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DESIGN OF PARALLEL LINK MOBILE ROBOT MANIPULATOR MECHANISMS BASED ON FUNCTION-ORIENTED ELEMENT BASE

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Для створення ефективних маніпуляторів мобільних роботів запропонована функціонально-орієнтована елементна база. Вибір елементної бази здійснено на основі аналізу схемних рішень маніпуляторів мобільних роботів. Обгрунтовано, що ефективними схемними рішеннями маніпуляторів є механізми з паралельними кінематичними зв'язками. Раціональною конструктивною схемою прийнято механізм, що має шість штанг змінної довжини (гексапод). Розглянуті схеми маніпуляторів мобільних роботів із різним числом і видом суміщених опор штанг. Доведено, що для реалізації різноманітних схем може бути застосована однотипна елементна база у вигляді сферичних шарнірів. Розглянуті різні варіанти реалізації схемних рішень маніпуляторів, побудованих на запропонованій функціонально-орієнтованій елементній базі. Сформульовані основні вимоги до елементної бази маніпуляторів мобільних роботів. Показано, що задоволення поставленим вимогам забезпечує функціонально-орієнтована елементна база на основі гідростатичних або аеростатичних шарнірів різного виду.

Запропоновано ряд варіантів схемних і конструктивних рішень регульованих сферичних гідростатичних та аеростатичних шарнірів. Високими точністними характеристиками відрізняється гідростатичний сферичний шарнір, що включає точну кулю із кераміки (карбід бора). Проведена технологічна апробація даного схемного рішення шляхом виготовлення експериментального зразка.

Розроблено регульований гідростатичний шарнір, оснащений мехатронною системою встановлення просторового положення сфери. Дане конструктивне рішення дозволяє регулювати положення сфери шарніра в межах діаметрального зазору.

Запропоновано комбінований аеростатично-гідростатичний опорний вузол агрегатований з приводами маніпулятора. Вузол має струменеву систему регулювання опорних реакцій аеростатично-гідростатичних опор сферичного шарніра. Проведена технологічна апробація розробленого пристрою.

Для підвищення ефективності запропонованої елементної бази розроблено спеціальні алгоритми системи керування положенням сферичних шарнірів маніпуляторів. Алгоритми розроблені на основі математичного моделювання динамічних процесів у шарнірних пристроях. Алгоритми включають реалізацію просторових полігармонічних переміщень сфери із цілеспрямованим вибором напрямку результуючих переміщень, що забезпечує необхідну точність та швидкодію процесу регулювання положення шарнірів маніпулятора

Ключові слова: мобільні роботи, схеми маніпуляторів, гідростатичні шарніри, аеростатичні опори, алгоритми керування

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1. Introduction

Parallel link manipulators have a high load capacity at low mass compared with traditional constructions. Such manipulators are effectively used in terrestrial robotic complexes designed to work with hazardous objects because they can significantly improve their mass and dimensional characteristics. The use of devices of this type is constrained by the lack of an effective element base. Therefore, work aimed at creating a function-oriented element base, which will enable the necessary functions of manipulators and improve their characteristics, is a vital issue.

2. Literature review and problem statement

The studies in the literary source [1] are devoted to the development of a device, which includes a complex configuration manipulator. At the same time, considerable attention is paid to kinematics, but the features of the element base functioning are not taken into account. The publication [2] presents the results of the analysis of statics and dynamics of manipulators. Unresolved issues include the practical implementation of the system with improved dynamic characteristics. Considerable attention is paid to the requirements of manipulators, reliability and load-carrying capacity in particular [3]. The ways and methods of ensuring the accuracy of manipulators are indicated in the literary source [4]. It is shown that the accuracy parameters depend significantly on the dynamic properties of manipulators. Unresolved issues include the need to consider the change in the inertial properties of parallel manipulators. The study of the dynamics of manipulators is described in [5]. The dynamics of the manipulator for mobile robotic systems depends on the road conditions and the type of propeller [6], but there is limited data on the element base of manipulators, in particular, mobile robotic systems. On the basis of the literature review, it is found that the problem in general is to create an element base, which will ensure the design of highly reliable manipulators with necessary work life in tough operating conditions. The source [7] states that key elements of the manipulators are hinges that provide mobility of spatial structures and drive system manipulators. The improvement of the characteristics of these elements is a promising way, which will increase the technical level of mobile robot manipulators. The publication [8] outlines a number of requirements for geometric parameters, the ranges of transverse angular displacements of joints, in particular. Separate designs of manipulator hinges constructed on the basis of parallel link mechanisms [9] are considered. The study of the dynamics of spatial manipulators is discussed in [10]. As a result of research, it is found that taking into account dynamic processes of different speed scale allows to improve the positioning accuracy of manipulators.

The above-mentioned literary sources do not suggest specific technical solutions for hinges that provide the necessary characteristics for accuracy, rigidity and speed. Therefore, as a result of the analysis, it is found that there is an unresolved part of the general problem focused on the development of a function-oriented element base of mobile robot manipulators designed on the basis of parallel link mechanisms.

3. The aim and objectives of the study

The aim of the study is to develop and technologically test a function-oriented element base of mobile robot manipulators designed on the basis of parallel link mechanisms.

To achieve the aim, the following objectives were set:

– to investigate schematics of mobile robot manipulators designed on the basis of parallel link mechanisms and define functional requirements to the element base of manipulators;

– to develop the design and manufacturing technology of the spherical hinge, which includes a high-precision sphere;

– to develop the design and manufacturing technology of an adjustable spherical joint with a drive, which is the main element of the manipulator on the basis of the parallel link mechanism;

– to conduct mathematical modeling of the mechatronic control system of manipulator hinges and to develop a dynamic regulation algorithm of the sphere.

4. Analysis of schematics of mobile robot manipulators

A promising type of mobile robot manipulators are systems based on spatial hinged mechanisms with drives for changing the size of individual parts of the mechanisms. Examples of such systems are tripod and hexapod mechanisms. Mechanisms with links of permanent length with movable pivots are also used. Currently, stationary manipulators, metal cutting machines, sensors, test machines, measuring machines of various types and others are developed and used. The most common are hexapod-type having six rods of variable length. Also, triglide-type manipulators with three rods of constant length with hinges moving along the guides are used. Hinges of different types are used in manipulators. The main part of the manipulator based on parallel link spatial mechanisms is the operational unit. To ensure a fixed position of the operational unit in space, it is necessary to fix at least three of its points A_1, B_1, C_1 (Fig. 1).

The figure shows the manipulator based on the hexapod mechanism, which has 6 joint hinged rod supports. Three of them A_1, B_1, C_1 are located on the operation unit, and three A, B, C are situated on the mobile robotic complex chassis. Depending on the number of joint supports n there is a corresponding schematic of the hexapod mechanism (Fig. 2).

All the proposed schematics can be implemented on the typical function-oriented element base, which includes hinges and drives adjusting the length of the rods.

A special case of a schematic is the mechanism without the joint supports. The mechanism is implemented as a module and includes a basic hexagon of the arrangement of hinges on the basis of the module (Fig. 3).

The hinges A,..., F are located on the basis 1 of the manipulator, and the hinges A_1,..., F_1 corresponding to the ends of the rods are connected to the operation unit 2. The base is installed on the chassis of the mobile robotic complex, and the operation unit is used to mount necessary mechanisms for manipulating objects and devices for object processing. The element base required for the implementation of this schematic includes joints with the required number of degrees of freedom and aggregated drives.

A schematic of the manipulator as a hybrid hexapod mechanism is proposed, which additionally contains two movable spherical supports.

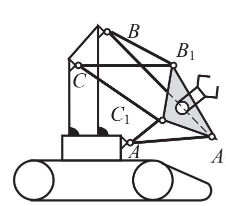


Fig. 1. Geometric scheme of mobile robotic complex with manipulator based on hexapod mechanism

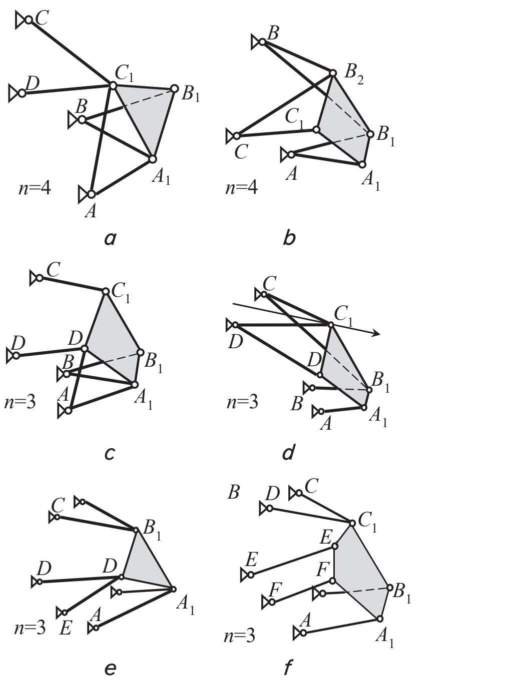


Fig. 2. Schematics of hexapod mechanisms with a different number of joint hinged supports: *a, b* – 4 joint supports; *c* – *f* – 3 joint supports

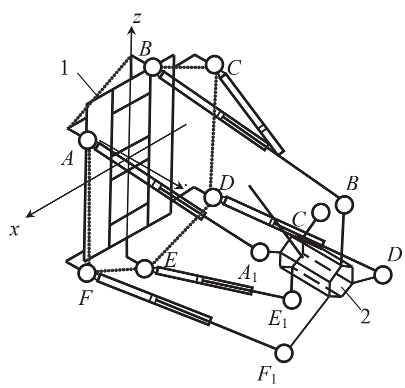


Fig. 3. Schematic of the manipulator based on the hexapod mechanism without joint hinges

To implement the proposed schematic, an element base in the form of hinges with a different number of degrees of freedom is required. The number of degrees of freedom is one of the functional requirements for hinges. As a rule, hinges with 2 and 3 degrees of freedom (spherical hinges) are used.

Hinge displacement, corresponding to the existing number of degrees of freedom, occurs in a certain range. Necessary ranges of transverse angular displacements are established on the basis of geometric analysis of the mechanism of the chosen scheme.

The proposed element base provides additional degrees of freedom of the hinge within micro-displacements in two or three directions. This makes it possible to improve the accuracy of the hinges significantly, and, accordingly, the accuracy of the manipulator in general. Micro-displacements of the hinges are carried out with special mechatronic control systems equipped with the proposed element base. The control system includes a hinge position meter.

An important functional requirement for an element base is the bearing capacity of the hinge. High load-bearing capacity is provided with minimal friction forces using a liquid or gas working medium. Therefore, the function-oriented element base is based on hydrostatic or aerostatic hinges of different types. The availability of a liquid or gas working environment causes the expediency of using hydraulic manipulators or pneumatic drives in manipulators. These statements are the basic constituents of the functional requirements for the element base of mobile robot manipulators based on parallel link mechanisms.

5. Design embodiment and technological testing of high-precision spherical hydrostatic hinge including high-precision sphere

As a rule, sliding and bearing supports on roller bearings are used in parallel link spatial mechanisms as hinge supports. The disadvantage of the sliding hinge is that there are significant frictional forces, backlashes and gaps in the friction pair. This results in significant static and dynamic loads in the hinge joint, increased wear of the hinge parts. Friction forces are much smaller in supports of rolling bearings, but mechanical contact causes abrupt load changes, impact, and, respectively, noise and vibration in the mechanism. As a result of the analysis of available technical solutions, it is found that the sliding and rolling bearings do not meet the requirements of mobile robot supports designed on the basis of parallel link mechanisms.

Non-contact hydrostatic supports meet the above-mentioned technical requirements. Such supports have high precision and rigidity, satisfactory damping qualities. The supply pressure in the hydrostatic supports is 4–6 MPa and higher. This fact determines the high bearing capacity of hydrostatic supports. In this case, the stability of the support position is ensured regardless of load variation. The problem of developing a spherical hydrostatic support is to provide high accuracy of the surface (about 1 μm). The problem is solved using an accurate ceramic (boron carbide, boron nitride) ball.

The variant of hydrostatic support with spherical insert element has been developed and its technological approbation has been carried out. Testing prototype of the support was made for this purpose, (Fig. 4).

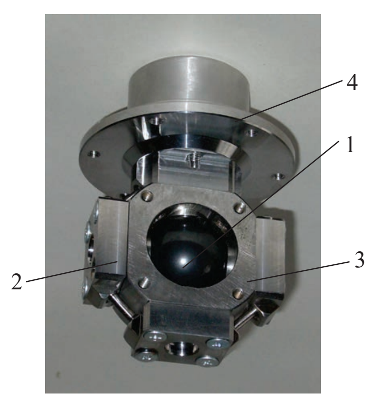


Fig. 4. Testing prototype of the manipulator hydrostatic support, which includes a ceramic ball: 1 – ball; 2 – support inserts; 3 – frame; 4 – lid

The ball made of boron carbide 1 has a deviation from sphericity of about 1 μm. Temperature changes practically do not affect the size of the ball. Spherical hydrostatic bearings interact with the sphere made in the supporting inserts 2 fixed in the frame 3, connected to the lid 4. The figure shows the joint, which enters the cavity of the support casing 5 (Fig. 5).

The casing 5 has openings 6, in which the sleeves 7 are fixed for holding the ceramic ball (Fig. 6).

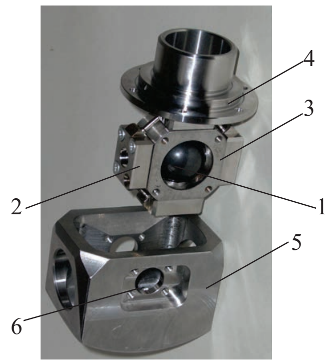


Fig. 5. Assembling the spherical support:
1 — ball; 2 — support inserts; 3 — frame; 4 — lid; 5 — casing; 6 — openings

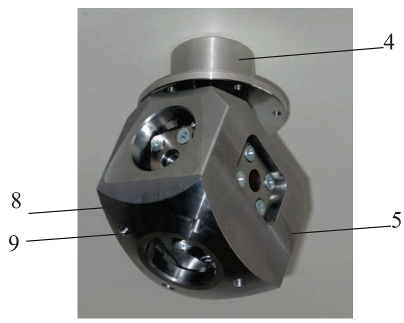


Fig. 6. Casing with openings for the sleeves to fix the ceramic ball: 4 — lid; 5 — casing; 8 — spherical surface; 9 — threaded openings

The lid 4 carries transverse-angular displacements in space within a certain range. On the casing 5, a spherical surface 8 is provided, in which threaded openings 9 are located for fixing the support casing. The availability of the spherical surface makes it possible to establish the required initial position of the support relative to the fixed base or manipulator.

The support lid is secured to the manipulator rod (Fig. 7).

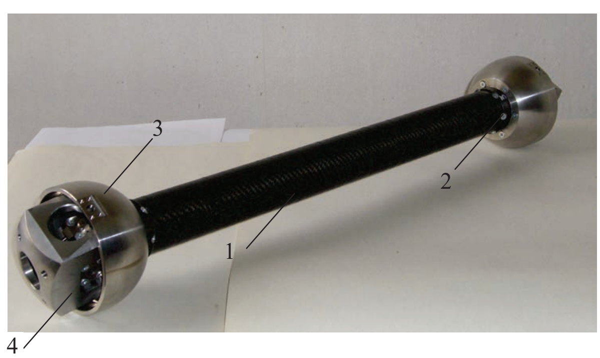


Fig. 7. Manipulator rod with spherical supports mounted at its ends: 1 — tube; 2 — screws; 3 — housings; 4 — casings of the supports

The rod has a tube 1 made of composite material (carbon fiber plastics). The lid of spherical supports is fixed on the tube with screws 2. Housings 3 are mounted on the lids, which protect the supports against dirt. Rubber-fabric metal bellows, which seal the cavities of the hydrostatic supports, are fixed on the housings. The casings of the supports 4 are fixed on a movable platform of the manipulator or on guide carriages. The rod is designed in different variants. It is possible to embody a rod of permanent length or install a drive with the screw-nut rolling transfer in the middle of the rod.

The developed high-precision spherical hydrostatic ball joint, which includes a ceramic ball, has high technical characteristics relative to the accuracy of the hinge position within 1 μm. The high hardness of the boron carbide or boron nitride ball determines the high durability and stability of the parameters of the hydrostatic hinge. Therefore, such a hinge is recommended as a typical representative of the function-oriented element base of manipulators of mobile robots designed on the basis of parallel link mechanisms. It is most expedient to use these hinges for hexaglide manipulators, having a rod of constant length. In this case, the errors due to changes in the rod length, can be compensated by the displacement drives of the hinge supports. The design of the hinge, which is improved in the direction of expanding its functionality by adjusting the position of the hinge sphere, is proposed for manipulators designed on the basis of ordinary spatial mechanisms, as shown below.

6. Scheme and design embodiment and technological testing of an adjustable hydrostatic ball hinge

The developed hydrostatic ball support hinge is intended for the perception of the necessary loads (up to 5 kN) acting on the ball, and precise adjustment of ball position in space. Along with the adjustment of the ball position, the actual position of the ball relative to the hinge casing is measured. Adjustment and measurements of the ball position are provided with the hydroautomatics system.

The hinge ball can perform limited transverse-angular displacements within the cone at an apex angle of 40°. The displacement of the ball in the radial direction is conducted within the radial clearance between the ball and the walls of the casing and lid. The maximum diameter clearance can be 50–100 microns.

Additionally, the support hinge performs the function of supply and drainage of the working fluid to the moving parts of the manipulator drive system under significant changes in its position and configuration. The supply and drainage of the working fluid are performed through the openings in the moving hinge area and the corresponding communications in the support casing.

The adjustable hydrostatic support hinge is designed with a fixed casing 1 (Fig. 8).

The casing 1 is connected to the lid 2. In the ball cavity of the casing and the lid there is a movable ball 3. The movable ball is connected to the upper housing 4. Fittings 5 and 6 are installed in the casing and lid for the «nozzle-damper valve» meters and hydrostatic couplings.

The upper housing is attached through the metal bellow 7 to the bottom housing 8, which is rigidly connected to the fixed casing 1.

There are nine threaded openings in the casing arranged along the casing perimeter, and there are six threaded openings in the lid.

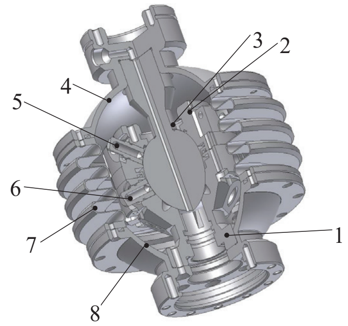


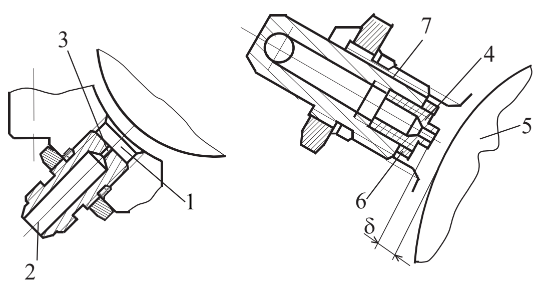
Fig. 8. Design embodiment of an adjustable ball hydrostatic support unit: 1 – fixed casing; 2 – lid; 3 – ball; 4 – upper housing; 5, 6 – fittings; 7 – metal bellow; 8 – bottom housing

Six openings in the casing are used to install three «nozzle-damper valve» ball position meters and three hydrostatic couplings. Three openings in the casing are used to install three hydrostatic couplings. Six openings are used to install three «nozzle-damper valve» meters and three hydrostatic couplings.

Threaded openings are identical. There are hydrostatic couplings with metering valves or «nozzle-damper valve» meters (Fig. 9).

Hydrostatic couplings (Fig. 9, *a*) have chambers 1, to which the working fluid is fed from the main line 2 through the metering valves 3. The «nozzle-damper valve» ball position meter (Fig. 9, *b*) has a nozzle 4 whose end is located parallel to the surface of the ball 5.

The nozzle 4 is installed with the ability to move along the axis of the meter. It ensures the adjustment of the initial position of the nozzle.



a *b*

Fig. 9. Scheme of the hydraulic system: *a* – hydrostatic coupling; *b* – «nozzle-damper valve» meter

The lock nut 6 is used to fix the nozzle. A groove 7 is provided on the threaded part of the meter, which serves to drain the liquid from the meter cavity.

The adjustable ball hydrostatic support unit has a branching water scheme which includes a number of subsystems. The main subsystem is the perception subsystem of the support reaction and ball displacement in the direction of the *z* axis. This subsystem combines six hydrostatic couplings 1B, 3B, 5B, 1H, 3H, 5H, grouped in two zones: upper (1B, 3B, 5B) and lower (1H, 3H, 5H) (Fig. 10).

Couplings are connected through a metering valve to a proportional hydrodistributor valve P1. The perception of the support reaction and ball displacement in the *x* and *y* directions is carried out by three hydrostatic couplings 1D, 2D, 3D, which are connected through metering valves in a differential scheme to two proportional hydrodistributor valves P2, P3.There is a system for measuring the ball position, which contains three pairs of «nozzle-damper valve» meters included in the differential scheme. The pairs of meters (4H, 6B), (2H, 4B) and (6H, 2B) are located in three diametrical directions relative to the ball.

The meters are connected to the membrane transducers П1–П3, which determine the value of the pressure difference for each pair of meters. The movement of the membranes is recorded by the tensile meters Δ_1–Δ_3.

In the system of automatic control of the adjustable spherical hydrostatic support there is an intelligent control unit (not shown in Fig. 10), which serves to form the necessary laws for the displacement of the hydraulic distributors P1–P3 taking into account the measured actual spatial position of the sphere.

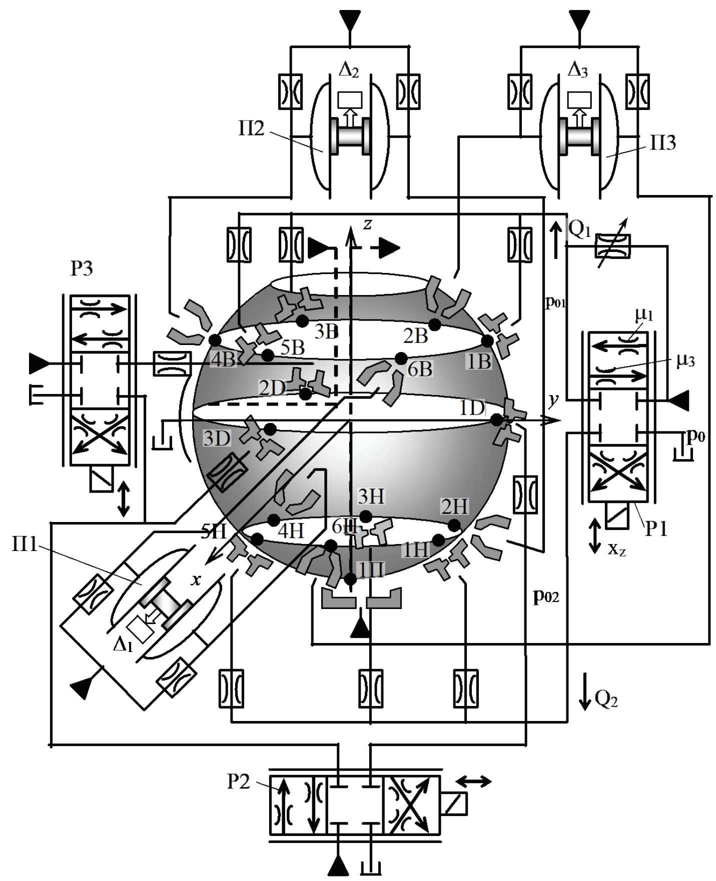


Fig. 10. Hydraulic scheme of an adjustable ball hydrostatic support unit

The developed adjustable spherical hydrostatic support unit has wide functionality in terms of providing accuracy and adjusting the hinge position. Such a unit is recommended as a progressive representative of the element base of mobile robot manipulators. This unit should be used as hinges of manipulators with links of variable length, designed according to hexapod mechanisms. In this case, the errors of the manipulator are compensated by direct regulation of the positions of the corresponding support units.

The disadvantages of these support units include the need for cavity sealing and insufficient flexibility of adjustment. Therefore, the adjustable support unit is improved in the direction of using a liquid and gas or gas working environment and improving the efficiency of sphere position regulation. In this case, the possibility of aggregating the support unit with the drive for changing the length of the manipulator link connected to the hinge, as shown below, is foreseen.

7. Spherical adjustable aerostatic and hydrostatic support unit aggregated with the manipulator drives

The developed spherical aerostatic and hydrostatic support unit is aggregated with the drive to change the length of the manipulator rod. The device can use both liquid and gas as a working medium. In this case, the device is allowed to work on a gas and liquid mixture. The unit accepts loads in the range up to 500 N and provides effective regulation of the sphere position up to 100 microns.

The hinge of the support unit has a casing 1, to which the lid 2 is connected (Fig. 11).

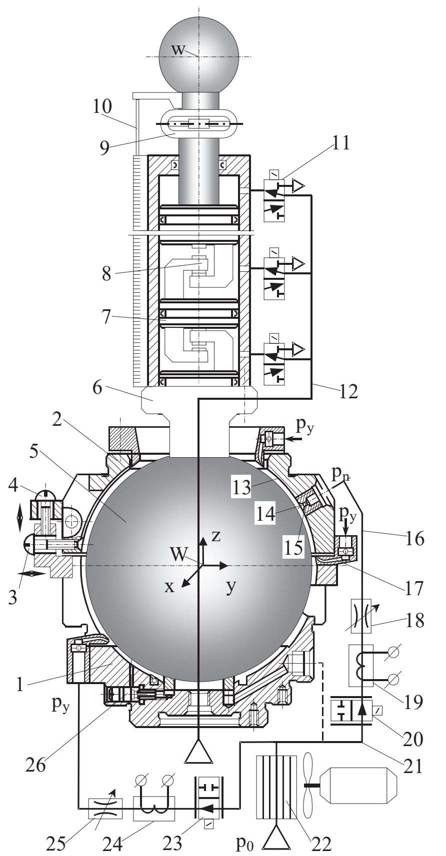


Fig. 11. Design scheme of adjustable aerostatic and hydrostatic spherical support with a drive to change the rod length: 1 – casing; 2 – lid; 3, 4 – screw drives; 5 – precise spherical surface; 6 – manipulator rod; 7 – pistons; 8 – detent; 9 – micro-displacement device; 10 – meter; 11 – adjustable throttles; 12 – tubing; 13 – pockets; 14 – throttle; 15 – support units; 16 – tubing; 17 – nozzle; 18 – throttle; 19 – heater; 20 – distributor; 21 – tubing; 22 – radiator; 23 – distributor; 24 – heater; 25 – adjustable throttle

The device has special screw drives 3 and 4 designed to move the lid relative to the casing. As drives, screw mechanisms and special thermomechanical displacement drives are used. Screw mechanisms serve for initial adjustment of the support, and thermomechanical – to compensate for the temperature deformations of the manipulator parts, which occur when the temperature changes.

The casing and the lid have a cavity with sections of precise spherical surfaces 5, in which a mobile sphere is placed with a gap, connected with the manipulator rod 6 constructed on the basis of the parallel link mechanism. Spherical sections of the casing and lid are equipped with aerostatic and hydrostatic supports with inserts. The supports have throttles, which are supplied with air or liquid under pressure p_n. The support unit has several aerostatic and hydrostatic supports. Some of them have adjustable throttles, which allow, within certain limits, to control the average (zero) position of the center of the sphere *W* relative to the casing.

The support unit has a hydraulic jet system for adjusting the bearing capacity of individual aerostatic supports. This is done by the dynamic action of jets of the working fluid on the peripheral areas of the aerostatic supports. The jets are formed in nozzle devices made by the method of laser stereolithography. The change in the pressure of the working fluid p_{y1}, p_{y2}, p_{y3} provides a change in the parameters of the jets, and, accordingly, the sphere position adjustment relative to the casing in the x, y, z directions.

The support unit has communications for the supply of liquid or gas to the moving rod, which is an integral part of the manipulator mechanism and includes rod length control drives.

Electromechanical, hydraulic or pneumatic devices are used as drives. The proposed schematic and design solution, shown in Fig. 11, includes discrete action drives (digital drives). The drives have a number of pistons 7 with detents 8, as well as the microdisplacement drive 9. The precise dimensions of the rod length are determined by the meter 10.

Discrete action drives are guided by a special system, which includes a number of distributors that feed the working environment in the cavity of cylinders. The working fluid supply to the regulated throttles 11 is carried out from the tubing 12.

The movable sphere is installed in the casing and lid on static liquid friction supports (aerostatic or hydrostatic). The support units are arranged regularly along the periphery of the spherical surface. The support units 15 have pockets 13, in which the working environment is fed from the tubing 16 through the unregulated throttles 14.

The support units have a system of nozzle devices 17 on their periphery, which serve for the hydrodynamic locking of the gap at the outlet or aerostatic and hydrostatic support unit.

Each support unit has an autonomous adjustable power and control system. Adjustment of the medium flow to the pocket of the aerostatic support is carried out by a system of adjustable throttles 18, 25 and heaters 19, 24. The supply of the working medium to the throttling system is carried out through the distributors 20, 23 from the tubing 21, into which the working medium cooled in the radiator 22 is fed. The adjustment of flow parameters in the nozzle devices is carried out by similar control systems, including adjustable throttles and heaters. Design embodiment of adjustable throttle allows manual adjustment of the throttle resistance and provides the necessary initial position of the movable sphere.

Adjustment of the sphere position is carried out in different ways: the change of the mutual position of the elements and deformation of the support parts, heating of separate areas of the parts, introduction or disconnection of additional supports, change in flow rates and thermodynamic parameters of the working environment.

The support unit has a system for measuring the sphere position relative to the casing. Non-contact «nozzle-damper» meters are used for this purpose, which are included in accordance with the above-mentioned scheme (Fig. 10).

The developed design scheme served as the basis for the production of the support unit prototype. Technical documentation has been developed, technological problems of support production have been solved. The support prototype was made. The main aspects of the technological support of quality parameters are the parts of the support unit with precise spherical surfaces (Fig. 12).

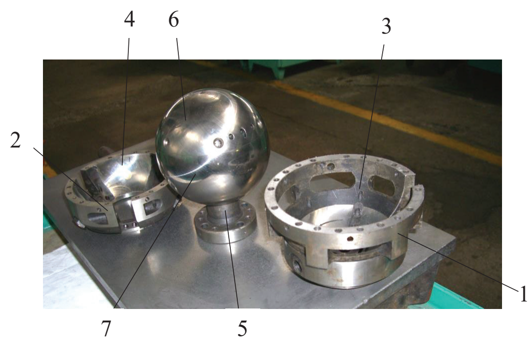


Fig. 12. Main parts of the produced support unit and areas of the precise spherical surfaces of the parts: 1 – casing; 2 – lid; 3 – spherical segment; 4 – spherical sector; 5 – movable sphere; 6, 7 – spherical surfaces

The main technological difficulties of manufacturing the support unit are in the processing of areas of precise spherical surfaces of the casing, lid and sphere. The casing 1 and the lid 2 have spherical surfaces in the form of a spherical segment 3 and spherical sectors 4. Spherical surfaces of the casing and lid are performed with a tolerance of sphericity of 15–30 microns. The inner spherical surface of the lid 2 has an adjustable geometry, which causes significant deviations of the real surface from the nominal spherical surface. The movable sphere 5 of the support unit is made of two separate parts with precise spherical surfaces 6 and 7, which are fixed on a common axis 5. Spherical surfaces, designed on the upper and lower halves of the moving sphere, must coincide with each other and when compiled to form one precise spherical surface. Ensuring the accuracy of this surface is carried out by fitting the base and centering surfaces in the connection of the upper and lower halves of the moving sphere. The intermediate and final control of the resulting surface is carried out on a measuring machine (Fig. 13) with the processing of measurement results by a special method.

Geometry measurements of the assembled unit of the movable sphere were carried out within one installation of the sphere on the table of the measuring machine. Measurements of the real surface of the upper half of the movable sphere are made within the square section of the projection of the spherical surface on the horizontal plane 0*xy*. When measuring the probe of the measuring machine scans the spherical surface while moving in the *x, y* directions, corresponding to the horizontal axes of the Cartesian rectangular coordinate system *xyz*. Geometry measurements of the lower part of the sphere were made by scanning of the spherical surface while moving the probe in the *xz* and *yz* directions. It is found that the deviation from the sphericity of the set sphere is within 7 μm.

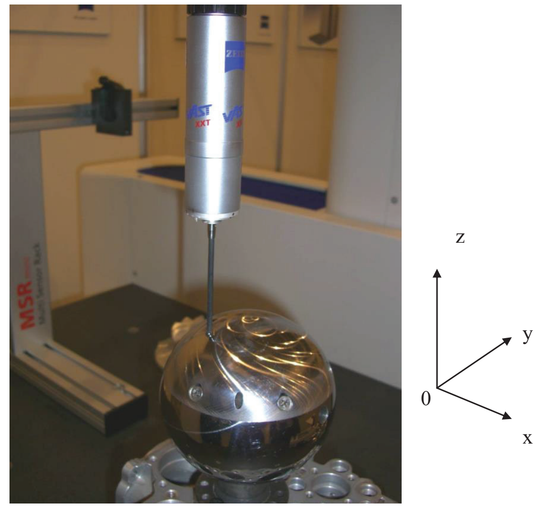


Fig. 13. Measurement of the spherical surface of the movable sphere with the measuring machine when scanning the surface in the direction of x and y coordinates

The developed spherical adjustable aerostatic and hydrostatic support unit is aggregated with the manipulator actuators. It is recommended as an effective element base of mobile robot manipulators designed on the basis of parallel link mechanisms. The application of the liquid-gas medium substantially increases the efficiency of the hinge unit of the manipulator. A flexible system for adjusting the sphere position provides high precision indicators of the manipulator. Improved accuracy is further ensured by special algorithms for the control system of the support unit, the development of which is carried out on the basis of mathematical modeling results, which are set out below.

8. Mathematical modeling and hinge control system and algorithm for adjusting the sphere position

Improved accuracy of the hinge is realized using a special algorithm for adjusting the sphere position based on the mathematical modeling of the dynamic control processes of the support unit.

Dynamic characteristics of the spherical support unit are defined through the system of transfer functions, which describe the dynamics of each hydrostatic coupling and sphere displacement as a whole. This system of transfer functions is implemented as a structural model.

The vector equation of the sphere dynamic displacements in an arbitrary direction (Fig. 4) has the form:

$$m\frac{\mathrm{d}^2\vec{e}}{\mathrm{d}t^2}=-\vec{F}_\Sigma(t,e)-b\frac{\mathrm{d}\vec{e}}{\mathrm{d}t}+\vec{F}(t), \tag{1}$$

where m is the mass of the movable sphere; $\vec{F}_\Sigma(t,e)$ is the total force acting on the sphere in the e direction of all hydrostatic couplings 1B, 3B, 5B, 1D–3D, 1H, 3H, 5H and 1П; b is the coefficient of resistance within sphere displacement; $\vec{F}(t)$ is external dynamic loads on the sphere; t is time.

The vector equation (1) corresponds to three scalar equations defining the projections of the sphere displacement on the *x, y, z* coordinate axis. The most important is the sphere movement in the direction of the *z* axis, which coincides with the rod axle.

To simulate the sphere displacement in the z direction from equation (1), we obtain a scalar equation that determines the sphere displacement. In accordance with this equation, a structural mathematical model is designed in the Simulink system of the Matlab R2014a package. The structural model has the form of a dual integration circuit with local feedback (Fig. 14).

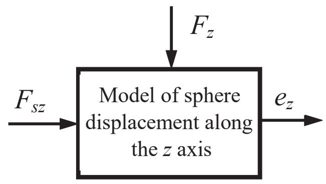


Fig. 14. Research of sphere dynamic displacements

The inputs of this model are the projection onto the z axis of the external load on the sphere F_z and the total force F_{sz}, acting on the sphere in the z direction of all the couplings. The output of the model is the sphere dynamic movement ez in the direction of the z axis.

The sum of the responses of all individual couplings of the support is determined by the dependence:

$$F_{\Sigma}(t,e)=\sum_{i=1}^{N}F_i(t,\delta_i)\cdot\cos\alpha_i,$$

where α_i is the angle between the direction of sphere displacement (z axis direction) and the axis of the i-th coupling; $F_i(t, \delta_i)$ is the force acting on the sphere from the i-th coupling, which received a gap change $\delta_i=e\cdot\cos(\alpha_i)$, as a result of displacement e.

The total force acting on the sphere in the z direction of all couplings is determined by the structural model (Fig. 15).

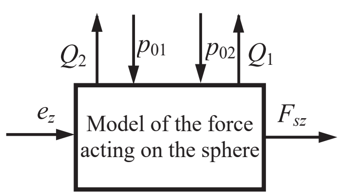


Fig. 15. Mathematical model of the total force acting on the sphere in the *z* direction of all hydrostatic couplings

The inputs of this model is the pressure difference p_{01}, p_{02}, which is formed at the output of the hydraulic distributor P1 (Fig. 13). The dependent input of the model is the sphere displacement e_z and the pressure in the cavity of the support unit p_{a1}. The outputs of the model are the total force F_{sz} acting on the sphere and the flow of liquid through all three couplings (1B, 3B, 5B) of the upper belt Q_2 and all three couplings (1N, 3H, 5H) of the lower belt Q_2. The relationship of pressure and losses of the distributor is established by means of a special model. The mathematical model of the throttle distributor is constructed using the equations of the hydraulic characteristics of fluid flow in the adjustable throttles of the hydrodistributor. The model links the values of the pressures p_{01}, p_{02} with the parameters of the distributor by the following relationships:

$$p_{01}=p_0-\frac{\rho}{2}\frac{Q_1}{\mu_1^2 f_1^2}|Q_1|,\quad p_{02}=p_c+\frac{\rho}{2}\frac{Q_2}{\mu_3^2 f_3^2}|Q_2|, \tag{2}$$

where p_0, p_c are supply pressure and hydraulic tank pressure; ρ is the fluid density, μ_1, μ_3 are flow coefficients in liquid flow through throttle gaps of the distributor; f_1, f_3 are equivalent to the intersection area of the throttle gaps; Q_1, Q_2 are flow rates of liquid and hydrolines at the distributor output.

It is accepted that the intersections of the throttles correspond to fuzzy dependencies:

$$f_1=f_0+kx_z+\delta f_1,\quad f_3=f_0-kx_z+\delta f_2, \tag{3}$$

where f_0 is the nominal equivalent gap area; x_z is spool displacement; k is the coefficient of proportionality; δf_1, δf_2 are the fuzzy equivalent area changes of the cross section of the distributor gaps.

Fuzzy equivalent gap area changes also take into account changes in the flow coefficients of the gaps.

Therefore, in the mathematical model it is assumed that the flow coefficients correspond to some average values and are constant. So:

$\mu_1=\text{const}$, $\mu_3=\text{const}$.

On the basis of dependences (2) and (3), a structural mathematical model of the hydrodistributor is constructed.

The structural model of the distributor (Fig. 16) has spool displacement xz as the main input and liquid flow Q_1, Q_2 in hydrolines as additional inputs.

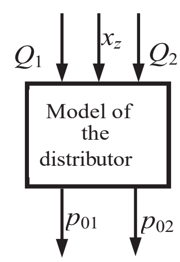


Fig. 16. Mathematical model of the hydraulic distributor P1

Fuzzy changes in the characteristics of the spool distributor included in the dependences (3) are given in the mathematical model by random processes with constant spectral density at different frequencies of perturbations of the operating frequency range.

The outputs of the mathematical model of the distributor are the values of the pressures p_{01} and p_{02} at the distributor output.

By combining the block models of the distributor (Fig. 16) with the strength characteristics of the support unit (Fig. 15) and dynamic displacements of the sphere (Fig. 14), we obtain the general structural-block model of the control system of the support unit in the z coordinate (Fig. 17).

The structural mathematical model is proved by the calculation of the transitional process of sphere displacement z with a step change in the input signal in the form of displacement of the spool p_1 x_z.

From the analysis of the transition process, the time of the transition process is 0.7...0.8 s. There is a significant readjustment of the system (120 % or more).

In order to improve the dynamic properties of the system, it is expedient to introduce feedback loops on the actual position of the sphere in space using the measurements of the actual sphere position.

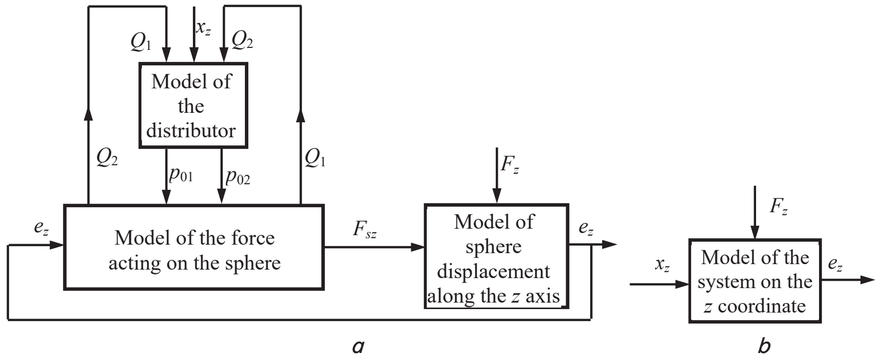


Fig. 17. Control system of the support unit in the *z* coordinate: *a* – structural-block model; *b* – block diagram of the given model

The mathematical model of the control system of sphere position by the *z* coordinate is supplemented with similar models for the *x* and *y* coordinates and a mathematical model of the measurement system of sphere position. As a result, a general mathematical model of the control system was obtained (Fig. 18).

The control system has an intelligent block that generates an optimal control algorithm of the sphere spatial position. The output of the intelligent block is the signals corresponding to the displacement of the spools of the distributors. Data about the actual position of the sphere is given to the block input in the form of three spatial coordinates of the sphere corresponding to the measured values Δ_1, Δ_2, Δ_3. The main input parameters of the block are external signals U, φ, Θ, which specify the necessary spatial position of the sphere center.

On the basis of the conducted mathematical modeling of the mechatronic control system of the support unit, a rational algorithm for dynamic adjustment of sphere position was developed. The algorithm provides for increasing the speed of the adaptive automatic control system of the support unit and improving the control characteristics of the unit.

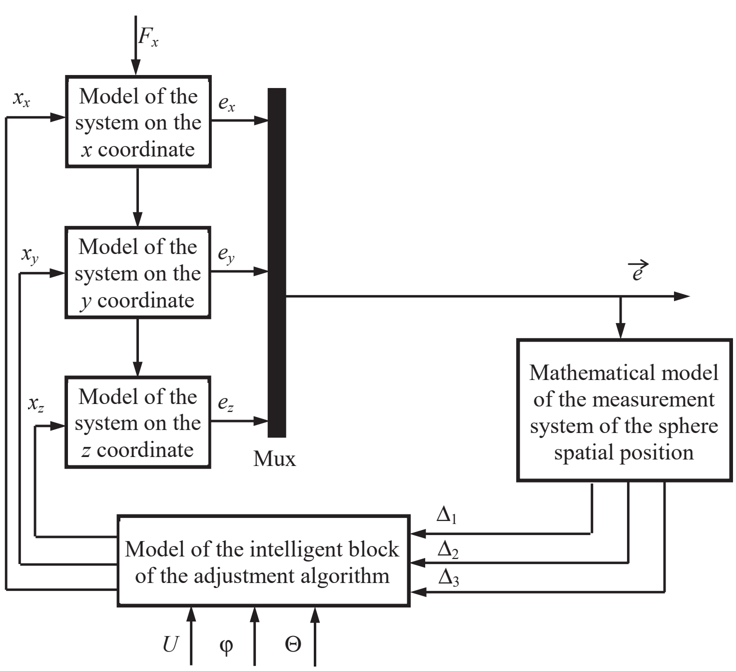


Fig. 18. Block diagram of the general mathematical model of the control system of the support unit

The algorithm is based on the principle of dynamic (pulse) displacement of the sphere. Dynamic adjustment of the support unit is carried out by additional oscillatory displacement of the spools according to harmonic laws. This ensures the pulse change in pressure and flow in the supply channels of the working fluid to individual hydrostatic couplings, which allows for the implementation of the polyharmonic laws of changing the sphere position.

According to the developed algorithm, the sphere displacement in the ξ direction corresponds to the polyharmonic law:

$$\xi = \alpha_1 \cdot a_x \sin\left(\omega_x t + \psi_x\right) + \alpha_2 \cdot a_y \sin\left(\omega_y t + \psi_y\right) + \\ + \alpha_3 \cdot a_z \sin\left(\omega_z t + \psi_z\right), \quad (4)$$

where α_1, α_2, α_3 are directional cosines, which define the direction of sphere displacement ξ; a_x, a_y, a_z are the amplitudes of sphere displacements in the *x*, *y*, *z* directions; ω_x, ω_y, ω_z are the frequencies of sinusoidal displacements of the sphere; ψ_x, ψ_y, ψ_z are the initial phases of the sinusoidal displacements of the sphere.

The directional cosines included in the dependence (4) are determined by the input parameters φ, Θ of the support unit and the given direction of sphere displacement x. The frequencies of sinusoidal displacements of the sphere with an established oscillatory motion correspond to the frequencies of sinusoidal displacements of the spools of the hydrodistributors. The amplitudes and initial phases of the polyharmonic law of sphere displacement are determined by the frequency characteristics of the support unit and the automatic control system.

The polyharmonic law of sphere displacement in an arbitrary direction determined by the dependence (4) corresponds to the sphere center dynamic displacement by the type of spatial Lissajous figures.

Lissajous spatial figures cover some volume, the geometric position of the sphere center in space. There are trajectories of dynamic sphere displacements within this volume. Depending on the frequency ratio of the components of the oscillations included in (4), the shape of the sphere center trajectories and the geometric location of the sphere center points in space change.

According to the proposed rational algorithm, the intelligent block of the adaptive control system defines the necessary frequency ratio of the projections of the sphere harmonic displacements while changing the volume configuration, where the sphere center is located, from ellipsoidal to discoid. Thus, the sphere displacement in the direction perpendicular to the disk plane is reduced to zero.

Thus, there is a purposeful change in the sphere position in a certain direction, and, accordingly, regulation of the sphere position as the main element of the hinge mechanism of the manipulator.

9. Discussion of the research results of the function-oriented element base of mobile robot manipulators

According to the research results, terrestrial robotic complexes, equipped with parallel link manipulators, have considerably better mass and dimensional characteristics.

A promising element base of hinge mechanisms with drives changing the size of individual links requires the use of hinges and aggregated drives.

The developed spherical hydrostatic hinge (Fig. 4) is a typical representative of the function-oriented element base, because it provides high accuracy. The errors caused by changes in the rod length can be compensated by the hinge. The developed support unit (Fig. 8) can accept significant stresses acting on the sphere; its another function is to provide measurements and control the sphere position in space.

The support unit adjustment is carried out using the hydraulic circuit (Fig. 10), and the automatic control system ensures the formation of the necessary laws for the displacement of the distributor spools. The advantage of this approach is that the manipulator errors are compensated by the direct adjustment of the respective support units.

The technology for manufacturing parts of the support unit was developed through experimental testing. The main technological problem that has been solved is to provide the quality and accuracy parameters of parts with precise spherical surfaces. It was found in the course of experimental research that the adjustable geometry of parts allows to compensate the deviation of the real spherical surface from nominal.

The real geometry of spherical surfaces is determined using a measuring machine (Fig. 13). The presented mathematical models do not fully take into account the deviation of the real spherical surface from nominal. Therefore, the direction of further research is to take into account the real geometry of spherical surfaces in the study of working processes in hydrostatic support elements.

Improved hinge accuracy is accomplished by mathematical modeling of dynamic processes of the support unit. Dynamic characteristics of the spherical support unit are defined as a system of transfer functions that describe the dynamics of each hydrostatic coupling according to the dependence (1), as well as sphere displacement. The developed mathematical model takes into account the working processes of the throttle distributor according to the dependence (2).

The unification of the block models of the distributor (Fig. 16) of the power characteristic of the support unit (Fig. 15) and sphere dynamic displacements (Fig. 14) allows us to obtain a general structural-block model of the control system of the support unit (Fig. 17). The control system, developed on the basis of the presented model, will allow high accuracy and adjustment possibility of the support unit.

The optimal control algorithm of the sphere position requires dynamic regulation, which uses the polyharmonic law of sphere displacement and corresponds to the dynamic sphere center displacement by the type of Lissajous spatial figures. According to the proposed algorithm, the necessary frequency ratio of the projections of sphere harmonic displacements is set, while changing the volume configuration, where the sphere center is located, from ellipsoidal to discoid. Thus, the sphere displacement in the direction perpendicular to the disk plane is reduced to zero.

10. Conclusions

1. As a result of the research, it was found that a promising type of mobile robot manipulators are systems based on spatial hinge mechanisms with drives for changing the size of individual parts of the mechanisms. To implement the proposed schematics, the element base in the form of hinges with a different number of degrees of freedom is required, ensuring the load-bearing capacity, precision and adjustment possibility.

2. The developed adjustable hydrostatic support unit provides the perception of a dynamic load of up to 5 kN and the range of adjustment of the sphere position –25...+25 microns in an arbitrary direction. The adjustment is carried out with the help of the developed automatic control system, which allows to change the supporting reactions of hydrostatic support elements, provided that feedback sensors are used to determine the sphere position in space.

3. The structural mathematical model is based on the block principle and includes the blocks describing hydrodynamic processes occurring in the supporting elements, which allows obtaining the power characteristic of the support unit, as well as the blocks describing hydrodynamic processes in the distributors. The structural mathematical model also includes the block describing the dynamic movement of the sphere and allowing dynamic analysis of performance and synthesis of the control laws of the spherical support unit.

4. To improve the dynamic characteristics of the adaptive control system, it is advisable to implement a special algorithm that provides the polyharmonic law of sphere displacement in space as Lissajous spatial figures. In this case, effective adjustment of the sphere position in the given direction is carried out.

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