A new classification table for spatial nR linkages

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Abstract—This work presents an analytical review of spatial nR linkage studies, which to determine the main directions and trends of their development. The work focused on two important aspects: the structure of the linkages and the methods of their synthesis. As result, a table of classification of spatial nR linkages was obtained. All spatial linkages are divided into four types: 4R, 5R, 6R and nR. Each element is represented by includes a structure scheme and a caption. The classification is based on findings of foreign as well Russian and Tatarstan researches that were not well-known until recently.

Keywords: spatial nR linkages, classification, synthesis, structure scheme

I. Introduction

There is a significantly increasing interest of researchers and designers in the use of opportunities of spatial nR linkages in constructing different devices. These mechanisms are widely used in many industries: in the textile industry for robotization of technology process [1,2], in architecture for construction of movable deployable structures and shelters [3,4], in mechanical engineering for immersion cleaning of details [5], in food industry for mixing the components [6-9], in mechatronic and robotic systems [10,11]. The main advantage of spatial mechanisms is more natural reproduction of the desired spatial movements. The presence only of rotational pairs can transmit high loads at low wearing.

This work presents an analytical review of spatial nR linkages studies, which to determined the main directions and trends of their development. This work focused on two important aspects: the structure of the linkages and the methods of their synthesis.

II. Analytical review

The active study of spatial nR linkages has begun since the first half of the XX century, when Bennett [12] theoretically proved the possibility of the existence of the four-bar mechanism with non-parallel and non-intersecting joint axes (Fig. 1a). Later he reported [13] the geometric features of isogram 4R linkage (Fig. 1b).

His study created a new direction of spatial nR linkages researches with number of links less then seven. Spatial 4R linkage has become “primary cell” in a design of multi-link spatial linkages with revolute pairs only.

Myard [14] firstly described the principle of obtaining a five-bar linkage by combining the two “rectangular” Bennett linkages (Fig. 2). The two Bennett linkages ABCD and EFGH are first disposed as mirror images of each other. Then the common links AD (or EF) and CD (or GH) and joint D (or H) are removed to form a 1-DOF 5R plane-symmetric spatial linkage.

Chen [15] has used Myard linkages as a basic unit to construct large deployable structures that includes two and more Myard linkages. The main feature of these structures is the ability to fold into a compact unit and unfold into a flat structure. So Chen proposes to use these structures in the aerospace industry in design of antennas and solar panels.

In 1943, Goldberg [16] described spatial 5R linkage constructed by combining two Bennett linkages in such a way that a link common to both was removed and a pair of adjacent links was rigidly attached to each other. This technique was commonly known as the summation of two Bennett linkages to produce a 5R linkage (Fig. 3).
Wohlhart [17] and Song & Chen [18] suggested two different construction methods to combine two Goldberg 5R linkages into a double-Goldberg 6R linkage (Fig. 4). Chen [19] has analyzed this construction ways. Both methods request that two 5R linkages contain an identical link-pair. Wohlhart [17] merged two Goldberg 5R linkages together and removed the commonly shared identical link pair $ED=FG$ and $DC=GH$ to obtain Goldberg 6R linkage. This method called as CLP method (Common Link Pair). In another way, two identical link-pairs from two Goldberg 5R linkages are constructed into a Bennett linkage. Removal of this commonly shared Bennett linkage results in a double-Goldberg 6R linkage, which is called the CBL method (Common Bennett Linkage).

Song and Chen [19] used two different types of Goldberg 5R linkages and built a new family of mixed double-Goldberg 6R linkages through the CLP and CBL combination methods (Fig. 5).

Another area of research is the synthesis of multi-link spatial movable structures. These structures are spatial linkages that can be folded into a compact unit (for ease of movement) and unfolded in a certain form of rigid structure for the different tasks. To create such structures Chen & You [20] use the method shown in figure 6. Here “+” and “−” denote the twist of axis being $\alpha$ and $\beta$. Links $EQ$ and $HI$ are joined together at $E$ and connected to the Bennett linkage at points $I$ and $Q$ with revolute joints. The structure remains mobile because the four-bar linkage $AIEQ$ satisfies conditions of the existence of Bennett linkage.

Based on this studies, Soru [21] proposes to use the spatial movable structures in architecture in the construction of mobile shelters in the theater buildings. However, Soru noted that the mobility of such structures may be greater than one. Therefore, structural elements must be connected by a network of drives that allow the correct operation of the whole of the assembly.

III. Russian researches

Academician V.P. Goryachkin is the founder of spatial mechanisms theory in Russia. He developed the fundamental issues as the mass and velocity theory, the theoretical basis of calculation and construction of agricultural machinery and implements. Scientific papers of Goryachkin still are major in engineering.
In 1925 engineer Tomsk Technological Institute V.V. Verkhovskiy regardless of other researches proved the possibility of the existence of the four-bar spatial linkage with cylindrical pairs and non-parallel and non-intersecting joint axes [22]. Verkhovskiy determines that linkage has single mobility only in special conditions. Later he studied 6R spatial hinge linkages. In particular, he considered 6R linkages and classified them into three main groups (Fig. 7):

- mechanisms of the first group have two points of axes intersection,
- mechanisms of the second group have symmetrical opposite links,
- mechanisms of the third group have a plane of symmetry.

Great meaning to the study of spatial nR linkages made by the scientists of Kazan School of Mechanics (TMM) P.G. Mudrov [23], A.G. Mudrov [24], M.G. Yarullin [25, 26]. Mudrov [23] noted that the spatial linkages with rotational pairs can be obtained by a simple combination of links only with the number of links equal to seven.

Linkages with fewer links are possible only with certain agreed geometric parameters.

Mudrov presented schemes to obtain spatial 6R linkages by combining three types of 4R linkages: planar, spherical and spatial. Construction schemes are shown in Fig. 8.

We should also mention the method of obtaining spatial 6R linkage by combining two similar Bennett linkages (fig. 9). It is necessary to take two similar linkages $ABKF$ and $DCKE$, that $l_{ab} / l_{bk} = l_{dc} / l_{cx}, \alpha_{ab} = \alpha_{dc}, \alpha_{bk} = \alpha_{cx}$, where $l_{ab}, l_{bk}, l_{dc}, l_{cx}$ – length of links $AB, BK, DC$ and $CK$, $\alpha_{ab}, \alpha_{dc}, \alpha_{bk}, \alpha_{cx}$ – the angles of twist. Then linkages merged such a way that the links $BK$ and $CK$, $FK$ and $EK$ are coincided. The result is 1-DOF spatial 6R linkage.

The linkage has a feature that the link $AB$ always parallel to the link $DC$, and the link $DE$ parallel to the link $AF$.

Mudrov provided the method of obtaining a spatial 6R linkage by obtaining of three 4R linkages. The figure 10a shows a consistent combination of 4R linkages and figure 10b shows a blanket combination of 4R linkages.

Professor Dvornikov paid attention to the basics of classification, problems of structural synthesis and kinematic analysis of mechanisms. In particular, Dvornikov [27] investigates the problem of spatial 4R linkage existence and concludes that it can be constructed on the surface of pseudo. He notes that there are pseudo surface is versatile – it can be set up all three types of 4R linkages (planar, spherical and spatial) (Fig. 11).
To combine the known spatial nR linkages and arranging them in chronological order by the date mentioned was construct chronological table of appearance spatial nR linkages (fig. 12). In general, the fundamental investigations of the XX century are devoted to describing methods for the synthesis and analysis of spatial 1-DOF 4R, 5R and 6R linkages. Such mechanisms are mainly intended for: a) transmission of motion from one plane to another and b) transmit conversion of input crank rotational motion into the output complex dimensional motion. In the first half of the 20th century there were designed new 4R and 5R linkages (Bennett’s 4R and Verhovsky’s 4R linkages, Myard’s 5R and Goldberg 5R linkage) [13-17]. It is worth noting that some linkages (for example Bennett’s and Verhovsky’s 4R linkages) have been obtained by various authors independently each other. 4R and 5R linkages played an important role for further investigations in this area. During the second half of the century new methods of synthesis of the family of spatial 6R linkages (Goldberg 6R linkages, Waldron 6R linkages, Schatz 6R linkage, Mudrov 6R linkages) have been described [18-23]. A new 6R linkages were synthesized in two ways: (1) combining some 4R and 5R linkages (planar, spheric or spatial) into one, (2) subtracting a composite loop from a basis loop to form a syncopated linkage.

Beginning of the XXI century witnessed active evolution of mechatronic and robotic systems. This resulted in necessity of creating devices of working body which is able to perform controlled spatial movements to provide wide range of tasks: movement the objects in space with variable velocities and accelerations, positioning on objects of complex geometric shapes, reproduction of human movements or replacement of humans in difficult and hazardous place. Therefore, one of the areas of research was the creation of spatial multi-link movable linkages-structures. These structures represent a combination of a large number of basic mechanisms – “primary cells”.

As result the classification of spatial nR linkages was obtained (fig. 13). The table contains spatial nR linkages and organizes them into two main criteria: the structural parameters and method of synthesis.

Conclusions

This work presented an analytical review of spatial nR linkage studies. The structural features of the nR linkages considered and methods of synthesis are presented. Studied mechanisms collected together in a chronological table. The table traces the development of research nR linkages in direction from creating first 4R linkage to synthesis the multi-link structures. As result the classification of spatial nR linkages was obtained. The table contains spatial nR linkages and organizes them into two main criteria: the structural parameters and method of synthesis.
Fig 12. Chronology table of spatial nR linkages
## Classification table of spatial nR linkages

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<th>multi doubling</th>
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*Fig 13. Classification table of spatial nR linkages*
References


