IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Development of structural schemes of parallel structure manipulators using screw calculus

To cite this article: G V Rashoyan *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **327** 042090

IOP Conf. Series: Materials Science and Engineering **327** (2018) 042090 doi:10.1088/1757-899X/327/4/042090

Development of structural schemes of parallel structure manipulators using screw calculus

G V Rashoyan[1], K A Shalyukhin[1], EV Gaponenko[2]

[1]Institute of Mechanical Engineering named after A.A. Blagonravova, the Russian Academy of Sciences, 4, M. Kharitonyevskiy Lane, 101990 Moscow, Russia
[2]Belgorod State Technological University named after V.G. Shukhov, 46, Kostyukov St., Belgorod, 308012, Russia

E-mail: rl_bgtu@intbel.ru

Abstract. The paper considers the approach to the structural analysis and synthesis of parallel structure robots based on the mathematical apparatus of groups of screws and on a concept of reciprocity of screws. The results are depicted of synthesis of parallel structure robots with different numbers of degrees of freedom, corresponding to the different groups of screws. Power screws are applied with this aim, based on the principle of static-kinematic analogy; the power screws are similar to the orts of axes of not driven kinematic pairs of a corresponding connecting chain. Accordingly, kinematic screws of the outlet chain of a robot are simultaneously determined which are reciprocal to power screws of kinematic sub-chains. Solution of certain synthesis problems is illustrated with practical applications. Closed groups of screws can have eight types. The three-membered groups of screws are of greatest significance, as well as four-membered screw groups [1] and six-membered screw groups. Three-membered screw groups correspond to progressively guiding mechanisms, to spherical mechanisms, and to planar mechanisms. The four-membered group corresponds to the motion of the SCARA robot. The six-membered group includes all possible motions. From the works of A.P. Kotelnikov, F.M. Dimentberg, it is known that closed fifth-order screw groups do not exist. The article presents examples of the mechanisms corresponding to the given groups.

1. Introduction

In this paper, the structural analysis and synthesis of robots of a parallel structure based on the mathematical apparatus of groups of screws are considered. The results of synthesis of mechanisms of a parallel structure with a different number of degrees of freedom are presented. It is established that closed groups of screws can be of eight forms. The greatest attention is paid to three-member groups of screws, four-member groups and six-member groups of screws.

2. Description of the algorithm of structural synthesis

The algorithm of structural analysis and synthesis is based on structural formulas that correspond to the order of the corresponding closed group of screws.

Three-member groups of screws correspond to translational mechanisms, spherical mechanisms, and plane mechanisms. The four-member group corresponds to the movement of the robot SCARA. The six-member group includes all possible movements.

The article presents examples of mechanisms corresponding to these groups.

As noted, the mechanisms of the parallel structure [2-5] can be described in the most effective manner on the basis of the theory of screws [6]. In this case, each kinematic pair is associated with a unit screw - ort. To analyze the power screws transferred to the output link, it is necessary to find the screws, reciprocal axes of the axes of these unactuated pairs [5].

Such consideration is used to ascertain whether this or that position corresponds to the limiting values of the pressure angles [7-8]. It is worthwhile to understand what angle is between the line of action of the force and the velocity vector, which is formed for all, except for one fixed, generalized coordinates.

This problem is adjacent to the problem of constructing robots with a kinematic solution, in which each drive controls the motion with only one coordinate [9]. Similar problems are also solved when creating robots of a parallel structure with a different number of degrees of freedom and kinematic chains [10].

As an algorithm of structural synthesis, the application of the modified structural formula proposed in 1991 for mechanisms of parallel structure can be proposed [5]. The meaning of this formula is that a solid body moving in space, corresponding to one or another closed group of screws, has λ degrees of freedom, where λ can be equal to six, four, three, two and one in the limiting case.

Each attached kinematic chain can impose some connections, the number of which is (λ-p), where p is the number of moving kinematic pairs.

In the particular case when λ = 6, the following structural formula was obtained:

$$W = 6 - \sum_{i=1}^{k} (6 - p_i) \quad (1)$$

here W – the number of degrees of freedom, k– the number of kinematic chains, p_i – the number of single-kinetic kinematic pairs.

In the general case, the structural formulas corresponding to the spaces of the mechanisms of the parallel structure become:

$$W = \lambda - \sum_{i=1}^{k} (\lambda - p_i), \quad (2)$$

where λ - the dimension of the space in which the robot's mechanism functions.

The use of groups of screws to construct robots of a parallel structure and a spherical mechanism of a parallel structure (Fig.1) is considered. Each kinematic chain consists of one driving rotational pair and two rotational pairs, with the axes of all pairs intersecting. Unit screws characterizing the positions of kinematic pairs are: $\boldsymbol{K_{11}}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{K_{12}}$ (k_{12x}, k_{12y}, k_{12z}, *0, 0, 0)*, $\boldsymbol{K_{13}}$ (k_{13x}, k_{13y}, k_{13z}, *0, 0, 0)*, $\boldsymbol{K_{21}}$ *(0, 1, 0, 0, 0, 0)*, $\boldsymbol{K_{22}}$ (k_{22x}, k_{22y}, k_{22z}, *0, 0, 0)*, $\boldsymbol{K_{23}}$ (k_{23x}, k_{23y}, k_{23z}, *0, 0, 0)*, $\boldsymbol{K_{31}}$ *(0, 0, 1, 0, 0, 0)*, $\boldsymbol{K_{32}}$ (k_{32x}, k_{32y}, k_{32z}, *0, 0, 0)*, $\boldsymbol{K_{33}}$ (k_{33x}, k_{33y}, k_{33z}, *0, 0, 0).*

IOP Conf. Series: Materials Science and Engineering **327** (2018) 042090 doi:10.1088/1757-899X/327/4/042090

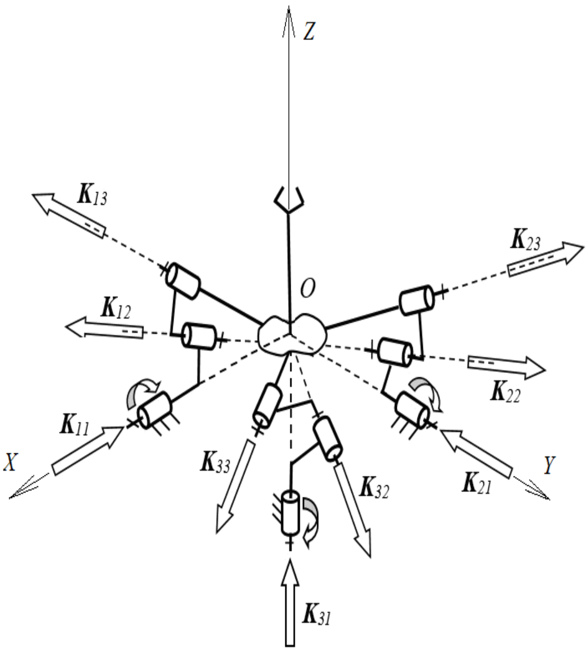

Figure 1. Spherical mechanism

For this mechanism, the structural formula takes form (2).

The power screws of the links have the following coordinates: $\boldsymbol{Q_1}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{Q_2}$ *(0, 1, 0, 0, 0, 0)*, $\boldsymbol{Q_3}$ *(0, 0, 1, 0, 0, 0)*, and the kinematic screws of the output link have the form: $\boldsymbol{\Phi_1}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{\Phi_2}$ *(0, 1, 0, 0, 0, 0)*, $\boldsymbol{\Phi_3}$ *(0, 0, 1, 0, 0, 0)*. These three screws are reciprocal to the indicated power screws and correspond to the required movements of the output link.

The plane mechanism of the parallel structure (Fig. 2) is considered. In this mechanism, two kinematic chains contain three rotational pairs with parallel axes, and one kinematic chain contains a rotary drive pair and two translational pairs. Unit screws of kinematic pairs have the coordinates: $\boldsymbol{K_{11}}$ $(0, 0, 1, 0, 0, 0)$, $\boldsymbol{K_{12}}$ $(0, 0, 1, k_{12x}, k_{12y}, 0)$, $\boldsymbol{K_{13}}$ $(0, 0, 1, k_{13x}, k_{13y}, 0)$, $\boldsymbol{K_{21}}$ $(0, 0, 1, 0, 0, 0)$, $\boldsymbol{K_{22}}$ $(0, 0, 1, k_{22x}, k_{22y}, 0)$, $\boldsymbol{K_{23}}$ $(0, 0, 1, k_{23x}, k_{23y}, 0)$, $\boldsymbol{K_{31}}$ $(0, 0, 1, 0, 0, 0)$, $\boldsymbol{K_{32}}$ $(0, 0, 0, k_{32x}, k_{32y}, 0)$, $\boldsymbol{K_{33}}$$(0, 0, 0, k_{33x}, k_{33y}, 0)$.

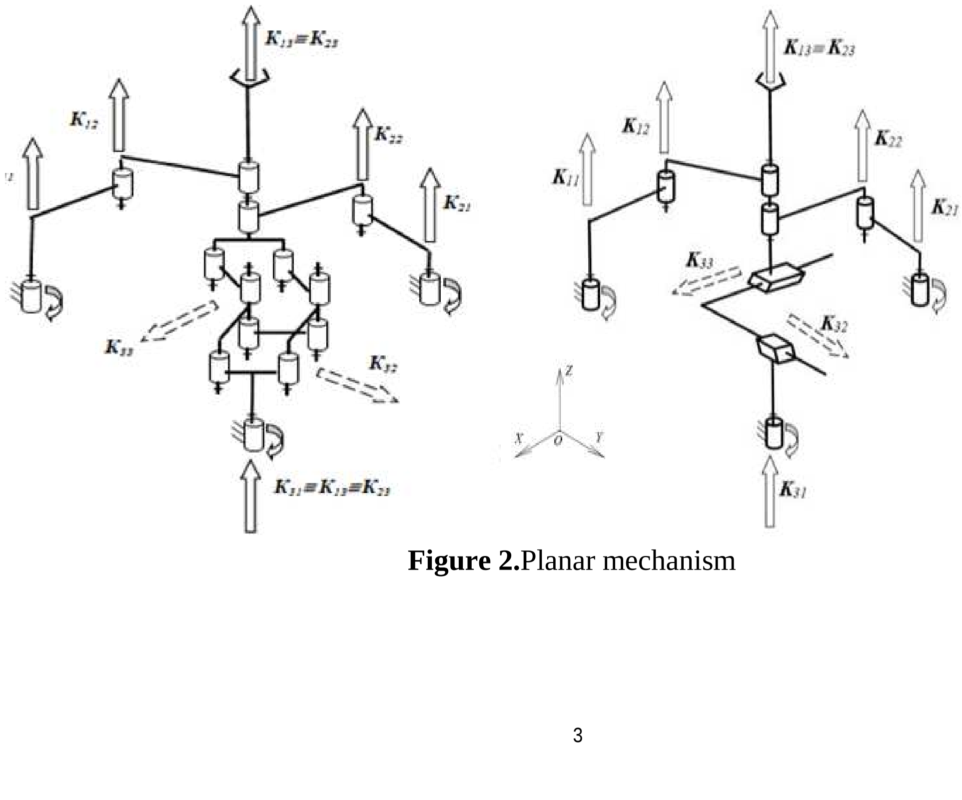

Figure 2. Planar mechanism

For the mechanism under consideration, the structural formula (2) takes the form (3). In this case, the kinematic chains impose the same bonds. The power screws of the links have the following coordinates:$\boldsymbol{Q_1}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{Q_2}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{Q_3}$*(0, 0, 1, 0, 0, 0)*. Kinematic screws of the motion of the output link:$\boldsymbol{\Phi_1}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{\Phi_2}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{\Phi_3}$ *(0, 0, 1, 0, 0, 0)*. These three screws are reciprocal to the indicated power screws and correspond to the required movements of the output link.

3. Application of the algorithm for the synthesis of some types of manipulators

In more detail, let us consider the manipulators of the parallel structure, which correspond to the cases of overlapping kinematic chains of various connections. In particular, it will be a question of the mechanisms that ensure the Schoenfliesor movement like SCARA. These movements are very important from the point of view of practice and represent three translational movements and rotations around axes parallel to any one axis.

There are schemes [11], in which chains impose the constraints, are of different nature. The algorithm for constructing these manipulators should be based on the fact that for each chain, its own structural formula must be used.

Let two kinematic chains superimpose one bond, and the third chain give two links (Fig. 3). The first and second kinematic chains consist of a single drive translational pair (linear motor) located on the base of three intermediate rotational pairs located with axes parallel to the axis of the linear drive and the final rotational pair (the axes of the final rotational pairs of the two chains coincide). The third kinematic chain contains one rotary drive pair (rotary drive) mounted on the base, one driven translational pair (the axes of the two pairs coincide), and two translational pairs made in the form of hinged parallelograms. The unit screws characterizing the positions of the axes of the indicated kinematic pairs have the coordinates:$\boldsymbol{K_{11}}$ $(0, 0, 0, 1, 0, 0)$, $\boldsymbol{K_{12}}$ $(1, 0, 0, 0, k^o_{12y}, k^o_{12z})$, $\boldsymbol{K_{13}}$ $(1, 0, 0, 0, k^o_{13y}, k^o_{13z})$, $\boldsymbol{K_{14}}$ $(0, 0, 1, k^o_{14x}, k^o_{14y}, 0)$, $\boldsymbol{K_{21}}$$(0, 0, 0, 0, 1, 0)$, $\boldsymbol{K_{22}}$ $(0, 0, 0, k^o_{22x}, 0, k^o_{22z})$, $\boldsymbol{K_{23}}$ $(0, 0, 0, k^o_{23x}, 0, k^o_{23z})$, $\boldsymbol{K_{24}}$ $(0, 0, 1, k^o_{24x}, k^o_{24y}, 0)$, $\boldsymbol{K_{31}}$ $(0, 0, 1, 0, 0, 0)$, $\boldsymbol{K_{32}}$ $(0, 0, 0, 0, 0, 1)$, $\boldsymbol{K_{33}}$$(0, 0, 0, k^o_{33x}, k^o_{33y}, 0)$, $\boldsymbol{K_{34}}$$(0, 0, 0, k^o_{34x}, k^o_{34y}, 0)$.

The screws $\boldsymbol{K_{11}}$, $\boldsymbol{K_{21}}$, $\boldsymbol{K_{32}}$, $\boldsymbol{K_{33}}$ and $\boldsymbol{K_{34}}$ have an infinitely large parameter [1], or infinite pitch. The remaining screws have a zero parameter. The first and second kinematic chains impose one bond, the third chain corresponds to two bonds. These links of the first and second kinematic chains can be considered repetitive, since they do not affect the total number of degrees of freedom equal to four. The power screws of the bonds imposed by the kinematic chains have the coordinates [11]:$\boldsymbol{Q_1}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{Q_2}$ *(0, 0, 0, 0, 1, 0)*. All kinematic screws of the motion of the output link can be represented as screws reciprocal to the indicated power screws: $\boldsymbol{\Omega_1}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{\Omega_2}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{\Omega_3}$ *(0, 0, 0, 0, 0, 1)*, $\boldsymbol{\Omega_4}$ *(0, 0, 1, 0, 0, 0)*. Screws $\boldsymbol{\Omega_1}$, $\boldsymbol{\Omega_2}$ and $\boldsymbol{\Omega_3}$ are of an infinitely large parameter, screw $\boldsymbol{\Omega}$4 of a zero parameter.

To form the corresponding structural formula, it is necessary to consider the kinematic chains in more detail. The chain number three (located in the middle) imposes two connections.Chains numbered one and two (located on the sidesimpose one bond, but these links are repeated with the average kinematic chain.)

Each three intermediate rotational pairs can be replaced by two parallelograms.

IOP Conf. Series: Materials Science and Engineering **327** (2018) 042090 doi:10.1088/1757-899X/327/4/042090

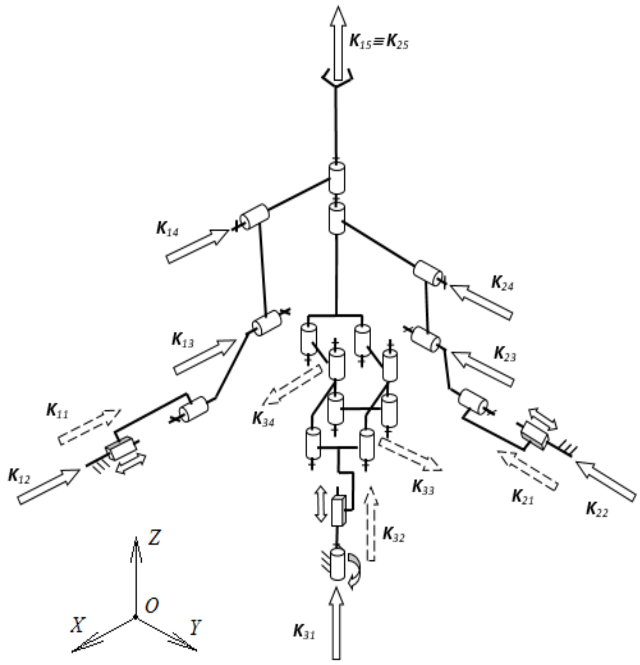

Figure 3. Mechanism with four degrees of freedom and three chains imposing different connections.

Next, let us consider the mechanism in which two kinematic chains superimpose two bonds (Fig. 4), and the third kinematic chain of links does not impose. The first and second kinematic chains, as in the previous case, consist of one drive rotational pair (rotary drive) located on the base, one intermediate rotational pair located with an axis parallel to the axis of the rotary drive and a final cylindrical two-movable pair (the finite cylindrical pairs of the two chains coincide). The third kinematic chain contains one rotary drive pair mounted on the base, one driven translational pair (the axes of the two pairs coincide), and two cardan joints, each of which is made in the form of two rotational kinematic pairs with perpendicular intersecting axes arranged in horizontal planes (Fig. 4).

The unit screws characterizing the positions of the axes of the indicated kinematic pairs have the coordinates: $\mathbf{K_{11}}$ $(0, 0, 1, k^o_{11x}, k^o_{11y}, 0)$, $\mathbf{K_{12}}$ $(0, 0, 1, k^o_{12x}, k^o_{12y}, 0)$, $\mathbf{K_{13}}$ $(0, 0, 1, k^o_{13x}, k^o_{13y}, 0)$, $\mathbf{K_{14}}$ $(0, 0, 0, 0, 0, 1)$, $\mathbf{K_{21}}$ $(0, 0, 1, k^o_{21x}, k^o_{21y}, 0)$, $\mathbf{K_{22}}$ $(0, 0, 1, k^o_{22x}, k^o_{22y}, 0)$, $\mathbf{K_{23}}$ $(0, 0, 1, k^o_{23x}, k^o_{23y}, 0)=\mathbf{K_{13}}$ $(0, 0, 1, k^o_{13x}, k^o_{13y}, 0)$, $\mathbf{K_{24}}$ $(0, 0, 0, 0, 0, 1)=$ $\mathbf{K_{14}}$ $(0, 0, 0, 0, 0, 1)$, $\mathbf{K_{31}}$ $(0, 0, 1, 0, 0, 0)$, $\mathbf{K_{32}}$ $(0, 0, 0, 0, 0, 1)$, $\mathbf{K_{33}}$ $(k_{33x}, k_{33y}, 0, k^o_{33x}, k^o_{33y}, k^o_{33z})$, $\mathbf{K_{34}}$ $(k_{34x}, k_{34y}, 0, k^o_{34x}, k^o_{34y}, k^o_{34z})$, $\mathbf{K_{35}}$ $(k_{35x}, k_{35y}, 0, k^o_{35x}, k^o_{35y}, k^o_{35z})$, $\mathbf{K_{36}}$ $(k_{36x}, k_{36y}, 0, k^o_{36x}, k^o_{36y}, k^o_{36z})$. Let us note that $k_{33x} = k_{35x}$, $k_{33y} = k_{35y}$, $k_{34x} = k_{36x}$, $k_{34y} = k_{36y}$.

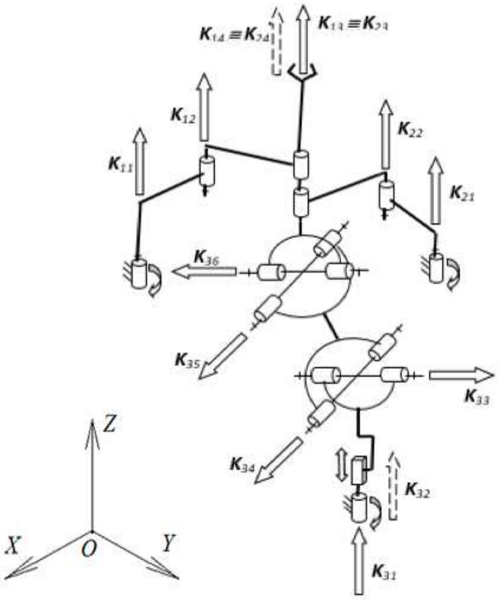

Figure 4. Mechanism with four degrees of freedom, one chain of links does not impose.

The screws $\boldsymbol{K_{14}}$, $\boldsymbol{K_{24}}$, $\boldsymbol{K_{32}}$ have an infinitely large parameter. The remaining screws have a zero parameter. The first and second kinematic chains impose two bonds, which can be considered repetitive, they determine the number of degrees of freedom equal to four. The third kinematic chain of links does not impose. The power screws of the bonds caused by the kinematic chains, as in the previous cases, have the coordinates: $\boldsymbol{Q}_1$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{Q}_2$ *(0, 0, 0, 0, 1, 0)*. Accordingly, all the kinematic screws of the motion of the output link can again be represented as screws that are reciprocal to the indicated power screws: $\boldsymbol{\Omega_1}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{\Omega_2}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{\Omega_3}$ *(0, 0, 0, 0, 0, 1)*, $\boldsymbol{\Omega_4}$ *(0, 0, 1, 0, 0, 0)*.

Specific provisions related to the loss of one or more degrees of freedom arise if the kinematic screws corresponding to the unit vectors $\boldsymbol{K_{i1}}$, $\boldsymbol{K_{i2}}$ and $\boldsymbol{K_{i3}}$ *(i = 1, 2)* or $\boldsymbol{K_{33}}$, $\boldsymbol{K_{34}}$, $\boldsymbol{K_{35}}$ and $\boldsymbol{K_{36}}$ are linearly dependent. This is the case if any three screws $\boldsymbol{K_{i1}}$, $\boldsymbol{K_{i2}}$ and $\boldsymbol{K_{i3}}$ *(i = 1, 2)* or if four screws $\boldsymbol{K_{33}}$, $\boldsymbol{K_{34}}$, $\boldsymbol{K_{35}}$ and $\boldsymbol{K_{36}}$ are in the same plane. In particular, if any three screws $\boldsymbol{K_{i1}}$, $\boldsymbol{K_{i2}}$ and $\boldsymbol{K_{i3}}$ *(i = 1, 2)* are located in one plane parallel to the *y* axis, then there are three power screws of the bonds imposed by the kinematic chains: $\boldsymbol{Q}_1$ *(0, 0 0, 1, 0, 0)*, $\boldsymbol{Q}_2$ *(0, 0, 0, 0, 1, 0)* and $\boldsymbol{Q}_3$ *(0, 1, 0, 0, 0, 0)*. And only three kinematic screws of the output link are reciprocal to these screws $\boldsymbol{\Omega_1}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{\Omega_2}$ *(0, 0, 0, 0, 0, 1)* and $\boldsymbol{\Omega_3}$ *(0, 0, 1, 0, 0, 0)*. Let us note that $\boldsymbol{Q}_{3n}$ is located along the *y* axis.

This mechanism has the property of a partial kinematic decoupling. Rotary drivers of the first and second kinematic chains move the output link in a horizontal plane. The linear driver of the third kinematic chain moves the output link along the vertical axis.

To form the corresponding structural formula, it is necessary to consider kinematic chains. Chain number three (located in the middle) does not impose connections. Chains numbered one and two (located on each side) impose two identical connections corresponding to the movements of Schoenflies or the robot SCARA

Since the third chain does not impose connections, the formula is also valid for the entire mechanism.

Let us consider the 6-DOF mechanism of a parallel structure with three connecting kinematic chains 3 *R-R-R-P-P-P* (Fig. 5). Each kinematic chain includes one rotary drive pair, one translational drive pair, two rotational pairs and two translational pairs. To ensure kinematic decoupling, the axes of all rotational pairs intersect at point *O*, and the axes of the drive rotational pairs are mutually orthogonal.

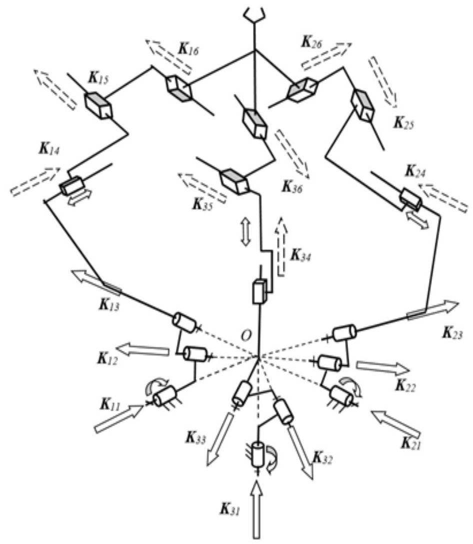

Figure 5. Mechanism with six degrees of freedom.

Unit screws directed along the axes of the kinematic pairs are described by the following plucker coordinates: $\boldsymbol{K_{11}}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{K_{12}}$ $(k_{12x}, k_{12y}, k_{12z}, 0, 0, 0)$,…, $\boldsymbol{K_{34}}$ *(0, 0, 0, 0, 0, 1)*, $\boldsymbol{K_{35}}$ $(0, 0, 0, k_{35x}, k_{35y}, 0)$, $\boldsymbol{K_{36}}$ $(0, 0, 0, k_{36x}, k_{36y}, 0)$. The possible movements of the output link (three displacements along the coordinate axes and three rotations around them) are described by the following kinematic screws (which are reciprocal to six power screws of the kinematic chains):): $\boldsymbol{\Omega_1}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{\Omega_2}$ *(0, 1, 0, 0, 0, 0)*, $\boldsymbol{\Omega_3}$ *(0, 0, 1, 0, 0, 0)*, $\boldsymbol{\Omega_4}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{\Omega_5}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{\Omega_6}$ *(0, 0, 0, 0, 0, 1)*.
Thus, a new 6-DOF mechanism is synthesized, with the structure described by formula (1). In this case, the kinematic chains do not impose any constraints on the motion of the output link.

The disadvantage of this structure is the arrangement of translational drives on the moving parts of the mechanism. The location closest to the base is more rational. In addition, coaxial installation of the translational drive and the rotary drive is possible. Here is an example of a mechanism based on three kinematic chains *3 R-R-R-R-P* (Fig. 6).

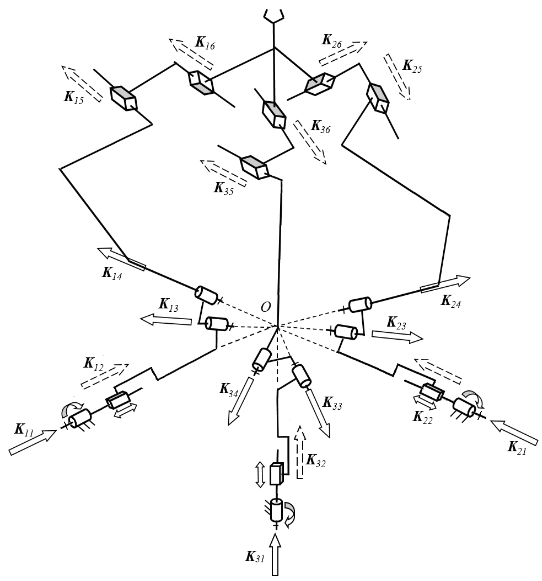

Figure 6. Mechanism with drives on the base.

Each kinematic chain includes one rotary drive pair and one translational drive pair placed on the base, as well as two rotational pairs and two translational pairs. All rotational pairs with their axes intersect at point *O*, which is taken as the center of the coordinate system. With moving translational drives, point *O* does not change its position. The kinematic pairs screws' plucker coordinates have the following form: $\boldsymbol{K_{11}}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{K_{12}}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{K_{13}}$ $(k_{13x}, k_{13y}, k_{13z}, 0, 0, 0)$, $\boldsymbol{K_{14}}$ $(k_{14x}, k_{14y}, k_{14z}, 0, 0, 0)$ $\boldsymbol{K_{15}}$ $(0, 0, 0, 0, k_{15y}, k_{15z})$, $\boldsymbol{K_{16}}$ $(0, 0, 0, 0, k_{16y}, k_{16z})$, , $\boldsymbol{K_{21}}$ *(0, 1, 0, 0, 0, 0)*, $\boldsymbol{K_{22}}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{K_{23}}$ $(k_{23x}, k_{23y}, k_{23z}, 0, 0, 0)$, $\boldsymbol{K_{24}}$ $(k_{24x}, k_{24y}, k_{24z}, 0, 0, 0)$ $\boldsymbol{K_{25}}$ $(0, 0, 0, k_{25x}, 0, k_{25z})$, $\boldsymbol{K_{26}}$ $(0, 0, 0, k_{26x}, 0, k_{26z})$, $\boldsymbol{K_{31}}$ *(0, 0, 1, 0, 0, 0)*, $\boldsymbol{K_{32}}$ *(0, 0, 0, 0, 0, 1)*, $\boldsymbol{K_{33}}$ $(k_{33x}, k_{33y}, k_{33z}, 0, 0, 0)$, $\boldsymbol{K_{34}}$ $(k_{34x}, k_{34y}, k_{34z}, 0, 0, 0)$, $\boldsymbol{K_{35}}$ $(0, 0, 0, k_{35x}, k_{35y}, 0)$, $\boldsymbol{K_{36}}$ $(0, 0, 0, k_{36x}, k_{36y}, 0)$.

Screws $\boldsymbol{K_{11}}$, $\boldsymbol{K_{13}}$, $\boldsymbol{K_{14}}$, $\boldsymbol{K_{21}}$, $\boldsymbol{K_{23}}$, $\boldsymbol{K_{24}}$, $\boldsymbol{K_{31}}$, $\boldsymbol{K_{33}}$, $\boldsymbol{K_{34}}$ have zero parameter; screws $\boldsymbol{K_{12}}$, $\boldsymbol{K_{15}}$, $\boldsymbol{K_{16}}\boldsymbol{K_{22}}$, $\boldsymbol{K_{25}}$, $\boldsymbol{K_{26}}$, $\boldsymbol{K_{32}}$, $\boldsymbol{K_{35}}$, $\boldsymbol{K_{36}}$ have an infinite parameter. The following group of kinematic screws (reciprocal to power kinematic chains' screws) determines the possible movements of the output link: $\boldsymbol{\Phi_1}$ *(1, 0, 0, 0, 0, 0)*, $\boldsymbol{\Phi_2}$ *(0, 1, 0, 0, 0, 0)*, $\boldsymbol{\Phi_3}$ *(0, 0, 1, 0, 0, 0)*, $\boldsymbol{\Phi_4}$ *(0, 0, 0, 1, 0, 0)*, $\boldsymbol{\Phi_5}$ *(0, 0, 0, 0, 1, 0)*, $\boldsymbol{\Phi_6}$ *(0, 0, 0, 0, 0, 1)*.

Translation drives move the output link with fixed rotary drives and unchanged orientation, similar to how it occurs in the 3-DOF translational mechanism. In this case, translational kinematic pairs are operating, which correspond to kinematic screws $\boldsymbol{K_{i2}}$, $\boldsymbol{K_{i5}}$, $\boldsymbol{K_{i6}}$ ($i=1,2,3$). With fixed translation drives, rotary drives perform rotations of the output link, similar to how it occurs in a spherical mechanism. In this case, rotational pairs are operating, which correspond to the screws $\boldsymbol{K_{i1}}$, $\boldsymbol{K_{i3}}$, $\boldsymbol{K_{i4}}$ ($i=1,2,3$). This new 6-DOF mechanism, like the previous one (Fig. 5), is decoupled and corresponds to formula (1) with all six drives located on the base, which gives significant advantages.

4. Conclusion

Thus, the article presents an algorithm for the structural synthesis of parallel structure mechanisms. The algorithm is based on consideration of closed groups of screws and corresponding structural formulas.

On the basis of the apparatus of closed groups of screws, planar and spatial systems are synthesized.

In particular, a number of decoupled mechanisms with a various number of degrees of freedom were obtained.

5. Acknowledgments

This work was supported by the Russian Science Foundation, agreement number 16-19-00148, using equipment of High Technology Center at BSTU named after V.G. Shoukhov.

References

[1] Dimentberg F M 1965 *The screw calculus and its applications in mechanics* (Moscow: Nauka)
[2] Merlet J-P 2006 *Parallel Robots (Second Edition)* (Springer)
[3] Kong X, Gosselin C 2007 *Type Synthesis of Parallel Mechanisms (*Springer)
[4] Rybak L A, Malyshev D, Chichvarin A 2016 On Approach Based on Lie Groups and Algebras to the Structural Synthesis of Parallel Robots *Advances in Mechanism Design II Proceedings of the XII International Conference on the Theory of Machines and Mechanisms* (Liberec, Czech) pp 37-42
[5] Glazunov V A, Koliskor A S, Krainev A F 1991 *Spatial mechanisms of parallel structure* (Moscow: Nauka)
[6] Glazunov V A, Danilin P O, Levin S V, Tyves L I, Shalyukhin K A 2010 Development of mechanisms of parallel structure with kinematic and dynamic interchange *Problems of machine building and machine reliability* **2** 23-32
[7] Glazunov V A, Arakelyan V, Brio S, Rashoyan G V 2012 Speed and strength criteria of proximity to the singularities of manipulators of parallel structure *Problems of machine building and machine reliability* **3** 10-17
[8] Glazunov V, Laryushkin P, Kheylo S 2012 3-DOF Translational and Rotational Parallel Manipulators *New Trends in Mechanism and Machine Science. Theory and Application in*

Engineering ed F Viadero and M Ceccarelli (Springer Dordrecht Heidelberg New York London) 199-207

[9] Nosova N Y, Glazunov V A, Palochkin S V, Terekhova A N 2014 Synthesis of mechanisms of a parallel structure with a kinematic interchange *Problems of machine building and machine reliability* **35** 34-40

[10] Laryushkin P, Glazunov V, Demidov S 2014 Singularity Analysis of 3-DOF Translational Parallel Manipulator *Advances on Theory and Practice of Robots and Manipulators. Proceedings of ROMANSY 2014 XX CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators* (Springer Cham Heidelberg New York Dordrecht London) pp 47-54

[11] Glazunov V A, Levin S V, Shalyukhin K A, Hakkyoglu M, 2010 Vo Dinh Tung Development of mechanisms of parallel structure with four degrees of freedom and partial interchange *Problems of machine building and machine reliability* **5** 3-9