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REALIZATION OF THE CONCEPTION OF FRAME CONFIGURATION MACHINE-TOOLS

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РЕАЛИЗАЦИЯ КОНЦЕПЦИИ СТАНКОВ КАРКАСНЫХ КОМПОНОВОК

The realization of the frame-configurations conception machine-tools with parallel structure mechanisms is presented. Principles and laws of formation of less metal-consumption layouts of multifunctional processing equipment are formulated. Design procedure of the proposed structural formulas is defined. Techniques to perform directed search and design of new machinery, which corresponds to the high level technological purpose proposed and tested. The machine-tools samples implemented on the principles of the conception
Keywords: *machine-tools; parallel structure mechanisms; frame-configuration*

Introduction. Extensive research of parallel kinematic mechanisms (PKM) began in the 1960s from studies purely kinematic properties of structures with multiple closed circuits operating simultaneously, the basis of this was laid by I.I. Artobolevskiy, V. O. Astatin, V.A. Glazunov, A.Sh. Koliskor, A.I. Korendyaev, F. M. Dimentberg, E.I Vorobyov, Gutyrya S.S., Yavlinskiy V.P., K. Cappel, J. Denavit, V. Gough, C. Gosselin, J. Gwinnett, K.H. Hant, D. Stewart, K. Sugimoto, M. Nakagawa and the others. In these studies, primarily resolved the theoretical questions such as the synthesis of wide class of spatial mechanisms, defining function that related of incoming and outgoing links positions and their special “dead” positions; definition of the kinematic relations surplus; analytical solutions for direct and inverse problems of kinematics; the definition of working space. Improved manipulation properties of PKM determined the next stage of their development - application in robotic systems. In this particular area the researches have been conducted by famous scientists as K.I. Zabolonskiy, I.T. Monashko, B.M. Schekin, R. Clavel, L. Tsai, J.-P. Merlet, R. Stamper. PKM become using for operations control, welding, coordinate measuring, loading-unloading work.

Starting from the 1980s using of machine-tools with PKM greatly expanded. They began to be part of metal-working equipment to process complex geometry working-pieces. The first PKM machine-tools hexapods, were built on the basis of the classic Stewart platform. The study of PKM as a machine-tools dedicated by V.L. Afonin, A.F. Kraynev, V.V. Bushuev, V.A. Krizhanovskiy, Yu.M. Kuznetsov, I.I. Pavlenko, P.V. Podzorov, Yu.V Poduraev, V.I. Sidorko, V.B. Strutinskiy, I.G. Holshev, I. Bonev, J S.Chen, U.Heisel, M.Honegger, R. Katz, L. Kubler, M.Valasek and the others.

Existing methods of PKM kinematic schemes synthesis do not unambiguously choose its kinematic scheme because the same output unit displacements can be performed by using different kinematic schemes. As PKM kinematic chains, that connect a base with output links, work in parallel, so each kinematic chain has own operational limit that depends on initial links location. In addition, there are many different types of connections .That is why synthesis of manufacturing equipment, built on the basis of mechatronic systems with PKM should be concorded with specific production tasks.

Purpose of work (article) - promotion of the main results of the Ukrainian scientific school studies (founder professor of the Department of designing machine tools and machines "KPI" Kuznetsov Yu. N) for the implementation of the proposed concept of a new generation of machines with computer numerical control (CNC), including PKM.

Statement of the problem. For developing usage of parallel structures in machine-tools, expanding to deepening areas of PKM employing in metal-working there are some requirements, namely [1, 2]:

1. Ensure high accuracy of processing and positioning the tool and the workpiece.
2. Provide increased rigidity of the moving links.
3. Multitasking of machine-tools new generation.
4. Ensure the necessary degree of freedom (DOF) of the end-effector (EE) to perform multifunctional tasks.
5. Increase the size of the machine-tools EE working space (WS).

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6. Provide high-performance processing.
7. Make free access for loading (unloading) of details, for maintenance and for tool and equipment installation.

PKM machine-tools configurations expansion and their improvement possible through the use of shell and frame structures constructed as for specific technological requirements and as for standardized units and components. This is achieved by the fact that the axis of the main frame to which the sliders translation movement mechanisms are attached such as that their point of intersection in the machine-tool layout are arranged in such a way to form a spatial polyhedral frame. Also the number of rods and guides mounted on the edges of the frame can be increased to the necessary number of drives, which allows to increase the functionality of the EE with the relative decline the layout mass-dimensional characteristics, increasing its stiffness and expansion of machine-tool technological capabilities. The essence of the proposed concept [7], which provides genetic and morphological approach, the use of frame and shell structures bearing systems [1, 2], aggregate-modular principle arrangements [1, 3, 6], advanced information technology and intelligent computer systems [1, 4].

Main part. Here are the basic system views to implement technical solutions according to the requirements of the modern trends of new metal-working equipment of machine-tool industry [3, 6].

POSITION 1 *(multiversion)* – is a formalized process of designing machine-tools with PKM. The main idea is taken multiversion of guides position in the machine-tools layout as geometric operators in layout field. Consider the process of designing machine-tools with PKM as some technical multilevel system, defined by the performance functions

$$\Pi = F_T \wedge F_G \wedge F_l \wedge F_m \ ,$$

where F_T - set of technological tasks; F_G - construction of extra-rigid rod structures by guides in the layout space; F_l - conditions for rod system coupling; F_m - set of functional machine modules that complements layout.

Function F_T establishes correspondence between work-pieces (details) set and their surfaces with machine-tool EE formative movements that determines the type of operation

$$\forall(P \in D)\exists(w \in W) \Leftrightarrow p_i \underset{D}{\forall} P \underset{W}{\exists} w$$

where $P = \{p_i....p_j\}$ - work-pieces surfaces set; D - work-pieces set ; $W = \{w_i...w_j\}$ - EE DOF and their combinations set. Therefore, $F_T{:}D \times P \to W(X \vee Y \vee Z \vee A \vee B \vee C)$.

The function $F_G{:}G \times N$ sets the relationship between layout rigidity and layout compactness that is formed by number of guides and conditions of their spatial position and interlocation. Thus, $G = \{g_i....g_j\}$ - guides design set, $N_g \in G$ - variable G range of geometric position parameters and guides coordinate systems orientation subset.

Function K_i specifies by joints kinematic properties set and by joints relevant class constraints, where K_i - kinematic pairs set, *i* – kinematic pair class.

The main idea is taken multiversion of guides position in the machine-tools layout as geometric operators in layout field. PKM machine-tools frame layouts correspond to frame layouts combinations sets. Frame layout of any machine-tool is a guides set and also consists of lower and upper bases. The upper base usually reduced to minimal sizes, namely point, line or any flat polygon, circle or frame polyhedron. The lower base usually either in the form of the polygon with the same shape as upper base or another shape polygon, circle, etc. The supporting stationary part of the machine-tool is shaped like a frame with vertical and inclined bars and centre axis of bars are parallel, crossed or have common points of intersection on the lower and upper bases and can be located above or below the moving platform with EE. At that translation movement mechanisms are mounted either at frame bars or at plane between frame bars. Configurations multiversion for one technological purpose is due to a variety of geometric shapes dimensional arrangement of functional modules and machine-tools design and due to character formation in metal-processing, performed by the relative movement of workpiece and tool. The same relative forming movement can be realized at different mobile blocks disposition relatively to each other and relatively to stationary unit.

POSITION 2 (*supporting system frame*) - use metal-intensive rigid blocks for modules and guides in the PKM equipment layout. Analysis of known configurations of machines with PKM that use constant length rods indicates that almost all of them are limited to prismatic system with elements to attach sliding carriages (massive columns, membranes in the form of wells, superstructure-massive bridges, cross arms, etc. Taking into account the structure complexity of the machine-tools with gear rod system the concept foresees that these machine-tools layout structure can be described fully only by step-by-step multi-staged description of the layout configurations with using of computer software. Then as symbol designation of the formula of coordinate and basic configurations of machine-tools with PKM only partly reflects their structure at the analysis. To create description of the stationary block proposes coding reference of PKM frame connections with stationary block on which it is based, in the form of binary relations of two matrices, namely, three-dimensional stationary block matrix $\|SB\|$ and three-dimensional detail working space matrix $\|3ws\|$ [3]. Between matrices $\|SB\|$ and $\|3ws\|$ there is a functional relationship $F(L_{i=N-n}) \subset [\|3ws\| \cap \|SB\|]$ in the form of rod system (either variable length rods or fixed length rods). One rods ends are attached to stationary block $\|SB\|$ on guides and theirs characteristic points belongs to this space $F(L_N) \subset \|SB\|$, and the other ends of the rods are in the detail working space $F(L_n) \subset \|3ws\|$ on the movable platform, or EE, which determines its position in the detail working space $\|3ws\|$. The order *n* matrix $\|SB\|$ and $\|3ws\|$ defines the dimension of the detail working spaces and stationary base also can take any value with steps between intermediate waypoints i, j, k, which can take any value for both spaces separately $\|3ws\|^{n(i)\times n(j)\times n(k)} \neq \|SB\|^{n(i)\times n(j)\times n(k)}$, and in the own space $n(i) \neq n(j) \neq n(k)$. Over matrices $\|SB\|$ and $\|3ws\|$ in the PKM machine-tools layout performs logical and mathematical operations. Logical operations characterise quality relationship between them, and mathematical characterise quantity (constructive) relationship. The system of rods $F(L_{i=N-n})$ in this definition stands as mathematical operator between $\|SB\|$ and $\|3ws\|$. The absolute value of the length of the rods is not taken in to account. Changing values i, j, k in the space $\|SB\|$ or $\|3ws\|$ and parameters $F(L_{i=N-n})$ in the ratio $\|3ws\| \cap \|SB\|$ there is a possibility of new configurations formation of machine-tools with the PKM, which should be in concordance with the symbolic notation of relevant structural layout formula. Thus, structural formula symbolic record that reflects the layout image should consist of variations with ratio $F(L_{i=N-n}) \subset [\|3ws\| \cap \|SB\|]$.

POSITION 3 (*hybridity*) - combination of mutual preferences of traditional structures and PKM. Layout structures analysis shows that the companies prefer the first group of machines – with variably-manageable length rods, abandoning the benefits of traditional configurations. At the same time the best solutions, perhaps, are between the traditional layouts and the first group of machine-tools where EE in form of tools placed on the platform, jointly connected with the base by constant length rods, as it implemented in the second group of machine-tools. This is third approach in aggregate-modular principle of layout construction of machine-tools with PKM based in the proposed concept for hybrid structures that have the same number of controlled coordinates as hexapod machine-tools.

Hybrid structures construction is not a new phenomenon, but not sufficiently developed in terms of componatics – the modules interrelations properties in the module set of equipment. Usually traditional coordinate modules (rotary spindle head, software-controlled machine tables) complemented the PKM at the located closer to the work-piece end of coordinate branch. That spoils overall effect of using PKM and increases size and metal intensity of the machine-tools.

POSITION 4 (*layout symmetry*) - desire for symmetrical and mass balanced unit arrangement of modules in the PKM equipment layout. PKM machine-tools frame layouts correspond to frame layouts combinations sets. Frame layout of any machine-tool is set of the guides and also consists of lower and upper bases. The upper base usually reduced to minimal sizes, namely point, line or any flat polygon, circle or frame polyhedron. The lower base usually either in the form of the polygon with the same shape as upper base or another shape polygon, circle, etc. The supporting stationary part of the machine-tool is shaped like frame with vertical and inclined bars and centre axis of bars are parallel, crossed or have common points of intersection on the lower and upper bases and can be located above or below the moving platform with EE. At that translation movement mechanisms are mounted either at frame bars or at plane between frame bars.

Symmetry properties allow to perform qualitative configurations conversion and quantitative adjustment of individual modules in the middle of layout by mathematical methods of rotation and reflection with respect to the axes and planes of symmetry.

POSITION 5 (*modular structure layout*) - uses common modular functional blocks and design to create PKM equipment with desired characteristics. Modular design allows to create a new high-performance equipment for optimal processing of work-pieces, and do not adapt the process to limited possibility of already existing equipment. The module is characterized by the smallest possible number of connections for the accession to it of new modules. Limited range of modules provides a multitude of different configurations of the machine-tools through the variety of combinations and positions of modules. The main advantage of the modular principle is the presence of the potential to provide a preliminary (prior to design) ranking of technical system elements. Frame layout analysis of equipment with parallel kinematics shows that all it consists of a specified number of modules. The choice of process equipment modification depends on complex technological problems, weight and dimensions of the details of its structural forms, the number of parties that are processed. The choice of specific modifications of technological equipment depends on technological problems complex, the mass and dimensions of the work-piece, the number and complexity of processed sides.

POSITIONS 6 (*visual software simulation during layouts creation*) - providing rapid assessment of kinematic properties and quality indicators check for PKM equipment, that may include any kinematic links composition in the frame layout. PKM kinematic links formative movements visualization is an integral component of the design of new configurations of machine-tools with parallel kinematics. The use of powerful software systems for calculating the kinematic and dynamic characteristics of future high-tech machine-tools, which are currently few, will reduce their development time and find the optimal layout. However, the development of software environments directly depends on the improvement of algorithms for calculating the properties of PKM. To create hierarchically connected software models of PKM machine-tools is necessary to determine the form of mathematical description of links movements as a system of geometric transformation and implement EE managing software.

The above mentioned configurations principles outline of combination groups of ways to mount rods (rails) with base defined as $C(n,m)=\frac{(n+m-1)!}{m!(n-1)!}$, where n - the number of rods (rails) m - permutation capacity. The geometrical properties of machine-tool base determine the quantity of permutation variety m (PKM kinematic scheme counts as constant).

The guides are located in one plane comply with conditions:

$$G \times N_g^S \to S$$

$i_p{:}g_k \vee G \in S, g_i \,||\, G$, - intersect any G_k guides – others parallel $m=k$, where $i_p \in I$ guides connection control points set;

$i_p{:}g_k \vee G \in S, \overline{g_i \,||\, G}$ - all guides are not parallel and intersect at various points;

$i_p{:}g_k \vee i_p \in I, \overline{g_i \,||\, G}$ - all guides have shared intersection point;

$i_p{:}\overline{g_k \vee G} \in S, g_i \,||\, G$ - all guides are parallel.

The guides are located in different planes comply with conditions:

$$S \times N_g^V \to V$$

$l_p{:}s_k \vee S \in V, s_i \,||\, S$, - intersect any S_k plane – the other parallel $m=k$, where $l_p \in L$ support surfaces crossing lines set;

$l_p{:}s_k \vee S \in V, \overline{s_i \,||\, S}$ - all the planes are not parallel and intersect in different lines;

$l_p{:}s_k \vee l_p \in L, s_i \,||\, S$ - planes are intersect the shared line;

$l_p{:}\overline{s_k \vee S} \in V, s_i \,||\, S$ - all planes are parallel.

The total set of combinations of guides attached to the frame base in the machine-tools layout.

$$S \times V \to \Omega .$$

Calculation of the position options for guides in the layout frame determines the main groups of machine-tools with PKM and with of constant length rods (the same kinematic type of drive links): (N=1296, m=7), (G_N=3; N=27225), (m=8, G_N=4);(N=511225, m=9, G_N=5);(N=1002001, m=10, G_N=6).

At fig. 1 show examples of new configurations according to accepted conditions of the frames formation of the lower and upper bases bearing system.

The new concept of hybrid frame configurations principles [2] can create new layout tools with parallel kinematics with the necessary degree of freedom of EE to perform multi-tasks by distributing technological movements between traditional structures and parallel modules.

The most favourable development seems machine-tools configurations with constant length rods; moreover this concept can be the most effectively implemented by using a modular principle of design (table 1).

The concept of PKM machine-tools hybrid frame layout can be implemented most effectively by using modern unified units and modules that use various components based on the same modular principle.

Due to different functional modules that placed on moving platform (spindle units with drives the main motion, either with power-operated tool actuator or without it) on stationary frame (coordinate traditional blocks) using different feed drives systems, and PKM machine-tools guides, equipped with constant or variable length rods, allow to create different machine-tools with different number of controlled coordinates.

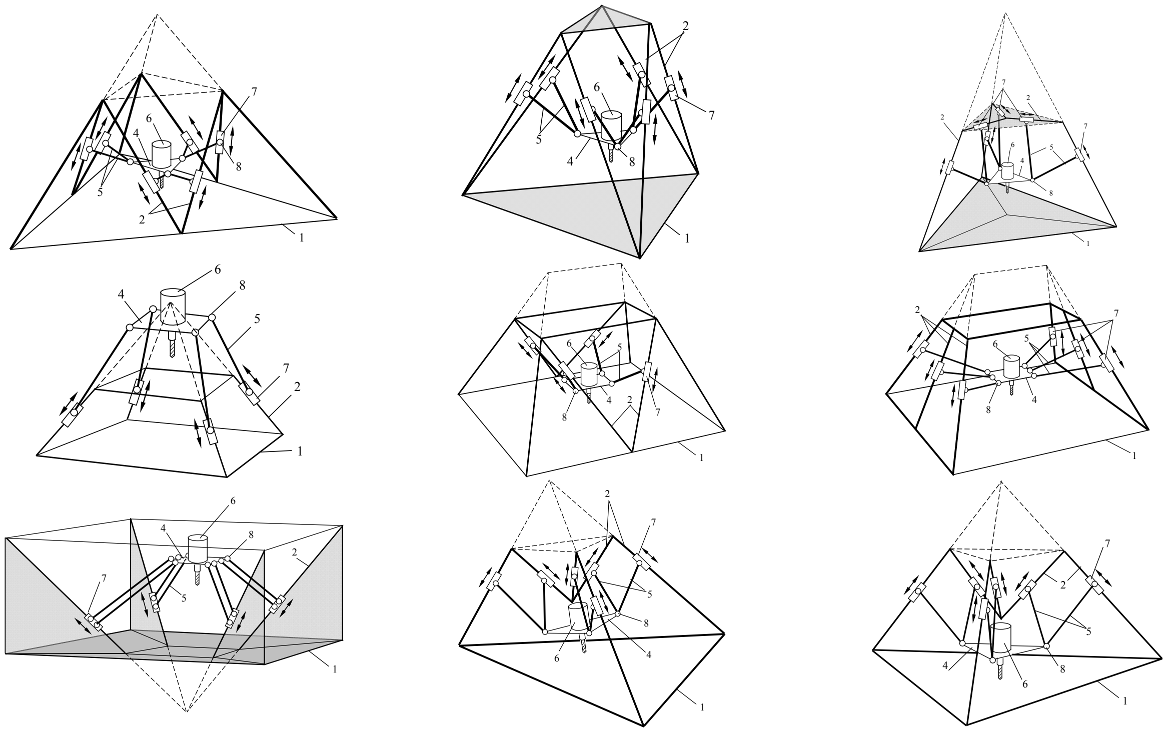
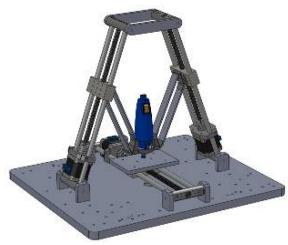
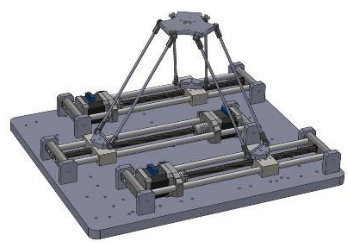
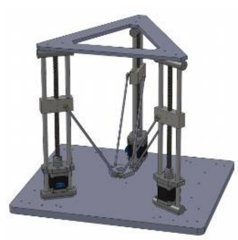
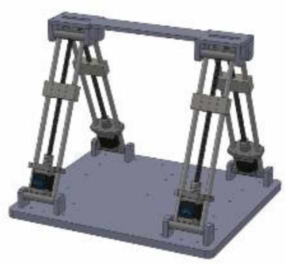
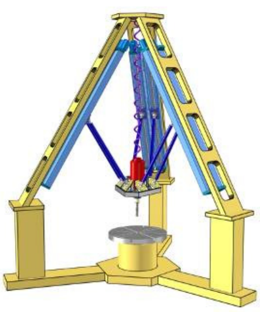
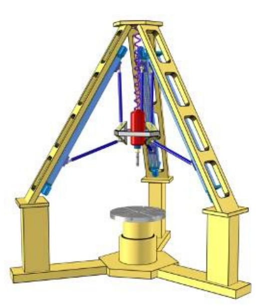
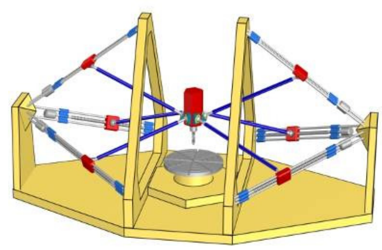


Fig. 1. Examples of forming a frame configurations set with depending on the functionality

Table 1

Selected basic layout solutions for traditional machine-tools and with parallel kinematic structure

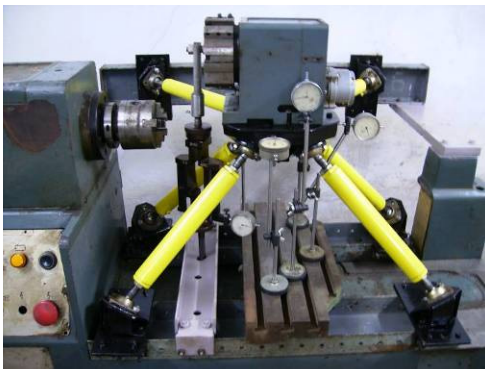
Biglide with movable table	Horizontal triglide	Vertical triglide
		
Triglide-pyramid	Tetraglide-pyramid	Tetraglide-wedge
		
Hexaglide-machine-tool with pyramidal frame layout		
		

At National Technical University of Ukraine "Kyiv Polytechnic Institute" produced a line of machine-tools to perform processing of complex geometry work-pieces. Machine-tools guide sliders at *l*-coordinates that form pyramidal frame and the work-piece in the XY plane, depending on the basic movements of EE in the workspace.

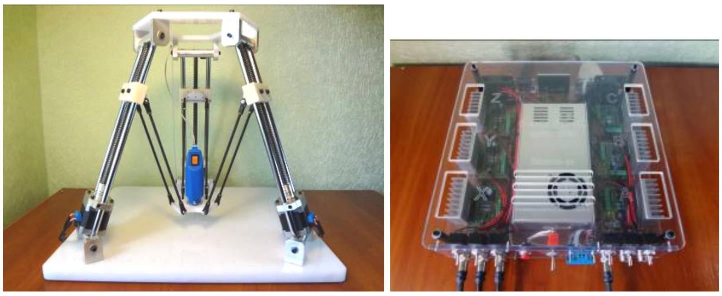
Machine-tools control system builds on the concept of Personal CNC , which has one-software architecture in which all control tasks (geometry, logic, terminal) resolved solely through software without using additional hardware devices. For interacting between computer and machine-tools control electrical parts uses special controller, which the convert computer signal to the step motor analog signals [4]. The computer receives signals of machine-tools EE zero position sensors. The controller has three independent axes in three coordinates and works by STEP/DIR (step/direction) protocol with LPT computer port in real time. The controller receives information on the steps number and direction of rotation that has to execute by step motors.

a - frame layout three coordinate drill-mill machine-tool with PKM [7]

b - frame layout five coordinate drill-mills machine-tool with PKM [5, 7]



c - multi-purpose machine-tool hexaglide [2, 7, 11]



d - machine-tool triglide with pyramidal frame layout and universal control system controller [4, 7]

Fig. 2. Frame configurations prototype models of machine-tools with PKM built for research

Conclusions. Principles of new technological equipment with PKM are systematized, based on the principles of multifunctionality, low metal-intensity, symmetry, hybridity, modularity, and software mathematical visual modelling. The basic group of PKM machine-tools layout frame configurations are exposed that correspond to frame layout rods combinations set and implemented in the form of existing test machine-tools. The concept of frame configurations allows to create new machine-tools with parallel kinematics with the required EE degree of freedom to perform multi-tasks by distributing technological movements between traditional structures and parallel modules.

Анотація. *Розглянуто принципи та закономірності формування малометалоемких компоновок багатофункціонального оброблюючого обладнання. Визначено проектні процедури, запропоновані структурні формули і прийоми, що дозволяють виконати спрямований пошук і проектування нового верстатного обладнання, яке відповідає високому рівню і технологічним призначенням. Показано виготовлені авторами дослідні зразки верстатів з механізмами паралельної структури, побудовані на принципах концепції створення верстатів каркасних компоновок.*
Ключові слова: *верстати; паралельні структурні механізми; конфігурація рамки.*

Аннотация. *Рассмотрены принципы и закономерности формирования малометалоемких компоновок многофункционального обрабатывающего оборудования. Определены проектные процедуры, предложены структурные формулы и приемы, позволяющие выполнить направленный поиск и проектирование нового станочного оборудования, которое соответствует высокому уровню и технологическому назначению. Показаны изготовленные авторами опытные образцы станков с механизмами параллельной структуры, построенные на принципах концепции создания станков каркасных компоновок.*
Ключевые слова: *верстать; параллельные структурные механизмы; конфигурация рамки.*

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