Integrated Structural Damage Assessment Using Aerial Images for Bridges

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Abstract

In the present research, an efficient structural damage assessment approach was investigated using aerial drone images for bridges. In the paper, a damage assessment algorithm was presented using aerial images for bridges in the US. Image processing was explained and applied in the damage assessment procedure. Visual survey and bridge inspection procedures were described and the applications in the US were provided as a part of the study. A representative bridge analysis was presented as a case study and in the conclusion, the damage assessment process was detailed. As technology develops, structural damage detection gets faster for transportation systems. Aerial images can be integrated into the structural damage assessment methodology. Collected images can be entered in image processing algorithms to identify damage patterns in highways. Since image processing is a fast and accurate technology of processing images to identify and compare differences and unexpected incidences, it can be used particularly for natural disasters and emergency cases. Periodic automated image processing of aerial images can help inspect wide areas to detect various damages in buildings, structures, bridges, highways, and infrastructures. This can offer time and cost savings in the long run. Pre-event and post-event satellite images from the disaster areas hit by earthquakes and tsunamis can be investigated using a propriety automated damage detection system to determine the structural damage caused by these natural disasters. Drone images can also be used in such investigations. Such investigations can be improved with high-resolution, real-time, and multiple consecutive aerial drone images. The advantages of aerial drone images include safety and reasonable cost of equipment use. An automated structural damage detection technique would be beneficial for structural damage assessment to examine buildings, bridges, and highways using drones.

Keywords
Structural damage assessment, Aerial images, Drone, and Image processing.

1. Introduction
Aerial images contain important information that can be used in mapping structural damages, detecting building failures, producing hazard maps, surface models, building details, and other area characteristics. Such information can be an important aid to response emergency conditions and determining the damage right after the event. Pre-event and post-event aerial images can be used to identify damages and immediate response once needed or to rescue people from the disaster areas. The data are collected before a disaster to define pre-event conditions of buildings, bridges, and infrastructure. Drones can be used to monitor environmental events and determine historical conditions. In such a process, drones can be used to collect data with their recently increased capability in acquiring high-resolution, real-time, and multiple consecutive aerial images. Drones with their remote sensing instrumentation technology enable the collection of accurate and processed data that can be part of the structural damage detection and assessment for buildings, bridges, and infrastructures from the areas under disaster risk from all over the world. Investigation of

existing infrastructures and bridges is very critical all over the world. Therefore, an efficient, fast, and accurate damage detection system help to improve the structural assessment. Image processing and vision techniques are way responsive and accurate compared to manual assessment. In general image process applications, the pure image difference process is used for calculating damage with pre and post images. In this process, different image conditions cannot be considered. In this research work, image segmentation will be implemented in the image processing tool to improve the quality of structural assessment. The flow diagram for the damage assessment using aerial images is provided in Figure 1 (Hisada et al. 2004, Rejaie et al. 2004, Berberian et al. 2002). The outline of methodology is developed with computing damage in the model. The red color in Figure 1 is connected with damages that occurred. Red areas in buildings, highways, bridges, and infrastructures give damages. In the research, C# programming in Microsoft Visual Studio is utilized to develop the algorithm in an easy and effective orientation.

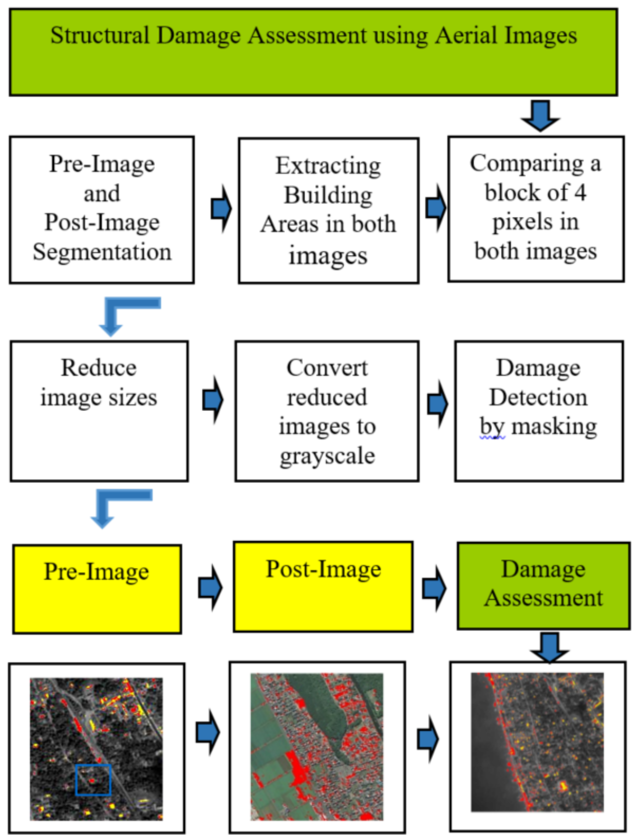

Figure 1. The flow diagram for the damage assessment

2. Image Processing

In the present study, image processing is implemented in damage detection. First, urban tools were modeled representing a real city with its all components as buildings, highways, bridges, and infrastructures in a scaled environment. To represent possible damage in the city, the model was given damages through scaled loading. Pre-event and Post-event, pictures were collected to define damages from differences between images. The pre-event and post-event images were compared, and damages were determined. With the image processing in images, damage detection was completed to define the damages. To define the occurred damages, a computer algorithm was developed in the research. The research methodology was easy and simple to enable effective use in future applications. The methodology and algorithm developed in the research were used for defined segmentation over the pre- and post-images, which is detailed in Figure 2 (Joyce KE et al. 2009, Yang and Chen 2010, Ehrlich et al. 2009).

As detailed in the flow chart in Figure 2, images have been processed through the image detection algorithm developed in the research. In the first part of the algorithm, pre-event and post-event images were resized and reduced the image sizes to be able to make image processing effective and fast. After reducing before and after the earthquake, the images were converted to grayscales. Image processing was carried out in grayscale accurately. Therefore, gray scaling is needed. After the gray scaling process, four pixels from the pre-event and post-event images were scanned. Images were compared with each other. Once the difference is defined over the given threshold, X and Y pixels were noted. The process was completed for all pixels of the images to define the damages. A full damage detection mechanism was completed through image processing. In the second part of the methodology, the damage was detected by determining the differences from the images. In the research, different pixels of the pictures were colored red to represent the damage in the model. Red colors are connected with damage. Red areas in buildings, highways, bridges, and infrastructures represent damages. Damages have occurred in the structural components of the bridges and buildings were considered to define the response of the algorithm. Damages are in the upper scale of the two images. Damages in buildings and bridges were given critical importance to save lives and bring rescue teams to defined areas in the damaged surfaces and damaged areas in the urban areas (Li et al. 2009, Anderson et al. 2009, Choi et al. 2009).

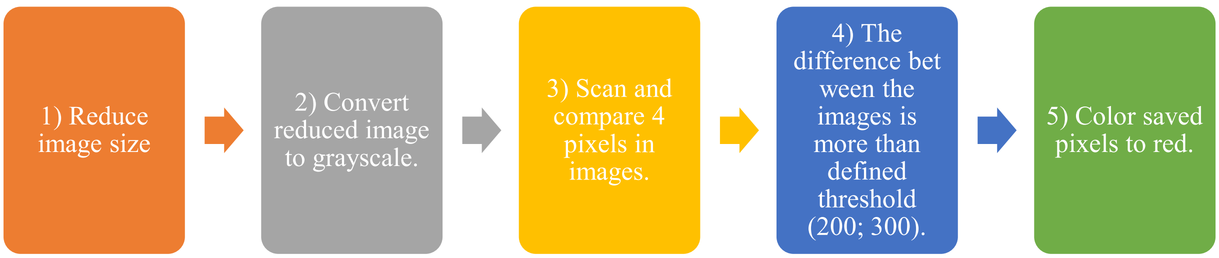

Figure. 2. The flow diagram for the damage assessment

One of the critical challenges associated with automated damage detection using drone aerial images is the fact that the reference points in images of urban areas vary significantly from one to another in addition to the color intensity spectrum. Therefore, just converting the image to grayscale and performing a traditional thresholding technique will cause several problems. This change is problematic for simple thresholding. To overcome this problem, a dynamic (local) thresholding technique was developed and implemented in this research. A more dynamic system for autonomous navigation in disaster areas such as that of point vision-based navigation can be a solution for data processing with drones. A similar method of damage detection based on image processing technology was used in the research work Yun-Zhao et. al (2020). Lingxin (2022) summarized various applications in damage detection using the same approach. Kim et. al (2019), Li et. al (2019), and Lee (2020) used the machine learning approach to define the cracks on the road surfaces. Road Damage Detection (RDD) using Deep Neural Networks with Smartphone Images was published by Maeda et. al (2018) and another approach with super-resolution and semi-supervised learning was published by Shim et al (2022). The developed dynamic technique can be used for a point vision-based drone navigation system utilizing disaster invariant features such as features that are likely to remain intact pre- and post-events. In Figure 3, sample testing results using the dynamic technique for an urban scaled model are given. In Figure 3, red areas are the ones with damaged structures (Wei et al. 2009, Yano et al. 2004, Mei et. al, 2020).

Figure 3. Damage Detection Test with Dynamic Technique

3. Structural Damage Assessment

There are various urban areas under disaster risk due to various reasons such as earthquakes and tsunamis. Existing buildings and bridges in these areas are in need of response in case of any disaster. Damage assessment was an essential issue for such areas and regions under risk. Structural components in such regions are mostly old and need structural strengthening or rehabilitation. Cities all over the world, under risk, are in need to develop disaster assessment tools for disaster-prone regions. The main problems for the cities are the gap of a systematic approach for the disasters. Image processing would be a great solution for them to respond to such problems especially in big cities. Disasters that occurred in recent years showed that an effective disaster assessment is critical for defining damages after the disaster. Once it is possible to define the damage, that algorithm will help to save lives as well. Effective disaster assessment processes, including image processing, can be effectively used for many cities all over the world. Big cities are having bigger risks in case of disasters. High-rise buildings, highways, bridges are more complex than in big cities. Structural damage assessment can be done in an integrated environment as given in Figure 4. With an integrated environment, image processing can be used more effectively, and results will be more accurate.

Figure 4. Integrated damage assessment

Structural damage assessment is completed pre-event and post-event pictures and images from the site. In the cities, in an integrated environment, before and after the disaster images can be effective to define the structural assessment for existing buildings, highways, bridges, and infrastructures (Adams et al 2004). For damage assessment, structural components of buildings, bridges as beams, columns, or slabs should be determined with their structural behavior and their resistance to the loading for the defined threshold capacities. This is very important to understand the structural capacity for defining the damage pattern for the existing buildings. All damages should be determined within structural components. Damages that occurred are connected with the impact on buildings from the disasters. Any disaster will have different characteristics and different impact on the buildings. Therefore, each of them should be defined in their own characteristics. The disaster assessment should also determine the level of damage if it is rehabilitated, repaired, or should be demolished. In the present study, a damage assessment has been completed for a city model by using segmented pre-event and post-event images as given in Figure 3. In Figure 3, a building with a roof at the left end of the upper part of the image was damaged and detected by the algorithm developed. Heavier redness is in the bottom right part of the image. Existing buildings such as schools, hospitals, and public spaces are the critical ones for damage assessment. With sufficient data collected from the site, an effective methodology can be developed for the image processing procedure in the algorithm.

The essential damage assessment philosophy for cities is to define the structural deficiency through multiple approaches as defined in Figure 4 that brings accuracy. In Figure 3, methodology results are demonstrated. In Figure

3, the red areas are the damaged areas. For existing bridges, drones can be used to collect data easily. Existing old bridges can be investigated through drone images that can prevent any collapse or unexpected damages to the bridges. As it was experienced in the past, bridges can collapse under traffic loading even without any disaster. Since many of the existing bridges in the US are old and deficient in terms of structural resistance, they should be investigated through a fast, simple, and also accurate methodology. An accurate investigation makes the decision-making process accurate and feasible. Structural damages can be prevented through such an approach. With image processing technology, structural damages can be automatically understood and processed. In various existing infrastructures in addition to bridges, structural deficiency can be determined with image processing in five steps as described (Liang, 2019):

- Step 1. Aerial Data Collection- Drones will be used to collect aerial data from several buildings and bridges in various locations. Collected images are stored.

- Step 2. Image Processing- The image processing technique will be improved by enhancing its capacity to process high-resolution, real-time, and multiple consecutive aerial drone images. A dynamic (local) thresholding technique will be developed and implemented.

- Step 3. Nondestructive Data Collection- Nondestructive data will be collected using multiple instruments such as a structural scan system, thermal detection equipment, and cameras.

- Step 4. Integrated Damage Assessment Development- A methodology is developed for structural damage assessment in an integrated damage detection environment using aerial and nondestructive data.

- Step 5. Risk mitigation for Cities-Drone aerial images of urban areas and structures in various locations are collected and stored in an imagery collection. This collection will be used for risk mitigation in cities for detecting structural risks and possible failures in buildings, infrastructures, and highway systems with high loss potential.

4. Visual Survey with Drones

Visual inspection with Drones for bridges can be carried out through image investigation. For defining the image processing findings, matrices were developed. In the developed matrices, a damage assessment algorithm has been demonstrated. As indicated in Table 1, a Visual survey matrix can be developed for the investigation of images. This matrix has been developed for damage assessment for existing bridges. In Table 1, a Matrix of Visual survey applications is given. Table 2 gives the Visual Survey Scale in Bridges. In Table 2, the probability of damage is given based on two different parameters. These parameters are Damageability Grading and Structural Risks for bridges. These parameters are explained in Table 3 and Table 4. Table 3 gives Damage Grading for bridges. Table 4 is for Structural Risks for bridges. These tables are the ones used in the structural bridge assessment with Drone images.

The research findings will be beneficial to determine the damages that occurred in the existing highways as well. Through the damage assessment, the risk in existing buildings for public safety has also critical importance. In Figure 5, a sample damage detection for highway systems in the US is given to represent the damage assessment for the highways. Such an integrated system can be used in a determined roadway surface to detect the cracks and surface problems as seen in Figure 5.

Detections on the roadway surfaces can be categorized through given Table 1. Such categorization as noted in Table 1 will make surface detection meaningful. Visual survey results can be validated in the first three ranks. The scale of the visual survey can be given in five different levels as given through Table 2 to Table 4. Using these tables, aerial images can be integrated into damage detection process. Damage detection will be more accurate with such approach.

Figure 5. A Sample Data Collection for a bridge with drone imagery and damage detection

Table 1. Matrix of Visual Survey Applications

Rank	Application	Visual Survey
1	Ranking Damage Rehabilitation Needs	Structurally Validated
2	Designing Damage Resistance	Structurally Validated
3	Developing Inventory	Structurally Validated
4	Planning post-event safety	-
5	Developing Bridge Scan Vulnerability	-

Table 2. Visual Survey Scale for Bridges

Bridges	Visual Survey Scale				
Damageability Grading	A5	A4	A3	A2	A1
Structural Risk	B5	B4	B3	B2	B1

Table 3. Damage Grading for Bridges

Damageability Grading	Levels
A5	Severe Damage
A4	Heavy Damage
A3	Moderate Damage
A2	Slight Damage
A1	No Damage

Table 4. Structural Risks for Bridges

Structural Risk	Levels
B5	Severe Risk
B4	High Risk
B3	Moderate Risk
B2	Slight Risk
B1	No Risk

5. Bridge Inspection

Bridges are an essential and critical component of the transportation systems, and their designs are critical for DOTs. Using drone technology, Bridge Inspection became an image process investigation. Inspected bridges and their structural elements will give stress distributions over the structural elements. Such investigation brings structural evaluation. The use of 3-D views is a technology demonstration to apply a load distribution definition. Structural evaluation of bridges can bring an understanding of bridge behavior. Finite Element Analysis can be connected through this investigation. Finite element models of bridges can be established and analyzed for models developed. Representative behavioral shapes of bridges are demonstrated in Figure 6. In Figure 7, Representative Displacement Variation for Bridges is given. Once the definition process is completed, complex analyses can be carried out for a detailed investigation. In finite element modeling, effecting factors can be taken from drones and modeled with finite element software. Factors can be simulated through the collected image data.

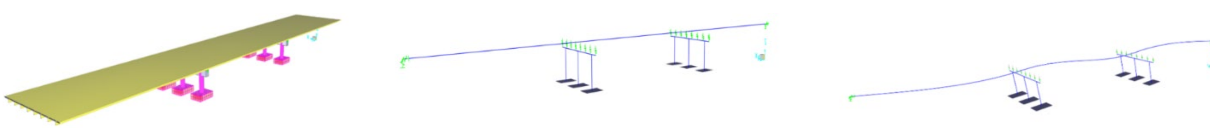

Figure 6. Representative behavioral shapes of Bridges

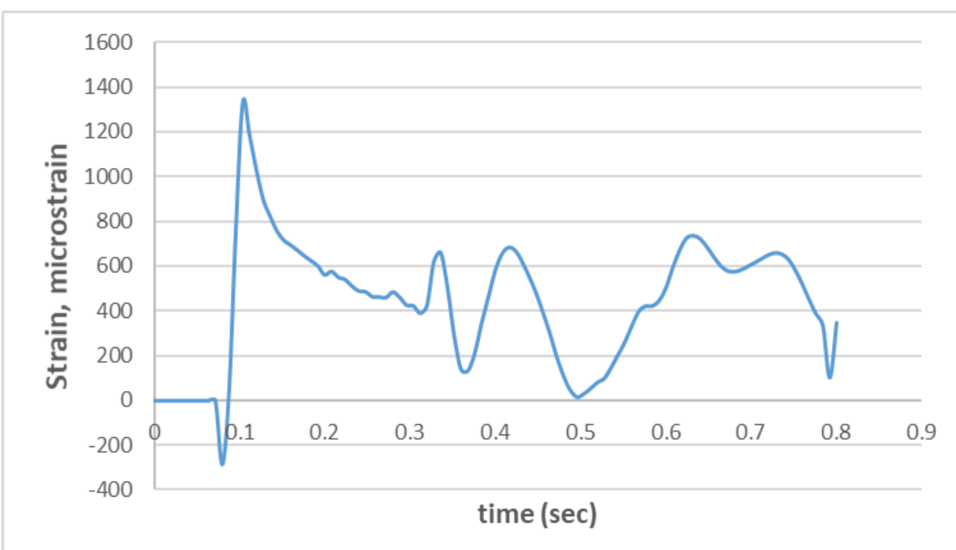

Figure 7. Representative Displacement Variation for Bridges

6. Conclusions

In this paper, a detailed investigation was presented about the damage detection approach for bridges. The damage assessment process is a very critical process for the bridge systems. With new technologies, it gets more accurate and rapid as detailed in the present research. In the paper, the image processing approach was given as a part of the damage assessment, and it is one of the new technologies to implement in the damage assessment. In image processing, defining the differences between pre-event and post-event is very important and makes the results meaningful. Once the detection algorithm is established, based on such different definitions, the next step is to integrate all evaluations in the overall damage detection procedure. Damages are defined in the structural components and their effects on the entire system as given in categorization. The damage level can be defined in the urban scale, not only the structural component scale. For instance, a damaged bridge is not only defining a structural member but also represents the blockage to access the city. Therefore, such integrated algorithms are important. In the present research, a damage assessment algorithm has been developed and implemented on a model. This model represents a real city with all structural components as buildings, bridges, highways, and infrastructures. Images were compared for pre-event and post-event conditions. Damage detection has been carried out throughout the entire city with its all components. Segmentation was carried out for damage assessment procedures. Damage levels were determined through the developed algorithm.

In the proposed damage assessment algorithm in this paper, an image detection tool was used to determine the damage profile for existing highways. In the research, a damage detection algorithm has been applied for the determination of damages. In big cities, damage detection is a critical problem and needs more implementation with real-life examples. This is also important to save lives after disasters. Disasters are causing live losses and live losses should be prevented in the cities in short term and long-term planning and scheduling.

As detailed in Figure 6 and Figure 7, bridge behavior was determined by Finite Element analysis. Such investigation gives accurate results in the investigation of the bridges. Especially for old bridges, determining behavioral shapes and displacement variations are very critical to determine which is called health monitoring of bridges. In addition to this approach, image assessment can be implemented in the assessment to get a more accurate result. As detailed in Tables 2 to 4, grades are assigned to bridges and bridges can be described. With such a description, bridge inspection can be done in an easier and faster way with accurate results. Results are used in the decision-making process at each step. The structural assessment would be integrated with visual assessment. Linking these two investigations validates the structural resistance of existing buildings and bridges.

As a result of this study, an integrated damage assessment philosophy has been introduced as an urban civil tool. Such assessment is very important to complete for structural health and lifesaving. The most common way to investigate the bridges is structural assessment. However, only one tool cannot be sufficient for damage detection. It should be noted that each tool has a different perspective and all of them should be used and integrated. Over the years, with developed technology, it is more common for an accurate evaluation. Especially for bridges, surface failure detection is the most common practice. Transit agencies are looking for integrated evaluations and assessments for existing bridges. The proposed approach can be adopted by the agencies for accurate damage detection for bridges.

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