Structural analysis of combined multi-link manipulators for forest handling

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Abstract. The materials of the article relate to the forest industry and can be used in the design of multi-link manipulators for forestry machines. Any design of manipulators involves a number of stages. The initial stage in the design of manipulators, after the construction of the layout-kinematic diagrams, is to carry out their structural analysis in order to check their operability. This article presents fundamentally new designs, confirmed by the RF patent, multi-link manipulators with one degree of mobility (freedom) and presents their structural analyzes to confirm their performance. This article presents fundamentally new design solutions protected by copyright and confirmed by patents of the Russian Federation, multi-link manipulators with one degree of mobility (freedom) and presents their structural analyzes to confirm their performance.

1. Introduction
In final felling and intermediate felling using assortment technologies, three fundamentally different groups of methods are possible directly at the stump: firstly, the felling of the cut tree to the ground, delimbing with cross-cutting of the trunk into assortments, that is, repeating the principle of operation of Scandinavian harvester machines [1-3]; secondly, holding the cut tree vertically (TsNIIME ML-20 or ML-118 machines) or obliquely over the machine (Finnish Pika-75 or Pika-100 machines) and pulling the trunk down through the processor head (also using its own weight) or forward with simultaneous delimbing and crosscutting into assortments; thirdly, assortment processing of trees from top to bottom, starting with cutting the crown part using a small-sized SPAAG with a mass of 300 kg and a carrying capacity of 500 kg [4].

For the third group of methods, it is necessary to equip the basic module of the forest machine with a special combined manipulator, which ensures the extension of the working body up to 18 m with an angle of inclination of the boom up to 60 degrees with a maximum horizontal outreach of up to 12.5 m.

It is known that the design prototypes of most modern forestry machines are heavy excavators [5]. Therefore, the traditional structural diagram of the executive manipulator mechanism of such machines is still a hinged kinematic chain of three or four links, pairwise closed by a swinging link mechanism, which simultaneously serves as a hydraulic motor of translational action. The only structural modification that forest machine designers have allowed themselves is a telescopic mechanism built into one of the moving chain links to control its length. Such a structural diagram of the manipulator provides a large volume of its working space, but creates difficulties in controlling excess degrees of freedom [6].
The authors of the article proposed designs of multi-link manipulators that correspond to the third method of harvesting assortments and are protected by copyright, confirmed by patents of the Russian Federation, given in the list of references. The widespread introduction of this kind of manipulators requires a detailed study of its individual units and requires a structural analysis of its work. Variants of structural analyzes of existing design solutions for manipulators of forest machines proposed by other authors are not suitable for these designs, since contains some distinctive elements, such as a rigid triangle link, a rocker arm and therefore requires structural analysis in order to verify their operability.

2. Methods and Materials

In this article, a structural analysis of executive manipulative mechanisms of a new type with a rectilinear-guiding mechanism for extending the handle is carried out in the form of: 1) a system - a link-link of a rigid triangle-lever [7] and 2) a rocker-pull-rocker system [8], the diagrams of which are shown in figures 1, 2.

When performing the structural analysis, the usual assumptions were made [9, 10]:
1) all links of the mechanism are absolutely rigid bodies;
2) there are no gaps in the movable joints of the links;
3) not taken into account the own degree of mobility of the working body - ZSU.

Further, we restrict ourselves to the analysis of the movement of the mechanism in the vertical plane, without taking into account the rotation and translational movement of the movable base on which it is installed. This is due to the fact that the analysis of the movement of the proposed mechanisms in the plane of the layout, while simultaneously lifting and extending the working body, is of the greatest theoretical interest. In addition, for technological reasons, the operations of turning (aiming) and lifting (extending) the working body (ZSU) are usually separated in time.

Accepted abbreviated designations of kinematic pairs A1, ......., A40:
PPK - rotational pair of the fifth class;
PPPK is a forward couple of the fifth grade.

The calculation of the number of degrees of mobility of the mechanism is carried out according to the Chebyshev formula for flat mechanisms without redundant links:

$$W = 3n - 2P_5 - P_4,$$

where, $n$ is the number of moving links of the mechanism; $P_4$ is the number of kinematic pairs of the fourth class; $P_5$ is the number of kinematic pairs of the fifth class.

3. Results and Discussion

The authors of the article have developed two designs of a multi-link combined manipulator.

In figure 1 shows a block diagram of a multi-link combined manipulator with a rectilinear-guiding mechanism for advancing movable sections in the form of a system: thrust-link of a rigid triangle-lever. The working body must be delivered, for example, to a predetermined height with a vertical movement. For this, the boom 2 is installed by turning the platform of the forest machine and the hydraulic cylinder. In this case, the lever 1 changes the position of the apex of the rigid triangle, the link 6 of which acts on the support section 7 of the telescopic arm through the rod 6. The support section 7 of the telescopic arm rotates relative to the axis of attachment to the boom. In this case, the rod 27 acts on the articulated truss, the two-link pantograph mechanism of which push the movable sections 8, 9, 10, 11, 12 relative to the support section 7 of the telescopic handle (figure 1).

When the rod of the hydraulic cylinder 3 is retracted, the common handle is folded, and the boom takes its original position.
Figure 1. Block diagram of a multi-link combined manipulator with a rectilinear-guiding mechanism for extending movable sections in the form of a system: thrust-link of a rigid triangle-lever: 1 - lever; 2 - arrow; 3 - rod of the hydraulic cylinder for raising and lowering the boom; 4 - body of the hydraulic cylinder for raising and lowering the boom; 5 - a link of a rigid triangle; 6 - thrust; 7 - support section of the telescopic handle; 8, 9, 10, 11 and 12 - movable sections of the telescopic handle; 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26 - levers forming pantograph mechanisms extension of the movable sections of the telescopic handle; 27 – thrust.

Let’s carry out its structural analysis.

Let us introduce the designation: a rotational pair of the fifth class (VPPK), a translational pair of the fifth class (PPPK).

Kinematic pairs of the mechanism: $A_1(0;1)$ - VPPK; $A_2(0;4)$ - VPPK; $A_3(0;2)$ - VPPK; $A_4(3;4)$ - PPPK; $A_5(2;3)$ - VPPK; $A_6(2;5)$ - VPPK; $A_7(1;5)$ - VPPK; $A_8(5;6)$ - VPPK; $A_9(6;7)$ - VPPK; $A_{10}(7;13)$ - VPPK; $A_{11}(7;8)$ - PPPK; $A_{12}(8;14)$ - VPPK; $A_{13}(14;15)$ - VPPK; $A_{14}(8;9)$ - PPPK; $A_{15}(9;16)$ - VPPK; $A_{16}(16;17)$ - VPPK; $A_{17}(9;10)$ - PPPK; $A_{18}(10;18)$ - VPPK; $A_{19}(18;19)$ - VPPK; $A_{20}(10;11)$ - PPPK; $A_{21}(11;20)$ - VPPK; $A_{22}(20;21)$ - VPPK; $A_{23}(11;12)$ - PPPK; $A_{24}(12;22)$ - VPPK; $A_{25}(21;22)$ - VPPK; $A_{26}(21;23)$ - VPPK; $A_{27}(19;23)$ - VPPK; $A_{28}(19;20)$ - VPPK; $A_{29}(19;24)$ - VPPK; $A_{30}(17;24)$ - VPPK; $A_{31}(17;18)$ - VPPK; $A_{32}(17;25)$ - VPPK; $A_{33}(15;25)$ - VPPK; $A_{34}(15;16)$ - VPPK; $A_{35}(15;26)$ - VPPK; $A_{36}(13;26)$ - VPPK; $A_{37}(13;27)$ - VPPK; $A_{38}(13;14)$ - VPPK; $A_{39}(2;27)$ - VPPK; $A_{40}(2;7)$ - VPPK.

For the first structural diagram of the mechanism (figure 1) we get:

$$W = 3 \cdot 27 - 2 \cdot 40 - 0 = 81 - 80 = 1,$$

(2)

The model of a multi-link manipulator designed by the authors of the article is made at a scale of 1:10 and is shown in figure 2. This structure is equipped with a rectilinear-guiding mechanism for extending the movable sections in the form of a system: thrust-link of a rigid triangle-lever.
Figure 2. Multi-link combined manipulator with a rectilinear-guiding mechanism for extending movable sections in the form of a system: pull-link of a rigid triangle-lever: (a) - at maximum departure; (b) - at minimum departure; (c) - on an intermediate departure.

In figure 3 shows the system for extending the movable sections: thrust-link of a rigid triangle-lever.

Figure 3. System of extension of movable sections: link-link of a rigid triangle-lever.

In figure 4 shows a block diagram of a multi-link combined manipulator with a rectilinear-guiding mechanism for extending movable sections in the form of a system: rocker-thrust-link.

To deliver the working body to a predetermined height with vertical movement by turning the platform of the forestry machine and the hydraulic cylinder, the boom 2 is set to a predetermined position. By means of the rocker arm 5, the rocker 1 changes the position of the rod 12. The support section 6 of the telescopic handle is rotated relative to the axis of attachment to the boom. The rod 27


acts on the articulated truss, the pantograph mechanisms of which push the movable sections 7, 8, 9, 10, 11 relative to the support section 6 of the telescopic handle (figure 4).

When the rod of the hydraulic cylinder 3 is retracted, the common handle is folded, and the boom takes its original position.

Let's carry out its structural analysis.

Kinematic pairs: $A_1(0;1) - VPPK; A_2(0;4) - VPPK; A_3(0;2) - VPPK; A_4(3;4) - PPPK; A_5(2;3) - VPPK; A_6(2;12) - VPPK; A_7(5;12) - VPPK; A_8(1;5) - VPPK; A_9(5;6) - VPPK; A_{10}(2;6) - VPPK; A_{11}(2;27) - ПППК; A_{12}(6;13) - VPPK; A_{13}(6;7) - VPPK; A_{14}(13;14) - PPPK; A_{15}(13;27) - VPPK; A_{16}(13;26) - VPPK; A_{17}(7;14) - PPPK; A_{18}(7;8) - VPPK; A_{19}(15;26) - VPPK; A_{20}(15;16) - PPPK; A_{21}(15;25) - VPPK; A_{22}(8;16) - VPPK; A_{23}(8;9) - PPPK; A_{24}(17;25) - VPPK; A_{25}(17;18) - VPPK; A_{26}(17;24) - VPPK; A_{27}(9;18) - VPPK; A_{28}(9;10) - VPPK; A_{29}(19;24) - VPPK; A_{30}(19;20) - VPPK; A_{31}(19;23) - VPPK; A_{32}(10;20) - VPPK; A_{33}(10;11) - VPPK; A_{34}(21;23) - VPPK; A_{35}(21;22) - VPPK; A_{36}(11;22) - VPPK; A_{37}(20;21) - VPPK; A_{38}(18;19) - VPPK; A_{39}(16;17) - VPPK; A_{40}(14;15) - VPPK.

for the second first structural diagram of the mechanism (figure 2) we get:

$$W = 3 \cdot 27 - 2 \cdot 40 - 0 = 81 - 80 = 1,$$  \hspace{1cm} (3)
In figure 5, 6 shows a model of a multi-link manipulator with a rectilinear-guiding mechanism for extending the movable sections in the form of a system: rocker-thrust-link, made on a scale of 1:10.

**Figure 5.** Multi-link combined manipulator with a rectilinear-guiding mechanism for extending the movable sections in the form of a system: rocker-pull-rocker: (a) - at maximum departure; (b) - at minimum departure; (c) - on an intermediate departure.

**Figure 6.** The system of extending the movable sections: rocker-pull-rocker.

From the foregoing, it can be concluded that the designs of multi-link combined manipulators with rectilinear-guiding mechanisms for advancing the movable sections in the form of a system: thrust-link of a rigid triangle-lever and rocker-thrust-link are efficient.

With the only degree of mobility of the considered flat mechanisms, their working space degenerates into a flat curve L - the trajectory of the end point $A_{34}$ of the mechanism in figure 1, or the trajectory of the end point $A_{36}$ of the mechanism in figure 4. The shape of this curve depends on the geometric parameters of the links of the mechanism. To increase the dimension and volume of the working space of these mechanisms, it is proposed to use the rotational degree of mobility of the
turntable of the forest machine, on which the manipulator mechanism is installed, as well as the translational degrees of mobility of the wheel or tracked base of the machine.

4. Conclusion

Multi-link manipulators must have one degree of mobility, since otherwise the controllability of the working body, made in the form of a small-sized gripping and cutting device, is lost. On the other hand, such a forest machine, which has a long outreach of up to 18 m, can handle growing trees. Moreover, this processing can be performed when looking after trees (pruning large lower branches), caring for a forest (small trees are processed like LP-19V, medium-sized trees are processed into assortments, and large-sized trees are cut to the ground).

The proposed schemes of combined multi-link manipulators are efficient, since the number of degrees of freedom corresponds to the number of drives that ensure the operation of manipulators; in this case, both the number of drives (hydraulic cylinders) and the number of degrees of freedom are equal to one. Reducing the number of degrees of freedom simplifies the control of the mechanism and will facilitate the work of the forest machine operator.

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