the scan-line of the line-scan camera compared to initial conditions of visual measurement in the coordinate frame *{M}* are determined by the following equations. Actually, the incremental linear movements are divided into two linear motions, one motion parallel to x-axis of *{M}* and the other motion parallel to y-axis of *{M}*.
Here, let

Δx_t : Incremental movement parallel to x-axis of *{M}*,

Δy_t : Incremental movement parallel to y-axis of *{M}*,

$\Delta \theta_t$: Incremental rotational movement with respect to the center point of the line-scan image.

Then,

$$\begin{pmatrix} \Delta x_t \\ \Delta y_t \end{pmatrix} = \begin{pmatrix} \cos(\theta_0 - \pi/2) & \sin(\theta_0 - \pi/2) \\ -\sin(\theta_0 - \pi/2) & \cos(\theta_0 - \pi/2) \end{pmatrix} \cdot \left(P_{C0} - P_{Ct}\right)$$

$$= \begin{pmatrix} \sin\theta_0 & -\cos\theta_0 \\ \cos\theta_0 & \sin\theta_0 \end{pmatrix} \cdot \left(P_{C0} - P_{Ct}\right),$$

$$\Delta\theta_t = \tan^{-1} a_t - \tan^{-1} a_0$$

where

$$\theta_0 = \tan^{-1} a_0,$$

a_0 : Slope of the scan line at initial time in *{M}*,

a_t : Slope of the scan line at time t in *{M}*.

The major advantage of the proposed approach is the fact that the slope and y-intercept of a scan line can be determined by dimensionless ratios between two lengths and there is no need for camera calibration.

3. EDGE TRACKING

In order to find and track five edge points of the mark in continuous images three-step image processing algorithm is proposed by combining thresholding of gray-level images, edge detection and edge tracking.

The threshold value to obtain binary images from gray level images has to be determined carefully since the brightness of images is distorted by the used zoom lens. The zoom lens is adopted in order to increase the accuracy of measurement but the brightness of images is distorted by the zoom lens since its magnification ratio is large. That is, the brightness of boundary area of the images is darker than the brightness of central area. So, it should be cleared by using multiple windows for thresholding. Fig. 4 shows an example for setting of multiple windows. Threshold values for binarization of three windowed regions are determined independently by using Otsu's optimal thresholding algorithm [5].

Edge detection is to detect white-to-black edges and black-to-white edges after thresholding in initial stage while edge tracking is for following each edge point when the motion of a pile is beginning by hammering. Since the images are one-dimensional data, the edge detection is to find rising or falling edges in binary images.

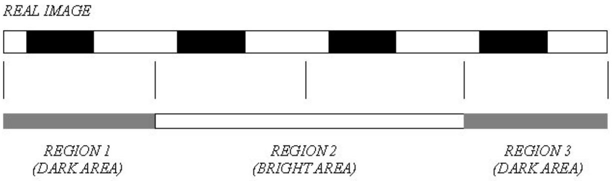

Figure 4. Windows for Thresholding

After initial edges are extracted from a binary image, exact location of each edge is determined by differentiating images for a small region in the near of the initial edge point. The point whose differential value is greater than a threshold is determined as an edge point.

For edge tracking, it is assumed that linear movement per sampling time is less than half of the height of a triangle in the mark. The new location of an edge is located by using binary search algorithm [6] in a bounded area based on the assumption. During edge tracking, if the absolute value of cumulative vertical movement from the beginning of hammering is greater than the quarter of the vertical view range of the video camera, new five edge points in the central area of an image are selected.

4. EXPERIMENTAL RESULTS

The measurement system is composed of a high-speed line-scan CCD camera DALSA CL-P1 equipped with a zoom lens and a 866 MHz Pentium III personal computer including a frame grabber, Matrox Meteor-2/DIG, for digital cameras as shown in Fig. 5. The resolution of the camera is 4096 pixels per line while its line rate is set as 10 KHz. The height of a triangle in the mark is 40 mm while the width is 200 mm.

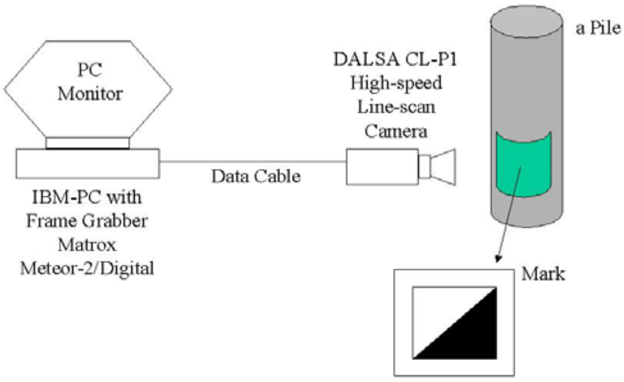

Figure 5. Measurement System

Fig. 6 shows an example image of 1000 lines obtained from the line-scan camera when the mark is at rest. A row means a scan-line while the left-hand side is the top of the mark and the right-hand side of the mark is the bottom of the mark. It is observed that the brightness condition is distorted by lens at the left-hand and right-hand boundary.

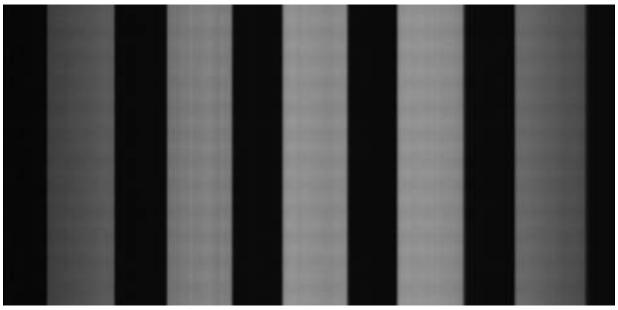

Figure 6. Scanned Image for 1000 lines

Since the sensitivity of the CL-P1 line-scan camera is low, a 500-watt halogen lamp is used for measurement. At the outside of buildings, sunlight brighter than 5000 lux is sufficient to obtain good images to process. When the weather is cloudy or rainy, external bright illumination is essential for the measurement.

At first, we measure the vertical movement of z-stage by moving the stage upward continuously in 0.5-millimeter step in order to measure the accuracy of the proposed measurement system and to analyze measurement errors. The maximum absolute values of measurement errors are less than 120 micrometers inside buildings. It is reasonable considering the natural vibration of buildings and vibration of the motorized z-stage for exact positioning. Next, the measurement test using a spring system is done successfully by generating high-frequency vertical motions through manual hammering after attaching a mark on the plate fixed to the spring system.

Finally, we have obtained measurement data of horizontal, vertical and rotational movement of a cylindrical pile under hammering in a real construction place. The weight of the hammer is 7,000 Kg while initial distance between the hammer and the top of the cylindrical pile is 2 meters. The real experimental environment is shown in Fig. 7 including a line-scan camera and a mark attached on a pile while Fig. 8 shows the measured data for 11 hammering. The motion of rebound and penetration of a pile is shown clearly. Despite the rebound of the pile is observed at each impact, the pile is penetrated into the ground in average sense. The vertical movement of a pile after an impact is composed of four intervals composed of penetration region at impact instant, rebound region after impact, settling region after rebound, and release region that the hammer is going upward for next impact. The motion characteristic in settling phase is determined by the vibration of the pile itself and ground conditions.

Figure 7. Real Experimental Environments

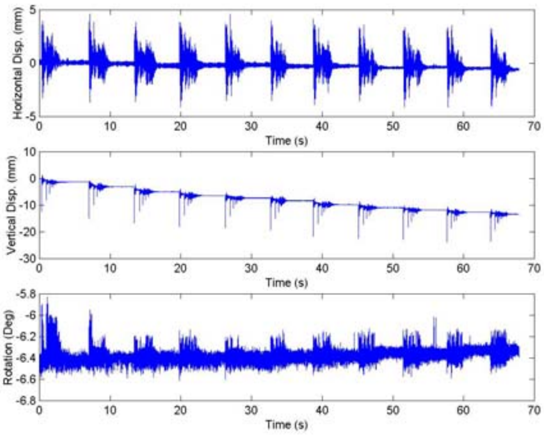

Figure 8. Measurement for a Real Pile Movement

Fig. 9 shows the motion trajectory of the attached mark in XY coordinate frame for a hammering. X-axis represents the horizontal motion of the pile and Y-axis shows the vertical movement of the pile during hammering. The largest penetration motion is the first movement after hammering and the movement is reduced continuously. Three large repelling motions of the pile by the ground are shown in Fig. 9. Since the sampling time for measurement is 100 microseconds, construction experts can investigate the dynamic characteristics of a pile in detail comparing with other equipments using laser sensors or accelerometers. Also, it is observed that the real penetration depth is shorter than the penetration depth at impact instant since repelling power from ground is very strong in finishing stage of pile penetration tasks.

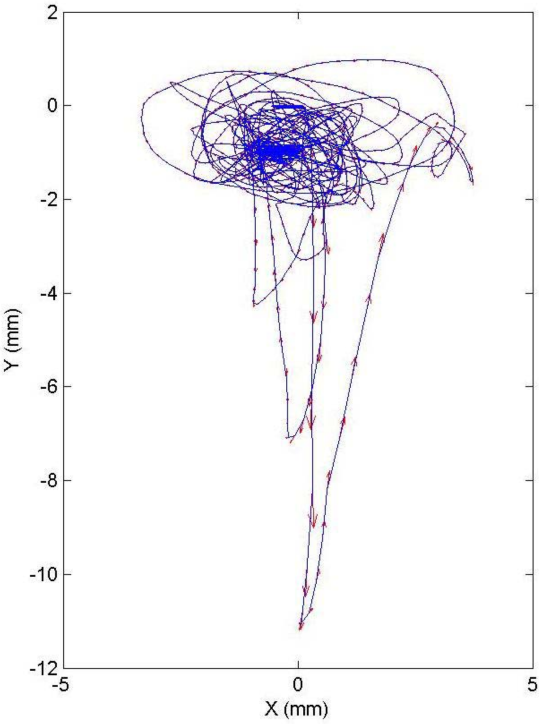

Figure 9. Pile Movement Trajectory in XY Coordinate

5. CONCLUSIONS

A high-speed real-time visual measurement system to observe pile penetration and rebound movement is proposed by adopting a high-speed line-scan camera and a specially designed mark to recognize two-dimensional motion parameters – horizontal, vertical, and rotational movement - of a pile. Movement information for vertical distance, horizontal distance and rotational angle is determined simultaneously and the information is calculated in real-time during hammering. Especially, by adopting a line-scan CCD camera whose line rate is 10 KHz, the measurement performance of dynamic characteristics of the pile at impact instant is improved dramatically and it is possible to analyze ground characteristics and material characteristics of a pile quantitatively based on the measurement data. Finally, the developed visual measurement system is applied for a real penetration and rebound measurement system for the construction of building and bridges successfully.

In real measurements, a cloud of dust and a lump of earth during hammering is troublesome obstacles when we capture images by the line-scan video camera since the dust and the lump of earth block a part of the mark and the continuous edge tracking becomes impossible sometimes. It is required to investigate a robust offline analysis method after capturing whole images during hammering.

6. REFERENCES

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