Post-Disaster Structural Evaluation Using a Terrestrial Laser Scanner

K. T. CHANG, E. H. WANG, Y. M. CHANG and H. K. CHENG, Chinese Taipei

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SUMMARY

Existing buildings mark the milestone of human civilization. Special care needs to be taken when conducting post-disaster mitigation measures of buildings to minimize addition damage to the remaining of structures. With limited time and spaces high-precision measuring equipments are highly demanded. The 3-D Laser Scanner technology that demonstrates high speed data acquisition has been well developed in recent years. Not only can scanners collect millions of precise digital information in a very short period of time but it also promotes the on-site safety of post-earthquake inspectors. As of today, the data received from the scanner have been widely used in survey applications, global positioning, maintenance of historical sites, and structural monitoring. This paper shows the image obtained from one of the buildings at the Center of Earthquake Education using Riegl LMS-Z360i. A 3-D animation of the building model was created first. The vertical displacements measuring from 1.63 to 2.25 meters around the building was recorded while the maximum relative horizontal displacement between the top and bottom of columns was confirmed to be 1.76 meters. The author found that the 3-D Laser Scanner has the capacity to obtain accurate dimensions under specific demand in a quick time. The technology should be used in post-disaster investigation of buildings to acquire the displacement information of columns and beams for safety evaluations.

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1. INTRODUCTION

The Laser scanning technology has been well developed in recent years. The scan speed exceeds tens of thousand points per second. High performance scanners are used widely not only to reserve fault information, structural damage during earthquakes, but in educational purposes also. The detail information of a fault as well as the remaining portion of the structures after seismic events recorded by the 3-D laser scanners can be used in a digital format. The digitized image can be further manipulated using coloring schemes to magnify the fault movements. Not to mention the animation of the digital images makes the earthquake activities more vivid and suitable for educators in demonstrating the seismic mitigation and training. The environmental technologists find this technique extremely valuable in overlapping images through long term monitoring.

Geologists investigated the earthquake damages and visited the ground rupture after the 1999 Chi-Chi Earthquake in Tai-Chung County. The location where the fault ruptured has been preserved and re-built as “921 Earthquake Museum of Taiwan”. The museum keeps the ground rupture and damaged structures in place to promote education in earthquake prevention. It has become a commonwealth of a living teaching material in earthquake awareness [Wang and Chang, 2007].

Buildings are evident of human civilization. The documentation of damaging structures after earthquakes advances a fundamental understanding of earthquake characteristics. It is important not to cause any damages at those structures when conducting field investigation and taking measurements. Some of the devastating structures are vulnerable under current condition. It is therefore advisable to invest more manpower, higher precision instrumentation and sophisticate technology to attain certain accuracy when taking measurements. For those structures deemed unstable, it is impossible to take measurements unless remote sensing technology is applied. The traditional surveying techniques fall short of such demand.

2. 3-D LASER SCANNERS

2.1 Theoretical Background of 3-D Laser Technology

A Scanning Laser Ranger is commonly named Laser Scanners. It is also called Light Detection and Ranging System, LiDAR in other applications. 3-D Laser Scanners are equipped with a total station that is equivalent to a laser surveyor except its electronic and opto-electrical components are somewhat different from a laser surveyor making the 3-D laser scanner a high speed scanning machine. There are two types of scanners categorized by ground-based and airborne LiDAR. The effective distances are classified into four ranges: short distance (< 1 meter), mid-distance (between 1 to 30 meters), and long distance (from 30 meter to 1 kilometer), and aviation range (> 1 kilometer). [Chang, et al., 2005a]

A 3-D laser scanner is a high speed, accurate laser surveying machine with a set of guiding reflectors. The skew angles can be measured from each station to designated points. Given the horizontal and vertical angles of the reflector the coordinating system of each scanned point can be calculated automatically. There are three main components of a laser scanner: 1. Laser Surveyor: it consists of opto-emission, receiver, wave assessor, scale magnifier, timer, and other related electronic devices. The overall system starts from one opto-signal to the end to ensure the scanning object stays within the "Field of View", namely the limits of the scanner. 2. Opto- or mechanical scanning components: a special lighting pattern guide that varies from manufacturers, such as: swaying mirrors, parallel turning reflector, or hosting motors etc. 3. data acquisition and processing mechanism: including computer, software operation system, post processors

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The center of 3-D laser scanners is identified by a self-adjusting coordinating system. It scans millions of points under interference-free condition in just a second. The distance and elevation of each point scanned can be immediately calculated taking into account of the skew and angles of the machine. The precision of a 3-D data clouds is less than a millimeter depending upon the scanning range. The detail theoretical background of the laser scanner can be found in Fig. 2.1 Scan under a dark condition can be overcome by activating the adjustable lighting. To show the progress in scanning, some of the machines are equipped with visible lights, such as MENSi GS100 system of France that uses green light [MENSi Co. web site], the system introduced by Riegl Company of Austria uses infrared [Riegl Co. web site].

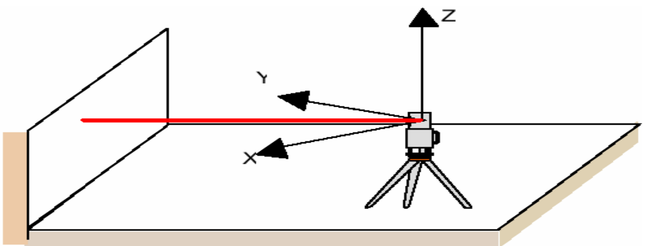

Figure 1 Theoretical Aspect of 3-D Laser Scanners [Chang, et al., 2005b]

2.2 POST PROCESSING SOFTWARE

The post-process software used by the Riegl Company of Austria is called RiSCAN PRO. It combined and overlapped the geometry transformation and data collections from scanning operation and the post processors. The system also links the direct adjustment and modeling function through a conversion of data information and Microstation/AutoCAD 3D Plug-in. The project file uses an XML format that is easy for end users. Data analysts are able to customize binary data clouds using supplementary RiSCANLib software that complements Visual C++ and any other COM languages. One of the examples of the image process function is shown in Fig. 2.2. Through implementing Riegl LPM-2K Long range laser scanner software, 3DLM Company developed a "3DLM Remote" and "3DLM Volume" to perform data mining techniques and volume calculation, respectively. These software are valuable in enhancing the functions of the Riegl laser scanners for the company only focused on developing the hardware [Riegl Co. web site].

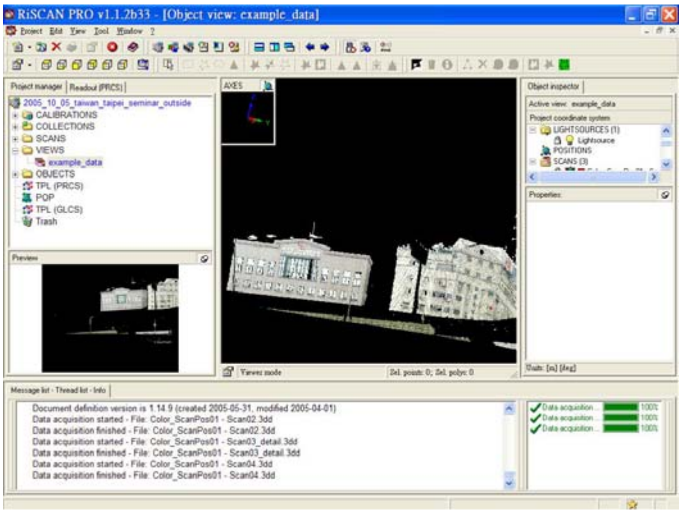

Figure 2. Function Screen of RiSCAN PRO

2.3 FUNCTIONS OF 3-D LASER SCANNERS

The 3-D laser scanners are a fast data acquisition system installing a high-speed laser surveying machine without reflectors to obtain accurate three dimensional coordination data point per second. It speeds up the measuring time in traditional spatial surveying. Additionally, it provides a safer working environment for surveyors. There is a great market demand in the near future.

The best way to use a 3-D laser scanner is where spaces are limited and the measuring object is surrounded by obstacles that can not be easily moved or relocated. Any unstable state or having difficulties in solid measuring condition a 3-D laser scanner can perform well. The applicability of 3-D laser scanner is wider than ever through massive production and well defined scope of work. It has been used in civil engineering, building construction, disaster mitigation, damage assessment, historical preservation, geodetic surveying, channels and caverns investigation, life lines allocation, objects modeling, remote monitoring, traffic condition reports, mining excavations and as-built plans. More applications can be found at manufacturer websites. Several typical cases are as follows:

1. Archeologists use 3-D laser scanners to digitize historical sites and precious remains. The data files are reserve for future study and information management.
2. Surveyors use 3-D laser scanners to construct as-built plans. The information collected through 3-D laser scanners in a long term monitoring such as the displacement of a high-voltage transmission tower is used to estimate the wind and earthquake damage to structures. Managerial steps can be taken once related information is provided.
3. Tunnel and bridge engineers use 3-D laser scanner to build up polygonal models of structures to quantity construction progress. The total volume of earth removed and placed in the construction sites can be estimated through 3-D laser scanners. As for bridge engineer, a monitoring system using 3-D laser scanner can provide vital information on bridge long term performance under the influences of changing environment [Chang, et. al, 2003].
4. Preservation of infrastructure can be done using 3-D laser scanning techniques providing information in relation to the strengthening and reconstruction.

5. Speleologists use 3-D laser scanner in modeling caverns and providing foundation in scientific research or exploration [Ono, et al., 2000; Hsiao, et al., 2003].
6. Topography mapping precision is greatly enhanced by using 3-D laser scanners [Nagihara, et al., 2002].
7. Reconstruction of a scene at traffic accident using 3-D laser scanner can help prosecutor make good judgment. The 3-D laser scanner is also a great tool in forensic investigation of an airplane disaster.

3 CASE STUDY

3.1 Research Methodology

The 3-D laser scanning technology related research involved in this article started with paper review through collections of books, journals, website and conferences papers. The actual operation of field investigation of a real building was scanned using a 3-D laser scanner. The building is at the “921 Earthquake Museum of Taiwan”, and the instrument used in the research was Riegl LMS-Z360i.
After reviewing the structure identified in the project and its surrounding the location of the 3-D laser scanner was determined. Several reflectors were placed near the structure to serve as references and common points when connecting images later on. A laptop computer was connected to the 3-D laser scanner to send command and store data. Reflectors are scanned first to preset the foundation of a 3-D model and the building was scanned. The 3-D computer model of the structure was built later in house using the 3-D clouds. The overall scanning procedure are recorded as Fig. 3.1

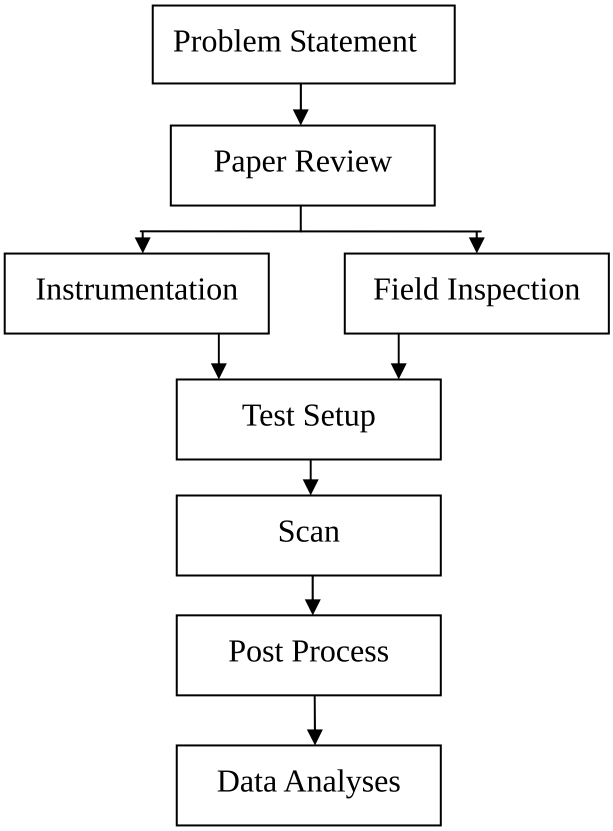

Figure 3.1 Flowchart of Research Plan

3.2 INSTRUMENTATION AND PLANNING

On August 4 2006 a group of four crew members were sent to the job site. The LMS-Z360i of Riegl Company was transported to the project site []. The speed of the scanner was adjusted to collect 10 to 20 thousands data points per second to control the duration of the scan. The instrumentation and setup are shown in Fig 3.2. It was deemed the most efficient scanning plan at the time.

The designated object is a classroom used for craftsman. It is a two-story building in a relatively square shape in the 921 Earthquake Museum of Taiwan. The total area estimated was 225 m^2 which can not be scanned in one stage. Therefore, a five-step scan operation was carried out and each took roughly 15 minutes including setting up. Step-by-step operations are sown in the following figures.

Figure 3.2 Instrumentation and Setup

(a) Scanner Location (b) Scan Area

Figure 3.2 Scan Station One Setup and Scope of Scan

(a) Scanner Location (b) Scan Area

Figure 3.3 Scan Station Two Setup and Scope of Scan

(a) Scanner Location (b) Scan Area

Figure 3.4 Scan Station Three Setup and Scope of Scan

(a) Scanner Location (b) Scan Area

Figure 3.5 Scan Station Four Setup and Scope of Scan

(a) Scanner Location (b) Scan Area

Figure 3.6 Scan Station Five Setup and Scope of Scan

3.3 MANAGING 3-D POINT CLOUDS

To combine data points from various stations, reflectors need to be installed in common spots between scanning stations and become point of control. Several points on the building also need to be registered prior to getting the point cloud. The data point consists of (X, Y, Z) components of a 3 dimensional coordinates, reflectability, and RGB information. A laptop computer equipped with RiScan Pro can be used to display the scan result simultaneously on the computer screen and the data file while perform scanning operation. The photographed appearance and texture of the building will be used to attach on the digitized model. A higher resolution camera is required if better quality of picture is desirable.
All the data cloud information is downloaded to computer memory once scanning operation ends. The basic information of five station is tabulated in Table 3.1. The volume of data is so large that it is prudent not to engage all the data point at the post process stage. Therefore, a powerful filter is required to eliminate unnecessary information and save data that are critical. The software RiScan Pro 1.2, a supplementary processor offered by Riegl Company, is used to handle huge amount of data information. The Function “Registration” is activated first to search for relative points and combines all the scan results together. The finish product is shown in Figure 3.7 to 3.8

Table 3.1 Scan Information at Each Location

Station No.	Raw Data Points	Filtered Data Points
1	227,144	130,632
2	817,932	424,800
3	1167,289	910,725
4	768,361	543,956
5	709,985	642,439

Every points on the digitized model represent a coordinate point once the 3-D model is constructed. Therefore, measurements can be easily taken from points. There is no need to conduct survey in the field again. Any dimension of interest can be obtained in house at any time. The software RiSCAN PRO offers post process function such as: Measurement, Animation, Filtering, and Triangulation. Refer to Chapter 7 of the User Manual for detail procedures of these function. Regarding the point survey function, the operational steps are as follows: 1. Establish an “Object View”. 2. Drag-in an object of interest. 3. From the drop down menu, press the right bottom of the mouse, select “ensure” on the list. The following selections will appear on the screen: 3-D point coordinates; distance between two points; area in a plane or volume in a space. A 3-D object can be shown in animation in the RiSCAN PRO depending on the pose defined by the camera location and orientation. A smooth flow between two images will be generated automatically to display a transaction. The animation can then be stored as an AVI file. The following steps should be taken: 1. Open or construct an “Object View” the “Object Scale” needs to be set as unity to obtain an optimum result. 2. Paste the scanned object into animation and select their attributes. 3. Press right bottom of the mouse select “create new animation” from the drop down menu. 4. Define the animation tracks that consist of several elements. Each element contains moving and holding modes. They determine the stop and finish of a camera location and direction. All the animation requires definition before activated. That is, the last pose will be the starting pose for the following picture. 5. Play animation by switching the screen into "recorder" and press "simulate" button and select "simulate with camera". The animation starts afterwards. It is noticeable that the speed used in the preview does not need to be the same as animation. It is especially true when playing large 3-D animation file. The speed at preview is slower than that of the normal display. 6. Select "Record" at the end to generate animation file.

Figure 3.7 Preview of a 3-D Image

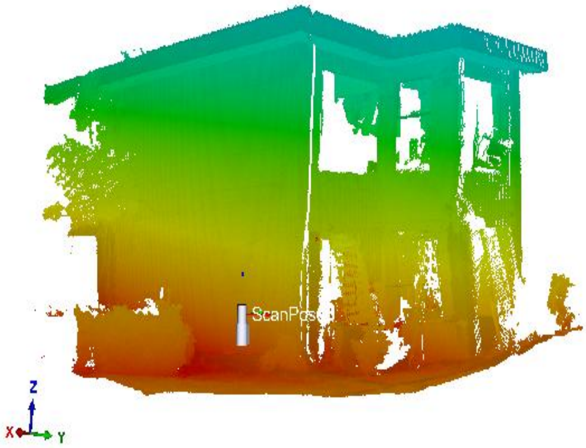

Figure 3.8 3-D Point Clouds at Station 3

3.4 ACTUAL MEASUREMENTS OF STRUCTURAL DIMENSIONS

The dimensions of major structural components can be analyzed after obtaining the digitized image at the scanning operation. The key structural sizes measured include: column length, width, beam width, depth, and wall width, height. It is obvious through visual inspection that the overall structure is unstable and it is not safe for inspectors to enter. A 3-D laser scanner that can take measurement from a distance becoming a valuable and economical solution to surveyors in this case. It is particularly true when taking measurements at the second floor and beyond since the stairway is unstable. It presents an obvious safety concern. The beam depth at the roof was scanned and measured without having the surveyor physically climb the ladder or enter the building in danger. The major dimensions of key structural components are recorded as follows: the exterior columns at corner are 43X40 cm excluding façade; other exterior columns at edge are 30X30 cm. All edge beams at first and second floor are 25X48 cm. The design philosophy follows “strong beams and weak columns” which was opposed to the “strong columns and weak beams” approach today.

Other than beams and columns, the roof performed well and demonstrates rigid plate movement. There exists no obvious cracking or wrinkles at plate surface. As the floor condition of the second story, it was undetectable owing to the presence of obstacles in the scanning process. It remains unclear unless scanning plan needs further refinement to achieve that goal. However, the deck of the first floor is severely damaged. It is bend because it was in direct contact with the ground where fault rupture occurred.

All of the exterior walls were built without proper steel reinforcement which was inadequate to current building code standard especially in the seismic region. It is foreseeable that certain building walls will need to be strengthened. Even though the existing walls were not designed as load bearing or shear resisting components the damage due to earth movement are remarkable. The 3-D laser scanner can scan and record every cracks and tilt of wall plates as small as 0.5 cm and larger. There might be a way to improve the precision of a 3-D laser scanners when used to detect cracks that are 0.5 cm or less.

3.5 SECTIONAL VIEW OF MAIN STRUCTURAL COMPONENTS

The structural damage of columns causes major destruction of the building. The common problem occurs where the cross section is insufficient, and the steel ratio is less than what the specification is required, the reinforcement spacing of ties are greater than the demand. It is also remarkable that there exists a ten cm horizontal displacement at all column base between the bottom of columns and the top of foundations. It is attributed to the insufficient overlap length between the steel rebar extended from the top of foundation to the vertical column steel rebar. As the fault ruptured, the whole building was pulled and pushed to the east. The as-built plans were unavailable at the time of investigation. It was visible to see 8 No. 6 bars that were used in a 36X40 cm column cross section. The effective area of steel area ratio was adequate by design standard that it was recommended not to be less than 1% of the gross area. The actual steel used is around 1.7% which is better than the ACI (American Concrete Institute) requirement.

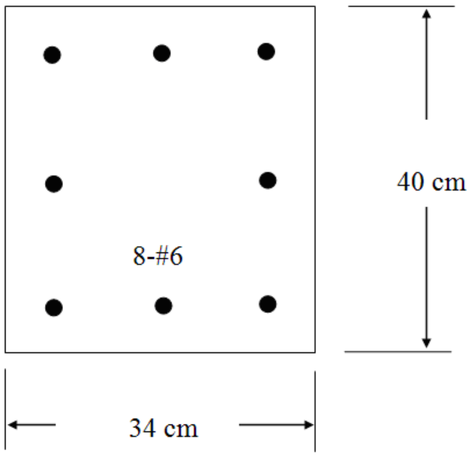

Figure 3.9 Detail on the Rebar Overlap

The overlapping lengths are estimated to be roughly 25 cm by visual inspection. It should be more than 40 cm by local building code. All of 8 rebar stopped at the same plane elevation. It was fetal to the design where they are supposed to be alternate in heights as indicated Fig. 3.10

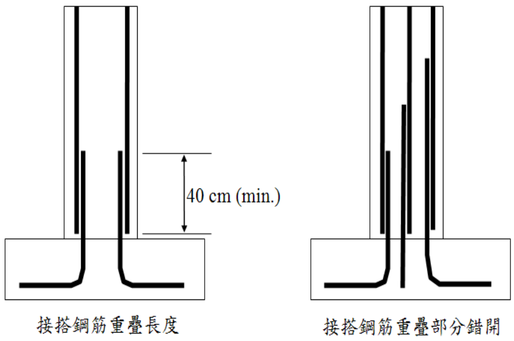

Figure 3.10 Shear Reinforcement of Columns by Code Standard

3.6 DISCUSSIONS ON BUILDING DEFORMATIONS

It occurs that the building was constructed right above an active fault. Therefore, the deformation due to fault rupture was tremendous under such a movement. However, the nearby building that was roughly 50 m away does not show any minor damage from the same fault. It is concluded that the fault rupture causes devastate damage to the building through large direct displacement in both vertical and horizontal directions. The vertical discrepancy between the top elevations of corner represents the relative movement caused by fault rupture. Other sign of damage in the structural components caused by fault rupture can be further investigated using geometrical calculations. The stress distribution can be derived using computer modeling technique. It is beyond the scope of this research.

The coordination of corners is identified through post-processing software after scanning. It is estimated that the relative vertical discrepancy between the corners is between 1.63 m to 2.25

m. The result is also compatible with measurement obtained through conventional surveying. Other horizontal and vertical displacement can be calculated using the coordination at the top and bottom of columns. For instance, the maximum horizontal displacement of a column was found to be 1.76 m. it is obvious that all of the strains and deformation can be obtained once the coordinates of two points minus the “assumed” dimensions. It is used as a base to find all of the displacement in various structural and non-structural components. Other deformation such as: distortion of doors and windows, twisting of balcony floor plates, leaning damages of walls and vertical components were also computed using the same geometrical calculation.

4 SUMMARY AND SUGGESTIONS

Laser scanners survey and receive every signals as the instrument swings its way without filtering. Many points and irrelevant data are also collected simultaneously. Proper planning including the optimum locations of scanners, scanning density, and scan duration are crucial in an effective scanning process. To elaborate the potential applications of laser scanners in disaster mitigations, this research uses a 3-D laser scanner to digitize a damaging structure that was traumatized during the Chi-Chi Earthquake. It is concluded that the 3-D laser scanner performed well in gathering measurements especially at the building subjected to unstable condition. The scanning plan was executed followed by removal of trees and obstacles. The size and height of the structure studied are appropriate for scanning and makes the scanning process manageable. Several lessons learned and knowledge gained as the project endorsed by the owner.

1. A 3-D laser scanner can be used to survey damaging structure in a distance without jeopardizing the safety of surveyors. The data clouds representing various measurements of a structure that can be subtracted to demonstrate the actual dimension of beams, columns, and walls. The final product of the survey, a 3-D animation, can greatly help the surveying crew to visualize sections without physically enter the dangerous working environment.
2. The actual dimensions of beams, columns, and walls can be obtained through post-processing software after field scanning. The displacement of a major structural element and relative movements of structural components caused by seismic excitation can be obtained using 3-D laser scanners. The 3 dimensional variations can further be decomposed to analyze the effect of a fault movement. It is valuable in educational purpose for general public in the understanding of earthquake damages to a building.
3. the preliminary estimate of a structural damage consists of a vertical displacement at a range between 1.63 m to 2.25 m. It is close to the result obtained by traditional surveying approach. The maximum horizontal displacement between the top and bottom of columns were measured 1.76 m that can not be easily measured using common practice. Other deformation damaged by earthquake, such as: distortion of doors and windows, twisting of balcony floor plates, leaning damages of walls and vertical components can also be computed.

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BIOGRAPHICAL NOTES

Kuan-Tsung Chang received the Doctoral degree, in civil engineering, from National Chiao Tung University (NCTU), HsinChu, Taiwan, in 1998.
From 1998 to 2000, he served as a supply officer in the Army. Since 2000, he teaches in the Dept. of Civil Engineering, MhUST. He conducted several research and development projects in the area of landslide feature or linear object extraction, hyperspectral image analysis, and pavement capacity measurement using 3D Laser Scanner. His major research interests are in the field of environmental remote sensing, geoinformatic knowledge extraction, and spatial objects analysis.
Dr. Chang is an active member of the America Society of Photogrammetry and Remote Sensing (ASPRS).

CONTACTS

Assistant Professor, Kuan-Tsung Chang
Graduate Institute of Construction Engineering and Management, MhUST,
No. 1, Hsin-Sing RD., Sing-Fong, HsinChu, 304 Chinese Taipei.
HsinChu,
CHINESE TAIPEI.
Tel. +886-3-5593142 x 3297
Fax. +886-3-5573718
Email: ktchang@must.edu.tw
Web site:http://www.must.edu.tw