Optimization of Chainsaw Setting Angle in Pruning Robot

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Abstract. This paper presents an optimal mechanical design for a chainsaw setting angle to reduce the driving force of wheels in a pruning robot that cuts branches while spiraling up. Analysis and experimental results demonstrate the effectiveness of the optimal mechanical design for the chainsaw setting angle.

1. Introduction
Pruning is necessary in forests to produce high-quality wood and to maintain the forest environment. Pruning is, however, very dangerous work because a forestry worker must climb high trees, and support his body with one hand while cutting branches with the other gripping a pruning device. Thus, several engine-driven automatic pruning machines have been reported [1]; their use is limited, however, because of their heavy weight and the high frequency of branch bites. Pruning robots driven by servomotors have been developed, including a wheel-type [2, 3] and an inchworm-type [4]. Most of these robots are equipped with a strong pressing mechanism to protect the device from slipping downward due to its own weight. No practical and lighter weight pruning robot driven by servomotor has yet been realized.

We have developed the world’s first climbing robot that uses its own weight [5], and is thus effective for weight saving. This robot can remain on a tree using its own weight without energy consumption, since it is driven by four active wheels through servomotors, worm-wheel reduction mechanisms with non-back-drivability, and a center of mass located outside of the tree. Other climbing robots using their own weight have been reported [6, 7]; they have one active wheel, two passive wheels and a low climbing speed, since the robot slips off the pole when the active wheel slips.

Power saving is a major challenge for such pruning devices, because the pruning robots are battery driven, and pruning consumes a fairly large amount of energy. When a pruning robot cuts a branch with a chainsaw while spiraling up a tree, it must then cut open a cut section of the branch to turn around the tree, which requires a high driving force of wheels. An optimization design for the chainsaw setting angle could contribute to reducing the driving force of the wheels.

2. Developed Pruning Robot
As shown in Figure 1, our pruning robot is equipped with four active wheels. Two wheels are located above and two below the pruning device. Each wheel is placed at the same angle, ±π/4 rad relative to the x-axis, when viewed from the top of the cylinder. The active wheel is driven by a DC servomotor via a worm-wheel reduction mechanism, which has non-back-drivability and allows the robot to be at rest without any energy expenditure. The robot’s center of mass is located outside of the cylinder due to the controller being located by the down-side active wheels. Each of the four active wheels has a steering...
system to control the steering angle. The steering system is also driven by DC servomotors via a worm-wheel reduction mechanism.

The pruning device consists of a chainsaw with a pose-adjustment mechanism. When a branch bite occurs during pruning, work efficiency decreases considerably, because the operator must remove the robot/pruning device. To the best of our knowledge, no robot with a pruning mechanism that includes a branch-bite prevention function has yet been proposed. We previously presented a chainsaw prototype with a branch-bite prevention function [8]. In the prototype, a movable bar was mounted on the guide bar of the chainsaw so that it could move on the guide bar even if bitten by a branch. The robot could then continue to prune and advance, because the guide bar was not constrained by the branch. A movable bar is attached to the guide bar by a spring to enable planar motion of the movable bar.

![Visual appearance](a) Visual appearance  ![Schematic of the robot](b) Schematic of the robot

**Figure 1.** Developed pruning robot

### 3. Optimization of Chainsaw Setting Angle

When the robot prunes branches during the straight motion that is normal in the use of a chainsaw device, the power to open up a cut section of branch is not needed. However, such power is needed through the guide bar of a chainsaw when the robot prunes branches while moving up in a spiral around the tree, as shown in Fig. 2. In the figure, the orthogonal coordinate system is set at the center of the tree, points A / B are the right / left points of the chainsaw guide bar, point C is the right-side point of the cutting section of a branch, point C* is a transfer point of C, D is the diameter of the tree, D is the diameter of the branch, W is the width of the chainsaw, l is the displacement of the chainsaw along the y-axis, θ is the rotation angle of the chainsaw device around the tree, θ is the cut angle of the branch, and θ is the setting angle of the chainsaw guide bar. When the chainsaw cuts the branch at displacement l, point C moves to point C*, which means that the guide bar spreads the cutting section with ΔC. If θ is reasonably set, it is expected to reduce ΔC. On the other hand, an interference between the cut surface of the branch and the left surface of the guide bar, ΔC, is revealed. This means that the guide bar must compress the cut surface of the branch. This relation shows that an optimal setting angle exists for the pruning device.
Figure 2. Geometric model of pruning by chainsaw device

The opening force to spread the cutting section, $F_o$, is derived by the relationship between the bending moment and the deflection as follows:

$$F_o = \frac{2EI_\phi}{W((D_b + l)\cos \gamma + W \sin \gamma)}$$

(1)

where $E$ is the Young's modulus of the branch, $I_\phi$ is the moment of inertia of the area, $\phi_\theta$ is the deflection angle, and $\gamma = (\theta_d/2 + \theta + \xi)$ is the slope angle of the guide bar. When the displacement $l$ and the setting angle $\xi$ are given, then $\Delta x$, $I_\phi$, and $\gamma$ are obtained geometrically, and $F_o$ is computed using these values. The drive force of the wheel is needed to overcome the opening force and friction force between the guide bar and the cut surface of the branch, which is caused by the opening force.

The interference $\Delta x_p$ varies with the position of the guide bar along the $y$-axis, and its maximum is derived by

$$(\Delta x_p)_{\text{max}} = \frac{D_1}{2} (1 - \cos \xi).$$

(2)

This shows the maximum of $\Delta x_p$ does not depend on the displacement $l$ of the chainsaw. From the relationship between the compressive force and the deformation, the compression force $F_p$ is derived by

$$F_p = \int_{y_1}^{y_2} \frac{\Delta x_p}{D_1} E \sqrt{D_1^2 - 4y^2} dy$$

(3)

where $y_1$ and $y_2$ are both ends of the interference interval along the $y$-axis. The drive force of the wheel is needed to overcome the compression force and friction force between the guide bar and cut surface of the branch caused by the compression force. This varies with $\xi$. Therefore, it is desirable that the total of the opening force and compression force given by

$$F_{\text{total}} = F_o + F_p.$$  

(4)

be kept as small as possible by designing the optimal setting angle for the chainsaw device.
4. Numerical Analysis
To evaluate the effect of the setting angle of the chainsaw device, numerical analysis was conducted on the condition of \( E = 9kN/mm^2 \), which is the Young's modulus of Japanese cypress. Figure 3 shows the opening displacement \( \Delta \chi_e \) and the opening forces \( F_o \) with the condition \( D_e = 40,50,60 [mm] \), \( D_s = 250[mm] \), \( W = 6 [mm] \) and \( \xi = 0[rad] \). This shows that the curve of \( \Delta \chi_e \) does not vary with \( D_s \), while \( F_o \) varies with \( D_s \) remarkably.

![Figure 3. Opening displacement and opening forces.](image)

Figure 3. Opening displacement and opening forces.

Figure 4 shows \( F_o \), \( F_p \) and \( F_{total} \) with the conditions \( D_t = 250[mm] \), \( D_s = 50[mm] \), and \( \xi = -0.105 [rad] \) (-6 [deg]). \( F_p \) becomes drastically smaller than that of \( \xi = 0 [rad] \). \( F_p \) increases, and \( F_{total} \) is not so large. The maximum of \( F_{total} (= F_{max}) \) should be as small as possible.

Figure 5 shows \( F_{max} \) at \( D_t = 150,200,250[mm] \). It shows that the minimum \( F_{max} \) varies with \( D_t \) and \( \xi \). Optimum \( \xi \) minimizing \( F_{max} \) is -0.163, -0.128, -0.098 [rad] at \( D_t = 150,200,250[mm] \), respectively. For a simpler mechanical design, it is better that \( \xi \) is constant. This leads to an optimum \( \xi \) of about -0.142 [rad] (8.1 [deg]), which is the cross point of the curves of \( D_t = 150[mm] \) and \( D_t = 250[mm] \). Then \( F_{total} \) is 280 [kN], which is about 25% in the case of \( D_t = 150[mm] \) and \( \xi = 0 [rad] \).

![Figure 4. Force \( F_o \), \( F_p \) and \( F_{total} \).](image)

![Figure 5. Maximum of \( F_{total} \).](image)
5. Experiment
The design method was evaluated experimentally using the circular experimental unit shown in Figure 6. Two types of chainsaw guide bars were used, as shown in Figure 7. One was our developed chainsaw guide bar [8], which has the branch-bite protection function; the other was a commercial guide bar.

![Figure 6. Circular experiment unit](image)

![Figure 7. Two types of guide bar](image)

Table 1 shows power consumption and maximum torque of the circular motor drive system. The branch was a drying round bar, which was harder than a living branch of Japanese hinoki. The power consumption was evaluated during cutting time. Type (b) was evaluated at carriage velocity 3 [mm/s], because it could not cut the round bar at carriage velocity 9 [mm/s]. The power consumption and maximum motor torque of both types (a) and (b) were largely reduced by setting the angle from 0 to 9 [deg]. The large effect of type (a) was due to the tilt mechanism of the movable plate on the guide bar [8].

| Type of guide bar | Evaluation item               | Setting angle $\xi$ [deg] | Ratio [%] |
|-------------------|--------------------------------|--------------------------|-----------|
| Type (a) at 9 [mm/s] | Power consumption [ws] | 22.6 | 0.56 | 2.5 |
|                    | Maximum motor torque [mNm]  | 53.9 | 1.75 | 3.2 |
| Type (b) at 3 [mm/s] | Power consumption [ws] | 5.1  | 0.93 | 18.2 |
|                    | Maximum motor torque [mNm]  | 1.16 | 0.69 | 59.4 |

6. Conclusion
We demonstrated that the optimization of the setting angle of a chainsaw device contributed to reduce power consumption and maximum motor torque of the carrying unit substantially in pruning during rotational motion. In future work, we plan to apply this optimum setting angle for the chainsaw device to the developed pruning robot and to evaluate it in a field setting.

Acknowledgements
This research is supported by a Grant-in-Aid for Scientific Research from JSPS, Japan ((C) 18K04017) and NEDO project P14033.

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