Non Contact 3D Model Reconstruction Using Coded Targets

Vladimir A. Knyaz, Alexandr V. Sibiryakov

State Research Institute for Aviation System (GosNIIAS)

Moscow, Russia

Abstract

The central task of close-range photogrammetry is the solution of correspondence problem, i.e. determination of image coordinates for given space point for two and more images. The paper presents the results of developing and using new coded targets for automated identification and coordinates determination of marked points for 3D model reconstruction task.

The developed coded targets are independent to location and rotation, provide the possibility of reliable detection and localisation in textured image and precise centre coordinates calculation.

The coded targets have been used for automated 3D coordinates measurements by photogrammetric station of State Research Institute for Aviation System. The methodics of automated identification and 3D measurements technique are given. Also the estimations of system performance and measurements accuracy are presented.

Keywords: *close-range photogrammetry, 3D surface measurements, coded targets.*

1. INTRODUCTION

Last years close-range photogrammetry became effective and flexible technique for precise space coordinates measurements and producing 3D models for unique 3D objects. The performance and accuracy seem to be the main features describing the quality of photogrammetric system.

The processing speed of measurements depends on automation degree and can vary from hours for manual process to seconds for automated one. Therefore various methods (such as correlation matching for textured objects, structured light), based on pattern recognition were developed for automated correspondence problem solving. Another approach to the problem is to use coded target, which allow to recognise and identify interesting point in the image [1,2].

The precision of measurements depends on accuracy of correspondence problem solving (other conditions being equal) i.e. on accuracy of determination image coordinates of correspond points. The design of coded target of special shape allow to reach high accuracy of point position estimation due to subpixel target centre coordinates determination.

Another reason to use coded target is the possibility to measure the object surface in the set of preliminary given points.

So far for increasing the performance and precision of measurement on photogrammetric station of State Research Institute for Aviation System the new coded targets were developed and used in measurement process.

2. DEVELOPMENT OF THE CODED TARGETS

The coded targets should satisfy to the following requirements:

- Invariance to rotation and change of scale;
- Opportunity of robust recognition of number of a target with correction of possible mistakes;
- Exact measurement of centre of a target specifying a rule(situation) of a control point of object;
- Opportunity of detection of a target on the image with non-uniform contrast;
- The minimal time of processing;
- The compact size;
- Maintenance the large number of codes suffices.

For maintenance of these requirements the coded targets shown on Fig.1 were developed. They look like two concentric circles, the internal one has black colour, the external one has white colour with black border. Such alternation of brightness is necessary for maintenance of the maximal contrast of a target on a complex background of the image. The binary code of a target as small black circles settles down on a circle between internal and external circles. The central pixel of a target has white colour. Depending on distribution of brightness of the observable image of a target can be inverted. All sizes of a target in pixel units are shown on Fig.2.

The internal circle is intended for detection of a target centre with subpixel accuracy . The border of an external circle is intended for localisation of an internal circle and coding circles. The number of coding circles is equal 10. Thus it is possible to code 2^{10}=1024 numbers, however in view of the requirement of invariance of a code to rotation and reflection only 76 numbers can be coded. For coded numbers of targets the table *M(N)* is obtained allowing for each value of the code N = 1,...,1023 to find appropriate number of a target *M* = 1,...,76.

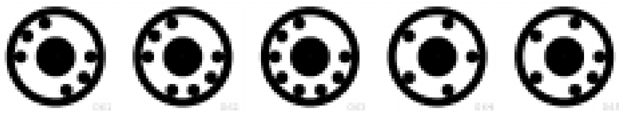


Figure 1: Structure of the coded targets. The integer value specifies the target number.

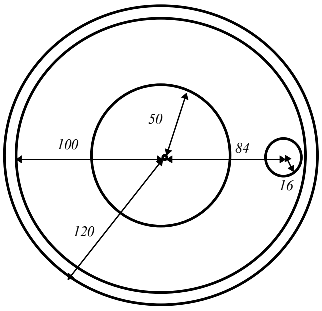


Figure 2: Target dimensions

On Fig.3 the test example of the image with coded targets is shown.

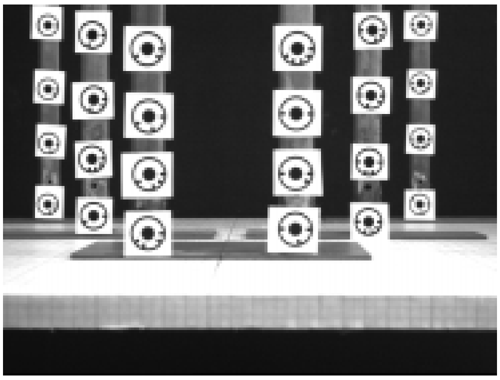


Figure 3: Test image with coded targets

3. AUTOMATIC TARGET RECOGNITION

The task of target recognition consists in an automatic detection of targets on the image, exact definition of their centres, and reading of coded numbers.

3.1 Algorithm of the target recognition

The algorithm of target recognition consists of the following steps:

1. Binarization of the image;
2. Definition of all eight-connected regions which are not laying on the image borders;
3. Seeking of all regions and searching of structure ‘ black region inside white region’;
4. Checking of the sizes for each found structure, storing the list of the possible coded targets;

For each target from the list modelling the internal and external circles. The model is set as an ellipse. Five parameters of an ellipse (subpixel centre coordinates, sizes of a large and small half-axis, inclination of a large half-axis) are calculated by the least squares minimisation;

Reading of a binary code between an internal and external ellipse.

3.2 Binarization of the image

For simplification of target recognition process it is necessary to transform the grey-level image in binary. Binarization of the image is carried out by thresholding:

$$b(x,y) = 0,\ if\ f(x,y) < t(x,y)$$

$$b(x,y) = 255,\ if\ f(x,y) \geq t(x,y)$$

where f(x,y) - original image, b(x,y) - binary image, t(x,y) - each pixel threshold.

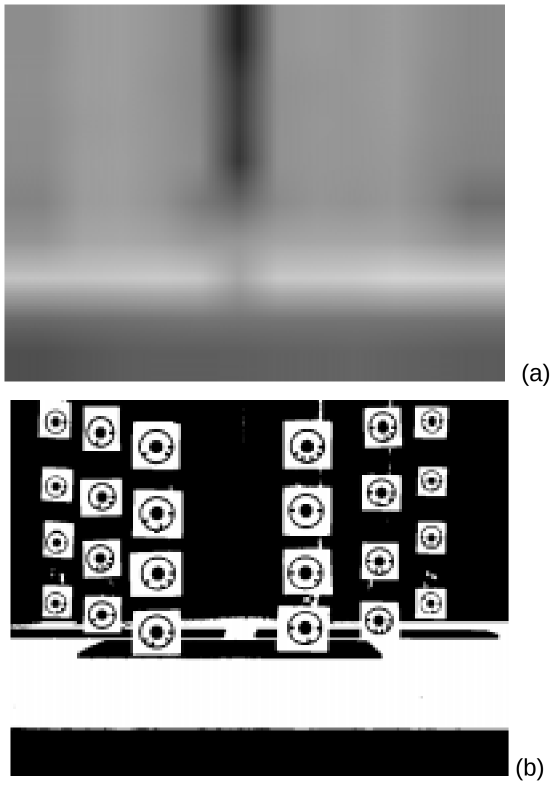


Figure 4: Binarization of the image. (a) local threshold image; (b) binary image obtained

The application of a constant threshold t(x,y)=t0 is not suitable because of non-uniformity of contrast in different parts of the image, and as consequences, impossibility of all targets binarization. Therefore an adaptive threshold calculated for each pixel (x,y) is used.

One of effective methods of an optimal threshold selection is the Otsu criterion, which estimates whether the image histogram contains two expressed peaks. For an area containing a target this assumption is correct therefore the target areas are precisely thresholded by Otsu criterion.

For local application of Otsu criterion it is necessary to set the approximate size S of a target on the image. Then the algorithm of definition of an adaptive threshold t(x,y) looks as follows:

1. Splitting the image f into overlapped square blocks Bij of the size S:

$$Bij(x,y) = f(x+(i-1)S/2, y+(j-1)S/2),\ x,y = 0..S-1$$

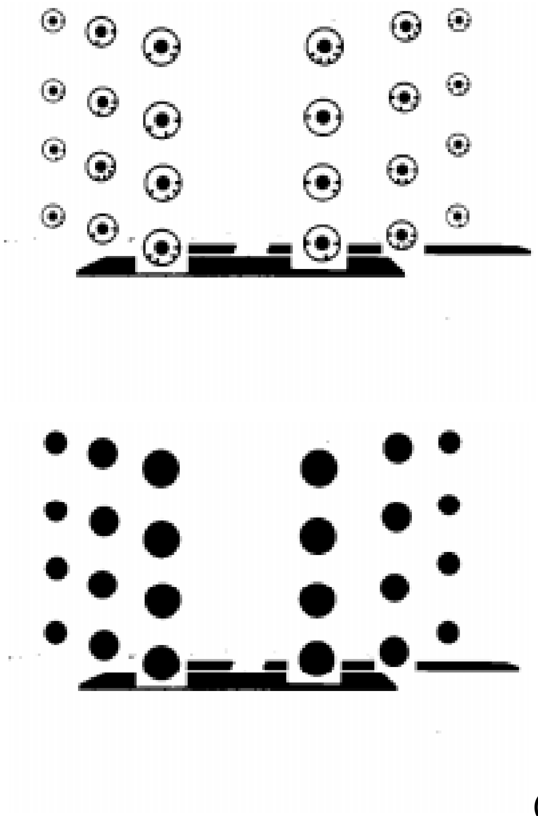
2. Calculation the threshold in each block by Otsu criterion:

$$t_{ij} = Otsu\ (B_{ij})$$

3. Bilinear interpolation of values tij for each pixel (x,y).

On Fig.4 the result of image binarization is shown.

3.3 Search for target candidates



(a)

(b)

Figure 5: Extraction of target candidates

For extraction the image regions the labelling algorithm is used. After labelling algorithm performing each region gets unique number. The procedure of target candidates search is shown on Fig.5.

At first on the binary image all black areas contiguous to borders of the image leave, since it is considered, that the target is imaged completely. Thus (see Fig.4b and Fig.5à) at once many black regions which are not areas of targets are excluded from consideration. Let's designate the obtained image by m1.

As the external black ring of a target limits its area a following step consists in filling all internal white regions (Fig.5á). Let's designate the image obtained as m2. For the further analysis the list of such black regions of the image m2 is made which contain inside themselves black areas of the image m1. The obtained regions are the target candidates.

3.4 Elliptic model of a target region

The adjustment of an ellipse to the region serves to two purposes:

1) Definition of the region centre with subpixel accuracy;

2) Checking, whether the region is an image of a circle.

The equation of an ellipse, to which the border of area should satisfy, is

$$Ax^2+Bxy+Cy^2+Dx+Ey+F=0 \quad (1)$$

The border of area only approximately satisfies to this equation, so we write down the equation in convenient form for the minimisation by least squares method:

$$ax^2+bxy+cy^2+dx+ey = -1+\varepsilon \quad (2)$$

In a matrix form (2) looks like

$$\mathbf{Ap = b + \varepsilon}$$

where $\mathbf{p}=[a,b,c,d,e]^T$ - a vector of equation parameters; **À** - design matrix with i-th line corresponding to i-th pixel of the region border: $[x_i^2\ x_iy_i\ y_i^2\ x_i\ y_i\ ]$; $\mathbf{b} = [-1,...,-1]^T$ - vector of observations; $\boldsymbol{\varepsilon}$- error vector.

The solution of the (3) is

$$\mathbf{p = (A^TA)^{-1}A^T\ b} \quad \mathbf{(4)}$$

The ellipse parameters expressed through parameters of the equation, are:

$x_0 = \dfrac{be-2cd}{4ac-b^2},\quad y_0 = \dfrac{bd-2ae}{4ac-b^2}$ - centre of an ellipse;

$\theta = 0.5\arctan\dfrac{b}{a-c}$ - inclination of a large semi-axis;

$p_1 = \sqrt{\dfrac{1}{a\cos^2\theta + b\sin\theta\cos\theta + c\sin^2\theta}}$ - large semi-axis;

$p_2 = \sqrt{\dfrac{1}{c\cos^2\theta - b\sin\theta\cos\theta + a\sin^2\theta}}$ - small semi-axis.

The ellipse should satisfy following invariants

$$I_3/I_1 < 0,\ I_2 > 0, \quad (5)$$

where: $I_1 = a + c$;

$$I_2 = \begin{vmatrix} a & b/2 \\ b/2 & c \end{vmatrix},\ I_3 = \begin{vmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & 1 \end{vmatrix}. \quad (6)$$

These invariants are checked for each region after a finding of ellipse equation parameters.

Thus in coordinate system obtained by transformation

$$x' = x_0 + x\cos\theta + y\sin\theta$$

$$y' = y_0 - x\sin\theta + y\sin\theta \qquad (7)$$

the parametrical equations of the ellipse are

$$x' = p_1\cos t, \quad y' = p_2\sin t, \qquad (8)$$

where t- parameter varied from 0 up to 2π.

3.5 Target code reading

After the parametrical equations of internal and external ellipses are obtained the algorithm of binary code reading follows. First the rectangular development of an elliptic ring between these ellipses is formed.

Let us denote $x_0^{(1)}$, $y_0^{(1)}$, $\theta^{(1)}$, $p_1^{(1)}$, $p_2^{(1)}$ - parameters of the internal ellipse, $x_0^{(2)}$, $y_0^{(2)}$, $\theta^{(2)}$, $p_1^{(2)}$, $p_2^{(2)}$ - parameters of an external one. Rectangular development of a code $K(p,t)$ using original image $f(x,y)$ and parametrical equations of ellipses is

$$K(p,t) = f(x,y),$$

where

$$x' = p\cos t, \quad y' = p\sin t,$$

$$x = x_0^{(1)} + x'\cos\theta^{(1)} - y'\sin\theta^{(1)}$$

$$y = y_0^{(1)} + x'\sin\theta^{(1)} + y'\sin\theta^{(1)} \qquad (9)$$

$$t = 0 \ldots 2\pi, \quad p^{[1]} < p < p^{[2]}.$$

The example of rectangular development of a code is shown on Fig.6. Code-supporting strip is determined using the target sizes (Fig.2). Inside the strip (Fig.6) grey-level profile (Fig.7) is binarized by Otsu criterion.

The reading of a binary code begins with the nearest zero element (from the left black circle on Fig.6). For an example shown on Fig.7 the following binary code is obtained:

01 01 11 01 11 01 01 01 01 11.

The given binary code will be transformed to number N, coded in a target, by the following transformation:

01 - > 1; 11 - > 0

The combinations 00 and 10 are inadmissible, therefore, if they meet with decoding, it is considered, that the region is not valid.

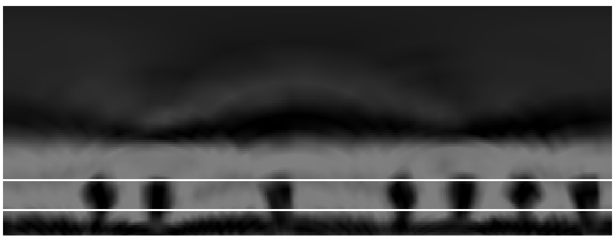


Figure 6: Rectangular development of a code

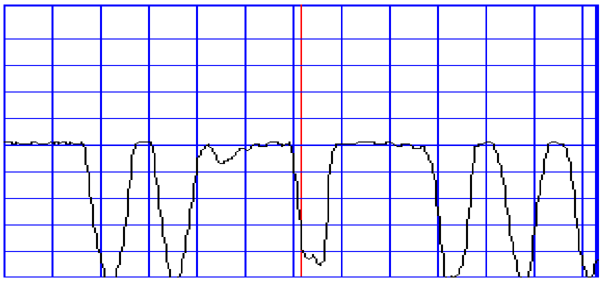


Figure 7: Profile of code-supporting strip

For an example on Fig.7

$$N = 1101011110_2$$

Further under table $M(N)$ number of the targets appropriate to read number N is determined.

On Fig.8 the result target recognition is shown.

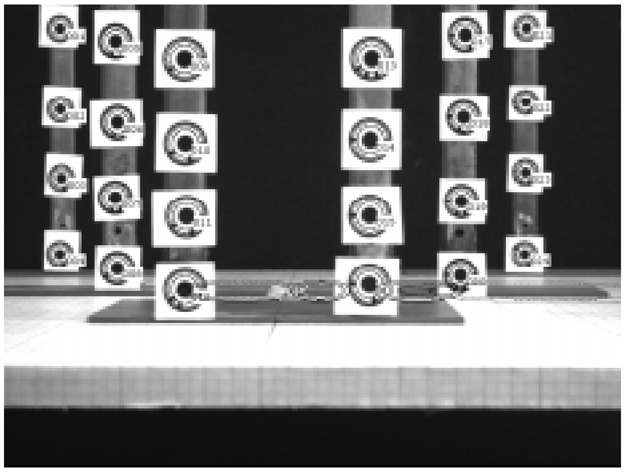


Figure 8: The result of target recognition

4. CODED TARGETS APPLICATION

4.1 Photogrammetric station

The researching photogrammetric station of GosNIIAS was created for developing new methods for non-contact measurements and 3D object reconstruction based on close-range photogrammetry technique. It includes:

- Personal computer as central processing unit
- Set of digital high-resolution cameras
- Frame grabber for image capture
- Set of testfields for purposes of camera calibration
- Structured light projector
- Dynamic tools for cameras arrangement
- Original software for image processing system calibration and 3D reconstruction.

GosNIIAS researching station is shown in Fig. 9.

The main steps of object 3D reconstruction by means of Researching photogrammetric station is given below:

1. Camera calibration
2. Photogrammetric network design and cameras arrangement

3. Image acquisition of given object (in structural light if needed)
4. External or relative orientation of images
5. Correspond points determination
6. Automatic surface reconstruction
7. Export to CAD format

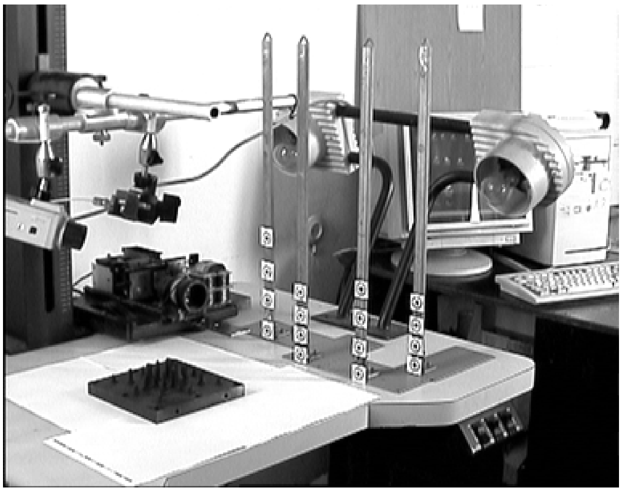


Figure 9: Researching photogrammetric station of State Research Institute for Aviation System.

4.2 Results of coded targets application

Camera calibration is the first important step in 3D reconstruction process. It requires to measure a great amount of image coordinates of reference points in representative set of testfield images. The quantity of measurements can achieve up to thousands and can take some days in manual regime. The developed coded targets were applied for automated identification of 32 reference points in 50 images of testfield, acquired from various points of camera position. Greyscale images (with dimensions 768(H) x 576(V) pixels) of reference points were captured with PSI framegrabber. Average processing time per image was about 100 sec for Pentium 133MHz, 48Mb RAM, all targets being decoding correctly. This allow to prepare data for camera parameters estimation by the period of 10 minutes instead 6 hours in manual regime.

External or relative orientation of images require to mark reference or correspond points in two or more images to determine camera coordinates in absolute or relative system of coordinates.

On Fig.10 the fragments of the left and right images containing 24 coded targets are shown. All targets were recognised correctly by just described algorithm.

Subpixel target centres were used for relative orientation. Residual parallaxes obtained at target centres after the first iteration of orientation algorithm are shown in Table 1. From the table that maximal residual parallax is equal to Δ_{max} = 0.17 pixels, and the variance of residual parallaxes is equal to σ_Δ = 0.085 pixels.

The results show that accuracy of the automatic measurement on the order surpasses the accuracy of hand-operated measurements.

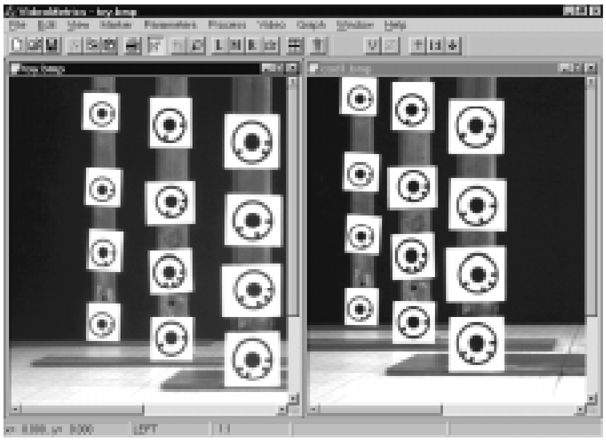


Figure 10: The application of coded target to relative orientation

N	P	N	P
1	0.04	13	0.17
2	-0.04	14	-0.12
3	0.11	15	0.05
4	0.01	16	0.11
5	0.07	17	-0.04
6	0.00	18	0.06
7	-0.12	19	-0.04
8	-0.05	20	-0.02
9	-0.09	21	0.11
10	-0.11	22	-0.07
11	0.01	23	-0.14
12	0.05	24	0.05

Table 1. Residual parallaxes at target centres obtained during relative orientation (N-number of target; P - residual parallax).

System performance and accuracy characteristic were obtained during three month testing and using developed coded targets in measuring process. About 800 images of various textured objects counting coded targets were captured and processed. All targets were detected for all cases when image resolution was enough for code reading (about 24x24 pixels per target). No cases of false code detection were fixed.

Original software for given coded targets identifying was realised for Windows-95. The performance characteristics was obtained for standard PAL format greyscale images (768(H) x 576(V) pixels). They are:

- 97 seconds per image for Pentium 133 MHz, 48 Mb RAM
- 66 seconds per image for Pentium 200 MHz, 64 Mb RAM

For measuring accuracy estimation the testfield with 24 coded reference points was developed. After bundle adjustment procedure of 16 images from convergent points of view an a-posteriori standard deviation of 0.1 pixel was obtained, image pixel resolution being 6.3 micron.

5. CONCLUSION

The developed coded targets demonstrate high reliability for recognition and identifying in wide variety of target scales and image texturing. There were no target leaks or false decoding for sufficient resolution for code reading.

The applying of elliptic model for target location provide high subpixel accuracy in point coordinates determination, the accuracy being higher for using external border of target as reference for centre location.

The developed code for target numbering is invariant to rotation and scaling and provide robust identifying.

The developed technology of coded targets application allows to automate and increase performance of measurement process in close-range applications such as calibration, relative and external orientation of cameras, 3D object reconstruction and also to increase accuracy of measurements.

6. REFERENCES

[1] Ahn, S.J., Schultes M., *A new circular coded target for the automation of photogrammetric 3D-surface measurements, Optical 3D Measurement Techniques, Edited by A.Gruen, O.Kuhbler, Zurich, 29 September- 2 October, 1997, pp. 225-234*

[2] C.-T. Schneider, *DPA-WIN - A PC Based Digital Photogrammetric Station For Fast And Flexible On-Site Measurement, International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, Part B5, Vienna, 1996,pp 530-533*

Authors:

Vladimir A. Knyaz, Head of group

State Research Institute of Aviation Systems

125319, Victorenko str., 7, Moscow, Russia

e-mail: knyaz@fenix.niias.msk.su

Alexander V. Sibiryakov, the postgraduate student of Moscow Institute of Physics and Technology

125319, Victorenko str., 7, Moscow, Russia

e-mail: avs@fenix.niias.msk.su

Бесконтактное построение 3D моделей реальных объектов методами короткобазисной фотограмметрии на основе использования кодированных меток.

Владимир А. Князь, Александр В. Сибиряков

Государственный НИИ Авиационных Систем

Москва, Россия

Аннотация. Основная проблема, которую необходимо решить при построении трехмерных моделей методами короткобазисной фотограмметрии это нахождение на нескольких разноракурсных изображениях объекта координат точек соответствующих одной и той же точке сцены (так называемая проблема стереосоответствия или стереоотождествления). Статья преставляет результаты разработки и применения кодированных меток для автоматизации решения проблемы стереоотождествления в задачах видео-метрического построения трехмерных объектов.

Разработанные кодированные метки инвариантны к вращению и положению на изображении, надежно детектируются и локализуются на сложном фоне и обеспечивают высокоточное субпиксельное вычисление координат центра метки на изображении.

Данные кодированные метки использовались для автоматического измерения трехмерных координат и построения трехмерных моделей на комплексе короткобазисной фотограмметрии ГосНИИАС. Представлены структура комплекса, методики автоматической локализации и идентификации меток и технология трехмерных дистанционных измерений и построения 3D моделей. Приводятся оценки производительности и точности системы дистанционных измерений.

Ключевые слова: *короткобазисная фотограмметрия, бесконтактные измерения, 3D модели, кодированные метки.*