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Health Monitoring of Civil Structures with Integrated UAV and Image Processing System

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Abstract

This paper describes an innovative protocol for full field mapping of a large civil structures involving effective use of Unmanned Aerial Vehicles (UAVs) to enable real time structural health monitoring. The proposed frameworks integrates UAVs, image processing and data acquisition procedures for crack detection and assessment of surface degradation. A novel approach is proposed combining hat transform and HSV thresholding technique for crack detection. In addition, grey scale thresholding is employed for the measurement of surface degradations. A Demonstration multi-rotor UAV model is developed to carry out full field inspection of civil structures and real time testing is performed in our large university campus. In order to provide sophisticated monitoring platform for users, a MATLAB Graphical User Interface (GUI) is developed to analyse real time as well as acquired images and the results are validated successfully. The obtained results confirms that, the envisaged approach is the foundation for cost effective and time compressing solution for monitoring of large civil structures.

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Keywords: Crack detection; Efflorescence; Image processing; Structural health monitoring; UAVs.

1. Introduction

The sustainability of civil infrastructures can be achieved by periodic and continuous assessment that necessitates easy and effective Structural Health Monitoring (SHM) tools and techniques. As is readily acknowledged by the global fraternity, the field of SHM represents an integrated paradigm of networked sensing and actuation, data interrogation and statistical assessment that helps to assess structural health. SHM practices are integral to functional safety of critical civil structures during the designated life spans and beyond. The conventional SHM procedures tend to be laborious, time consuming and capital intensive[1,2]. Especially, in the case of large span bridges, heritage structures, monuments and elevated buildings of national importance, traditional methods are not effective for rapid full-field monitoring and hence a radical monitoring approach is most needed.

In recent years, by virtue of low-weight high strength materials, versatile sensors, microelectronics, portable powerful computing systems and miniature propulsion systems, UAVs are gaining prominence in several sectors such

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as environmental monitoring, precision agriculture, industrial inspection, power line and telecom tower inspection, surveillance and exploration activities[3–6]. The employment of UAVs in SHM of bridges and other civil structures are exceptional and practical feasibilities are still under research. The deployment of UAVs for civil infrastructure monitoring is new arena and very few practical case studies are carried out for industries, monuments and other civil structures[7,8]. In most applications, UAVs are equipped with image acquisition system and the captured data are processed manually. Though this strategy is convenient, there is laborious work involved in quantifying and analysing the acquired data in a reliable way.

In this paper, we propose a novel strategy integrating UAVs with image acquisition and processing algorithm for inspecting extensive infrastructures in an effective way. The measuring instruments are mounted on UAVs to transmit information in real time thereby facilitating inspection from ground station. Along with that, real time interfacing with image processing systems can support processing of thousands of images which can expedite the diagnosis process significantly. The noteworthy benefit is, digitization of whole monitoring activity has widened the scope for easy storage, sharing and better accessibility to end user.

The paper is organized as follows: Section 2 describes the proposed image processing algorithms for crack and surface degradation measurement with its simulation results. Section 3 summarizes the technical specifications and capabilities of the demonstration UAV model. Section 4 describes the developed MATLAB GUI module and Section 5 briefs on real time testing with inference on results and real time feasibility and finally Section 6 summarize the highlights of the concluded work.

2. Image Processing Algorithms

Image oriented inspection algorithms are becoming an effective tool towards formulating a reliable and rapid monitoring procedure. The current work described in this paper focuses on, two primary structural anomalies such as identification of cracks and surface degrading effects like efflorescences, fading and surface erosion.

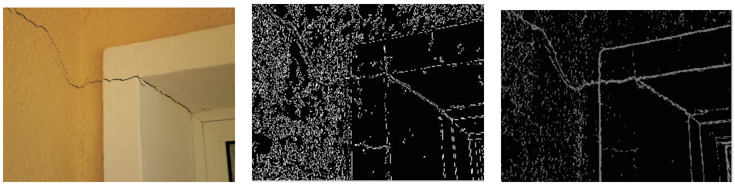
2.1 Crack detection

In general, the cracks on the concrete surface possess two main properties i.e. their structural shape is thinner and different than the other textural patterns and it exhibits low luminance. This necessitates the detection algorithm to have the capability of extracting the dark objects on the light background with some structural specifications. In literature, plethora of techniques are proposed for crack detection using morphological gabor filters[9], hat transforms[10], image fusion[11], baseyian classifiers[12], wavelet approach[13] and so on. It can be inferred from their research that, predominant methods rely on crack detection through gray scale images[14]. Even though gray scale approaches yield good results, many of them suffers from misidentification of other structural edges as cracks and results in surplus detection. For example, a test image from open source as shown in Fig. 1a is considered for the present study. The picture shows typical corner cracks observed in masonry walls around openings such as doors/windows and the cracks detected through canny and hyperbolic tangent filters are shown Fig. 1b & 1c. It can be inferred from the output that, both methods identify cracks along with the other edges and corners present in the scene and suffers from excessive detection. To overcome these drawbacks, a new strategy combining the hat transform and HSV thresholding technique is proposed. The proposed methods aims to achieve minimal detection with good accuracy avoiding ambiguities. In order to understand the overall picture of the algorithm, a block diagram showing the proposed method is depicted in Fig. 1d, in which the proposed algorithm combines the output obtained through two filters resulting in enhanced detection.

2.1.1 Hat transform approach

The hat transform is a gray scale morphological filter that can be used to extract small elements or objects out of a scene. The transform is classified into two types based on its operation and their details are given below.

- Top Hat Transform: $\mathrm{Img}_{TH} = f - (f \circ s)$; Used to extract bright feature which are smaller than the structuring element.



(a) Test Image (b) Canny Edge Detector (c) Hyperbolic Tangent Detector

Fig. 1. Canny and hyperbolic edge detectors.

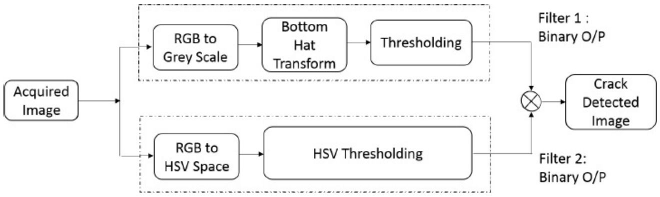


Fig. 2. Proposed crack detection algorithm.

(a) Test Image (b) Grey Scale Image (c) Bottom Hat T/f output (d) Thresholded Output

Fig. 3. Crack detection: bottom hat transform.

- Bottom Hat Transform: $\text{Img}_{BH} = (f \bullet s) - f$; Used to extract dark feature which are smaller than the structuring element

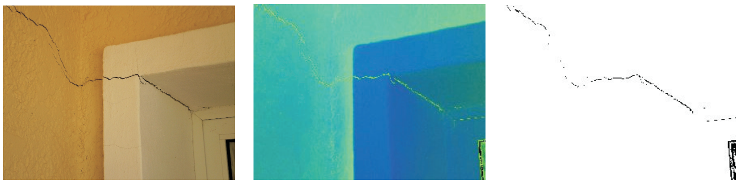
Img_{TH} and Img_{BH} corresponds to the output image of top hat and bottom hat transform, 'f' refers to the input image, '$\circ$' & '$\bullet$' indicate morphological opening and closing function and 's' refers to the structuring element. Among the two approaches, the present study utilizes bottom hat filter to extract dark and small structural elements out of scene. The application of filter removes all the portions in an image which are smaller than the structural element and darker than the background. From the literature and several trail experiments it has been found that the following filter parameters holds good for crack detection[15].

- Dimension of the structural element – 3×3 Square
- Thresholding Value – 0.9

However, these parameters have to be calibrated in real time circumstance based on image acquisition using UAV at specific clearance between the structure and UAV.

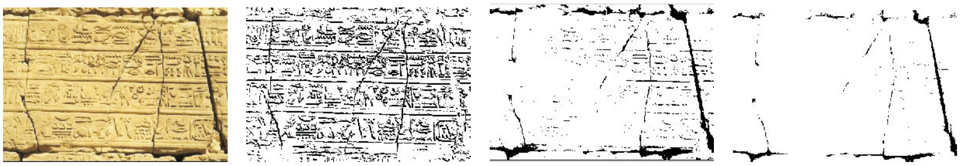
Simulations are carried out to evaluate the performance of the BHT considering a test image from an open source as shown in Fig. 3a in detecting cracks. The test image is converted to its gray scale version as shown in Fig. 3b and then BHT is applied. The results suggested that, BHT produces satisfactory results to detect the crack as shown in Fig. 3c. Further, thresholding is to be performed to obtain the exact crack pattern as shown in Fig. 3d.

Though the hat transform approach is satisfactory in detecting the cracks, in few cases it has been found that there are chances of misinterpretation of cracks when exposed to edges in windows, doors and other structures. For example, in the threshold image as given in Fig. 3d, there is a presence of sparsely distributed black points along the walls and doors (as indicated by red circles). This particular error can me minimized by combining an additional filter which



(a) Test Image (b) Grey Scale Image (c) HSV Output

Fig. 4. HSV thresholding.



(a) Monument Test Image (b) Hat Transform Output (c) HSV Output (d) Overall Output

Fig. 5. Crack detection.

works on HSV thresholding with BHT. The reliability and performance of the image processing system also improved with this method.

2.1.2 *HSV thresholding*

This technique can be implemented on the images which are represented in terms of hue, saturation and value. By properly setting the limits in HSV space, the object or element of interest can be extracted from the scene. As our earlier method works only on the gray scale version of the test image, the introduction of color based filters like HSV improves the reliability and adaptability of our algorithm to various infrastructures. In order to identify the threshold point, extensive trial tests are conducted for various open source images and it is found that cracks are characterized by low saturation and value. The simulation using HSV thresholding is performed for the existing image and results are shown in Fig. 4c. It can be noted that, sparsely distributed black clusters are removed yielding optimal results.

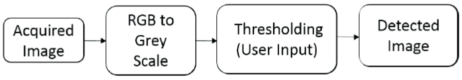
To evaluate the overall performance of combination of these two methods, a real time open source image as shown in Fig. 5a of Karnak Temple, Egypt is considered. Simulations are performed and it can be inferred from the results that, top hat transforms identifies multiple small edges (Figure 5b) and unable to spot large cracks. However, the HSV thresholding yields nearly optimal results (Figure 5c) in identifying the cracks.

Similar simulation is performed with various open source images of civil structures. It is found that, the combination of BHT and HSV thresholding accomplishes superior crack detection (Figure 5d) and to be consistent for various structural types.

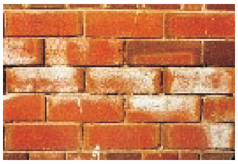
2.2 *Surface quality*

The surface of the concrete or granite blocks may get degraded due to prolonged exposure to atmospheric reactions and human activities. This results in change of surface color texture in the form of efflorescences, erosion and other degradation effects. In order to quantify the level of surface degradation, an effective algorithm is necessary. A simple grey scale thresholding is proven to be an effective strategy[16] in classifying the unaffected regions among surface degraded portions and is adopted in our work. In general, the thresholding value is calculated based on the surface color texture and varies for images acquired at different sites. In view of this, user has to indicate the unaffected area in the test image and algorithm determines the corresponding thresholding value for the rest of the images based on user input. In addition, the algorithm computes and indicates the degradation percentage depending on level of affected area.

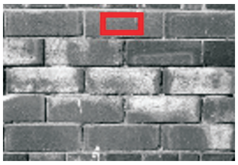
$$\text{Output}_{\text{Img}} = \begin{cases} \text{White} & \text{If pixels lies within user input limit} \\ \text{Black} & \text{Efflorescenes} \end{cases}$$



(a) Surface Quality Algorithm



(b) TestImage

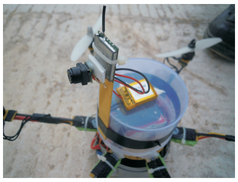


(c) GreyScale Image

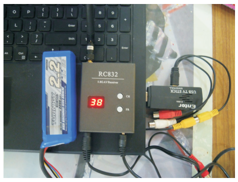
(d) Detected Output

Fig. 6. Surface quality algorithm and results.

(a) MUAV and Transmitter



(b) Camera Device



(c) Receiver Unit

Fig. 7. MUAV demonstration model.

The block diagram shown in Fig. 6a describes the overall process and the simulation results are shown in Fig. 6b & 6c. It is evident from the result that, the algorithm effectively detects the efflorescences on the brick masonry wall.

3. Demonstration UAV Model

A Multi Rotor UAV (MUAV) system is developed as a demonstration model as shown in Fig. 7, considering critical inspection and manoeuvring aspects such as ability to hover and reach higher altitudes of the structure, auto take-off and landing, and stable flight under harsh environment (or atmosphere). The MUAV system is equipped with color imaging sensors and interfaced to MATLAB, aiding real time processing with the help of integrated image diagnosis algorithms. The detailed technical specification of the MUAV and image sensors used are provided below.

Camera module specification

- Camera: PAL: 762*572; Current: 75 mA;
- Camera Transmitter: 5.8 GHz; 200 mw output; Current: 200 mA;
- A/V Transmitter: 5.G Hz; Sensitivity: −90 dBm; 2 dBi antenna;

MUAV specification

- Frame: Carbon Fibre and Glass Epoxy
- Payload: 100 g; Endurance: 20 minutes;

4. MATLAB Graphical Interface for Civil Structural Inspection

A sophisticated SHM module using MATLAB GUI is developed to provide users with multifaceted options to process real time and database images. It consist of three main panels to deal with image acquisition, efflorescences and cracks detection as shown in Fig. 8. The brief description of each block is given below.

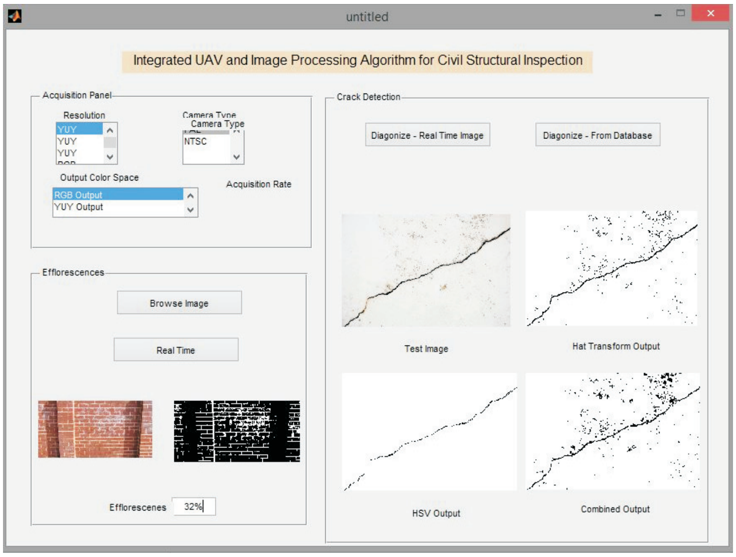


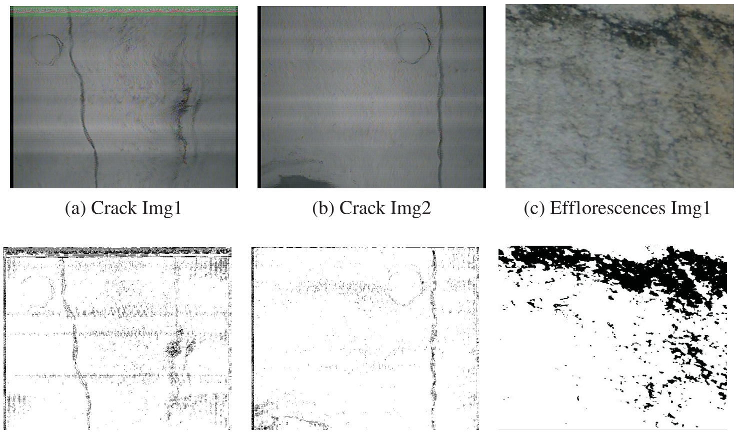
Fig. 8. Monitoring GUI system.

(a) Structural Inspectoin

(b) Closer Examination of Cracks

(c) Hovering

Fig. 9. Real time testing.



(a) Crack Img1 (b) Crack Img2 (c) Efflorescences Img1

(d) Crack Output1 (e) Crack Output2 (f) Efflorescences Output3

Fig. 10. Field test results.

Image acquisition This panel provides an option for the user to select the acquisition parameters associated with the real time imaging device. The selection factors are camera type, output colour model, acquisition rate and resolution. The user has to optimize these parameters according to processor capacity and database size.

Efflorescences This module is interfaced with surface degradation algorithms, which can compute and display the percentage of efflorescences. Once the test image is selected, the user has to click on "User Input" option to classify the unaffected area through which the thresholding value is computed. The module also displays the input and the detected efflorescence image in the axes.

Crack detection In this module, user can visualize the input image and the corresponding output of hat transform, HSV thresholding and also their combined output. This will help in optimizing the associated filter parameters and the performance evaluation between HSV and hat transform for enhanced crack detection.

5. Real Time Testing

The full field testing is conducted in the outdoor environment of our university campus to inspect various civil structures. The MUAV model flew near to the building as shown in Fig. 8 and with a capability of hovering real time images (Fig. 9) are acquired and processed through the MATLAB environment. The GUI enable us to identify the presence of cracks and efflorescences at different locality of the structures in less time. During the testing, practical factors such as wind speed and random image noises causes erroneous results for few acquired images, which can be avoided with advanced flight controllers and gyro stabilized camera systems. Some of the field results are shown in Fig. 10 and the future scope of this work would be to suppress random real time noises and to improve detection results.

6. Conclusion

A novel approach is proposed integrating UAVs and image processing algorithm for effective monitoring of civil structures. Image algorithms are developed to determine primary structural defects such as cracks and surface degradation. Combining hat transform and HSV thresholding method, an effective approach for crack detection is formulated and found to be suitable for inspection in versatile civil structures. To estimate surface degradation, a percentage index is formulated based on grey scale thresholding and tested for efflorescences of images. A demonstrative MUAV model is designed for deployment in full field monitoring of civil structures. The simulations and real time testing is successfully carried out to analyse the performance of our inspection system. The demonstrative model is proven to be a reliable and feasible for full field mapping and health monitoring for civil infrastructures.

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