Displacement Measurement of Structural Response using Matlab Image Processing and Object

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ABSTRACT: This paper presents a non-contact measurement method to measure displacements of a structural response, which is based on digital image processing and object tracking techniques. This method utilises MATLAB programming, which has been developed through three phases; object detection, calibration, and object tracking. For the object detection and calibration algorithms, Circular Hough Transform (CHT) technique is adopted, while for the object tracking algorithm, the Kanade–Lucas–Tomasi (KLT) feature tracker is employed. Videos are acquired through a vision-based system using a smartphone camera, and then they are analysed and interpreted using the developed program to obtain measurement data. The relationship between parameters of video resolution, distance between objects to camera and radius of target is established for guideline purposes. In order to evaluate the accuracy and reliability of this approach, parametric studies were carried out and the obtained results were compared against the ones provided by the conventional approach using a dial gauge. In overall, the computed results show a good agreement with the actual results with relatively small differences. This makes the proposed alternative method as a simple and cost-effective method yet provides favourable characterisation outcomes.

Keywords: Non-contact Measurement; Digital Image Processing; Object Tracking; MATLAB; Circular Hough Transform Technique; Kanade–Lucas–Tomasi Feature Tracker.

INTRODUCTION

Image processing and object tracking techniques, are both hybrid of the vision-based and computer-assisted system, where images or videos are acquired before analysed with the aid of a computer. Object tracking requires the detection of objects to initialize the tracking while the detection part is performed by image processing approach. These techniques adopt the concept of photogrammetry, in which the data and information are extracted from the images or videos for further analysis. The integration of image processing and object tracking implies a great potential to be further improved and developed for its practical capability in different areas.

Problem Statement

The application of image processing and object tracking techniques in structural analysis is as yet limited and uncommon. Although there is an increase in the number of research studies in the structural analysis field, there remain many research questions and uncertainties that need to be clarified; How does a thorough process perform in extracting the data and information from images or videos by using programming algorithms? Would the results of this method be accurate and reliable like theoretical and experimental testing? To what extent can this method be applied and its limitation?

Moreover, the uses of image processing and computer vision system toolbox in programming are also very general. There are indeed many ways to perform the image processing and object tracking depending on the data and outcome desired. However, the algorithms have not been standardized and hence not application-friendly. Thus, there is a need for a dedicated program to be developed for the ease of accomplishing the task.

Objectives

The main purpose of the research is to study the feasibility of developing a programming tool for analysing structures using a simple photogrammetric method with the use of smartphone digital camera technology and MATLAB software. The objectives of this study are:

1. To identify the available photogrammetric methods in engineering applications particularly in structural analysis problem;
2. To develop an image processing and object tracking model in detecting and tracking multiple nodal displacements of a structure using MATLAB programming, and;
3. To determine the accuracy and the reliability of the developed model through a parametric study.

Scope of Study

The study applies the concept of low-budget photogrammetric technique where the hardware and the software used are cost-effective and user-friendly. The study considers only 1-dimensional (1D) static analysis of structural problems where the structure is devised so that the displacements are in one direction only. The structure is assumed to be linear elastic with reasonably small deformation. The initiative of the study is to discover and explore photogrammetric method as a new technique in structural analysis that could replace the conventional measurement method and yet provides a reasonable accuracy.

The study utilises the available image processing and computer vision system toolbox in MATLAB software to acquire, collect, and analyse data from the captured images and videos. This also involves the development of programming codes in order to achieve the objectives of the study.
LITERATURE REVIEW

The science of acquiring, measuring, and interpreting the information about the characteristics of objects without any physical contact with the objects is called photogrammetry [1]. Photogrammetry is a measuring technique which uses numerous photographs of the same target but different views, to establish and provide a 3-dimensional coordinate of unknown points [2]. The professional equipment for photogrammetry, such as professional metric camera, CCD camera, and photogrammetry software is very costly and require a high level of photogrammetry knowledge. A low budget photogrammetry system, which refers to the combination of simple, available and cost-effective hardware and software, for geotechnical laboratories applications was developed by Thomas and Canre [3]. A digital rectifier (DIRECT) system, which is a combination of image processing and photogrammetric system with low-cost hardware, powerful software and user-friendly interfaces, had been presented at the early development stage of image processing [4].

There is a significant growth of the practice and application of image processing in a wide variety of the disciplines, particularly in the science and technology fields. Image processing is commonly used in medicine and biology for inspection and interpretation of images produced by X-rays, MRI or CAT scans and analysis of the cell images, in agriculture for quality inspection and classification of fruits and vegetables, in industrial areas for automatic inspection and control of the items on a production line. In law enforcement, it is used for fingerprint analysis and sharpening the speed-camera images [5]. Apart from that, the capability and feasibility of image processing techniques are being studied in the field of civil engineering, including in structural, material, geotechnical, and highway applications.

Despite obtaining information from a digital image, sometimes facts are also required to extract from the video. Image processing however, cannot perform the video processing and analysis unless the video is converted to numerous frames and interpreted one-by-one with the penalty of high time consumption. Hence, object tracking is introduced to overcome this drawback. Object tracking is the process of locating object of interest over time across multiple frames whereas object detection is the process of locating the object or multiple objects in a single frame [6]. Object tracking emerges to be one of the most important components in lots of application of computer vision, including surveillance, traffic control and medical imaging. Object tracking algorithm cannot perform alone without the affiliation of object detection. Kanade-Lucas-Tomasi (KLT) method is a feature-tracking algorithm. The pioneers in developing KLT tracker are Lucas and Kanade [7]. The associated early work was developed fully by Tomasi and Kanade [8], and was further modified by Shi and Tomasi [9]. KLT tracker performs the tracking task based on three basic assumptions: constant brightness, small increments in motion, and spatially coherent. Lots of researches have been made based on KLT tracker. For instance, a robust framework for human upper-body tracking in an indoor environment for security surveillance system using KLT feature aided by Kalman filter approach to predict and estimate the best tracked path of KLT tracking results was proposed [10].

MATLAB is a high-level programming language that provides a great platform for millions of engineers and scientists to solve the high complexity problems as it synthesises math, graphics, and programming in an interactive desktop environment. In addition, there is a variety of add-on toolboxes available to cover the application in multiples disciplines, such as image processing and computer vision toolbox. The integration of tools and capabilities of MATLAB makes it a simple and productive software.

METHODOLOGY

This research consisted of three key activities; development of MATLAB program, simple experimental testing set-up, and parametric studies.

Development of MATLAB Program

There are three phases in the development of a MATLAB programming, which are objects detection in an image, calibration of the object size in the image with real object and finally objects tracking in a series of images (a video). For object detection phase, image processing technique was employed where an image with a single point was tested initially and then increased to multi-points, whereas in object tracking phase, the algorithm was improved to enable it to detect and track moving objects instead of detecting static objects only. For this purpose, the object tracker toolbox (available in computer vision system toolbox in MATLAB) is adopted.

Simple Experimental Testing Set-Up

A strut of size 650 × 25 × 3 mm with both fixed-end condition was prepared and set-up in the structure teaching laboratory, Faculty of Civil Engineering, University Teknologi Malaysia. A vision-based system composed of a tripod, a portable and easy-to-install smartphone camera was formed to generate videos for measuring displacements of strut specimen. A black cardboard was used as a backdrop to facilitate the detection and tracking process as it minimizes the interference of the video acquired compared to other background colour as well as free from shadow images. The surface of the strut was attached with orange colour adhesive targets, which are circular shape with 19mm diameter. The adhesive markers represent the points of interest used to obtain the nodal displacements of the strut when the load is applied. The factors, such as lighting, distance from the strut surface, and angle during the video recording were kept constant and the direction of the camera was perpendicular to the strut surface. A series of videos in various resolutions were generated when the strut was loaded in small increments from the beginning to the end of the test.

Parametric Study

Two case studies were carried out to identify the relationship between several key parameters and also to determine its accuracy and reliability. The main purposes are to discover the practical capabilities and limitations of this proposed method. Besides, it serves as a guidance for users.
Case Study A: Analysis of Video Resolution, Distance, and Radius. During the assessment, videos that illustrated the horizontal movement of a box with one black point had been acquired by pre-establish vision-based system. The videos were recorded in various resolutions, $640 \times 480$, $1280 \times 720$ (HD) and $1920 \times 1080$ (Full HD), in RGB colour mode. The trial distance from the object to the camera was between 50 to 2000mm. These videos were then analysed by using the developed MATLAB program. From the obtained results, a general equation was established with the intention of discovering the relationship between the three parameters. A range of allowable distance, which provides satisfied outcome of the object detection and tracking process, was determined considering various video resolutions.

Case Study B: Verification of Accuracy and Reliability. Two videos were generated under HD mode while another two videos were recorded in full HD mode. The videos focused at the centre part of the strut specimen during recording as shown in Figure 1. In these videos, the specimen was loaded with different rates until the dial gauge reading reached around 15mm. The movement of the orange colour adhesive markers on the strut was observed throughout the process. Here, the developed MATLAB program performed the detection and tracking of the moving multi-points (the markers). For this particular case, the middle adhesive marker (near the position of dial gauge) was selected to be used in order to determine the scale factor, $k$. This was simply done by calculating the ratio between the radius of the circular marker (in pixels) with the actual radius of the circular marker (9.5mm). Besides, the same marker was employed to verify the accuracy of the measured displacement. The actual displacement of the target can be obtained by calculating the difference (only in x-direction) between the location of the centroid of the current frame and the initial frame, and then multiplied by the scale factor. This computed displacement was then compared with the readings provided by the dial gauge at every 20th frame.

RESULTS AND DISCUSSION

The results on the development of MATLAB program in detecting and tracking nodal displacements of structural response are discussed herein. The verification of the developed program was conducted via a lateral displacement strut testing with varying video resolution, as presented later.

MATLAB Program

Object Detection. The program employs `imfindcircles` function to perform the detection of circular shaped objects in images as shown in Figure 2. The function is based on the Circular Hough Transform (CHT) technique in finding and detecting circles in images. The syntax involves in the coding is shown as below:

$$[\text{centers}, \text{radii}, \text{metric}] = \text{imfindcircles}(\text{I},[\text{Rmin} \ \text{Rmax}], \text{Name}, \text{Value}) \quad \text{C \ (Equation 1)}$$

The function asks for several inputs; the name of an image ($I$) and the proposed radius range ($[\text{Rmin} \ \text{Rmax}]$), and returns several output; the coordinate of the centroid of a circle $[x \ y]$, the estimated radii, and the circles’ strength. Then the algorithm will detect circular objects, which their radii are in the interval of the given radius range. Note that, the coordinates and the radii are given in term of pixels. In MATLAB, the origin $(0,0)$ is located at the top left corner of the region of interest. Based on Figure 2, the coordinates for one dark circle was $[405.6631 \ 214.1320]$, radius was 66.1906 pixels and metric was 0.0367; the coordinates for one bright circle was $[405.5734 \ 214.2419]$, radius was 66.0858 pixels and metric was 0.0404. Whereas for image with multiple circles, a set of data was obtained and its sequence followed the strength of circles, from the highest to the lowest strength.

![Figure 2: Object detection of one dark circle (a), one bright circle (b) and multiple circles (c)](image)

In addition, the capability to detect circular target affects by the name-value pair parameters, which are object polarity, sensitivity, and edge threshold. The object polarity specifies the detection of circles, which is either brighter or darker than background in images. The sensitivity is used to control the sensitivity of the algorithm in the range of 0 to 1. The function detects more circles as the sensitivity factor increases. However, it will lead to the higher risk of false detection. In addition, the edge threshold adjusts the gradient value between 0 to 1 before it is considered and determined as the edge pixels in computation. A
lower value is preferable as it includes weaker edges (lower gradient value) in detection whereas a higher value will only allow strong edges to be detected, which leaves some circular objects with low contrast undetectable [11].

**Calibration.** The previous coding is modified by adding the coding of scale factor, \( k \) using a formula:

\[
k = \frac{\text{actual radius}}{\text{pixel radius}} \quad (\text{mm/pixel})
\]

(Equation 2)

The computed scale factor is 0.0875. The actual radius of circular targets is 9.5mm whereas the acquired radius is 108.5147 pixels. The concept applied in this context is that the predetermined radius of circle targets compared with the radius in pixel of the highest strength circle, which is obtained from the analysis. It is used to calibrate or to correct the units of measurement in an image.

**Object Tracking.** Figure 3 illustrates the tracking and moving path of the circular targets in videos. The results furnished with the coordinates of circular targets in each video frame along the tracking process. For instance, the point in Figure 4(a) had initial coordinate of [302.228 199.155], moved across the video, and stopped at [478.754 200.329] at the end of video. This programming utilised Kanade-Lucas-Tomasi (KLT) algorithm as the tracker because a desired set of points can be defined earlier in the first frame of input video before initialising the tracker. Modification of coding had been done at the detection approach where the object detection using `imfindcircles` replaced the original detector coding.

![Figure 3: Detected circles and centroid](image)

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![Figure 4: Object tracking of one point (a), two points overturning (b) and multi-points (c)](image)

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The modified algorithm performs tracking by creating a system object for reading and displaying video initially. The first frame in the video was read and selected as the object frame. The interest points were detected in this particular frame using the object detection algorithm created previously in the object detection stage. Markers were placed on the figure to ensure that the correct set of points had been detected before tracking. After that, a tracker was created and initialized based on the assigned detected points in the object frame. The tracker reads, tracks, demonstrates points and results in each video frame.

**Parametric Study**

**Case Study A: Analysis of Video Resolution, Distance, and Radius.** From the acquired results, a range of allowable distance between object and camera, which gives satisfied outcomes of object detection and object tracking for different video resolution, was determined. The optimum range of radius falls between 10 to 20 pixels for each resolution within the allowable distance. The object detection algorithm can function well and give more accurate results as the radius of the circles is greater than 10 pixels. If the radius is less than 10 pixels, the algorithm still can perform the detection but there will be a warning statement displayed in command window and the results may not be accurate. On the other hand, the larger size of the circle when the distance is relatively small causes singular spatial gradient matrix in the point’s neighbourhood, which makes the point invalid such that the tracker cannot perform tracking.

A set of data for scale factor, \( k \) obtained for each resolution, namely \( k1, k2, \) and \( k3 \) respectively, were plotted on a same graph and trendline were added to each curve to identify the pattern of the curve. It was found that the scale factor, \( k \) is almost linear as a function of distance, \( D \). In order to relate the video resolution with a general equation, a function of video resolution, \( f(S) \) was established by plotting a graph of coefficient versus resolution and the suggested equation was in terms of quadratic function. The quadratic function was then simplified with the intention of fitting the curves in with a general equation. Thus, the proposed general equation can be written as:

\[
R_p = (7e^{-10S^2} - 2.95e^{-6S} + 0.0036) \cdot D \cdot R_p
\]

(Equation 3)

where \( R_p \) the radius of circular object (mm); \( S \) is the video resolution; \( D \) is the distance between object and camera; and \( R_p \) is the radius of circular object (pixels).
In this paper, an innovative model that employed image processing and object tracking techniques for measuring displacement of structural response was proposed. This developed model serves as a potential alternative to the conventional methods for structural deformation measurements. Findings conforming to the objectives of this study can be summarised as below:

1. The available photogrammetric methods in engineering applications, especially in structural response measurement, is still limited and more studies are needed to amplify its applicability.

**CONCLUSION**

**Figure 5:** (a) Relationship between scale factor and distance (b) Relationship between radius and distance

**Case Study B: Verification of Accuracy and Reliability.** Lateral displacements of strut obtained from the developed MATLAB program and reading given by dial gauge in HD mode and full HD mode are displayed in Figure 5. It clearly illustrates that the computed displacement has good correlation with the actual displacement.

The differences between acquired displacement from video through MATLAB program and the actual displacement provided by the dial gauge for each video are shown in Figure 6. Some of the data from the few initial frames of video had been eliminated since the measure data from videos vibrated initially. The average difference for these four videos are ±0.137mm (±1.62%) from the actual value. This outcome is satisfying as the difference are relatively small.

**Figure 6:** Displacement measurement in HD mode (a) and full HD mode (b)

**Figure 7:** Difference of displacement measurement in mm (a) and percentage (b)

**Table 1:** Summary of allowable distance for three different resolution

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Allowable Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>640 × 480</td>
<td>250 - 500</td>
</tr>
<tr>
<td>1280 × 720 (HD)</td>
<td>450 - 950</td>
</tr>
<tr>
<td>1920 × 1080 (Full HD)</td>
<td>800 - 1850</td>
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</tbody>
</table>
A model to measure the displacement in structural response using MATLAB programming was developed by utilizing the `imfindcircles` function to detect objects and KLT feature tracker to track objects.

A relationship between three key parameters; video resolution, distance between object and camera, and radius of circular targets, is established. The range of allowable distance between object and camera is then determined. The optimum range of radius falls between 10 to 20 pixels in each video resolutions within the allowable distance.

Two parametric studies were conducted for verification. The computed displacement shows a good correlation with the actual displacement. The average differences between the computed results and actual readings provided by the conventional dial gauge are about ±0.137mm and ±1.62%.

This study concludes that, a simple photogrammetric tool for analysing structures using a low-cost technology devices and MATLAB software is feasible and practical to be considered for further development.

REFERENCE
