Smartphone application for structural health monitoring

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Abstract. In recent years, smartphone technologies have developed rapidly. They are increasingly taking on the role of laptops and compact personal computers, as well as digital cameras, through which measurements can be made in various fields such as sport, medicine, defence, transport, energy, industry and construction. Modern smartphones interact with the environment through a number of built-in and external sensors used in various software applications. Utilizing these sensors the smartphones are able to collect data that is used by specially developed applications for storage, processing and analysis. Due to their mobility, large data storage capacity, significant computing power and, last but not least, low cost smartphones, in addition to being a means of telecommunications, may with a suitable application, take on the role as a measuring system.

An example of using a smartphone as a measuring system is when inspecting the operational condition of building structures and their constituent parts (so-called "Structural Health Monitoring (SHM)). In the monitoring of engineering facilities, there are tasks for measuring the displacement and deformation fields. They cannot be solved with traditional contact methods such as the use of strain gauges, fibre optic sensors, ultrasonic sensors, etc., despite the fact that these technologies are also undergoing development and progress. In the last two decades, innovative sensors and displacement measurement systems [1, 2] have been developed in the field of SHM, based on displacement and strain sensor, laser Doppler vibrometers, GPS satellite research, terrestrial laser scanning.

1. Introduction

Over the past 15 years, smartphones have developed rapidly together with the advancement of technology. They have increasingly taken on the role of both portable and compact personal computers, as well as digital cameras, through which measurements can be made in various fields such as sport, medicine, defence, transport, energy, industry and construction.

Modern smartphones interact with the environment through a number of built-in and external sensors used in various software applications. Utilizing these sensors the smartphones are able to collect data that is used by specially developed applications for storage, processing and analysis. Due to their mobility, large data storage capacity, significant computing power and, last but not least, low cost smartphones, in addition to being a means of telecommunications, may with a suitable application, take on the role as a measuring system.

An example of using a smartphone as a measuring system is when inspecting the operational condition of building structures and their constituent parts (so-called Structural Health Monitoring (SHM)). In the monitoring of engineering facilities, there are tasks for measuring the displacement and deformation fields. They cannot be solved with traditional contact methods such as the use of strain gauges, fibre optic sensors, ultrasonic sensors, etc., despite the fact that these technologies are also undergoing development and progress. In the last two decades, innovative sensors and displacement measurement systems [1, 2] have been developed in the field of SHM, based on displacement and strain sensor, laser Doppler vibrometers, GPS satellite research, terrestrial laser scanning.
Initially, Morgenthal and Hopfner [3] measured displacements using the speaker and microphone of an Android-based smartphone. They concluded that significant inaccuracies might arise due to component calibration and fluctuations in temperature.

In [4], Zhao and team have proposed the use of a smartphone with an application based on the laser projection sensing method for real-time displacement measurement in bridges. A laser device emitting in visible region of spectrum is fixed on a structural element of the observed bridge and the laser spot is projected on a projection plate located in appropriate position. The iPhone recognized the movement of the laser spot on the projection plate, and structural displacement was calculated using image processing methods. Two mobile applications are used - D-viewer and Orion-CC for the purpose. In [5], the same author continues the development this technology by comparing the possibilities of two different smartphones for monitoring a series of static and dynamic displacements. The experiments were conducted to verify the stability of the newly developed D-Viewer mobile application. The smartphones used in this study had a short monitoring range and low acquisition frame rate. The future will see the improvement of these parameters with better data processing and camera units in the smartphones. In a 'follow-up publication' [6], the same authors used the D-Viewer mobile application again to measure bridge displacements.

A more recent work [7], sees, for the first time, a smartphone camera used for recording images of a speckle pattern on the surface of engineering objects while undergoing deformation. These speckle images are transmitted to a computer that implements the Digital Image Correlation algorithm (DIC) to determine the deformation fields. Other authors are exploring the possibility of using a smartphone camera, DIC equipment, D-Viewer mobile application and the smartphone processor to evaluate in-plane and out-of-plane displacements of bridges by tracking the movement of two circle-shaped markers on the observed surface [8].

In [9], the deformations of compressive concrete blocks are visualized, measured and tracked, also using a smartphone and DIC technique. The changes in displacements fields of monitored surfaces at different loads are analyzed. In the last three cited works [7-9], the smartphone works in combination with the DIC method, but for the realization of this algorithm, not only the potential of this device is used.

Analyzing the cited publications it can be concluded that the creation of smartphone applications to introduce and validate these devices as measuring tools is a current task. The aim of this work is to develop a smartphone application, by which the displacement/deformation fields of a monitored surface can be visualized and measured using the DIC algorithm implemented in real time from the smartphone processor.

2. Working principles of App
The main idea is to create an application which implements the DIC method to obtain displacement/deformation fields using of a smartphone as standalone unit. DIC is an optical method [10, 11], which tracks the displacements and deformations of the so-called speckle structures on the object surface. It is based on comparison of consecutive images pairs. The first (reference) image is taken before deformation, and the second - after deformation of the observed surface. In some publications, this surface is called a "zone of interest" (ZOI). The reference image is divided into equal-sized "correlation subsets" - most often square matrices of pixels. By numerically solving a correlation problem to find the maximum match of the pixel intensity of each subset belonging to first image with one of the subsets belonging to second image, we find the location where the considered subset has moved within the time interval, between the capture of that first image and the second image capture.

The operation algorithm of the application is as follows: 1. The original colour image is captured and is converted into a greyscale image on the smartphone; 2. Quick assessment of the image quality is carried out, taking into account the contrast and distribution of pixels intensity in ZOI; 3. A switch to measurement mode and save next frame as a reference; 4. Filtering and binarization of the frames pair is applied; 5. Performing correlation calculations to obtain the displacements of the centres of the...
matched subsets for which speckle pattern quality exceeds a predetermined threshold value (see step 2); 6. The application analyzes the images frame by frame to calculate in-plane displacements of the subsets centres. Then, by numerical differentiation, the field of deformations is determined.

3. App description
This application is designed for Android 8.0 and higher operating systems versions. The graphical interface is implemented using Java programming language. Functions for processing information from the camera and performing correlation analysis are written in C++ using parallel computing multiprocessor architecture of modern smartphones and OpenCV library. The authors intend to develop this application as "Open Source" to facilitate its use, development and improvement by other researchers that are working in this field.

The application aims to provide the user with an easy and accessible tool for gathering quantitative information on displacements and deformations of the inspected objects. It allows the user, equipped only with a modern smartphone to acquire data applying DIC measurement technology, by setting all the necessary parameters for optimal running the algorithm in each particular case and to visualize the results.

The user must perform the following procedures:
1. Open the start screen (figure 1).
2. Allow autofocus and capture images.
3. Selection of the correlation parameters (figure 2).
4. Selection of other parameters for analysis (figure 2).
5. Selection of measurement mode (displacement or deformation).
6. Start the measurement.
7. Acquisition and visualization of data.
8. Stop the measurement.
9. Extract output data files from the smartphone, if necessary.

After opening the initial screen (figure 1(a)), a rectangle in the middle of the frame is initially displayed, which gives an idea of the size of a correlation subset. The focus is adjusted automatically when the distance between the smartphone camera and the monitored object varies. Colour of this marker is used to indicate that the central frame area is in focus. Green denotes a focused frame and Red indicates an unfocused frame. Visualizing the marker with thick red lines shows the operator that the current distance from camera to the monitored surface is less than the minimum focal distance of the smartphone being used. The interface with its buttons occupies a large part of the screen and therefore a full screen mode is provided (figure 1(b)). This feature can be activated by shaking the smartphone.

![Figure 1. Screenshot of initial screen (a) and full screen modes (b).](image)

From the start screen, the user can go to settings screen, through which he can set and adjust the values of parameters. Due to the necessity of large number parameters during the measurement and monitoring process, a set of 4 buttons for setup pre-selected values are also provided on the respective display screen (figure 2). They define a set of suitable parameters for operation in measurement mode.
with low or high resolution camera, respectively, and with a size of the correlation subsets of 32 or 64 pixels.

![Parameters settings](image)

**Figure 2.** Screenshots of set up data window.

Capturing of the first (reference) image in the series of consecutive images is initiated by pressing the Scan button (figure 1(a)) or by tapping (clicking) on the screen in "full screen" mode. In this action, touching the smartphone, the operator can hardly avoid "shaking" the whole device including the built-in camera. Therefore, the software provides a delay for the moment of shooting the initial frame, consistent with the time required for relaxation of such an event. As an alternative measure to avoid this inconvenience, a RemoteShutter application has been developed, which is launched on a second smartphone. These two devices are connected via Bluetooth. Through the second smartphone, placed at a distance from the main smartphone, an operator can visually monitor the development of the process. The visual information received on this channel has a reduced quality, but it can be used to guide when to start or stop the measurement.

4. Preliminary test

To illustrate the workings of the DIC application for a smartphone, we conducted a modelling laboratory experiment by simulation of a mosaic plate displacement. The obtained real-time displacement field is presented in figure 3 (superposition of translation and rotation). The mosaic pattern is a type of ‘speckle pattern’ suitable for the implementation of the DIC algorithm. In cases when the studied surface does not have a good quality speckle like the mosaic pattern, different ways have been developed for computer generation of such patterns and their application on the surface to be monitored [10,11].

The result of a physical experiment simulating deformation field of a computer-generated speckle pattern is shown in figure 4.

The experiment was performed with a Samsung Galaxy S10e smartphone. This device has two cameras with a resolution of 12 MP and 16MP and a focal length of their lenses of 26 mm and 12 mm, respectively.
Figure 3. Example results of the translation and rotation measurements.

Figure 4. Example results presenting a deformation map.

5. Conclusions and future works
In this paper, we present a mobile application for real-time measurement and monitoring of displacement/deformation fields based on Digital Image Correlation algorithm. It is shown that technology, based on the smartphone built-in camera and the proposed smartphone application, allows 2D measurements to be realized quickly and with satisfactory accuracy. This equipment is relatively easily accessible, works remotely, and is non-contact, non-destructive and usable in both the laboratory and out of door conditions. The preliminary experiments suggest that a smartphone supplied with this software application can be utilized as a measuring tool in SHM.

In the future, this line of study will be focused on systematic and more detailed research of the effectiveness and the accuracy of measurements that could achieved with the proposed technology. We anticipate that in the near future this relatively inexpensive equipment will be applied for express and/or long time monitoring of real world engineering structures.

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