Digital simulation of forest machine for forest clearance

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Keywords: Digital simulation, Forest machine for forest clearance, Forest clearance, Urbanized forest park, Defective tree, Healthy tree.

Abstract: The article discusses the work of the forest machine patented by the author. The forest machine is designed to clear urbanized forest park from defective trees. The article presents the results of a digital simulation of the operation of a forest machine and a conventional harvester. Experiments with the digital model were carried out for the maximum outreach of the manipulator from 8 to 11 m. The possibility to cut a defective tree was determined by the criterion of machine stability from overturning moment. The results of simulation experiments showed the advantages of a forest machine compared to a conventional harvester. The forest machine cuts 30 to 190% more defective trees than a conventional harvester. With an increase the maximum outreach of the manipulator, the harvester cuts 25-30% less defective trees compared to a forest machine.

1 INTRODUCTION

Modern forest machines for cutting trees - conventional harvesters (hereinafter referred to as *CH*) are equipped with a manipulator and a cutting head (Shirnin Yu. A., 2004), (Heikki, 2012). The manipulator is used to deliver the cutting head to the tree and then pull the cut tree to the machine (Figure 1).

The disadvantage of machines is their limited technological capabilities on tending felling for the care of protected urbanized forests and parks.

Figure 1: Harvesting tree with the help of the head.

The design of the manipulator is not flexible and therefore the use of the machine to clear urbanized forests and parks from defective trees (hereinafter referred to as *DT*), is difficult. By *DT*, we mean rotten, decayed, faulty, dead trees etc., which are subject to removal.

The inflexible manipulator does not allow the cutting head to be delivered to individual hard-to-reach out *DT* if they are covered up by other healthy trees.

DT are often large defective trees with a diameter of more than 40 cm. Cutting large-sized trees requires the *CH* to drive up to the tree at a distance of the minimum reach of the manipulator. At a maximum outreach of the manipulator, there is a danger of the *CH* overturning due to large overturning moment when holding the tree.

In order to deliver the cutting head to hard-to-reach and large-sized trees, the *CH* is must to move off the road deep into the forest and make maneuvers. This causes soil damage, which is unacceptable in protected urbanized forests and parks (29.12.2007. The guidance documents).

The impact of the tree trunk when pulling it to the *CH* after cutting it down also causes damage to the soil cover.

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To solve the above problems, we have developed and patented a forestry machine with a flexible manipulator (power manipulator + delivery arm) and a movable carriage (hereinafter – FM) to clear urbanized forests and parks from *DT* (Nazarenko, 2020).

2 CONCEPTUAL MODEL AND TECHNOLOGY

The task solved by the *FM* presented in the article (Nazarenko, 2020) is to expand the technological capabilities of conventional forest machines such as a *CH*. This problem is solved by providing the possibility of delivering the cutting head to individual hard-to-reach and large-sized *DT*. The *FM* excludes damage to healthy growing trees and soil cover.

The conceptual model of the *FM* is shown in Figure 2.

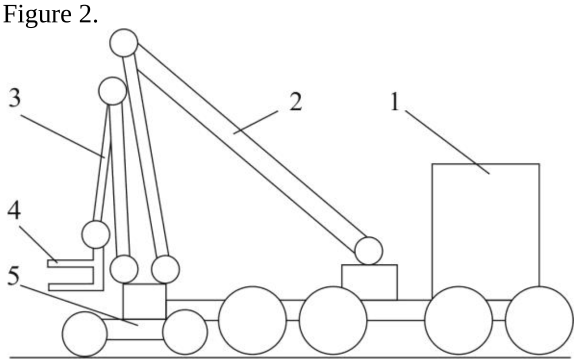

Figure 2: Conceptual model of a *FM*.

Conceptual *FM* model (Figure 2) includes base 1, power manipulator 2, delivery arm 3, cutting head 4, movable carriage 5.

Power manipulator 2 is fixed at one end to the base 1 of the *FM*. The other end of the manipulator 2 is attached to the movable carriage 5 with the possibility of its rotation relative to the manipulator 2. A delivery arm 3 is attached to the carriage 5 with the possibility of its rotation relative to the carriage 5. The other end of the delivery arm 3 is connected through a rotator with a cutting head 4 with the possibility of its location (Figure 3) inside the support contour 6 of the movable carriage 5.

The support contour 6 (Figure 3) is limited by the axes of the lateral and longitudinal overturning moments of the movable carriage 5. The movable carriage 5 can change its support contour 6, for example, by using a retractable telescopic wheel frame 7.

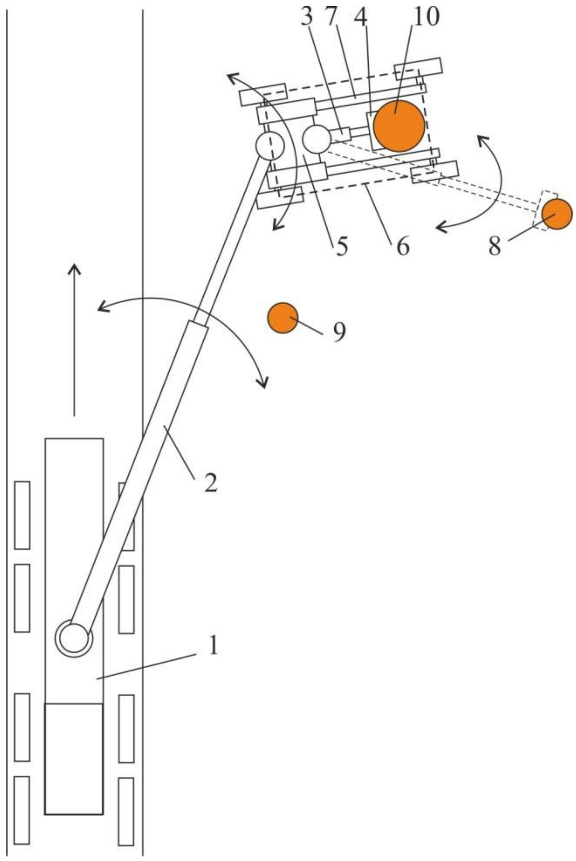

Figure 3: Conceptual model of a forest machine with a movable carriage.

The *FM* for clearing urbanized forests and parks from *DT* works as follows.

In the course of work (Figure 2), *FM* 1 moves along the established route, stops and cuts *DT* within the reach of power manipulator 2 and delivery arm 3.

In the case (Figure 3), when the *DT* 8 is covered by another tree 9, the power manipulator 2 moves through the air the movable carriage 5 with the delivery arm 3 and the cutting head 4 to the *DT* 8.

After that, the movable carriage 5 with the arm 3 and the head 4 is lowered to the ground and turned relative to the manipulator 2 towards the *DT* 8. Then, using the arm 3, the cutting head 4 is delivered to the *DT* 8 and cut off.

The cut *DT* 8 is held by the head 4 and pulled by the arm 3 to the carriage 5. Then the *DT* 8 is placed on the carriage 5 and transported to the *FM* 1.

In the case of cutting a large-sized *DT* 10, its big mass must be taken into account, which can cause a threatening overturning moment. The overturning moment from tree weight must be balanced by the restoring moment. To do this, the carrier 5 is placed so that the *DF* trunk 10 with the cutting head 4 is inside the support contour 6, as shown in Figure 3.

Note that the impact on the ground of the wheels of the movable carriage 5 when delivering the *DT* to the *FM* is much less than when pulling *DT*. In the case of protective urbanized forests and parks, this is especially important.

3 MATERIALS AND METHODS

The purpose of the research is to establish the effectiveness of the proposed *FM* in comparison with the *CH* in clearing protective forests and parks from *DT*.

The criterion for the efficiency of the machines is the number of medium and large-sized trees that the proposed *FM* can cut compared to the *CH*.

Studies of the efficiency of the *FM* were carried out by digital simulation methods on mathematical models for the conditions of Central Russia (Sergey Karpachev, and Maksim Bykovskiy, 2020), (S.P. Karpachev and R.I. Diev, 2022), (Karpachev S.P., Vjacheslav I. Zaprudnov, Maksim A. Bykovskiy, Irina P. Karpacheva, 2020).

The work considered the movement of the *DT* and *CH* down the road along the forest strip. The width of the forest strip is taken equal to the maximum outreach of the manipulator. In this article, the maximum outreach of the manipulator is taken to be from 8 to 11 m.

Trees were generated within the strip. Each tree was assigned coordinates X_i, Y_i and diameter d_i.

The density of trees on the strip was determined according to taxation indicators for Central Russia.

In the model, the diameter of each tree d_i was assigned according to the *beta*-distribution law. This distribution was obtained from the results of statistical processing of the experimental distribution (Figure 4). Mean diameter d_{mean} = 23.5 sm, S.D. =13.17 sm.

Each generated tree on the forest strip was assigned coordinates according to the uniform distribution law on the interval:

$$0 \le X_i \le R_{man\_max} \tag{1}$$

where:

R_{man_max} – maximum outreach of the manipulator, m

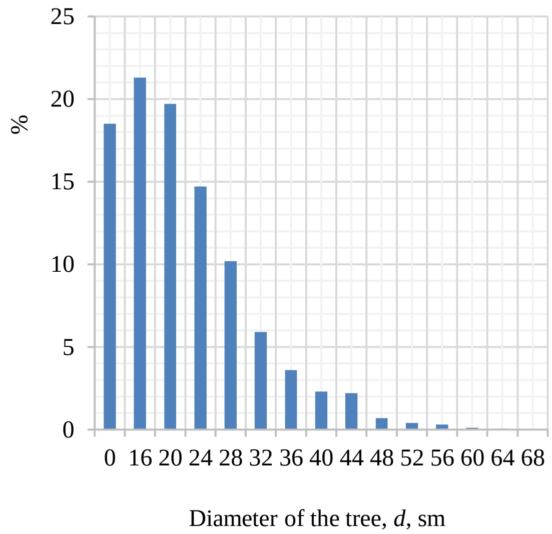

Figure 4: Experimental tree diameter distribution (Central Russia).

The volume of each tree was determined by calculating the diameter according to the empirical formula (Laptev A.V., Matrosov A.V., 2018), (Karpachev S.P., Bykovskiy M.A., Laptev A.V., 2021):

$$V_i = 0.00024 \cdot d_i^{2.3846}, m^3 \tag{2}$$

The weight of each tree was determined by the formula:

$$G_{tree\_i} = \rho \cdot g \cdot V_i = 8000 \cdot V_i, N \tag{3}$$

The following characteristics of the *CH* were taken into account in the calculations:

B = 2196 mm - support contour width of the overturning moment;

L_{stab} = 1098 mm – distance from the center of gravity of the *CH* to the lateral overturning axis;

G_H = 159 475.4 N – weight of the harvester;

G_{HH} = 13 524 N – weight of the harvester head with rotator;

G_{man} – manipulator weight. Weight varies depending on its maximum outreach.

In simulation experiments, simplifications and restrictions were accepted:

1. *FM* and *CH* move along the road and cut *DT* across the entire width of the forest strip.

2. Cutting the *DT* is done by turning the manipulator by 90º.

3. Limitations on the permissible load moment of the manipulator were not taken into account.

4. Overturning moments (Laptev A.V., 2013)

- from the weight of the *DT*:

$$M_{tree\_i} = G_{tree\_i} \cdot (X_i - L_{stab}) \quad (4)$$

- from the manipulator:

$$M_{man\_i} = 0.42 \cdot G_{man} \cdot (X_i - L_{stab}) \quad (5)$$

- from the harvester head:

$$M_{HH\_i} = G_{HH} \cdot (X_i - L_{stab}) \quad (6)$$

- total overturning moment:

$$M_{overturn\_i} = M_{tree\_i} + M_{man\_i} + M_{HH\_i} \quad (7)$$

5. The stabilizing moment of the machines was calculated by the formula:

$$M_{stab} = 0.714 \cdot G_{HH} \cdot L_{stab} \quad (8)$$

6. Condition for cutting a *DT*:

$$M_{stab} > M_{overturn\_i} \quad (9)$$

If condition (9) was not satisfied, then the *DT* was not cut.

In the experiments, all trees were divided into three groups according to their diameters.

1. Trees with a diameter of $d \leq 14$ sm were considered healthy and were not cut.
2. 30% of trees with a diameter of $14 < d \leq 40$ sm were considered as *DT* and checked for the possibility of cutting them;
3. All trees with a diameter d > 40 sm were considered to be *DT* and were checked for the possibility of cutting them.

The experiments did not take into account the limitation on the diameter of the *DT* tree.

To obtain statistically significant results, the number of generated trees in each experiment was taken to be 100,000 pcs. An experiment planning matrix is shown in Table 1.

Table 1: Experiment planning matrix.

Experiment number	Maximum manipulator length, m
1	8
2	9
3	10
4	11

4 RESULTS AND DISCUSSION

Some results of the study on digital models are presented graphically in Figure 5 and Figure 6.

Figure 5 shows the work of the *CH* and the *FM* in the clearing of the forests and parks from *DT*.

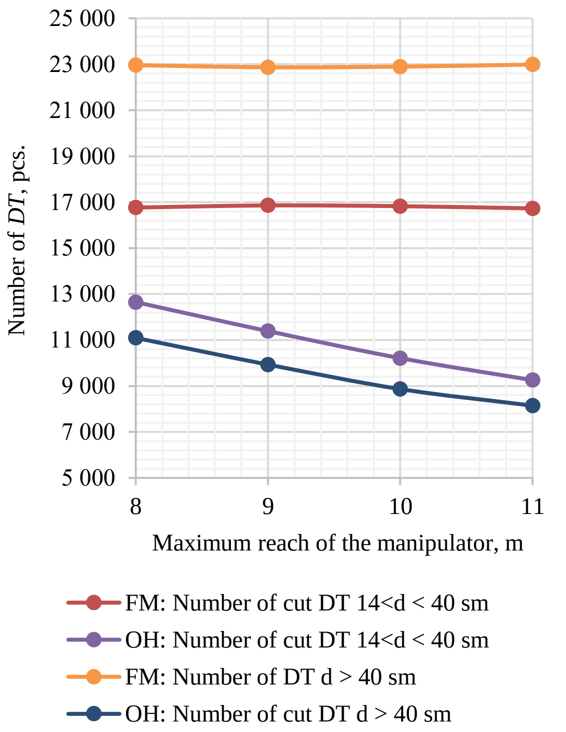

Figure 5: The work of the *CH* and the *FM* on clearing the forests and parks from *DT*.

Figure 6 shows a computer-generated forest strip 100x11 m in size with forests of different diameters. The density of the forest is assumed to be 400 pieces/ha.

The graph in Figure 5 shows that the *CH* cuts fewer *DT* than the *FM*. This is typical for all categories of trees and all maximum outreaches of the manipulator.

So, for example, when clearing the forest from *DT* 14< d <40 sm, the *FM* cut 17,000 trees, and the *CH* only 13,000. That is, the *FM* cut at the maximum reach of the manipulator 8 m, 4000 more *DT* than the *CH*.

This difference is even more significant for trees d > 40 sm.

So, for example, with a manipulator outreach of 8 m, the *FM* cut 23,000 *DT* d > 40 sm, and the *CH* only 11,000. That is, the *FM* cut 12,000 more large-sized *DT* than the *CH*.

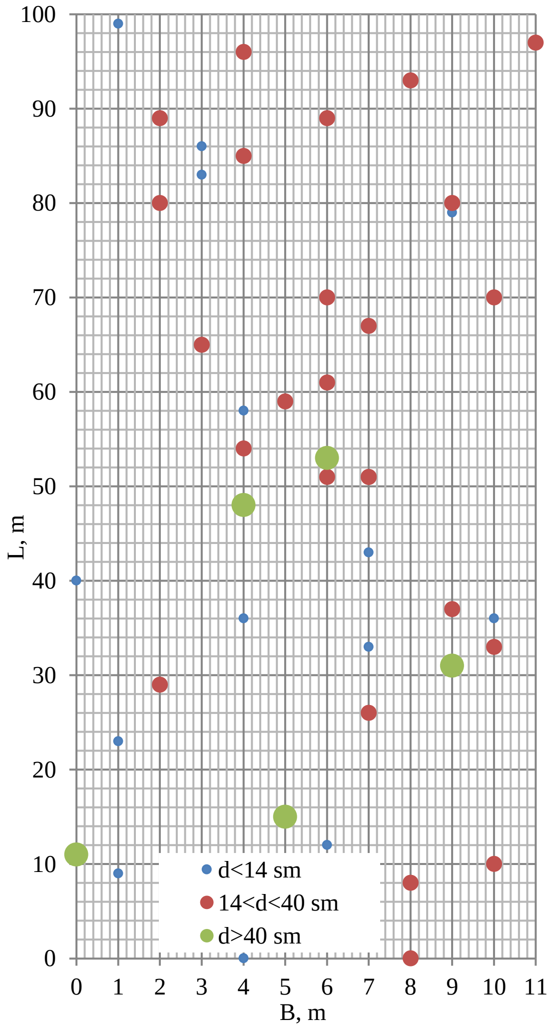

Figure 6: An example of computer generation of trees of different diameters on a forest strip 100x11 m^2 in size. Number of trees 400 pcs/ha.

The difference between the number of cut *DT* is explained by the fact that the length of the outreach of the manipulator increases the overturning moment of the *CH*, and the design of the movable carriage 5 of the *FM* (Figure 2 and Figure 3) does not increase this overturning moment.

The difference between the number of *DT* cut by the *CH* and the *FM* increases markedly with the increase in the maximum outreach of the manipulator.

So, for example, with a manipulator outreach of 8 m, the *FM* cut 23,000 *DT* d > 40 sm and does not change when the manipulator outreach increases to 11 m.

With a manipulator outreach of 8 m, the *CH* cut 11,000 *DT* d > 40 sm, and with an increase in the manipulator outreach to 11 m, only 8,000 trees.

The decrease in the number of *DT* cut by the *CH* is due to the increase in the overturning moment.

In all cases, if the overturning moment exceeds the restoring moment, the *DT* was considered uncut.

5 CONCLUSIONS

The results of digital simulation experiments of cleaning the forest from *DT* with a *CH* and a *FM* in protective urbanized forests and parks made it possible to draw the following conclusions (for the conditions of Central Russia):

1. The *FM* cleans the forest from *DT* better than the *CH*.
2. The *FM* cuts 31-47% more *DT* 14< d <40 sm than *CH* with a manipulator outreach of 8 to 11 m.
3. The *FM* cuts 110-190% more *DT* d > 40 sm than a *CH* with a manipulator outreach of 8 to 11 m.
4. With an increase in the outreach of the manipulator from 8 to 11 m of the *FM*, the number of cut *DT* does not decrease.
5. With an increase in the outreach of the manipulator from 8 to 11 m of the *CH*, the number of cut *DT* is reduced by 25-30%.

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