DEVELOPMENT OF POSITION MEASUREMENT SYSTEM FOR CONSTRUCTION PILE USING LASER RANGE FINDER

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ABSTRACT: This paper describes the development of an accurate long-distance position measurement system for construction pile using Laser Range Finders (LRF). The pile positioning and driving is the first work that is one of the important works to request the attentions in the building construction. In general, though the position of piling is measured by the total station that is high accurate survey machine by two workers, it has been often generated to measure the wrong points by mistake. In order to suppress such misunderstanding measurement, low-cost and simple position measurement system by LRF was developed. The LRF is a laser sensor that can measure the distance of a target object, an obtained data from the LRF are nothing more than the contours of objects. Therefore, as the survey target, we adopted the cylindrical shape object that was invariant against rotation and similar to the pile shape and the center position of the circular arc was analyzed by applying the least square method and maximum likelihood estimation. The error between the analysis and the measurement was corresponds enough to the allowable accurate range. Applying this measurement system to the construction pile work as a confirmation inspection, the exact pile positioning and real-time pile navigating and driving was achieved by only a worker, the high efficient and short term works were surely performed.

Keywords: *Laser Range Finder, Construction Pile, Position Measurement, Survey System, Estimation Method*

1. INTRODUCTION

In the survey of a construction site, the survey technology and its instrument have progressed rapidly in a short period of time. With advanced measurement instruments including an automated transit and a total station which are used light wave distance method, the measurement time becomes significantly short and positioning can be achieved with an accuracy of a few millimeters. Moreover, in civil engineering work where the work area is very wide and there are few buildings around the area, the Global Positioning System (GPS) is frequently employed for sufficient survey accuracy and efficient work.

Although the instruments can measure a position with high accuracy, they also have several disadvantages: (1) these instruments are very expensive, (2) these instruments are unavailable in some places due to environmental conditions, (3) multiple objects cannot be tracked simultaneously, (4) it is impossible to track a target in real-time, and (5) at least two workers are needed for the measurement. To overcome these problems, in this research, a simple, low-cost, highly accurate position measurement system have been developed applying the Laser Range Finders (LRFs) [1]. The LRF is a sensor which can measure distance to surfaces of objects by radiating laser beams from itself and receiving the reflected ones, and it has been widely used so far as the environmental recognition sensor of the movement object.

In the proposed concept of the position measurement system as shown in Fig.1, a worker moves in the construction field, carrying a reference bar and it is detected by multiple LRFs. This real-time position measurement system is low-cost according to the price of

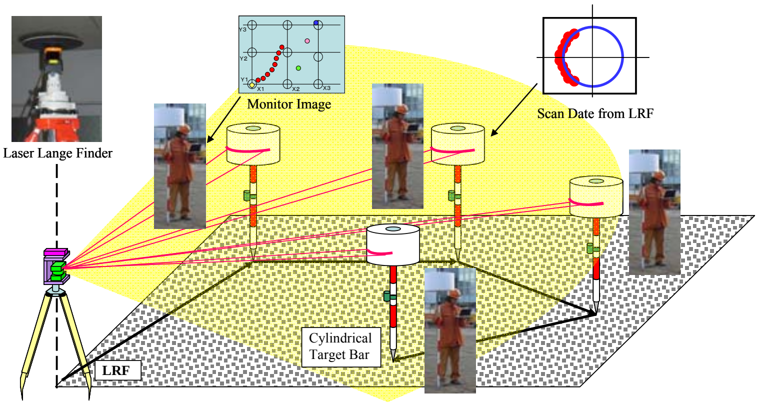


Fig.1. Surveying system using a laser range finder in a construction field

Fig2. Configuration of the developed pile position measurement system

the LRF, and can measure multiple positions at once when multiple reference bars are used, which leads to working time efficiency.

At a first application using this system, the real-time measurement of the pile marked positions and the pile driven positions were applied in construction work. As a result, a high accurate pile marking and pile drive positioning were recognized [2], [3]. Since this measurement was achieved by only a worker and the position and direction of the worker was easily found, the high efficient and short term works were surely performed.

In next stage, we propose a novel approach for accurate and efficient pile driving based on the extension of the system. In the proposed approach, the system measures a pile or piling machine and estimates the pile driving position directly. Compared to the conventional approach based on pile position marking, direct measurement of pile driving position has several advantages. In the conventional approach, once the machine starts to dig a hole in the marked position, the marked position cannot be seen any more. Therefore, during the pile driving process, workers need to keep checking that the pile is placed in the right position manually and this may degrade the accuracy.

On the other hand, in the proposed approach, since the target position is measured by this system during the operation, the pile can be kept in the desired position and additional workers to check the pile position are not needed. Since the driven pile position can also be measured, it becomes easier to evaluate a construction error.

In this paper, our position measurement system for the

Table 1 Specification of LRF

Model Number	UTM-30LX
Light Source	Laser Didde, λ=870 nm
Measureable Area	0.1～30 m, 270 deg
Accuracy	0.1～10 m, ±30 mm
	10 ～30 m, ±50 mm
Angular Resolution	0.25 deg
Scan time	25 ms

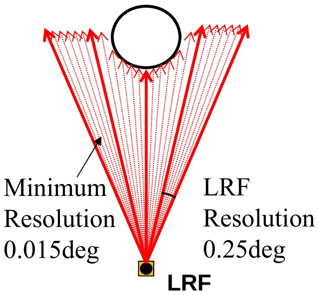
construction pile, the extensions of the surveying system to a pile driving position measurement system, a circle detection algorithm in order to extract the pile driving part from the scan data of the whole piling machine and its results are reported.

2. PILE POSITION SURVEYING SYSTEM

2.1 System Configuration

The configuration of the developed pile position surveying system is shown in Fig. 2. In the system, the LRF is set at a higher position than human height by using the tripod stand and also kept horizontal by using the leveling system. The LRF is mounted on a pan unit (explained later) which is used to improve the angular resolution of the LRF. The data acquired from the LRF are sent to the processing computer in which the center positions of the cylindrical reference bars are estimated. Then, the estimated center positions are sent to the mobile display device and the worker can easily gain information on where the current measured position is and where objective positions are in the construction field through a wireless network. The measurement process consists of four steps: data acquisition from the LRF, extraction of measurement data

(a) Pan unit mechanism



(b) Angular resolution with /without the pan unit.

Fig.3. Combination of a laser range finder and a pan unit

of reference bars from the whole scan data, position estimation from extracted contour data based on circle fitting, and visualization of surveying results using mobile displays. In the following subsections, we explain the details of each step.

2.2 Data Acquisition from the LRF

An LRF outputs both a distance to surface of an object and the reflected intensity of each scanning step. The specification of the LRF is shown in Table 1. In addition, the accuracy of circle fitting is usually dependent on the number of the data points and the length of the obtained contour. Here we consider increasing the number of data points belonging to the contour by improving the angular resolution of the LRF using a pan unit.

In order to increase the number of data points, we set the moving head pan unit which can be paned by the angular resolution of 0:015 deg. as shown in Fig. 3(a). Since the angular resolution of the LRF can be improved about 17 times by using the pan unit, by using 17 different scanned results, we can get a dense contour as shown in Fig. 3(b).

2.3. Extraction of Measurement Data of Reference Bars

To extract measurement data of reference bars from the whole scan data, we use a simple but efficient extraction algorithm based on background subtraction and clustering. In the extraction process, the static parts of scan (background) are subtracted from the current scan data in order for determining which parts of the scan are due to moving objects (foreground) at the beginning. The scan points in the foreground are then grouped using hierarchical clustering. The nearest neighbor method based on the Euclidean distance between foreground points is applied for clustering. This divides the foreground to a number of clusters, each belonging to one of the target object. Clusters with a small number of scan points are discarded as measurement noise. Since pile driving positions are determined in advance, we are able to improve the processing time and extraction accuracy by considering only the area around the desired positions.

Moreover, in order to improve accuracies of circle fitting, we focused on eliminating data points with large noise which cause a collapse of the contour's shape and obtaining arc-shaped contour. Since S/N ratios of such data points are worse than the others, we implemented a reflected beam intensity filter which eliminates data points whose reflected beam intensities are less than α [%] of the highest intensity in the contour.

2.4. Center Position Estimation

After extracting scan points belonging to reference bars, we fit a circle to each arc-shaped contour and estimate the accurate center position based on maximum likelihood estimation (MLE). Generally, the equation of a circle in 2D plane can be expressed as

$$x^2 + y^2 - 2ax - 2by + a^2 + b^2 - r^2 = 0 \qquad (1)$$

where (a, b) is the center position and r is the radius of the circle. The MLE for a circle is a method for deciding the center position (a, b) and the radius r of the circle so that the observed data can most easily be obtained from the assumed noise model [4]. In other words, the MLE is a method for deciding the parameters (a, b) and r which will maximize the likelihood of the measurement $\{\mathbf{x}_i\}$ (i = 1, 2, - - , N), where $\mathbf{x}_i = (x_i, y_i)$ is a data point and N and i denote the number of scan points in the cluster and index of each point, respectively. In this paper, we assumed that each data point obtained from the LRF had an independent error described by a Gaussian distribution with mean 0 and standard deviation σ. Then, the MLE for a circle is equal to estimate parameters a, b, and r which will minimize expressed as

$$J_{ML} = \sum_{\alpha=1}^{N} \frac{\left[x_\alpha^{\,2} + y_\alpha^{\,2} - 2ax_\alpha - 2by_\alpha + a^2 + b^2 - r^2\right]^2}{x_\alpha^{\,2} + y_\alpha^{\,2} - 2ax_\alpha - 2by_\alpha + a^2 + b^2} \qquad (2)$$

In our case, since the radius of the reference bar is given in advance, parameters which should be demanded become only a and b. In order to solve the non-linear equation (4) iteratively, we applied the Newton-Raphson method since it is known to have a faster convergence than other gradient method, conjugate gradient method if its initial value is close to the true value[6].

2.4 Evaluation of Surveying Error using Multiple LRF

Formerly, we have already recognized the characteristics of surveying error between true data and measurement data using the three estimation methods of Constant Distance Method (CDM), Least Square Method (LSQ) and Maximum likelihood Estimation (MLE) when only a single LRF was used [1], [4], [7]. However, the measurement range being very wide and several obstacles being in actual construction filed, the center position of standard bar was estimated using the connected data from multiple LRFs.

Fig.4 shows the location of two LRF and measurement points. Each LRF is sat on y-axis in contrast position to the x-axis and the standard bar is moved on x-axis. In the typical measurement points as reference, distributions of the laser points on the circle were indicated. Fig.5 shows the error rate to the distance of LRFs estimating by MLE. The horizontal axis represents the distance from the +LRF and -LRF, and the longitudinal axis represents the error rate of the estimated center position that error margin is divided by the standard absolute distance. Connecting the obtained scan data from +LRF and –LRF, the error rate of connected data was much lower than that of each data. It was thought that the accuracy of the estimation method was improved because the number of data increased.

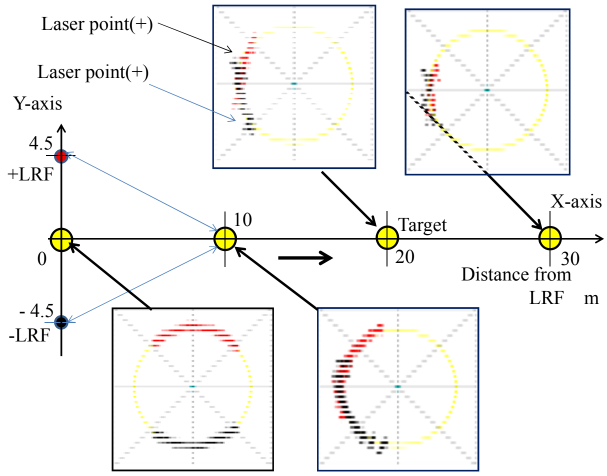


Fig.4. Location of two LRF and measurement points and distributions of the laser points on the circle

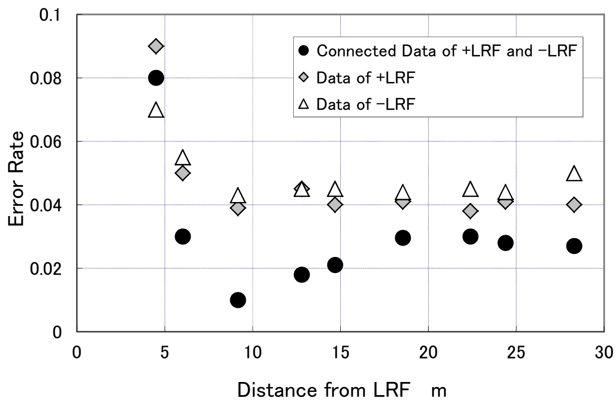


Fig.5. Error rate to the distance of LRFs estimating by MLE

3. EXTENSION OF THE SURVEYING SYSTEM TO A PILE DRIVING POSITION MEASUREMENT SYSTEM

3.1. Necessary Function for the Extension

As described in the previous section, the LRF based surveying system measures the position of cylindrical reference bars. Because there exist circular objects in the pile driving process, for example, cover of the earth auger and a pile itself as shown in Fig. 6, we can apply the most parts of the system directly to pile measurement.

However, since the scan image of the circular part is usually connected to the scan image of the piling machine and forms a large cluster when the clustering is used, it is impossible to apply MLE to the points obtained based on the extraction method shown in Section 2C. Therefore, it is necessary to develop a circle detection algorithm in order to extract the pile driving part from the scan data of the whole piling machine.

3.2. Circle Detection Algorithm

This subsection presents a method to detect circular part from laser range finder data. The method is based on random sampling from the data set in order to remove the points belonging to other objects. A candidate of a circle is calculated by using randomly selected points and it is considered as a circle if other points in the data set also fit well to the candidate. In addition, we utilize the information on the circle radius and constraints due to the convex shape of the object to reduce the computational time and the detection error. The details of the algorithm are described below. The following processes are performed to each cluster extracted by background subtraction and clustering.

(1) Selection of Points and Calculation of the Center: Since the radius of the target R is given in advance, if we select two points (x_i , y_i) and (x_j , y_j) from the cluster, we can calculate the center of the circle (a_{mij} ,b_{mij}) (m = 1, 2) passing through the two selected points by solving a quadratic equation. However, if the distance between the selected two points is larger than the diameter of the circle, there is no solution to the equation. Therefore, we select the first point randomly and choose the second point from neighborhood of the first point in order to reduce unnecessary selection. In addition, as shown in Fig. 9, a solution where the selected points do not lie on the observable arc is ignored as an improper solution.

(2) Calculation of Fitness: The obtained circle candidate based on the selected two points ($x_{i,}$ y_i) and (x_j , y_j)is then evaluated by using other points in the cluster. If the distance between the center (a_{mij} ,b_{mij})and a point in the cluster (x_k ,y_k) is nearly equal to the radius R, that is, the condition,

$$\left|\sqrt{(x_k - a_{ij}^m)^2 + (y_k - b_{ij}^m)^2} - R\right| < \sigma_R, \quad (3)$$

is satisfied, we consider that the point (x_k ,y_k) lies on the circle candidate which is defined by the center (a_{mij} ,b_{mij}) and the radius R, where ¾R is a positive threshold value. Similar to the calculation of the center position, if (x_k ,y_k) is not on the arc which can be observed by the LRF, the calculation is not performed. When many points in the cluster are considered to be on the circle candidate, the algorithm judges that a circle is detected. But the number of scan points belonging to the circle decreases if the distance between the LRF and the circle becomes large because an LRF emits a laser ray radially. Therefore, points which meet (5) are more than β[%] of the observable points when we assume the circle is at (a_{mij} ,b_{mij}) , we consider a sufficient number of points are obtained. In the case that a circle is detected, the center position (a_{mij} ,b_{mij}) and points which satisfy (5) are recorded and these points are removed from the cluster.

(a) Cover of earth auger. (b) Pile side.

Fig.6 Possible measurement object using LRF

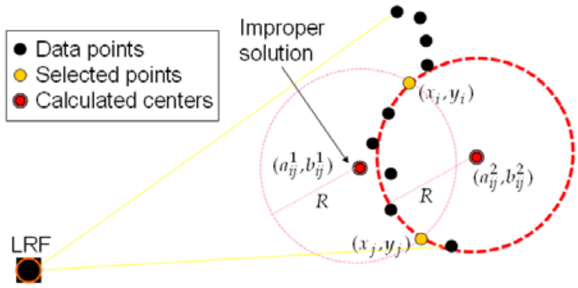


Fig.7 Calculation of the center based on the sampled points

(3) Determination of Termination: The algorithm goes back to the first step unless the all points in the cluster are removed or the number of iterations exceeds a certain threshold.

3.3. Simulation Results of Circle Detection

We performed simulations to test the detection algorithm in several situations. In the simulations, the sensor noise is modeled by a Gaussian distribution and we used sensor parameters of UTM-30LX. An example of the simulation result is shown in Fig. 6. In this situation, the LRF is placed at the origin of the coordinate system and measures a pile which is 9 meters away from the LRF. We can find that the points belonging to the circular part is successfully extracted from the large cluster by using the proposed method.

As a result of 10000 simulations, the mean estimation error was 26 mm. In addition, we used the estimated center position as an initial guess of the Newton-Raphson method and applied the MLE explained in Section 2D to the extracted points on the arc. In this case, the mean error was 11 mm and it is almost the same accuracy as the surveying system described in Section 2 [7].

4. EXPERIMENT IN AN ACTUAL CONSTRUCTION FIELD

To verify the proposed positioning system, we made the experiment in an actual construction field. Our purpose is to measure the position of a pile which is being put into the pile hole and show the feasibility of the proposed approach. Tracking the position of a pile could help to make it be put at the expected place, which requires an accuracy of 100 mm.

4.1. Experimental Setup

As mentioned in chapter 2, the LRF is assembled with a pan unit which is used to improve the angle resolution of the LRF. The LRF and pan unit are placed on the tripod which can be adjusted to keep the scan plane of LRF horizontal. The height of tripod also helps to keep the other moving objects (waking humans, etc) from the scan range of the LRF. The object to be measured is the pile shown in Fig.9, with a radius of 200 mm. Limited by the arrangement of the construction field, the distance between the measured object and the LRF is about 15 m. As also shown in Fig. 10, the pile was lifted by the pile driver and being slowly put down into the hole. During the process, the pile was kept to the expected position by manual work as done in most construction fields, that is, three well trained workers measured whether the pile is in right place or not using sticks. The developed system also measured the pile position to show that it is possible to track the pile.

4.2. Calibration of the Laser Range Finder

Before the position measurement, calibration of the LRF is needed for proper calculation from the local (sensor's) coordinate system to the world coordinate system. First, the LRF was set on the exact position measured by a total station (precision: 2 mm/km). To calculate the orientation of the LRF, we used a narrow reflective tape attached to a metal thin stick. The thin stick was also placed at a known position and the LRF measured the direction to the stick by finding the direction of the high intensity laser reflection using a pan unit to determine the orientation of the LRF.

4.3. Experimental Results

The procedure of pile driving was recorded by the LRF. It started when the pile was got to about 1 m of the expected position. After arriving the top of the hole, the pile was kept going down at a position with error around 50 mm.

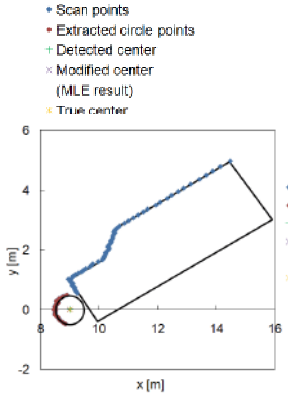


Fig.8 Simulation result – circle detection from a large cluster

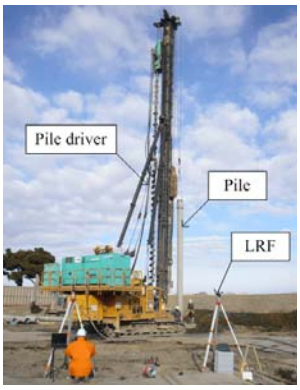


Fig.8 Scene of pile driving position measurement

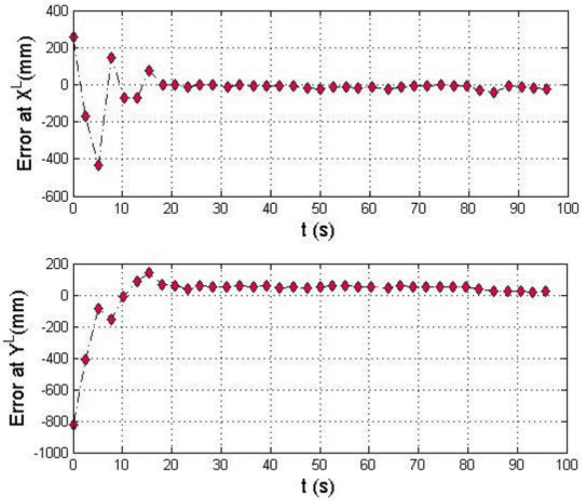


Fig.10 X and Y error in the LRF coordinate system between the measured position and the expected pile position

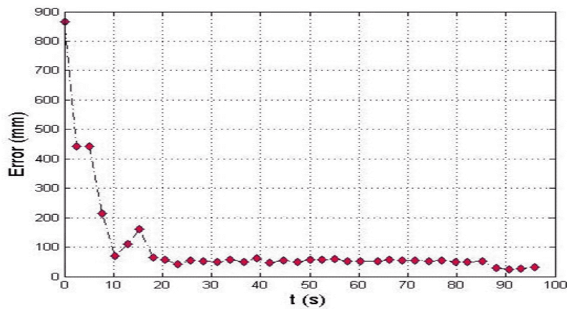


Fig.11 Error between the measured position and the expected pile position

The placement of pile was adjusted to be more accurate at the final 10 s. The position adjustment by workers can be seen in Fig. 8. The error between estimated center position and expected design position of the pile is shown in Fig. 11. The final position error given by the proposed system was around 25 mm. Currently, there is no direct way to measure the real time center position of pile. However, since the accuracy of the previous surveying system is 10 mm, we can guess that the construction error is within the range of 15-35 mm. Considering the manual adjustment process, the result is considered reasonable. Therefore, we may say that with the proposed system it is possible to measure the pile driving position directly which cannot be measured by conventional surveying instruments. In addition, from this experiment, it is certain that the pile was driven within the allowable range.

5. CONCLUSION

In this paper, we proposed an approach for accurate and efficient pile driving based on pile or piling machine measurement. Since it is difficult to observe the pile driving position directly by using conventional surveying instruments, we utilize the laser range finder based surveying system. The surveying system is extended by adding the circle detection function in order to extract the pile driving part from the scan data of the whole piling machine and successfully applied to pile driving position measurement. The experiment conducted in an actual construction field showed the feasibility of the proposed approach.

For future work, we will develop a more complete measurement system including an operator navigation function. By using the function, the operator of the piling machine is able to know the current machine position and the target and thereby adjust the position easily. We will also evaluate the developed system in construction sites.

REFERENCES

[1] H. Tamura, T. Sasaki, H. Hashimoto, F. Inoue, "Shape Based Position Measurement Method Using Laser Range Finders", *Proc. of Int. Conf. on URAI*, pp.570-574, 2009.

[2] J. Ryde and H. Hu, "Fast Circular Landmark Detection for Cooperative Localization and Mapping", *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 2745-2750, 2005.

[3] N. Chernov and C. Lesort, "Least Square Fitting of Circles", *Journal of Mathematical Imaging and Vision*, Vol. 23, pp. 239-251, 2005.

[4] K. Kanatani, "Statistical Optimization for Geometric Fitting: Theoretical Accuracy Analysis and High Order Error Analysis" *Int. Journal of Computer Vision*, Vol. 80, no. 2, pp. 167-188, 2008.

[5] N. Ando, T. Suehiro, K. Kitagaki, T. Kotoku, and W. K. Yoon, "RT-Middleware: Distributed Component Middleware for RT", *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robotics and Systems*, pp. 3555-3560, 2005.

[6] T. Sasaki and H. Hashimoto, "Design and Implementation of Distributed Sensor Network for Intelligent Space Based on Robot Technology Components", *Proc. of the 2nd Int. Conf. on Human System Interaction*, pp.400-405, 2009.

[7] F. Inoue, S. Doi, X. Huang, H. Tamura, T. Sasaki and H. Hashimoto, "A Study on Position Measurement System Using Laser Range Finder and Its Application for Construction Work," *The 5th Intl. Conf. on the Advanced Mechatronics*, pp.361–366, 2010.