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A Pruning Robot With a Power-Saving Chainsaw Drive

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***Abstract* - We present a novel pruning robot that uses self-weight and a power-saving chainsaw drive. The pruning robot consists of a climbing up-and-down mechanism, a chainsaw mechanism, and a controller. The climbing up-and-down mechanism has four active wheels equipped with a steering mechanism and a two-DOF posture adjustment mechanism to keep the pruning robot in a horizontal posture. The robot can stay on a tree without energy consumption by using its own weight. The chainsaw mechanism consists of a chainsaw and a two-DOF pose adjustment mechanism, which has a liner joint to maintain a specified distance between the tree surface and chainsaw, and a tilt joint to keep the chainsaw in a specified posture against the tree surface. In the chainsaw power-saving drive, there are two modes of a high input and a low input, and its switching is executed based on the disturbance estimation. It is shown experimentally that the developed robot can do pruning work with low power consumption.**

Index Terms – Pruning, Robot, Chainsaw, Forest

I. INTRODUCTION

Forest pruning is an important aspect of the forestry industry that produces high-quality wood greatly contributes to the maintenance of forest environments. The work accident rate in the forestry field in Japan is approx. 10 times that in the manufacturing industry [1]. Pruning is very dangerous work, because a forestry worker doing pruning must climb high trees, support his body with one hand and cut branches with the other hand. There are thus high expectations for the development of safe and effective pruning robots. Automatic pruning machines with an engine drive have been reported [2], but their use is limited because of their heaviness and the high frequency of branch bites. Pruning robots with a servomotor drive have been described, including a wheel-type [3], a crawler-type [4], and an inchworm-type [5]. Since most of the wheel-type robots are equipped with a strong pressing mechanism to protect the robot from slipping downward due to its own weight, they are rather heavy. With the inchworm-type robots, it is not easy to increase the speed of climbing and grasping because of the grasping mechanism that keeps the robot from falling down. To our knowledge, a practical and lighter-weight pruning robot driven by a servomotor has not yet been created.

We have developed a climbing robot that uses its own weight [6]. It needs no pressing or grasping mechanism but instead takes advantage of its own weight. The results of our analysis of its principles of operation are published elsewhere [7]. The climbing robot is driven by four active wheels through servomotors and warm-wheel reduction mechanisms that do not have back-drivability. We confirmed that this robot can remain on a tree using its own weight, since the center of its mass is located outside of the tree. Other climbing robots that use their own weight have been reported [8, 9]; they have one active wheel and two passive wheels and a low climbing speed since the robot slips off the pole when the active wheel slips. In addition, these robots can only climb straight up; they cannot climb in a spiral, which prevents the robots from pruning omnidirectionally.

Concerning the cutting mechanisms of pruning robots, there are several potential types including a chainsaw, a circular saw and a reamer, but for all of these cutting mechanisms it is necessary to prevent or protect the operator from branch bites (i.e., when a tree branch "bites" the blade or the saw during cutting). Our pruning robot has a branch bite prevention function in its chainsaw, and the posture of the robot fluctuates in accord with the irregularities on the tree surface. A mechanism to keep a specified distance and posture between the tree surface and the cutting mechanism is thus required, and since pruning robots with a battery drive use a significant amount of energy, power saving is a major goal.

Here we present a novel pruning robot with a power-saving pruning drive that can remain stationary by using its own weight without energy consumption. This robot is equipped with a climbing up-and-down mechanism, a posture-adjustment mechanism for the robot body, a chainsaw mechanism, and a controller. The robot can move straight up and down and spirally and can steer the active wheels that enable it to climb not only straight cylindrical poles but also conical poles. The power-saving chainsaw drive adopts a switching approach between a low-input voltage mode at no cutting and a high-input voltage mode at cutting. The switching timing is decided by a disturbance estimation in the chainsaw.

II. STRUCTURE OF NOVEL PRUNING ROBOT

The new pruning robot consists of a climbing up-and-down mechanism, a pruning mechanism, and a controller as shown in Fig. 1. The robot is fixed on the tree by oping and locking the frame connection. This robot is remote-controlled by an operator. It climbs straight up-and-down for intervals on a tree that have no branches, and for intervals with branches, it climbs in a spiral as it prunes the branches with its chainsaw. Switching between the straight climbing and the spiral

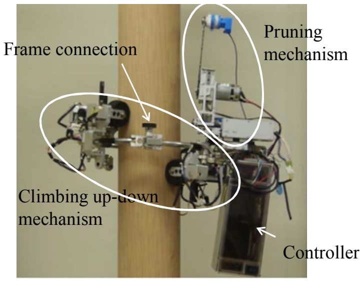


Fig.1 Developed pruning robot

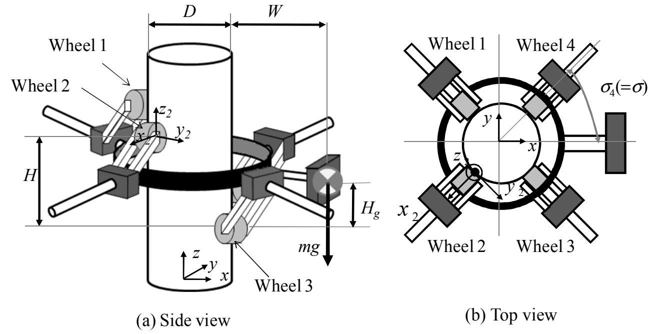


Fig. 2 Climbing up-and-down mechanism equipped with four active wheels

Table 1 Characteristics of the pruning robot

Item	Specifications
Mass	13 Kg
Straight climbing velocity	0.25 m/s
Spiral climbing velocity	0.02 m/s
Target Tree diameter	0.06 – 0.25 m
Target branch diameter	Less than 0.05 m

climbing is executed by the operator. The characteristic features of the robot are given in Table 1. The mass is 13Kg, the straight climb maximum velocity is 0.25 m/s, the spiral climb velocity at pruning is 0.02 m/s, the target range for the tree diameter at chest-height is 0.06–0.25 m, and the target branch diameter is less than 0.05 m. The climbing up-and-down mechanism and the pruning mechanism are as follows.

A. Climbing up-and-down mechanism

Traditional Japanese timberjacks use a set of rods and ropes as a ladder when climbing a tree. The timberjack stays aloft on the tree by friction force (produced by a rope around the tree), supporting his weight on a rod. Friction force can be used because the timberjack's center of mass is located outside of the tree. He can prune the branches using a chopper, since his arm lightly supports his body. In this way, the timberjack stays on the tree due to the friction force between the rope and rod.

We demonstrated that our climbing robot can rest on a tree using its own weight without a holding mechanism and without any energy, and it can climb up and down [6]. We accomplished this by placing the active wheel-which is driven by a servomotor with a warm-wheel reduction mechanism without back-drivability-at the point corresponding to the rod and rope as inspired by the traditional timberjack rod-and-rope method.

It is desirable that a climbing robot has more than two wheels, since it is quite possible for a wheel to slip out of place; more wheels contribute to stable climbing. As shown in Fig. 2, our climbing robot is equipped with four active wheels. Two wheels are located on top (numbers 1 and 2) and two wheels are located on the bottom (numbers 3 and 4). Each wheel is placed at the same angle $\pm \pi / 4$ rad relative to the $\boldsymbol{x}$-axis when viewed from the top of the cylinder. The active wheel is driven by a 20-watt DC servomotor via a warm-wheel reduction mechanism. The warm-wheel reduction mechanism, which has no back-drivability, allows the robot to be at rest without any energy expenditure. The placement of the controller at the side of the down-side active wheels insures that the center of mass of the robot is located outside of the tree. Each of the four active wheels has a steering system to control the steering angle for spiral climbing. The steering system is driven by a 3-watt DC servomotor via a warm-wheel reduction mechanism.

In our three-dimensional (3D) statics analysis for the climbing robot, as shown in Fig. 2, we defined the base coordinate system fixed on the center axis of a pole with the z-axis as the anti-gravity direction, and each contact coordinate system (i =1, …4) is defined on the contact point between each active wheel and the pole, where the subscripts 1 and 2 are the contact points on the upper side and subscripts 3 and 4 are the contact points on the down-side. The symbols in Fig. 2 are as follows: $\boldsymbol{x_i}$ is a normal direction toward the outside of the cylinder at a contact point, D is the diameter of the cylinder, W is the distance from the cylinder's surface to the center of its mass, H is the distance between a down-side wheel and an up-side wheel along the $\boldsymbol{z}$-axis, m is the mass of the robot, and g is the acceleration of gravity.

When the robot climbs a conically shaped pole, the body inclines as the robot climbs upward. If the tilt angle of the body becomes large enough, the pole gets stuck between two wheels. In addition, the required steering torque is increased even if the pole is not stuck between two wheels, since the steering axis does not match the i-th z-axis. We therefore designed and implemented a posture-adjustment mechanism consisting of two link arms on the right and left sides linked by one 2.5-watt arm motor (Fig. 3). This can move the active wheels, which are attached to the arm tip, to the center direction of the pole. We reported the design method [10] to meet the allowable ranges of the gap angle λ related to the reference line and the wheel posture φ at the tree surface, as shown in Fig. 4, in which O_0 is an origin of the arm base coordinate system and $\underline{O}$ is a center of the tree. The maximums of φ and λ become less than 6 degrees in the robot design. The arm system, installed in the upper part and the lower part of the robot, can shorten the distance between the wheels to be opposed by the arm motor and can adjust the tilt angle of the body.

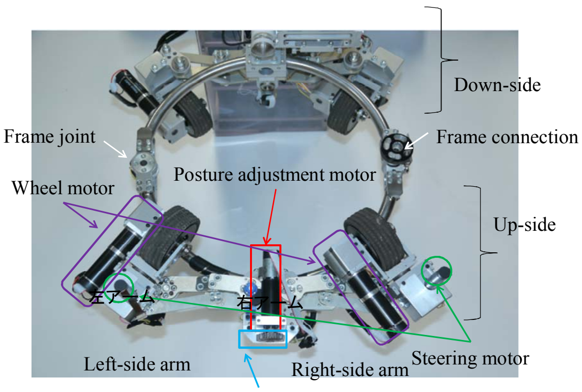


Fig. 3 Body posture adjustment mechanism

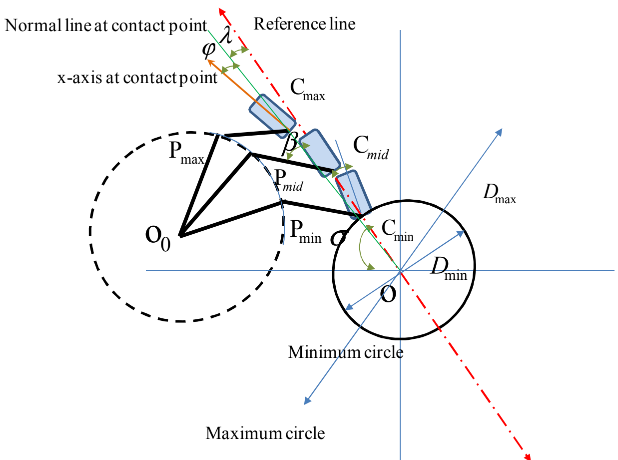


Fig. 4 Design of the postural adjustment mechanism

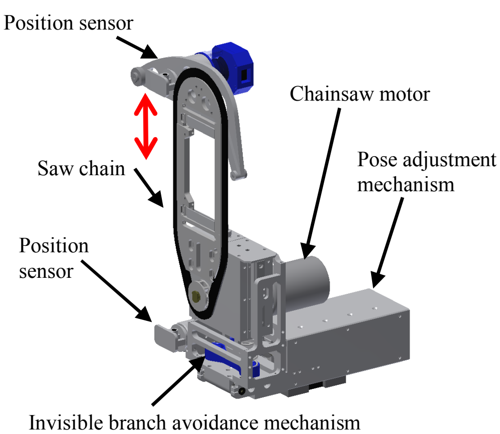


Fig. 5 Structure of the pruning mechanism

B. Pruning mechanism

The pruning mechanism consists of a chainsaw and a posture-adjustment mechanism as shown in Fig. 5. There are several challenges regarding pruning. One is that a chainsaw guide plate is often grabbed by a branch at pruning, which is called a branch bite. When this happens, the robot cannot proceed for pruning. Another challenge is to shorten the remaining length of a pruned branch without injuring the tree surface. In addition, power-saving pruning is required because

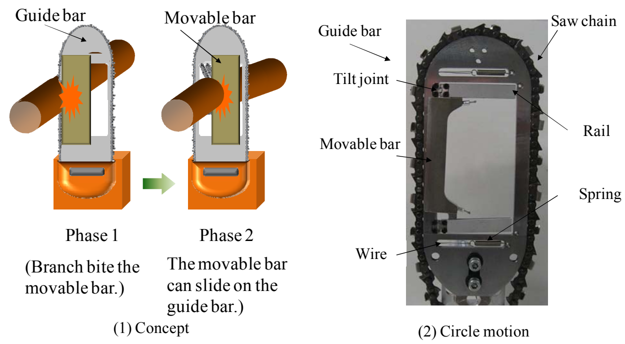


Fig. 6 Mechanism for branch bite prevention

charging batteries in a forest environment is not easy. To address these problems, our novel pruning robot has a:

(a) Branch bite prevention function
(b) Low friction chainsaw
(c) Posture adjustment mechanism of the chainsaw
(d) Power-saving chainsaw drive

(a) *Branch bite prevention function*

When a branch bites happens during pruning, the work efficiency decreases considerably because the operator must remove the robot/pruning device. No robot with pruning mechanism that includes a branch-bite prevention function has been proposed by other researchers, to our knowledge. We presented a chainsaw prototype that has a branch-bite prevention function [11]. In this prototype, a movable bar is mounted on the guide bar of the chainsaw so that it can move on the guide bar even if it is bitten by a branch, as shown in Fig. 6 (1). The robot can then prune and advance because the guide bar is not constrained by the branch. The movable bar is attached to the guide bar by a spring so that planar motion of the movable bar is possible. In addition, power to open up a cut edge of the branch by the guide bar is not needed when the robot prunes the branch with a straight motion, which is a normal use of a chainsaw. However, power to open up the cut edge by the guide bar is needed when the robot prunes the branch with a circular motion around the tree. To greatly reduce this power, we established a tilt mechanism for the guide bar, which permits the movable bar to swing according to a radius of rotation of the chainsaw, as shown in Fig. 6 (2). The effect of the tilt mechanism will be presented in detail experimentally in [12].

(b) *Low friction chainsaw*

The friction force in a chainsaw is large because the saw chain contacts the chase of the guide bar strongly and slides on the chase. The force is particularly large at the upper corner part of the guide bar. This friction force leads to useless energy consumption. A sprocket can be set at the corner part to reduce the friction, but its size is large because the width of the guide bar with the branch-bite prevention function is relatively large. We therefore developed a new chainsaw guide bar equipped with two compact, passive sprockets in the upper corner part to avoid this (Fig. 7). The friction in the new guide bar is reduced to about 25% of the friction without a sprocket

Fig.7 Novel chainsaw guide plate with two sprockets

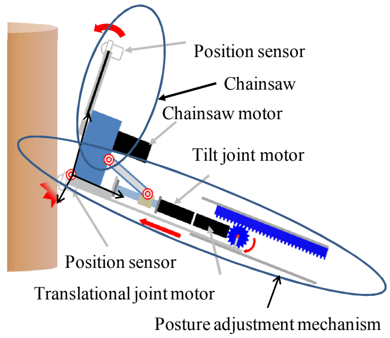


Fig. 8 Chainsaw posture adjustment mechanism

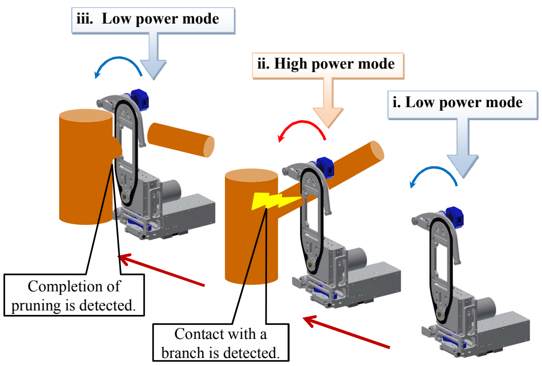


Fig. 9 Power-saving chainsaw drive

(shown in Fig.6) (2). This reduction in friction contributes significantly to the electric power saving.

(c) *Posture-adjustment mechanism of the chainsaw*

Most of the trees in an artificial plantation stand straight, but some are at a slight slant. In addition, although the posture of our novel robot's body is controlled by the posture-adjustment mechanism, the body may incline due to irregularities on the tree surface because its frequency response is not high. It is necessary to keep the chainsaw in the specified posture with reference to the tree surface and to keep the remainder branch at a specified length from the tree surface without injuring the tree surface with the chainsaw. We thus developed the chainsaw posture-adjustment mechanism (Fig. 8) that consists of a two-degrees of freedom (DOF) mechanism: one is a translational joint to keep the chainsaw at the specified distance from the tree surface, and the other is a tilt joint to keep the chainsaw in the specified posture with respect to the tree surface. Each joint is driven by a 2-watt DC motor through a satellite reduction gear mechanism and a warm-reduction mechanism. Position sensors to measure the posture are located on the upper side and lower side of the guide bar of the chainsaw.

(d) *Power-saving chainsaw drive*

The electric capacity of the chainsaw motor is about 330 watts, larger than that of the summation of other motors in the pruning robot. A chainsaw motor is usually driven with a large input voltage, but this entails useless energy consumption when the robot does not prune a branch. In addition, when the saw chain contacts a branch in the stationary state, it is difficult to turn the saw chain even if a large input voltage is added to the chainsaw motor. We therefore developed a power-saving chainsaw drive (Fig. 9) in which the saw chain is driven by low-input voltage at the non-contact interval with the branch and high-input voltage at the contact interval with the branch. Experimental results obtained when the new robot pruned a 25-mm-dia. cedar branch are shown in Fig. 10. The contact timing is estimated by the magnitude of the motor electric current. As a result, the power consumption decreases from 200 watts to 100 watts at the non-contact interval. This contributes to a reduction of 34% of the power consumption for the average branch distribution [13].

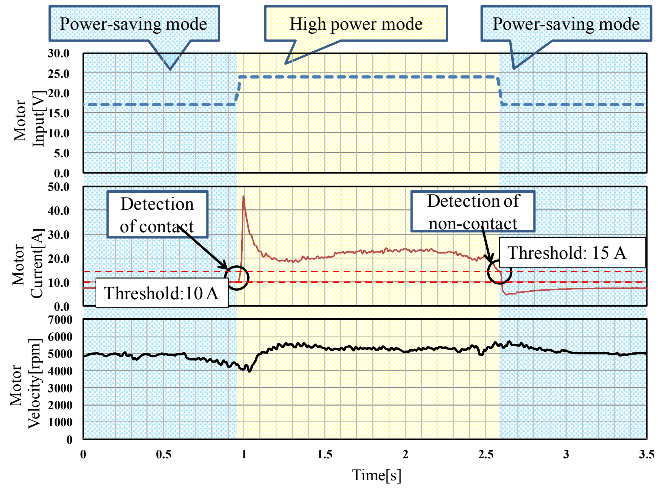


Fig. 10 Switching timing and motor current at pruning by the proposed power-saving chainsaw drive

III. Control

A. *Control unit*

The robot uses 11 motors: 4 for climbing up and down, 4 for the steering, 1 for the body posture adjustment, 2 for the chainsaw posture adjustment, and 1 for the chainsaw drive. We developed a field-programmable gate army (FPGA)-based control circuit and motor driver circuit as shown in Fig. 11 toward maintaining an overall light weight for the robot and for low power consumption of the controller. The FPGA-based control circuit reads motor encoders and sensor signals in order to output the pulse-width modulation (PWM) motor input signals and communicate wirelessly with the operation terminal. The power supply is a 24-volt, 700-watt-hour lithium-ion battery. A worker can operate the pruning robot remotely by wireless communication.

B. *Robot control*

The climbing up-and-down control law for the active wheel is a velocity proportional-integral (PI) control, and the steering control law is an angle proportional-integral-derivative (PID) control.

The tilt of the climbing robot is measured by the posture sensor 3DM-GX3-25 (MicroStrain, Inc., Williston, VT). The precision and the resolution in the static state of this sensor are ± 0.0087 [rad] and 0.0017 [rad], respectively. In order to match the central axis of the robot to that of the tree, one of the two arms (the main arm) has a posture PID control, and the

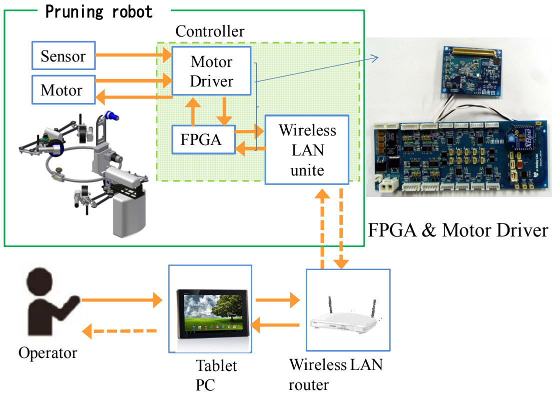


Fig. 11 Controller


Fig. 12 Field test of the pruning robot in an experimental forest

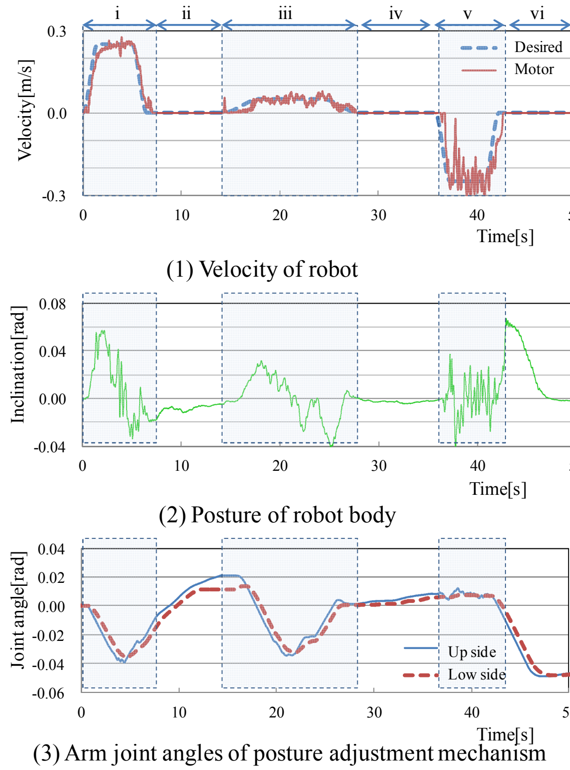


Fig.13 Responses of the pruning robot's velocity and posture and the arm joint angles of the posture adjustment mechanism: i. Straight claiming up, ii. Steering, iii. Spiral climbing up, iv. Steering, v. Straight claiming down, and vi. Stop

other (the slave arm) has a joint-angle PID control in which the desired value is the arm joint angle of the main arm. The desired posture angle is set to zero. In the joint-angle PID control law for the down-side arm, the desired joint angle of the slave arm is set to be the joint angle of the main arm.

The poses of the chainsaw are controlled by a position PID control for the translational joint and a joint-angle PID control for the tilt joint. The chainsaw input is a 24-volt PWM command, and the upper limit of the motor current is set to 20A.

IV. Experiment Evaluation In a Forest

A. Climbing up and down mechanism

In general, the cedars and hinoki trees in the man-made forests in Japan have a tapering characteristic feature in which the diameter of the tree is reduced by approx. 0.01 m with each 1 m increase in height from the base of the tree [14]. To assess the performance of the climbing up-and-down mechanism and the posture-adjustment mechanism, we tested the climbing robot as shown in Fig. 12 in an experimental forest at Gifu University. The tree was a 0.155-m-dia. hinoki at chest height. The motion profile of the robot for the test was comprised of six motions: straight climbing upward for approx. 1.25 m, wheel steering with the steering angle 1.36 rad, spiral climbing for approx. 0.5 m, wheel steering with the steering angle −1.36 rad, straight moving down the tree, and then stopping with posture adjustment. Fig. 13 shows the experiment results for the velocity and posture of the robot and the arm joint angles of the posture-adjustment mechanism.

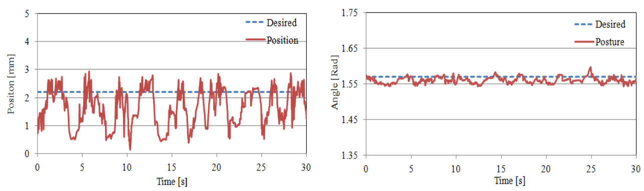
Interval i is the straight climbing, intervals ii and iv are the wheel steering, interval iii is the spiral climbing, and interval v is straight moving down. The velocity PI control was used for the wheels that were active at moving up and down. The control gains of each wheel control system were the same. In Fig. 13, (1) is the robot's velocity, (2) is the posture of the robot body, and (3) shows the arm joint angles of the posture-adjustment mechanism. The label "Desired" indicates the targeted value, and "Wheel" shows the velocity of one of the four active wheels, which was calculated from the rotation angle of the wheel motor and the diameter of the wheel. The Wheel velocity almost converged to the target velocity, 0.25 m/s.

The posture of the robot changed not a little at the interval of straight climbing, due to the taper of the tree and the irregularity of the tree surface. However, the posture error was less than ±0.02 rad during the steering interval and less than ±0.04 rad during the spiral climbing; these values are within the tolerance level for wheel steering and pruning. The arm joint angles of the down-side almost followed the arm joint angle of the up-side. This means that the central axis of the robot was nearly the same as that of the tree.

These experimental results confirmed that the pruning robot with the posture-adjustment mechanism can climb up and down a tapered cylindrical column.

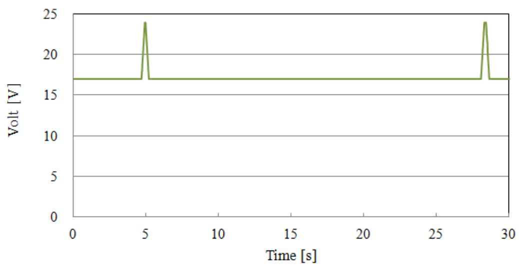
B. Pruning mechanism

The responses of the posture adjustment in the pruning mechanism are works from the steering section. Fig.14 shows

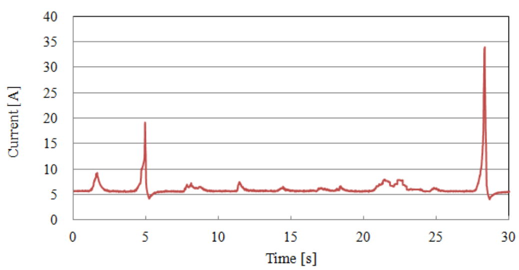


(1) Straight (2) Tilt motion

Fig.14 Tilt motion of the chainsaw posture adjustment mechanism



(1) Chainsaw Input



(2) Chainsaw motor current

Fig.15 Responses of chainsaw drive system

the responses while cutting the branch in steering section. The distance adjustment between the chainsaw mechanism and tree surfaces starts at the switching point from the straight climbing to the spiral climbing, and the posture adjustment by the tilt joint control starts afterwards. The posture of the chainsaw mechanism is always controlled during spiral climbing. At the termination of the pruning work, these adjustments are carried out in reverse. The experimental results confirm that the posture of the pruning mechanism is well controlled even if there are the irregularities on the tree surface.

Contact with the branch is estimated by the chainsaw motor electric current. The motor is driven in a high-voltage mode at the time of contact and in a low-voltage mode at the times of non-contact. The target branch diameter is 25 mm and the spiral climbing speed is 0.035 m/s. The responses of chainsaw drive system (Fig. 15) show that the motor input is changed from low voltage to high voltage at the contact with the branch, and from high voltage to low voltage at the termination of pruning by the level detection of the chainsaw motor electric current. These results also show successful execution of the pruning work.

V. Summary

We have developed a novel pruning robot with a power-saving chainsaw drive. The robot can remain stationary by using its own weight without energy consumption. It is equipped with a climbing up-and down mechanism, a posture-adjustment mechanism, a pruning mechanism using a chainsaw, and a controller. The robot can climb straight and in a spiral up and down and can steer the active wheels in case of not only straight cylindrical poles but also conical poles. The robot's straight climbing velocity is 0.25 m/s, which is the fastest velocity among the existing climbing robots. The posture of the chainsaw during pruning is well controlled by the two-DOF posture-adjustment mechanism. The chainsaw is driven using two input modes whose switching is made by disturbance estimation, resulting in a significant reduction of the electric power use.

There are many irregularities on the surfaces of tree trunks and in the foliage. We have a plan to improve the robot for more robust pruning and to evaluate the robot's ability to perform continuous pruning.

Acknowledgment

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