Crosscorrelation image processing for surface shape reconstruction using fiducial markers

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Abstract. Optical methods for deformations diagnostic and surface shape measurement are widely used in scientific research and industry. Most of these methods are based on triangulating a set of two-dimensional points in the images appropriate to the same three-dimensional points of the object in space. Various algorithms to search such points are applied. The possibility of using cross-correlation processing of digital images to search these points is considered in the work. Algorithms based on the correlation function calculation are widely employed in such a popular flow diagnostic method as PIV. The cameras of a stereo system for surface shape measurement can be widely spaced, and the tilt angles relative to the surface can differ significantly. This leads to the fact that the images taken from the cameras cannot be directly processed by the correlation function because it is not invariant to rotation. To solve this problem, fiducial markers are used to find an initial estimate of displacement of the images relative to each other. This approach makes it possible to successfully apply correlation processing for stereo system images with a large stereo base.

1. Introduction

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The task of surface deformation diagnostics often occurs in the automotive industry, building, and aviation. Such diagnostic is usually performed using close-range photogrammetry, a measurement technique that is used to determine the geometry, shift, and deformation of construction using images. Two-dimensional (2D) photogrammetry uses one fixed camera and is limited to measurement deformations and shifts in a plane. If the test object is curved, three-dimensional (3D) deformations occur, and 2D photogrammetry cannot provide acceptable results. In such cases, two video cameras (stereo system) are used to obtain a pair of images.

Photogrammetry has over the past three decades developed significantly and have been applied in deformations measurements of airplanes wings [1–3], rotating propellers of airplanes [4] and helicopter [5], surfaces deformations of metal constructions [6–7]. In the conditions of the field experiment, the cameras of a stereo system for surface shape measurement can be widely spaced, and the tilt angles relative to the surface can differ significantly. This leads to the fact that the images formed by the cameras differ considerably and cannot be directly processed by the crosscorrelation algorithms. One of the solutions to this problem is to search for corresponding points in two stages. The first stage is an initial estimation of displacement of the images relative to each other. It is performed by searching for fiducial markers [8] on the images and determining an image perspective transform from the second
camera to match the image from the first camera. The second stage is the classical crosscorrelation processing, which determines the shifts of image areas from different cameras relative to each other. The total shift of the areas in two stages allows determining the coordinates of the corresponding points for subsequent triangulation.

2. Surface shape measurement algorithm
The surface shape measurement algorithm scheme is shown in figure 1. The algorithm consists of two parts. The first part is the calibration of the digital camera stereo system. Its purpose is to determine the internal (focal length and distortions introduced by the optical system) and external (position of one camera of the stereo system relative to the second) parameters. To carry out the calibration, a series of images of the calibration target in different positions (different distances to the camera and angles of inclination to it) is recorded. Typically, the target is a chessboard (or checkerboard) pattern applied on a flat surface (figure 2). All intersections of squares are found using standard image processing algorithms. These intersections will be points with known 3D (from target known geometry) and 2D coordinates (from determining intersections on images). The area of the calibration target should cover as much as possible the field of view of the camera in total on all images that are involved in the calibration.

The second part of the algorithm is determining the shifts of the background pattern points and triangulating the found corresponding points. Since the crosscorrelation function is not invariant to rotation, it is necessary to perform preliminary alignment of images. For this purpose fiducial markers are used. In this work, the ArUco markers were chosen. They represent a black square with pronounced borders, inside which there is a black and white pattern that identifies its number. Markers are detected on images and are matched using identification numbers. Next, four markers from detected are selected...
so that the area of the quadrangle composed of them is maximum. The perspective transformation is calculated from the coordinates of these markers. And the image from one camera is transformed with its help to align with the image from another camera.

![Figure 2. Example of a pair of stereo images of a calibration target.](image)

Aligned images undergo standard crosscorrelation processing. The images are divided into small areas (interrogation windows), for which the normalized correlation function is calculated. The coordinates of the function maximum are found with subpixel precision. They allow us to estimate the displacement of the areas relative to each other.

Before measuring, it is necessary to prepare the surface of the investigated object. For this, a structure with randomly distributed dots (high-contrast speckle pattern) - background pattern is applied to it. Each area in processing has a unique structure because of a randomly created speckle pattern. It allows to robustly calculate the displacements of these areas on images from different cameras. For the initial alignment, ArUco markers were additionally placed on the surface so that they were located in its corners.

3. Measurements results
The processing algorithm presented above is implemented in the DeformVision software in the programming language C#. Calculation of the correlation function, search for markers, and other operations with images are carried out using libraries Math.Net Numerics [9] and OpenCV [10] (OpenCVSharp [11]).

For experimental research, a test installation described in [12–13] was used. It allows to set a random three-dimensional surface and measure its profile using a laser distance sensor with an accuracy of 75 µm. A stereo system with two Basler piA2400-17gm cameras and the lenses Fujinon HF25HA-1B were used. Cameras have a resolution of 2456×2058 pixels, and a pixel size of 3.45×3.45 µm. The lenses have a focal length of 25 mm and an aperture ratio of 1:1.4.

Figure 3(a)-(b) shows examples of experimental images. Background pattern with randomly distributed black dots applied to the test surface. ArUco markers have also been added to the surface. Figures 3(c)-(d) show examples of the results of image processing using the developed algorithm. Figure 4 shows an example of the reconstruction of a three-dimensional surface.

The figures show that despite the large difference between the original images, crosscorrelation processing gave satisfactory results. Direct application of such processing to the raw images would not allow us to determine the necessary offsets of the background pattern points. The size of the interrogation window during processing was 64-96 pixels. Therefore, the corresponding points of the background pattern would be indifferent interrogation windows.

The use of ArUco markers for the first stage of processing made it possible to align the images by the detected marks. Alignment was accurate enough for crosscorrelation processing determines correct shifts of areas in the images.
Figure 3. Example of experimental results: (a), (b) – experimental images of measured surface, (c) – founded markers on images with rectangle for perspective transform, (d) – vector field of shift calculated with crosscorrelation processing.
4. Conclusions
The paper presents a description of an algorithm for crosscorrelation image processing for reconstructing the surface shape using fiducial markers ArUco. It is shown that the detection of markers and the calculation of the perspective transformation made it possible to optimize and improve the correlation calculation due to the initial estimation of displacement of the images relative to each other. The developed image processing algorithm can be successfully applied for deformable surface shape reconstruction for stereo system images with a large stereo base.

A further direction in improving the developed algorithm will be the implementation of an iterative crosscorrelation algorithm with a decrease in the size of the interrogation windows at each iteration. This approach will increase the dynamic range of measured displacements and improve accuracy. It is also planned to implement the division of the measured surface into several rectangles according to the detected ArUco markers to increase the accuracy of the calculated perspective transformation. This approach will reduce the size of the interrogation windows used during processing and thus increase the measurement accuracy.

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