Acquisition Model for 3D Shape Measurement Data

Jong Sik Park[1], Wang Jin Jang[1], Seong Beom Lee[2,#] and Chanseok Park[3]

1 Department of Mechanical Engineering, Inje University, 607 Obang-dong, Gimhae, Gyeongnam 621-749, South Korea
2 High Safety Vehicle Core Technology Research Center, Inje University, 607 Obang-dong, Gimhae, Gyeongnam 621-749, South Korea
3 Department of Mathematical Sciences, Clemson University, Clemson, South Carolina 29634, USA
Corresponding Author / E-mail: mechlsb@inje.ac.kr; TEL: +82-55-320-3667, FAX: +82-55-324-1723

KEYWORDS: 3D laser scanner, 3D shape measurement, Laser scanning, CCD, 3D scan data, Accuracy

The demand for three-dimensional (3D) shape measurements is increasing in a variety of fields, including the manufacture of molds and dies. The most popular technology for 3D shape measurement is the coordinate measuring machine (CMM) with a contact trigger probe. Although a CMM provides a high degree of accuracy, it is inefficient due to its long measuring time. It also has difficulty measuring soft objects that can be deformed by the touch of the contact probe. In addition, a CMM cannot digitize areas that are difficult to reach, and cannot capture very minute details on the surface of complex parts. For these reasons, optical non-contact measurement techniques are receiving more attention since they eliminate most of the problems associated with contact methods. Laser scanning is emerging as one of the more promising non-contact measurement techniques. This paper describes various acquisition considerations for laser scanning, including the accuracy of the 3D scan data, which depends on the charge-coupled device (CCD) gain and noise. The CCD gain and noise of a 3D laser scanner are varied while keeping the other conditions constant, and the measurement results are compared to the dimensions of a standard model. The experimental results show that a considerable time savings and an optimum degree of accuracy are possible by selecting the proper CCD gain and noise.

Manuscript received: September 18, 2007 / Accepted: June 16, 2008

1. Introduction

The current rapid advance of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies has enabled functional and aesthetic designs of complex sculptured surfaces to be used extensively in the automotive, die and mold, and aerospace industries. The acquisition of precision three-dimensional (3D) descriptions of complex surfaces plays an important role in the design, manufacture, and inspection of these high-quality parts. Scanning and digitizing 3D complex sculptured surfaces has emerged as an effective tool for inspection and reverse engineering.[1,2]

While the normal manufacturing process involves machining a part from a CAD model, reverse engineering involves creating a CAD model from the actual part,[3] where the surfaces of the part are digitized using a coordinate measuring machine (CMM), a laser scanner, or some other digitizing tool. Digitization is the process of obtaining the coordinates of points on the surface of the part. Digitization techniques can be divided into contact and non-contact methods.

The most popular contact method involves the use of a CMM, in which a mechanical touch probe is used to obtain the coordinates of selected points on the surface of the part.[4] The CMM has gained acceptance in manufacturing for its flexible approach to inspection and verification tasks.[5] The aeronautical and automotive manufacturing industries, in particular, frequently encounter complex surfaces, an d rely on CMMs for dimensional inspection. Recent improvements in CMMs have enlarged their application range and increased the reliability of their measurement results.[6,7] Unfortunately, CMM systems require extensive operator training, both to set up and to operate the equipment.[8] They also have two significant disadvantages: an inability to digitize hard-to-reach spots and an inability to capture very minute details on the surface of complex parts. An even greater drawback, however, is that CMMs are very slow, especially for digitizing complex parts.

Non-contact techniques eliminate most of the problems associated with contact methods. Laser scanning is one of the most popular non-contact digitization techniques to emerge, and has the advantages of low cost, high speed, and ease of operation.[4] But despite the increasing use of laser scanners, there are still some improvements required, the most challenging of which is an increase in the digitizing accuracy.

Most previous research efforts on laser scanning have focused on the development of application-specific laser scanning systems and path planning for commercial laser scanners. Larsson and Kjellander[9] proposed path planning for laser scanning with an industrial robot. Kim et al.[10] used a 3D scanner to investigate the ideal location and bristle dimensions dental patients with fixed prostheses and severe periodontitis. Kovacs et al.[11] compared breast volume measurements using 3D surface imaging and classical techniques while Ryu et al.[12] proposed automated measurements using a 3D scanner with a robot simulator. Feng et al.[7] proposed a structured light-based system for human heads.

Research work into improving the application of commercial laser scanners has been mainly oriented toward developing automated planning approaches for the laser scanning process. Detectability constraints of the laser scanning process have been considered to determine the optimal laser scanner viewpoints and paths.[13,14] Earlier work by Rioux et al.[15] determined that the intensity of the diffuse laser light focused on the photodetector array was the main factor affecting laser digitizing accuracy. Random errors in the triangulation-based laser-scanned data were primarily caused by speckles in the laser images due to the mutual cancellation and reinforcement of the light waves.[16] Kim et al.[17] studied 3D modeling using a 3D scanner with Visual LISP. Tamura et al.[18] examined the systematic errors in a 3D laser scanning system that resulted from setup errors in the galvanometers that are used to control the laser beam direction, and developed a calibration technique to improve the measurement accuracy. More recently, Smith and Zheng[19] developed a simulation model for point laser triangulation probes, and demonstrated the effect of the sensor-to-surface orientation on the scanning errors.

The primary aim of this study is to investigate 3D scan data acquisition considerations and accuracy, which depend on the gain and noise parameters of the charge-coupled device (CCD) camera used in the 3D laser scanner. We also aim to reduce the model creation time and investigate the accuracy of models composed of merged 3D scan data.

2. 3D laser scanning and experimental device

2.1 3D laser scanning

Three-dimensional laser scanning is a non-contact digitization procedure that provides fast and consistent acquisition of component geometry data through the use of a laser beam. The z-axis values in laser scanning are measured on a grid of predetermined x- and y-coordinates. The basic elements of the system are a non-contact laser probe that emits a low-energy laser beam, a scanning mechanism that projects the laser beam onto the surface being digitized, and optical receptors with collecting lenses that detect the reflected laser beam. The z-coordinate of each point on the target object surface is calculated by trigonometric algebra applied to the projection direction (scanner angular position) and the detection direction made by the light spot position on the sensor. Figure 1 shows the principle of a laser triangulation sensor. The laser beam is projected onto the object. The lens images the laser point onto the CCD or position-sensing detector (PSD) sensor. An offset on the object causes an offset in the image. In the figure, DZ indicates difference in the positions of the two objects.[20]

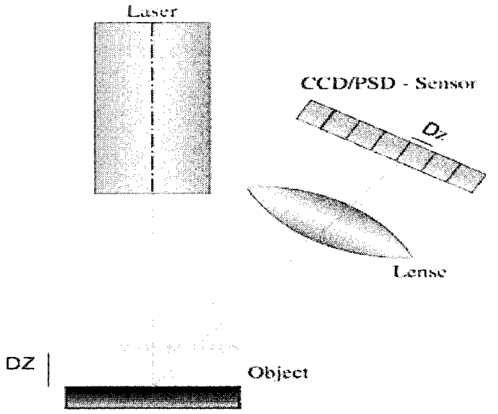


Fig. 1 Principle of a laser triangulation sensor

Each surface of the object is scanned separately in this process to obtain point cloud data. In reverse engineering applications, the point cloud data for all the surfaces are merged into a single point cloud for the entire object. This point cloud is then used to develop the CAD model of the object, which is used for the toolpath generation and machining. The point cloud data for each surface may be used to generate NC toolpaths directly for that surface. The part is then machined using these toolpaths.[21]

2.2 Experimental device

The Exyma-ES300 is non-contact 3D scanner that uses both the Moiré method and phase measuring profilometry (PMP) to produce a high degree of accuracy and resolution while providing a simple system configuraton.[22] Like other laser scanners, the Exyma-ES300 uses a Class II laser that does not present a hazard to the human eye. The lasers have about the same power as the barcode scanners used in supermarket checkouts. They typically have a wavelength of 670 nm, which is within the visible spectrum. This means the eye will blink when exposed to the laser and thus limit exposure to the laser light.[23] Table 1 lists the specifications of the Exyma-ES300.

Table 1 Specifications of the experimental device

	Exyma-ES300
Scanning area	300 × 225 × 200 mm
Scanning time	1.5–7.0 s
Optimal scanning distance	750 mm
Maximum number of data points per scan	1,300,000
Operating temperature	10°C–30°C
Scanning method	Moiré and PMP
Scanning head size	450 × 280 × 105 mm
Weight	3.2 kg
Camera resolution	1300 × 1024 pixels
Light source	Class II laser
Power	220 V, 50/60 Hz
Computer	Pentium IV, 1 GHz, minimum 512 MB, Windows XP/2000/NT

3. Materials and methods

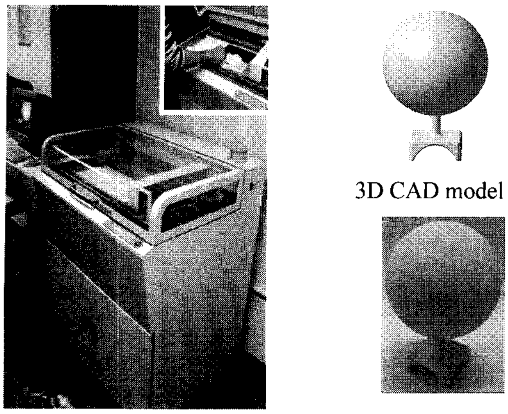
3.1 Reference model

The reference model was based on a 3D CAD design produced with CATIA V5 (Dassault Systèmes SA). The first step in producing the reference model was to create a 3D CAD base model in CATIA V5 and export the model file in STL format. This STL file was used to produce a reference model with the rapid prototype 3D printer. The 3D base CAD model, the reference model, and the rapid prototype 3D printer are shown in Figure 2. The reference model was produced to create a standard for determining the measurement accuracy. The test was performed using only the head of the reference model, which had a diameter of 100 mm.

Rapid prototyping is the automatic construction of physical objects using solid freeform fabrication. The first techniques for rapid prototyping became available in the late 1980s and were used to produce models and prototype parts. Today, rapid prototyping is used for a much wider range of applications, and even to manufacture production-quality parts in relatively small numbers. Some sculptors use the technology to produce complex shapes for fine art exhibitions.

In the additive fabrication technique, the machine reads the CAD data and lays down successive layers of liquid, powder, or sheet material to build up a model from a series of cross-sections. These layers, which correspond to virtual cross-sections from the CAD model, are joined or fused automatically to create the final shape. The primary advantage of additive fabrication is its ability to create almost any shape or geometric feature.

The standard data interface between CAD software and rapid prototyping machines is the STL file format. An STL file approximates the shape of a part or assembly using triangular facets.[24]


3D CAD model

The 3D printer (Z Corp. Z400) Reference model

Fig. 2 Generation of Reference Model

3.2 Data acquisition

Figure 3 shows a simplified version of the data acquisition process. Three-dimensional laser scanning involves the following steps.

1. Preparing the object for scanning.
2. Setting up the 3D laser scanning system.
3. Adjusting the 3D laser scanner settings. The CCD gain and noise conditions were varied during this test.
4. Scanning the object.
5. Finishing the 3D scan data acquisition.

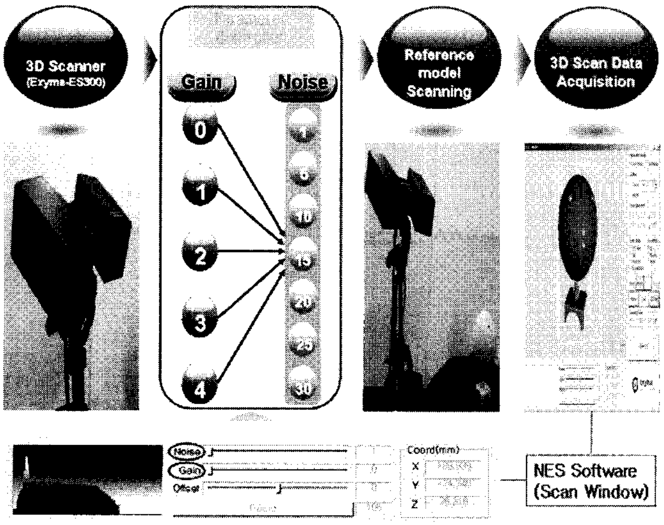


Fig. 3 Data acquisition process

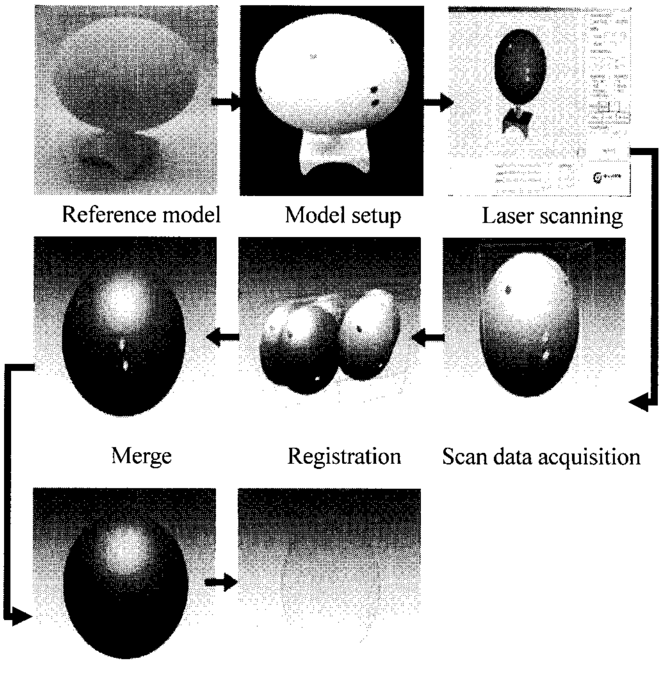
Stickers were attached to the reference model to divide the area and make it easier to merge the scanned data. We acquired 3D laser scan data for five patches on the surface of the model. Placing the reference model in five different positions allowed us to obtain five laser measurements of the surface from different angles.

3.3 Scanned data processing

The main tools used for the 3D scan data processing were Rapidform 2004 (INUS Technology, Seoul, Korea) and NES (Z-Scan Co., Ltd) software. The scanned 3D scan data were converted to STL format by the NES software, and then processed and merged by Rapidform 2004.

The scanned data were processed using the following steps.

1. Complete the 3D laser scanning.
2. Export the scanned data in STL file format using the NES software.
3. Import the STL files into Rapidform 2004.
4. Use the "Register | 2 Shells | Initial" function of the Scan workbench to combine and align the scan data patches.
5. Use the "Register | Fine" function of the Scan workbench to recombine the entire scan data patch set using an automatic algorithm.
6. Use the "Merge | Meshes | Surface" function of the Scan workbench to blend the different patches into a model and construct a surface with the 3D values of each corresponding point of the different scan data patches.
7. Use the "Select | Entities, Edit | Delete" function from the menu bar to remove rough areas of the scan data patches.
8. Use the "Fill Holes | Surface (Curvature method)" function of the Polygon workbench to fill the holes in the surfaces that remain after deleting the rough areas of the scan data patches, manually or automatically.
9. Use the "Clean | Find Abnormal Faces" function of the Polygon workbench to eliminate surface abnormalities of the previously processed shell.


Reference model Model setup Laser scanning

Merge Registration Scan data acquisition

Fill holes Completed model

Fig. 4 Scanned data processing

3.4 Model comparison

We developed a method for comparing each previously processed model. Figure 5 shows the process of extracting the diameter for model comparison. Our method uses a specified section for model comparison because of the different number of points obtained in 3D laser scanning. The steps are as follows:

1. Open a file of completed models.
2. Use the "Ref. Geometry | Create | Plane | At Min/Max Boundary with X, Y, Z Axis" function to create planes at the minimum and maximum positions of the *x*-axis, and the maximum position of the *z*-axis.
3. Use the "Ref. Geometry | Create | Vector | Pick Points" function to create a vector to include the minimum and maximum points of the *x*-axis.
4. Use the "Ref. Geometry | Create | Point | From Ref. Vector" function to create a center point on the vector.
5. Use the "Ref. Geometry | Create | Plane | Pick Parallel Plane & Point" function to create a plane on the center point.
6. Divide the completed model on the center plane.

7. Extract the diameter information from a divided section.

The complete merged scan data set was processed using the above sequence. The results of the processing were compared with the standard diameter of the reference model to evaluate the scan data accuracy.

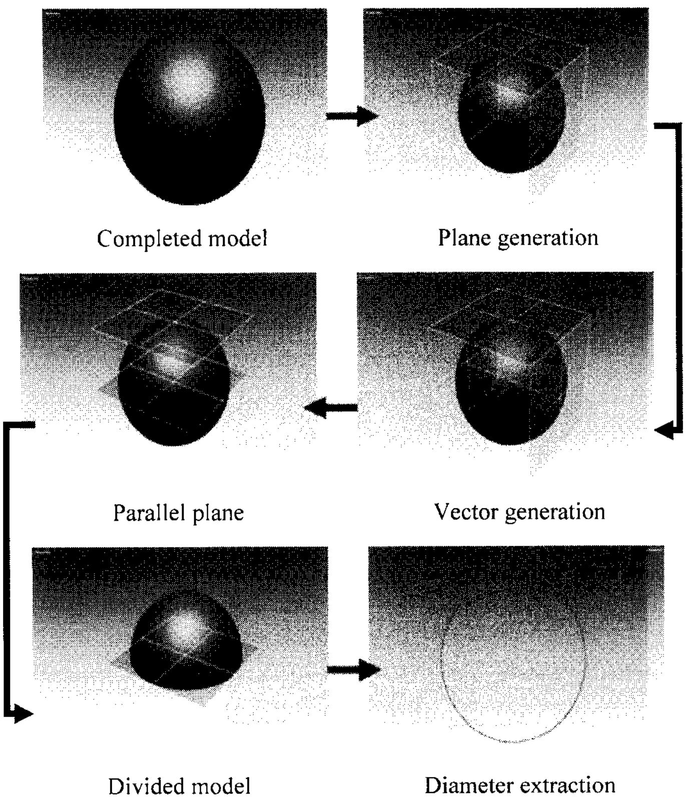


Fig. 5 Diameter extraction process for model comparison

4. Results and discussion

The reference model was scanned 525 times using different combinations of CCD gain and noise. A total of 105 diameter measurements were obtained with 3 trials.

Each diameter measurement was compared with the standard diameter from the CAD model file. The real diameter of the reference model was 100 mm, but a standard of diameter of 99.98024 mm was used as a basis of comparison for each diameter measurement. This illustrates why the method of extracting the diameter information does not involve simply measuring halfway down the model. Our proposed methodology ensures that a specified section is used for the model comparison.

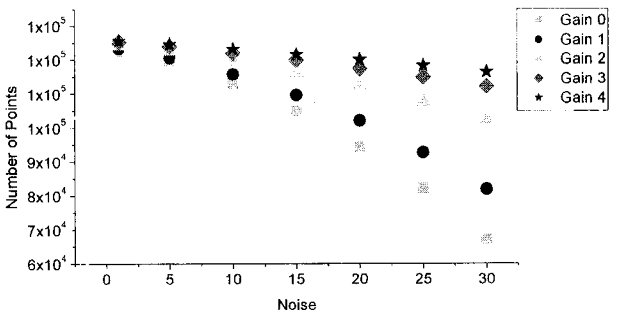


Fig. 6 The number of points of the first laser scanned data

A total of 105 model comparison tests were conducted to demonstrate the accuracy of the extracted diameter information. Figure 6 shows the number of points in each scan of the first laser-scanned data set. In general, the number of scanned points increased as the gain increased and the noise decreased. The results from the first diameter measurement are shown in Fig. 7. Scan data with a gain of 0 were very unstable and rough. Although there was only a slight difference of 0.24–0.51%, most results did not accurately measure the standard diameter of the reference model. The scanned data processing caused minute experimental errors, especially in the data registration step. A specified measurement accuracy also implicitly includes specifying the overall registration accuracy. However, registration accuracy does not appear on any laser scanner specification sheet. Therefore, the entire scan data patch set was recombined using the automatic algorithm in Rapidform 2004. The residual errors may be due to the effects of the incident angle and the scan depth, which could be the subject of further research. Figure 8 shows average diameter obtained from the first laser scanning attempt. A gain of 3 resulted in a diameter that was closest to that of the reference model.

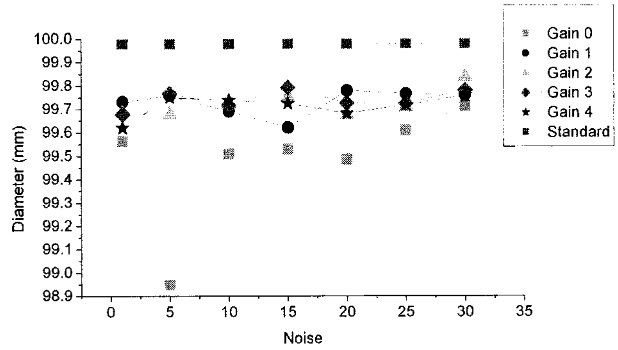


Fig. 7 Diameter Results of the first laser scanned data

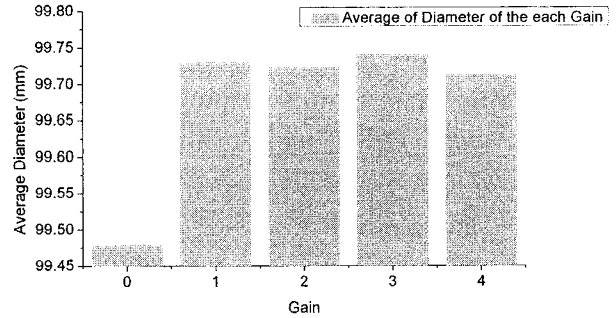


Fig. 8 Average of Diameter Results of the first laser scanned data

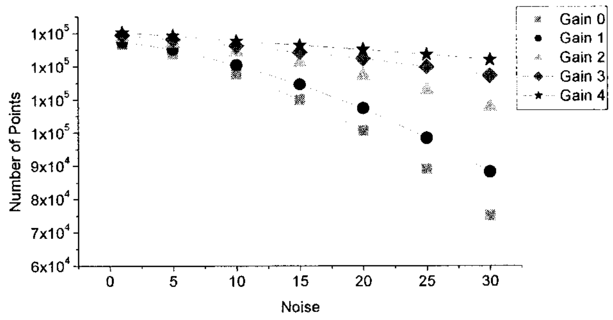


Fig. 9 The number of points of the second laser scanned data

The number of points in each scan of the second laser-scanned data set is shown in Figure 9. The results, shown in Figure 10, were similar to those of the first laser-scanned data set. Figure 11 shows average diameter obtained from the second set of measurements. The diameter accuracy of the scanned data with a gain of 0 was very poor, as was the case for the first set of measurements. The average diameter information from the second set of laser-scanned data reinforced that a gain parameter of 3 produced results that were closest to the standard diameter of the reference model. This finding was also supported by the third laser-scanned data set (see Figures 12–14).

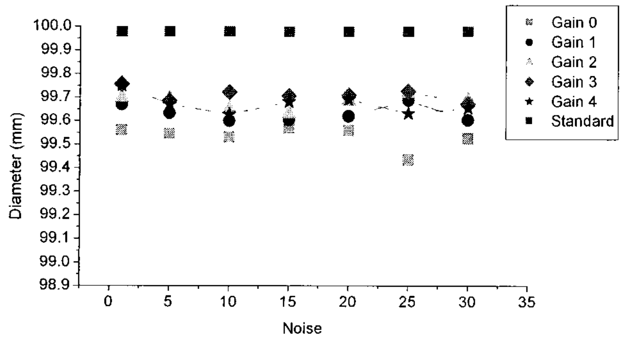


Fig. 10 Diameter Results of the second laser scanned data

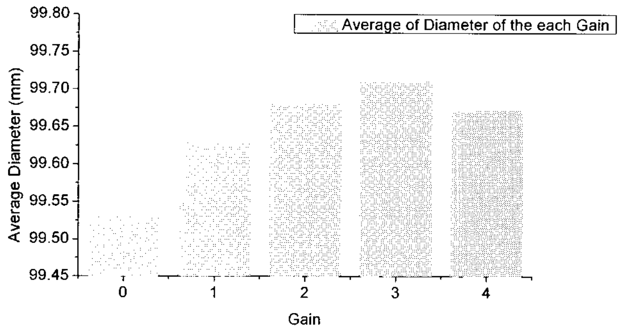


Fig. 11 Average of Diameter Results of the second laser scanned data

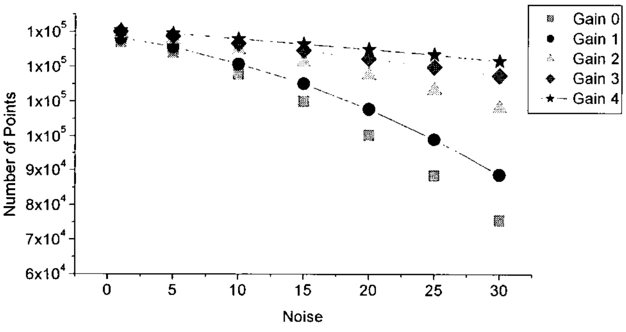


Fig. 12 The number of points of the third laser scanned data

5. Conclusions

Experiments were conducted to evaluate 3D laser scanning data acquisition considerations and data accuracy, which depend on the CCD gain and noise parameters. Test results demonstrated that the number of scan points was directly proportional to the CCD gain and inversely proportional to the CCD noise. The accuracy of the model made up of the scanned data patches was highest for a gain of 3. The diameter values obtained using a gain of 0 were very unstable and rough. Although the number of scanned points obtained for a gain of 4 was slightly more than those obtained for a gain of 3, the accuracy of the scanned data decreased. Therefore, laser scanning with a gain of 3 required less time and provided the highest degree of accuracy. The techniques examined in this study can be applied to a variety of laser scanning systems using an optical conversion formula. However, these experimental results are restricted in their applicability because of the simple shape used. In the future, we plan to extend the scope of this study to extend its validity.

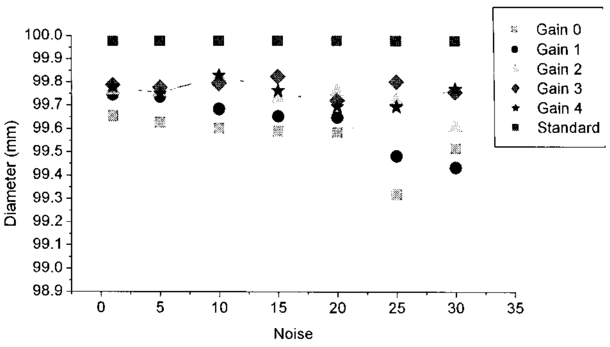


Fig. 13 Diameter Results of the third laser scanned data

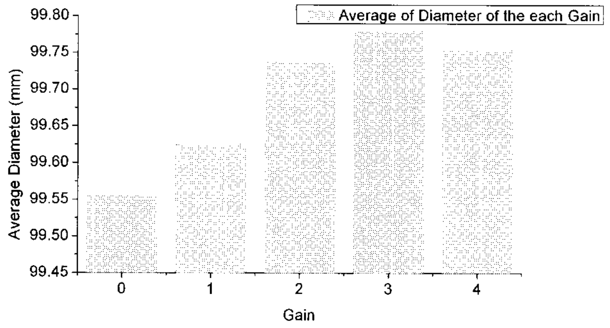


Fig. 14 Average of Diameter Results of the third laser scanned data

ACKNOWLEDGEMENT

This work was supported by the Inje Research and Scholarship Foundation in 2007.

REFERENCES

1. Wohlers, T., "3D digitizing for engineering," Computer Graphics World, Vol. 18, No. 3, pp. 1-3, 1995.
2. Xi, F., Liu, Y. and Feng, H. -Y., "Error Compensation for Three-Dimensional Line Laser Scanning Data," International Journal of Advanced Manufacturing Technology, Vol. 18, No. 3, pp. 211-216, 2001.
3. Schreiber, R., "The dynamics of digitizing," Manufacturing Engineering, pp. 59-63, 1992.
4. Chow, J. G., "Reproducing Aircraft Structural Components Using Laser Scanning," International Journal of Advanced Manufacturing Technology, Vol. 13, No. 10, pp. 723-728, 1997.
5. Traylor, A., "Health monitoring agenda for a CMM machine," SME Technical Paper, (Series) MS 1989 var paging MS89-527, 1989.
6. Menq, C. -H., Yau, H. T. and Wong, C. L., "An intelligent planning environment for automated dimensional inspection using coordinate measuring machines," ASME Journal of Engineering for Industry, Vol. 114, No. 2, pp. 222-230, 1992.
7. Wu, X., Li, D., Gang, J. and Zhou, Z., "A structured light-based system for human heads," Optics & Laser Technology, Vol. 36, Issue 5, pp. 387-391, 2004.
8. Johnston, K., "Automotive Applications of 3D Laser Scanning," Metron Systems, Inc., URL http://www.metronsys.com.
9. Larsson, S. and Kjellander, J. A. P. "Path planning for laser

scanning with an industrial robot," Robotics and Autonomous Systems, Vol. 56, Issue 7, pp. 615-624, 2008.

10. Kim, H. J., Suh, M. W. and Bae, J. H., "Shape Design of the Bristle for the periodontally involved patients by Using 3D Scanner," Journal of the Korean Society for Precision Engineering, Vol. 24, No. 1, pp. 93-100, 2007.

11. Kovacs, L., Eder, M., Hollweck, R., Zimmermann, A., Settles, M., Schneider, A., Endlich, M., Mueller, A., Schwenzer-Zimmerer, K. and Papadopulos, N., "Comparison between breast volume measurement using 3D surface imaging and classical techniques," The Annual Meeting of the German Association of Plastic Surgeons(VDPC), Vol. 16, Issue 2, pp. 137-145.

12. Ryu, H. W., Jang, P. S. and Chang, M. H., "Automation measurement of a 3D scanner using a robot simulator," Proceedings of the Korean Society for Precision Engineering Autumn Conference, pp. 5-8, 2004.

13. Zussman, E., Schuler, H. and Seliger, G., "Analysis of the geometrical features detectability constraints for laser-scanner sensor planning," International Journal of Advanced Manufacturing Technology, Vol. 9, No. 1, pp. 56-64, 1994.

14. Xi, F. and Shu, C., "CAD-based path planning for 3-D line laser scanning," Computer-Aided Design, Vol. 31, No. 7, pp. 473-479, 1999.

15. Rioux, M., Bechthold, G., Taylor, D. and Duggan, M., "Design of a large depth of view three-dimensional camera for robot vision," Optical Engineering, Vol. 26, No. 12, pp. 1245-1250, 1987.

16. Baribeau, R. and Rioux, M., "Influence of speckle on laser range finders," Applied Optics, Vol. 30, No. 20, pp. 2873-2878, 1991.

17. Kim, S. M., Lee, S. S., Kim, M. J., Jang, S. G. and Jeon, E. C., "A Study on 3D modeling using a 3D scanner and VisualLISP," *Proceedings of the Korean Society for Precision Engineering* Spring Conference, pp. 410-413, 2001.

18. Tamura, S., Kim, E. K., Close, R. and Sato, Y., "Error correction in laser scanner three-dimensional measurement by two-axis model and coarse-fine parameter search," Pattern Recognition, Vol. 27, No. 3, pp. 331-338, 1994.

19. Smith, K. B. and Zheng, Y. F., "Accuracy analysis of point laser triangulation probes using simulation," ASME Journal of Manufacturing Science and Engineering, Vol. 120, Issue 4, pp. 736-745, 1998.

20. Answers Corporation, "3D scanner," URL http://www.answers.com.

21. Chow, J. G., "Reproducing Aircraft Structural Components Using Laser Scanning," International Journal of Advanced Manufacturing Technology, Vol. 13, No. 10, pp. 723-728, 1997.

22. Inustech. Inc, "exyma-ES Series," http://www.3dscanning.co.kr.

23. Schuster, C. M., "3D Laser Scanning in the Metal Fabricating/Sheet Metal Industry," Laser Design, Inc, URL http://www.laserdesign.com.

24. Wikimedia Foundation Inc, "Rapid prototyping," URL http://en.wikipedia.org.