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AN ATLAS OF LINKAGE-TYPE ROBOTIC GRIPPERS

NICOLA PIO BELFIORE

Università degli Studi di Roma *La Sapienza*, Dipartimento di Meccanica e Aeronautica, via Eudossiana, 18, 00184 Roma, Italy

ETTORE PENNESTRÌ

Università degli Studi di Roma *Tor Vergata*, Dipartimento di Ingegneria Meccanica, via della Ricerca Scientifica, 00133 Roma, Italy

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Abstract—In this paper an atlas of 64 linkage-type grippers is presented. For each mechanism one of the possible functional schematic is provided for a better understanding of its kinematic properties. Some of the linkages herein depicted are believed to be novel. The atlas should be helpful to designers in the field of robotics. Graph theory is involved, as far as the concepts of enumeration and isomorphism. The enumeration methodology adopted is described in detail and an extension of the concept of isomorphism to the class of actuated mechanisms briefly recalled. © 1997 Elsevier Science Ltd

1. TERMINOLOGY

Although symmetric graphs have been already studied [1], new more simple definitions about symmetry in graphs are herein proposed for the sake of the particular application.

—*Breakpoint of a graph*: vertex whose removal increases the number of connected components.
—*n-vertices-binary chain*: a sequence of *n* binary links connected in series by kinematic pairs.
—*Binary cycle*: circuit where all the vertices have degree 2 except one called the *hook vertex*.
—*Cycles-graph*: graph composed of binary cycles having a common hook vertex and identical label distributions of edges and vertices.
—*Symmetric vertices of a cycles-graph*: corresponding vertices on the binary cycles.
—*Binary edge-cycle*: circuit where all the vertices have degree 2 except two which are adjacent to each other. The common incident edge is called the *hook edge*.
—*Edge-cycles-graph*: graph composed of binary edge-cycles having a common hook edge and identical label distributions on edges and vertices.
—*Symmetric vertices of an edge-cycles-graph*: corresponding vertices on the binary edge-cycles.

2. INTRODUCTION

Grippers play an important role in robot performances. Their task is to grasp and release objects. These devices can be classified according to the mechanical structure, actuator type, and grasping action.

Reference [2] suggests the following list:

—Mechanical finger type;
1. Linkage type
2. Gear-and-rack type
3. Cam-actuated type
4. Screw-driven type
5. Rope-and-pulley type
6. Miscellaneous type

—Vacuum and magnetic type
—Universal grippers
1. Inflatable grippers
2. Soft fingers
3. Three fingered type
4. Mouldable grippers

There are various sources in technical literature where structures of robotic grippers can be found depicted and described [2]. However, it seems that very few papers address the problem of methodologies suited for the systematic enumeration of such structures [3–5]. From the practical point of view, there are two main reasons that justify investigations in this field. The first one regards the possibility for a designer to scan the entire solution set, the second the search for design alternatives to already patented kinematic structures.

This paper describes an algorithm for systematic enumeration of linkage type grippers for prescribed structural and functional requirements. The theoretical tool adopted for the topological synthesis is based on the correspondence between mechanisms and labeled graphs.

3. THEORETICAL BASES

The first stage of design requires a careful analysis of all the feasible alternatives. The typical questions during this phase are:

1. How many links will constitute the kinematic chain?
2. Which link connects to which other link by which type of joint?
3. Which is the frame link?
4. Which is/are the input (output) link/s?

An answer to these four questions allows to define the kinematic structure of a mechanism. Unfortunately, this stage is often bypassed by practitioner designers for many reasons. First of all, the analysis of the previous solutions usually yields several different choices with little effort. Moreover, large catalogues of mechanisms have been available in literature (e.g. [6, 7]). However, this is not a systematic approach because a designer is never sure if another kinematic structure exists which suits requirements better than the one chosen.

In the last decades many papers on Type Synthesis of mechanisms for different purposes appeared in the literature [8]. Different classes of mechanisms have been involved in the search and a certain number of atlases presented. Most of the new catalogues were obtained making use of the correspondence between graphs and mechanisms. Accordingly, links and kinematic pairs are respectively represented by vertices and edges, which can be conveniently labeled with different integers and/or characters. For example, integer 1 and character R may respectively denote the frame link and a rotoidal pair.

The next sections report a simple procedure for the systematic enumeration of robotic grippers. Because of the small number of links involved, no computer code was needed for any step of the procedure. However, as the number of links increases, one needs *ad hoc* algorithms for testing graph isomorphism [9].

4. PROPOSED ALGORITHM

The proposed algorithm consists of the following four main steps:

—Choice of functional and structural requirements.
—Choice of the kinematic chain.
—Choice of the frame vertex, the actuating vertices, and the jaw vertices.
—Enumeration of non-isomorphic sets of edge labels.

Before starting the actual enumeration process of non-isomorphic kinematic structures, a list of structural and functional requirements must be compiled in order to bound the class of mechanisms to be enumerated. This task is accomplished in the first step.

The second phase imposes a further restriction to the search. Usually, kinematic chains with a lower number of links are to be preferred to keep the final layout simple.

Subsequent steps are labeling procedures of vertices and edges of the graph representing the chosen kinematic chain.

5. STRUCTURAL AND FUNCTIONAL REQUIREMENTS

The following requisites were adopted:

1. Only rotoidal joints and sliding pairs are allowed. This first requirement has been chosen for a more simple and practical layout. Usually, rotoidal pairs are inexpensive and easy to assemble. Sliding pairs may be a bit more expensive even though they make both the kinematic analysis and synthesis easier. Geared pairs are excluded.
2. For each tri-connected structure, the input and the frame links must correspond to adjacent vertices. This assumption guarantees that the actuator is ground connected.
3. The frame vertex is one of the vertices which has the maximum degree. This maximizes the number of ground connected kinematic pairs.
4. Vertices corresponding to the jaw links must be selected in such a way to appear symmetric with respect to a given (hook) edge or vertice.
5. Labels corresponding to subchains including different jaws must be selected in such a way to appear symmetric with respect to a given edge or binary chain.

The last two requirements imply that the selected graphs must be cycles-graphs or edge-cycles-graphs (see Terminology).

6. Vertices corresponding to distinct jaw links must not be adjacent vertices. This ensures that relative motion between jaws is not a simple translation or a revolution.

6. ENUMERATION OF THE FEASIBLE GRIPPERS

In order to simplify the final layout only 1 degree of freedom (1-DOF for short) kinematic chains of up to six links have been taken into account.

—4-bar chain.
—Watt's chain.
—Stephenson's chain.

For the first two kinematic chains a group of 32 actuated mechanisms has been sketched out (see Appendix). Each schematic drawing represents only one possible functional representation of the actuated mechanism. In fact, continuous variations of link dimensions do not affect topological properties of the mechanism. All the presented drawings were derived by the authors of this paper with no need of procedures for automatic sketching. While a certain number of algorithms for automatic sketching of kinematic chains and geared mechanisms are available in the literature [10–12] only a few concern the automatic sketching of mechanisms [11, 13].

Functional schemata herein depicted were obtained using the aesthetics commonly accepted in literature. Furthermore, additional requirements have been assumed:

—all the presented mechanisms obey the general DOF equation:

$$F = \lambda(l - j - 1) + j_P + j_R \tag{1}$$

where F, λ, l, j_P and j_R respectively denote the number of DOF, the mobility number (equal to 3 for general plane mechanisms), the number of links and joints, and the number of prismatic and rotoidal pairs.

—absence of rigid subchains.
—singular configurations have also been avoided.

In some cases, as for grippers 8, 24, 45, and 56 of the atlas, the authors of this paper ignored the restriction imposed by the general DOF equation in order to present the full set of mechanisms relative to a given graph.

6.1. 4-bar chain

This very simple class of mechanisms is composed of a loop of 4 bars. From the topological viewpoint there is no reason to distinguish one vertex from the other. For this reason each one can be chosen as the frame vertex, all the other choices being equivalent. Similarly, one of the two vertices, adjacent to the frame vertex, can be chosen as input link. As for the jaw links, only two remaining adjacent vertices are available. If the two jaws are connected through a rotoidal or a sliding pair the relative motion between fingers is expected to be limited, respectively, to a rotation or a translation. For a general purpose gripper such a simple layout can be in many cases unable to handle complex situations, especially when a high dexterity or mechanical advantage is required. Furthermore, only 4 links may offer, in some cases, a small number of design parameters.

For this reason, a different class of $1 + 3n$ links, n fractionated DOF, 1 break point grippers were considered, with $n > 1$. The corresponding graphs are *cycle-graphs* with *n binary cycles* (see Terminology). The frame corresponds to the hook vertex and finger links are set as symmetric vertices. Hence, they cannot be adjacent. The simplest case is when $n = 2$. However, the cases where $n > 2$ are not more complex from the topological point of view. In fact, each 4-bar loop can be regarded as a single 4-bar mechanism. Hence, grippers were generated combining single 4-bar loops. Grippers from 1 to 32, as presented in the atlas, were built using $2 \times$ (4-bar) loops each corresponding to a binary cycle.

Due to the required symmetry, the jaw vertices are both adjacent either to the frame vertex, or to the input vertices (see mechanisms from 1 to 32). Similarly, edges incident to vertices having the same functions must have the same label. For instance, in each one of the graphs from 1 to 32, there are two edges belonging to the two 4-bar loops, which are incident both to the frame and to one input vertex. Edges with such features represent actuating pairs [14]. The final result is that both drivers consist of two linear to two rotoidal actuators.

The problem of identifying the feasible set of labels is straightforward when the search is restricted to rotoidal and sliding pairs only.

It is worth noticing that all the 16 possibilities yield non-isomorphic actuated mechanisms. Let us consider, for example, mechanisms 20 and 23. It is easy to recognize that if we do not define any couple of input links they are isomorphic. However, since we are interested in *actuated* mechanisms, the moving links must be taken into account and the two actuated mechanisms are not isomorphic anymore. In fact, for actuated mechanism 20, the moving links are composed of linear actuators which drive sliders, while, for mechanism 23, actuators drive revolute joints.

Such an extension of the concept of isomorphism to actuated mechanisms has been inspired by [14], where it is suggested to consider as kinematically distinct two mechanisms whose only difference is the location of the actuator pair.

6.2. Watt's chain

The Watt's chain is composed of 6 links arranged in two 4-bar loops having two links in common. As shown in drawings from 33 to 64 of the Appendix the corresponding graph is a biconnected *edge-cycle-graph* with two *edge-binary-cycle* (see Terminology).

Only two possible non-isomorphic choices of the frame link are possible. In fact, there is no special reason, at this point of the enumeration procedure, to distinguish one of the two vertices of degree equal to 3. Therefore any one of the two can be selected as the frame vertex. The same applies to the vertices with degree two, in the sense that any of the four binary vertices can be selected as the frame link. However, assumptions require that the frame vertex is one of the two having degree equal to 3.

As for the input link only one of the three vertices adjacent to the frame vertex can be selected.

The choice of the jaw links can be performed in three non-isomorphic ways. That is both, one, or no vertex corresponding to the jaw links being adjacent to the frame. In this investigation only the first and the third possibility have been chosen, since the second choice implies that the two 4-bar loops are not symmetric. In fact, according to the second solution, one finger would be ground connected, the other floating. In this case, requirements concerning symmetry imply the following *functional* characteristic: the two jaws are both floating or grounded.

Grippers from 33 to 64 depicted in the atlas were obtained by applying the labeling phase to the two classes of grippers having, respectively, both or none of the jaw vertices adjacent to the frame link. Each class is composed of a group of 16 mechanisms, obtained through a combinatorial assignment of the two labels P and R to the seven edges. The total number of possible combinations is greater than 16. However, the one depicted is a particular subset of the whole solution set. This subset has been selected imposing that the corresponding graph was labeled in such a way to become an *edge-cycles-graph* (see Terminology). For example, if labels R and P are assigned to the edges of one of the two edge-cycles, the same group of labels, in the same order, must be given to the other.

6.3. *Stephenson's chain*

This chain is composed of 6 links and 7 pairs. The kinematic structure can be considered as composed of two ternary links connected by two *1-vertex-binary chains* and one *2-vertices-binary chain*. The corresponding graph is depicted in Fig. 1.

The frame vertex can be one of the two vertices which have degree 3. It is clear that neither of the two can be distinguished from the other using topological information. Therefore only one possible choice for the frame link can be taken into account.

Jaw links can be assigned to two of the five remaining vertices. Symmetry requirements can be extended to Stephenson's chain, by imposing that the two *1-vertex-binary chains* must have the same distribution of labels on links and vertices. According to this assumption, jaw vertices must be those of the two *1-vertex-binary chains*. In the figure, the *2-vertices-binary chain* is drawn in the middle of the two *1-vertex-binary chains*.

The input link can be any link adjacent to the frame link. However, from the point of view of the kinematic structure, only two non-isomorphic solutions are possible: either a jaw vertex is chosen as input or not.

The labelling problem is straightforward. First of all, the three edges of the *2-vertices-binary chain* must be labeled: two objects must be assigned to three positions, hence eight possible choices are available. Then, the labeling procedure must be applied to the two *1-vertex-binary chains*. This second problem consists in the assignment of two objects to two positions and yields four different solutions. Therefore, the total number of mechanisms satisfying the imposed requirements is equal to 32.

According to the above described enumeration only two non-isomorphic solutions are possible:

—The input link is coincident with one of the fingers.
—The input link is not coincident with a finger link.

In the first case, the *2-vertices-binary chain* is completely idle, since no contribution is given to the motion nor to the power transmission. In the second case, the only given contribution is providing the input force to the system. However, the motion of the finger links is not affected by the

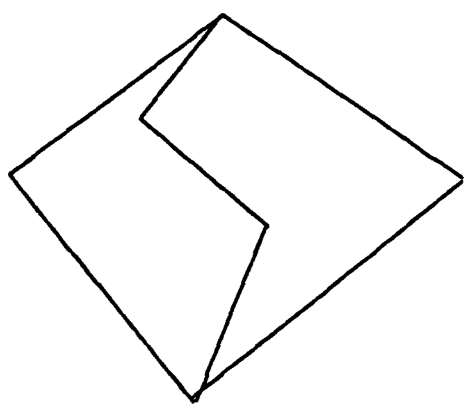

Fig. 1. Unlabeled graph corresponding to the Stephenson's chain.

2-vertices-binary chain which only depends on the 4-bar loop made of the two 1-vertex-binary chains.

Furthermore, the mechanisms belonging to the Stephenson's class have a floating link of degree 3. This may cause drawbacks in the kinematic analysis and synthesis and in the physical embodiment of the structure.

For these reasons, the authors of this paper did not extend the atlas to the class of mechanisms derived from the Stephenson's chain.

7. COMMENTS ON THE PRESENTED ATLAS

The atlas includes two kinds of representations: on the left column *functional graphs* are drawn. A functional graph is defined as a planar representation of a given labeled graph; on the right column *functional schemata*, defined as functional representations of grippers, are depicted. *Functional graph* and *scheme* belonging to the same row correspond to the same labeled graph. However, as previously mentioned, only one of the infinite possible functional schemata and only one of the infinite possible functional graphs corresponding to each given labeled graph have been shown in the atlas. Such a one-to-infinite correspondence between a labeled graph and its representations is due to the fact that the nature of a graph is that of an abstract object. Although all the *functional graphs* corresponding to the same labeled graph are equivalent, in the sense that they all provide complete information on the graph, each single *functional scheme* describes a gripper which can be very different from others corresponding to the same labeled graph. In particular, permanent or temporary critical forms of mechanisms are possible [15]. For this reason, each proposed *functional scheme* must be considered as a suggested sketch of functional embodiment of a given topology. Different *functional schemata* can be obtained by changing the dimensional parameters of each suggested *functional scheme*. For instance, any continuous variation of the dimensions of the links is a possible option.

With reference to actuated mechanisms n.1, symbols denoting vertices 1, 2 and 4 will be respectively used to represent the frame, jaw, and input vertices.

7.1. *One break point structures*

For 2 fingers-plane grippers (i.e. $n = 2$) some special changes are possible. For example, considering the particular *functional scheme* 1, links 4 and 7 may become a unique link. This could be convenient in order to have only one moving link. Another special change may be the transformation of two simple joints into one triple joint. For instance, considering the particular *functional scheme* 2 joints 1–4 and 1–7 may become a triple rotoidal pair.

Actuated mechanisms 8, 15, 16, 23, 24, 31, and 32 deserve additional comments.

Grippers 8 and 24 are both composed of two independent loops of 4 links and 4 prismatic joints (see Appendix). The two mechanisms cannot be considered as isomorphic as far as *actuated mechanisms* are concerned. In fact, jaw links are kinematically connected to the frame in gripper 8, while they are floating in 24. Furthermore, their common structure makes them difficult to use for practical purposes. In fact, once a finite displacement is applied to the moving links, the final configurations are not determined yet. For example, if a finite displacement is applied to link 2 of gripper 8, links 3 and 4 can still move. In both the cases, the general law of DOF is violated and the two mechanisms should be discarded. However, as previously explained, they were kept in the atlas for the sake of completeness.

In gripper 15 the two loops contain three consecutive prismatic joints. For every input motion of sliders 2 and 5, jaw links 4 and 7 must keep the same orientation (see Appendix). At the same time, they are ground connected by rotoidal pairs 1–4 and 1–7, that is only rotations would be allowed. Therefore, jaw links 4 and 7 simply cannot move making grasping not possible. The same situation occurs for the next mechanism 16, in which the series of constraints 1–4, 4–3, 3–2, and 1–7, 7–6, 6–5, respectively keep input links 2 and 5 always oriented in the same ways. On the other hand, input motion is provided by revoluting links 2 and 5. Therefore, input is not applicable.

In gripper 23, links 2 and 5 are connected by means of two revolute joints, respectively, to links 3 and 6, while sliding pairs keep links 2, 3, 5, and 6 always in their original orientations. Therefore, rotoidal joints do not work, pairs 2–3 and 5–6 being as fixed 0-DOF joints.

Finally, grippers 31 and 32 suffer the same problems of grippers 15 and 16. In fact, the actuator link is the only difference between such structures. However, gripper 32 is not feasible since links 2 and 5 cannot actuate the mechanism.

7.2. Six-link biconnected structures

For this class of mechanisms only one moving link is required.

As for the previous class, a further analysis is offered. For example, in mechanism 44 links 2 and 6 are forced to keep the same orientation for all configurations of the rest of the structure. Therefore, no grasping action is possible.

Mechanisms 45 and 56 have only prismatic joints. Once the position of the input link is prescribed, the rest of the structure still remains not uniquely configurated.

In grippers 48 and 63 input is not applicable. In mechanism 48, for example, link 4 is forced to maintain the same orientation while the power input should be transmitted by its rotative motion. On the other hand, links 6 and 2 are not feasible as input candidates because one of two loops is always uncontrollable. Similarly, in mechanism 64 links 2 and 5 never rotate. Therefore, they cannot be selected as input links. Even though power input could be provided through link 4, rotoidal pairs 1–2 and 1–5 would not be properly used.

8. CONCLUSIONS

In this paper an atlas of linkage-type grippers of up to 6 links is suggested. For each mechanism two representations are provided. The first one shows a labeled graph which fully describes the topological characteristics. The second is a corresponding possible functional representation. The latter is particularly useful to derive functional embodiments which suit a given industrial application.

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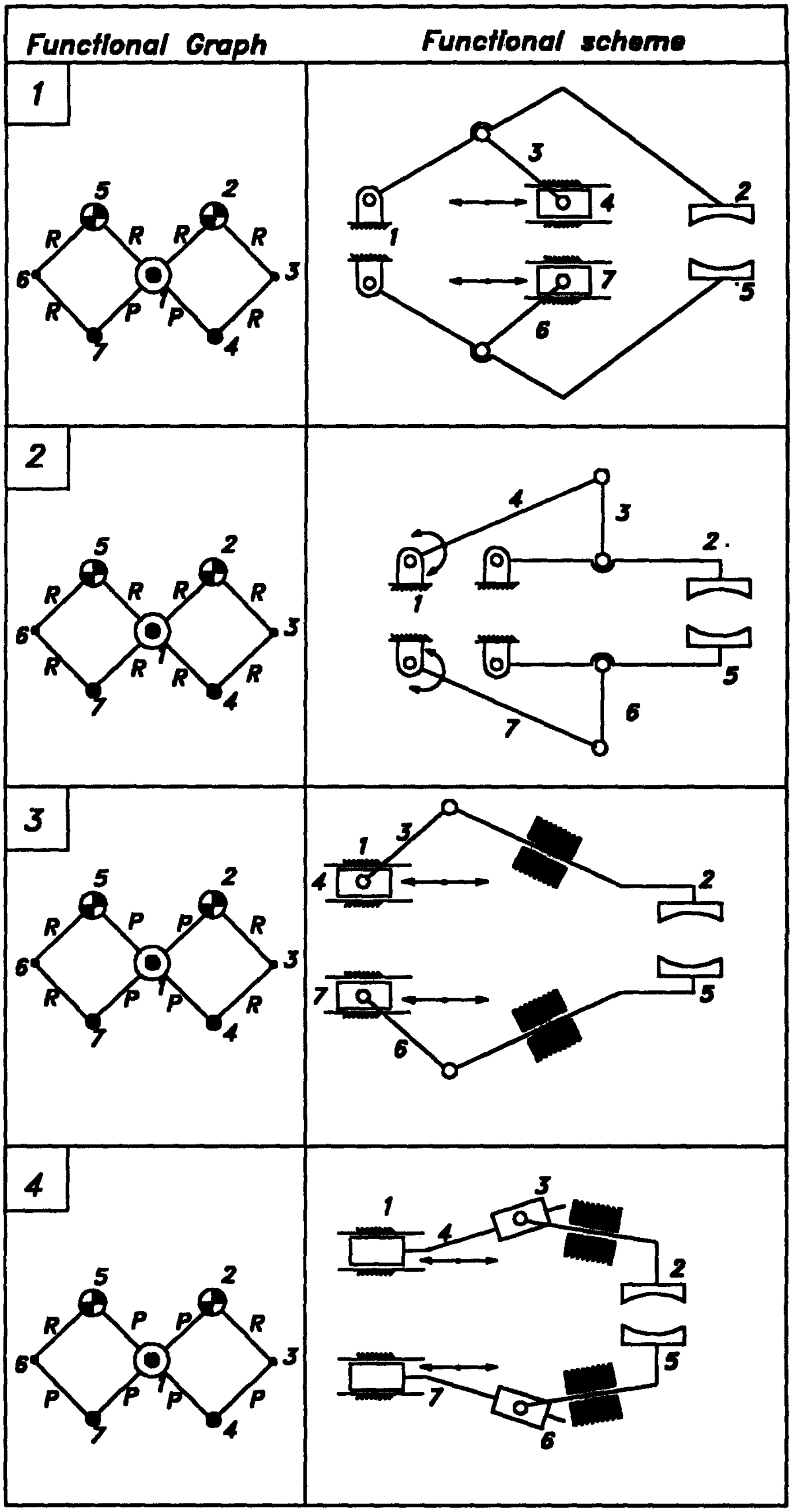
APPENDIX

See Overleaf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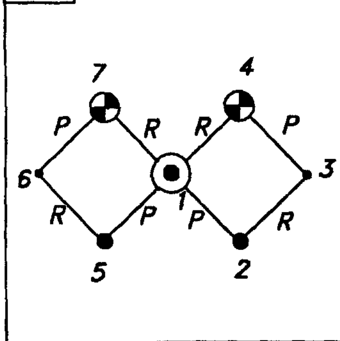
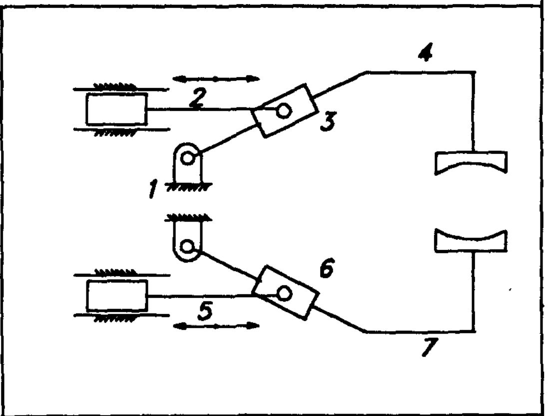
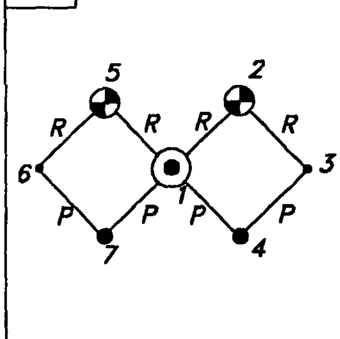
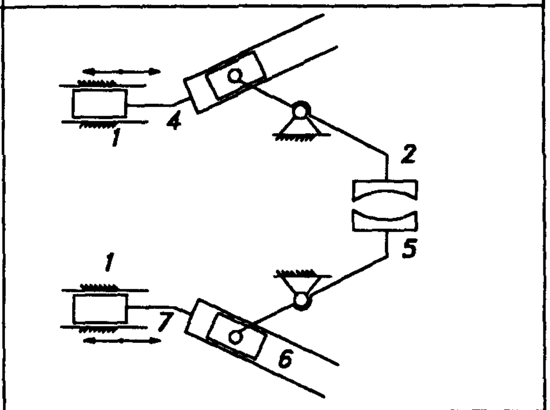
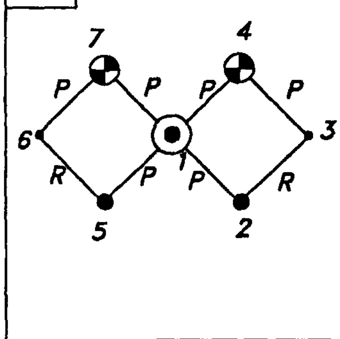
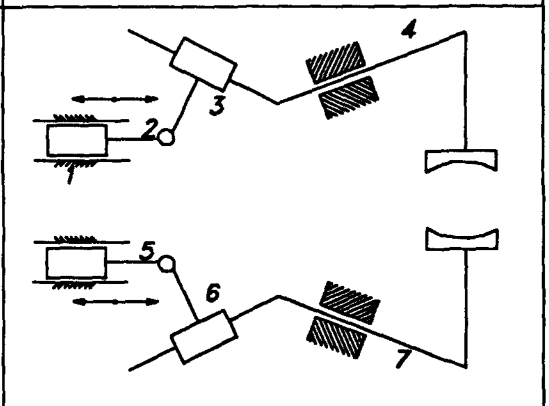
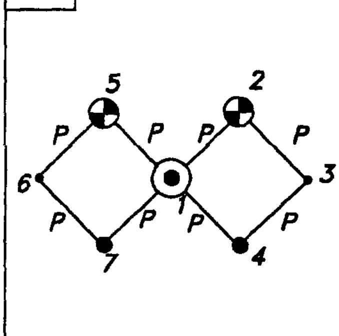
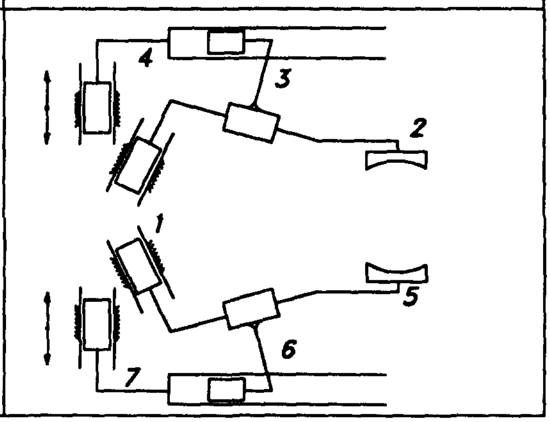
5 	
6 	
7 	
8 	

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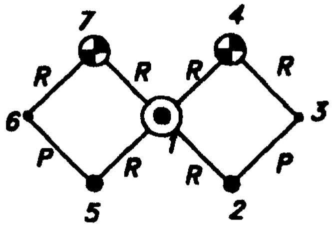
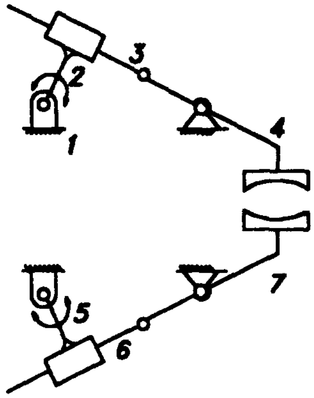
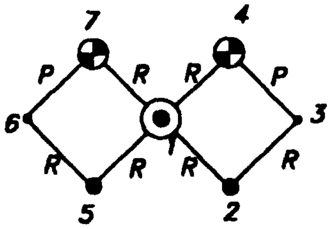
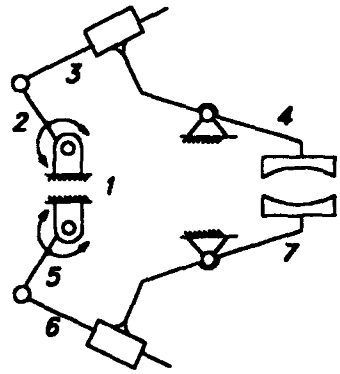
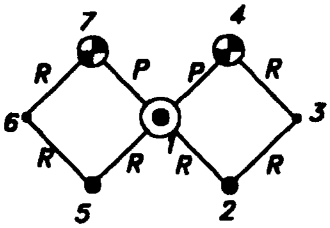
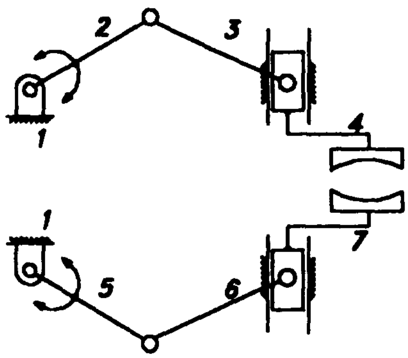
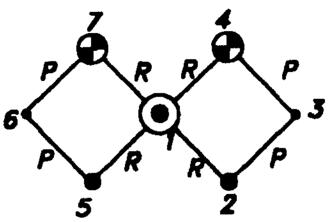
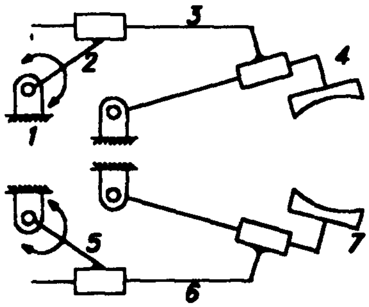
9 	
10 	
11 	
12 	

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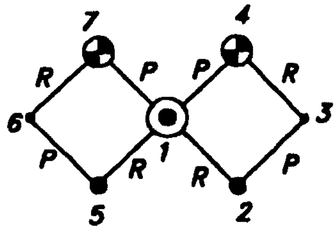
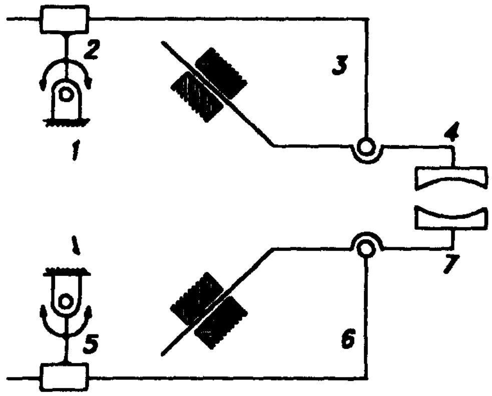
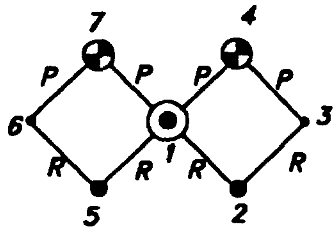
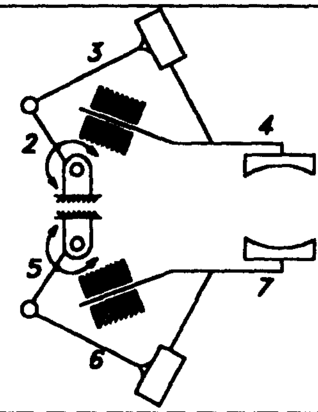
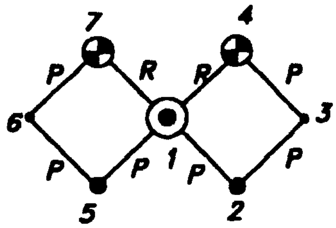
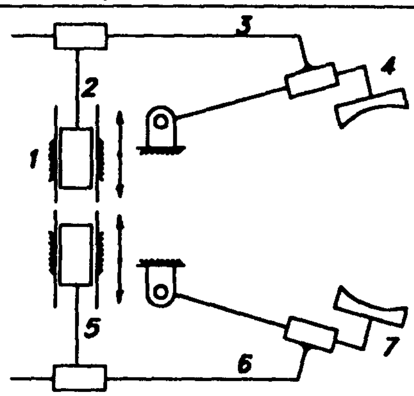
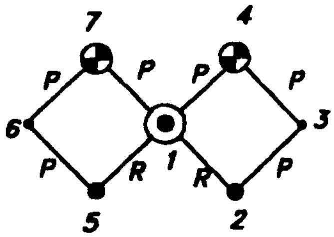
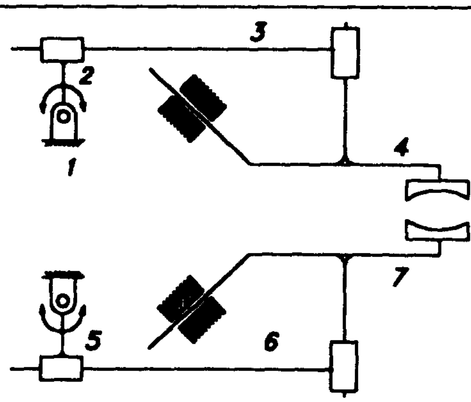
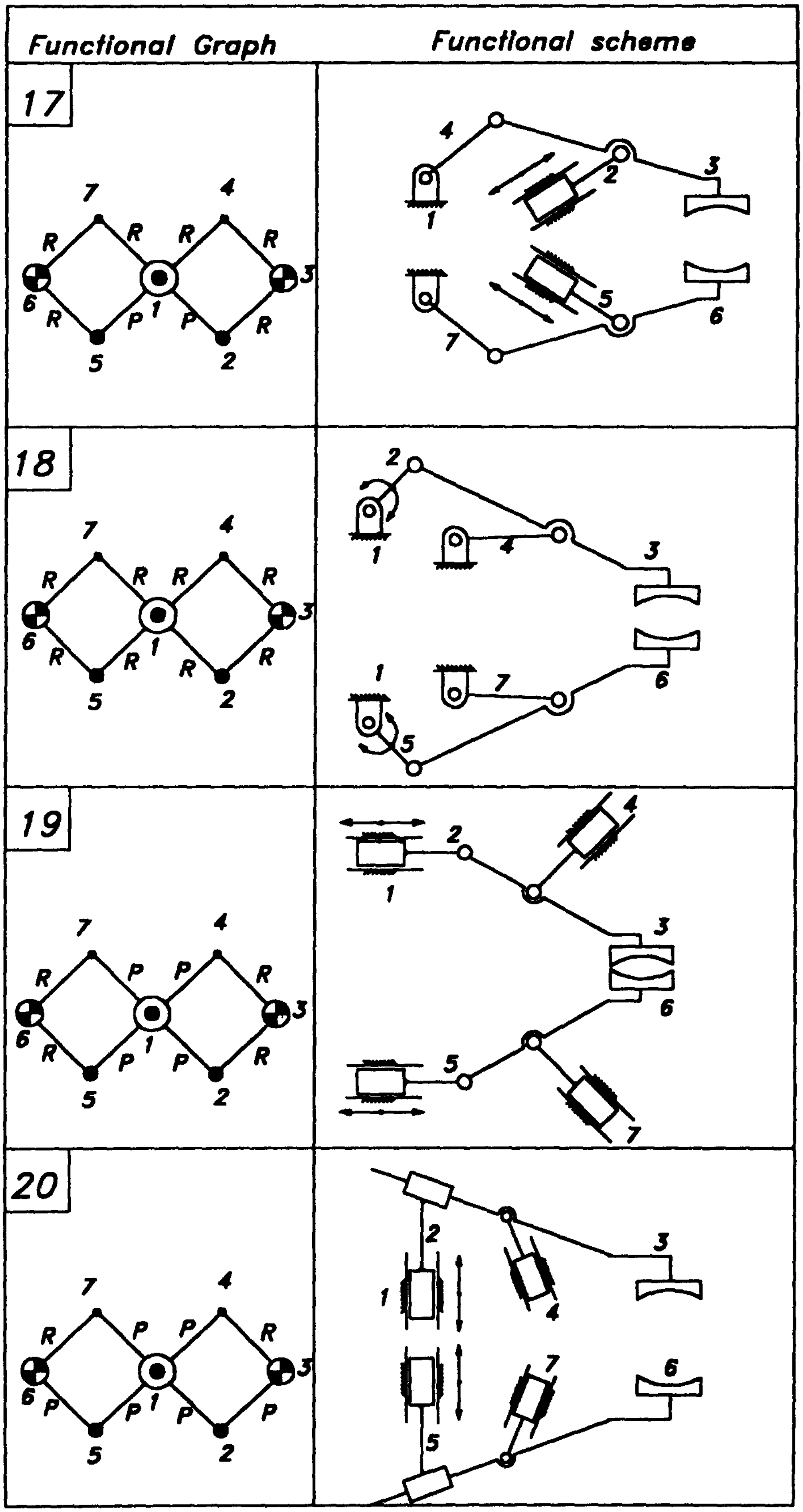
13 	
14 	
15 	
16 	


Functional Graph
Functional scheme
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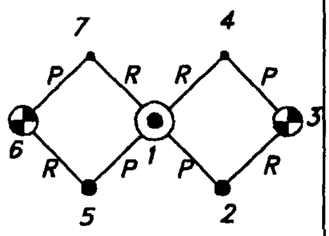
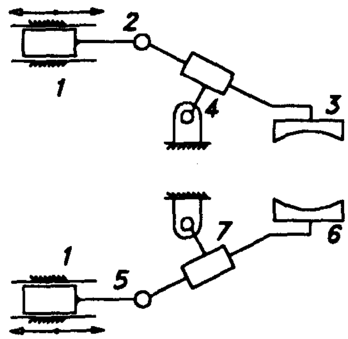
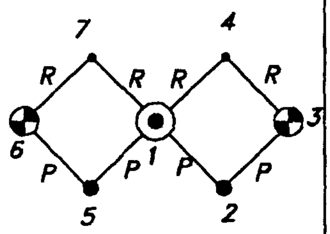
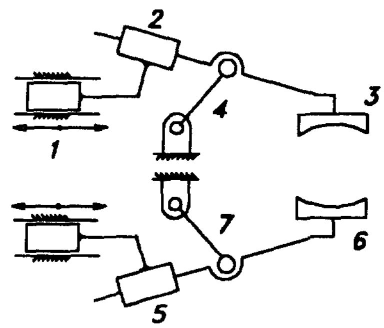
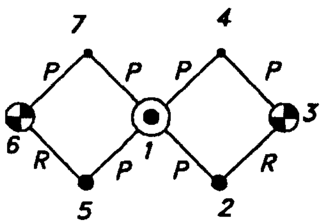
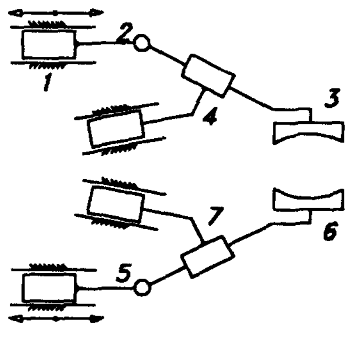
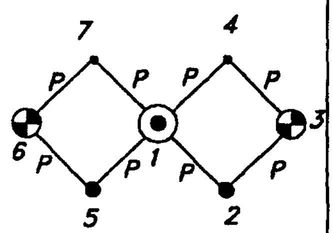
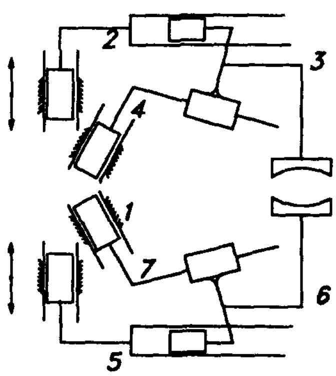
Functional Graph	Functional scheme
21 	
22 	
23 	
24 	

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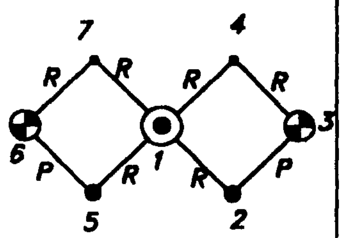
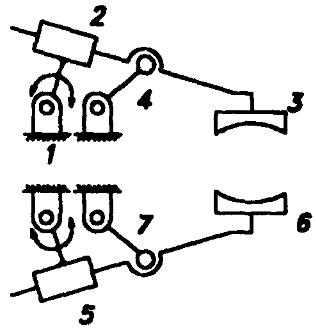
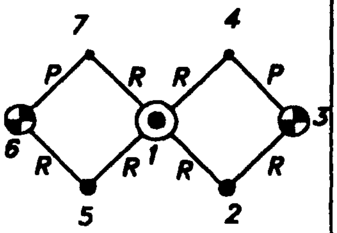
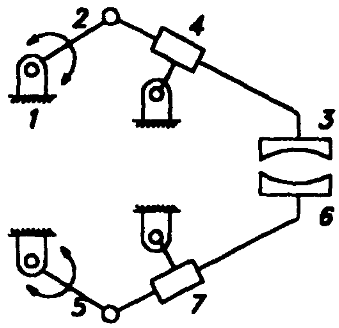
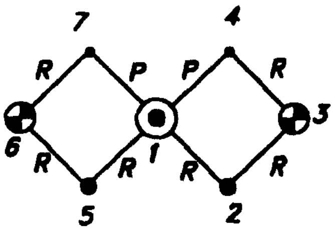
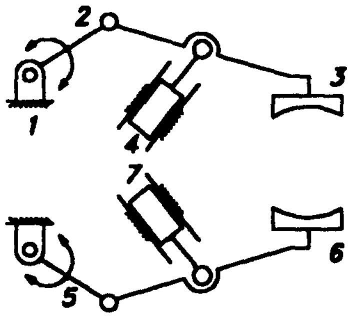
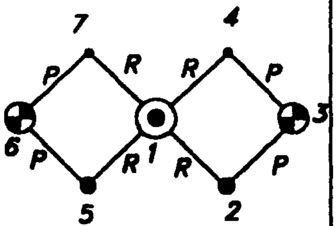
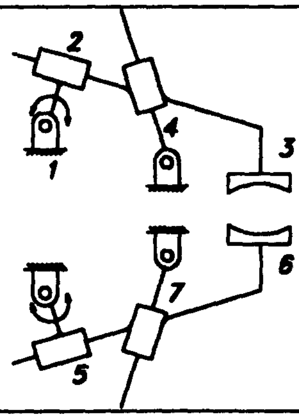
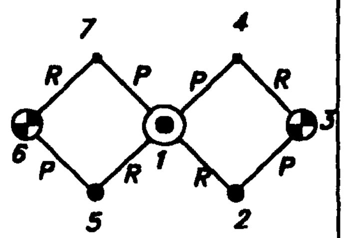
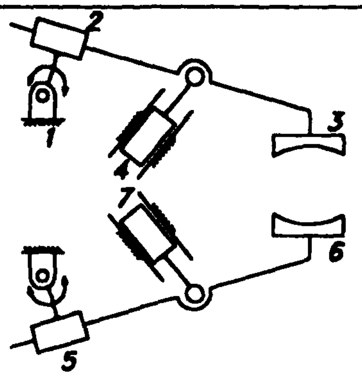
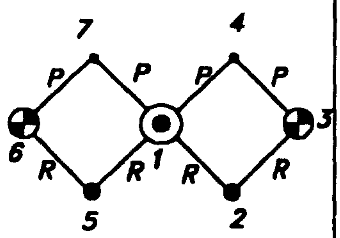
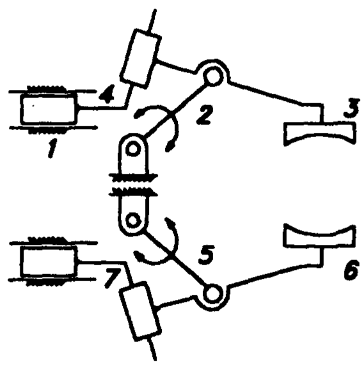
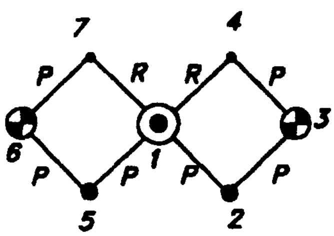
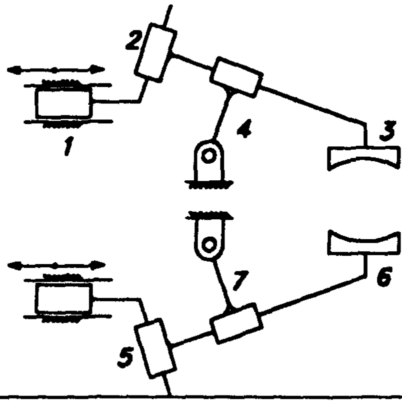
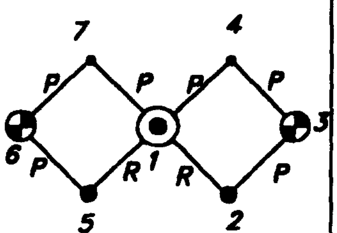
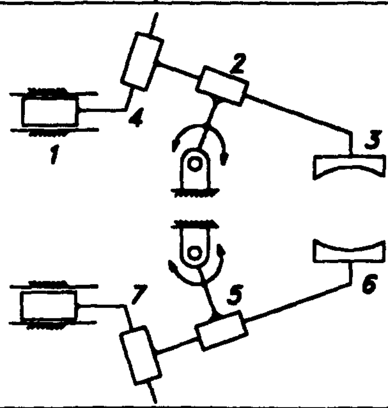
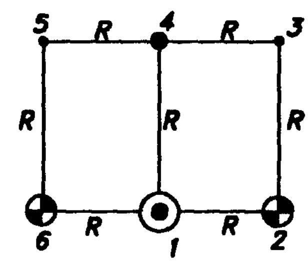
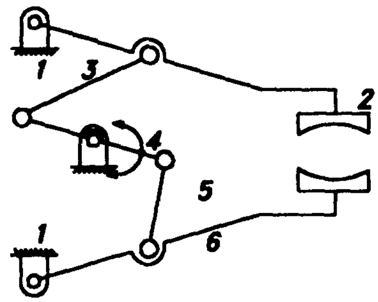
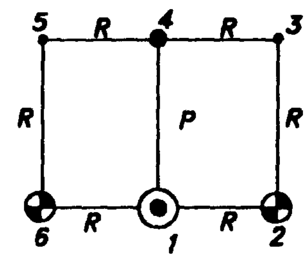
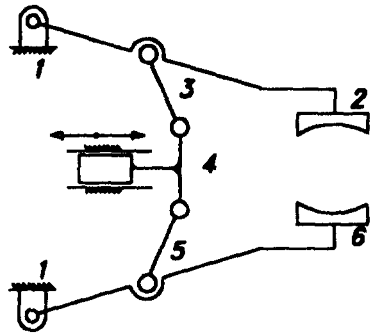
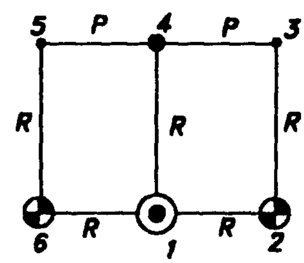
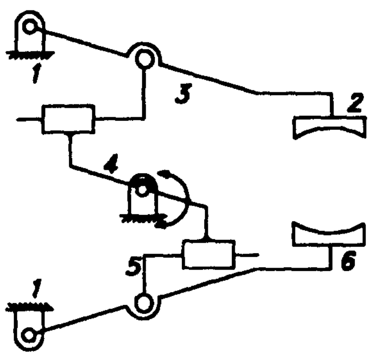
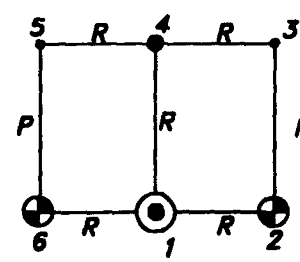
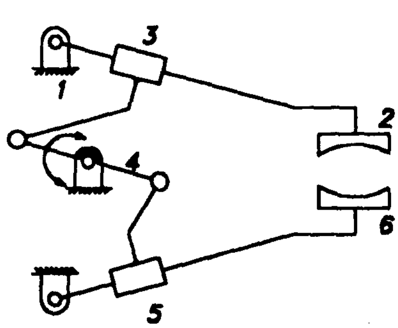
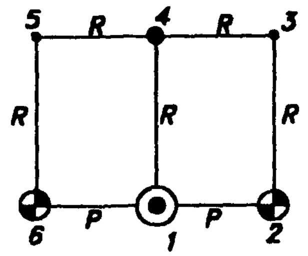
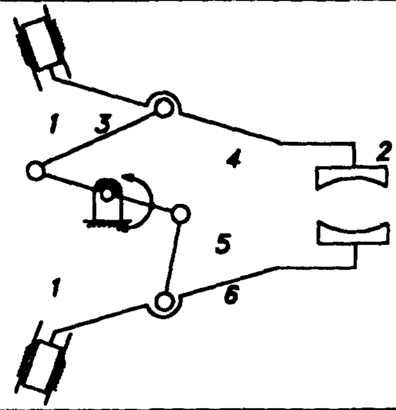
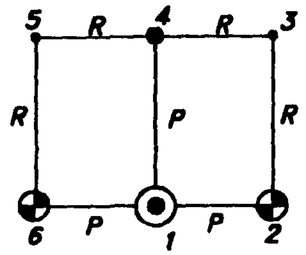
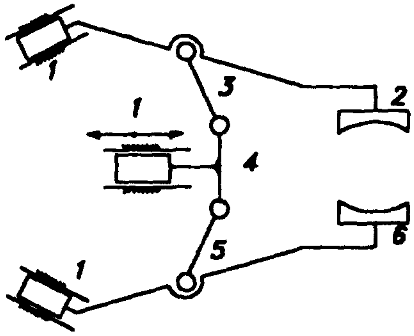
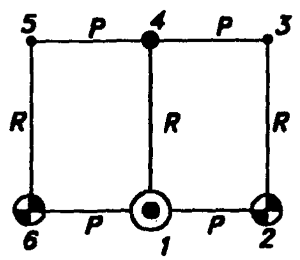
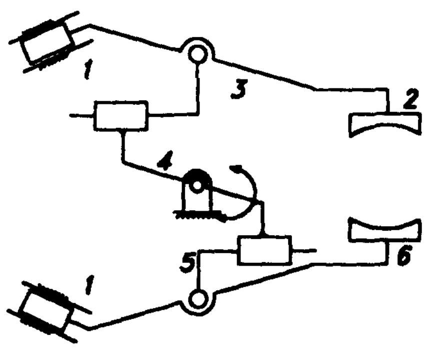
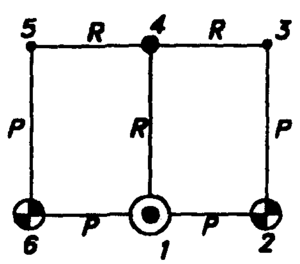
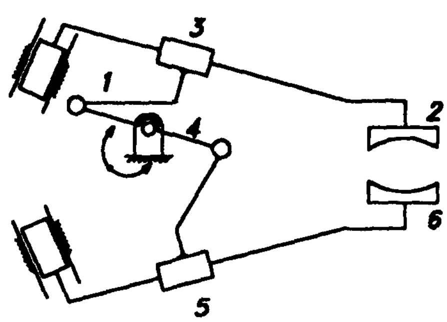
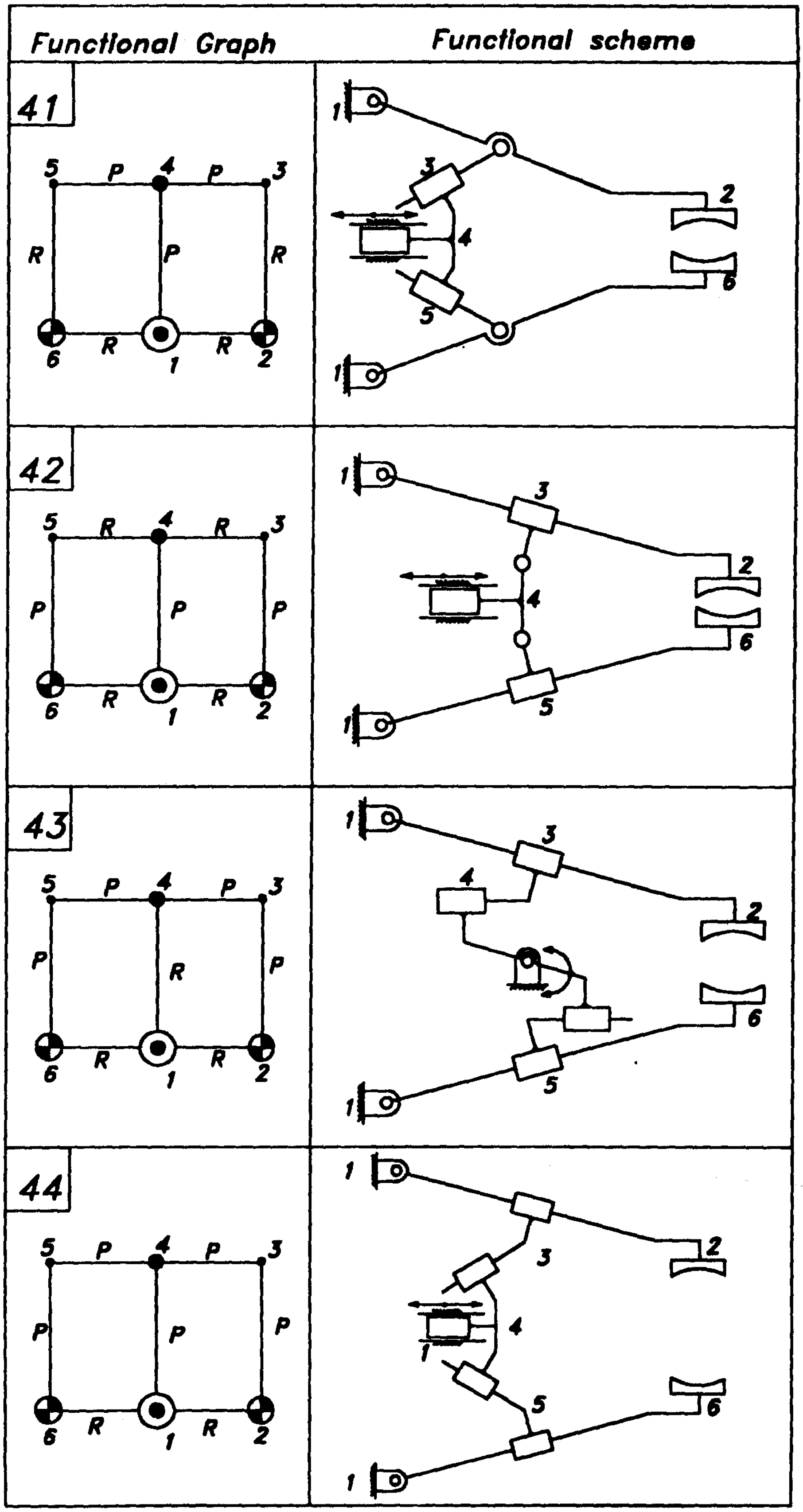
25		
26		
27		
28		

Functional Graph	Functional scheme
29 	
30 	
31 	
32 	

Functional Graph	Functional scheme
33 	
34 	
35 	
36 	

Functional Graph	Functional scheme
37 	
38 	
39 	
40 	


Functional Graph
Functional scheme
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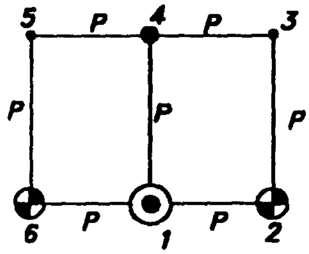
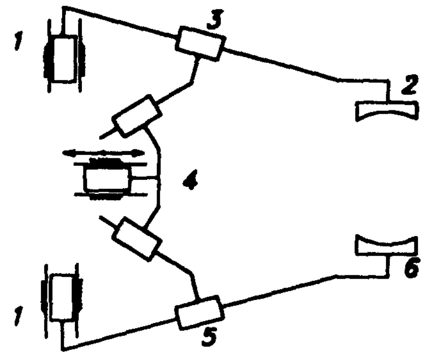
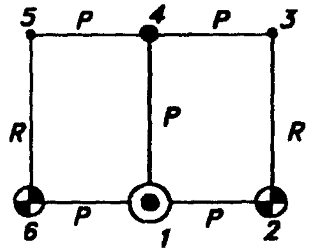
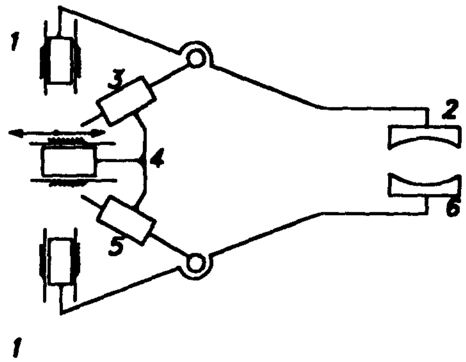
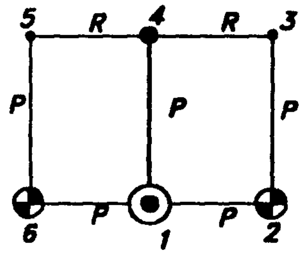
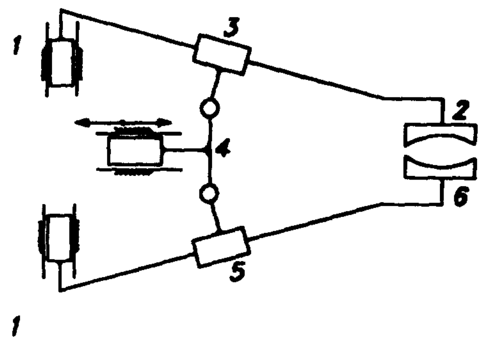
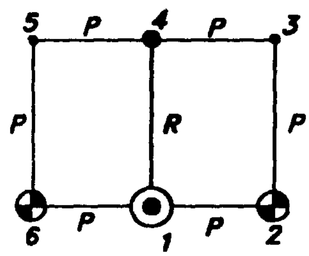
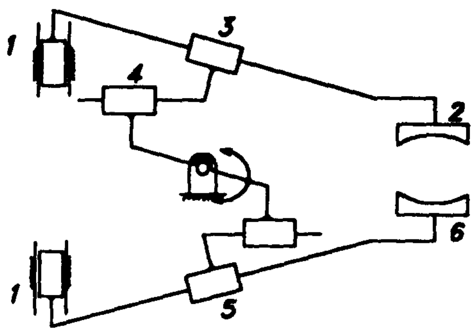
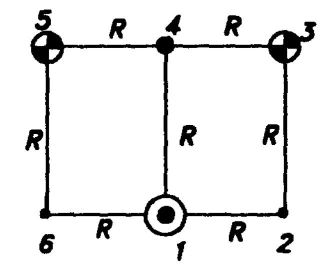
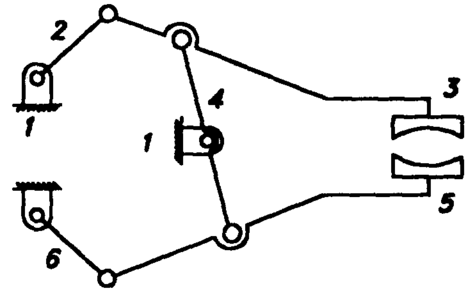
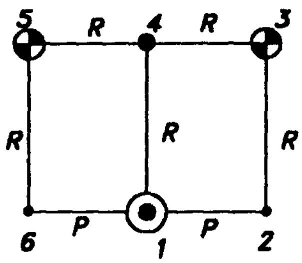
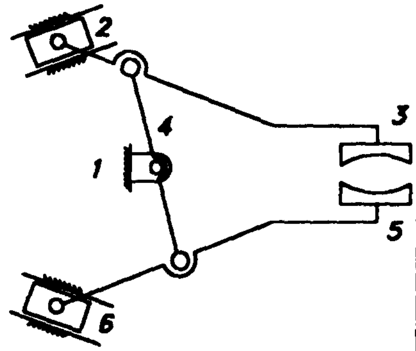
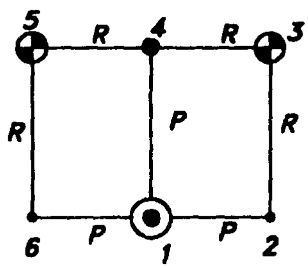
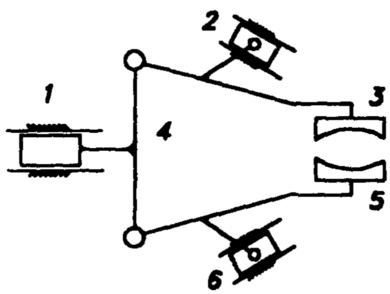
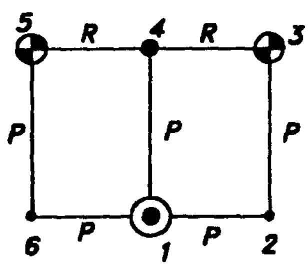
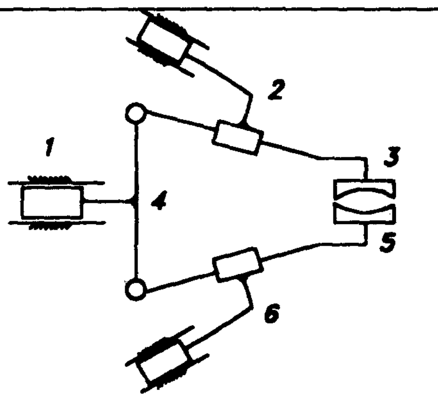
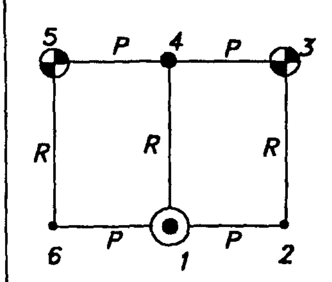
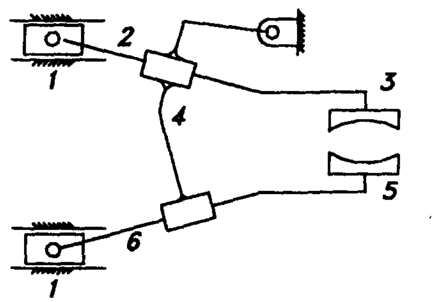
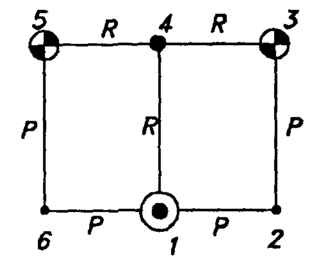
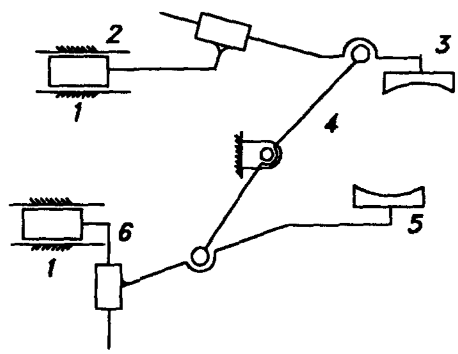
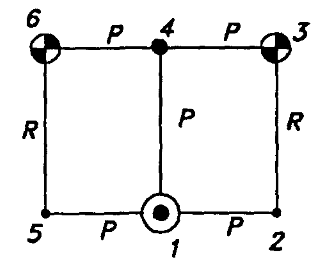
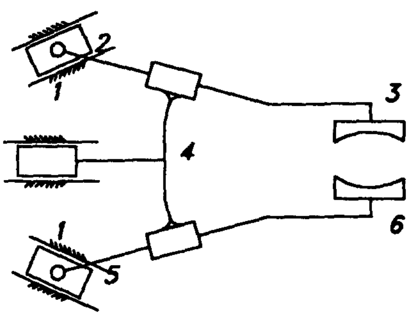
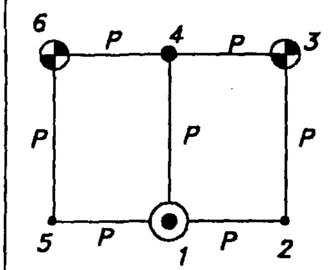
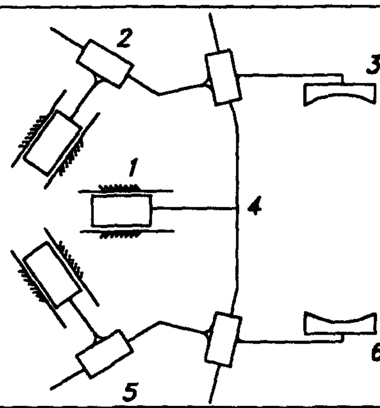
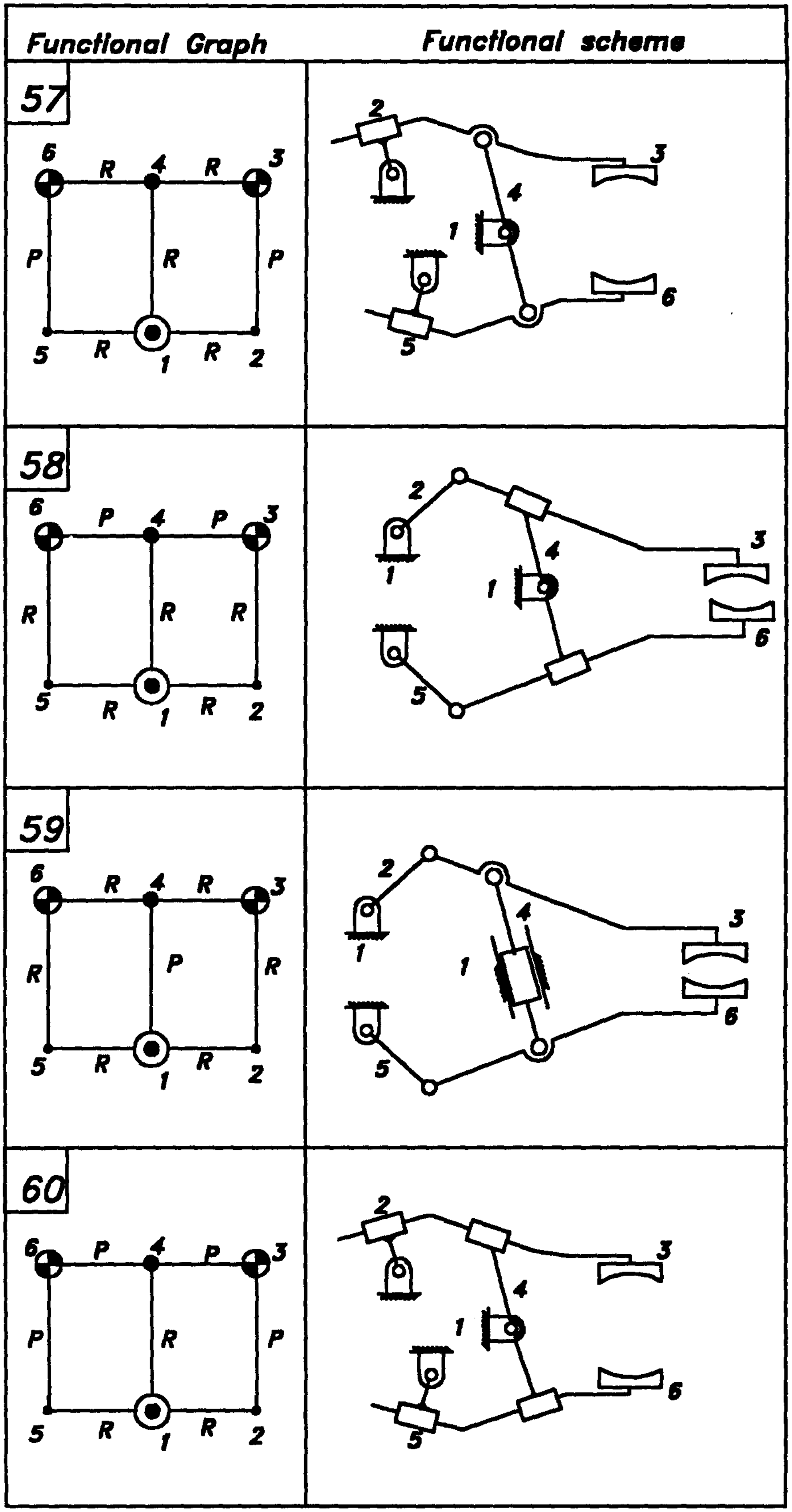
Functional Graph	Functional scheme
45 	
46 	
47 	
48 	

Functional Graph	Functional scheme
49 	
50 	
51 	
52 	

Functional Graph	Functional scheme
53 	
54 	
55 	
56 	


Functional Graph
Functional scheme
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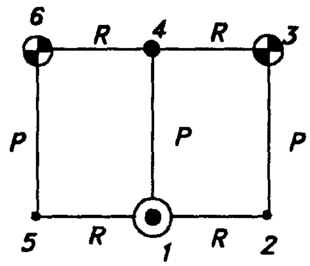
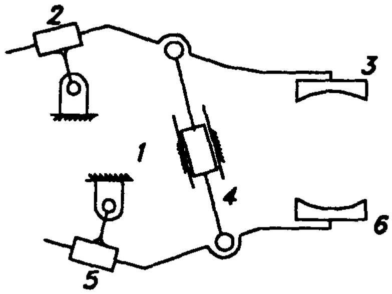
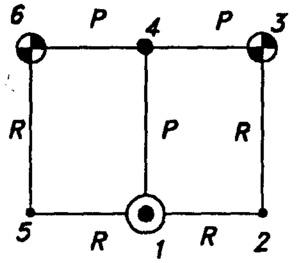
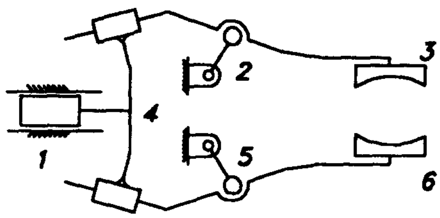
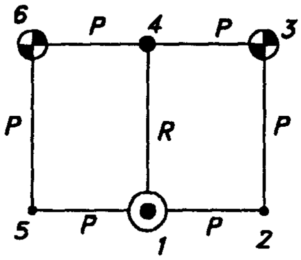
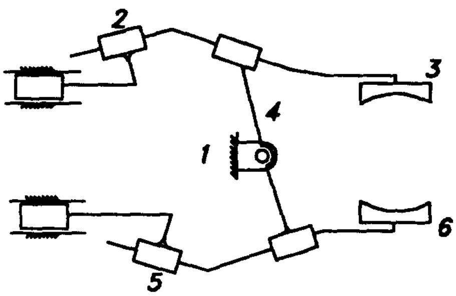
Functional Graph	Functional scheme
61 	
62 	
63 	
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