Evaluation of Close-Range Photogrammetric Technique for Deformation Monitoring of Large-Scale Structures: A review

F. Esmaeili*[1], H. Ebadi[2], A. Mohammadzade[3], M. Saadatseresht[4]

1- Ph.D. Student, Geodesy and Geomatics Eng. Faculty, K.N.Toosi University of Technology, Tehran, Iran
faridesm@mail.kntu.ac.ir

2- Professor, Geodesy and Geomatics Eng. Faculty, K.N.Toosi University of Technology, Tehran, Iran
ebadi@kntu.ac.ir

3- Associate Professor, Geodesy and Geomatics Eng. Faculty, K.N.Toosi University of Technology, Tehran, Iran
a_mohammadzadeh@kntu.ac.ir

4- Associate Professor, Surveying and Geospatial Eng. Faculty, Tehran University, Tehran, Iran
msaadat@ut.ac.ir

(Received: May 2018, Accepted: August 2018)

Abstract

Close-range photogrammetry has been used in many applications in recent decades in various fields such as industry, cultural heritage, medicine and civil engineering. As an important tool for displacement measurement and deformation monitoring, close-range photogrammetry has generally been employed in industrial plants, quality control and accidents. Although close-range photogrammetric application in displacement measurement of large-scale structures was not introduced as much as its other application, but successful utilizations in this field prove it to be a potentially effective procedure in this area. In order to get familiar with these applications, this paper reviews the research conducted on the use of close-range photogrammetry for measuring displacement in large-scale structures. There are several unique advantages of having close-range photogrammetry employed in this field including the unnecessary of being in direct contact to the structure during the observation, the rapid acquisition of observations, and the immediate access to the results by automating the procedures. Moreover, the instant recording of observations in moving features and possibility of creating an archive from these observations to be used in future processing if required are more examples of these beneficial characteristics. In addition, the high flexibility and adaptability of this method to the project conditions made it possible to achieve high accuracies while, each photogrammetric target practically acts as an instrumentation sensor at a lower cost. Accordingly, based on the reviewed literature, on average, this method was able to reduce up to 60% of the costs and time compared to the other conventional methods as an effective and efficient tool.

Key Words: Close-range Photogrammetry, Displacement Measurement, Deformation Evaluation, Camera Calibration, Network Design

* Corresponding Author

1. Introduction

Deformation detection, which is determining changes in shape, direction, and displacement in the structure, is a sensitive and complex issue concerning the monitoring of structural behavior. There are several methods for measuring the inserting compactions and stresses on a structure and monitoring its responses. There are several methods that are being utilized for measuring displacement in large-scale structures including microgeodesy, satellite positioning (GPS) [1], laser scanner [2], the use of accurate instrumentation, and mechanical equipment as well as photogrammetric method [3] [4].

Photogrammetry is a technique for obtaining information about the position, dimensions, and shape of an object by performing measurements on images taken from the objects rather than directly measuring them. Close-range photogrammetry is a branch of photogrammetry in which the images of the object are taken closely or on the ground, and the object-camera distance is about 100 meters or less [5]. This measurement technique is a non-destructive method that can provide accurate 3D measurements at low cost and high speed without having direct contact to the feature. Photogrammetric targets can easily be placed on separate locations on the structure and on other important positions. Then images are quickly captured without interrupting other project activities. In addition, continuous and dense modeling of surfaces and generation of accurate 3D models of feature make the accurate measurements possible for measuring displacement through photogrammetric techniques.

There are various and successful applications of close-range photogrammetry in the fields of industry, biomechanics, archeology, architecture, to name but a few [3]. Although close-range photogrammetry is not as common as other areas in structural engineering and in particular monitoring in civil engineering field, successful applications in this area present a potential growth for this technique. Moreover, the continuous and rapid development of digital imaging and computer technology, use of close-range photogrammetry has become further feasible in monitoring applications. In the mid-1990s, the use of photogrammetric measurement techniques for studying the behavior and displacement of structures were significantly increased with the development of close-range digital photogrammetric systems. As measuring tools for deformation and displacement, photogrammetry provides useful features such as non-direct contact with objects, high-speed image capture, easy access to proper digital cameras, low cost of observation and the ability to process combined and instantaneous data with easy operation. Moreover, the high flexibility of this method in measuring precision, and design capability to achieve predetermined accuracy accounted to be some of important features related to this tool.

The main objective of this paper is to investigate and evaluate the achievable accuracy, reliability, flexibility, efficiency of close-range digital photogrammetric as a tool for studying the deformation and displacement of large-scale structures. Additionally, the evaluation and conclusion of the common components and structures for the displacement of large-scale structures by close-range photogrammetry method is considered by using the previously conducted research. In this regard, among the research has been carried out in recent years in this field, some of them have been chosen to study based on several criteria including: the specific conditions of the structure, the objectives of the measuring displacement structure deformations, and utilization of new and specific methods in the process of applying close-range photogrammetry.

2. An analytical review of the use of a close-range digital photogrammetric in the displacement monitoring of large-scale structures

Depending on the nature of displacement and structure conditions, a close-range photogrammetric system for the monitoring of large-scale structures can generally be designed and implemented based on one of the following general frameworks. (1) Real-time monitoring systems; and (2) Monitoring systems with time-gap epochs. In real-time systems, structural deformations occur instantaneously. Accordingly, the imaging network must record each observation epoch simultaneously and generally, in such structures, the distance between each epoch is small, being in order of seconds or less. In the latter, generally, the structural deformation is not expected to occur during the observation of an epoch from different stations separately. Moreover, the behavior evaluation of such structures during each time-epoch depends on the project progress or changes to the structure through the time. Based on this general classification, the technical specifications for the applications being studied are summarized in Table 1, which include the type of measurement, the camera type being employed, the targeting, the network control method, the software used and the displacement accuracy. The applications listed in this table are being reviewed based on the time the research is carried out.

Table 1. Specifications of measuring displacement projects on a variety of large-scale structures using close-range photogrammetry

Research Fellow	**Measured Structure**	**Measurement Type**	**Targeting and Imaging Type**	**Utilized Camera**	**Network Control**	**Displacement Measurement Accuracy**	**Employed Software**	**Project Special Conditions**
X. Luo et al. (2017) [6]	Large inflatable structures	Strain fields from a circular fabric film subjected to a bulge test	Retro-reflective targets and coded targets	INCA3	Measuring displacement with Delaunay triangulation and using EFM[1]	Approximately 1 mm	V-STARS	Delaunay triangulation between targets
Daniel J Cerminaro (2014) [7]	Retaining wall between non-level highways	Displacement measurement of retaining wall between two epochs	Retro-reflective targets on the wall pinhole camera model	Nikon D5100	Measuring displacement based on cloud point matching	Approximately 5 mm	Agisoft Photoscan Profession & Cloud Compare	Monitoring the retaining wall in separation joint
Farid Esmaeili et al. (2013) [8] [9]	supported excavation wall using nailing method	3D displacement towards the excavation site	Retro-reflective targets on wall and out of excavation as control point – Shooting with flash	Canon PowerShot SX130 IS	Measuring displacement using CPDA-independent of external data	7 mm	Australis & Matlab	Monitoring between progressing excavation epochs
Zhenzhong Xiao et al. (2010) [10]	Transmission tower	load–deformation measurement	Non-coded and coded retro-reflective targets - external ring flash is adopted	CANON400D (SLR)	Using coded targets in stationary positions for epoch results match	0.1 mm/m	3D optical deformation measurement system called XJTUSD, is developed with VC++	Measuring displacement was performed in 10 epochs with different pressure changes
Ruinian Jiang et al. (2010) [11]	Steel Bridge	Bridge Deformation during loading	Retro-reflective Targets on the body and tripod - Shooting with a flash	Kodak DCS660 & Kodak Pro SLR/n	Using level targets RDC method	1mm In X,Y direction 2 mm In Z direction	PhotoModeler	Monitoring between loading epochs
Muammer Ozbek et al. (2010) [12]	Wind Turbine	Deformation due to wind on turbine	Retro-reflective targets on blades and column – Shooting with flash	four CCD cameras	Using Markers	25 mm	GOM PONTOS system	Real Time Monitoring
T.K. Lee et al. (2008) [13]	Reinforced concrete T-beams	Rupture of Concrete Bridge Beams due to shear	Retro-reflective coded targets column – Shooting with flash	GSI INCA 4.2	linear variable displacement transducers (LVDTs) and strain gauges	0.06mm	-	Monitoring of displacements from loading to rupture threshold
Fraser et al. (2005) [14]	Aerial antenna	Matching to the original model and deformation in vertical, 45 degree, and horizontal states	Retro-reflective targets – Shooting without flash	INCA 4.2	Displacement measurement using available mathematical models	0.065mm	Australis	Network Design based on high accuracy achievement
G. Johnson et al. (2004) [15]	Wooden Bridge	The deformation caused by the loading of the locomotive	Retro-reflective targets – Shooting without flash	Nikon D100	Use of Targets in the bottom of the bridge bases as fixed points	0.7mm	iWitness	Monitoring two epochs before and after loading with a time interval
Clive Fraser et al. (2003) [16]	Metal Structure	Measuring displacement due to glazing and de-propping	Retro-reflective coded targets – Shooting without flash	INCA 4.2	Use 6 Target datum with low displacement	0.15mm	V-STARS	Monitoring between several epochs before and after loading with a time interval
Calvin Li et al. (2002) [17]	Monument	Measuring displacement due to drilling	Retro-reflective targets – Shooting without flash	Fujifilm MX2700	Using Control Points and Microgeodesy	2mm	Elcovision 10	Monitoring displacements due to drilling in the area
Clive Fraser et al. (1999) [18]	Ore crusher machine	Relative measuring displacement between two machine component	Retro-reflective coded targets – Shooting with flash	GSI INCA 4.2	Relative measuring displacement on feature's target	0.15mm In X,Y direction 0.25mm In Z direction	-	Monitoring changes in machine due to amperage change
Gerd Maas et al. (1998) [4]	Dam	Evaluation of photogrammetric potential in determining the coordinates of points on the dam	Retro-reflective targets – Shooting without flash	Kodak DCS460	Reading the control points by theodolite and creating a geodetic network	2-3 mm	Developed Software	Use the helicopter to increase the network consistency

[1] Finite Element Method

X. Luo et al. 2017, measured the impact of pressure on large inflatable structures using photogrammetric methods. They measured the displacements caused by pressure change on uneven and irregular surfaces using combination of digital photogrammetric method and Delaunay triangulation. In this method, after determining the 3D coordinates of the points on the structure using the photogrammetric method, points were converted into a triangular mesh using the Delaunay triangulation method. Then, the amount of changes in the surface was determined based on the point coordinates and finite element method (FEM). The proposed system included the INCA3 digital camera, reflector targets, coded targets (Figure 1a), a carbon fiber reinforced plastic (CFRP) bar with length of 1340.182 mm, an auto-bar, and V-STARS 4.6 software package [6].

In this research, a bulge test for a circular fabric sheet (Figure 1b) was performed to verify the validity of the proposed method. The results were evaluated using the digital image correlation (DIC) method. Good agreement was found between photogrammetry and DIC measurement results (Figure 1c) [6].

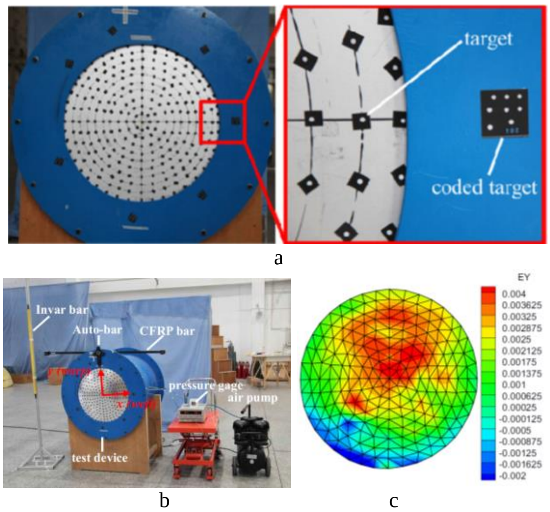


Figure 1. (a) Close views of the target distributions. (b) Photogrammetric equipment and locations of the targets on the surface. (c) The contour plots of the strain distribution [6]

Daniel J Cerminaro, 2014, at the University of Michigan, employed close-range photogrammetry to measure displacement of retaining walls across freeways (Figure 2a). This research was conducted in four main steps. Firstly, the target bases were created on the wall to scale and co-reference the 3D models. Secondly, Observations were collected in the form of imaging with the Nikon D5100. As the third step, 3D modeling was generated in the form of 3D point clouds from the wall using Agisoft Photoscan Professional software. Eventually, in the fourth step, the cloud point comparison was performed to determine the displacements using Cloud Compare software. The recordings were conducted from the wall through three epochs each of which separated by three month time interval. The results were evaluated by measuring tapes and tilt meter installed in the wall separation joint. The results indicated displacements from 0.5 cm to 2.5 cm in the walls separation joint (Figure 2b). In this study, it was also demonstrated that the measurement accuracy depended on the distance from the camera to the wall, the 3D base point positions, and the focal length of the camera [7].

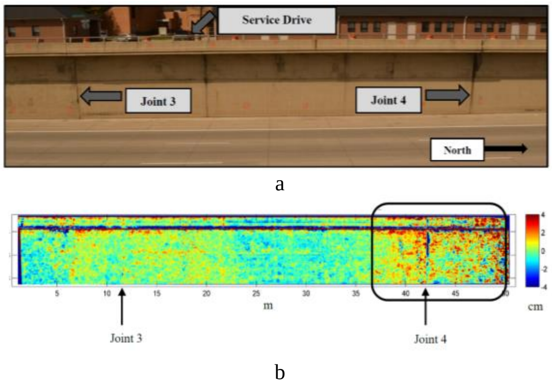


Figure 2. (a) A view of the retaining wall studied for displacement measurement and its separation joints. (b) An overview of the conformity of the first and third Epoch cloud point over a period of 6 months and their maximum displacements [7]

Esmaeili et al. 2013, used close-range photogrammetry to monitor the displacement of nailing-supported excavation walls during drilling. The displacement of the soil nail walls, due to necessity of monitoring for even small displacements to prevent burdensome accidents such as wall erosion, is of crucial importance. Due to limitations of the microgeodesy and instrumentation methods, there is no precise control on displacement process in most of excavation projects [8] [9].

In this research, the close-range photogrammetric system produced several great advantages including: shorter observation durations, ease of observation, achieved to high precision, conformity with project execution conditions, very low cost, and presentation of visual observation archives while eliminating many limitations related to conventional methods. In this research, a photogrammetric system including: general components of the structural design and target dimensions, the determination and measurement of the scale-bar length, the camera and its settings were implemented. In addition, design, placement and creation of base coordinate system and the measurement targets on the structure, calibration, observation recordings, orientations and calculations to determine point coordinates in the common coordinate system in each epoch were considered to this photogrammetric system. Structural monitoring was based on the Combined Photogrammetry Displacement Adjustment (CPDA). The images were taken in less than one hour. Finally, precisions of 3 mm and 8 mm were achieved in determining the coordinates determination and measuring deformation respectively. Figure 3 illustrates the photogrammetry implementation conditions on the structure for two epochs [8] [9].

a

b

Figure 3. (a) The layout of mounted targets and their role. (b) A set of measured coordinates on the wall in two time epochs [8].

Xiao et al. 2010, used the close-range photogrammetry as a non-contact method for monitoring a transmission tower displacement (Figure 4k), which was affected by pressures of varying force intensity. Due to the complexity of the transmission tower structures, determining the strength and structural capability in bearing different weights is of great importance. To do this, the displacement measurement was performed by using close-range photogrammetric imaging in ten epochs (Figure 4a-j) by changing the applied pressure from 0 to 320 Torr. Having the movement stable each time after the pressure was applied, the imaging of the two target sets mounted on the structure were performed in a convergent way. The first coded target set was used to match the three-dimensional coordinates derived from different epochs to each other. The second target set, which was non-coded, was used to determine the amount of displacement for the structure. To determine the corresponding targets that represented displacement at a point, a simple innovative method based on the search for the closest neighbor after the coordinate conformation was employed. In addition, cross-shaped direction scale-bar and a fixed-length scale-bar were used to position the coordinates in real dimensions. In this research, the 3D optical deformation measurement system called XJTUSD was developed using VC++ 6.0 to perform required processing [10].

The displacement between points was between 30 to 40 mm before the structural crack and 300 to 400 mm after the structural crack. The evaluation of the results demonstrated that absolute displacement accuracy of about 0.1 mm/m was achieved along with high speed and valuable results on the mechanical behavior of the structure [10].

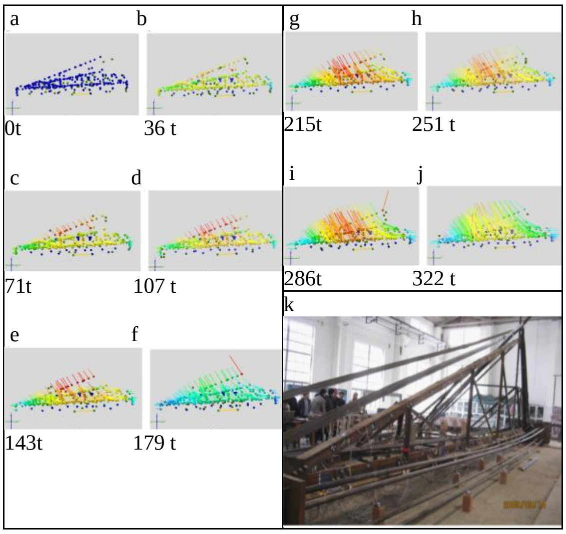
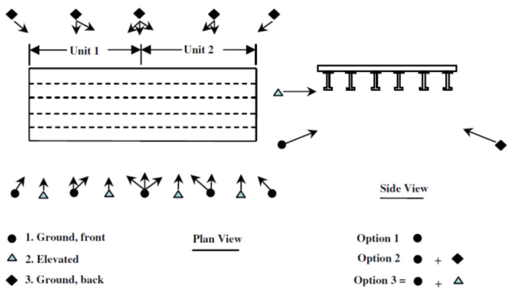


Figure 4. (a–j) The progress of the deformation for the tower displacement with different loads. (k) The real scale tower and the point displacements [10].

Ruinian Jiang 2010, measured the deviation of a steel bridge in New Mexico. The objective was to determine the extent of the bridge's deformation by placing two fully loaded trucks on the bridge. Figure 5a shows how targets and scale-bars were set for this measurement. In this research, Refined Distance Constraint (RDC) method was applied to control the network, in which the three double-sided targets were located on a tripod at a constant height, thus the direction of the Z-axis and the plumb-line bearing in network coordinate system were determined. Since the displacements occurred in Z direction, this method yielded better precision than control points [11].

a



b

Figure 5. (a) Target arrangement to measure bridge deformation. (b) Various measurement options [11].

In this research, three types of network arrangement were used, as shown in Figure 5b, and the results were compared to each other. The first network was on one side of the bridge with a specific height, the second network was on both sides of the bridge with double-sided targets and the third network placed on one side but pictures were taken from two different elevations. Network two and three provided more accurate measuring displacement results. In this study, a Kodak Pro SLR camera with a CMOS sensor was investigated in comparison with a Kodak DCS660 camera with a CCD sensor. The results demonstrated that the CMOS sensor was more sensitive to camera calibration, and with proper calibration, displacement accuracy had been further enhanced with CMOS. In total, the accuracy of the proposed method was determined 2 mm for displacement measurements [19] [11].

Ozbek, 2010, conducted a study on determining the frequency of vibrations generated on wind turbine blades. These wind-blasting vibrations, if exceeded, could disrupt the wind turbine performance. In this project, close-range photogrammetry was implemented and images were captured by four CCD cameras located at a distance of 220 m from the turbine (Figure 6). Concerning the turbine rotation, the cameras and lighting system were synchronized by a central computer and all data and processes were simultaneously monitored. The 80-meter blades of each turbine were covered by 11 reflector targets. The close-range photogrammetry with real-time monitoring, having many advantages compared to the conventional method of using electronic instruments, was employed for these targets and turbines [12].

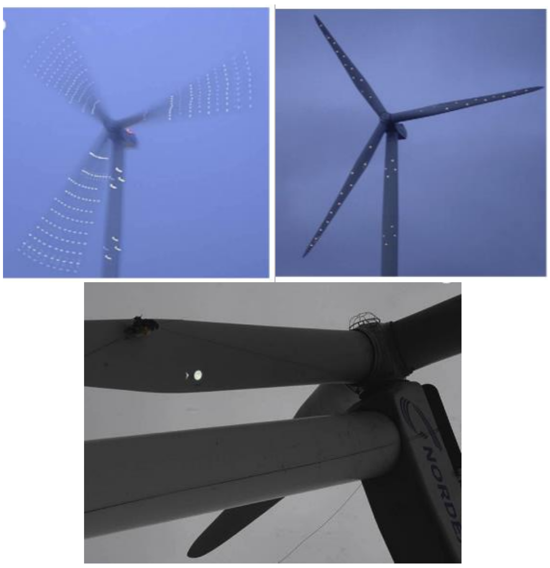
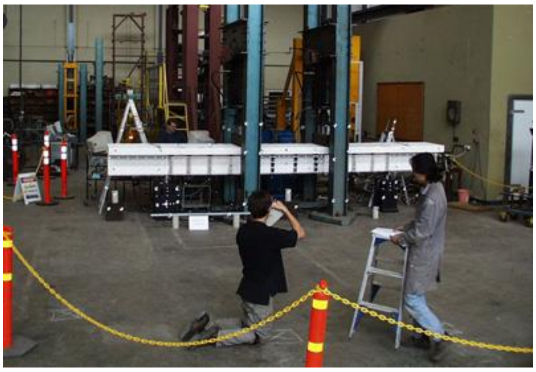


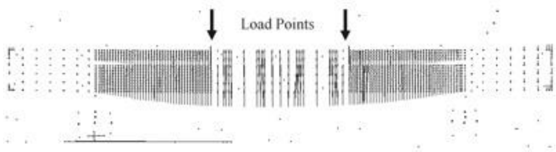
Figure 6. An overview of installed targets on the turbine and the images were taken from turbine [12]

In this study, the standard measurement error of the coordinates was about ±5 mm and the deformations were measured with an average accuracy of ± 25 mm [12].

Another application of close-range photogrammetry in deformation study was to investigate the shear-rupture mechanism of concrete beams. T.K. Lee, 2008, used close-range photogrammetry to measure the displacement of four increasing-load bearing T-beams reinforced by carbon-reinforced plastics. When the amount of static load on a beam reaches a certain size, it is necessary to minimize the required time to obtain images to ensure that the beam remains unchanged during this time. Therefore, fast data collection was one of the requirements in this project. For each tested beam, between 1000 and 1500 targets had been used. In order to achieve the required precision, a network of 20 camera stations was considered. At each station, an image was taken with a digital camera GSI INCA 4.2 at a distance of 7 meters. Having a small movable ladder available, it was possible to gain access to all 20 stations and perform shooting in less than 1 minute (Figure 7) [13].



a

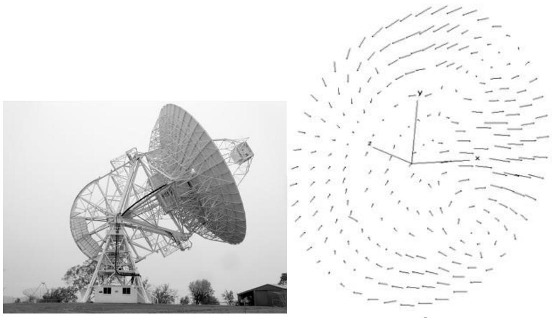


b

Figure 7. (a) Taking images for T-beam displacement measurement. (b) Displacement characters for a loaded T-beam [13]

The standard error in determining the point positions in all investigated beams was better than 0.06 mm and for a 6-meter T-beam, the bending variations between unloaded states and fully loaded reached up to a maximum deviation of 3cm before the rupture due to shear. Figure 8b shows the changes in the loaded T-beam state before shear-rupture. In this project, the photogrammetric measurement of the deformation provided valuable and new information on the mechanism evaluation and the flexibility of the T-beams against shear-rupture. This information was provided from bridge concrete-beam deformations due to loading to the rupture stage [13].

Fraser, 2005, used the close-range photogrammetry to determine the precise deformation for the reflector surface of the Hubart Radio Telescope due to the change in elevation settings (horizontal, 45° and vertically) (Figure 8). The required precision for surface measuring of the Hobart antenna surface was 0.065mm, which allowed determining the displacement of the surface points to a precision of 0.1mm. In order to achieve this precision, the concept of hyper redundancy had been introduced. Hyper redundancy is a concept in which, when the general network is in its correct place, a large number of additional images are recorded; these additional images have a significant impact on the point-accuracy of the objects being investigated. Here, it was proved that this method is a very effective way to increase the accuracy of the measurement at the least extra work performed during imaging stage [14].

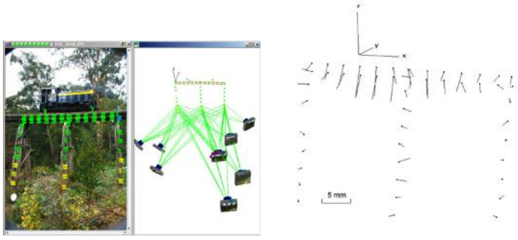


a b

Figure 8. (a) Hobart Radio Telescope with a diameter of 26 m. (b) displacement vector between the horizontal and vertical position of the antenna [14]

In this research, the images were taken by an INCA 4.2 camera with a pixel size of 9μm. The surface measurements precision in all three states (horizontal, 45 degrees and vertical) was 0.065mm, which was processed using the Australis software (Photometrix Company). The reflection surface deformation analysis for the Hobart radio telescope had two components; an assessment of the reflection surface's conformance with a rotational parabolic and the determination of the reflecting surface deformation when it changed from vertical to 45 ° and horizontal. A parabolic surface in each telescope orientation was fitted to it, and the RMSE difference between the designed and measured surfaces was measured at about 1.5 mm in each mode. Figure 5b shows the displacement vector of each individual surface point between the vertical and horizontal modes. The length for RMSE difference vector in the direction of the telescope axis (Z-stroke) was 0.6mm. The largest deformation in the outer panels was 2.6mm, where the greatest displacement of the point was due to the induced gravity. The deformation corresponding to change from the vertical to 45 ° was lower which was set to 0.3mm [14].

Johnson et al. 2004, studied a wooden bridge constructed for the passage of Puffing Billy tourist train in 1899-1900. The purpose of this study was to determine the deformation caused by loading a locomotive with a precision of 2mm in the vertical direction. To do this, the Nikon D100 was employed with an 18mm lens (8μm pixels) capable of fully covering the bridge deck from a distance of 15 meters and producing an image with a scale of 1: 800 (Figure 9) [15].

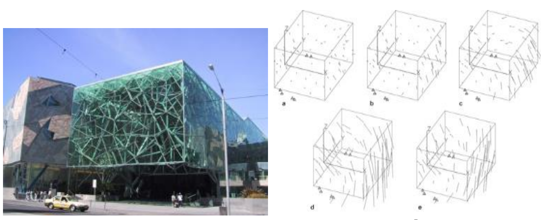


a b

Figure 9. (a) Targeting on the bridge deck. (b) Point displacements due to locomotive movement [15]

In the project, the close-range photogrammetric software system, iWitness, and high-contrast targets were utilized. The average standard error of the obtained coordinates in the direction of maximum variation (vertical) was 0.4mm. After transforming based on three points at the bottom of each base, the measured point coordinates were transferred into a common coordinate system. The displacement vectors, shown in Figure 6b, had an average accuracy of 0.7mm. The results showed that the maximum vertical deviation on the deck was 5.6mm, which was within the acceptable range from the engineering point of view. This measurement process lasted about 1 to 2 hours [15].

The study of the behavior for steel structures during construction was another implementation for close-range photogrammetry employed by Fraser et al. in 2003. This study was conducted on the Atrium structure located in the Federation Square located in Melbourne, Australia (Figure 10a). The purpose of this study was to determine the associated displacements due to glazing and de-propping of the suspended part of the structure. Due to the complexity of the Atrium structure, a 5-step monitoring program was considered, in which the 3D coordinates of the 71 structural node points was determined at each stage with accuracy of 0.3mm using the automatic visual inspection system V - STARS (Geodetic Systems Incorporated) [16].

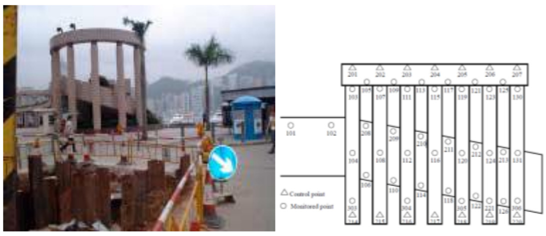


a b

Figure 10. (a) North Atrium with its 14-meter external component. (b) Measured point displacements between measuring epochs (the effect of de-propping, after the de-propping, glazing (applied the entire load)) [16]

In this system, an INCA 4.2 digital camera was used to measure the reference points marked with 2-cm coded retro-reflective targets. Observations were recorded in a template of a 32-station network in which 100 and 140 images with scales of 1:500 to 1:2000 were taken. The image recordings at each stage took 25 minutes while bundle adjustments and the deviation vector calculations took only 5 minutes. In this project, the exterior orientation process was performed automatically using the coded targets, and the hyper redundancy was employed to increase the accuracy. The measured coordinates allowed the calculation of the points absolute and partial deformations, to the required accuracy of 0.5 mm. The maximum measured displacement on this structure was 20 mm, which was consistent with the theoretically predicted values (Figure 10b) [16].

Calvin Li, 2002, studied the deformation of the Star Ferry, a cultural artistic structure, in Hong Kong, (Figure 11a). A channel 1.5m away from the structure was drilled to drain the accumulated water from frequent raining due to the area climatic conditions. Therefore, the purpose of the study was to monitor the structure for the effect of this subsurface channel digging. A camera (Fujifilm MX2700) with a CCD structure was used to take the images on average scale of 1:400. Images were measured using the Elcovision 10 software. In this work, two types of targets were introduced that were referred as Targets of Monitoring Points and Control Points were 3M 7610 retro-reflective and Leica-retro-reflective targets respectively. In Figure 11b, the structure of these target installations is shown [17].

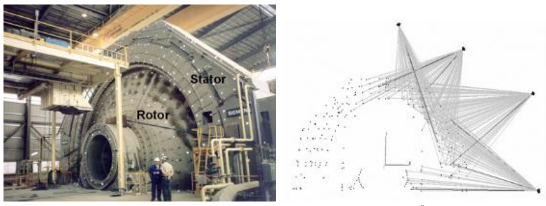


a b

Figure 11. (a) Star Ferry structure. (b) Control and measurement target arrangements [17]

In this study, the displacement accuracy of 2 mm was obtained and statistical tests were used to prove the structural displacement. The results demonstrated that at 95% confidence level no significant overall displacement was occurred in the structure [17].

Fraser, 1999, implemented multi-stage deformation evaluation using close-range photogrammetry to determine the relative displacement between stator (stationary part) and the rotor (moving part) in an ore concentrator / crusher machine. The purpose of this study was to determine the structural behavior during the amperage change in the machine input power. This large circular electric motor, known as one of the largest in the world, was located in a gold mine in Australia (Figure 12). In this project, the structural instability and the presence of significant shocks prevented the use of conventional three-dimensional measurement technologies such as laser scanners [18].



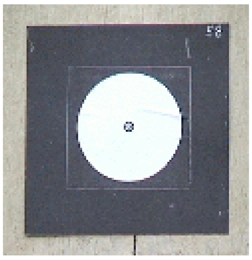
a b

Figure 12. (a) Circular electric motor and target on the stator and rotor. (b) Part of the photogrammetric network and the position of the targets and cameras [18]

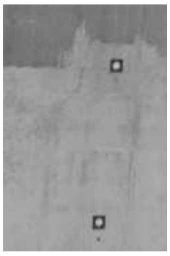
The measurements on the device front were carried out in six stages involving more than 260 monitoring points. From the data collected in these six stages, the main dimensions, the point displacements, and deformation patterns were determined and analyzed. The rear part of engine was measured in three positions. At each measurement step, between 90 to 100 images with average scale of 1:600 were taken during 25 minutes while it took five minutes to have all images automatically measured, the bundle adjustment calculated, and the coordinates (X, Y, Z) fully determined. In the early stages, it was determined that the rotor part of the electric motor was not deformed during the loading test. However, in the later stages, it was observed that the point displacements occurred on the stator due to the increase in load caused by the current change amperage from zero to the specified value A and then from zero to the specific value B. These displacements were calculated having accuracy of 0.15 mm in the direction x, y and 0.25 mm in the z direction [18].

Gred Maas, 1998, studied the potential evaluation of close-range photogrammetry for dam displacement measurements on the Nalps dam in Switzerland (Figure 13a). The dam is about 100 meters high and has a length of 480 meters in the crest. To carry out this project, 60 targets with diameter of 25cm were regularly placed on the structure (Figure 13-b and c). In addition, special targets were utilized to be measured by the theodolite to verify the results. The images were taken using the Kodak DCS460 digital camera with a CCD structure, and in seeking network consistency, some of these images had been taken using a helicopter. The data were acquired in two epochs with different focal lengths in one day and the potential of using close-range photogrammetry was evaluated to achieve the required accuracy in measuring dam displacement. The image orientation was performed semi-automatically using the least squares template matching and 3D point coordinates were acquired by self-calibrating bundle block adjustment. By determining the RMSE values obtained from geodetic and photogrammetric methods, the results of the possibility to achieve the accuracy of 2 to 3 mm in determining the point coordinates in all three dimensions on the dam was confirmed. In this research, close-range photogrammetry was introduced as an effective method in addition to geodetic methods for increasing the number of points to be evaluated as well as the displacement accuracy [4].

a



b



c

Figure 13. (a) Measuring structure (b) Targets were used (c) Target display in acquired images [4]

3. Discussion

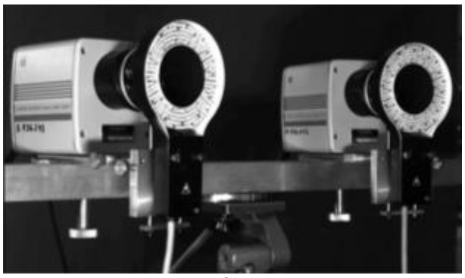
Most of the research overviewed in this paper, can be described in three common categories from structural point of view. Firstly, the use of professional and semi-professional digital cameras, secondly, targeting and point-to-surface displacement measurement and the use of scale-bars, and finally, the network design based on the required accuracy and the use of constraints and control system to achieve the required accuracy for measuring displacements. In the following, a comprehensive discussion about these projects is evaluated in terms of these components.

3.1. Camera for imaging

In all studies, the employed imaging camera was non-metric. Self-calibration and pre calibration methods were used to estimate the interior orientation parameters. The mathematical model used to perform the camera calibration was Brown Mathematical Model which was developed for large format analogue aerial cameras [20] [21].

DSLR cameras are more commonly used for measuring displacements. Both CMOS and CCD technology were implemented on the employed cameras. There is no significant difference in the results of these types of cameras, but it is noted that in the results of CMOS-based cameras, there is a higher sensitivity to the interior orientation parameters than to those of the CCD-based cameras. In other words, the accuracy of the CMOS-based camera after the correct calibration has increased more than the CCD-based camera [11] [19]. In specific circumstances, where there were no possibility to utilize adequate number of targets with proper distributions due to feature limitations, the use of a prefabricated test fields for the camera pre-calibration or a more accurate estimate of the initial values for the interior orientation parameters have been found quite useful [10] [22](Figure 14a).

a



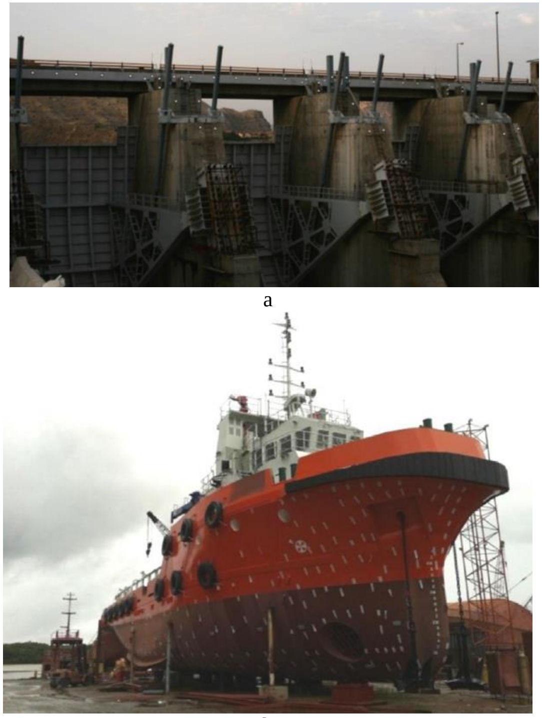
b

Figure 14. (a) Sample Using pre-fabricated test fields with coded targets for camera calibration and accuracy evaluation [10]. (b) camera placements on tripods in the displacement measurements of concrete walls under pressure [23]

The use of tripods and stabilization of imaging stations were considered in most studies (Figure 14b). Using the camera flash to create more contrast between the center and the target background were performed in most research. In some research, the process of measurement is implemented in a non-contact way by using IP cameras, which transfer images to the server by cable or wireless technologies [24].

3.2. Targets or Measurement Points

Concerning the goal of measuring displacements in the investigated studies, the accuracy of image observations is of great importance. In other words, high coordinate extraction accuracy of the entirely identical images in the overlapping images is a necessary condition for increasing the reliability of the 3D coordinates and, consequently, achieving the correct values in the structural displacement. The regular geometric shapes of photogrammetric targets, usually circular, help to achieve further certainty and precision using this constraint to extract an individual point on the image. The main reason for this increase in accuracy is that the position of the center or the target gravity point on the image, is determined by finding the center of gravity of the set of pixels placed inside the target, and is not limited to positioning and extraction of one or more pixels. Therefore, in most research, the use of photogrammetric retro-reflective targets is observed as the base points on the structure to determine the displacement values (Figure 15). In addition, it seems that the application of localized feature extraction algorithms such as MSER or Harris and their improved version in recent years, which increases the positioning accuracy of locally extracted features in images, can replace the use of photogrammetric targets for base point extraction in some projects related to the measuring displacements in large-scale structures.



a

b

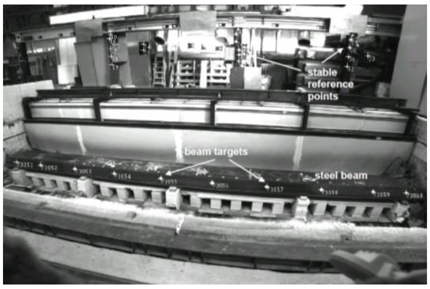
Figure 15. (a) Utilization of retro-reflective targets in the dam displacement measurements using close-range photogrammetry [25] [26]. (b) A case example of using photogrammetric targets in large-scale industrial projects for preparing As-built maps and determining the ship's body deviations [27]

In some research conducted by X. Luo et al. [6] and Daniel J Cerminaro [7], 3D point clouds technique on structural surface was employed to measure displacement between two epochs. In order to implement this method, it is required for structural surface components to be relatively stationary with respect to each other during displacement. In other words, the structural surface comparison can be used to measure displacements between two epochs if and only if the displacements at the surface are merely indicative of the structural displacement and they do not have relative local displacements with respect to each other. For example, in the measuring of excavation wall displacements, the surface of the wall is affected by shotcrete, and the wall surface comparison in two epochs does not necessarily reflect the total wall displacement value. Coded targets were used in most projects to automate extraction and matching processes (Figure 1a). This is especially true in projects where quick assessments of displacement values are of crucial importance to be used for subsequent decisions.

3.3. Network design and control system

The required precision in most measuring displacement projects is much higher compared to other close-range photogrammetric projects. Accordingly, it is necessary to use an accurate control system to unify the results in the real scale and absolute orientation of the points in a local or global coordinate system. In some large-scale structures, due to the wide dimensions of the observational feature, it is not possible to use scale-bars proportional to the feature dimensions. In other words, it is not logical and accurate to construct and use the scale-bars with a length of 10 m or higher. Moreover, in some projects, it is important to differentiate and determine the displacement components in the vertical and horizontal directions consistent with the global coordinate system. Therefore, it is inevitable to use tools such as total stations or GPS to determine the coordinates for some of the targets and geo-reference the results using close-range photogrammetry. However, along with a proper photogrammetric network design, the ability to produce scale-bars with high accuracy below 0.01 mm and even the possibility of purchasing such equipment allows for achieving such accuracies in displacement measurements. Therefore, what is observed in some of the investigated projects is the combination use of the scale-bars and total stations in calculations with its own measuring weights to control the network. The use of innovative techniques in this area indicates the high sensitivity and dependency of the final results to the network control systems. Some of this innovative methods are as: (1) Combined Photogrammetry Displacement Adjustment (CPDA) [8] [28], (2) Stabilization of the camera positions and their precise positioning in small scale projects such as crash tests (Figure 16b) [29]

[28], and the RDC method [11] which creates low altitude targets employing level to resolve the leveling problem in projects. Some project conditions even become more limited and sensitive in this regard for instance, instantaneous measurement requirements concerning to the moving measuring condition such as wind turbine requires a real-time imaging and multi-camera network design (Figure 6). However, the need for a set of points and observations independent of displacement along the structure is common for every network control system in all of the measuring displacement projects, so that the two epoch results can be matched with each other (Figure 16a). In addition, specific lengths, accurate scale-bars, and their proper distribution in the observation space provide more accuracy and the ability to evaluate the results more precisely.



a

b

Figure 16. (a) The use of stable reference points to match the epoch results in multi-epoch deformation monitoring of a series of super-hot steel beams by digital close-range photogrammetry [30]. (b) The use of fixed and predetermined positions for cameras as a Network Control method in the car crash test [29]

The photogrammetric network design was performed in all projects either computationally or experimentally depending on the type of camera and the conditions and limitations of the project to locate the imaging stations. The use of scale constraints, accessibility constraints, spatial resolution constraints, field of view constraints, workspace constraints, landing angles or retro-reflective target field constraints, hidden area constraints, the number and distribution of image points and field depth constraints [31] [32] were considered to optimize network design In order to achieve the predetermined accuracies. The error propagation equation [3], which is an experimental relationship, was used as the basis for the network design in many projects (Eq. 1 [3]).

$$\overline{\sigma}_c = \frac{q}{k^{1/2}} S\sigma = \frac{q}{k^{1/2}} d\sigma_a \tag{1}$$

Where, σ_c is the mean standard deviation of the point coordinates (XYZ), q is the design factor or grid geometric consistency coefficient, k is the average number of images taken at each camera station, S is the scale number which is the ratio d (the average distance from the camera to the object) to C (the principal distance), σ is the average error for the image point coordinates xy, and σ_a is the corresponding angular error which is equal to σ / c. Concerning the q factor, it is necessary to note that this parameter is the consistency parameter of a convergent network to a stereo network, and may range from zero to one. For example, in the Puffing Billy bridge project, which was carried out by Johnson and colleagues in 2004 [15], the achievable accuracy was calculated to 0.46 mm according to Eq. 2.

$$\overline{\sigma}_c = \frac{q}{k^{1/2}} S\sigma \rightarrow \overline{\sigma}_c = \frac{0.7}{\sqrt{1}} \times 833 \times 0.1 \times 8 \times 10^{-6} = 0.00046 \text{ m} \tag{2}$$

In this project, network design factor (q) was 0.7, the number of images from each station (k) was 1, the average imaging scale (S) was 1: 833, visual coordinate measurement accuracy (σ) was 0.1 pixels, and Pixel dimensions on the camera sensor were 8μm. The achievable accuracy for the Hobart radio telescope displacement measurement project was also a predetermined value [14]. In this study, with required accuracy of (0.065 mm), Eq.3 was used to determine the parameter k, which represented the required number of images from each station. In order to achieve the redundancy in the observations and the desired accuracy, according to the relation 3, the k value was set to 4.

$$\overline{\sigma}_c = \frac{q}{k^{1/2}} S\sigma \rightarrow k = \left(\frac{qS\sigma}{\overline{\sigma}_c}\right)^2 \rightarrow k = \left(\frac{0.6 \times 1000 \times \frac{1}{40} \times 8 \times 10^{-3}}{0.065}\right)^2 = 3.4 \tag{3}$$

In this project, network design factor (q) was 0.6, the average imaging scale (S) was 1:1000, visual coordinate measurement accuracy (σ) was 1/40 pixels. Each pixel dimensions on the camera sensor were also 8μm. The required accuracy in the network was $\overline{\sigma}_c = 0.065\text{mm}$, and finally, the number of images from each station (k) was calculated to be 3.4. Therefore, four images were taken from each station [14]. As stated in these project evaluations, the main parameters of the network design can be determined according to the required accuracy. Also, according to the project conditions, the achievable accuracies can be pre-analyzed. It can be concluded that the photogrammetric methods with respect to the required accuracy for the large-scale structural displacement are highly flexible by determining the various network parameters based on the project's requirements.

3.4. General Evaluation

In all of the investigated projects, concerning to the project structure, the close-range photogrammetry was able to achieve the required accuracy in displacement measurements. The designing flexibility of close-range photogrammetric systems to achieve the desired precision makes it possible to create special constraints and additional observations to increase the accuracy of measurement in project conditions. There are some unique advantages for photogrammetric methods that none of the other methods has such capabilities. Some of these advantages are listed as follows: There is no need for direct contact to the structure during the data acquisition, the rapid preparation of feature observations, the instant access to the results by automating the algorithms, the ability to record instantaneous observations of moving features and the possibility of archiving observations for future processing, if needed. In Figure 17, a comparison is made between photogrammetric, microgeodesy, GPS, laser scanner and instrumentation methods (such as strain gauges) for displacement measurement of large-scale structures. The results of this table are based on the investigated research. Scores are ranked from 0 to 5, and in each parameter, the higher the score points, the better the performance of that method in that parameter.

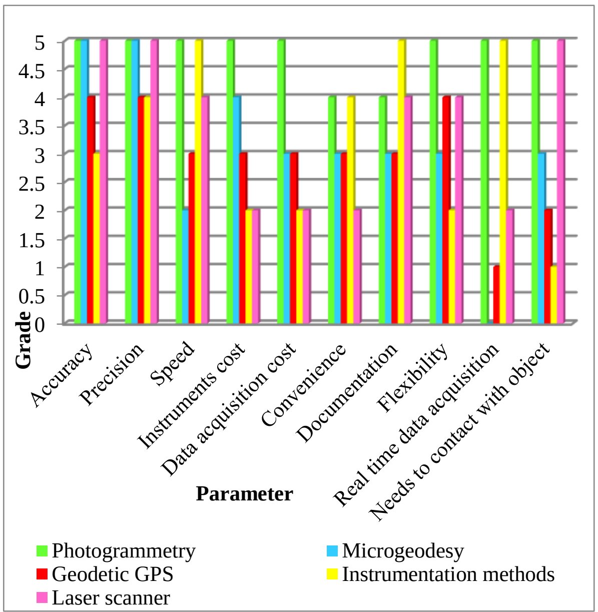


Figure 17. A qualitative comparison between close-range photogrammetric method and other methods in the measuring displacement of large-scale structures

According to Figure 17, in terms of displacement accuracy, the close-range photogrammetry method can be considered equivalent to the microgeodesy and laser scanner methods. Of course, the close-range photogrammetry technique has the potential to achieve an accuracy in the order of micrometer, but in the large-scale structures, the required accuracy of the millimeter is often required, which is achievable by all three methods. The GPS method has generally a lower accuracy than compared to that of the microgeodesy method in terms of the height parameter. Achieving to a specific accuracy in using instrumentation method depends on the installation type of the tool and its maintenance conditions, and it is often impossible to accurately measure absolute displacements in three dimensions similar to microgeodesy or photogrammetry method. Regarding the observation speed, due to the nature of the imaging in close-range photogrammetry, the observation speed is very high. In the instrumentation, after installing the equipment, the results can be quickly available. However, the need for multiple observations and angles from different stations in each epoch in the microgeodesy approach makes it the slowest method to acquire observations. The need for a long deployment of GPS receivers for observation is also a relatively slow process and acquiring observations using Laser scanners at different stations is time consuming. With regard to the cost of the equipment used, the close-range photogrammetry method is the cheapest one. The general tools in this method are digital imaging cameras, targets and scale-bars, which are cheaper than accurate total stations, geodetic GPS receivers, laser scanners, and expensive instrumentation equipment. Close-range photogrammetric methods, as compared to other methods, requires less time for observation. In addition, unlike the instrumentation method, the equipment installation and maintenance does not come with high expenses. Therefore, the cost of acquiring data is lower than the other methods, and concerning this parameter, it possesses a high score. In terms of implementation and acquitting observations, the close-range photogrammetry method is more convenient than other methods. Due to the project space limitations, photogrammetric methods may also be subject to limitations in imaging or determining the stationary base points. However, this limitation is also available for microgeodesy, laser scanner and GPS techniques. There is also a limitation concerning the appropriate installation position in the instrumentation method. Due to the nature of the imaging, the photogrammetric method has high capability to record details and generate observation archives. High speed and ease of acquiring observations enhance this ability. As Laser scanners often equipped with imaging cameras, they have a great ability to archive the observations. After installation, the instrumentation methods continuously send and store their data making this method predominate concerning this characteristic. The flexibility of the photogrammetric method especially in achieving the desired accuracy is much higher than other methods due to its ability to increase independent observations and create more image redundancies and network control constraints and the points on the feature. The possibility of high-speed real-time 3D data acquisition especially in structures where displacements take place instantaneously, is only available in close-range photogrammetric methods. The ability to use a set of high-speed imaging cameras (such as cameras that can take an image in every millisecond) makes the observation acquisition by photogrammetry method unravel. Among other methods, close-range photogrammetry and laser scanners are capable of acquiring data without the need to directly contact the feature. In addition, they are the only methods that are capable of measuring displacements by generating and comparing 3D surfaces. In the photogrammetric method, each of the targets on the structure actually act as an instrumentation sensor or a microgeodesy target, providing much better performance at much lower cost. In all investigated studies, close-range photogrammetry had promising performance in measuring displacement and deformation in large-scale structures.

4. Conclusions

Photogrammetric displacement analyzes are usually implemented in projects in which the investigated feature or environmental conditions do not allow for sufficient time or space for large geodetic measurements. Moreover, the use of images provides an objective documentation for the feature condition at the time of taking images. Temporal and spatial problems of data acquisition and project cost are among the considerations that make the photogrammetric methods more competitive versus other methods.

Achieving high accuracy in photogrammetric feature measurements requires an optimal evaluation and observance of several parameters such as proper network design in locating imaging stations, proper camera selection, the selection of appropriate calibration methods, the selection of appropriate target points and their proper deployment, determining the way of creating the base coordinate system, determine the method for solving the coordinate system orientation (such as selecting scale-bars, targets with similar altitudes, or combined adjustment), determining the observation redundancy, determining the performance speed in data acquisition and processing, determining the proportional mathematical equations for the project, and choosing the proper software for observation processing. Accordingly, the structure for close-range photogrammetric system for measuring large-scale structural displacements should be specifically designed according to its particular constraints and requirements. The limitations usually encountered in close-range photogrammetric displacement projects include limitations on the size of the object under imagery, the distance from the camera to the object, the limits on the accuracy of the target resolution, the restrictions on the location of the imaging stations and limitations related to the base level definition. The use of coded targets and the automation of the orientation process and the point 3D coordinate extraction, provides the opportunity to apply more observations and achieve higher accuracies simultaneously or shortly after data acquisition. This is of particular importance in measuring displacement of some specific structures, such as those structures that support the excavated walls, which sometimes require real-time monitoring.

Close-range photogrammetry is a very useful tool for determining the displacements and deformations in large-scale structures. In investigated studies, close-range photogrammetry was able to save up to 60% in cost and time compared to the other conventional methods while retaining similar or even higher accuracies. In addition, due to the unique results in this method, more useful evaluations are made on the structure behaviors. Concerning the structural dimensions and the appropriate imaging station, using UAV systems provides the opportunity to achieve optimal network design and ultimately improve the displacement measurement results. It is expected that in the near future, in both hardware and software sectors, a unique close-range photogrammetric system will be developed for each type of structure. With the advent of such systems, engineers without complex photogrammetric expertise can use them, and they will be an alternative to the current costly and complicated methods.

5. References

[1] Erol, S., ÇELİK, R. N., Erol, B., & Ayan, T. (2004). Assessment of Satellite Based and Terrestrial Measurement Techniques in Monitoring Vertical Deformations. FIG Working Week 2004. Athens, Greece.

[2] Gordon, S., Lichti, D., Franke, J., & Stewart, M. (1 July 2004). Measurement of Structural Deformation using Terrestrial Laser Scanners. 1st FIG International Symposium on Engineering Surveys for Construction Works and Structural Engineering. Nottingham, United Kingdom.

[3] Fryer, J., Mitchell, H., & Chandler, J. H. (2007). Applications of 3D measurement from images. Whittles.

[4] Maas, H.-G. (1998). Photogrammetric techniques for deformation measurements on reservoir walls. IAG SC4 Symposium Geodesy for Geotechnical and Structural Engineering. Eisenstadt/Austria.

[5] Jiang, R., V. Jáuregui, D., & R. White, K. (2008). Close-range photogrammetry applications in bridge measurement: Literature review. Measurement , 41 (8), 823–834.

[6] Luo, X., Tan, H., Lin, G., & Lian, Y. (2017, June). Strain Field Measurements Using Digital Photogrammetry for Large Inflatable Structures. Experimental Techniques , 1-10.

[7] Cerminaro, D. (2014). Implementation of photogrammetry to improve proactive assessment of retaining walls along transportation corridors. Thesis, Michigan technological university.

[8] Esmaeili, F., Varshosaz, M., & Ebadi, H. (2013). Displacement measurement of the soil nail walls by using close range photogrammetry and introduction of CPDA method. Measurement , 46 (9), 3449–3459.

[9] Esmaeili, F., Varshosaz, M., & Saadatseresht, M. (2013). Displacement Measurement of Soil Nail Walls using Close Range Photogrammetry. Procedia Engineering , 54, 516–524.

[10] Xiao, Z., Liang, J., Yu, D., & Liu, J. (2010). Rapid three-dimension optical deformation measurement for transmission tower with different loads. Optics and Lasers in Engineering , 48, 869–876.

[11] Jiang, R., & V. Jauregui, D. (2010). Development of a digital close-range photogrammetric bridge deflection measurement system. Measurement , 43, 1431-1438.

[12] Ozbek, M., Rixen, D. J., Erne, O., & Sanow, G. (2010). Feasibility of monitoring large wind turbines using photogrammetry. Energy , 35 (12), 4802–4811.

[13] Lee, T., & Al-Mahaidi, R. (2008). An experimental investigation on shear behaviour of RC T-beams strengthened with CFRP using photogrammetry. Composite Structures , 82, 185–193.

[14] Fraser, C., Woods, A., & Brizzi, D. (2005). Hyper redundancy for accuracy enhancement in automated close range photogrammetry. The Photogrammetric Record , 20, 205–217.

[15] Johnson, G. (2004). Deformation determination and comparison of the trestle bridges on Puffing Billy using digital close-range photogrammetry. Internal student project report, Department of Geomatics,University of Melbourne, Victoria, Australia., Victoria, Australia.

[16] Fraser, C., Brizzi, D., & Hira, A. (2003). Vision-based, multi-epoch deformation monitoring of the atrium of federation square. 11th FIG Symposium on Deformation Measurements. Santorini, Greece.

[17] Li, C., & King, B. (2002). Close range Photogrammetry for the Structural Monitoring of the Star Ferry Colonnade. Journal of Geospatial Engineering , 4 (2), 135-143.

[18] Fraser, C. (1999). Automated vision metrology: a mature technology for industrial inspection and engineering surveys. 6th South East Asian Surveyors Congress. Western.

[19] Jiang, R. (2005). Development of a digital photogrammetric system for bridge deformation measurement. Las Crues, New Mexico: New Mexico State University.

[20] Luhmann, T., Robson, S., Kyle, S., & Boehm, J. (2014). Close-Range Photogrammetry and 3D Imaging (2nd edition ed.). Berlin, Germany: Walter de Gruyter GmbH.

[21] Fraser, C. (1997). Digital camera self-calibration. ISPRS Journal of Photogrammetry and Remote Sensing , 52, 149-159.

[22] Tasci, L. (2015). Deformation Monitoring in Steel Arch Bridges Through Close-Range Photogrammetry and the Finite Element Method. Experimental Techniques , 39.

[23] Hampel, U., & Maas, H.-G. (2009). Cascaded image analysis for dynamic crack detection in material testing. ISPRS Journal of Photogrammetry and Remote Sensing , 64, 345-350.

[24] Tsvetkov , R., Shardakov, I., Shestako, A., Gusev, G., & Epin, V. (2017). Deformation monitoring of load-bearing reinforced concrete beams. Procedia Structural Integrity , 5, 620-626.

[25] Shirkhani, A., Varshosaz, M., & Saadatseresht, M. (2007). Deformation analysis of dams by photogrammetry. Conference Proceeding.

[26] Shirkhani, A., Varshosaz, M., & Saadatseresht, M. (2007). Different methods in dam 3d measurements and evaluating capibility of photogrammetry on dams (Case study: Marun dam). Conference Proceeding.

[27] Tang, C., Tang, H., & Tay, P. (2016). Low cost digital close range photogrammetric measurement of an as-built anchor handling tug hull. Ocean Engineering , 119, 67-74.

[28] Esmaeili, F., & Ebadi, H. (2018). Determination of Car Body Deformation due to Collision Using Close-Range Photogrammetry. Engineering Journal of Geospatial Information Technology (jgit) , 6 (1), 117-129 (in Persian).

[29] Honda Fit. (2016). Vehicle to frontal barrier crash test in support of NHTSA’s frontal research program. Calspan corporation transportation test operations, Honda Fit, Washington.

[30] Fraser, C., & Riedel, B. (2000). Monitoring the thermal deformation of steel beams via vision metrology. ISPRS Journal of Photogrammetry & Remote Sensing , 55 (4), 268-276.

[31] Mason, S. (1995). Expert system-based design of close-range photogrammetric networks. ISPRS Jurnal of photogrammetry and remote sensing , 50 (5), 13-24.

[32] Atkinson, K. (2001). Close Range Photogrammetry and Machine Vision. Scotland, UK: Whittles Publishing.