Doctoral Thesis

A Grasping-Pruning Mechanism for Pruning Tasks by Aerial Robots

March 2019

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Doctoral Thesis Reviewed
by Ritsumeikan University

A Grasping-Pruning Mechanism for Pruning Tasks by Aerial Robots

(飛行ロボットによる枝切り作業のための把持・枝切り機構)

March 2019

2019 年 3 月

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Abstract

In this research, we propose a hexarotor aerial robot equipped with a robotic gripper and a circular saw for pruning tree branches in high place. External forces will apply to an aerial robot during pruning, making it instable. To avoid such instability, a robot gripper mounted on a hexarotor aerial robot was attached, so that the robot can grasp a branch to fix the robot's body near to the branch before performing pruning. We propose a novel skew-gripper so that the aerial robot can grasp a branch easily.

We tested a skew-gripper using an aerial robot for grasping a straight branch. The experiments showed that the skew-gripper was able to grasp without any problem due to its wide-open mechanism configuration. For controlling the pruning task, we firstly proposed to use only the backEMF (Electromotive Force) as a feedback control signal without the necessity of using encoders or tachometers to regulate the speed of the circular saw. Next, we used a commercial motor driver called Sabertooth, which reduced the electronic components and, although the system worked in open loop, it proved that the motor driver could cope with the disturbances produced by the contact operations.

Through indoor and outdoor experiments, we verified the effectiveness of both proposed approaches. To know how the contact operation between the circular saw and the branch affects the motion of the pruning mechanism, we prepared a set of experiments in an indoor testbed. The results of these indoor experiments showed that the swinging motion of a circular saw and the motor control were helpful to prune a tree branch. We performed experiments outdoor; these experiments showed that the pruning mechanism could prune tree branches using a swinging motion, which allows a circular saw contact to a branch intermittently. In addition, the performance of the circular saw was wireless monitored to know how the contact between the circular saw and the tree branch affects its speed.

Acknowledgements

I would like to thank everyone who contributed to finish this job, specially to my supervisor, professor Shinichi Hirai for accepting me in his laboratory and allowed me to work with aerial robotics. I would also like to thank to professor Ma and professor Shimonomura for their kindness and for the invaluable advise I got from them. I also want to thank to Hatanaka-san for helping me in all the administrative issues as well as to Tanaka-san, Hamada-san and Ishii-san from core station office for bringing me back to Japan. It is important to say that without all those persons, this job could not have been done. Thanks to professor Wang for being patient with me, I really appreciate his friendship and I admire his perseverance in life. finally, I want to extend my gratitude to CONACYT Mexico for the generous grant I received to study in Japan.

Shiga, Japan — February 2019

Javier Molina

Dedicado a
mi familia.

Chapter 1

Introduction

Multirotor aerial vehicles have been used for research purposes for the last fifteen years. This is largely because of their mechanical simplicity compared with the traditional helicopter (main-rotor tail-rotor), low cost, and easy maintenance. Multirotor helicopters are widely used for aerial video and photography, this is mainly due to technological advances on the field of flight controllers [1], GPS navigation and a variety of accessories whose prices have been decreased and therefore, nowadays are available for almost everyone. Currently, there are several research areas in which this aircraft has found acceptance, such as linear and nonlinear control strategies [2–6], vision based navigation [7] as well as swarms of small quadrotors [8].

Aerial manipulation is a topic related with aerial robotics which is gaining popularity around the world. Basically, aerial manipulation involves two main activities:

- Transportation
- Contact Tasks

The first one includes the interaction between a gripper and an object to be manipulated, the aim was grasping and transporting the payload from one place to another. There are several researches around the world trying to solve the problem of aerial transportation using multirotor helicopters. In [9], an adaptive controller was proposed to deal with the changes in the center of gravity of a quadrotor and hence, achieve swing-free of a suspended load. An adaptive sliding mode controller was designed in [10] to control a quadrotor and a two-DOF robot arm attached to it for moving and delivering an object.

A hierarchical motion control scheme for an aerial manipulator was proposed in [11] and a hexarotor helicopter with a commercial flight controller and a couple of grippers was used to move long-size payload in [12].

The second one uses multirotor helicopters to interact with the physical environment to perform a specific task. In this case, the multirotor system is endowed either with a tool or with a manipulator which allows it to execute the task. Examples of this research are: an Astec Pelican quadrotor and a custom-made manipulator for contact inspection [13], an aerial vehicle and a couple of robotic arms for turning a valve using a human machine interface [14] and a ducted-fan aerial vehicle for ultrasonic non-destructive structural inspection [15].

Considering the scenario in which there are some trees whose branches a person wants to remove for specific reasons, it might be necessary to achieve the three branch in some way and use a tool to prune them. There are some important reasons to remove these tree branches, it ranges from garden decorations and tree-maintenance for security reasons. Regarding with tree maintenance, it contribute to the health and the safety of the trees. On the other hand, security reason involve tree limbs growing close to roads, houses, apartments, electrical power lines, etc. This tree branches may produce visual obstructions of signs as well as sight distance obstructions in intersections, driveways and curves among any other safety problems. Electrical power lines may also be affected by these tree branches because they may touch the cables causing power interruptions and fire around the area. These security-related issues are traditionally solved pruning such problematic tree branches using three main elements: a crane, a powerful tool for pruning, and a person to execute the job.

There exists some representative research related with climbing and pruning tree branches using a robotic approach as it is mentioned as follows: In [16], the authors showed a human-inspired climbing robot with some remarkable characteristics like a simple design, control and fast climbing speed; this climbing robot use wheels for locomotion, a typical characteristic used in climbing-pruning robots. In [17], a climbing-pruning mechanism was presented; in this research, the authors showed an hybrid climbing strategy for pruning tree branches. This robot can climb a tree straight until the target branch is reached and then, it switchs to a spiral climbing method for pruning the tree branch optimaizing the climbing-pruning time using such hybrid mechanism. In [18], a fuzzy-controller was implemented in a climbing-pruning robot for automatically find and prune tree branches. In [19], a power-saving chain saw drive mounted in a climbing robot was presented. This robot is able to climb straight cylindrical poles as well as conical poles, some practical experiments in the forest showed the well performance in both, climbing and pruning tasks.

On the other hand, regarding with aerial grasping and perching by hanging an object using a gripper mounted on the top of a multirotor helicopter, in [20], a visual servoing approach for autonomous perching using a monocular camera was presented. In the letter, the authors showed the development of a geometrical model which describes the pose of the quadrotor relative to a cylinder to be grasped and a controller was also presented. There are also some research related not only with grasping and perching, but also for performing a task, in this case, pruning. In [21–25] some results regarding with the idea of pruning tree branches using such a novel mechanism using a multirotor helicopter to transport it to the working area are shown.

Considering that maintenance of the electric power lines plays an important role in safety; that is, tree branches growing too close to power lines represent a potential hazard for the security of the residents as well as for the electricity supply, it is necessary to find an alternative solution to avoid using humans in the process of removing these tree branches. 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 [26]. 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. Under normal conditions, for pruning tree branches is needed to reach the target using a crane mounted on a truck, which represents a cost of such equipment not to mention the fuel expenses related with the transportation. In addition, to prune tree branches are not only necessary a skillful person to perform the activity but also a safety equipment to prevent a possible accident while completing such task.

This work is devoted to show an alternative way to prune tree branches for maintenance purposes using an hexarotor helicopter, a couple of claws for bracing the branch and, a circular saw to prune it.

Chapter 2

Concept

2.1 Branch pruning task

As it was mentioned before, there is a particular problem related with pruning trees that we are interesting in; this problem is about tree branches growing close to electric power lines that represents electrical hazards and power interruptions whose effects have to be prevented. Performing this task might be dangerous and expensive. The idea that we propose to prune tree branches close to electrical power lines is to use a multirotor helicopter, a gripper, and a circular saw to perform such activity. This new concept not only reduces the costs of using a truck with a crane but also reduces human risks of a potential accident because of the high voltage around the working area. Fig. 2.1 shows the concept of the aerial pruning robot.

2.2 Aerial pruning robot workspace

Generally speaking, there are three different ways to trem trees close to electric power lines [27]. These techniques are, “V” pruning, “L” pruning, and side pruning. In this project, we are focusing only in the side pruning technique, this is due to the mechanical characteristics of the multirotor and the grasping technique used to fix its body to the the target. Side pruning technique requires a good contact between the saw and the branch to be pruned. When the saw is pruning, it appears a reaction force in the opposite direction to the cutting generated by the contact between the rotating saw and the branch. Since this reaction force acts in the pruning process, the cutting task will become difficult or even impossible.

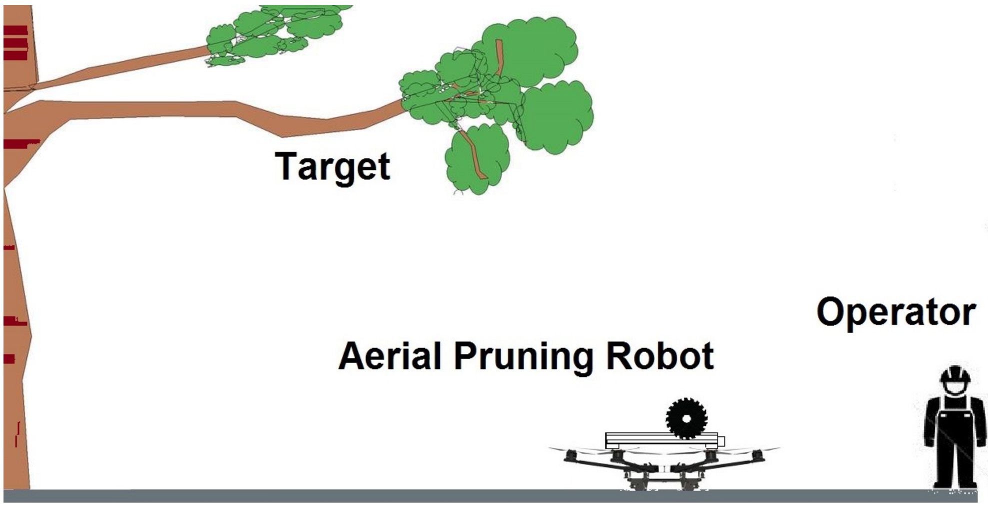

Figure 2.1: Aerial pruning robot, main concept.

2.3 Pruning with bracing technique

As an alternative to prune tree branches like the traditional way, a multirotor helicopter with a circular saw and a robotic gripper, both mounted on the top of it is proposed. Unlike climbing pruning robots proposed in [19] and [18], a multirotor helicopter is needless a long flying time to achieve the target and therefore, it can execute the task faster than a climbing robot. Another important advantage of multirotor helicopters is that because they do not need to climb, the shape of the trunk is irrelevant.

The contact between the pruning tool and the tree branch produces a reaction force in the helicopter, which yield undesirable behavior such as instability, vibrations and low accuracy in the task to be performed. One idea to cope with these kind of reaction forces is "bracing" [28] to obtain a better contact with the surface and therefore, reduce the disturbances produced by the contact operations. Pruning with bracing technique can drastically improve the performance of the task, this is due to the reaction force acting on the body of the helicopter is counteracted by the gripper braced to the branch. This allows a better control of the circular saw and improve the force applied to the surface to be pruned. Fig. 2.2 shows a sketch of the pruning process using the bracing technique. Basically, the helicopter should fly close to the branch to be pruned and, by using the couple of claws, grasp the target to fix the hexarotor's body for the pruning task.

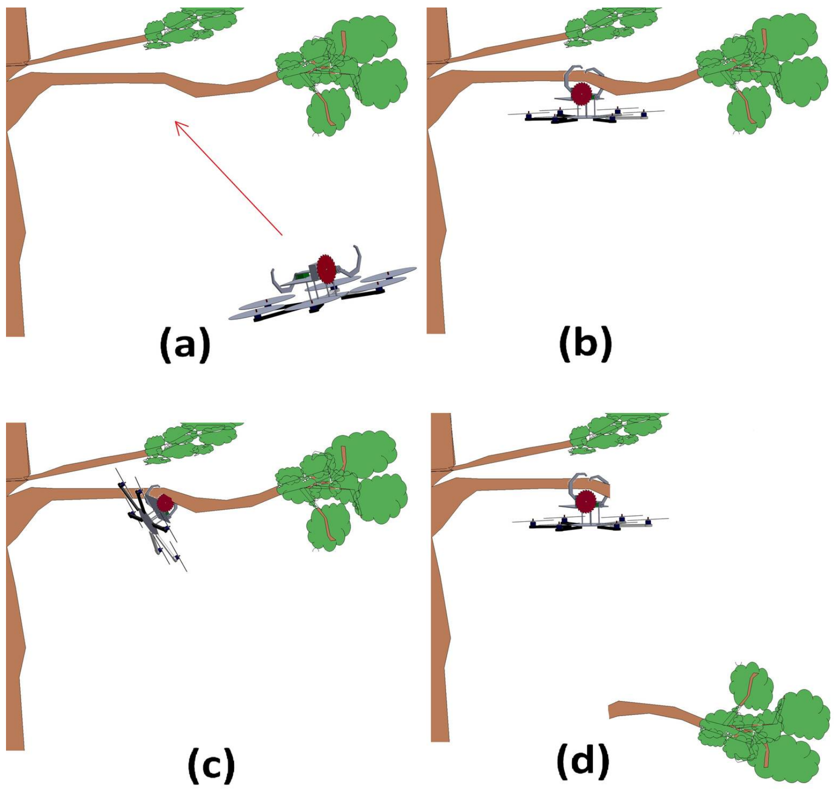

Figure 2.2: Sketch representative of the task to be performed. (a) The helicopter is flying to the target. (b) The helicopter is grasping the branch to be pruned. (c) Using a circular saw, the helicopter is pruning the branch taking advantage of the bracing technique. (d) The process of pruning is completed.

This research explains the design of a mechanism for pruning trees using the bracing technique. In order to reduce this contact force, in this research, we propose a mechanism that we have called "skew-gripper", so that this mechanism is used to fix a helicopter onto a branch during pruning. In addition, we propose to use the couple of servomotors of the skew-gripper to produce a relative rotational motion between it and the helicopter's body to guide a tool (circular saw) around the target (branch) to prune it.

Chapter 3

Mechanical Design

3.1 Description of the grasping system

The aerial pruning robot is basically composed by three main parts: a pruning mechanism, a multirotor helicopter and a gripper for hanging the whole system from tree branch. These three main parts will be described to show the benefits as well as to show the simplicity compared with a climbing-pruning robot.

3.1.1 Grasping for pruning

One of the most important things to consider for pruning tree branches is the forces interacting at the moment of pruning. Considering that the tree branches will be pruned using a saw mounted on a multirotor helicopter, the contact between the saw and the tree branch produces a reaction force like the experiment performed in Tested [29], which become almost impossible to prune. In addition, the circular saw is attached to the multirotor's belly, the air blowing from the propellers also affects the position of the tree branches creating an additional disturbance in the target branch increasing the degree of difficulty. Fig. 3.1 shows a sketch representing this reaction force acting in a multirotor's body as a result of the contact of the circular saw and a tree branch.

As a result of a poor pruning performance from the air without any kind of supporting point, we propose to use a gripper for bracing the tree branch while the saw is pruning. By simply aplying a normal force rigidation can be achived [30], namely, human being needs to brace when they are performing precise force or position control [31]. By using this main concept, our idea is to use a gripper for bracing the tree branch while the circular saw is pruning. This approach reduce the vibrations and the reaction force produced by the contact between the pruning mechanism and the target branch. Moreover, using a gripper for hanging the helicopter's body and the pruning mechanism, the energy consumption will be reduced. This because the helicopter only flies to the target branch and grasp it and therefore, the rest of the task will be performed without flying.

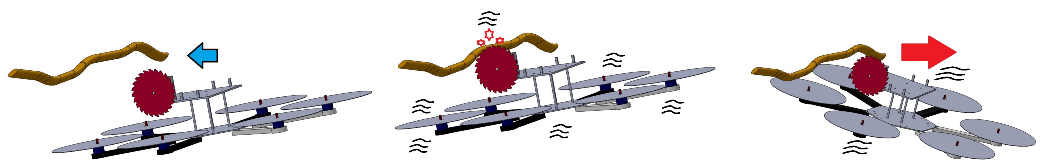

Figure 3.1: Reaction force resulting from the contact between the circular saw and a tree branch. From left side, the multirotor helicopter is flying to the tree branch and, at the moment of the contact, the reaction force throw the multirotor helicopter away.

3.1.2 Skew-gripper

The gripper proposed for grasping and hanging from tree branches has a simple but useful design. Some considerations were taken into account in order to get the current prototype:

- Light weight.
- Low energy consumption.
- Wide open mechanism for easy grasping.

The skew-gripper is composed by two claws placed in different planes, that is why we use the term "skew" to emphasize this concept. Fig. 3.2 shows the CAD model of the proposed gripper, we may appreciate that the skew-gripper has teeth for fixing the mechanism to the tree branch and avoid drifting at the moment of pruning. It may also be appreciate that the skew-gripper use two servo motors for opening and closing and everything is mounted on a base-plate. All the components listed before were placed on a baseplate. Fig. 3.3 shows the dimensions of the skew-gripper.

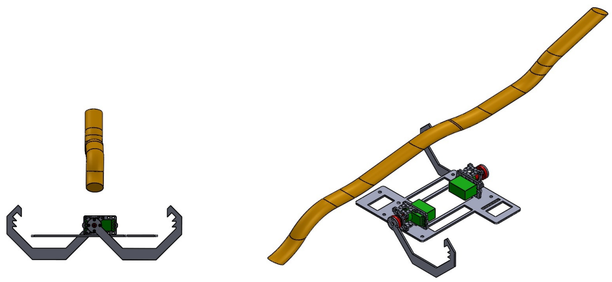

Figure 3.2: Skew-gripper, CAD design.

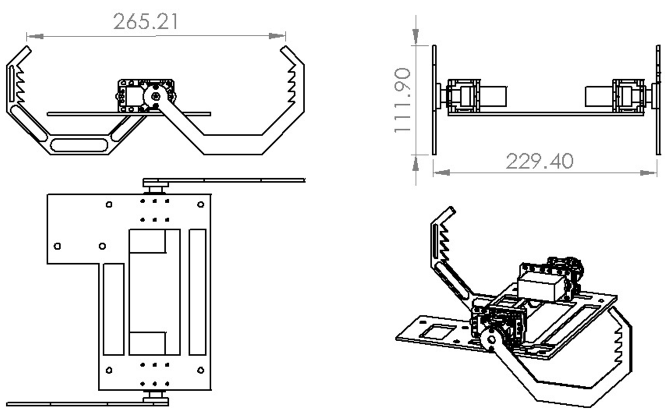

Figure 3.3: Skew-gripper design, dimensions in mm.

3.1.3 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 2.5 m, this is to avoid to fly close to the tree trunk and grasp the tree branch approximately at the middle of it.

3.1.4 Volume of grasping

According to Fig. 3.4, 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.

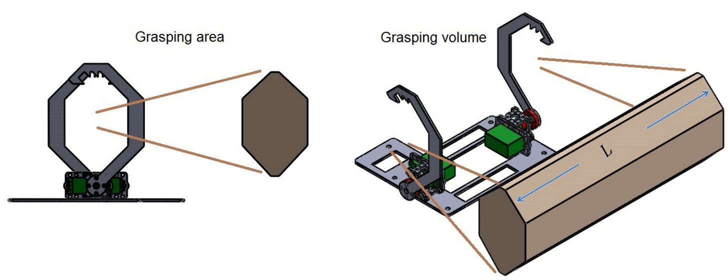

Figure 3.4: Area and volume of grasping. As long as a tree branch fits inside the shadow region, it can be grabbed.

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. 3.5, the total area A is defined as:

$$A = A_5 - \sum_{i=1}^{4} A_i, \tag{3.1}$$

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:

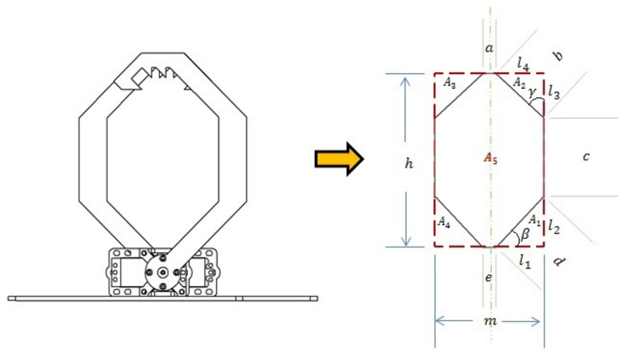

Figure 3.5: Skew-gripper and its internal representation for calculating the total grasping area.

$$A_1 = \frac{d^2}{4}, \tag{3.2}$$

$$A_2 = \frac{b^2}{4}. \tag{3.3}$$

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 $A = 7.11 \times 10^2$ mm^2 and $V = AL = 2.49 \times 10^2$ cm^3 respectively. Table 1 summarizes the numerical values used to determine these parameters and Fig. 3.6 shows a 300-mm diameter tree branch inside of the grasping volume.

Table 3.1: Dimension of the main components for calculating the grasping volume.

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

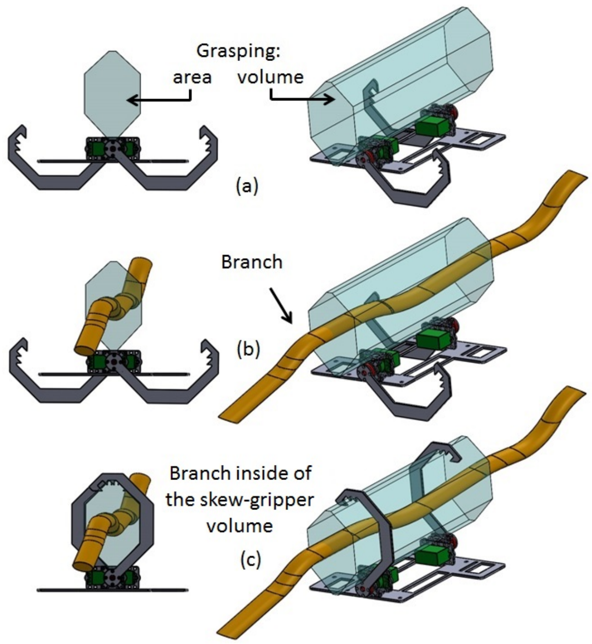

Figure 3.6: Grasping area and volume available. (a) shows the area and volume available for grasping, (b) shows an irregular body representing a 30-mm tree branch inside of the grasping volume and (c) shows the skew-gripper closed and a tree branch inside of the grasping volume.

3.1.5 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. Fig. 3.7(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. 3.7(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:

$$\pi/4 \leq \theta_1 \leq 3\pi/4 \tag{3.4}$$

$$-3\pi/4 \leq \theta_2 \leq -\pi/4 \tag{3.5}$$

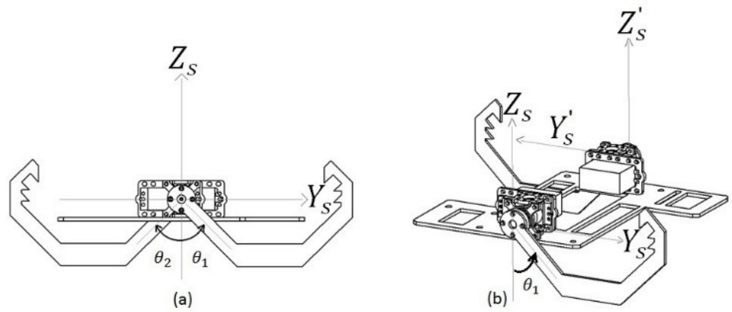

Figure 3.7: Representation of the two planes (Y_s, Z_s) and (Y_s', Z_s') in which the skew gripper works. It may also be appreciate that the angles θ_1 and θ_2 represent the opening and closing mechanism.

3.2 Description of the pruning system

The skew-gripper is able to perform two different tasks: the first one is grasping and the second one is rotating the base along the X_s-axis formed by the shafts of the servomotors for pruning purposes, see Fig. 3.8. For the first task, the claws should turn each other in an opposite angle θ_1 and θ_2 respectively. Once the branch has being grasped and it is well fixed by the claws, there is no possibility to move them for opening and closing; however, if the servomotors turn in the same direction, the baseplate can turn an angle ϕ_s around the X_s-axis. This is due to that the servomotor shafts are in the same axis X_s. Fig. 3.8(a) shows the grasping and Fig. 3.8(b) shows the rotating process. For the sake of illustration of the pruning kinematics, we used an ideal branch like a pipe; Fig. 3.8 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 which can be mounted on the base plate. For describing the kinematics, a skeleton of the main parts of the pruning mechanism was designed, see Fig. 3.9. The coordinates $(y_s p, z_s p)$ represents the top edge position of the circular saw, which is in contact with the tree branch. These coordinates are described as follows:

$$y_{sp} = d \sin\left(\frac{\pi}{2} - \phi_s\right) - l \sin\phi_s, \tag{3.6}$$

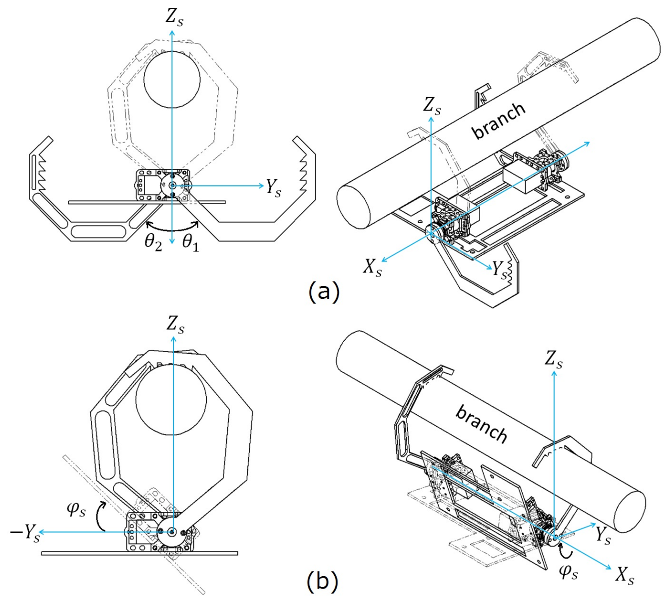

Figure 3.8: Kinematics of the skew-gripper. Fig.6(a) shows the gripper opening and closing an angle θ_1 and θ_2 for grasping a tree branch. Fig. 6(b) shows a rotating angle ϕ_s around the X_s-axis once the tree branch has been grasped.

$$z_{sp} = d\cos\left(\frac{\pi}{2} - \phi_s\right) + l\cos\phi_s, \tag{3.7}$$

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:

$$\sin\left(\frac{\pi}{2} - \phi_s\right) = \cos\phi_s, \tag{3.8}$$

$$\cos\left(\frac{\pi}{2} - \phi_s\right) = \sin\phi_s, \tag{3.9}$$

The above equations turn into:

$$y_{sp} = d\cos\phi_s - l\sin\phi_s, \tag{3.10}$$

$$z_{sp} = d\sin\phi_s + l\cos\phi_s. \tag{3.11}$$

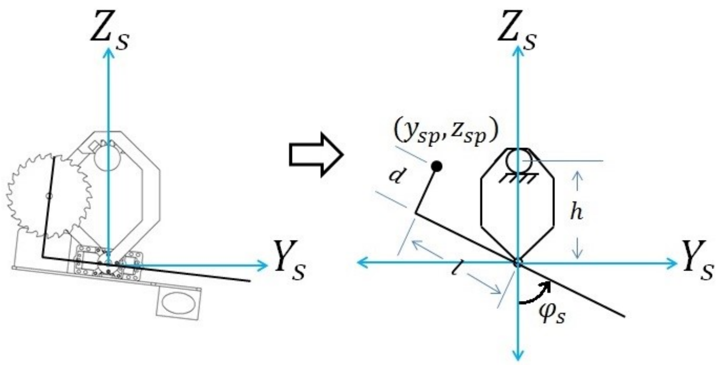

Figure 3.9: Skeleton of the pruning mechanism. The coordinates (y_{sp}, z_{sp}) represents the edge of the circular saw which is in contact with the tree branch.

where 3.10 and 3.11 represent the direct kinematics of the pruning mechanism. The inverse kinematics is given by:

$$\phi_s = \text{atan2}(-ly_{sp} + dz_{sp}, dy_{sp} + lz_{sp}), \tag{3.12}$$

where:

$$-ly_{sp} + dz_{sp} = (d^2 + l^2)\sin\phi_s, \tag{3.13}$$

$$dy_{sp} + lz_{sp} = (d^2 + l^2)\cos\phi_s. \tag{3.14}$$

The skew-gripper can grasp a tree branch with a maximum diameter of 40 mm without any problem; however, the final goal is pruning, therefore, the diameter range, d_b is set as:

$$a \leq d_b \leq b, \tag{3.15}$$

where a and b are smallest and largest diameters of the branch respectively; this is due to the diameter of the circular saw introduce a restriction in the pruning task. In other words, the effectiveness diameter d_b of the branch to be pruned using a circular saw is given by:

$$d_b = r_s - r_a \tag{3.16}$$

Where r_s is the radius of the circular saw to be used and r_a is the radius of the outer washer used to lock the saw to the actuator. Hence, the maximum diameter of the branch b to be pruned is determined by two factors, the circular saw and the outer washer. Fig. 3.10 shows this relationship and Table 5.1 shows the diameter of the circular saw to be used depending on the diameter of the branch the operator wants to prune.

The total weight of the aerial pruning robot, on the other hand, is another factor which restricts the diameter d_b of the branch to be pruned. This means if the branch is too small, the weight of the multirotor may bend it resulting in an inappropriate grasping or even the tree branch can not be strong enough and the helicopter may fall down. In order to prevent this possible issue, the minimum diameter a, was determined experimentally in several branches resulting in $a = 17$mm, which can hold the helicopter safely.

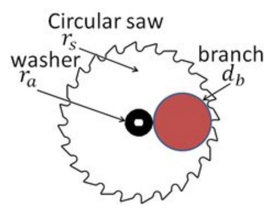

Figure 3.10: Relationship between the circular saw, the washer and the branch to be pruned.

Table 3.2: Relationship between the branch and the circular saw to be used

Diameter of the branch and circular saw	
Diameter of branch(mm)	circular saw (mm)
17-29	85
30-39	110

3.3 Prototype

3.3.1 Skew gripper and pruning system

For the construction of the skew-gripper, a couple of high-torque servomotors from HITEC [32] were used to provide the necessary torque for both tasks, grasping and rotating. Also, two servo bases from servocity [33] were used between the aluminum claws and the servomotors shafts to reinforce them.

Finally, an aluminum plate was used as base to support the skew-gripper mechanism, the motors, and the circular saw. Table 3.3 shows the description of the components in detail. A 16.5 V DC motor together with a gear box were used to provide rotational movement to the circular saw. The maximum angular speed of the gearbox's shaft is 2046 RPM. Fig. 3.11 shows the CAD model of the complete skew-gripper mechanism in detail ready to be mounted on a hexarotor helicopter and Fig. 3.12 Shows the mounting process on an hexarotor helicopter.

Table 3.3: Component description of the skew-gripper

	Main Components	
Part	Description	weight(g)
claw	Made of aluminum	19.6×2
baseplate	Made of aluminum	105.7
servo base	Made of aluminum	36.85×2
HITEC servo	Torque=29 kg.cm (7.4 V)	65.20×2
Pruning system	Circular saw, DC motor and gearbox	722
HS-7954SH	Size in mm =39.88×19.81×36.83	
Pruning system	Circular saw, DC motor and gearbox	722
	Total weight	**1071**

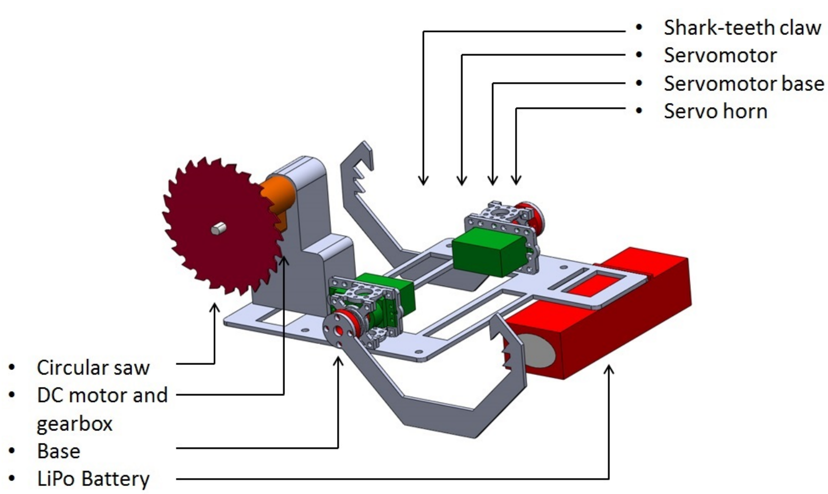

Figure 3.11: Pruning mechanism, main parts.

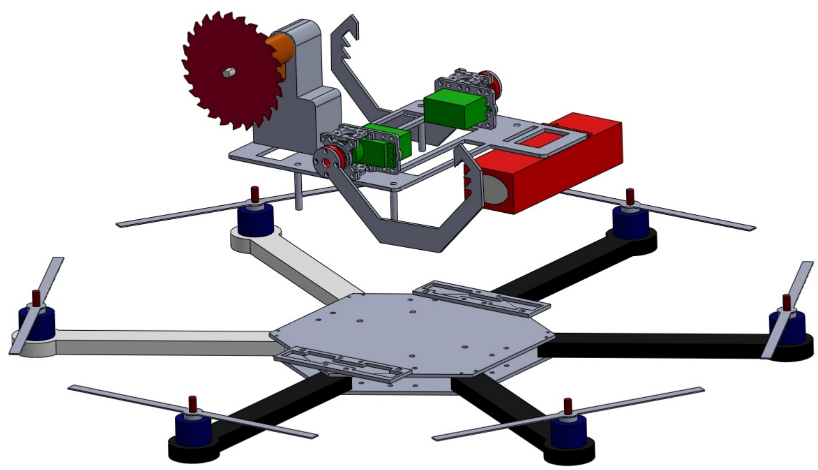

Figure 3.12: Mounting the pruning mechanism on an hexarotor helicopter.

Fig.3.13 shows the complete design of the prototype hanging on a tree branch. It is important to remark that for pruning a real branch, the mechanism should swing up and down repetitively.

3.3.2 Hexarotor helicopter

A DJI Flame Wheel F550 hexarotor helicopter [34] and a DJI A2 flight controller [35] were chosen for testing the skew-gripper and the pruning system. The DJI A2 flight controller provide a stable flight which is suitable for the initial testings, this is because the grasping task will be performed by manual control using a radio transmitter. The main components of the flight controller are: a GPS-COMPASS unit, an IMU (Inertial Measurement Unit) and the controller unit. The main characteristics of the frame are listed in Table 3.4. Fig.3.14 shows the helicopter hanging from a tree branch carrying the skew-gripper.

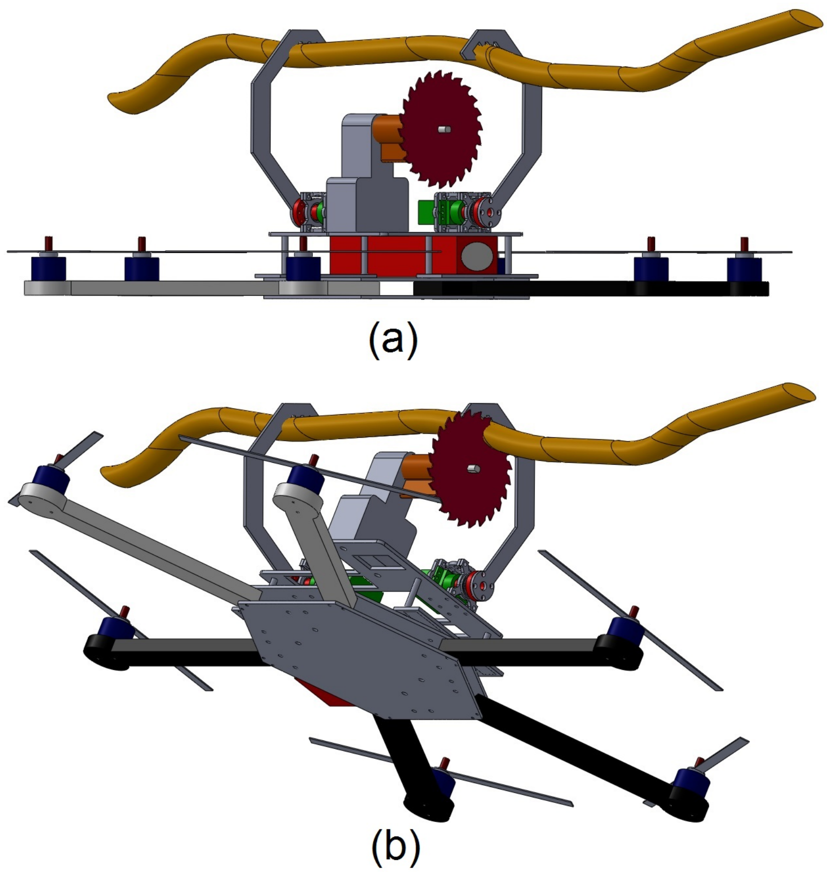

Figure 3.13: Prototype of the aerial pruning robot. In (a), the aerial pruning robot is hanging on a tree branch. In (b), the mechanism is pruning a tree branch rotating around the axis formed by the shafts of the two servo motors.

Table 3.4: Main characteristics of DJI F550 frame

Frame Weight	478 g
Diagonal Wheelbase	550 mm
Payload capacity	0.7∼1 kg
Propeller	9.4×5 in
Battery	3S∼4S LiPo
Motor	920 kV
ESC	15 A

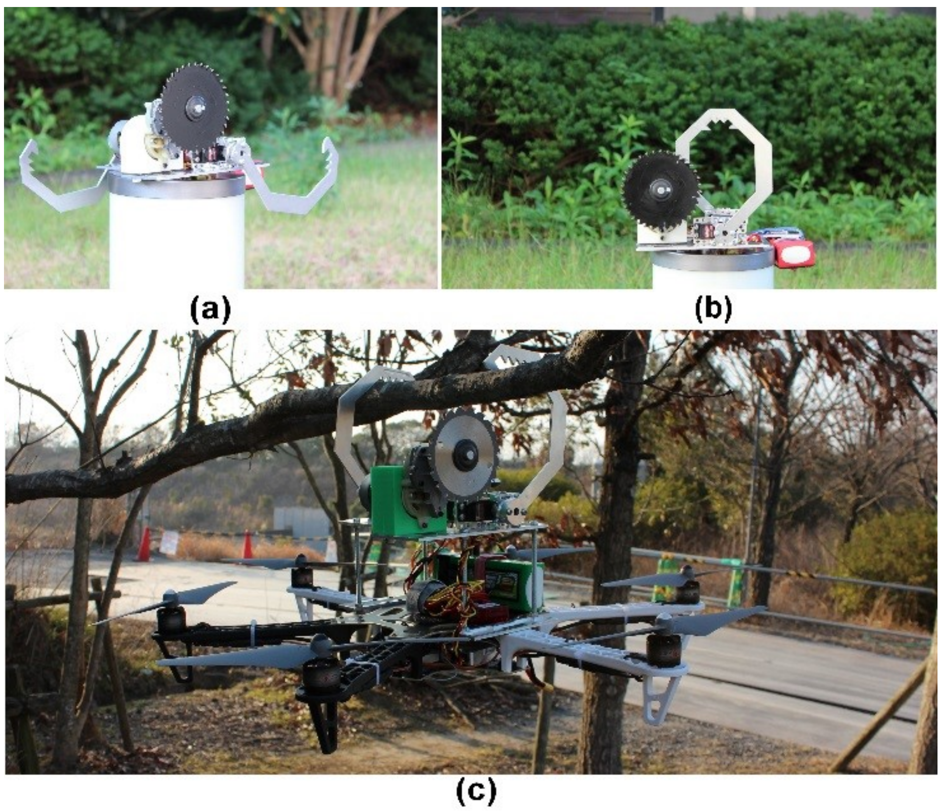

Figure 3.14: Real prototype of the skew-gripper. (a) and (b) show the skew-gripper opened and closed respectively. (c) shows the skew-gripper mounted on a hexarotor helicopter and it hanged on a tree branch.

Chapter 4

Controlling the Grasping and Pruning Process

4.1 Grasping

The first task the aerial pruning robot should do is grasping the target tree branch. In order to do that, the grasping mechanism should be controlled remotely. Basically, the couple of servomotors, which provide rotational motion to each claw, should be controlled by a couple of channels from a radio receiver. Fig. 4.1 shows the basic schematic of the connection between the gripper's servomotors and the transmitter. Notice that it is necessary a small 2 cells 7.4 V LiPo battery to power this transmitter. Later, we will explain in the system integration how to connect the gripper, circular saw and the helicopter with its respective radio receiver to control the whole system with a single radio transmitter. For the initial testing of the grasping mechanism, the experiments were performed outside the laboratory. Unlike the pruning process, which was performed in a testbed in the laboratory, the grasping process was completely performed outside. Fig. 4.2 shows one of the first experiments using the skew gripper in a real situation.

4.2 Pruning

One of the crucial points in this project is pruning tree branches. Once a tree branch has been grasped, the next step will be pruning it. In order to do that, two approaches were designed and tested to achieve the best performance and efficiency.

The first approach was designed to control the speed of the circular saw for pruning purposes. This idea was conceived because we realized that in some experiments performed in open loop, the circular saw drastically reduced its speed just when it begun to prune a tree branch. The second approach use

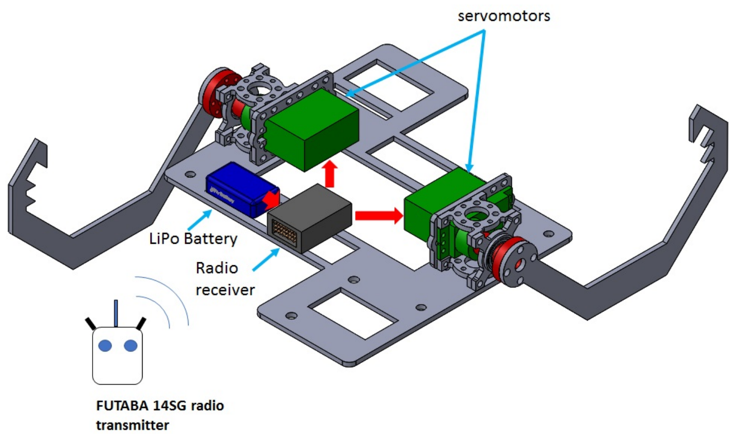

Figure 4.1: Futaba transmitter and receiver for commanding the servo motors of the skew-gripper.

a motor driver which is a regenerative. The regenerative topology means that the battery get recharged whenever you command your robot to slow down or reverse. this motor driver also allows the user to make very fast stops and reverses. As we will explain later, for pruning a tree branch using the proposed mechanism, the user should swing up and dawn the pruning mechanism to prune a tree branch.

4.2.1 PI speed controller for the circular saw

In order to prune the target (tree branch), one of the requirements is to keep the speed of the circular saw constant. We thus designed a PI controller for the DC motor of the circular saw. Because of the weight and the energy restriction of the system, we decided to use only the back-EMF for sensing the speed of the DC motor. Using this voltage, which is proportional to the angular speed, we can reduce the components and the energy consumption in the complete system.

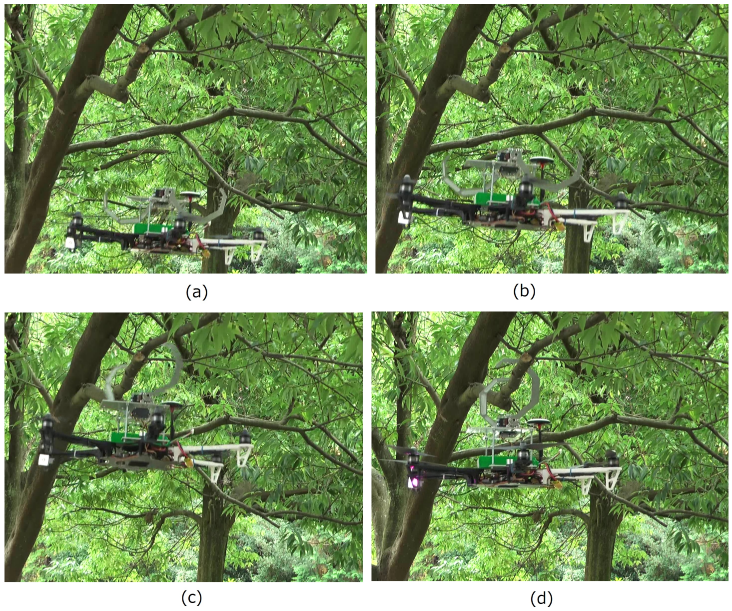

Figure 4.2: Testing the skew gripper in a real situation. This was one of the first experiments using this idea for grasping a tree branch.

Sensing the back-EMF

The back-EMF is proportional to the motor's speed, Fig. 4.3 shows the schematic of the electrical parts of a brushed DC motor; $u(t)$ represents the input voltage, $i(t)$ represents the current and R, L represent the resistance and the inductive respectively. The voltage $e_a(t)$ represents the back-EMF and is given by the expression:

$$e_a(t) = k_e\dot{\theta}(t) \tag{4.1}$$

where k_e represents the back-EMF-constant and $\dot{\theta}$ represents the angular speed of the motor's shaft. For sensing this voltage $e_a(t)$, an electronic interface between the microcontroller and the DC motor was designed. Fig. 4.4 shows the main components used for sensing the voltage; first of all, a 940 Hz PWM signal from an arduino UNO is sent to the gate of a N-Channel MOSFET transistor which is connected to a 16.5 V power supply and this in turn is connected to the DC motor. The back-EMF is then read from the Drain pin of the MOSFET, the voltage measured in this pin with respect to ground is around 16.5 V (0 RPM) to 0.3 V (2046 RPM), which is the maximum speed. In order to obtain a signal from 0 V to 5 V and reduce the noisy, a voltage divisor and a low-pass filter were implemented. A Rail-To-Rail OP-AMP in a voltage follower configuration is used to reinforce the signal and limit it to 5 V and avoid the spikes produced by the motor's coils.

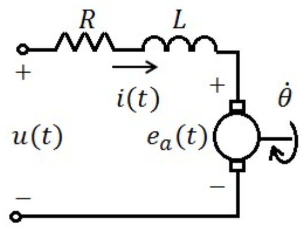

Figure 4.3: Equivalent electric circuit for a brushed DC motor.

Fig. 4.5 shows the graphic of the back-EMF produced by the DC motor once it was filtered and adapted for a microcontroller. We use the linear region from 0.3 V to 1 V corresponding to an angular speed of 2046 RPM to 1737 RPM respectively, this is due to the filter adds a time delay which modifies the linear response of the backEMF.

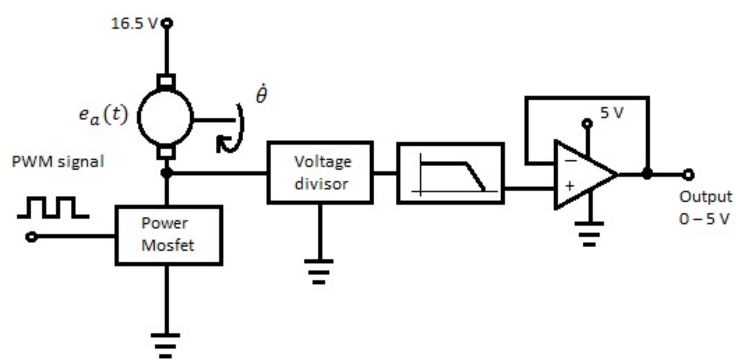

Figure 4.4: Electronic interface for reading the back-EMF.

PI Control

We experimentally found that for pruning a tree branch of a 30 mm of diameter, an angular speed of the circular saw between 1700 RPM and 1900 RPM is needed. Attending this requirement, a PI speed controller was designed and tuned experimentally. Fig. 4.6 shows the block diagram of the

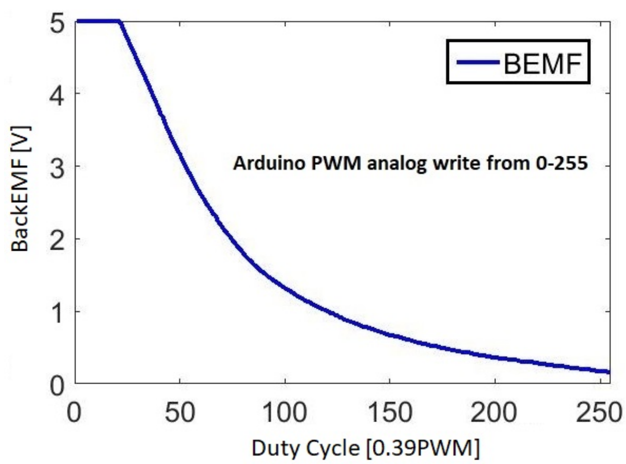

Figure 4.5: Back-EMF vs PWM duty cycle.

controller in which $r(t)$ is the reference input in RPM, $y(t)$ is the desired output in RPM and $u(t)$ is the control voltage for the DC motor. The PI controller has the following structure:

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{4.2}$$

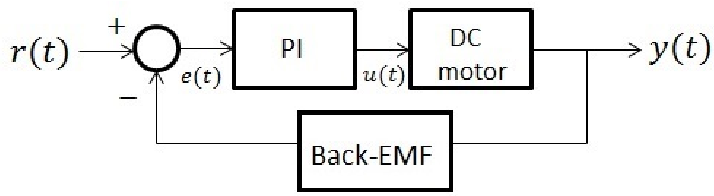

Figure 4.6: PI control using the back-EMF a a feedback sensor.

The gains chosen were for $K_p = 78$V/RPM and for $K_i = 3.9$V/(RPM)(s), Fig. 4.7 shows the performance of the controller when the set-point $r(t)$ is changed from 1750 RPM to 2000 RPM using a potentiometer as a set point which its voltage from 0 V to 5 V was mapping from 0 RPM to 2200 RPM.

4.2.2 PI speed controller, experimental results

In order to validate the pruning performance using the pruning system, the aerial pruning robot was tested indoor using a piece of wood of 30 mm in diameter to simulate the branch. Although the torque of the servomotors used to produce the rotational movement ϕ_s are small and lack of power, the results shown that this disadvantage was overcome due to the helicopter has on the one side of the X_s-axis, the pruning system and in the other side, the battery; the weight of these elements not only helps to keep the helicopter well balanced during flying but also produce a torque around the X_s-axis helped by the torque of the servomotors, in addition, this torque was also useful to provide force to the circular saw to prune the branch. The sharp-teeth of the claws also shown its effectiveness helping to fix the helicopter to the branch during the pruning process preventing the helicopter from falling down.

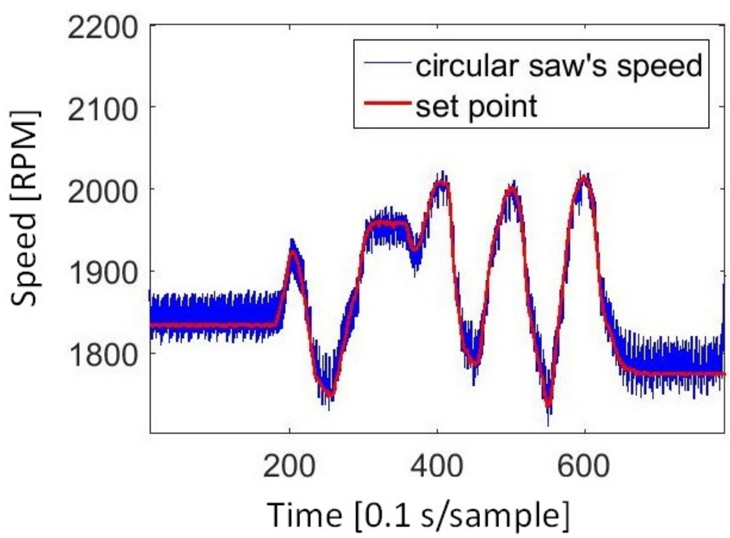

Figure 4.7: PI speed control following a reference set-point. A potentiometer was used to set the circular saw's speed reference mapping from 0 V (0 RPM) to 5V (2200 RPM).

For testing the effectiveness of the PI controller for regulating the circular saw's speed, it was tested in an open and close loops to compare the performance. The experiment was conducted as follows: First of all, the pruning system was activated for pruning a 30 mm tree branch in a testbed without the PI controller, namely, in open loop. Fig.4.8 shows the performance; it can be observed that at the moment of the contact with the branch, the speed is reduced considerably; moreover, after the second try, the speed is reduced to almost zero RPM, which means that the circular saw was stopped because it got stuck into the branch.

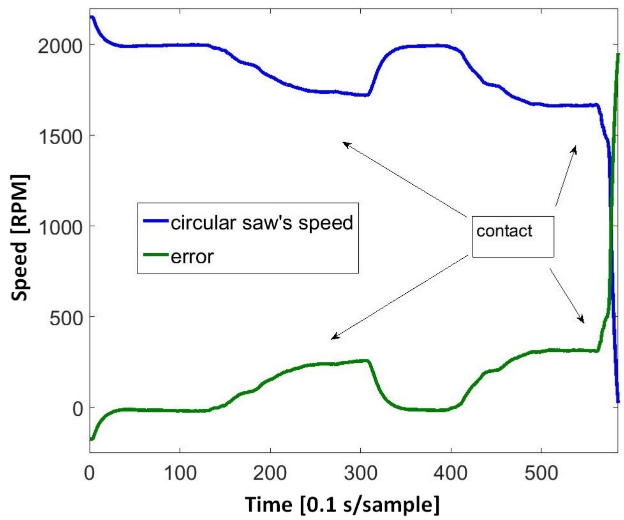

Figure 4.8: Pruning a branch in open loop. The error is between the desire and the actual speed of the circular saw.

After testing in open loop the PI controller, the next step was to test it to regulate the speed of the circular saw at the moment of pruning, analyzing Fig. 4.9 one can appreciate that the speed of the circular saw and the error are kept constant, which means that the goal was achieved. Fig. 4.10 shows the sequence of pruning, it takes around 2.5 minutes to complete the pruning task.

4.2.3 Using a commercial motor driver Sabertooth

Although the performance of the PI speed controller showed a good performance, the hardware needed to implement it makes that the total amount of components become high. In addition, the interface used to connect the controller with the radio receiver to command the pruning system remotely use extra energy and space in the helicopter.

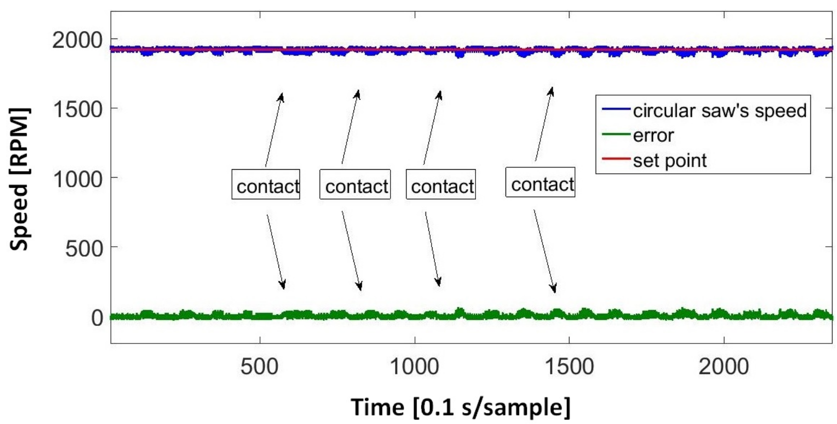

Figure 4.9: PI speed controller under a load disturbance, the set-point is at 1920 RPM.

In order to reduce the hardware and the energy consumption, we choose a commercial motor driver called Sabertooth [36]. Basically, the motor driver is composed as Table 4.1 shows.

Table 4.1: Sabertooth motor driver

Main Characteristics	
Input voltage	6-30 V with a maximum of 33.6 V.
Output current	Up to 25 A per channel. Peak loads up to 50 A per channel for a few seconds.
5 V BEC	Up to 1 A continuous.
Power sources	5 to 20 cells high capacity NiMH or NiCd 2s to 8s Litium Polymer (LiPo) battery. * The motor driver Sabertooth have a LiPo battery mode to prevent cell damage due to over-discharge of these battery models.

This motor driver works in a simple way, the battery is connected to the red terminals (positive and GND). Sabertooth allows the user to connect two motors simultaneously to its terminals, one of these motors may be connected to terminals M1A and M1B and the other one may be connected to M2A and M2B. The control signals that activate the Sabertooth should be connected to terminals S1 and S2; the 5V and GND terminals are used to provide energy

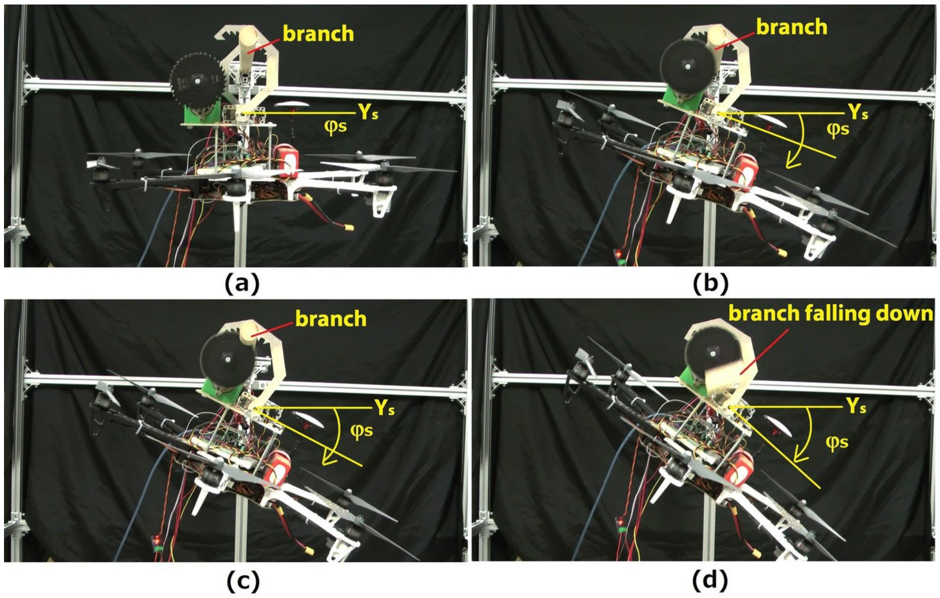

Figure 4.10: Pruning sequence. In (a) the system is ready to prune, in (b) The circular saw is starting and the helicopter is rotating an angle ϕs, in (c) the pruning is almost done and finally in (d) the pruning task has been completed.

to a microcontroller or another similar low power consumption device. The 5 V terminal is a 5 V output, the motor driver uses a 1 A Battery Eliminator Circuit (BEC), to provide energy to the motor driver's electronics and to provide energy to the receiver as well. The DIP switch allows the user to change between different modes of operation, among others, two of them are quite important for our design purposes, these are:

- Mode 1: Analog Input

  Analog input mode takes analog inputs and uses them to set up the speed and direction of the motor. The input range is from 0 V to 5 V. This mode allows the user to control the motor driver using a potentiometer, the PWM signal from a microcontroller or a simple analog circuit.

- Mode 2: Radio Controller (R/C) Input

  Radio Controller input mode takes two radio signals from a radio receiver and uses them to set the speed and direction of the motor to be commanded.

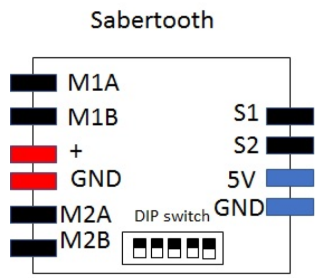

Figure 4.11: Connection diagram of the Sabertooth motor driver

As it is shown, Fig. 4.11 displays a simplified schematic of the Sabertooth motor driver. In order to connect the Sabertooth to the circular saw's DC motor, the output PIN M1A was chosen. The battery used to power the DC motor and the Sabertooth motor driver was the same battery used for powering the multirotor helicopter. For controlling the speed of the circular saw, the S1 input PIN was chosen. This PIN was connected to an RC receiver which receive a proportional signal from a radio control used to control the multirotor helicopter as well. Fig. 4.12 shows the connections between the DC motor and a RC receiver. Notice that this motor driver works in open loop; however, the Sabertooth can be expanded with a PID module to control either position or speed in a DC motor.

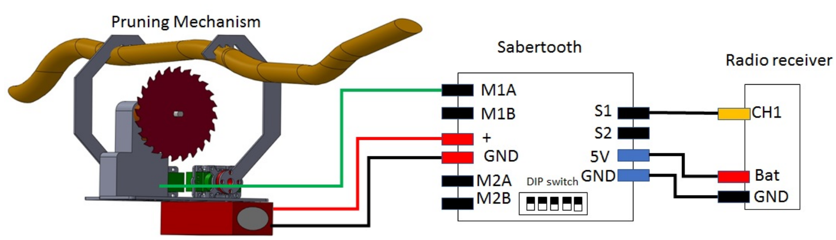

Figure 4.12: Sabertooth motor driver and its connections.

Using the configuration described above, we started a new set of experiments to test the motor driver performance pruning a 30 mm piece of stick in a testbed environment. The result of this experiments showed that even thought the control of the circular saw was in open loop, it could work properly and prune the piece of wood in around 1 minute. This is due to the motor driver can stands overcurrent as well as thermal protection, which allows to protect the whole driver in case the circular saw stops abruptly. This main characteristic helps to prune the stick faster than the previous motor driver design, in which was necessary to protect it from overcurrent pruning slowly swinging the mechanism up and down. With this current driver, the operator avoid to overuse the swinging technique thanks to the over current protection embedded in the motor driver. Fig. 4.13 shows the sequence of pruning, notice that unlike the former design, now the electronics is more compact and it helps to place all the components between the pruning mechanism and the multirotor helicopter.

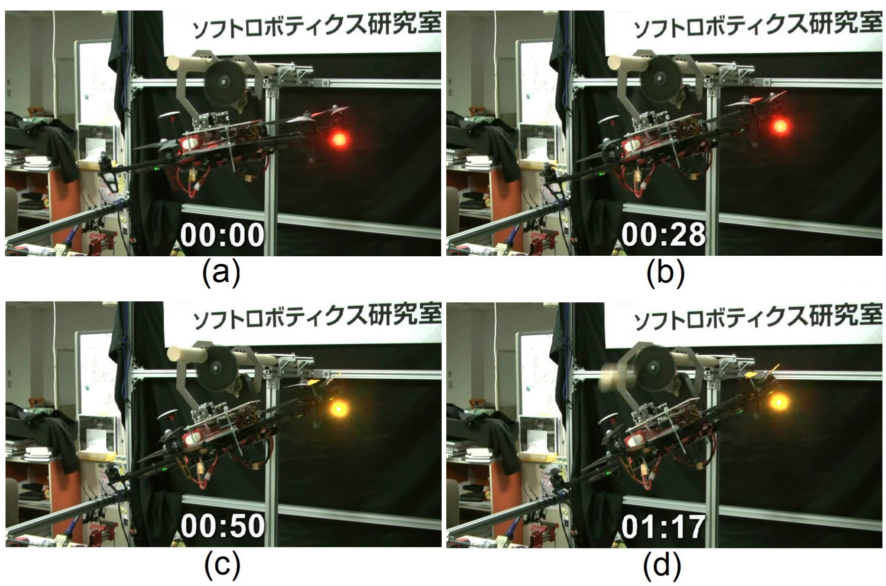

Figure 4.13: Pruning a 30 mm stick using the Sabertooth motor driver to control the circular saw. In (a) the mechanism is ready to prune, in (b) and (c) the circular saw is going through the stick and finally, in (d) the task is done.

Chapter 5

System Integration

In order to integrate all the electronic components in a compaq way, we decide to keep a free space for the flight controller in one site and the electronic hardware for the pruning mechanism in another site. This was helpful for maintenance purposes and repairing the aerial robot in case of a crash as well. Two approaches were implemented, the PI speed controller approach and the Sabertooh motor driver approach. Both approaches were tested in a real environment as them will be explained in the experimental results chapter.

5.1 First approach: PI speed controller implementation

The hardware designed for controlling the speed of the circular saw is composed by a power electronic module, which is used for commuting the DC motor used to move the circular saw, a back-electromotive force (back-EMF) module for sensing the motor's speed, a PI controller programmed in an Arduino UNO for regulating the speed of the circular saw and a RF XBee wireless module for transmitting the information of the pruning process to the operator. Fig. 5.1 shows the schematic of the power system module, PIN 1 and 2 of J1 are connected to ground and to 16.5 V respectively, PIN 1 and PIN 2 of J2 are connected to the terminals of the DC motor of the circular saw. From the connector J3, PIN 1 is the back-EMF signal used for sensing the motor's speed, PIN 2 was used as a back-EMF with a low-pass filter but it was not worked well because of the noisy and we decide to use the raw signal and design a filter separated as it will be explained later. Finally, PIN 4 is the PWM signal from the Arduino UNO for controlling purposes. The power electronic module is composed by a power MOSFET transistor together with a photo-transistor to protect it in case of over-current since the gate of this type of device is quite sensitive.

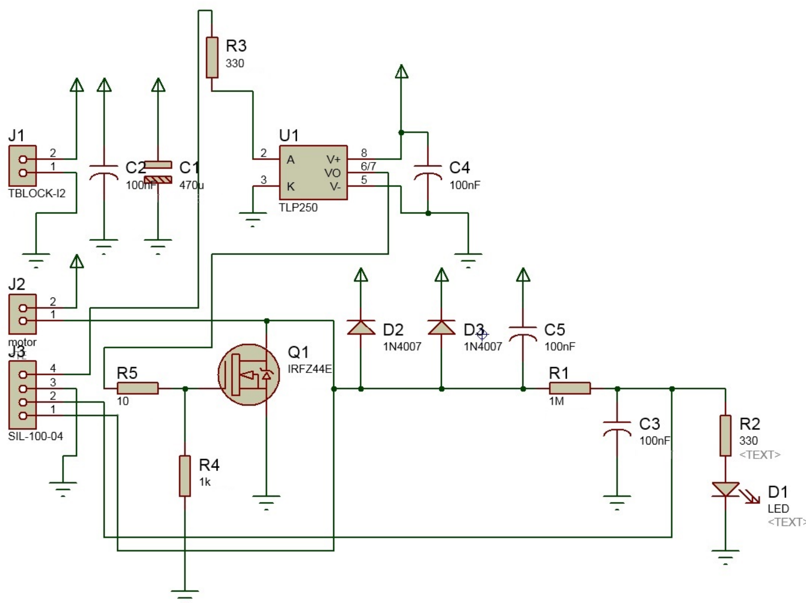

Figure 5.1: Power electronics module.

Fig. 5.2 shows the schematic of the back-EMF sensing module. This sensing module for reading the back-EMF is composed by a resistor divisor to reduce the voltage from 16.5 V to 5.5 V (J1 PIN 3) coming from the drain pin of the MOSFET transistor; in addition to this, a low-pass filter is used for filtering the noisy from the DC motor. An operational amplifier configured as a follower is used to reinforce the signal from the low-pass filter and for setting the output voltage from 0 V to 5 V (J1 PIN 5), suitable for reading using an ADC from Arduino UNO microcontroller.

The wireless communication module to communicate the aerial pruning robot with the computer's ground station is composed by two XBee series 1 (S1) from DIGI International [37], some of the most important characteristics are summarized in table II.

One of the two XBee modules was connected to an XBee shield from

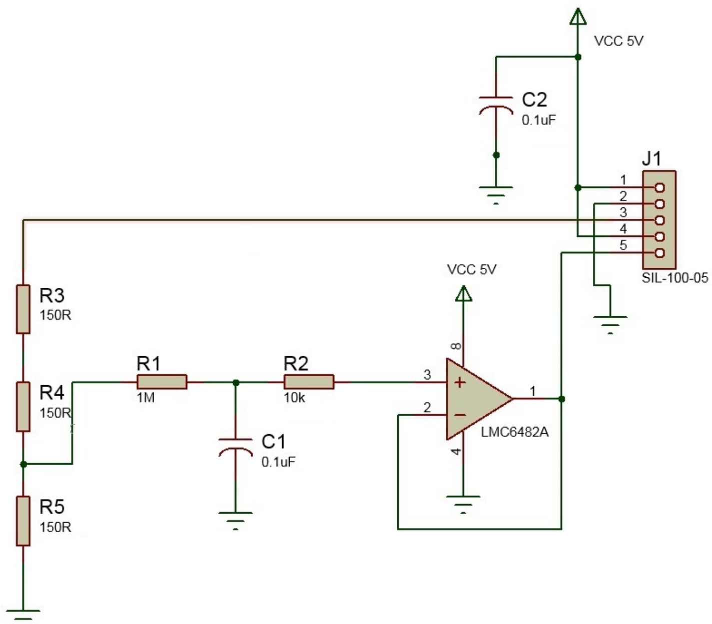

Figure 5.2: Module for sensing the back-EMF.

sparkfun [38] for interfacing with the Arduino UNO control board and hence send the data to the computer placed in the ground station. The other XBee module, which plays the role of receiver, was connected to the USB port of the computer's ground-station for receiving the data from the aerial pruning robot. Unlike the XBee module used in the aerial pruning robot, the XBee module connected to the computer's ground station needless an interface to connect to it. This module is called "XStick", and its shape is similar to an USB memory; however, it is used for wireless communication purposes. Fig. 5.3 shows the wireless interface between the Arduino UNO and the computer for data transmission and Fig. 5.4 shows the complete block diagram used for controlling and sending the data to the computer in the ground station. In this case and because this first approach used several components and modules for implementing the pruning hardware control, we decide to test the pruning system without the flight controller to check only the performance of the pruning machine in both real and testbed environment.

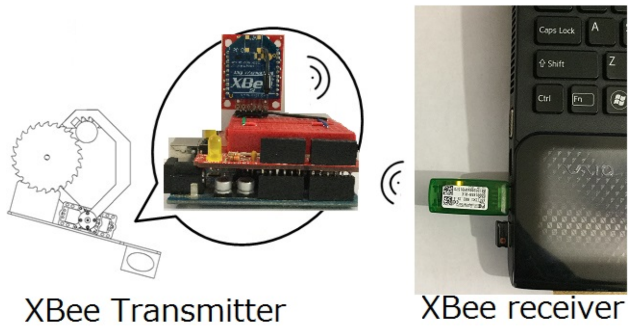

Figure 5.3: XBee modules for wireless communication.

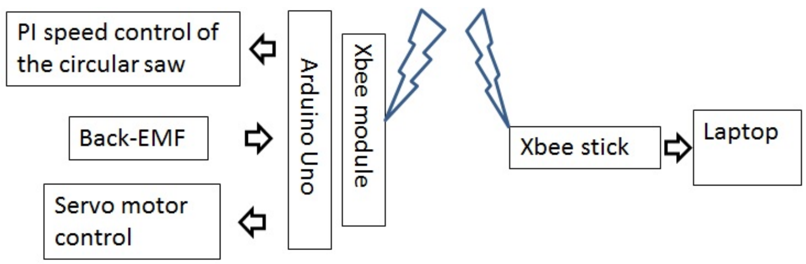

Figure 5.4: Modules for controlling the pruning process.

5.2 Second approach: Flight controller and Sabertooth motor driver

First of all, the connections of the flight controller will be explained. It is important to remark that throughout the project, we use different commercial flight controllers to test the aerial pruning robot as the DJI A2 flight controlled described previously in Chapter 3, section 3.3.2. The main desirable characteristics related with the flight controller performance are:

- Stability
- Low energy consumption
- Low weight

The latest flight controller we used was the NAZA V2 [1]. Unlike the DJI A2 (225 grams) flight controller, NAZA V2 weights only 66 grams. Although

Table 5.1: Specifications of the XBee S1 Module

XBee S1 module	
Specification	Performance
Indoor/Urban Range	Up to 100 ft (30 m)
Outdoor RF line-of-sight Range	Up to 300 ft (90 m)
RF Data Rate	250,000 bps
Serial Interface Data Rate	1200 bps - 250 kbps
Supply Voltage	2.8 – 3.4 V
Transmit Current (typical)	45mA (@ 3.3 V)
ADC	6 10-bit ADC input pins
Operating Frequency	2.4 GHz

it lacks of a built-in receiver and some advanced navigation functions, we only need the basic functions for testing the grasping performance. The main connections are showed in Fig. 5.5, notice that we will not use the gimbal function.

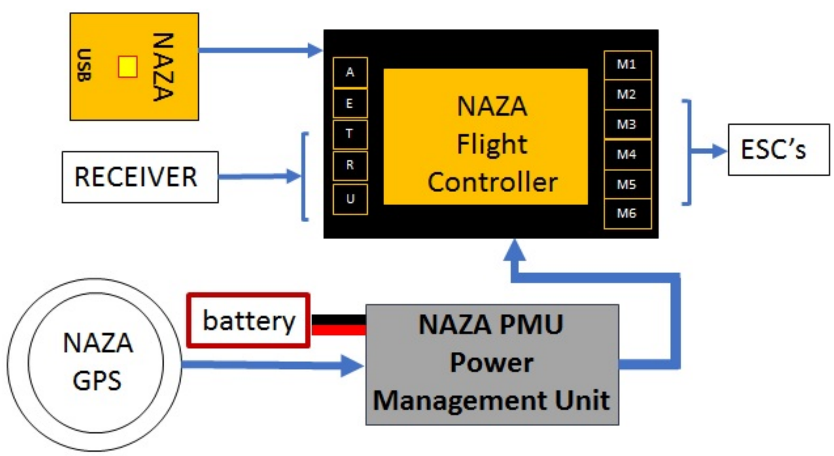

Figure 5.5: DJI NAZA V2 flight controller, main conecctions.

Connecting all the components of the DJI NAZA V2 like the Fig. 5.5 except the gimbal connection, which is not used, the next step is to connect the motors of the hexarotor helicopter through the outputs M1 to M6. This is the easiest part of all the connections, the complicated part arise at the moment of connect the two radio receivers since one of them will be used for controlling the helicopter and the circular saw and the other one will be used to control the skew gripper functions. Fig. 5.6 shows a general schematic of the connections between the flight controller, circular saw and skew gripper, all of them connected to the radio receivers. Notice that there is a relationship between the grasping and swinging tasks using the skew gripper, since both operations are perfomed by it. For grasping a tree branch, the couple of servo motors's shafts should rotate in opposite directions; however, for pruning, the shafts should rotate in the same directions to swinging up and down. In order to to do that, we are using four channels of the radio receiver, two for grasping and two for swinging. A 4-channel RC servo multiplexer from POLOLU [39] was used to select the appropriate task, namely, grasping or pruning. The operator use a switch from the radio transmitter to select which action should be performed by the aerial pruning robot. A FUTABA 14-channel [40] was used to control the whole system, this radio transmitter allows the operator to control both, the hexarotor and the pruning mechanism by means of two radio receiver mentioned above.

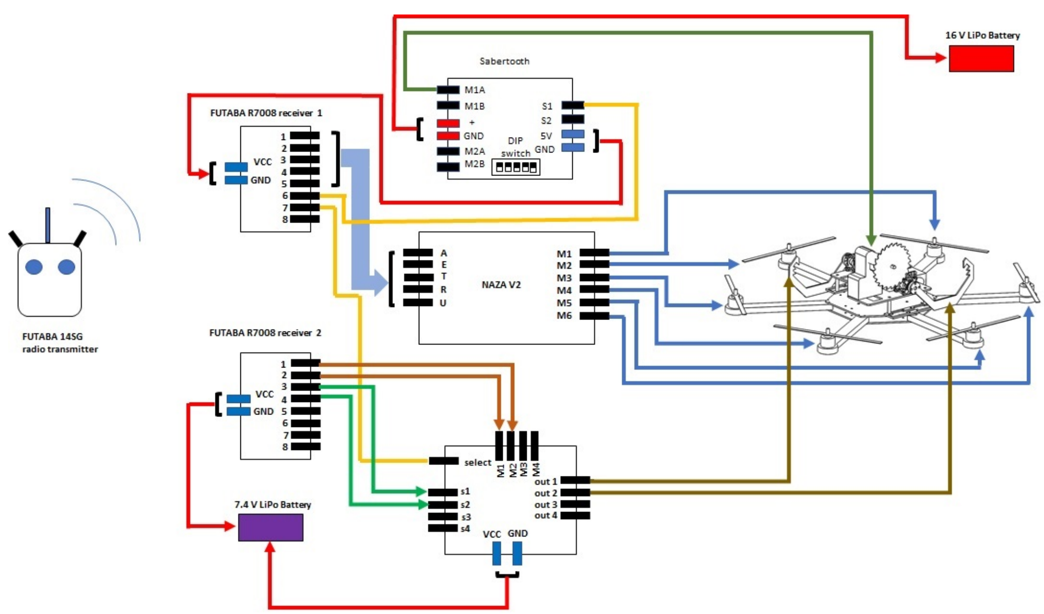

Figure 5.6: Main components used to control the aerial pruning robot.

Fig. 5.7 shows the prototype flying close to a tree branch, ready to prune.

Figure 5.7: Aerial pruning robot flying with all the control components embedded on the hexarotor helicopter.

Chapter 6

Experimental Results

6.1 Grasping tree branches in a real environment

For validation of the skew-gripper mechanism, different size of branches were grasped. The experiment consisted of three sub-operations:

1. Flying the multirotor to the target branch commanded by the radio control.

2. Grasping the branch as fast as possible.

3. Release the branch and come back to the home position.

The experiment shown that the skew-gripper grasped successfully branches from 19 mm to 31 mm with angles of inclination around zero degrees with respect to the ground. Moreover, grasping the branches was relatively easily, this is because the skew-griper is a wide-open mechanism, which allows the user to place the helicopter close to the target branch with a minimum effort. The longest flying time from the starting point to the grasping moment was about 2.35 minutes, in spite of the helicopter was commanded manually. This prove that there is no need to fly long time to achieve the target, which is important for saving energy. Fig. 6.1 shows the grasping sequence in a real environment.

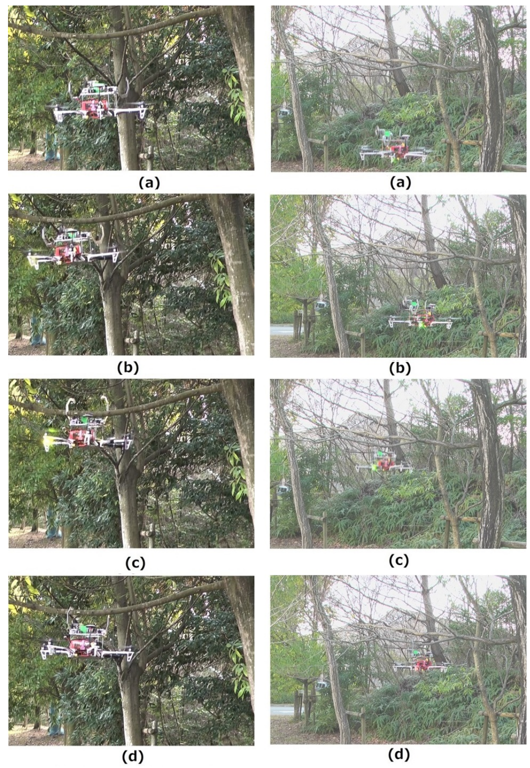

Figure 6.1: Two grasping sequences in a real environment. (a) The helicopter is flying to the target. (b) The helicopter is preparing for closing the gripper. (c) The gripper is closed for grasping the branch. (d) The branch is grasped.

6.2 Pruning

Fig. 6.2 shows how the skew-gripper grab and prune. For grasping a tree branch, the couple of claws have to open in opposite direction and, when the tree branch is firmly grasped, there is no way for opening and close anymore because of the shark-like teeth. As the couple of shafts of the servo motors of the skew-griper are placed on the same rotational axis, the body of the helicopter with the circular saw are able to rotate along such axis creating a circular motion to prune tree branches.

In order to validate the performance of the pruning mechanism in a real environment, several experiments were performed. The aim of these experiments was to prove the effectiveness of the wireless communication between the aerial pruning robot and the ground station for monitoring the speed of

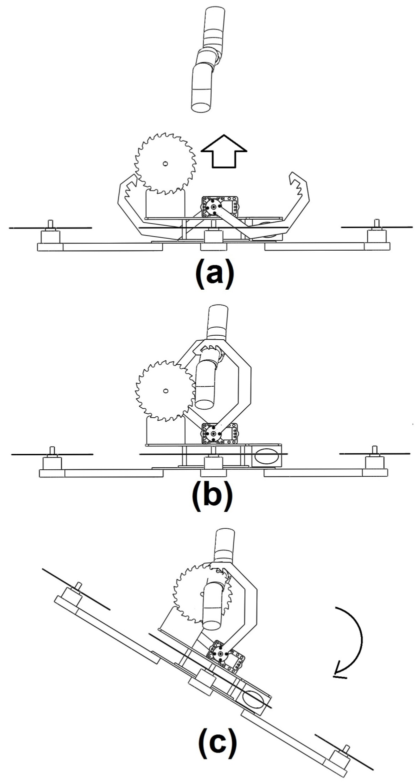

Figure 6.2: Transition between grasping and pruning process. In (a) the helicopter is flying to the tree branch. In (b) the tree branch is firmly grabbed and in (c) the helicopter's body is rotating for pruning the tree branch.

the circular saw; in addition, the swinging motion for the pruning process produced by the couple of servomotors was also tested. For this experiments a professional tipped-saw was selected as it will be described later.

6.2.1 Pruning sequence

In order to prune a tree branch ranging from 12mm to 40 mm, the pruning mechanism should start swinging to go with the saw through the tree branch progressively. In these initial tests, the user decides when the pruning mechanism should turn back and goes again through the tree branch based on a visual inspection, in case of the Sabertooth motor driver controller or based in the graphic of the circular saw's speed provided by the computer placed in the ground station, in case of the PI speed controller approach. For the sake of clarity, Fig. 6.3 shows the complete pruning task in four single steps, understanding that in a real situation, this swinging process should be repeated several times until the tree branch has been completely pruned. Fig. 6.4 shows the sequence of pruning of the real prototype pruning a 17-mm-diameter tree branch. The circular saw used in these experiments has the characteristics mentioned as follows:

- Outer diameter: 100mm
- Blade thickness: 1.3 mm
- Number of blades: 36
- Inside diameter (for attaching to the gear box): 20mm

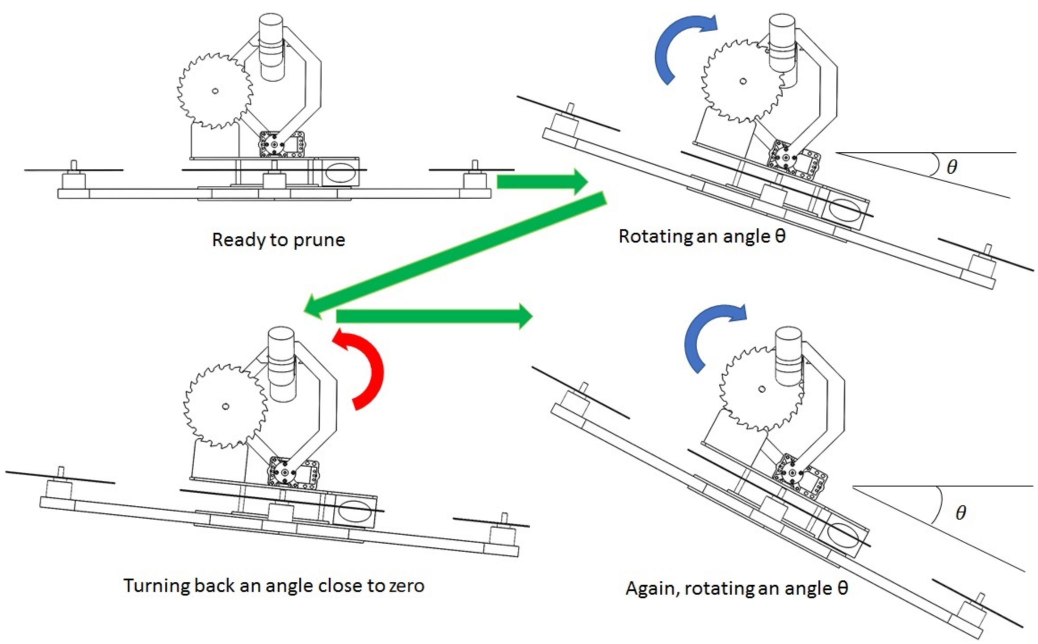

Figure 6.3: Pruning sequence, from the left to the right, the pruning mechanism should rotate an angle θ and turn back to the initial position several times until the tree branch has been pruned

Figure 6.4: Real pruning sequence. From the left to the right, the pruning mechanism is idle and later, it starts pruning swinging repeatedly

6.2.2 Wireless communication and PI control performance approach

The Fig. 6.5 shows the graphics of the performance of the pruning process, as it can be observed, the circular saw's speed is constant with some fluctuation as a result of the contact force at the moment of pruning.

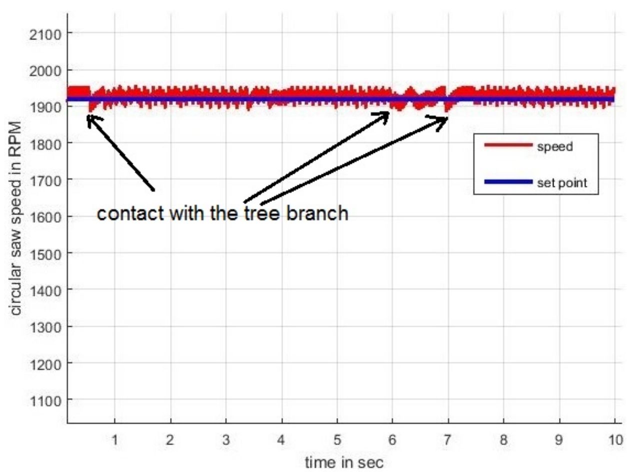

Figure 6.5: PI speed control. The graphic shows the performance of the PI speed controller working at the set point of 1900 RPM

6.2.3 Pruning results

The tree branch used in this experiments as well as the performance of the pruning mechanism are mentioned in table 6.1. From this table one may appreciate that the pruning time is related with two important factors: the stiffness of the tree branch and the diameter. Fig. 6.6 shows the tree branch pruned at approximately 90% of the total process.

Table 6.1: Main characteristics of the tree branch pruned in this experiment

Tree Branch	
Length from the pruning area to the tip	1.1 m
Diameter	17 mm
Time for pruning	8 minutes

Figure 6.6: Diameter of the tree branch pruned in this experiment. Notice that in the right side picture is shown the cut produced by the circular saw.

6.2.4 Sabertooth motor driver approach

Regarding with the Sabertooth motor driver approach, it was tested in a real environment for pruning a 25 mm tree branch. In this case there is no graphic performance since the motor driver was connected with out an XBee radio transmitter to save energy. Based on the practical experimentation and using that we call ”helping hand” to provide support to the tree branch while the circular saw is pruning we may say that the motor driver sabertooh and the helping hand will be the next step in the improvement of the aerial pruning robot.

Figure 6.7: Sabertooth motor driver approach using the super helping hand to provide support at the moment of pruning.

6.2.5 Energy consumption

Regarding the energy consumption of the whole system, the main source of energy consumption is the multirotor helicopter, and it consumes around 25 A during flying. On the other hand, the circular saw consumes only 4 A during the pruning process which takes around 8 min or less, depending of the diameter of the tree branch. In these experiments, a 5100-mAh 4S LiPo battery was used for powering the multirotor and the circular saw as well. This battery at full charge gives 16.8 V and should not go down less than 12.8 V at full discharge. For practical applications, we establish a boundary in 14.5 V to have enough time for landing in case the battery has achieved the minimal boundary and thus prevent a permanent damage. This range allows the operator to fly the multirotor around 7 minutes which is enough time for grasping and pruning at least, one tree branch.

Chapter 7

Conclusions and Future Work

In this research, a novel mechanism called ”skew-gripper” for grasping and pruning tree branches was described. The mechanical design, the grasping area and volume as well as the kinematics was also described. Experimental results showed the capacity of the ”skew-gripper” for grasping different types of tree branches; that is, no matter its body-shape, as long as they fit inside the grasping volume, it can be grabbed. The ”skew-gripper” also experimentally prove 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. In addition, a PI speed controller to keep constant the angular velocity of the circular saw using only the back-EMF of its DC motor as a feedback signal was successfully tested. Although the bracing method and the controller proposed shown a good performance, it is important to remark that in the future, the swinging movement for pruning purposes should be controlled automatically. Finally, the hardware description and some experimental results regarding with pruning tree branches in a real environment using an aerial pruning robot were shown. Results obtained shown that the PI control implemented to control the speed of the circular saw was helpful for pruning a real tree branch. In addition, the wireless communication between the aerial pruning robot and a ground station has shown that it is possible to follow the pruning task monitoring the performance of the speed of the circular saw to avoid possible accidents. In the future, some improvements to increase the performance of the pruning task such as monitoring the process using either a smart phone or a tablet instead of a PC along with a more powerful wireless communication to cover a large working area are needed. A quadrotor helicopter in a coaxial configuration to increase the payload capacity and thus allow the operator to place an extra battery to increase the flying time, which is a crucial factor to accomplish the pruning task will also be considered.

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