Development of a Photogrammetric System for Measuring Spatial Coordinates of Control Points of Large-size Structures

B. Suhovilov, E. Sartasov, E. Gornykh, and S. Aliukov

***Abstract*— We developed a photogrammetric system (PS) for measuring spatial coordinates of control points of large-size structures. To use the system we place retro reflective circular targets onto the assigned control points of the structure under measure. The centers of targets have to coincide with the assigned points of the coordinates under measure. To identify circular targets we apply fiducial markers, which are placed onto an object or near it. A fiducial marker can be identified by the unique pattern created by its constituents. A special kind of scale rule is applied to automatically calculate the real sizes of objects. The structure under measure, equipped with the circular targets, fiducial markers and scale rule, is photographed with a digital camera (DC), which is set to operate as a part of the PS. Spatial coordinates of assigned points are determined during computer post processing of photos. Basing on the obtained spatial coordinates of the control points, we can design a three-dimensional geometrical model of the structure, and calculate such characteristics, as its overall dimensions, volume, deviation of the real sizes from the design ones, etc. This system can be applied in mechanical engineering, computer-aided inspection of building structures, and in other fields of science and technology.**

***Index Terms*— Circular retro reflective target, digital camera, fiducial marker, photogrammetric system, scale rule**

I. Introduction

THE paper deals with the task of measuring coordinates of assigned points of space structures. There are several techniques of such measuring by contact and noncontact methods with the help of a coordinate measuring machine (CMM), laser trackers, tachometers, 3D-scanners and photogrammetric measurement systems [1]. Each technique has its advantages and disadvantages.

When a CMM, laser trackers and tachometers are used, measurement effort is directly proportional to the quantity of controlled points and is quite big for large-size surfaces. When the CMM, laser trackers, tachometers and stationary 3D-scanners are readjusted, the basic controller requires a shift. It is difficult to make measurements with these devices in hard-to-reach spots. Mobile 3D-scanners are devoid of these drawbacks, as they can operate “from hand”. However, these devices have limits on sizes of objects under measure. Measurements devoid of the above noted limits can be made by means of a PS.

Manuscript received January 23, 2017; revised March 04, 2017.

The work was supported by Act 211 Government of the Russian Federation, contract № 02.A03.21.

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II. PS Operation Principles

When using a PS, retro reflective circular targets are placed onto the structure under measure. The target centers have to coincide with the assigned controlled points. The structure, marked with circular targets, is photographed with a digital camera. The quantity and geometry of the DC planned positions (during shooting) is theoretically evaluated and tested by experience, basing on the measurement error analysis and the possibility of observing retro reflective targets which have a limited angle of retro reflection. Application of flash and short exposure allows us not to take into account the DC vibrations and take photographs «from hand», without a tripod, which is very convenient under shop conditions. When flash is used, retro reflective targets are distinctly seen against the object background, which makes the system independent from the external light. Fiducial markers and a scale rule are used to determine the position of the DC in space and to calculate the scale of the object under measure [2].

Different profit and nonprofit research groups engage in developing PS. The most famous commercial project is the system V-Stars of the company Geodetic System (USA) [3]. The noncommercial project of the group ArUco, Aplicaciones de la Visión Artificial (University of Cordoba, Spain) is actively developing [4–6].

One of the main elements of a PS are fiducial markers. As long as the photogrammetric system V-Stars is a closed one, the coding of fiducial markers (Figure 1) is kept secret. Creating a photogrammetric system on the basis of V-Stars fiducial markers seems to be impossible.

The project ArUco is an open one, the source code of generation and detection of fiducial markers is accessible [7], the software has the BSD license, which allows it to be used when generating and detecting fiducial markers. An ArUco fiducial marker is given in Figure 2.

As the points to be measured (basic points) we took the points of coincidence of the main square, which contains the identification part of the FM, with the external squares, which constitute the test section of the FM. The main reason of measurement errors of the basic points' pixel coordinates are blurry borders in the photo and inaccurate positioning of the external square with regard to the main square. The blurry borders at the basic point are shown in Figure 3.

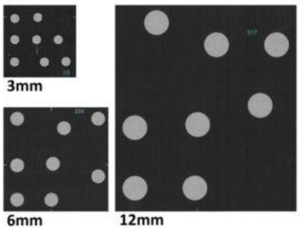

Fig. 1. V-Stars markers

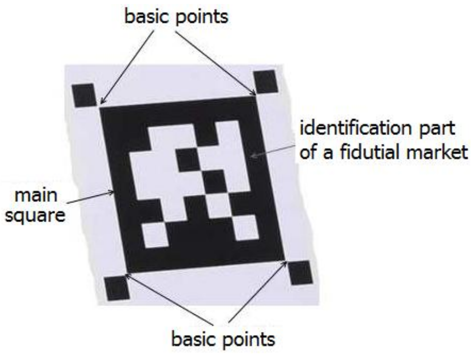

Fig. 2. ArUco fiducial marker

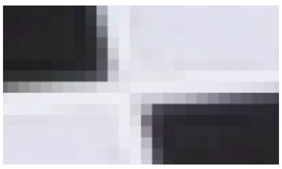

Fig. 3. Blurry borders at the basic point of a FM ArUco

Experimental studies showed an unacceptable for the PS under development miscalculation of pixel coordinates of ArUco FM reference points. Therefore we proposed new architecture of a fiducial marker, which is based on circular instead of square elements. An example of such fiducial marker is shown in Figure 4. Since the central projection of a circle represents an ellipse, we will call the circles, situated in the main square, internal ellipses and the circles of the FM test part – external ellipses.

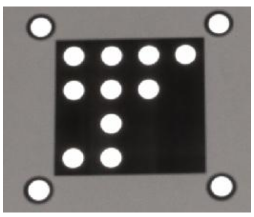

Fig. 4. Proposed fiducial marker

We propose to take the centers of external ellipses as the basic points. According to the results of experimental studies, the coordinates of the centers of ellipses can be calculated more accurately, than the coordinates of the ArUco FM basic points. Therefore we took the ArUco FM architecture as the basis for the identification part architecture of the proposed fiducial marker, and the test part architecture of a fiducial marker and the corresponding algorithms were modified to improve the accuracy of measuring the coordinates of FM internal and external ellipses [2].

Experimental results showed that the proposed fiducial marker architecture allowed us to determine with adequate accuracy the initial relative position of the coordinate systems of the digital camera and the fiducial marker. Besides, one fiducial marker of the proposed architecture is sufficient. The number of fiducial markers increases only in case of photographing an object by parts (with image overlapping). On the contrary, the fiducial marker architecture of the V-Stars system requires a group of fiducial markers or a special positioning device, AutoBar (in terms of V-Stars) to determine the position of the camera coordinate system [3].

The developed procedure for determining the relative position of the coordinate system of the digital camera and that of the fiducial marker allowed us to apply an effective method of identifying circular targets. The method is based on the iterative scheme of finding the corresponding points, which uses the approximate algorithms of searching the super clique of a graph, built on the basis of the epipolar geometry of photos, the triangulation of 3D-points with sifting the outliers, the equalization of 3D-coordinates and positions of cameras by means of the method of bundle adjustment [8], with subsequent reverse projection aiming to search for new images of points in the photos. Owing to this, it became possible to use heuristic algorithms (of polynomial complexity) for searching cliques at a separate iteration step. As a result, the proposed scheme offers an exact solution to the task of searching for the corresponding points and estimating their 3D-coordinates in acceptable time [9].

III. PS TOOLSET AND PS SOFTWARE

The PS toolset includes:

- A digital camera, circular retro reflective targets, fiducial markers, a scale rule (Figure 5);
- A photogrammetric local vertical plotter (Figure 6), which is applied in inspecting building structures.

The software includes preprocessing the data of each photo and final processing of the whole set of photos. The tasks of preprocessing:

- Measuring the centers of circular targets;
- Measuring and identifying fiducial markers;
- Determining scale rules;
- Determining vertical plotters.

The tasks of final processing:

- Identifying circular targets;
- Triangulating circular targets with sifting false correspondences;
- Auto-calibrating digital camera parameters;
- Calculating spatial coordinates and normal vectors of the centers of circular targets for all photos;

ISBN: 978-988-14048-3-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

- Solving applied problems.

When implementing the software, we used the open source library OpenCV [10].

Fig. 5. Digital camera, targets, code marks, scale rule

Fig. 6. Photogrammetric local vertical plotter

IV. Experimental Research of the PS

To preliminarily estimate the PS measurement errors we carried out a test using the following equipment: the PS based on a DC Nikon D810 with the lens Nikkor 20 mm f/1.8G ED.; 31 circular retro reflective targets; 2 scale rules; 1 fiducial marker; coordinate measuring machine (CMM) Cim Core Stinger II. The CCM was installed onto the horizontal plane. The retro reflective targets were placed within the radius of operation of the CMM (±1500 mm) (Figure 7) [11].

The PS error was determined by simultaneously estimating the coordinates of the centers of the circular targets with the help of the PS and the CMM. During the experiment there were five series of measurements for each center of the coordinates of the circular targets, which were taken with the help of the PS and the CMM.

In each series between 15 and 20 photos were taken from different perspectives along the perimeter of the experiment scene, and the correspondence of the numbers of points measured by the CMM to those measured by the PS according to the developed program was automatically calculated; the program algorithm is based on superposing the vertices of the polyhedron, built on the cloud of points measured by the CMM, with the matchable vertices of the polyhedron, built on the cloud of points measured by the PS. It is noteworthy that the program allows detecting and preventing noise in the cloud of points of the PS.

Fig.7. Experiment scheme

Then, in each series “n” points were assigned as the reference ones for calculating the relative position of the coordinate systems (CS) of the PS and the CMM. We chose the first 20 out of 31 targets, measured by the CMM, as the reference ones.

The relative position of the coordinate systems of the PS and the CMM was determined according the developed program; its algorithm is based on minimizing the mean squared error of the deviation of reference point coordinates measured by the CMM from the ones measured by the PS.

With account of the relative position of the coordinate systems of the CMM and the PS, the rest 31 – n = 11 points are converted from the coordinate system of the PS into the coordinate system of the CMM for each experimental series. Only in 5 series m = 55 points are converted. These points served as the basis for calculating the difference vectors of the coordinates x, y, z, measured by the CMM and the coordinates x, y, z, measured by the PS. Basing on the difference vectors of each coordinate x, y, z, sample squared deviations from the mean (SDM) σ_x, σ_y, σ_z of the mentioned coordinate differences are calculated. Since the CMM and the PS simultaneously try to estimate the true coordinates of points and random errors of the CMM and the PS measurements are independent, each sample SDM can be represented by the formula (let us take the SDMσ_x as an example):

$$\sigma_{pSx} = \sqrt{\sigma_x^2 - \sigma_{CMMx}^2}; \quad (1)$$

$$\sigma_{pSy} = \sqrt{\sigma_y^2 - \sigma_{CMMy}^2}; \quad (2)$$

$$\sigma_{pSz} = \sqrt{\sigma_z^2 - \sigma_{CMMz}^2}. \quad (3)$$

Using the above noted formulas, the SDM for the PS were calculated by 2 scenarios (depending on the assigned value of the SDM of the CMM):

– "the worst scenario" (greatest possible error) for the PS, where the SDM of the CMM equals to 0. In this case the sample SDM σ_x, σ_y, σ_z equal to the SDM of the PS. The calculation results for this case:

$$\sigma_{pSx} = \sigma_x = 0.1697\ mm;$$
$$\sigma_{pSy} = \sigma_y = 0.2466\ mm;$$
$$\sigma_{pSz} = \sigma_z = 0.1987\ mm;$$

– «a realistic scenario», where the CMM and the PS equally contribute to the sample SDM σ_x, σ_y, σ_z. The calculation results for this case:

$$\sigma_{pSx} = \sigma_x / \sqrt{2} = 0.1200\ mm;$$
$$\sigma_{pSy} = \sigma_y / \sqrt{2} = 0.1744\ mm;$$
$$\sigma_{pSz} = \sigma_z / \sqrt{2} = 0.1405\ mm.$$

Given calculations of SDM are preliminary estimations of errors in measuring spatial coordinates by a photogrammetric system.

V. Conclusion

In this paper we considered the photogrammetric system, which we developed for measuring spatial coordinates of control points of large-size structures. We proposed the PS toolset and the fiducial marker construction, developed the algorithms and the software for the PS. In the experimental part of the paper we estimated the squared deviations of the mean of the spatial coordinates measured by the PS.

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