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Development of Approach to Automatic Machining of Composite Parts Without their Rigid Fixing by Means of Multilink Manipulators

Vladimir Filaretov, Alexander Zuev*, Anatoly Khvalchev

Far Eastern Federal University, 8 Suhanova St., Vladivostok 690950, Russia
Institute for Automation and Control Processes FEB RAS, 5 Radio St., Vladivostok 690041, Russia

Abstract

This paper presents the new advanced approach for automatization of machining of nonrigid composites parts that have arbitrary geometrical form. This approach is based on using multilink manipulators with stereo vision system and allows not using the expensive individual equipment for parts rigid fixing before processing. This is achieved by special intelligent formation and correction of program's motions of manipulator cutting tool in real time using information about current position of processed parts from vision system.
The results of performed simulations have completely confirmed the working capacity and high quality of the proposed approach.

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Keywords: composite parts; machining; manipulators; stereo vision

1. Introduction

Now the questions of creation and effective implementation in industry (especially into the aircraft industry) of modern mechatronic and robotic systems have big attention. Herewith, one of the most important directions is automatization of technological processes of parts machining from polymer-based composite materials (PCM): cleaning, polishing, cutting, etc. For this purpose, the various automated complexes are widely used. All today

* Corresponding author. Tel.: +79149617735.
E-mail address: zuev@iacp.dvo.ru

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known approaches to creation of machining complexes for PCM parts are focused on use of the 5-axial processing centers with numerical programmed control and additional equipment for parts fixing in the course of their machining. In general, this additional equipment is produced individually for each part and has high cost. Conducted researches have shown, that such technology is difficult for realization at producing and machining of PCM parts into of aircraft industry. It is caused by specificity of PCM parts production in aircraft industry, associated with small seriation, but the big nomenclature of produced parts (including large-sized parts). Obviously, that using of individual additional equipment for fixing of each such part is not effective. Besides, outdated technology does not allow to provide the high-speed continuous multicoordinate machining.

Due to noted, it is expediently to change technology of machining of specified PCM parts, having completely excluded use of individual equipment for fixing and expensive 5-axial processing centers from technological process, having replaced them by industrial multilink manipulators (MM) and universal devices of positioning and fixing. The use of MM for automatic processing of PCM parts require ensuring of flexibility of production and convenience of their fast reorganization for machining of new parts. Besides, it is necessary to take into account the main feature of PCM parts production - possible variability of a form of thin-walled spatial parts in the course of their fixing and the subsequent machining. This is inadmissible for the traditional manipulators and processing centers [2]. The control program of traditional industrial MM is formed in advance by using computer-aided design models (CAD models) of parts and completely determines motions of the cutting tool (CT). Any change of the MM parameters and PCM parts (for example at not accurate fixation or at change of its geometrical sizes in the course of forced acting of CT) demands additional reprogramming, use of new procedures of debugging, etc. Noted features require development of essentially new intellectual informational-control system for MM, which will allow in real time to form and to correct the operating program of CT motion at machining of spatial PCM parts in the conditions of their possible continuous deformation.

Conducted researches have shown [5], that to provide high-quality formation and correction of program CT motions in the course of machining of spatial PCM parts without their rigid fixing in individual equipment it is necessary to use the modern stereo vision systems (SVS) which allow to ensure exact data about processing parts in real time.

This paper presents results of the researches directed on development of new advanced approach to high-precision automatic machining of spatial PCM parts by means of MM with SVS without their rigid fixing in individual equipment.

2. The analysis of possible approaches to automatic machining of PCM parts by means of MM with SVS

The conducted preliminary researches show that by means of universal fixing equipment, as a rule, it is possible to fix rigidly in strict accordance with CAD-model only a small set of processed PCM parts. Besides this, the additional deformation of their separate segments at forced milling is possible. The machining of such parts based on data only about CAD models will inevitably lead to errors of motion of their CT and, thereby, - to marriage of machining.

In the course of the analysis of possible approaches to automatic machining of PCM parts by means of MM, three variants of alleged change of their geometrical form were considered. These variants significantly influence on machining strategy and key technical solutions.

The first variant assumes that parts are fixed rigidly, correspond to their CAD models and there will not deformation during machining. This variant is characteristic for machining of the not large rigid PCM parts. These parts can be machined by using only CAD-models. Herewith an important task is to ensure fast and exact basing of parts in universal equipment and definition of them position and orientation in coordinate system of MM. This task can be solved qualitatively with use of modern SVS and optical 3D scanners [14].

The second variant supposes the rigid fixation of parts in universal equipment without deformation in the course of machining, but not with the corresponding to its CAD - models. In this variant, the important task is formation of geometrical model of spatial CT motion trajectory with taking into account simultaneous movement of positioner with universal equipment on which the processed parts are fixed. This task can be solved also with use of the SVS, which capable to give the exact data about fixed parts. For this purpose, it is necessary to use effective recognition algorithms of cutting line, which are marked on PCM parts (marking of these lines is made in advance after polymerization of composite parts) and creation of program signals for each degree of freedom of MM based on the obtained data. The third variant supposes fixation of nonrigid parts with discrepancy of CAD models and their possible deformations in the course of processing. In this variant at automatic formation of CT motion trajectories it is necessary to compensate deformations arising in them from acting of CT. This compensation can be achieved by using information about arising deformations of concrete segments of the marked cutting lines at continuous tracking of their by SVS which are mounted near with end-effector of MM.

Thus, the carried out analysis allows to define three main approaches to automatic machining of PCM parts: machining by using only CAD-models, machining on in advance marked cutting line by using vision systems and continuous machining by trajectory which are formed in real time. Thus, the first approach is traditional for industrial processing complexes [13]. Further, we will consider features of practical realization of two other described approaches, which are most perspective at realization of modern robotic complexes for machining of spatial PCM parts without their rigid fixation.

3. Formation of spatial CT motion trajectory for machining of PCM parts which was deformed at fixing in universal equipment

As noted above, the deformation of geometrical form of nonrigid PCM parts at which they any more do not correspond precisely to the CAD models is possible at fixation in universal equipment. Nevertheless, this equipment does not allow the parts deformation at the subsequent force impact of CT on their surface in the course of spatial machining.

At automatic machining of such parts by means of MM on their surface according to CAD models by known way cutting lines are marked, which at mechanical fixing of details also are deformed. Therefore, before machining of already fixed parts it is necessary to provide the automatic formation of the current position of earlier marked spatial cutting lines by using SVS. However, on average and large-size PCM parts of difficult form, being in an initial position, SVS can identify only one segment of marked line. For formation of full spatial model of cutting line in system of coordinates (SC) connected with the basis of MM, it is necessary to provide the corresponding movements of SVS or equipment on which processed parts are fixed. This procedure will be described below.

In paper [16] the problem of creation of models of large-size objects by using mobile television cameras is solved. However, the offered algorithms allow to receive spatial coordinates of separate segments of considered objects only at the small curvature of their recognizable contours. In papers [11, 12] for the solution of a problem of movement of MM from one object of working area to another, the methods of formation of the SVS movements fixed on end-effector are offered. As showed researches, these methods do not allow to form qualitatively program movements of MM based on SVS when tracking not completely visible contours.

As a whole, the made analysis showed that when SVS is moving in space (round the object) by using mobile basis, the essential errors in determination of spatial coordinates of observed objects arise [10]. For elimination of this problem, it is necessary to use the high precision and expensive systems for SVS motion. But more effectively instead SVS motion to use the rather cheap serial two-axial positioners allowing precisely to turn parts fixed on them in vertical and horizontal axes (i.e. move the parts).

In works [1, 15], the approach allowing to consider the partial objects movement in SVS view is offered, but the problem of formation of program signals of position and orientation image changing for obtaining demanded information about processed object isn't considered.

Important problem at creation of full and exact spatial models of cutting lines marked on large-size parts at changing of their spatial position is "stitching" of coordinates of points of received segments of lines by means of SVS to uniform spatial line. For the solution of this task there is some approaches, however all of them are focused on use of difficult system of the calibration templates which application in the conditions of real production is ineffective.

Thus, the task of development of creation method of models of spatial cutting lines for large-size parts with difficult form by means of SVS and two-axial positioner clamp of PCM parts is set. This method should ensure continuous by-turn getting in SVS field of view of all segments of extensive marked cutting lines and subsequent stitching of these segments.

At the solution of this task, we will use the generalized block diagram of the robotic machining complex shown in Fig. 1. This complex consists of MM 1, SVS 2, two-axial positioner 3 on which by means of universal fixing equipment the nonrigid PCM part 4 with the marked cutting line 5 is fixed.

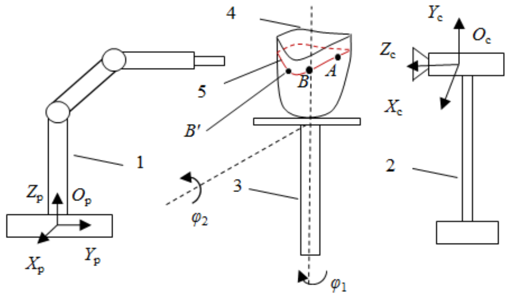


Fig.1. Generalized block diagram of the robotic machining complex.

Initially, only small segment AB of marked cutting line on large-size parts with difficult form may be seen at firmly fixed in the space SVS. After identification of this segment (based on known algorithms [8, 17]) and construction of its spatial model, it is necessary to turn this part by means of positioner-fixator so that the next segment of line would be seen. At that, for stitching all segments of cutting line, it is necessary to ensure movement of point A to point B, and point B to other frontier point of the next segment of cutting line in tangent plane of SVS and so forth. In order to solve this task, it is proposed to use the following three-stage algorithm.

Before the first stage, for the correct calibration of SVS it is necessary to define the position and orientation of the camera in SC of MM. For this purpose it is offered to use a method [9, 19], based on fixing arbitrarily on surface of part of special rectangular tag. This method is based on the analysis of so-called "disappearing points" [19], formed by crossing in the picture planes of SVS the distorted parties of this rectangle and allows to receive required vector of position of part $T^k \in R^3$ (k = 1) and a matrix of its orientation $R^k \in R^{3\times3}$ (k = 1) is relative to coordinate system connected with the basis of MM. These a matrix and a vector look like:

$$R^k = [v_x \;\; v_y \;\; v_x \times v_y \;], \; T^k = \begin{bmatrix} X_{ps} \\ Y_{ps} \\ Z_{ps} \end{bmatrix} - R^k \begin{bmatrix} X_{cs} \\ Y_{cs} \\ Z_{cs} \end{bmatrix},$$

where v_x, $v_y \in R^3$ are vectors of coordinates of two disappearing points in SC of SVS $O_cX_cY_cZ_c$; $[X_{cs}, Y_{cs}, Z_{cs}]^{\mathrm{T}}$ is a vector of coordinates of any top of a rectangle in SC $O_cX_cY_cZ_c$; $[X_{ps}, Y_{ps}, Z_{ps}]^{\mathrm{T}}$ is a vector of coordinates of this top of the specified rectangle in SC of the basis of MM of $O_pX_pY_pZ_p$.

At the first stage by means of methods of recognition of images [8], spatial coordinates of boundary points of visible SVS of a segment of marked line in SC O_c,X_c,Y_c,Z_c are obtained. Herewith (see Fig. 2) for the subsequent planning of a positioner motions it is necessary to consider not all visible segment AB, but only its part - segment AD, where $D_1 = [U_{t_i B} - \mu_U \;\; V_{t_i B} + \mu_V \;\; 1]^T$ is a uniform coordinates of point D_1 in i-oh pixel's CS of SVS. This procedure repeats for all segments of line for full viewing of all this marked line. Introduction of point D_1 is necessary for high-quality "sewing together" of all segments of marked line after the next turn of positioner as at a difficult type of this line losses of extreme points of considered segments are possible.

In Fig. 2 the following designations are entered: j is a number of the next segments of cutting line (j = 1, 2, 3, …); μ_U, μ_V are parameters of shift of a point D_j, chosen at the SVS control, $i = 1,2$ is number of pixel SC of SVS.

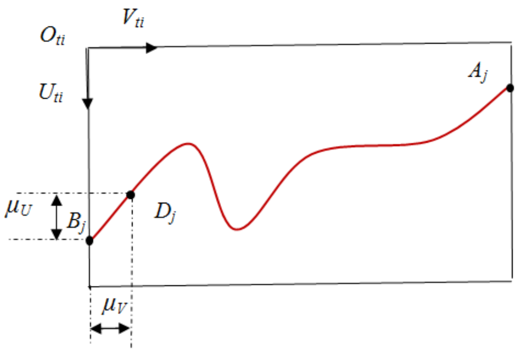


Fig. 2. The image j-th segment of marked cutting line concerning to pixel SC $O_{ti}U_{ti}V_{ti}$ of the picture plane of SVS.

At the second stage, considering already received spatial arrangement of the next segment A_jD_j it is possible to define desired joints rotation of positioner $\varphi_1{}^d$, $\varphi_2{}^d$ for combination of boundary points of A_j and D_j (for combination of straight lines the O_cA and O_cD). For the explanation of the solution of this task it is possible to use Fig. 3. Apparently from fig. 4, for combination of direct $O_c A$ and $O_c B$ it is necessary to execute two turns of a piece of O_c A: round the O_cY_c axis on a corner φ_1^* and then round an O_cX_c axis on a corner $\varphi_2^* = \beta_D - \beta_A$ which are calculated by means of expressions

$$\begin{aligned}\varphi_1^* &= \alpha_A + \alpha_D = \operatorname{arctg}\left(\frac{X_c^D}{Z_c^D}\right) + \operatorname{arctg}\left(\frac{X_c^A}{Z_c^A}\right),\\ \varphi_2^* &= \beta_D - \beta_A = \operatorname{arctg}\left(\frac{Y_c^D}{\sqrt{X_c^D + Z_c^D}}\right) - \operatorname{arctg}\left(\frac{Y_c^A}{\sqrt{X_c^A + Z_c^A}}\right).\end{aligned} \tag{1}$$

Considering that φ_1^*, φ_2^*, define SVS turn for combination of noted straight lines, upon transition to turns of axes of a positioner in expressions (1) it is necessary to change signs, that is

$$\begin{aligned}\varphi_1^d &= -\operatorname{arctg}\left(\frac{X_c^D}{Z_c^D}\right) - \operatorname{arctg}\left(\frac{X_c^A}{Z_c^A}\right),\\ \varphi_2^d &= -\operatorname{arctg}\left(\frac{Y_c^D}{\sqrt{X_c^D + Z_c^D}}\right) + \operatorname{arctg}\left(\frac{Y_c^A}{\sqrt{X_c^A + Z_c^A}}\right).\end{aligned} \tag{2}$$

Using the equations (2) for formation of program signals of positioner motion, when machining of large-size PCM parts it is possible to joint all segments of marked cutting lines.

At the third stage of algorithm for correct "stitching" of boundary points of all segments of cutting line in a uniform contour when moving PCM part by positioner it is necessary to redefine constantly coordinates stated above a vector T^k and a matrix R^k taking into account this movement as follows (k = 1, 2, 3, …):

$$R^{k+1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi_2 & -\sin\varphi_2 \\ 0 & \sin\varphi_2 & \cos\varphi_2 \end{bmatrix} \begin{bmatrix} \cos\varphi_1 & 0 & \sin\varphi_1 \\ 0 & 1 & 0 \\ -\sin\varphi_1 & 0 & \cos\varphi_1 \end{bmatrix} R^k, \quad T^{k+1} = \begin{bmatrix} X_{\text{p}_S} \\ Y_{\text{p}_S} \\ Z_{\text{p}_S} \end{bmatrix} - R^{k+1} \begin{bmatrix} X_{cs} \\ Y_{cs} \\ Z_{cs} \end{bmatrix}.$$

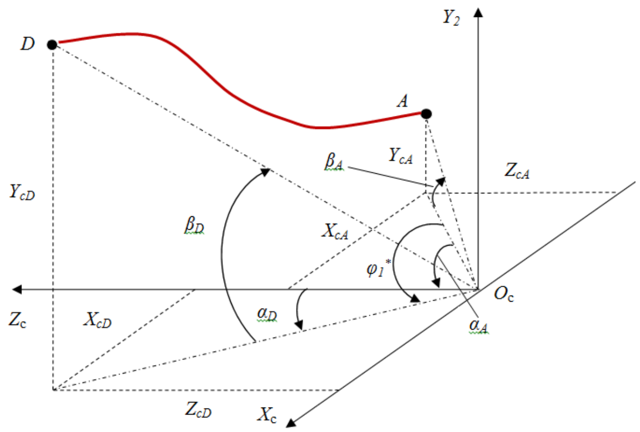


Fig. 3. Mutual location of points A and D of cutting line in SC $O_cX_cY_cZ_c$.

Besides, at the third stage it is necessary to define the moment of completion of work of the described algorithm when SVS will determine put on a processed part all necessary coordinates of an extended spatial cutting line. It is possible to realize by using indications of the sensor of joint φ_1. Work of algorithm stops when the value of φ_1 will be equal or exceeds to 360 degree.

Thus, the considered algorithm allows to form automatically program signals of movement of a two-axial positioner with universal fixation equipment of PCM parts, providing obtaining all necessary coordinates of an extended spatial cutting lines.

4. Machining of PCM parts without rigid fixing at presence of deformation deviation of form from mathematical CAD – models

As it was noted above, deformations of geometrical form of PCM parts at the fixing in universal equipment can occur. The specified equipment also permit deformation of the parts fixed in it at the subsequent force acting of CT on their surface in the course of spatial machining. As a rule, such deformation is possible at milling of thin-walled PCM parts [7].

For machining of such parts it is necessary to form and correct automatically in the course of processing the CT motion trajectory on the basis of information on the current arrangement of the parts of trajectories of cutting marked on surfaces, received by means of SVS. Thus the SVS has to be fixed on end-effector of MM near with CT [3, 4].

At the machining of deformable details it is necessary to determine previously coordinates of all points of the marked trajectory of cutting by the approach developed in the previous section. Further the MM begins cutting of parts in real time on the recognizable trajectory of cutting. Thus the SVS fixed on end-effector, carries out shooting of a site of a trajectory before CT and in case of its deformation of control system of MM carries out correction of originally certain trajectory of movement CT by means of the data received from SVS. Let's consider the method of implementation of this correction.

It is possible to determine two components of arising deformation of processed segment of PCM part: lengthwise and crosscut deformations. The analysis showed that deformation of PCM parts at the milling caused by lengthwise acting of CT will be inconsiderable. The main contribution to deformation of processed PCM parts will be made by crosscut influence of CT, therefore further the main attention will be paid to research of crosscut deformation.

One of the possible advanced approaches for machining PCM parts with arising deformation is to use the automatic formation and correction of CT motion trajectories with use of information on current state of processed segments of these parts. At realization of this approach it is supposed that program values of coordinates of the points forming cutting line of fixed parts are stored in memory of control system of MM. These coordinates are formed in advance in coordinate system connected with the basis of MM and can be received using CAD models of details or by means of methods of recognition marked cutting line.

Except coordinates of the points cutting trajectory in computer memory also admissible values of crosscut deformations of current segments δ^d_l (l = 1, …, N, where N is a quantity of set points of cutting line) in i-th trajectory points are setted. These admissible values, generally, can be various for each of sites of processed parts and are defined during experimental studies for each concrete PCM part. On the basis of the obtained in advance and current data of control system of MM can form program speeds of movement CT on concrete cutting trajectories.

Process of milling of PCM part (see Fig. 4) begins with a moving of CT to its surface in some initial point of cutting line (see A_1 point in Fig. 4) according to its CAD model. Thus at cutting down of mill the deformation of not rigidly fixed segment of part can begin, and at further movement of CT to next point of trajectory A_2 (in advance created on the basis of CAD-model) there will be a mill descent from a trajectory of cutting. It will lead to a stop of process of milling and by the beginning of new procedure of the CT installation on this trajectory.

To eliminate the arising deformation it is necessary to introduce the corresponding corrections in originally set cutting trajectory using SVS near with CT. This SVS defining the current position of CT concerning to cutting line should provide the calculation of real spatial coordinate of the following point of cutting line on deformable segment of PCM part (see A^*_2 point in Fig. 4) . At this the control system of MM in tracing mode has to remove an arising mismatch between program coordinates of trajectory points and coordinates of real points, continuously received by means of SVS. Herein it's necessary to consider also continuously the size of the current deformation of parts in new real point. If arising deformation δ_l exceeds admissible δ^d_l on a considered segment of part, it is necessary to reduce the speed of movement of CT in the specified direction until the condition $\delta_l < \delta^d_l$. will start being satisfied.

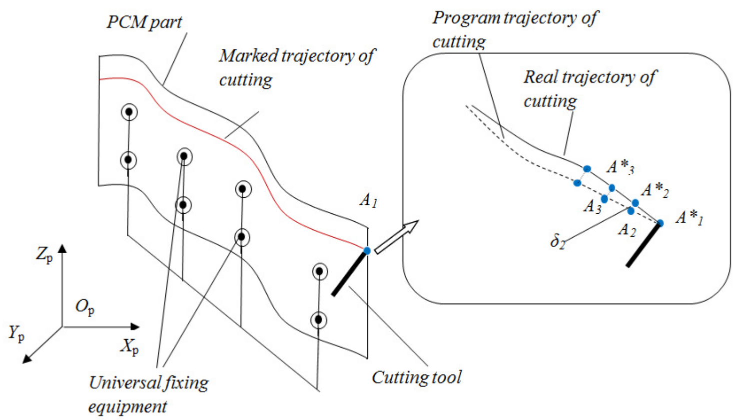


Fig. 4. Illustration of deformation of processed details under the influence of CT.

For realization of automatic system of adaptive fine tuning of speed of movement of CT on the basis of the size of arising current deformation of PCM part it is possible to use the approaches described in works [6].

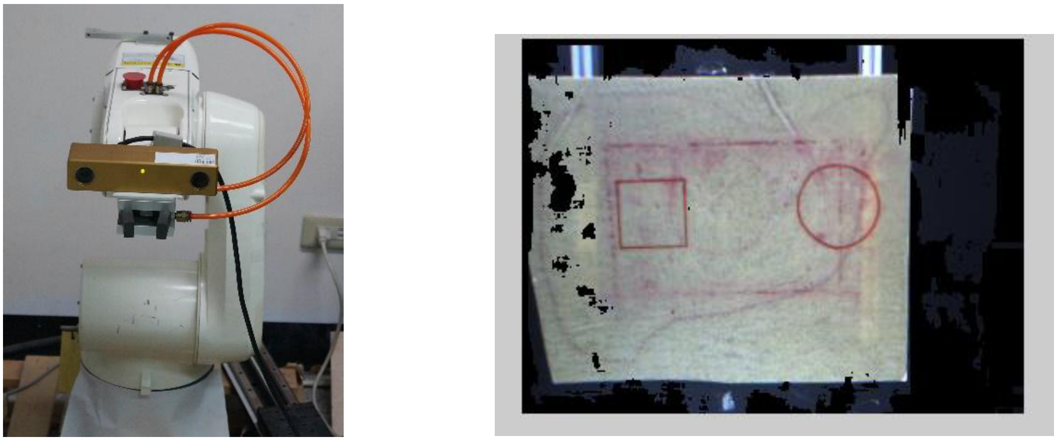
Another approach to working off of arising deformations is to use of force/position control system for MM providing not only exact movement of CT on the set trajectory, but also simultaneous control of its force impact on PCM part surface. As showed the conducted researches for development of high-precision force/position control system at the solution of problems of milling of nonrigid PCM parts it is possible to use simultaneous force/position control system of MM [18] which without use of force sensors can provide high-quality performance of operations on machining of difficult PCM parts (including with high speed).

5. Results of simulation of diagnostic system

To confirm the efficiency of the chosen strategy and approaches to machining of nonrigid PCM parts by means of MM with SVS were carried out experimental researches of efficiency of processing of details with use of information on spatial cutting line received from SVS. In particular, the accuracy of determination of coordinates of the points forming line marked on part, by means of this SVS and also the accuracy of tracking of the received trajectory by CT was investigated.

At experimental researches, the DENSO VS-6556G B/RC 7M manipulator and the stereo camera Bumblebee®2 1024x768 which mounted near with end-effector were used. This of experimental installation is shown in Fig. 5a.

Before carrying out of experiment in working zone of MM arbitrarily at some distance PCM part with previously marked contours in the form of a square with sides of 72 mm and circles with radius of 3,5 mm (see Fig. 5b) was established. Preliminary calibration of SVS was carried out by means of a Camera Calibration Toolbox of MATLAB. In the course of carrying out experiment consecutive recognition of the marked trajectories, definition of their spatial position and orientation in coordinate system of SVS was carried out. Experiments showed that errors of determination of lengths of the side of square and radius of circle didn't exceed values of 0,3 mm and 0,42 mm, respectively.



a) *b*)

Fig. 5. General view of experimental installation.

In experiment imitation of automatic machining by means of CT (the simulator of a laser cutting head) flat part on the revealed contours was made. The error of working off of CT of both trajectories revealed by means of SVS didn't exceed 0.6 mm.

As a whole, the provided experimental researches completely confirmed the efficiency of offered approaches and algorithms, and also operability of the technical solutions which have provided high precision of processing of flat PCM parts by means of MM with SVS.

6. Conclusion

The conducted researches and experiments confirmed possibility of high-precision automatic machining of PCM parts by means of the MM, equipped by SVS, without use of expensive individual equipment for their rigid fixing before processing. For effective realization of the offered approaches, it is necessary to use the high-speed algorithms of exact recognition and determination of spatial coordinates of the points forming marked trajectories of cutting on processed parts, especially when these parts have a difficult spatial surface, and the marked trajectories are not accurately recognized on processed surface.

It is important to note, that the proposed approach is new technology in industry, and for practical implementation of this decision necessary to solve the complex fundamental and applied problems in the field of robotics and intelligent control. The future research of authors will be focused on solving of these problems. One of the most important problems is that the requirements of formation and correction of spatial motion trajectory of CT in real time by using SVS, imposes basic restrictions on existing creation approaches of control systems for industrial MM, which have demand of extremely fixed environment, and not assuming corrections of operating programs at the machining. Noted factors demand development of new architecture and subsystems of information control systems of MM and architecture and structure of its SVS, which will allow to form and correct the operating programs. At the solution of this task, it is expedient to use ideology of creation of the intellectual control systems, which involves the introduction of additional contours of formation of CT motion trajectories with their subsequent correction based on vision information and aprioristic knowledge of parts CAD models.

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