Kinematic Analysis of a Novel Skew-gripper for Aerial Pruning Tasks

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Abstract. In this paper, we present the kinematic analysis of a novel skew-gripper for pruning tree branches close to electrical powerlines using a multirotor helicopter. By means of two claws attached to a couple of servomotors, the skew-gripper can perform two different tasks: grasping and pruning. This is possible due to the servomotor's shafts are aligned in the same rotational axis, allowing that the mechanism can grasp a tree branch by rotating the shafts in opposite directions; the pruning task is performed by rotating the base-plate around the servomotor's shafts once the claws are well fixed to the branch. The kinematical and geometrical analysis of the skew-gripper mechanism show that it can grasp straight and non-straight tree branches due to the wide grasping area and volume provided by the claw-like grippers. The initial results showed that the proposed mechanism successfully grabed tree branches parallel to the surface.

Keywords: Skew-gripper, hexarotor, electrical powerlines, grasping, pruning

1 Introduction

A tree growing near powerlines represents a potential hazard for the security of the residents as well as for the electricity supply. If a tree branch hits one of the cables of the power line, it may cause an electrical arc and sparks affecting the energy supply or even fire around the contact area. In order to keep the security, tree branches must be kept away from electric power lines. For removing these branches, usually we need a working person and a crane, the latter is to access the target and the former one to prune branches with a specialized tool. Pruning trees close to electric powerlines represents a risk; this means, there is always the possibility of an accident caused by a high voltage. Usually, the minimum required working distance for pruning trees close to a primary distribution lines (between 750 Volts and 150,000 Volts) and a transmission lines must be 3 and 6 meters respectively (website: trimming trees around powerlines). For a human worker, pruning these branches may become a difficult and hazardous task, that is, it is necessary to find a solution to keep safe the people working in such activity.

Attending this situation an aerial pruning robot is being designed and tested. Unlike climbing robots for pruning tasks like reported in Kawasaki *et al.* (2008), Fu *et al.* (2015), Soni *et al.* (2010), Chonnaparamutt (2009), in which the robot should climb from the base of the trunk to the branch to be pruned, or like a cable-climbing robot reported in Fengyu *et al* (2015), or a climbing robot using omnidirectional wheels like Tavalokoli *et al.* (2015), a typical multirotor aerial vehicle like reported in Chan (2015)

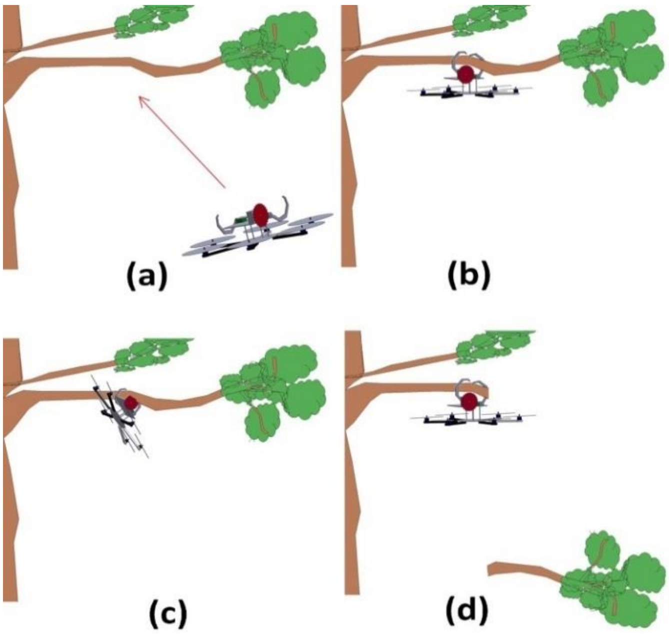

Fig. 1. Sketch representative of the task to be performed (a) The helicopter is flying to the target. (b) The helicopter is grasping the branch to be pruned. (c) Using a circular saw, the helicopter is pruning the branch taking advantage of the bracing technique. (d) The process of pruning is completed.

needless to do such activity. Instead of that, the aerial pruning robot should fly to the target, namely, the tree branch to be pruned, fix the body of the multirotor using a gripper, prune the branch and finally, come back to the home position. Basically, the aerial pruning robot is composed by three main parts: a multirotor helicopter, a gripper and, a pruning system. This paper is devoted to describe the kinematics of the grasping and pruning system called "skew-gripper". In addition, analyzing the geometrical shape that forms the two claws, we prove that the skew-gripper can grasp both straight and non-straight tree branches. The rest of the paper is organized as follows: Section 2 shows the mechanical design and the kinematical description of the skew-gripper. Section 3 shows the prototype of the skew-gripper, and finally, Section 4 shows conclusions and future work.

2 Pruning Mechanism

The aerial pruning robot is mainly designed for pruning tree branches; this means that the multirotor should be strong enough for carrying the pruning tool, the battery, and the skew-gripper. For this first approach, a hexarotor helicopter was chosen for the initial testing, Fig. 1 shows a sketch of the complete task which should be performed by the aerial pruning system.

The pruning mechanism is composed by two subsystems: a skew-gripper and a DC motor with a circular saw. The skew-gripper was designed for two principal tasks, grasping and pruning. There are two shark-teeth claws attached to two servomotors and these in turn are placed in a servo base manufactured by servo city. This servo-base avoid to attach directly the claws to the servomotor's shafts, which could potentially damage them due to the grippers are the only way to support the complete aerial pruning robot while it is hanged on a tree branch.

The servo base has a servo horn which is attached to the servomotor's shaft and between them there is a bearing mounted in a small frame which provide the support instead of the servomotor shaft. The pruning system is composed of a DC motor and a gear box mounted on a base and it in turn is mounted on a base-plate which keeps all the components together. There is a 16 **V** LiPo battery placed on the opposite side of the circular saw, this battery not only provides the necessary voltage for the pruning system but also helps to turn the base-plate creating a counterweight for pruning tasks. The complete mechanism is placed on the top of a hexarotor helicopter; Fig. 2 shows the main components and Fig. 3 shows the dimensions in mm.

2.1 Characteristics of the Skew-Gripper

The skew-gripper mechanism proposed has the ability to perform two different activities, namely, grasping and pruning. Grasping a tree branch requires precision and because of the limitation of the power supply a drone can carry on it, the grasping task should be done as fast as possible. Thanks to the claw-like gripper, the skew-gripper has a wide range area for grasping and therefore, it can be used not only for grasping tree branches but also for delivering tools in a construction building or even in pipe maintenance applications in which is necessary a carefully inspection and a possible repairing task.

For computing the available grasping volume, the skew-gripper was tested grasping an irregular surface, which mimics a tree branch 30 mm diameter but it is also applied to a regular surface, like a pipe. Notice that even though if the motor's shafts of the skew-gripper are not aligned along the target (tree branch) it is still possible to grasp it due to the wide grasping area of the claws. It should be remarked that the minimum length of the tree branch should be 350 mm.

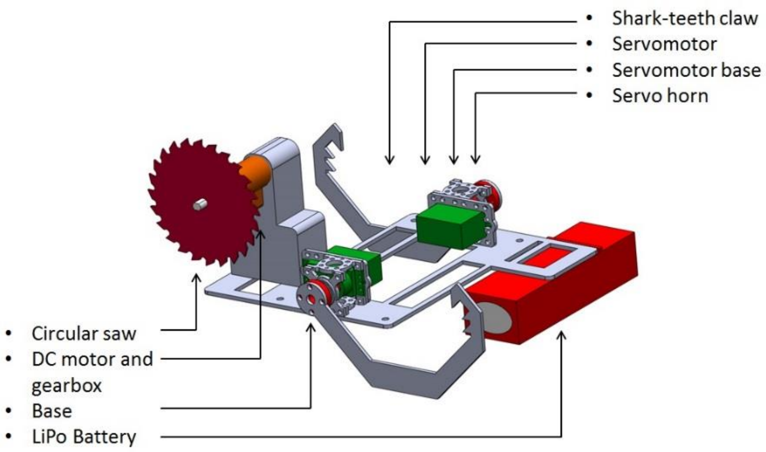

Fig. 2. Pruning mechanism, main parts.

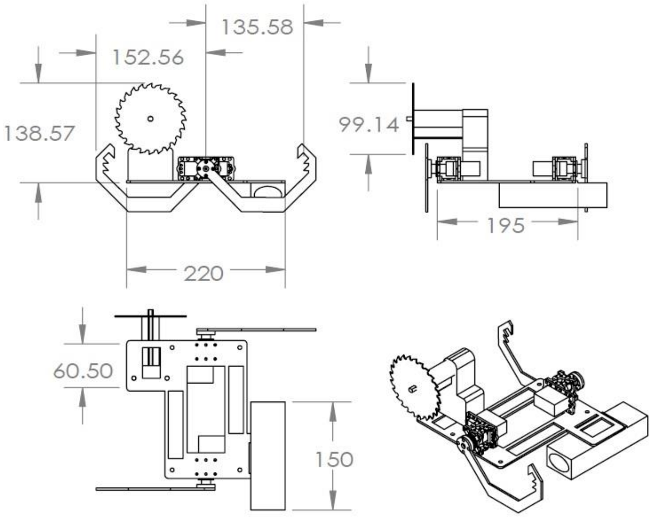

Fig. 3. Dimensions of the pruning system (mm).

2.2 Volume of Grasping

According to Fig. 4, the couple of claws have an irregular octagon shape; if this octagon area A is prolonged from the front claw (besides the circular saw) to the rear claw, it will appear a volume V that represents the 3D space in which a branch can be grasped. Moreover, this volume shows that no matter if the tree branch is not completely straight, as long as it remains within the grasping volume, it can be grabbed by the skew-gripper. In order to calculate the grasping volume, first of all the grasping area of the octagon was calculated. By completing it with four right triangles, as it is shown in Fig. 5, the total area A is defined as:

$$A = A_5 - \sum_{i=1}^{4} A_i \ , \tag{1}$$

where $A_5 = hm$ is the area of the square represented with red dashed lines and A_i represents the area of the i-th right triangle.

By using the angles β, γ and the lengths d, b, one can calculate the area of the right triangles A_1 and A_2 as follows:

$$A_1 = \frac{d^2}{4} \ , \tag{2}$$

$$A_2 = \frac{b^2}{4} \ . \tag{3}$$

Because of the symmetricity of the octagon with respect to the vertical line, $A_4 = A_1$ and $A_3 = A_2$. Substituting the parameters of the octagon, the total area and volume calculated are A =7.11x10^2 mm^2 and $V = AL$ =2.49x10^2 cm^3 respectively. Table 1 summarizes the numerical values used to determine these parameters and Fig. 6 shows a 300-mm diameter tree branch inside of the grasping volume.

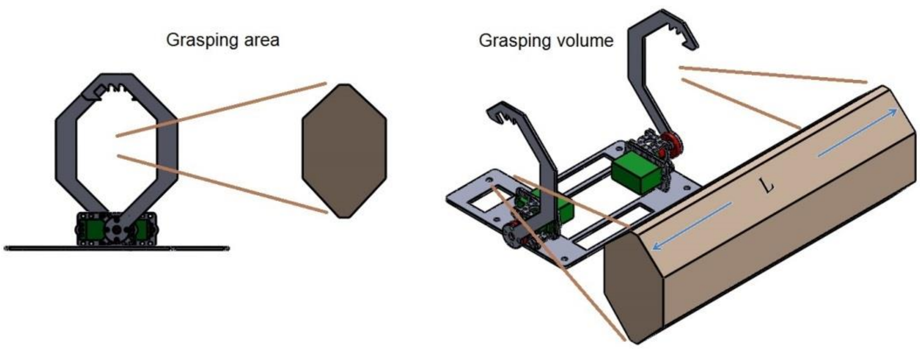

Fig. 4. Area and volume of grasping. As long as a tree branch fits inside the shadow region, it can be grabbed.

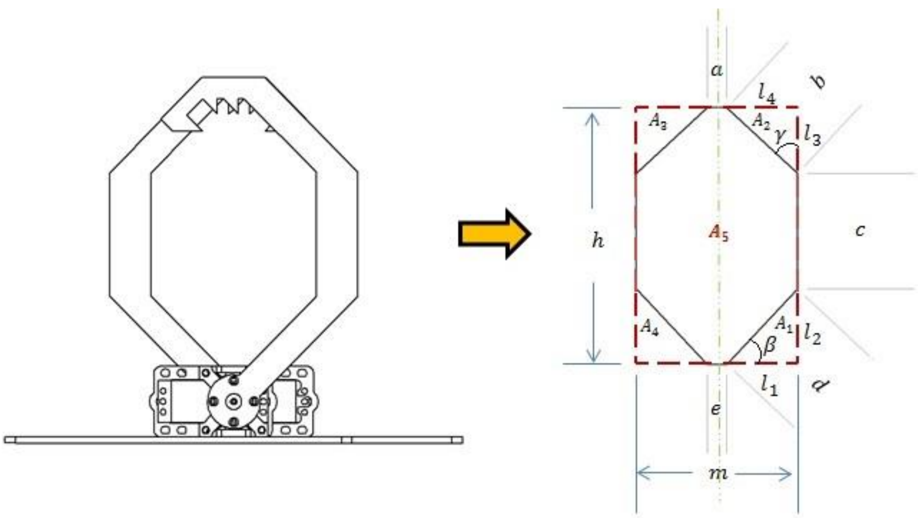

Fig. 5. Skew-gripper and its internal representation for calculating the total grasping area.

Table 1. Dimension of the main components for calculating the grasping volume.

Parameter	Value
d	47.17 mm
b	48.94 mm
h	118.91 mm
m	79.24 mm
L	350 mm
β, γ	$\pi/4$

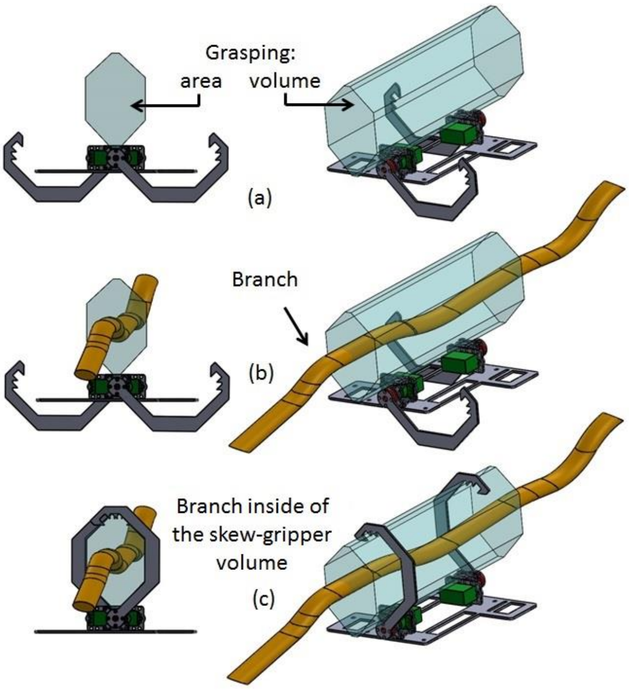

Fig. 6. Grasping area and volume available. (a) shows the area and volume available for grasping, (b) shows an irregular body representing a 30-mm tree branch inside of the grasping volume and (c) shows the skew-gripper closed and a tree branch inside of the grasping volume.

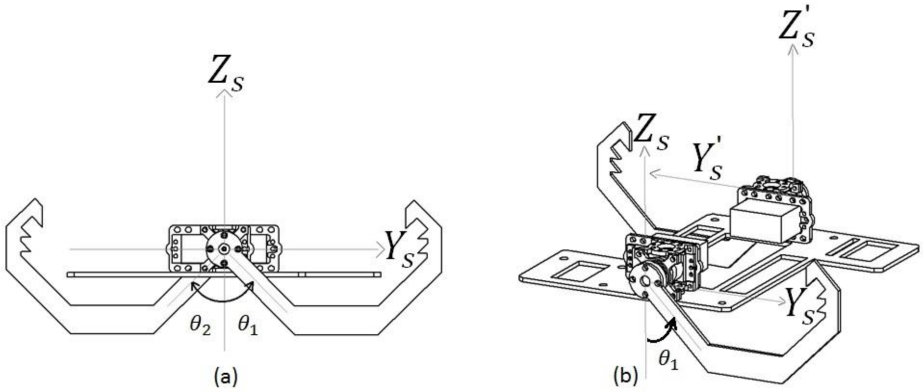

Fig. 7. Kinematics of the skew-gripper. For grasping and releasing a tree branch, the couple of claws should open and close an angle θ_1 and θ_2.

2.3 Kinematics of the Skew-Gripper

Each claw of the skew-gripper is placed symmetrically with respect to the Z_s and Z'_s axes respectively; see Fig. 7(a). Recall that the two claws are placed in different planes, *i.e.*, one of the claws is placed in Y_s-Z_s plane, and the other one is placed in Y_s'-Z_s' plane; see Fig. 7(b). This feature allows the skew-gripper to grasp long-size bodies like pipes or tree branches. For opening and closing, the angles θ_1 and θ_2 operates between the boundaries:

$$a \leq |\theta_1, \theta_2| \leq b \ . \tag{4}$$

where $a = \pi/4$ and $b = 3/4\pi$.

2.4 Kinematics of the pruning system

Once a tree branch has been grasped by the skew-gripper, there is no way to move the claws due to they have teeth used to "bite" the tree branch and fix the complete mechanical system to it. For releasing, the mechanism should be pushed from the bottom and after that, opening the skew-gripper to complete the releasing task.

For the sake of illustration of the pruning kinematics, we used an ideal branch like a pipe; Fig. 8 shows the pruning mechanism fixed to a branch using the skew-gripper, let us use the coordinates (Y_s, Z_s) to describe the rotational angle φ_s around the X_s-axis. Notice that taking advantage of this rotational movement, the pruning mechanism can prune a branch by means of a circular saw as it was shown in Fig. 2. For describing the kinematics, a skeleton of the main parts of the pruning mechanism was designed, see Fig. 9. The coordinates (y_{sp}, z_{sp}) represents the top edge position of the circular saw, which is in contact with the tree branch. These coordinates are described as follows:

$$y_{sp} = d \sin\left(\frac{\pi}{4} - \varphi_s\right) - l \sin\varphi_s \ , \tag{5}$$

$$z_{sp} = d \cos\left(\frac{\pi}{4} - \varphi_s\right) + l \cos\varphi_s \ , \tag{6}$$

where d, l and φ are the distance from the base-plate to the edge of the circular saw, the distance from the servomotor's shaft to the center of the circular saw, and the angle from the vertical axis Z_s, respectively. Notice that:

$$\sin\left(\frac{\pi}{4} - \varphi_s\right) = \cos\varphi_s \ , \tag{7}$$

$$\cos\left(\frac{\pi}{4} - \varphi_s\right) = \sin\varphi_s \ , \tag{8}$$

The above equations turn into:

$$y_{sp} = d \cos\varphi_s - l \sin\varphi_s \ , \tag{9}$$

$$z_{sp} = d \sin\varphi_s + l \cos\varphi_s \ . \tag{10}$$

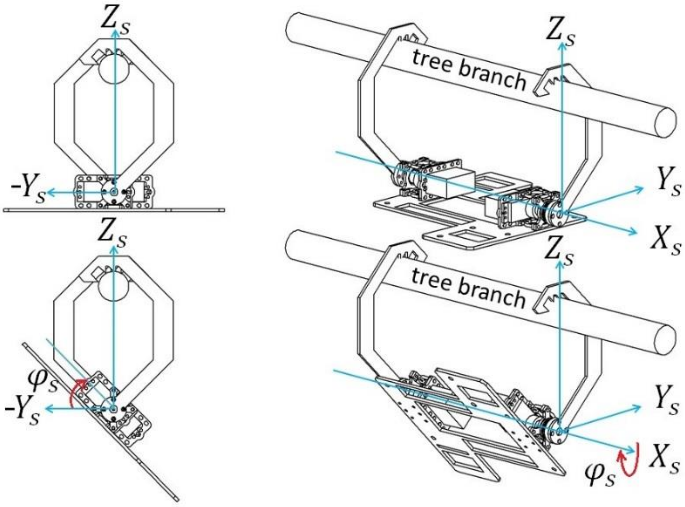

Fig. 8. Kinematics of the pruning mechanism. For rotating around the X_s-axis, the couple of servomotors should exert a torque to produce a rotational angle φ_s.

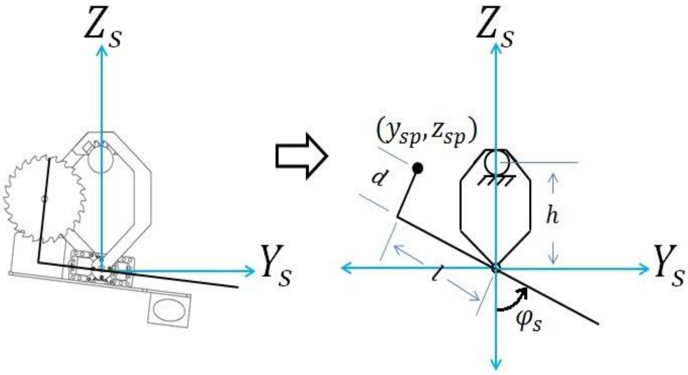

Fig. 9. Skeleton of the pruning mechanism. The coordinates (y_{sp}, z_{sp}) represents the edge of the circular saw which is in contact with the tree branch.

where (9) and (10) represent the direct kinematics of the pruning mechanism. The inverse kinematics is given by:

$$\varphi_s = atan2\left(-ly_{sp}+dz_{sp} \ , dy_{sp}+lz_{sp}\right) \ , \tag{11}$$

where:

$$-ly_{sp}+dz_{sp} = (d^2+l^2)\sin\varphi_s \ , \tag{12}$$

$$dy_{sp}+lz_{sp} = (d^2+l^2)\cos\varphi_s \ . \tag{13}$$

Equations (9), (10) and (11) describe the kinematics of the pruning system. These set of expressions will help in the next step for developing the force control of the pruning system. Since the torque exerted by the two servomotors to the rotational mechanism should be controlled to avoid that the circular saw get stuck into branch, it will be necessary to consider controlling the pruning force through the complete pruning process.

3 The Prototype

The prototype was built with aluminum for the base-plate and the claws. Two HITEC servomotors were chosen for the skew-gripper as well as a 16**V** DC motor for the pruning system. Fig. 10 shows the skew-gripper in detail mounted on a hexarotor helicopter, Table 2 summarizes the main components and, Fig. 11 shows the helicopter flying close to a tree branch carrying the skew-gripper.

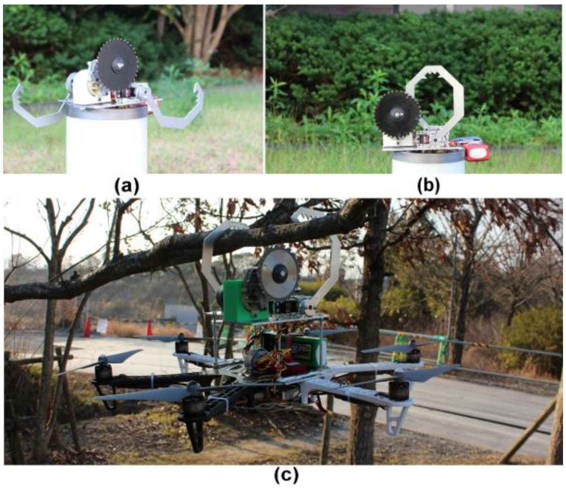

Fig. 10. Real prototype of the skew-gripper. (a) and (b) show the skew-gripper opened and closed respectively. (c) shows the skew-gripper mounted on a hexarotor helicopter and it hanged on a tree branch.

Table 2. Main components of the pruning mechanism.

Main components		
Part	Description	Weight (grs)
Claw	Aluminum	19.6 x 2
Base-plate	Aluminum	105.7
Servo base	Aluminum (from servo city)	36.85 x 2
HITEC servomotor HS-7954SH	Torque = 29kg.cm (7.4**V**)	65.20 x 2
DC motor and gear box	16**V,** 3**A**	765
Circular saw	100-mm diameter	48
	Total weight	**1162**

For testing the grasping performance, the skew-gripper and the helicopter were tested in a real environment. The helicopter was manually commanded remotely without GPS assistance. The experiment showed that the skew-gripper successfully grasped tree branches from 19 mm to 31 mm. The average time was about 2.35 minutes. Fig. 12 shows the sequence of grasping a tree branch using the skew-gripper.

Fig. 11. Hexarotor helicopter using the skew-gripper for grasping a tree branch

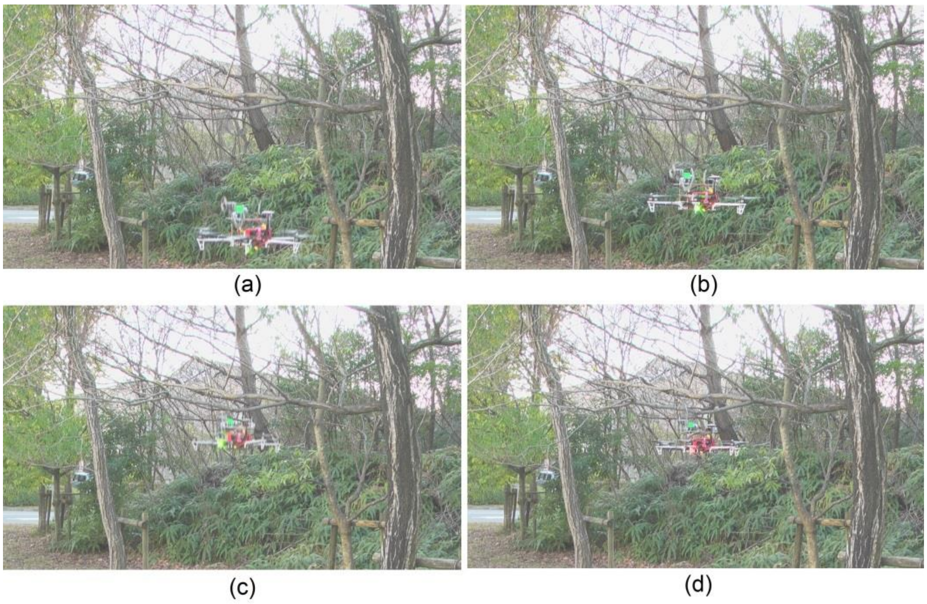

Fig. 12. Complete process of grasping a tree branch. In (a) the helicopter is flying to the target, in (b), (c) the helicopter is flying close to the tree branch and finally, in (d) the tree branch was grabbed.

3 Conclusions and Future Work

We have described a novel mechanism called skew-gripper for grasping and pruning tree branches. The mechanical design, the grasping area and volume as well as the kinematics was described. Experimental results show the capacity of the skew-gripper for grasping different types of tree branches; that is, no matter its shape, as long as they fit inside de grasping volume, it can be grabbed. The skew-gripper also prove experimentally that helps the user for an easy control of the process of grasping, this is due that the skew-gripper do not hit the tree branch because it is widely open. The next step will be to design the controller for the pruning task and the automatic control for assist the user in the grasping process.

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Trimming trees around power lines: https://www.esasafe.com/assets/image/Tree-Trimming.pdf

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