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The Automatization Method of Processing of Flexible Parts without their Rigid Fixation

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Abstract

This paper presents a new advanced approach for automatization of processing of flexible parts with arbitrary geometrical forms. This approach based on using multilink manipulators with vision system and allows to exclude the individual equipment for rigid fixing of processed parts. This is achieved by formation and correction of program motions of cutting tool of manipulator using information about current position of processed parts from 3D vision system.

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Keywords: Manipulatos; flexible items; motion paths; vision systems; CAD model

1. Introduction

Today, creation and implementation of modern mechatronic and robotic systems to industry (especially to aircraft industry) has big importance. Herewith, one of the most important direction is automatization of technological processes of processing of flexible parts (for example, spatial parts of cover of aircrafts from polymer-based composite materials or plastics). For this purpose, the various automatic complexes are widely used. All presently known approaches to creation of machining complexes for flexible parts are focused on use of CNC machining centers [1] and additional equipment for rigid fixing of parts in strict compliance with CAD models at the

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processing. In general, this additional fixing equipment is produced individually for each part and has high cost. Conducted researches have shown, that such technology is complex for realization at producing and processing of flexible parts in aircraft industry. It is caused by specificity of flexible parts production in aircraft industry, associated with small seriation, but the big nomenclature of produced parts (including large-sized parts). Obviously, that use the individual additional equipment for fixing of each flexible part is not economically effective. Therefore, it is expedient to change technology of processing of specified flexible parts. This new technology should be based on using of industrial multilink manipulators and one universal device for fixing of all parts.

At using of such approach, it is necessary to take into account the main feature of processing of flexible parts - variability of spatial form of parts in the course of fixing and the subsequent processing.

This is inadmissible for the traditional industrial manipulators [2]. The control program of traditional industrial manipulators is formed in advance based on CAD model of parts and completely determines program motions of the working tool. Any change of the manipulator parameters and processed parts (for example, at the fixation with deformation) demands additional reprogramming, using of new procedures of debugging, etc. Noted features require the use of new intelligent architecture of information-control system of industrial robot and developing new algorithms of planning and correction of motion trajectory of working tool at processing of spatial flexible parts in the conditions of deformation. Conducted researches have shown, that to provide the formation and correction of tool motions in the course of machining of spatial flexible parts without their rigid fixing in individual equipment it is necessary to use the 3D vision systems, which allow to ensure exact data about parts in the form of cloud of points. Thus, in this paper a new method to automation of processing of flexible parts with complex spatial form without their rigid fixation is proposed. This method is based on two principles: 1) simple and rapid fixation of any part with the help of universal device with possible deformation its geometric form; 2) automatic generation and correction of motion trajectory of working tool of manipulator based on information obtained from the 3D vision system.

The conducted preliminary researches show that by means of universal fixing device, as a rule, it is possible to fix rigidly in strict accordance with CAD-model only a small set of processed flexible parts. Besides, the additional deformation of their separate segments at forced milling is possible. The processing of such parts on the basis of data only from CAD models will inevitably lead to big errors of motion of working tool of manipulator and therefore to incorrect processing.

In the course of the analysis of possible approaches to automatic processing of flexible parts by means of multilink manipulators, three variants of change of their geometrical form were considered. These variants will significantly influence to cutting strategy and key technical solutions. The first variant assumes that parts are fixed rigidly, correspond to their CAD models and will not deform during processing. These parts can be cut by using only CAD-models. The second variant supposes the rigid fixation of parts in universal device without deformation during processing, but without the corresponding to its CAD - models. In this variant, the important task is formation of geometrical model of spatial tool motion trajectory. This task can be solved with use of the 3D optical scanners [3], which capable to give the exact data about fixed with deformation parts. The third variant supposes fixation of flexible parts with discrepancy of CAD models and their possible deformations in the course of processing. In this variant, it is necessary to compensate in real time deformations which arising in parts from tool acting. This compensation can be achieved by using information about arising deformations of concrete segments of the marked cutting line at continuous tracking of their by stereo video camera which should be mounted near with end-effector of manipulator. In this paper, we will consider features of practical realization of two last described approaches, which are most perspective at realization of modern robotic complexes for processing of spatial flexible parts without their rigid fixation.

2. Developing of architecture of adaptive information-control system for manipulators with vision system

Discussed above features require the development of an architecture and set of subsystems of information-control system of manipulators, that will provide the generation and correction of trajectory of motion of working tool in real time during processing of spatial parts in terms of their possible deformation of the individual sites. Efficiently solve this problem is possible only using the synthesis principles of adaptive information-control systems [4]. This approach provides automatic generation of control programs of manipulators using knowledge of CAD - model of parts and information about the current state of them from vision system. Generalized block diagram of proposed adaptive information-control system for industrial manipulators is shown in Fig. 1.

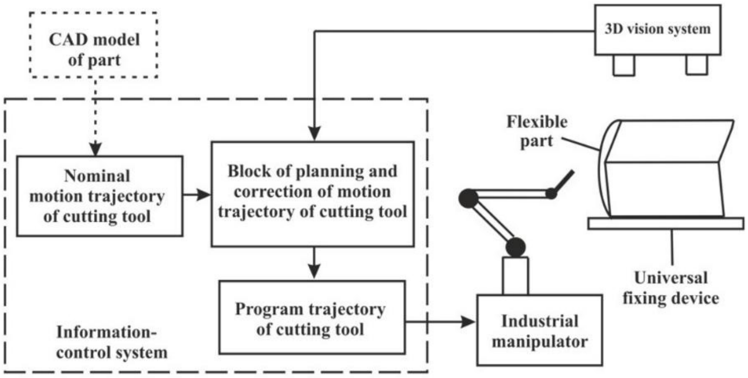


Fig. 1. A generalized block diagram of adaptive information-control system of manipulator.

The main source of sensory information are 3D vision systems (3D optical scanners and stereoscopic video cameras), which should supply information on the current CAD model of parts fixed in the universal device with deformation. Information from vision system in the form of points cloud transmitted to the control computer. Then it is possible to obtain the program trajectory of working tool based on the combination of the resulting CAD model of part with its nominal CAD model. Further, discuss the features of the formation of motion trajectory of the working tool on the basis of fusion data from CAD- model of parts and data from the vision system when there are real deformation of fixed parts. The solution to this problem is split into two phases. First, a new algorithm of combining models of scanned parts, fixed in the universal device and having real deformation, with their original CAD - models is developed. Second, the method of forming of new motion trajectory of cutting tool on scanned models considering its trajectory defined on the undeformed CAD - models is developed. Below we will consider the solution of these problems more detailed.

3. Development of the algorithm of combining the CAD model of fixed with deformation parts in form of point of cloud to its nominal CAD-model

Currently, there are several algorithms for combining CAD models of parts described by clouds of points. Qualitative of them is ICP algorithm [8]. However, this algorithm cannot take into account possible deformations of parts during fixing. This is because in the process of combining of two point clouds is minimized value of the mean-square deviation between pairs of nearest points of these clouds. In the presence of deformations in one of the clouds, this algorithm will generate a pair of points, the distance between which will be rather big even at ideal combination of these clouds on other couples of the next points. This effect leads to increase of functional of optimization, therefore the algorithm calculates parameters such conversion functions that reduce these long distances due to some increase in the others, which inevitably leads to incorrect combination of these clouds. For elimination of the specified problem at combination of two clouds of points, it is necessary to consider only deviations between couples of points corresponding to not deformed sites of items. At this case, expression for errors of combination of two clouds of points will be:

$$E(a,D,M) = \sum_{i=1}^{N_{dn}} \| d_i - m_{ni} \|^2 , \tag{1}$$

where N_{dn} is a quantity of points in the CAD-model, corresponding to not deformable sites of part; m_{ni} are points in the part model, belonging to its not deformed sites; *M* is cloud of the points describing scanned model of the part; *D* is cloud of points describing nominal CAD - model of part; d_i are points of cloud *D*.

However, there is a problem of determination of set of points from a cloud of *M* in (1), which belong to not deformed sites of parts. As existence and size of deformations in the fixed parts are unknown it is impossible to define which points it is necessary to reject from clouds of *M* and *D* for correct combination.

Because the distances between couples of the next points near the deformed sites of part are big, at combination of the corresponding clouds it is necessary to reject couples of the next points distances between which have the greatest values. Thus, it is necessary to define number of the specified couples as rejection of too large number also worsens the accuracy of combination of clouds of points. For solving of this problem is proposed to use an iterative algorithm, which is as follows. Initially clouds *M* and *D* are combined based on the full set of points within them. The result of combining is estimated by the mean-square deviation between pairs of closest points. If this size exceeds admissible, the share of rejected couples of the points having the greatest deviation is set. Then the algorithm combining repeated. If the value of the mean-square deviation again exceeds the permissible value, the proportion of discarded points increases and the combination is repeated as long as the value of the mean-square deviation becomes less acceptable. Further, we will consider offered algorithm, which consists of the following steps in more detail.

1. Preliminary combination of clouds of the points describing nominal CAD-model of part and scanned model of part, fixed in universal device.

2. If preliminary combination of clouds of points was executed with big deviations $(E > E_{des})$, combination of clouds repeats after rejection of a certain number of couples of the points corresponding to deformed parts of the part. These couples are defined on big distances between them, than at other couples by using the following algorithm. In the beginning, the array of couples of the next points of clouds is formed *M* and $D' = T(a, D)$:

$$P = \{m_i, d'_j\},\ i = (\overline{1, N_m}),\ j = (\overline{1, N_d}), \tag{2}$$

where D' are points of cloud, describing CAD-model of part taking into account the algorithm of combination of parameters of transformation received as a result of ICP algorithm work; m_i are points of cloud *M*; d'_j are points of cloud D'. Further sorting of array *P* (2) according to distance increase between points in each couple is made. From the received array P_S N_{neg} elements are removed:

$$N_{neg} = round(N_m \eta),$$

where η is a share of couples of the next points which shouldn't be considered during the work of algorithm of combination.

Thus, in the course of repeated combination it is necessary not only to form the array of couples of the next points, but also to make its sorting for the purpose of rejection of couples of points with the greatest distances. The specified procedure needs to be carried out on each iteration of work of algorithm of ICP.

3. If after repeated combination, resultant mean square deviation is more admissible, it is necessary to repeat a step 2, having increased a share of rejected couples of points by size Δ:

$$\eta(k+1) = \eta(k) + \Delta,$$

where *k* is a number of iteration of use of algorithm of combination of clouds of points.

It should be noted, that new iteration of combination of clouds of points should be begun from situation, which was reached on the previous iteration. In this case, completion of iteration of combination will require a small amount of iterations of algorithm of IPC as mismatches in orientation of these clouds of points will be insignificant.

Thus, the proposed algorithm can determine the position and orientation of parts with unknown deformations according to coordinate system of manipulator. Furthermore, the algorithm developed to determine areas of specific sites of parts, which have undergone deformation and to determine the magnitude of the deformation. All this information is contained in the pairs of points that are not used in the algorithm of combining models. It is evident that the considered algorithm requires more time for combination of said three-dimensional models of parts in case of deformation. However, this time is not determinative, since all calculations to determine the trajectory of the forthcoming cuts are made before the start of the processing of parts and require computational tools relatively low power.

After combination of clouds of points describing fixed part and its CAD - model, it is necessary to carry out calculation of coordinates of points of motion of working tool taking into account the deformations which have appeared in this part after its fixing. For its sites which have no deformations, the required trajectory of motion of working tool (let us consider the operation of cutting parts as an example) completely is defined by the line of the cut which has been set for CAD - models, by means of function of the transformation received at combination of scanned model of this part with its CAD - model. However, the deformed sites of these parts will require additional actions. Thus, there is a problem of development of algorithm of transfer of the points, which are precisely setting the cutting line on CAD-model on deformed sites of model of fixed parts. In the course of development of this algorithm will assume that the parts fixed in universal device have only the separate deformed sites, which will not be displaced on considerable distances. Also will assume, that the material of items don't stretch therefore at their deformation distances between the points entering a concrete cloud of points, describing three-dimensional model of a processed items don't change.

Taking into account the accepted assumptions the following algorithm of transfer of points of the cutting line with CAD - models on the deformed sites of the fixed parts represented in Fig. 2 is offered.

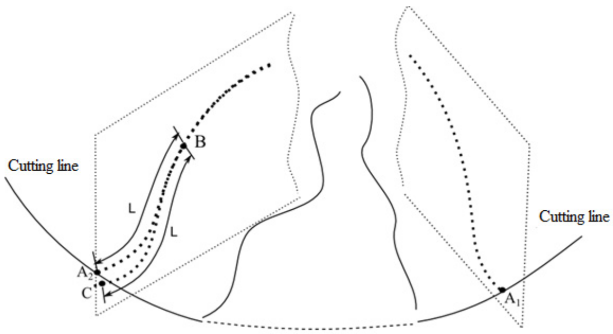


Fig. 2. Illustration of algorithm of transfer of points of the line of a cut from CAD-model on the deformed site of model of the fixed part.

After combination of clouds of the points describing CAD - model and model of the deformed part through points of the line of the cut, being for CAD - models (point A_1) and on model of the deformed detail (point A_2) we carry out sections the planes, perpendicular this line.

As a result we receive two sets of the points describing the profiles of two CAD-models which have both coincident (not deformed), and the different (deformed) sites (see Fig. 2). If the point A_2 of the cutting line defined for CAD – models a point A_2, located on not deformed site of model of the fixed item, A_1 point transfer in a point A_2 is carried out by means of the transformation received at combination of clouds of points and if - on deformed, on model of the fixed item it is necessary to find a point *B,* in which wasn't subject to deformation, and to shift along the section of the deformed model distance of *L*, equal to distance from a point *B* until point A_2. This procedure will define an arrangement of a required point from the cut line on model of the deformed detail.

4. Processing of flexible 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 flexible parts at the fixing in universal device can occur. The specified device also permit deformation of the parts fixed in it at the subsequent force acting from working tool on their surface in the course of spatial machining. As a rule, such deformation is possible at milling of thin-walled flexible parts.

For machining of such parts, it is necessary to form and correct automatically in the course of processing the working tool motion trajectory based on information on the current arrangement of the parts of trajectories of cutting marked on surfaces, received by means of stereo vision cameras. Thus, the stereo vision camera has to be fixed on end-effector of manipulator near with working tool [5 -7].

At the machining of deformable parts, 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 manipulator begins cutting of part in real time on the recognizable trajectory of cutting. Thus, the vision system fixed on end-effector carries out shooting of a site of a trajectory before working tool and in case of its deformation the control system of manipulator carries out correction of originally certain trajectory of movement tool by means of the data received from cameras. Let us consider the method of implementation of this correction.

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

One of the possible advanced approaches for cutting parts with arising deformation is to use the automatic formation and correction of tool 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 manipulator $O_pX_pY_pZ_p$. These coordinates are formed in advance in coordinate system connected with the basis of manipulator and can be received using CAD models of parts 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 ($l = 1, \ldots, N$, 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 items and are defined during experimental studies for each concrete part. On the basis of the obtained in advance and current data the control system of manipulator can form program speeds of movement tool on concrete cutting trajectories.

Process of milling of flexible parts (see Fig. 3) begins with a moving of tool to its surface in some initial point of cutting line (see A_1 point in Fig. 3) 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 tool to next point of trajectory A_2 (in advance created on the basis of CAD-model) there will be a mill deviation from a trajectory of cutting. It will lead to a stop of process of milling and by the beginning of new procedure of the working tool installation on this trajectory.

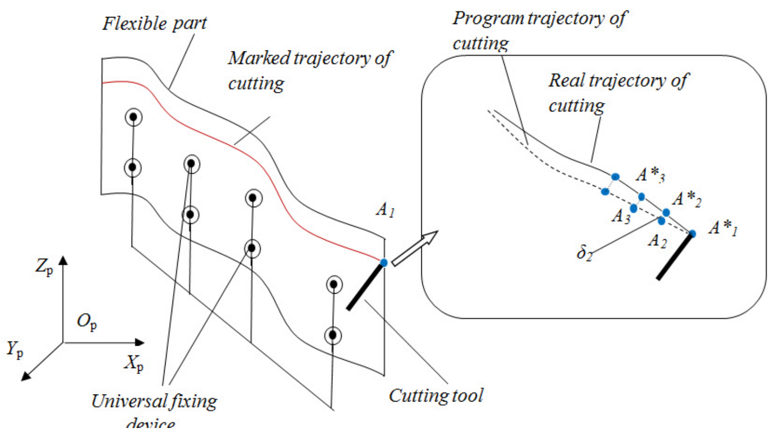


Fig. 3. Illustration of deformation of processed items under the influence of cutting tool.

To eliminate the arising deformation it is necessary to introduce the corresponding corrections in originally set cutting trajectory using stereo cameras near with cutting tool. This camera defining the current position of tool concerning to cutting line should provide the calculation of real spatial coordinate of the following point of cutting line on deformable segment of part (see A^*_2 point in Fig. 3) . At this, the control system of manipulator in tracking mode has to remove an arising mismatch between program coordinates of trajectory points and coordinates of real points, continuously received by means of stereo camera. Herein it is 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 cutting tool in the specified direction until the condition $\delta_l < \delta^d_l$ will start being satisfied.

For realization of automatic system of adaptive fine tuning of speed of movement of tool on the basis of the size of arising current deformation of flexible parts it is possible to use the approaches described in [9].

Another approach to working off of arising deformations is to use of force/position control system for manipulators providing not only exact movement of cutting tool on the set trajectory, but also simultaneous control of its force impact on surface of flexible part. As showed the conducted researches for development of high-precision force/position control system at the solution of problems of milling of flexible parts it is possible to use simultaneous force/position control system of multilink manipulators [10].

5. Modelling and experimental research of proposed algorithms

For check of algorithm of correction of motion trajectories of working tool on the basis of combination of the data obtained from optical scanner and CAD - models of parts, mathematical simulation was made. In the course of simulation the accuracy of combination of nominal CAD - model with the scanned model of this part having deformations was checked. Also we provide the investigation of the accuracy of transfer of the cutting line with CAD - models on the deformed sites of the fixed part.

The part model, which part was deformed, received from initial by CAD - models by means of its transformation in the editor 3DMax. Thus in the course of CAD change - distance models between points of its surface remained. Appearance initial (black color) and deformed (gray color) parts of model is shown in Fig. 4.

The right edge of the item fixed in device shown in Fig. 4, in comparison with its CAD - model is taken away inside. This type of deformation is chosen as the most probable at the parts fixation. The cutting line which has been set for CAD – models, also was deformed. During the simulation the accuracy of transfer of points of the cutting line with CAD - models on model of the deformed part was estimated. Thus, considered models were transformed to the clouds containing 191835 and 176093 points, respectively.

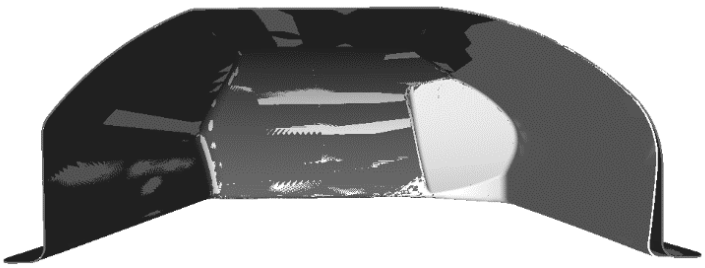


Fig. 4. General view of CAD models of the initial and deformed parts.

Results of work of algorithm of combination are shown in Fig. 5. In this figure the black firm line corresponds to mean square distance between the next points in combined clouds of points, the black dashed line corresponds to a mean square deviation between identical points of these clouds, gray - a share of rejected couples of the next points, and gray dotted – to number of the iterations which are carried out in the course of the next combination.

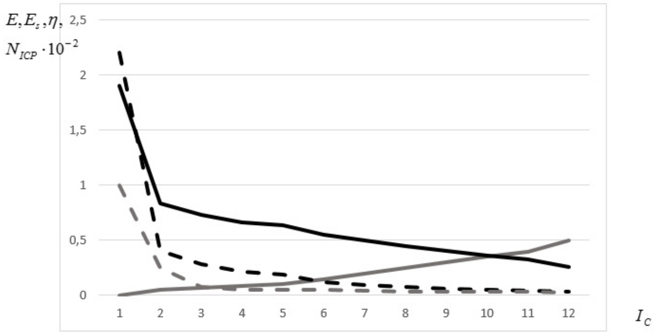


Fig. 5. Result of work of adaptive algorithm of combination of clouds.

On abscissa axis in this drawing number of iteration of algorithm of combination of clouds of points is postponed. From this figure it is visible that the offered adaptive algorithm of combination of two clouds of points possesses big efficiency. With its help, it is possible to combine the specified clouds with accuracy of 0.033 mm. In the course of accomplishment of combination 335 iterations of algorithm of ICP were executed totally, thus the first combination happens for 200 iterations. That is use of developed adaptive algorithm does not lead to the essential growth of time of calculations, but thus the accuracy of combination increases almost by 70 times.

From the figure, it is visible that by means of the algorithm developed in paper it is possible to transfer points of the cutting line with CAD - models to model of the deformed part with an accuracy of 0.2 mm.

Thus, results of the carried-out mathematical simulation confirmed efficiency and high precision of work of developed algorithm of adaptive correction of trajectories of movement of cutting tool on the basis of a fusion of the data received from system of technical sight and CAD - models of parts, in the presence of deformations in the course of fixing of these parts before cutting.

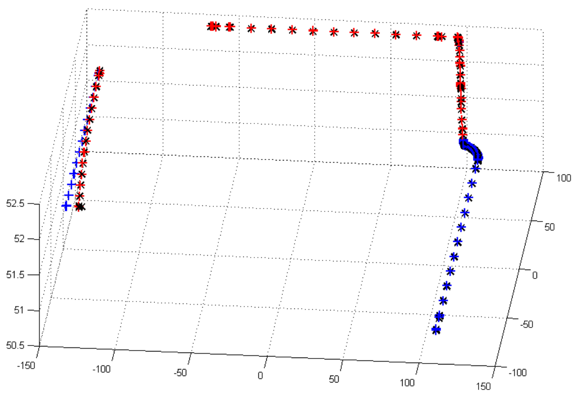


Fig. 6. Result of transfer of points of the cutting line with CAD - models on model of the scanned deformed part.

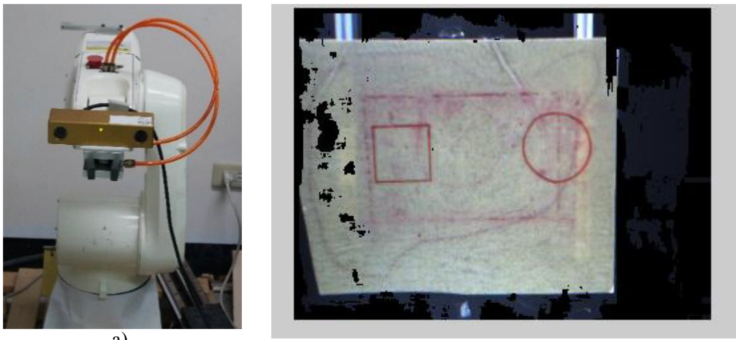
To confirm the efficiency of the chosen strategy and new approaches to processing of flexible parts by means of manipulator with vision system also were carried out experimental researches of efficiency of processing of parts with use of information on spatial cutting line received from stereo camera. In particular, the accuracy of determination of coordinates of the points forming line marked on part, by means of this stereo camera and the accuracy of tracking of the received trajectory by cutting tool 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. 7a.

Before carrying out of experiment in working zone of manipulator arbitrarily at some distance flexible part with previously marked contours in the form of a square with sides of 72 mm and circles with radius of 35 mm (see Fig. 7b) was established. During conducting experiment consecutive recognition of the marked trajectories, definition of their spatial position and orientation in coordinate system of stereo camera 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.

In experiment, imitation of automatic machining by means of cutting tool (the simulator of a laser cutting head) flat part on the revealed contours was made. The error of working off tool of both trajectories revealed by means of stereo camera did not exceed 0.5 mm.

As a whole, the provided experimental researches completely confirmed the efficiency of offered approaches and algorithms, and operability of the technical solutions, which have provided high precision of processing of flexible parts by means of multilink manipulators with vision system.



a) b)

Fig. 7. General view of experimental installation.

Conclusion

The conducted researches and experiments confirmed possibility of high-precision automatic processing of flexible parts by means of the manipulators, equipped by vision system, 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 and algorithms of correction of motion trajectories cutting tool on the basis of combination of the data obtained from optical scanner and CAD - models of parts. Future research will focus on improving the accuracy of the proposed algorithms.

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References

[1] Y. Altintas, Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, 1st ed. Cambridge University Press, NY, USA, 2000.
[2] J.J. Craig, Introduction to robotics: mechanics and control. Prentice Hall, 2003, 450.
[3] G. Marshall, G. Stutz, Handbook of Optical and Laser Scanning, Second Edition (Optical Science and Engineering). CRC Press, 2011.
[4] A.A. Petrov, A General System Logical theory and its Application to Task Descriprion for Intelligent Robots, Artificiial Intelligrncr and Information-Control Systems of Robots, Singapore: World Scirnt. Publ. (1994) 353-360.

[5] H. Wu, L. Lou, C.C. Chen, S. Hirche, Cloud-Based Networked Visual Servo Control, IEEE Transactions on Industrial Electronics. 60(2) (2013) 554 – 566.

[6] A. Dame, E. Marchand, Mutual information-based visual servoing, IEEE Trans. on Robotics. 27 (5) (2001) 958-969.

[7] M. Keshmiri, Wen-Fang Xie, A. Mohebbi. Augmented Image-Based Visual Servoing of a Manipulator Using Acceleration Command // IEEE Transactions on Industrial Electronics. 61 (10) (2014) 5444 – 5452.

[8] E. Munoz, J. Buenaposada, L. Baumela, Efficient model-based 3D tracking of deformable objects, Proceedings of the Tenth IEEE International Conference on Computer Vision (ICCV'05) (2005) 1-6.

[9] V. Filaretov, A. Gubankov, Adaptive system forming extremely high speed of multilink manipulator gripper, Proc. of the 23rd International DAAAM Symposium. Vol. 23, №1 (2012) 0473-0476.

[10] A. Zuev, V. Filaretov, Features of Designing Combined Force/Position Manipulator Control Systems, Journal of Computer and Systems Sciences International. 48(1) (2009) 146-154.