ACCURACY IMPROVEMENT IN AREA-BASED MATCHING FOR STRUCTURAL DISPLACEMENT MEASUREMENTS

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DEDICATION

To my parent, family and brothers…

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ABSTRACT

Measuring and monitoring of structure deformations such as beams have an essential role in civil structural analysis. Measurements obtained pertaining to their displacements, among others, provide the information needed for the studies on material behaviours and structural designs. These measurements can also provide important indicators regarding to their failures. Under controlled laboratory conditions, these displacements can be determined using, for instance, high precision Linear Voltage Differential Transducers (LVDT). The high precision capabilities of these sensors make them suitable for structural deflection experiments. However, these LVDT sensors face a number of major drawbacks, such as, the sensors may be subjected to movement or damaged during the experiment, and the points measured are at pre-determined locations. In other words, displacements can only be measured at points where the LVDTs sensors are fixed. In addition, when large numbers of points of displacement are required or desired, the use of these sensors becomes prohibitively expensive and laborious. Whilst various researchers have used digital close range photogrammetry and the area-based matching approach in determining movements but work on the use of more than two images and surface models has not been reported. Therefore, this study proposes a revised method of precisely determining the displacements of structures using a multi-image area-based matching approach that uses surface models, i.e. a non-contact method. Experiments on beams under loading were performed under laboratory conditions. A series of multiple digital images were captured simultaneously using three digital single-lens reflex cameras throughout the experiments. The beam's vertical displacements obtained from the proposed method were then validated by comparing against those obtained from the LVDTs. The results indicate that the mean differences between the displacement obtained from the proposed method and LVDTs are less than 0.5mm.The t_{test} conducted with a confidence level of 5% revealed that the differences between the two sets of results are not significant. It can be concluded that the use of multi-image area-based image matching using surface models is capable of measuring displacements and be used as an additional approach that complements the traditional methods in beam displacement measurements.

ABSTRAK

Mengukur dan memantau anjakan struktur rasuk memainkan peranan penting dalam kerja-kerja analisa ketahanan struktur binaan awam. Ukuran anjakan pugak merupakan maklumat penting yang diperlukan dalam kajian tahap ketahanan bahan binaan dan rekabentuk struktur. Pengukuran ini juga dapat memberikan petunjuk penting berkaitan dengan kegagalan sesuatu struktur. Ujikaji di makmal yang dijalankan secara terkawal mampu mengukur anjakan struktur rasuk dengan ketepatan tinggi menggunakan LVDT. Keupayaan mengukur nilai anjakan pada kejituan tinggi menjadikan LVDT adalah alat yang paling sesuai digunakan untuk ujikaji pengukuran anjakan pugak komponen struktur. Walaubagaimanapun, penggunaan LVDT terdedah kepada beberapa kekangan. Sebagai contoh ianya berkemungkinan terganggu atau rosak semasa ujikaji makmal dijalankan. Tambahan pula, anjakan pugak struktur rasuk hanya boleh diukur pada kedudukan yang dipasang LVDT sahaja. Sekiranya pengukuran titik anjakan pugak struktur yang menyeluruh diperlukan, proses pemasangan LVDT melibatkan masa dan kos yang tinggi. Pelbagai kajian berkaitan dengan pengunaan fotogrametri berdigit jarak dekat dan padanan imej kawasan dalam pengukuran anjakan pugak struktur rasuk telah dilaporkan. Walaubagaimanapun kajian yang menggunakan lebih daripada dua imej beserta maklumat model permukaan dalam pengukuran anjakan struktur rasuk masih tidak terdapat. Justeru itu, kajian ini mencadangkan penambahbaikan kaedah menentukan anjakan melalui teknik kepadanan berbilang imej berasaskan model permukaan. Ujikaji bebanan pada struktur rasuk telah dijalankan secara terkawal di makmal. Sepanjang tempoh ujikaji, imej struktur rasuk telah dirakam secara serentak menggunakan tiga unit kamera DSLR. Nilai ukuran anjakan pugak struktur rasuk yang diperolehi menggunakan kaedah yang dicadangkan telah dibandingkan dengan nilai anjakan pugak yang diperolehi menggunakan kaedah LVDT. Keputusan menunjukkan purata perbezaan min anjakan pugak struktur rasuk berbanding dengan ukuran menggunakan LVDT adalah kurang 0.5mm. Hasil ujian t_{test} pada tahap keyakinan 5% mendapati nilai perbezaan antara dua set keputusan menunjukkan perbezaan yang tidak signifikan. Kesimpulannya teknik kepadanan berbilang imej berasaskan model permukaan berkeupayaan untuk mengukur anjakan pugak struktur rasuk serta boleh digunakan sebagai kaedah sokongan dalam pengukuran anjakan struktur.

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LIST OF ABBREVIATIONS

1D	-	One Dimensional
2D	-	Two Dimensional
3D	-	Three Dimensional
ABM	-	Area Based Matching
CCD	-	Charge Couple Device
CRP	-	Close Range Photogrammetry
DIC	-	Digital Image Correlation
DIM	-	Digital Image Matching
DCRP	-	Digital Close Range Photogrammetry
DSLR	-	Digital Single Lens Reflex
DTM	-	Digital Terrain Model
f	-	Principal Distance
FBM	-	Feature-Based Method
FRP	-	Fibre-Reinforced Plastic
HB	-	Hybrid Method
KN	-	Kilo Newton
LSM	-	Least Square Matching
LVDT	-	Linear Voltage Differential Transducer
RMS		Route Mean Square
SVD	-	Singular Value Decomposition
STD	-	Standard Deviation
TLS	-	Terrestrial Laser Scanner

LIST OF SYMBOLS

$c_1 \ldots c_6$	-	Unknown Radiometric Parameter
$I_m(x,y)$	-	Grey Level of Mask Window
$I_s(x,y)$	-	Grey Level of Search Window
Gx	-	Surface Gradient in x Direction
Gy	-	Surface Gradient in y Direction
$g^c(x,y)$	-	Corrected Grey Level of Mask Window
$g_m(x,y)$	-	Mask Image Grey Level
$g_s(x,y)$	-	Search Image Grey Level
m_m	-	Mean Grey Level of Mask Window
n(x,y)	-	Noise at Image Coordinate x and y
p_1	-	Translation in The x Direction
p_2	-	Translation in the y Direction
sf_{minor}	-	Scale Factor Along Minor Axes
sf_{major}	-	Scale Factor Along Major Axes
μ_m	-	Mean Grey Level of Mask Window
μ_s	-	Mean Grey Level of Search Window
σ_m	-	Standard Deviation of Mask Window
σ_s	-	Standard Deviation of Search Window
σ^2	-	Variance
σ	-	Standard Deviation
f	-	Focal Length
f	-	Principal Distance
K_1, K_2, K_3	-	Radial Lens Distortion Parameters
F_{test}	-	Hypothesis Statistical *F-Test*
t_{test}	-	Hypothesis Statistical *t-Test*

H_o	-	Null Hypothesis
H_a	-	Alternative Hypothesis
t_o	-	Critical Value from t_{test} table
X, Y, Z	-	Ground Coordinates
X_o, Y_o, Z_o.	-	Corresponding Object Space Coordinates of The Central Point
ΔX, ΔY, ΔZ	-	The Known Shift on The Object
x_T,y_T	-	Image Coordinates of The Reference Pixel
x_L,y_L	-	Corresponding Image Coordinates of The Left Image
x_R,y_R	-	Corresponding Image Coordinates on The Right Image
n(x,y)	-	The Difference Caused by Noise at The Point (x_T,y_T) on The Reference Image
I(x_i,y_i)	-	The Grey Level Value at Pixel Coordinates (x_i,y_i)
I(x_m,y_n)	-	The Interpolated Grey Level Value at Pixel Coordinates (xi,yj)
Δx_T and Δy_T	-	Shifts on The Left Image (typically, integer number of pixels)
D	-	Beam Displacement
P	-	Monitoring Point
P_1, P_2, P_3	-	Perspective Centre
O_1,O_2,O_3	-	Principal Points

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Structure elements (e.g. beams, column, slabs, etc.) are parts of the main components in civil engineering applications such as bridges, highways, tunnels, buildings and dams. The design of large manmade structure is mainly based on information about the materials that is usually obtained experimentally. Normally, small-scale specimens are used and simplified assumptions are made with regard to the geometry and the behaviour of the structure elements and structure components.

In a study conducted by Benning *et al.* (2005) on steel, timber and concrete beams, it was concluded that deformations or displacement measurements play an important role in structural management. Other studies conducted by, among others, Whiteman *et al.* (2002); Tsakiri *et al.* (2004); Psaltis and Ioannidis, (2004); Chounta and Ioannidis (2012; Koken *et al.* (2014); Maas and Liebold (2016) and Almeda *et al.* (2016), also concurred that deformation and displacement measurement information in structure elements under laboratory control conditions, constitute a very useful tool for assessment of strength for the validation of the theoretical design models and material behaviour. Furthermore, these deformations can also provide important indicators pertaining to its failure (Mustaffar, *et al.* 2004).

The application of photogrammetry, or more aptly, digital close range photogrammetry (DCRP), in the measurements of structure displacements have been reported by many researchers. For example, Whiteman et al. (2002) and Jauregui et al. (2003) applied the DCRP method to measure vertical displacement of bridges span. Mustaffar *et al.* (2004, 2007, 2009) applied the DCRP approach using area-based surface matching in determining deformation of civil structures (such as steel, concrete and timber beams), Benning *et al.* (2005) and Lecompte *et al.* (2006) investigated on the relationship between beam displacement and the concept of two dimensional deformations on concrete beam for crack evolution by using DCRP approach to detect the appearance and evolution of cracks.

While, Whiteman et al. (2002), Fraser (2000), Jauregui *et al.* (2003), Gordon *et al.* (2003), Psaltis and Ionnindis (2004), Benning *et al.* (2005), Gordon and Litchi (2007), Chang and Ji (2007), Chauta *et al.* (2012), Detchev *et al.* (2011 and 2013), Tesauro *et al.* (2014), Costa *et al.* (2011 and 2014), Koken *et al.* (2013), Stochino *et al.* (2015) and Stavroulaki *et al.* (2016) were among the other researchers who contributed the DCRP method to the structural cracks and displacement measurements.

DCRP is a method where the three dimensional measurements are made from two dimensional images taken on one object. In general, digital images are taken from an object from at least two camera positions. From each camera position, there is a line that run from each point on the object to the perspective centre of the camera. Using a principle of triangulation, the point of intersection between the different lines of sight for particular points is determined mathematically to identify the spatial or three dimensional locations of the object points.

1.2 Statement of the Problem

In general, beam displacement measurement is critical to structural assessment (Whiteman *et al.* 2002) and typically undertaken using LVDTs or dial gauges to perform displacement measurement at a point or point wise of a structure with an accuracy of 0.01mm-0.1mm (Psaltis and Ionnidis, 2004). However, this method, which requires direct contact between the test samples and the LVDTs, suffers from major drawbacks, such as, the measuring instruments may be damaged during the experiment, and the points measured cannot be densed and well distributed (Psaltis and Ionindis, 2004). In addition, deformations can only be measured at points where the sensors are fixed and in many cases would not cover the entire surface (Mustaffar *et al.* 2004; Gordon and Lichti, 2007) leaving the data between the sensors to be assumed rather than definitively determined. In addition, when large numbers of points of displacement are required or desired, using these sensors becomes excessively expensive and requires considerable time and effort (Whiteman *et al.* 2002; Fu and Moosa, 2002; Kuang *et al.,* 2003; Mustaffar *et al.*, 2004).

In field applications to monitor structures displacement (e.g. bridges), installation of contact sensors requires a motionless platform or support for the LVDTs to be fastened. The reference platform has to be steady and close to the structure because the sensor sizes are relatively small compared to the size of the structure to be tested. This is a typical problem when dealing with field testing because to establish the required platform as an access to the structure is costly and tedious. Furthermore, it is difficult when large numbers of displacement points are required (Fu and Moosa, 2002). Moreover, the disadvantage of the present contact method does not allow a complete analysis of the local damage mechanisms which lead to the failure of the structure, due to the heterogeneous nature of the materials (Hassaoun and Manaser, 2005).

Due to the number of drawbacks that have been highlighted and because of the difficulties in measuring the vertical displacement by using the existing traditional contact method, many researchers have put their effort to alleviate the existing problem on structural displacement measurements by using non-contact methods (Psaltis and Ioanindis, 2004) such as videometry technique (Luhman, 2006), digital close range photogrammetry (Atkinson, 1996; Clarke and Robson, 1993; Fraser, 1992; Fraser, 2000; Whiteman *et al.*, 2002; Psaltis and Ioannindis, 2004; Gordon and Litchi, 2007), geodetic method by using precision robotic total station (Tsakiri *et al.,* 2004) and terrestrial laser scanner (TLS) system (Gordon *et al.* 2003; Gordon and Litchi, 2007). Nevertheless, these method require specialised equipment or sensors which render them to be not cost effective for small studies. DCRP, on the other hand, only requires off-the-shelves cameras that are more affordable and accessible.

Moreover, the advancement of computer technologies and storage capacity, has made image processing task more reliable, faster and applicable to many applications that deal with digital images. The digital images captured by the digital cameras can then be downloaded to a computer for further images processing and analysis. Whiteman *et al.* (2002), Jauregui *et al.* (2003), Gordon *et al.* (2003), Mustaffar *et al.* (2004) and Psaltis and Ionnidis (2004) had applied DCRP using high resolution digital cameras to investigate the structural displacements by using digital image matching (DIM) or digital image correlation (DIC) technique.

The terms digital image matching and digital image correlation technique are widely accepted and well known in digital photogrammetry, computer vision and optic applications. The ideas and development of image matching in photogrammetry has been discussed since 1950's by many researchers as explained by Atkinson (1996) and Shenk (1999). Digital image matching in photogrammetry applications is a method or a process of finding conjugate points in a pair or more pairs (multi images) of digital stereoscopic images automatically (Shenk, 1999).

In other words, image matching method are used to identify and uniquely match identical object features (points, patterns, edges) in two or more images of the object (Luhman *et al.*, 2006). As explained by Atkinson (1996), Wolf and Dewitt (2000), digital image matching can be classified into three categories: area-based matching, feature-based matching and hybrid-method (combination of the area-based and feature based method). However, the interest of this study is the implementation of the first category image matching method, i.e., the area-based matching technique in beam displacement measurement of reinforced concrete and timber beams by using multiple images.

A revised area-based matching that uses surface models, or surface modelled area-based matching, will be developed based on a three camera arrangement, i.e., multi-image correlation. The image form one camera will be assigned as a template or reference image and the other two images obtained from the other two cameras will be assigned as pairs to the template or references image. In other words, three images will be used to monitor the structural elements displacements. If more cameras are used, this means more images can be used to determine the displacements. The revision is based on the image matching algorithms introduced by Mustaffar (1997) which was developed using only two images taken simultaneously. It is anticipated that the redundancies resulted in using three images would enhance the accuracy of the results.

1.3 Objectives of the Study

The aim of this study is to develop and investigate the accuracy of the multi-image area-based matching that uses surface models in measuring the structural beam displacements under laboratory conditions. The specific objectives of study are:

i) To develop a new surface modelled area-based matching approach using multiple images with the premise of improving the correlation of conjugate points in the image space.

ii) To assess the overall performance of the proposed method's functional model using objects of known dimensions.

iii) To verify the accuracy of the proposed method by comparing the results with those obtained from conventional method in tests conducted under laboratory conditions.

1.4 Scope and Limitations of the Study

The scope and limitations of the work undertaken in this study can be summarised as follows:

i) Revising the existing area-based matching functional model so that a multi-image solution can be developed. This revision is based on a three camera configuration that captures images simultaneously.

ii) Dimensions of objects with known dimensions will be determined using the developed functional model in order to verify its fidelity and reliability.

iii) Conducting laboratory based experiments on structural beam displacement measurements using the proposed and conventional methods. The results were compared to assess the accuracy of the proposed method.

iv) Structural beams tested are limited to three types of beams such as *'Balau'* timber beam, reinforced concrete beam and H-Shape reinforced concrete beam and column connection, respectively.

v) Due the limited numbers of DSLR cameras available experiments were conducted using two Nikon D70, one Nikon D80 and one Nikon D300. All the cameras were calibrated prior to the experiments.

1.5 Significance of the Research

The significance of the proposed method is in its capability to provide a complementary approach in examining structures' displacements with high accuracy and precision that are comparable to the present laboratory contact methods (using dial gauges and LVDTs).

1.6 Thesis Outline

This thesis is presented in seven chapters which are summarised as follows:

Chapter 1 highlights the background of the study, statements of the problem, objective of the study, scope and limitations of the study and significance of the study.

Chapter 2 highlights the literature review related on the theory of DCRP and the applications of DCRP technique in various field of civil engineering applications especially in structural deformation measurements. The basic theory of image matching is also highlighted in detailed.

Chapter 3 describes in detailed the derivation of the new proposed multi image matching algorithm which was derived from the conventional affine mathematical model. The calculations of the multi-image matching is also explained.

Chapter 4 discusses the applications of the proposed multi-image matching algorithms on flat surface by using small scale objects. Small scale object such as flat surface aluminium plate has been used to test and verify the accuracy of proposed method.

Chapter 5 describes the laboratory experiment arrangements on the structural elements such as timber beam, reinforced concrete beam and H-shaped reinforced concrete structure using DCRP techniques to test the proposed method. The laboratory experiments set-up are discussed in details.

Chapter 6 presents the results obtained from the laboratory experiments that have been conducted on structural components load test to verify the accuracy of the proposed method using DCRP technique. The results obtained from the proposed method (DRCP technique) were compared with those obtained using LVDT. In addition, this chapter also discusses the findings of the research.

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