A Study on the Structural Safety of Buildings using Image Metrology

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ABSTRACT

This research aims to explore the potential of image metrology as a substitute for monitoring building structural deformations. It utilizes stereo-photogrammetry and the Kalman filter in its approach. The ultimate goal is to reduce the damage to human lives and property caused by the collapse of building structures in urban areas. Image metrology and conventional geodetic surveying were both used in monitoring the deformation of a selected building prone to land subsidence. Four geodetic monitoring stations were established using the GNSS surveying technique, while 10 photo points were placed on the selected building for deformation monitoring. Simultaneous observation of photo points and acquisition of

their images were carried out during the first three months of this study. The data acquired via geodetic survey were subjected to least square adjustment while the images acquired were subjected to stereo-photogrammetry and Kalman filtering for extraction and refinement of photo point coordinates. The preliminary results show that image metrology is comparable to conventional geodetic survey methods for monitoring building deformation down to 100 mm. The t statistic value of 1.524234 and t critical value of 1.7291333 justify the comparability.

Keywords-deformation studies; building faliures; image metrology, Kalman filter

I. INTRODUCTION

The collapse of large structures can have severe consequences, including threats to public health and safety, environmental contamination, and significant economic loss. These impacts are especially pronounced in developing countries and densely populated cities [1-3]. Over the past 50 years, building collapses in Lagos State, Nigeria, have resulted in the loss of over 400 lives, with at least 135 cases reported between 2007 and 2013 [2]. The recurring building failures in Lagos may be linked to the constant threat of sea-water encroachment, weakening foundations and causing structural instability [4-5]. Structural analysis of building materials can give more insight to causes of building failures in response to climatic and natural phenomena [6].

Deformation in engineering and building structures is an intriguing area of research for scientists, environmentalists, and engineers alike, given the wealth of knowledge available in the field [7-15]. The existing knowledge indicates that each target structure for deformation studies has its own unique characteristics in terms of instrumentation and techniques. While satellite-based data and open data algorithms can be used for large structures like dams and bridges [9, 12], field data and novel algorithms need to be developed for smaller structures, including residential buildings [8, 10-11]. Among all the reviewed approaches employed for monitoring, including the use of Building Information Management (BIM) [15], image-based deformation measurement has attracted the attention of scientists and researchers due to its cost-effectiveness, time efficiency, and instrumentation [7-9, 11-14, 16-19]. In this research, the concept of image-based deformation measurement was investigated in comparison with the conventional geodetic surveying technique [7]. To advance the concept of image metrology for building deformation studies, and to make it simple and accessible for use, especially in developing cities where building failures are frequent, there is a need to develop both field and data processing procedures. The results should be comparable to those obtained using the conventional geodetic surveying technique.

This research employs the concept of a geodetic control network for deformation measurement. The deformation measurements of interest in image metrology include lateral displacement (Δx), horizontal displacement (Δy), and vertical displacement (Δz) [7, 11]. The deformation measurements from image metrology can be expressed mathematically as:

$$X = f(L) \quad (1)$$

$$X = [\Delta x, \Delta y, \Delta z] \quad (2)$$

$$L = [x_i, y_i, z_i, x_f, y_f, z_f] \quad (3)$$

where X is the matrix of the parameters, Δx, Δy, and Δz represent the displacement along the x, y, and z direction, respectively, x_i, y_i, z_i, x_f, y_f, and z_f are the initial and final points coordinates, and L is the observation matrix.

The concept of image metrology for building deformation monitoring encompasses two major concepts: (1) Stereo-photogrammetry and (2) the Kalman Filter (KF) algorithm. In terms of stereo-photogrammetry, two instantaneous photos of the target building from different exposure stations are subjected to rigorous analytical image processing. This process extracts the photo-point coordinates and computes the corresponding ground coordinates, from which lateral displacement and other deformation measurements can be computed and extracted [20] (Figure 1). The KF, on the other hand, identifies the suitable temporal function that describes the movements of points, disregarding any possible correlations with causative elements [19]. Kalman filtering involves two stages: (a) The forecast phase, where predictions are made using the dynamic model, and (b) the adjustment phase, where corrections are made using the observation model to minimize the estimator's error covariance, thereby optimizing the estimator [7]:

$$X_k = \varphi_{k,k-1} X_{k-1} + W_k \quad (4)$$

$$I_k = A_k X_k + V_k \quad (5)$$

where X_k is the state vector at time t_k, $\varphi_{k,k-1}$ is the transition matrix from time t_{o-1}, to t_k, W_k is the noise vector representing the dynamic model at time t_k, I_k is the observation vector at time t_k, A_k is the design matrix for the measurement model, and V_k is the noise vector, which represents the measurement model at time t_k.

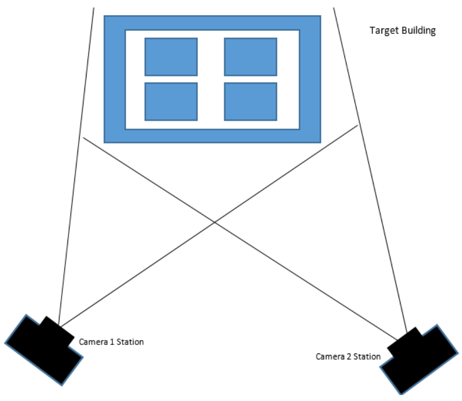

Fig. 1. Concept of stereo-photogrammetry.

This study seeks to investigate the concept of image metrology as an alternative for building deformation monitoring using stereo-photogrammetry and KF, aiming to minimize the loss of lives and the destruction of property due to failures of building structures in developing cities.

II. STUDY AREA

The selected building structure of focus in this study was the National Centre for Energy Efficiency & Conservation Building (Figure 2), which is part of the University of Lagos. This building is situated along Oduduwa Drive, within the University of Lagos, Akoka, in the Lagos Mainland Local Government Area of Lagos State, Nigeria. The geographical coordinates of this location fall between latitudes 6°30'N to 6°31'N and longitudes 3°25'E to 3°27'E. The structure stands at approximately 16 m height. Despite being in existence for a few years, it was only recently commissioned for use due to some observed deformations. Remedial measures have been implemented to ensure its stability. However, this study aims to conduct ongoing monitoring of the building's structural health and evaluate the effectiveness of the implemented remedial measures.

Fig. 2. Ground view of the study area.

III. MATERIALS AND METHODS

The instrumentation and data collection spanned a period of 3 months as a baseline study [22]. Field and office reconnaissance were conducted, which included a desk study on the historically relevant data on the selected building sites, field investigation for in-situ GNSS control points and networks, and instrumentation and planning of continuous field observations. The adopted field procedures involved the use of conventional geodetic surveying for building deformation monitoring, and a method of image metrology for building deformation. With regard to the deformation study, two GNSS geodetic controls were used in the establishment of four monitoring geodetic control points using the fast static GNSS technique [23]. Ten photo-points were also marked at strategic locations covering the façade of the building and falling within the monitoring points' Instantaneous Fields of View (IFOV).

In establishing the geodetic monitoring stations, the locations were sited away from environments susceptible to vibrations and disturbances [17]. Trimble R8 GNSS receivers were used, following the observation procedure of [23]. The post-processing results were adjusted and compared using CORS station data, which were located within a 150 m radius from the monitoring stations. Data collection from the photo-points was carried out in two phases: (1) Stereo-image acquisition, and (2) geodetic survey of the photo points. These phases were carried out simultaneously each day of observation. The stereo-image acquisition field procedure involved the use of a non-metric camera (Canon EOS 200D), centered and leveled with the aid of a tripod and a plumb bob on each monitoring station for instantaneous photos of the selected building. The field procedure followed the guidelines of [7], involving the use of an M3 total station in bisecting the photo-points from each monitoring station, while using a robotic total station for deformation study in order to minimize errors and adjust the redundant observations [18]. A file management database was created and used to store all recorded measured data and acquired images.

At the end of the data acquisition period, the acquired images were subjected to rigorous analytical stereo-image processing (stereo-photogrammetry), wherein, image conversion, extraction of pixel coordinates of photo-points, computation of photo coordinates and ground coordinates of the photo-points using the polynomial adjustment technique were implemented in MATLAB [18]. After the application of the stereo-photogrammetry techniques on the acquired images, the KF was used to compute the error covariance matrix of the photo-points' ground coordinates and for further refinement [18]. Finally, the coordinates of the photo points collected via the geodetic survey were adjusted using the least square utility to minimize and inherent random errors.

IV. RESULT

The instrumentation and data collection spanned over a period of 3 months [22]. Field and office reconnaissance were conducted and these included: desk study on the historical relevant data on the selected building sites, field investigation for in-situ GNSS control points and networks, and instrumentation and planning of continuous field observations. From Table I, it could be inferred that point positioning using either image metrology or conventional geodetic method coincide with a difference of 100 mm or less which is in accordance with [24].

V. DISCUSSION

Looking at the comparability of values from the two methods, image metrology via stereo-photogrammetry for geodetic applications is rigorous and subjected to several factors that could influence the accuracy of its product [25]. The linear displacements per point per epoch were computed and are presented in Table II. It could be inferred that no point remained static over the observation period. Table II highlights point PH20.1 as having the highest velocity regardless of the method, showing the comparability of methods. From Table II, points of interests with high velocities were noted based on individual method and neighboring points. PH20.1, PH21.1, and PH21.2 were the points with the highest velocities per epoch under the image metrology while PH20.1, P03.1, and PH04 were the points with the highest velocities under the conventional geodetic method. The results show irreconcilable differences in the velocities and this may be due to variations in the directional movement of each point [16]. Physical investigation on the selected points indicates the presence of cracks around PH20.1, with the other points close to the base of the building.

TABLE I. MEAN COORDINATES OBTAINED BY CONVENTIONAL AND IMAGE METROLOGY METHODS

Photo-point ID	Conventional			Image metrology		
	X	Y	Z	X	Y	Z
P03	720390.455	544078.000	13.553	720390.200	544077.800	13.122
P04	720404.775	544067.300	13.747	720405.100	544067.500	14.043
PH20.1	720389.554	544075.300	5.789	720400.600	544072.700	6.318
PH21.2	720403.240	544070.000	5.815	720405.000	544070.200	5.229
PH22.1	720404.579	544067.300	6.094	720407.700	544067.000	4.668
P02.1	720380.518	544081.900	13.638	720380.700	544082.600	13.022
P03.1	720390.649	544079.800	13.573	720390.400	544077.400	13.831
P04.1	720404.82	544067.500	13.779	720405.000	544068.300	13.572
PH01.1	720380.671	544081.800	3.094	720380.400	544081.500	2.968
PH02.1	720380.861	544081.600	6.163	720380.800	544081.700	5.93
PH03.1	720385.649	544079.800	7.431	720385.300	544079.200	7.486
PH04.1	720390.241	544078.000	7.469	720389.800	544076.700	7.852
PH20	720389.617	544075.300	5.807	720390.300	544075.900	6.012
PH21.1	720403.287	544070.000	5.909	720403.500	544069.600	6.773
PH22	720404.633	544067.300	6.123	720404.800	544068.400	6.909
P02	720380.505	544081.900	13.631	720380.400	544081.900	13.621
PH01	720380.641	544081.800	3.103	720380.600	544081.700	3.08
PH02	720380.826	544081.600	6.171	720380.800	544081.700	6.19
PH03	720385.611	544079.800	7.429	720385.700	544079.800	7.422
PH04	720390.203	544078.000	7.472	720388.600	544078.700	7.334

TABLE II. VELOCITIES FROM IMAGE METROLOGY AND CONVENTIONAL OBSERVATIONS

	Image metrology	Conventional
PCP	Meters per epoch	Meters per epoch
P03	0.081	0.001
P04	0.044	0.037
PH20.1	1.335	2.098
PH21.2	0.628	0.009
PH22.1	0.342	0.003
P02.1	0.019	0.002
P03.1	0.040	0.091
P04.1	0.186	0.009
PH01.1	0.054	0.002
PH02.1	0.033	0.003
PH03.1	0.059	0.033
PH04.1	0.084	0.036
PH20	0.117	0.001
PH21.1	0.921	0.004
PH22	0.345	0.000
P02	0.011	0.001
PH01	0.007	0.002
PH02	0.005	0.001
PH03	0.004	0.003
PH04	0.244	0.063

Overall, the results show that image metrology can be used in monitoring the relative deformation in buildings by comparative analysis of the movement of neighboring points, which is in agreement with the argument posited in [7, 11].

Also, by examining the correlation statistics and conducting a t-test, Table III shows a relatively fair correlation value of 0.7 between image metrology and conventional geodetic survey for deformation monitoring of buildings [7, 11]. The t stat value of 1.524234 is comparable to the t critical value of 1.7291333, showing that there is no significant differences in the means from the two methods (fail to reject the null hypothesis).

TABLE III. STATISTICAL SUMMARY

	Image metrology	Conventional method
Mean	0.227847	0.120025691
Variance	0.123941	0.217365743
Observations	20	20
Pearson correlation	0.734848	
Hypothesized mean difference	0	
df	19	
t statistic	1.524234	
P (T<=t) one-tail	0.071961	
t critical one-tail	1.729133	
P (T<=t) two-tail	0.143923	
t critical two-tail	2.093024	

VI. CONCLUSION

Image metrology presents a novel approach in monitoring relative deformation in large buildings in terms of cost and execution. In this study, an effort was made to measure and quantify the relative deformation of selected photo-points on a building using both the conventional geodetic surveying technique and image metrology. Under image metrology, stereo-photogrammetry observation techniques were employed, along with the Kalman Filter algorithm for data filtering and analysis. A comparative analysis was carried out to assess the viability of image metrology for building deformation monitoring.

The preliminary results show that for relative point positioning, image metrology could be employed with an accuracy of 100 mm for deformation studies and applications. The use of the Kalman Filter on the stereo-photogrammetry values allows for minimization of random errors in the final values of photo-points. The results of the study indicate comparability in the results of both methods and a further area of research in developing algorithms to address the millimeter comparability of the proposed method.

This study answers the call for a less capital intensive approach to building deformation monitoring [2]. The study therefore, recommends further development of algorithms and field procedures in image metrology in terms of cost and effectiveness in order to make the use of image metrology in monitoring of building deformation and collapse an off-shelf concept for engineers and the general public.

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