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Mobile version of Digital Image Correlation for deformation measurements of engineering objects

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Abstract

Digital Image Correlation (DIC) is a widely used image based technique for measurements of displacements, strains and shape of different kind of objects. The method was at first used in the field of experimental mechanics, but features of the method, such as full-field, non-contact measurement, 3D data or scalable accuracy, attract the attention of industry. However, the scale of industrial installations as well as requirements connected with DIC setup and object preparation hinder adaptation of DIC to industrial practice.

In the paper we present DIC technique designed for mobile devices, that enables DIC measurements with cameras that are built-in the smartphones, tablets or smart cameras. The application provides instant access to deformation and shape measurement results for non-qualified staff in industries. In order to attune functionality to industrial requirements, the mobile version of DIC integrates procedures for merging of DIC data distributed in time and a single-camera 3D shape measurement technique. The simplified measurement process as well as initial accuracy assessment are discussed in the paper.

Introduction

Digital Image Correlation [1] is well-established method for laboratory and also out-of-laboratory full-field measurements of displacements, strains and shape of different kind of objects. Current off-the-shelf DIC systems typically include a control computer, one or two digital cameras, a tripod and a dedicated software for data analysis. Setting up the measurements and analyzing data is straightforward but still requires some experience and knowledge about optics in order to obtain good quality results. Diligence and precision are especially required in the case of setting up the out-of-laboratory DIC measurements. In particular in an industrial environment vibrations, dusts, high temperature or limited access can additionally impede measurements. Although successful applications of DIC in industry have been reported in literature [2, 3], the method fails to be used as a standard method in industrial practice. On the other hand, growing safety, increased production and diagnostics requirements that are put on industries, trigger the need to look for new tools for inspection and monitoring of installations. In some cases, especially for the installations prone to frequent malfunctions or burdened to a long history of failures, additional qualitative data even with decreased accuracy (in relation to the standard, certified measurements method) would be desired and used.

Another field of application of the DIC technique, in which simplicity of measurements is one of the most important factors is a conservation of art. Works of art (in particular canvas paintings) are sensitive to changing environment conditions [4], due to their complex, multilayer structure or due to inappropriate treatments. Influence of the environment can be studied with the use of optical methods of measurements [5, 6, 7] but due to hardware requirements and the need of expert knowledge, tests are often limited to laboratory conditions. Simplifying the DIC would create an opportunity for museums to testing their collections periodically without the need of using external services.

Both mentioned fields of applications often require long-term monitoring (displacements or strains can occur after months or even years of operation or storage). In the case of DIC it can be carried out with the use of the automatic DIC data merging procedure [8, 9]. In both versions of the procedure (2D and 3D), a transformation between consecutive data sets (images acquired from different view points) is determined based on coordinates of markers printed on a merging artifact. In 2D version of the method geometry of the merging artifact (real world coordinates of the markers) has to be known, while in 3D version of the method it is not required.

Nowadays whole hardware that is required for DIC measurements is typically integrated in consumer electronics devices. People are accustomed to use mobile devices and mobile applications also for work. Mobile version of DIC technique would solve mentioned issues and would provide powerful deformation and shape measurement technique for personnel that is not experienced in using optical methods. It can be also used for private purposes of individual persons. Depending on the field of application, appropriate device could be selected for DIC measurements (i.e. high-resolution, interchangeable-lens digital camera with operating system can be used for accurate measurements in industry, while a simple smartphone or tablet can be used for qualitative analysis of displacement maps).

In many cases 3D version of DIC (in which a stereo setup of cameras is required) has to be used. In typical smart devices there is only one camera (sometimes the second camera is mounted on the front side of a device, but this is not useful for 3D measurements) what necessitated hybrid DIC-SfM technique development. The Structure from Motion (SfM) is an optical method for shape reconstruction of 3D objects [10]. On the basis of a set of 2D images acquired from different view point, 3D point clouds representing an observed scene are reconstructed. The method is straightforward and hardly requires any equipment (besides of a digital camera) and thus can be used in laboratory as well as in out-of-laboratory conditions. Shape reconstruction is based on determination of correct correspondences of previously found features between the acquired images. Corresponding features are inputs for bundle adjustment procedure [11], which is a non-linear optimization method that simultaneously refines camera parameters and scene structure. Strong dependence on the scene pa-

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rameters [12] limits the method to be used only for qualitative scene reconstruction (not for measurements). The reconstruction accuracy with SfM can be significantly improved if the correspondences between features will be determined with better precision [13]. This can be achieved by covering an observed object with a speckle pattern and use standard DIC procedures to determine accurate correspondence maps. Improving the accuracy may in consequence lead to engineering applications of the SfM. There are SfM pipelines, which allows scene reconstruction with mobile devices and with good accuracy (i.e. by using inertia sensor of a mobile device [14]).

Point clouds reconstructed with SfM are represented in local coordinate system and thus it is not possible to calculate displacements or strains that occur between consecutive measurements. A hybrid DIC-SfM method can be used to provide this functionality.

The paper is organized as follows: in the first Section architecture of the developed mobile version of DIC is presented; in the Second Section implemented measurement modes are discussed; in the third Section preliminary tests of mobile version of DIC are presented; conclusions and directions of future works are given in the fourth Section.

Mobile DIC System description

The developed mobile version of DIC is based on a client-server architecture. The idea is to keep functionalities for data acquisition, visualization of results and user interface at the mobile device and transfer activities that require computation power to the server. A scheme of the system's architecture is presented in Figure 1. Transferring computation part to the server ensures satisfactory accuracy of the results, while keeping reasonable computation times. Scripts that are run on the server are based on C++ library libCCI, that is being developed at the Institute of Micromechanics and Photonics since 2012.

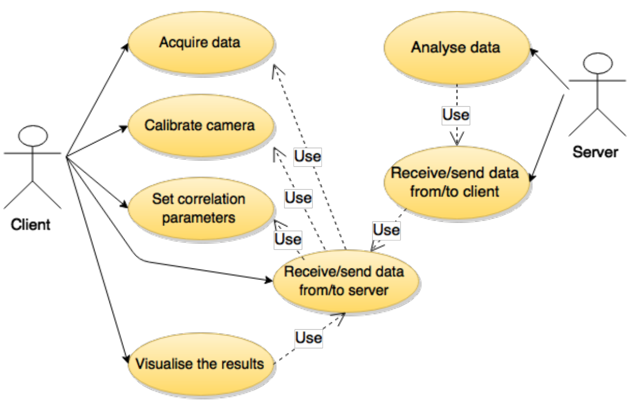

Figure 1. Scheme of the architecture of the mobile version of DIC.

Server application

The server application has been implemented with the use of FLASK platform, which is a Web Application Framework, that supports transfer of big files (e.g. digital images of speckle pattern in the case of DIC) and which is continuously being developed. FLASK is designed for Python programming language thus scripts run on the server are implemented in Python. As it was mentioned, all DIC computations are implemented in C++ (for efficiency) and linked as DLL library. The interface between the server and the client is generated within the Python script from HTML templates and can be displayed in an internet browser as a form, that allows any number of images and appropriate parameters for DIC analysis (i.e. subset size, step, AOI, start point) to be attached. The interface reads all the parameters entered in the form and creates a configuration file in JSON format on the local drive. Next, a path to the configuration file is passed as a parameter to a function from linked DLL library. The function loads the parameters and depending on the selected measurement mode runs appropriate libCCI functions for processing and analysis. The results are being stored on a local drive and are available for the client via web interface.

Client application

The client application has been implemented in Java programming language and is designed for Android operating system. The application uses external libraries such as OpenCV, AAHC and GraphView. The client application allows user to acquire image data for correlation analysis, to set all required correlation parameters, to visualize obtained results (as displacement maps, 2D plots or tables) and to communicate with the server. Example screenshots of the client application are presented in Figure 2.

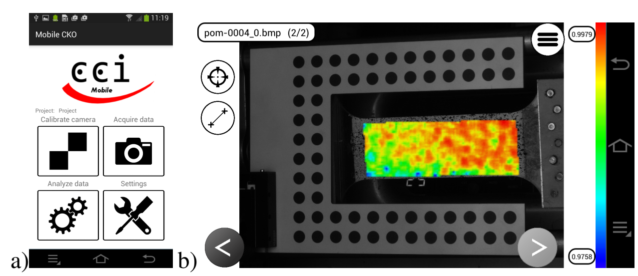

Figure 2. Example screenshots from a mobile application: a) main activity (menu), b) analysis activity (cross correlation coefficient map).

A typical application use-case is as follows:

1. select measurement mode,
2. acquire images,
3. select correlation parameters,
4. select other parameters for analysis,
5. send a query and data to the server and await for the results,
6. receive output files and visualize results.

Measurement modes

The concept of the system includes four measurement modes: typical 2D DIC (Mode I, in-plane displacements), 2D DIC with automatic data merging procedure [8] (Mode II, in-plane displacements distributed in time), 3D shape (Mode III, shape of the object) and 3D DIC (Mode IV, in-plane displacements, out-of-plane displacements and shape of the object). Modes I and II can be easily adapted from the standard, desktop DIC setup. In Mode II typical DIC calculations are aided with the automatic DIC data merging procedures [8]. There are two options to implement Modes III and IV: utilize a smart device with two cameras (in a stereo setup) or develop a method which allows shape measurements with a single camera. At the moment there are no devices equipped with a stereo camera setup working under Android

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operating system. This is the reason why the Authors' work focused on development of the hybrid DIC-SfM technique for Mode III. Mode IV uses the same technique additionally aided with 3D version of the automatic DIC data merging procedures [9].

2D DIC measurements with automatic data merging procedure

In order to ensure mobility of the developed system, 2D DIC measurement mode has been enhanced with the automatic 2D DIC data merging procedure. In this mode it is possible to analyze displacements based on images that had been acquired from different view points. It also allows to monitor displacements of the object in a long period of time, provided that an artifact for data merging procedure had been fixed to the object and remained fixed during the time between the measurements. A flowchart of this mode of measurements is presented in Figure 3.

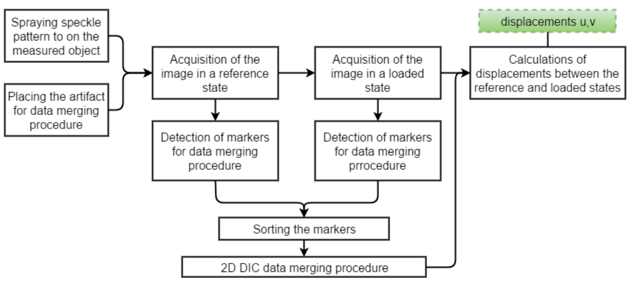

Figure 3. Flowchart of the 2D DIC with data merging mode of the measurements.

Because of the advisable user input, detection of markers for data merging procedure is held in the client application (not on the server). Data send from the client application to the server includes: a reference image with an unloaded object, series of images of a loaded object, locations of AOIs, correlation parameters, geometry of a data merging artifact, a list of positions of artifacts markers detected in all images, geometrical calibration of a camera for each image.

3D shape and displacement measurements - hybrid DIC-SfM method

A flowchart of hybrid DIC-SfM shape measurements is presented in Figure 4.

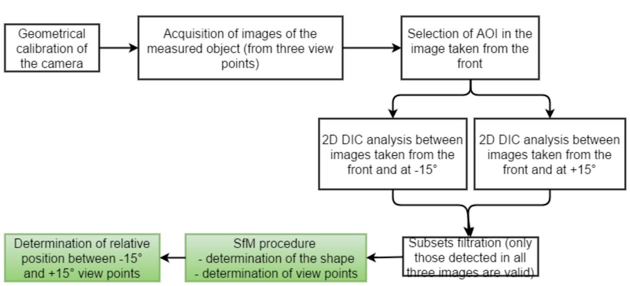

Figure 4. Flowchart of hybrid DIC-SfM shape measurements with a single camera.

In the typical SfM method, shape of a measured object is reconstructed on the basis of analysis of a series of views (images) of the object. The corresponding object features detected in the images are used as an input data for bundle adjustment procedure. The introduced modification of the basic concept is to take an advantage from the presence of a random speckle pattern on a measured object. Object features are being looked for only within the AOI (in which speckle pattern is present) and feature correspondence is calculated based on standard 2D DIC analysis. The problem of this approach is, that in DIC analysis subsets deformations are described with the affine transform [15]. According to [1], the affine approximation can be used only if the relative angle between viewing positions is relatively small. Cross correlation coefficient decreases with the increase of the angle. It can be assumed that affine approximation can be used if the angle between viewing positions is smaller than 20°. Above this range it is advisable to use homography to describe subset deformations. However, in the case of 3D DIC measurements, approximately 30° stereo-angle is advisable to ensure good depth sensitivity [15]. Due to this trade-off, in the proposed method, object's shape is being reconstructed with the use of exactly three images: the first image is taken from the front and two other images are taken at approximately -15° and $+15^\circ$. The first image is selected as the reference image for 2D DIC procedure and images taken at -15° and $+15^\circ$ are used as the deformed images. Taking the first image as the reference ensures the correct correspondence of subsets between all three images. Obtained correspondence map is subsequently passed as the input data for bundle adjustment procedure, what yields 3D point cloud representing the measured object and 3D viewing positions of the camera.

In order to measure displacements and strains with the use of a single camera, the described method for shape measurements has to be aided with the 3D DIC data merging procedure [9] (the flowchart is presented in Figure 5).

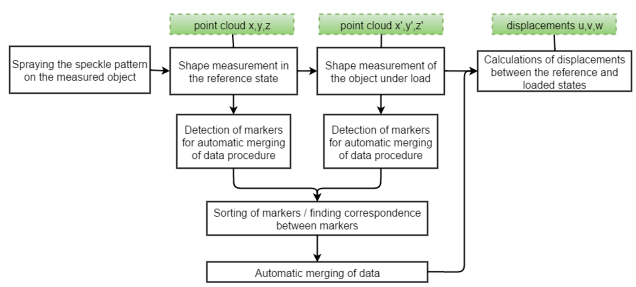

Figure 5. Flowchart of the 3D displacements measurements with the use of a single camera.

Obtained 3D point clouds representing a measured object in different load states are transformed to a common coordinate system and then projected on the camera's viewing positions from the reference load state. The generated images are subjected to the standard 3D DIC analysis in the final step of the procedure. Transformation is being determined by detecting markers that are deliberately placed next to the measured object and remain at the same position during the measurements (in 3D DIC data merging procedure real world coordinates of the markers do not have to be known).

Preliminary tests results

Preliminary tests have been carried out in order to assess accuracy of displacement measurement with the use of consumers electronic, to validate developed DIC-SfM measurement method

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and to test both parts of the mobile DIC system (client application and server scripts).

Accuracy assessment

In order to check accuracy of displacement measurements obtained with consumer electronic devices, laboratory measurements have been carried out. Experimental setup is presented in Figure 6a.

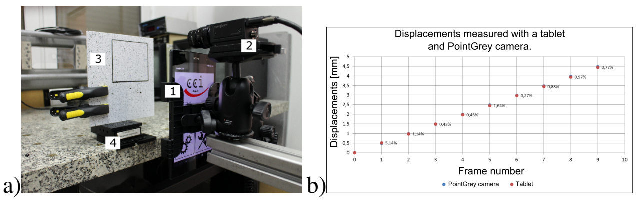

Figure 6. *a) Laboratory setup used for assessment of the accuracy of displacement measurements with consumer devices: 1 - tablet, 2- camera, 3- specimen, 4- linear stages. b) Example results.*

The setup consisted of a mobile device (tablet) equipped with 8Mpx camera and 5Mpx PointGrey camera equipped with 16mm focal length lenses. The camera has been placed above the tablet and has been used as a reference device. An object under investigation was a flat specimen mounted on a set of linear stages. The object has been moved on and images of the object have been captured with both devices simultaneously. In order to improve quality of images captured with the tablet, it had been calibrated prior the measurements and all images had been undistored. Example results of comparisons are presented in Figure 6b.

As one can observe, the results obtained with both devices are similar and discrepancies are less than 1%. Small discrepancies could have occurred due to parallax error or inaccurate selection of an object point used for comparisons.

DIC-SfM method tests

The aim of the experiment was to test the developed methodology of the shape measurements with the use of a single camera built in a mobile device (data processing script for displacements and strains measurements, which includes 3D DIC data merging procedure is currently under development). A laboratory setup is presented in Figure 7.

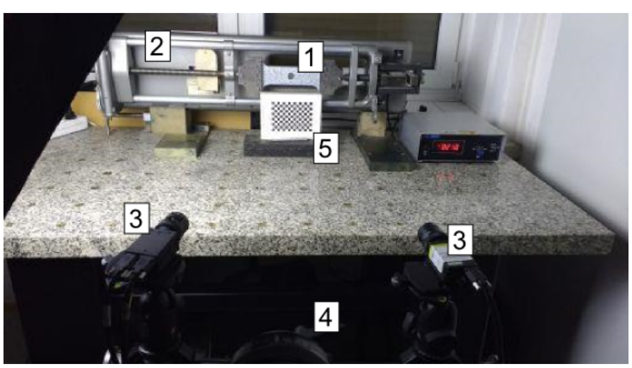

Figure 7. *Laboratory setup used for testing mobile version of DIC: 1 specimen, 2 testing machine, 3 stationary 3D DIC setup used a a reference, 4 digital with Android operating system, 5 chessboard used for data data merging procedure.*

A measured specimen was a plexiglass sample with a hole in the middle. The sample has been stretched in a testing machine. The camera has been set on a tripod (to ensure stability during image acquisition) and consequently moved to the preferred viewing positions (from the front and at -15° and $+15^\circ$ angles). Example series of images acquired in one of the load states is presented in Figure 8. Chessboard calibration target placed in the front of the testing machine will be used in the last step of the data processing path, which is 3D DIC data merging procedure.

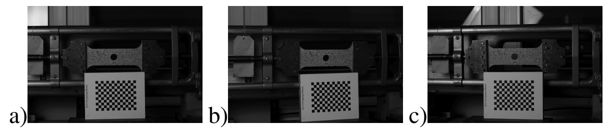

Figure 8. *Example series of images used to reconstruct shape of a measured object: a) image captured from the front, b) image captured at -15°, c) image captured at $+15^\circ$.*

Calculations have been carried out with the custom made libCCI library (DIC part of the method) and OpenMVG library (SfM part of the method). Example shape measurement results are presented in Figure 9.

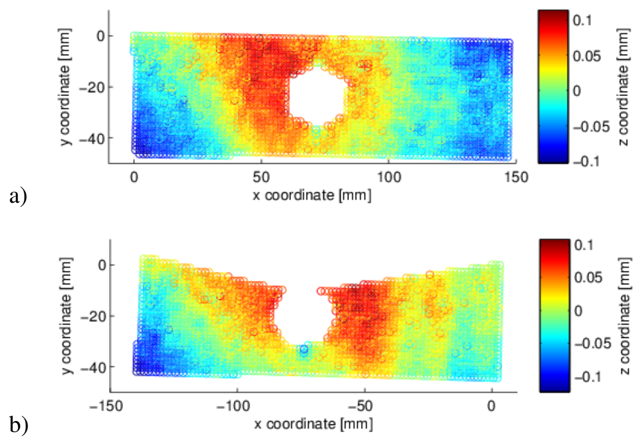

Figure 9. *Example shape measurement results: a) lower load state, b) higher load states.*

SfM method outputs shape up to a scale. In the presented case, the scale factor has been determined by analysis of a chessboard calibration board placed in the front of the specimen. In order to facilitate analysis of the results, obtained point clouds have been transformed to the best fitted plane. Deviations from flatness (z coordinate) are coded in color.

The quality of the shape reconstruction can be expressed as a Root Mean Square Error of differences between observed 2D coordinates of subsets and their projections from the reconstructed 3D point cloud. OpenMVG package allows to select parameters of the model (3D coordinates of points, view points coordinates, cameras' intrinsics) that are refined in the optimization procedure. In order to increase the accuracy, the camera has been calibrated prior the measurements and intrinsic parameters have been fixed in the bundle adjustment procedure (typically bundle adjustment refines camera's intrinsics and scene structure at the same time). Also the better model (lower RMSE) has been obtained by run-

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ning the optimization procedure several times and providing output model from a given iteration as input parameter for the next iteration.

The maps presented in Figure 9 have been reconstructed with RMSE 0.019 and 0.021. The accuracy is sufficient to use the data for the data merging procedure and to calculate displacements that occur between the two load states. Comparing to the typical SfM measurements, in the presented method, the correspondences between features detected in different views are determined much more accurately due to presence of a speckle pattern and utilization of the digital image correlation algorithm. Inaccurate correspondences have been filtered-out before the model reconstruction by the cross correlation coefficient treshold ($cc = 0.9$ in this case). The effect of this filtration can be observed in Figure 9b in the upper part of the sample.

The quality of reconstruction strongly depends on the quality of acquired images. Acquiring images with a fixed optical parameters (focal length and aperture) imposes requirement to keep the same distance to an object. This requirement is sometimes difficult to satisfy. Also bundle adjustment procedure should be aided with a user input in order to avoid finding local minima. An example of bad reconstruction (due to low cc values in correspondence determination step and falling into a local minimum by bundle adjustment procedure) is presented in Figure 10.

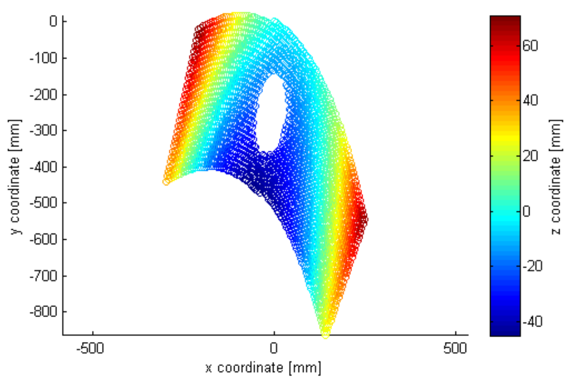

Figure 10. *Example of incorrectly reconstructed shape map.*

Mobile application functionality tests

Series of laboratory and out-of-laboratory measurements have been carried out in order to test mobile (client) application functionality. The tests have been carried out in:

- hydroelectric power plant in Roznow,
- power plant in Jaworzno.

The main aim of the experiments was to test feasibility of the system in hard industrial environment. Mobile DIC client application was installed on Samsung Galaxy NX camera with Android operating system. Resolution of the camera $20Mpx$ and $18-55mm$ focal length lens ensured measurement accuracy (less than $0.1mm$ in this case). The local server was installed on a laptop computer. The analysis have been carried out with 2D version of the mobile DIC system (modes I and II). The main outcome from the experiments concerns modification of the image acquisition module of the mobile device, support the use of a flash light and improve inertia sensor readings. Example displacements maps obtained during the measurements in Roznow are presented in Figure 11.

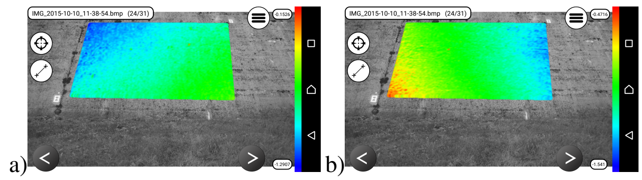

Figure 11. *Example results of 2D DIC measurements with the use of mobile version of DIC: a) U displacement map, b) V displacement map.*

Conclusions and future works

In the paper we presented mobile version of Digital Image Correlation method. The system based on client-server architecture enables 2D displacement measurements (also in a long-term monitoring mode), shape measurements and will allow 3D displacement measurements. 2D modes of the system have been adapted from the stationary, desktop DIC application, while 3D modes (shape measurements and 3D displacement measurements) are based on a hybrid technique, which combines SfM and DIC. The developed SfM-DIC technique enabled accurate shape measurements with the use of a single camera. Combining the method with automatic DIC data merging procedure will also enable full-field, 3D displacement measurements with the use of a single camera.

The mobile version of DIC can be used in laboratory as well as in out-of-laboratory conditions. The ability to monitor displacements over a long period of time, low hardware requirements and simple user interface may allow to use DIC for qualitative measurements in industrial practice. However, further development of the system and tests of the accuracy have to be carried out.

Preliminary experiments shows that DIC measurements are possible with the use of consumers electronic devices. It has been shown that typical camera calibration procedure suffices to obtain results with an acceptable accuracy. For tasks which do not require good accuracy, devices equipped with lower quality optics can be used, while high resolution digital cameras with Android system and equipped with interchangeable-lens can be used for measurements of engineering structures.

The main task for the future works is to assess the accuracy of the developed 3D displacement measurement method with the use of a single camera. It is also planned to simplify the automatic 3D DIC data merging procedure by using arbitrary detected markers to calculate transformation between consecutive point clouds (instead of using special calibration targets).

In-situ tests of the 3D mode of the system will be carried out in measurements of the graded metal plates hall's arch [16]. It is planned to monitor a full-scale object (span up to $18m$) for a few weeks in a few AOIs.

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