Application of Smart 3-D Laser Scanner in Structural Health Monitoring

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1 INTRODUCTION

As one of Full Field Optical Measurement (FFOM) technologies, Smart 3-D Laser Scanner measurement technique enables to monitor the shape and dimension measured-objects in non-contact, remotely and globally. By taking its capability in capturing 3-D spatial information, 3-D Laser Scanner has been utilized effectively in numerous field application, such as, landscaping simulation during structural design stage, bridge load test, and maintenance purposes. In order to provide a rational maintenance strategy, it is important to assess current structural properties of existing structures due to long-term structural degradation, static and dynamic loads [5,7,8]. However, they mostly lack of sufficient information of their spatial shapes and dimensions. In this paper, a structural health monitoring-based maintenance scheme is proposed and its schematic description is shown in Figure 1.

The structural health monitoring process is conducted as follows:

(i) Conduct initial structural information (shape and dimension);

(ii) Capture visible structural degradation factor (crack distribution) and create a data base for current structural condition;

(iii) Perform structural analyses to assess its current structural performance;

(iv) Monitor their degradation condition periodically (crack propagation), update the crack distribution data base; and

(v) Execute fractural-based structural analyses on the deteriorated structures.

Through field-application experiences, it is confirmed that 3-D Laser Scanner is an easy-handled device to capture spatial information of shape-complicated structures. It can be integrated with generic structural health monitoring system to assess the updated structural performance of existing structures.

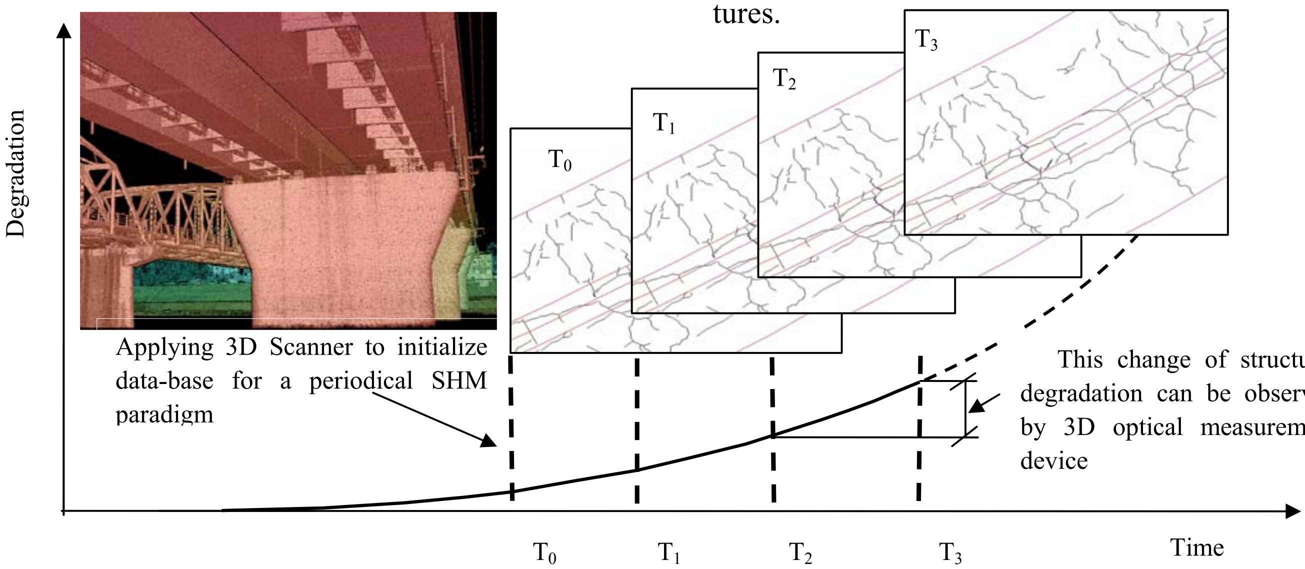


Figure 1. Proposed Structural Health Monitoring_Based Maintenance Scheme

2 THE STATE OF THE PRACTICE

2.1 *Monitoring Principle*

A 3D scanner is a device that analyzes a real-world object or environment to collect data on its shape and possibly color. The collected data can then be used to construct digital, three dimensional models that are used in a wide variety of applications. These devices are used extensively in structural health monitoring practices [1,2,3].

The purpose of a 3D scanner is usually to create a point cloud of geometric samples on the surface of the subject. These points can then be used to extrapolate the shape of the subject (a process called reconstruction). If color information is collected at each point, then the colors on the surface of the subject can also be determined [6].

3D scanners are very analogous to cameras. Like cameras, they have a cone-like field of view, and like cameras, they can only collect information about surfaces that are not obscured. The field of view or so called field of vision is the angular extent of the observable world that is seen at any given moment. While a camera collects color information about surfaces within its field of view, 3D scanners collect distance information about surfaces within its field of view. The "picture" produced by a 3D scanner de-scribes the distance to a surface at each point in the picture. Figure 2a shows a descriptive picture of a 3D laser scanner, where R is the distance between measured object and the scanner, D is the diameter of spot and S is the space between two spots.

If a spherical coordinate system is defined in which the scanner is the origin and the vector out from the front of the scanner is $\varphi=0$ and $\theta=0$, then each point in the picture is associated with a φ and θ. Together with distance, which corresponds to the r component, these spherical coordinates fully describe the three dimensional position of each point in the picture, in a local coordinate system relative to the scanner. For most situations, a single scan will not produce a complete model of the subject. Multiple scans, even hundreds, from many different directions are usually required to obtain information about all sides of the subject. These scans have to be brought in a common reference system, a process that is usually called alignment or registration, and then merged to create a complete model.

The time-of-flight 3D laser scanner is an active scanner that uses laser light to probe the subject. At the heart of this type of scanner is a time-of-flight la-ser range finder. The laser range finder finds the distance of a surface by timing the round-trip time of a pulse of light. A laser is used to emit a pulse of light and the amount of time before the reflected light is seen by a detector is timed. Since the speed of light c is a known, the round-trip time determines the travel distance of the light, which is twice the distance between the scanner and the surface. If t is the round-trip time, then distance is equal to (c.t)/2. Clearly the accuracy of a time-of-flight 3D laser scanner depends on how precisely we can measure the t time.

The laser range finder only detects the distance of one point in its direction of view. Thus, the scanner scans its entire field of view one point at a time by changing the range finder's direction of view to scan different points. The view direction of the laser range finder can be changed by either rotating the range finder itself, or by using a system of rotating mirrors. The latter method is commonly used because mirrors are much lighter and can thus be rotated much faster and with greater accuracy. Typical time-of-flight 3D laser scanners can measure the distance of 10,000~100,000 points every second.

The applications of 3D Laser Scanner in capturing 3-D spatial coordinate of shape-complicated existing structures and their contributions to structural health monitoring are engaged widely as shown in Figure 6. Captured spatial data were converted into surface data and solid data to perform three dimensional finite elements for dynamic structural analyses. Moreover, by integrating with a post-processing system such as structural analysis system, this monitoring technology enable to provide current structural performance information of existing structures in a long term structural health monitoring scheme. Figure 2b shows an imaginative description of ubiquitous monitoring society by integrating full field monitoring information with other telecommunication and other supporting technology.

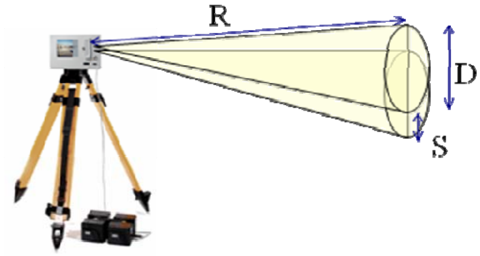


Figure 2a. Schematic description of 3D Scanner

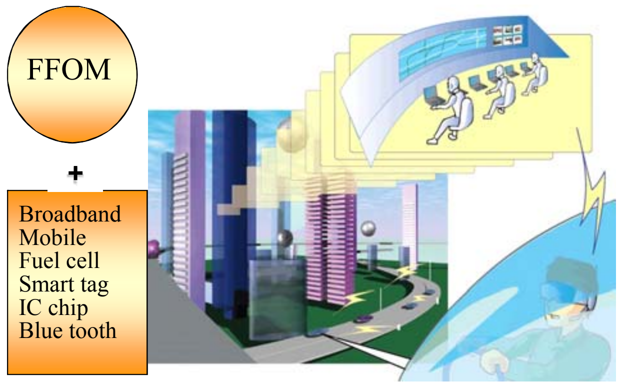


Figure 2b. Ubiquitous monitoring society

2.2 *Advantage of FFOM*

The advantages of FFOM in structural health monitoring-based maintenance (SHMBM) contribution such as:

1. safe and save non-contact monitoring: scaffold, attachment and cabling are not necessary;
2. short time and huge information: different from Point by Point measurement technique, FFOM provides not pointless, but plane and spatial information;
3. high resolution in a wide range of measurement; and
4. enable to grasp planar information globally.

The application of optical sensor devices on civil engineering structural monitoring has a large scope from bridge, tunnel, dam, coastal structures, harbor, airport, underground structures to highrise building. Along with the development of advanced optical technology, the resolution is getting scrutinizingly [4,5].

Figure 3 shows the relationship between the resolution S and remotely distance of L. Nowadays, it enables to achieve S/L better 10^{-6}, in the other word "Precision of 0.1mm can be monitored in a distance of 100m". In case of strain monitoring it achieves 1micron or 10^{-6} as well. Additionally, by minimizing the influences of temperature, sun-light, atmospheric change, rainfall, lightning, and other environmental effects, the durability, capability and performance in long term structural health monitoring is getting progressed. Therefore, optical base sensing technology would be able to provide necessary data for interpretation, appraisal and applications of life cycle cost assessment on civil infrastructures.

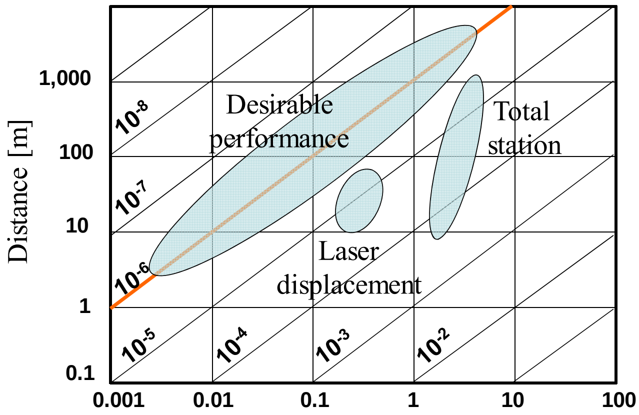


Figure 3. Performance in civil infrastructure monitoring

2.3 *Monitoring Device Specification*

In this verification field test ILRIS-3D was used (see Figure 4). Its specification is shown in Table 1.

Table 1. Device Specification

Performance Range	350 m (4% target) 800 m (20% target)
Sample rate	20,000 points/second
Mod. accuracy	3 mm
Power input	24 VDC
Size	L312 W312 H205mm
weight	12kg
Eye Safety	Class I laser
Accuracy	Target reg. accrc 4mm Modeling accrc 3mm Depth reslt 3 mm

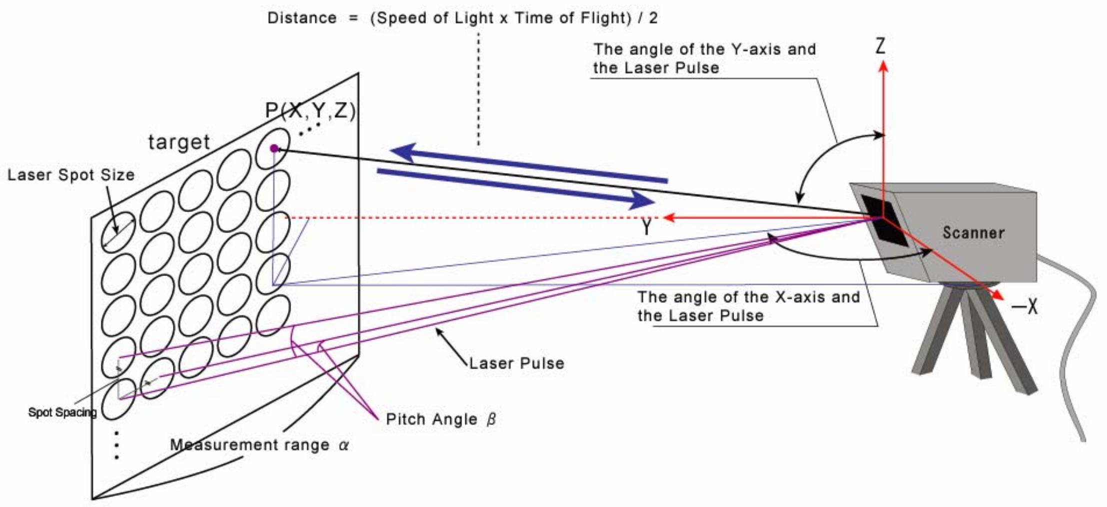


Figure 4. ILRIS-3D

3 DATA PROCESSING

Computerized data processing from shape spatial coordinate measurement to geometrical model can be summarized as:

1. Point-wise spatial model
2. Wire-frame model
3. Surface model
4. Solid model

3.1 *Spatial Coordinate*

The shape of a captured object is stored as 3D coordinates spatial data. Then, 3D coordinates of the entire surface of the specimen are precisely calculated and divided into same range. The results are the 3D shape of the component at the 3D point-wise model.

3.2 *Wire Frame Model*

A wire frame model is a visual presentation of an electronic representation of a three dimensional or physical object used in 3D computer graphics. It is created by specifying each edge of the physical object where two mathematically continuous smooth surfaces meet, or by connecting an object's constituent vertices using straight lines or curves.

The object is projected onto the computer screen by drawing lines at the location of each edge.

3.3 *Surface Model*

Surface model is used in CAD and other computer graphics processing software to describe the skin of a 3D geometric element. The wire frame at the surface of a captured object will be combined to perform a surface model.

When defining a form, an important factor is the continuity between surfaces. It affects how smoothly they connect to one another. The continuity is defined using the terms:

G0 – position (touching)
G1 – tangent (angle)
G2 – curvature (radius)
G3 – acceleration (rate of change of curvature)

3.4 *Solid Model*

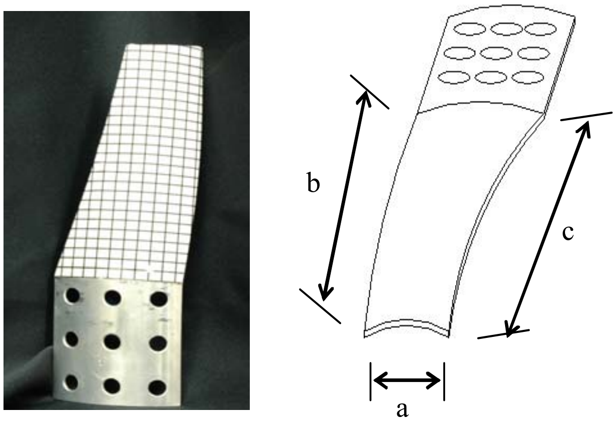
Solid model is the unambiguous representation of the solid parts of an object, that is, models of solid objects suitable for computer processing. It is also known as volume modeling.

4 SYSTEM VERIFICATION

Verification of measurement precision of 3D photogrammetry and analytical precision of dynamic structural analysis was performed by using a warped plate as shown in Figure 5(a). The material properties were shown in Table 1.

Three dimensional side length of the warped plate were measured as shown in Figure 5(b), compared to the analyzed values. As a result, as shown in Table 3, it is confirmed that the measurement was done at high precision at three places entirely.

Finite element model was generated from the measurement data, and the dynamic structural analysis was performed by using generic finite element method (FEM) program. Three nodal shell elements were used to perform the FE model.



(a) Photogrammetry (b) Measured

Figure 5. Warped plate verification

Furthermore, the analytical natural frequencies were verified by the modal measurement by holography interference method. As the result, they have good agreements in dynamic mode shape and natural frequencies for each measured modal.

By considering the appropriateness of this system, it is confirmed that photogrammetry can be integrated with post-processing system such as structural analysis system, to provide sufficiently current structural performance information of existing structures.

Table 2. Material Properties

Young Mod.	Poisson Ratio	Density
71GPa	0.33	$2.7 g/cm^2$

Table 3. Measured vs Analyzed –Length [mm]

	a	b	c
Measured	43.8	155.5	155.5
Analyzed	43.7	155.3	155.5

5 APPLICATION EXAMPLES

The Smart 3D Laser Scanner Integrated System has been applied to capture the spatial information of Peace Statue at Nagasaki Peace Park, Nagasaki, Japan. The statue's right hand points to the threat of nuclear weapons while the extended left hand symbolizes eternal peace. The mild face symbolizes divine grace and the gently closed eyes offer a prayer for the repose of the bomb victims' souls. The folded right leg and extended left leg signify both meditation and the initiative to stand up and rescue the people of the world as shown in Figure 6. Unlike the usual buildings, the most parts of the statue are curved surfaces in high intricacy, therefore, it was scanned from 8 directions as shown in Figure 7.

Figure 8 shows the triangular element generation process from spatial data, wire frame model and surface model.

Figure 6. Peace Statue

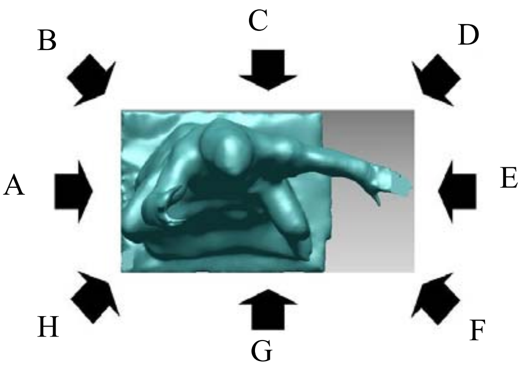


Figure 7. Capture directions

(a)Spatial Coordinate (b)Wire Frame Model (c)Surface Model

Figure 8. Geometric Model

5.1 *Field Verification*

For verification purpose, a theodolite was utilized to measure distance at three parts of the statue as shown in Figure 9 and the comparison results are shown in Table 4.

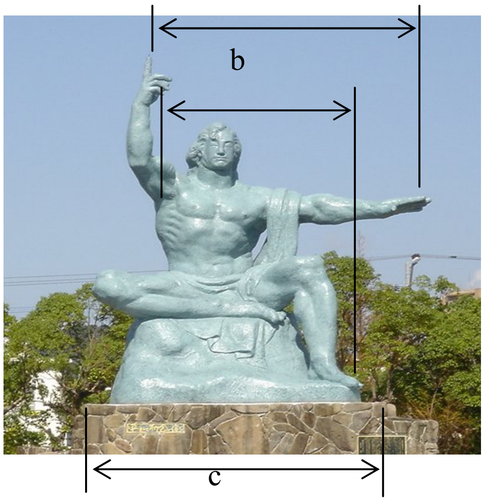


Figure 9. Measured length

Table 4. Measured Distance [m]

	a	b	c
Theodolite	6.89	5.33	7.33
3D Scanner	6.80	5.27	7.21

5.2 *Structural Analyses*

Finite Element Model was easily performed by transforming 3D surface information into .STL file through MARC MENTAT. The .STL is a file extension that stands for STereoLithography. Basically, it's a file that uses a mesh of triangles to form the shell of a solid object, where each triangle shares common sides and vertices.

The material properties of the 18mm thickness bronze is shown in Table 5. The embedment is assumed as fixed boundary condition. For convenience during structure analyses the data is reduced from approximately 600k elements to about 17k elements. From the frequency spectrum analysis result as shown in Table 6, it is confirmed that the reduction data effect is negligible.

Table 5. Material Properties (Bronze)

Young Mod.	Poisson Ratio	Tensile Strg.
1100GPa	0.385	130MPa

Table 6. Natural Frequencies [Hz]

Mode	1st	2nd	3rd	4th
600k	3.60	5.10	9.02	9.36
17k	3.47	5.07	8.94	9.34

The Peace Statue was constructed in 1955. To strengthen its earthquake resistance capability, it was retrofitted in 1978 with an additional stainless support as shown in Figure 10a.

A dynamic analysis with a presume earthquake wave was performed to compare the structural performance with and without stainless support. The fixed-end stainless support's material properties are summarized in Table 7. Its FE model is shown in Figure10b. The Frequency spectrum analysis results are shown in Figure 11. The effectiveness of stainless support was confirmed through their natural frequencies in the first two modes.

Table 7. Material Properties (Stainless)

Young Mod.	Poisson Ratio	Tensile Strg.
2000GPa	0.3	450MPa

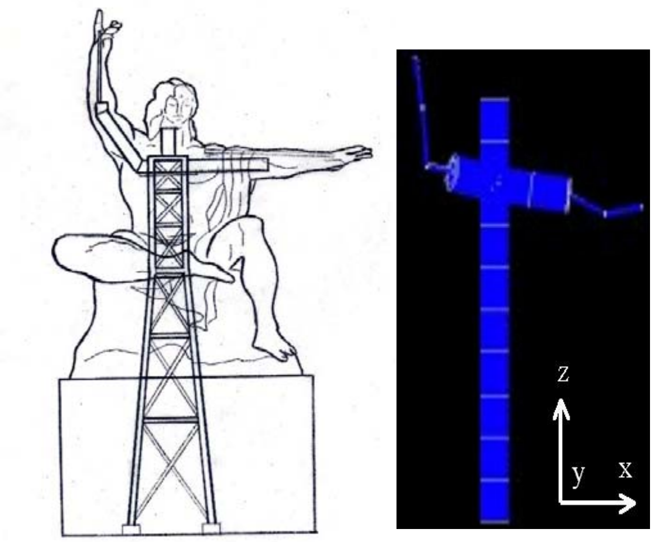


Fig.10a. Retrofit

Fig.10b. FE Model

Figure 10. Stainless Support

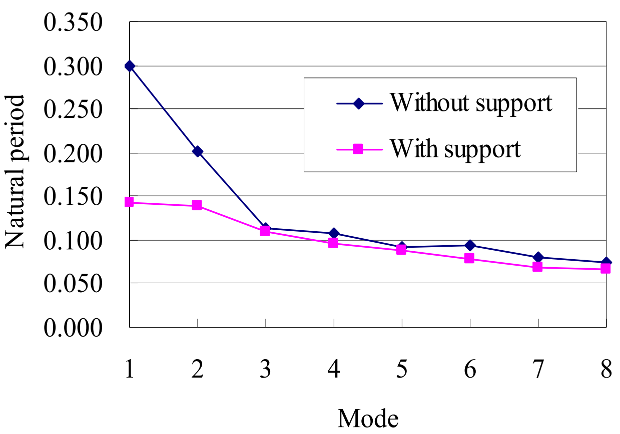


Figure 11. Natural Frequencies

CONCLUDING REMARKS

The concluding remarks can be summarized as follows:

1. The integrated 3D Laser Scanner System with a structural analysis post-processing program enables to provide current structural performance information of existing structures in a long term structural health monitoring scheme.
2. The deteriorated structural information and conditional information during a life cycle of an as-constructed structure can be documented, updated and accessed timely.
3. Human memory limitation, job position transformation, imperfection and inability to provide a reliable monitoring system can lead to overly optimistic reports on structural health. This system can be considered as a presentation tool to show the reliability of structure performance.

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