Bachelor's Degree Final Project

Design and programming of endurance testing equipment for a powered secateur

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Escuela de Ingeniería y Arquitectura
Universidad Zaragoza

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MAIN AIM OF THE PROJECT

The main aim of the project is the development of an automated endurance test of the new tool that the Power Tool department of Robert Bosch GmbH in Miskolc is developing.

The supervisor of the project is Dr. Jozsef Kakuk (head of engineering at Robert Bosch Power Tool Kft.) and the academic supervisors are Dr. Szabó Tamás (teacher at *Miskolci Egyetem*) and Dr. Javier Civera Sancho (teacher at *Universidad de Zaragoza*).

To achieve this aim, building a new working area is required to store and transport branches to test the powered secateur as well as to locate and measure the necessary sensors to make possible the monitoring of the process by using a Programmable Logic Controller Rexroth.

Several data of the results have to be stored and interpreted to decide whether the endurance test of the tool is satisfactory or not.

Contents

1. Introduction

1.1 Framework.

This Final Project has been developed in collaboration with the department of Research & Development of Power Tool that Robert Bosch GmbH has in Miskolc (having as supervisor in that environment Dr. Jozsef Kakuk) and with the Robert Bosch Mechatronical Department of the *University of Miskol*c (with the academic supervisor Dr. Szabó Tamás).

The Robert Bosch Power Tool Ltd. Was founded in 2001 in Miskolc. This division is world market leader of portable electric power tools and power tool accessories. The power tool business unit is a leading supplier of systems that simplify the work of the small-scale industry, the household and gardener as well as industrial users. The so called “green product line” of the Bosch hand-tools are manufactured in this center.

The project has been carried out entirely from November of 2015 to May of 2016.

1.2 Justification.

The justification of the project is the need of performing the automated endurance test to the new power tool that the department of Research & Development at Robert Bosch Power Tool Ltd. Miskolc is developing. The automated endurance test has to simulate the normal operating usage of the owner of the powered secateur.

On that way, the tool could be tested in a fast, efficient and interesting way due to the possibility of analyzing important parameters of the internal technological devices of the power tool. The department will be able to change basic parameters of the power tool before the powered secateur will be launched onto the market.

Basic lifetime requirements are fixed for the tool and with the development of an endurance testing equipment we will know if it is possible to achieve this requirements with the current design and parameters of the tool or not.

1.3 Different parts of the project.

The main parts of the project are going to be briefly explained to the reader to be able to understand the framework of each section of the project.

The first part will be a research of the current existing powered secateurs on the market. This research was entirely web searched focusing in the main market competitors of Robert Bosch Power Tool systems. Two big kinds of powered secateurs were founded at the current market.

The next part of the project will focus on understanding each part of the powered secateur developed and its function as well as its basic design parameters decisions. Inside this framework, each part of the power tool will have three subparts that are function, working principle and design specifications.

Continuing with the project, the next step will be to explain how we collect the features and parameters of the powered secateur to be tested and measured during development. We have four important parameters that are the user force (F_{USER}), the motor current (I_{MOTOR}), the battery temperature ($T_{BATTERY}$) and the motor temperature (T_{MOTOR}).

Next section will focus on collect the lifetime requirements of the product, trying to find the limit criteria of the product, estimating the amount of branches that could be cutted in a normal battery cycle.

After, we will talk about the choosed design proposal for the automation of wood feeding, with all the technology that is required to have a normal operation during testing.

The penultimate section is about collecting the necessary measuring inputs for the automation and the required measurements from the tool that will define the workspace requirements.

The last section of the project will talk about the PLC Program taking into consideration the inappropriate functionality of the workspace. The way of showing this configuration is using a place/transition net (Petri net).

2. Research of the current existing powered secateurs on the market (web searching)

In order to analyze the requirements that the current market of the power tools is searching for, a small research about the current existing powered secateurs on the market has to be done. The decided source of information is by web searching, focusing on the products of the main competitors of the company Robert Bosch Power Tool Ltd.

A basic research is enough to understand that there are two kinds of powered secateurs on the market:

2.1 Cordless powered secateurs.

Cordless powered secateurs	EAST ET1002
Product photo	
Max Cutting diameter (mm)	16 mm
Battery autonomy (h)	600 cuts (8mm soft wood)
Net Weigh of the tool (g)	600 g
Battery charging time (h)	4 hours
Tool size (cm)	23 cm
Average Price (€)	52 €
Operating speed (sec)	(No load) 1,2 seconds/time
Battery capacity (Ah)	1,3 Ah Li-ion (7,2 V)
VONHAUS 15/014	RYOBI BSH-120
	
14mm(softwood),10mm(hardwood)	12 mm
500 cuts	-
770 g	700 g (600 g body + 100 g chargers)
1,5 hours	60 minutes
24,3 cm	30 cm
40 € (Amazon) - 50 €	80 €
-	1,2 seconds
-	1,3 Ah Li-ion (3,6 V)

BATAVIA Clipper	COOPERS of Stortford Secateur
	
14 mm	16 mm
-	200 cuts (of 16 mm thick branches)
700 g	630 g
5 hours	5 hours
-	28 cm
46 €	46 €
-	-
1,3 Ah Li-ion (7,2 V)	1,3 Ah Li-ion (7,2 V)
GTL CS-01	**RYOBI RLP 416 TEK4**
	
14mm(softwood),9mm(hardwood)	16mm(softwood),10mm(hardwood)
450 cuts	500 cuts (of 9 mm thick branches)
800 g	700 g
3-5 hours	3,5 - 4,5 hours
-	-
-	60 €
-	-
1,3 Ah Li-ion (3,6 V)	1,3 Ah Li-ion (4 V)
CRAFTSMAN 74431	**RYOBI CHP-72**
	
13 mm (softwood)	14 mm
500 cuts(9 mm greenwood branches)	450 cuts / charge
560 g	770 g
3 - 5 hours	1 hour

-	-
40 €	30 €
-	-
1,1 Ah Li-ion (4 V)	1,3 Ah Li-ion (7,2 V)

2.2 Secateurs with battery harness.

Secateurs + Battery harness	BAHCO PX-POWER 9320
Product photo	
Max Cutting diameter (mm)	35 mm (wide opening) 20 mm (narrow)
Battery autonomy (h)	3,5 hours
N.W of the tool + battery (kg)	3,47 kg harness + 945 g the tool
Battery charging time (h)	-
Tool size (cm)	32 cm
Average Price (€)	1.500 € (whole pack)
Power (W)	90 W
Operating speed (sec)	-
Product life (years)	-
Battery capacity (Ah)	(3,5 Ah) 2 batteries of Ni MH (24 V)
ARVIPO PS100	PELLENC LIXION EVOLUTION
	
40 mm	35 mm
more than 8 hours	3 days
2,35 kg harness + 945 g tool	1,9 kg battery + 787 g tool
-	5 hours
-	19,7 cm
900 - 1.500 €	1.500 - 2.600 €

200 N*m (Max. Torque)	150 W (16000 rpm)
fast	-
Battery with 3 years of warranty	Battery with 3 years of warranty
4,8 Ah Li-Ion	4,5 Ah Li-Ion (43,2 V)
ZENPRORT SCA3	**MAKITA 4604DW**
	
46 mm	30 mm
12 h (15000 continuous pruning cuts)	7 h (10000 continuous pruning cuts)
5,44 kg (whole pack) + 900 g tool	2,5 kg battery + 1 kg tool
-	1 hour
15 cm	28,6 cm
920 €	1.020 €
-	-
-	0,4 sec / section
-	-
4 Ah Li-ion (36 V)	3 Ah Ni-Cd (24V)
KPC KS3000	**ZAK30**
	
25 cm (hard), 30 mm (soft), 53 mm Max	25 - 30 mm
15 hours (3 days max)	8 hours
950 g tool + 800 g battery	2,2 kg battery + 800 g tool
2 - 3 hours	4 hours
15 cm	23 cm
700 €	980 €
-	160 W
-	-
-	-
4,4 Ah Li-ion (24 V)(Samsung)	4,5 Ah Li-ion (24V)

INFACO ELECTROCOUP F3010	**STIHL ASA 85**
	
40 mm (56 mm Max.)	45 mm
8 hours	10 hours
2,4 kg battery+500g harness+830 g tool	1,7 kg battery + 980 g tool
5 hours	3,5 hours
20 cm	24 cm
2.100 €	1.700 €
-	-
-	-
12 months warranty,3 years gear motor	-
Ni Mh (48 V)	6 Ah Li-ion (36 V)
FELCO 820	**FELCO 801**
	
45 mm	30 mm
12 - 24 hours	12 -24 hours
0,8kg battery+0,9kg harness+980g tool	0,8kg battery+0,9kg harness+745g tool
2 hours	2 hours
29 cm	25,5 cm
2.000 - 2.300 €	1.300 - 1.600 €
-	20000 rpm
-	-
-	-
2,5 Ah Li-Po (37 V)	2,5 Ah Li-Po (37 V)

3. Functions & Parts of the powered secateur

We are going to resume briefly the different parts of the tool that we can differentiate at the *Figure 1* and its functions with the working principles:

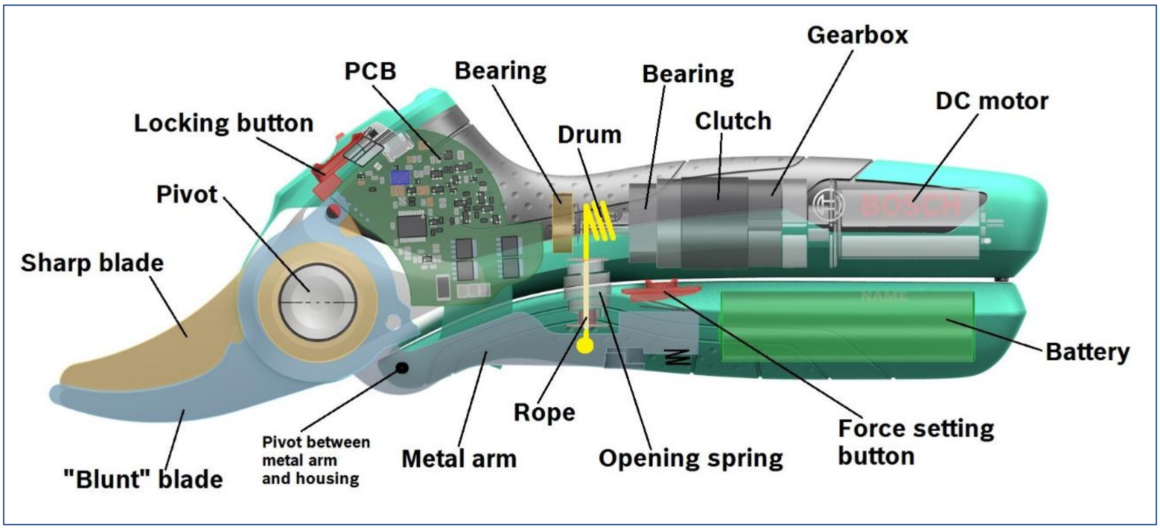


Figure 1: Different parts of the power secateur. [1]

3.1 Housing.

Function: The housing will protect all the parts and devices that the tool needs to work from the external conditions (dust, water and more). So we need a level of shielding from the environment for that goal.

Also another main function of the housing is to keep the DC motor, the gearbox, the clutch, the drum and the center of the bearings on the same axis to ensure an optimum operation.

On the upper handle the housing will prevent the tool from slipping out of the hand of the user as well as giving a better impression of the product appearance and a more comfortable use.

Design specifications: The material chosen for the housing has to be strong enough to resist all the gripping force of the user in the worst case (maximum force of the user without the mechanic helping system working). Taking into consideration this fact, a Polyamide – 30% Glass Fiber (PaGF30) will be strong enough.

To prevent the tool from slipping out of the hand of the user, a black soft thermoplastic elastomer (TPE) component on the upper handle is a good and adequate solution. The process for producing this TPE component is by an injection moulding. The design of the tool and the housing shape will guarantee a nice user experience as well.

3.2 DC Motor.

Function: The direct current motor delivers the kinetic energy needed to wind the rope of the tool and therefore to help the user to close the tool while cutting hardwood branches with the help of a gearbox as well.

Working principle: Is a device that converts electrical energy (direct energy from a battery in our case) into kinetic energy using both poles of a magnet.

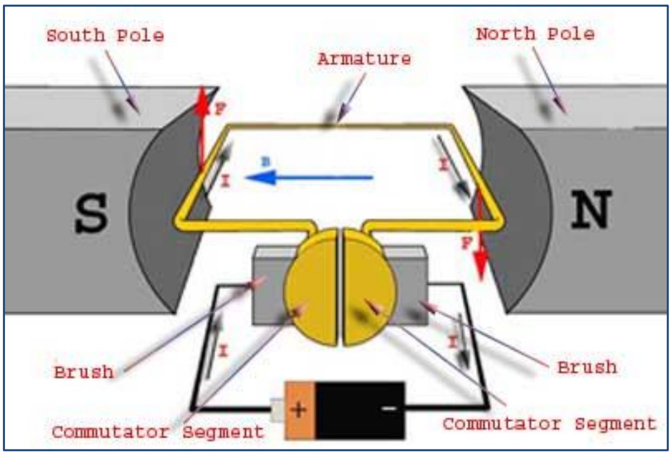


Figure 2: Different parts of a DC motor. [2]

The basic construction of a DC motor contains, as it is shown in the *Figure 2*, a current carrying armature which is connected to the supply end through commutator segments and brushes and placed within the north south poles of a permanent or an electro-magnet as shown in the diagram below.

Design specifications: The basic specifications for supplying the system enough kinetic energy are around 16000 revolutions per minute (rpm) of optimum rotational speed and 47 millinewton meter (mN·m) of stall Torque (M_{STALL}). The stall Torque is the torque load that causes the shaft to not rotate. We can understand this concept better with the *Figure 3*:

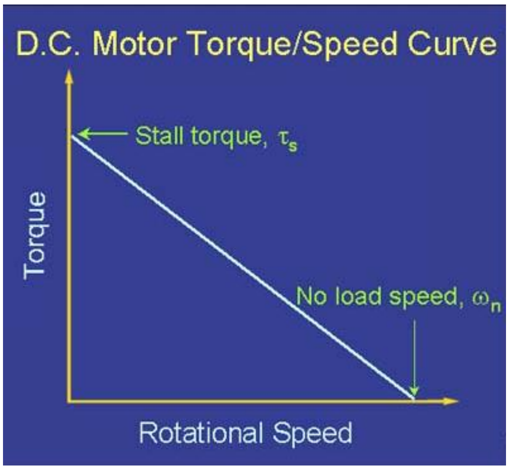


Figure 3: DC Motor Torque/Speed Curve. [3]

The chosen type of DC motor is flat type with dimensions near to 24 x 18 mm, with 36 mm long maximum.

3.3 Gearbox.

Function: The gearbox uses gears and gear trains to provide speed and torque conversions from the DC motor. The gearbox reduces the rotational speed in the DC motor shaft and increases the torque in the output shaft of the gearbox. Thus, a higher torque can be used to cut bigger branches.

Working principle: A planetary/epicyclic gearbox (this is the type that we are going to use in the tool) consists of two gears mounted so that the center of one gear revolves around the center of the other. A carrier connects the centers of the two gears and rotates to carry one gear, called the planet gear, around the other, called the sun gear. The planet and sun gears mesh so that their pitch circles roll without slip. A point on the pitch circle of the planet gear traces an epicycloid curve. In this simplified case, the sun gear is fixed and the planetary gear(s) roll around the sun gear. The *Figure 4* show graphically the different parts of the planetary gearbox.

The motion of the carrier can be transmitted to an output shaft or to another reduction group. In our case, we are going to hook up three planetary systems to create a gear train. On this way, the torque at the output shaft will be higher. This gear train is called "three stages planetary gearbox".

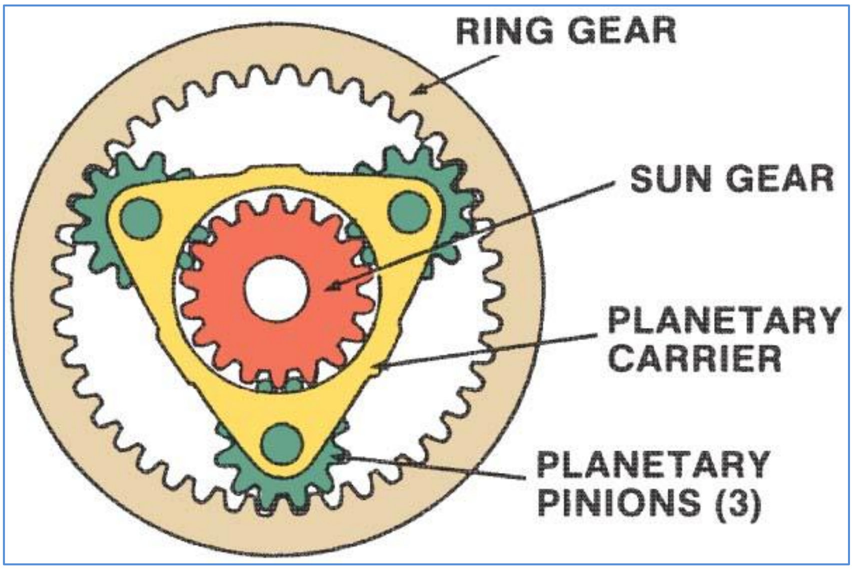


Figure 4: Planetary gearbox system. [4]

An interesting data that we can calculate is the torque ratios of a standard planetary gearbox. In a steady state condition, only one torque must be known, in order to determine the other two torques. The equations which determine torque are:

$$\tau_a = \tau_s * \frac{N_a}{N_s} \qquad \tau_a = \tau_c * \frac{N_a}{N_a + N_s} \quad (1)$$

$$\tau_c = \tau_a \frac{N_a + N_s}{N_a} \qquad \tau_c = \tau_s \frac{N_a + N_s}{N_s} \quad (2)$$

$$\tau_s = \tau_a * \frac{N_s}{N_a} \qquad \tau_s = \tau_c * \frac{N_s}{N_a + N_s} \quad (3)$$

Where τ_a— Torque of annulus (ring), τ_s— Torque of sun, τ_c— Torque of carrier.

In the cases where gears are accelerating, or to account for friction, these equations must be modified.

Design specifications: The most appropriate type for this project is a three stages planetary/epicyclic gearbox. The basic requirements are:

A minimum output torque of: τ_a= 4 N·m

An output ratio of: $\frac{N_a}{N_s} = 240$

3.4 Clutch.

Function: The clutch lock the drive with the rope drum during cutting and unlock the drive from the rope drum at the end of cut or when the user stops cutting.

The clutch connects both shafts (DC Motor shaft and output gearbox shaft) so that they can either be locked together and spin at the same speed, or be decoupled and spin at different speeds. The engagement of the shaft will be smooth thanks to the clutch torsion springs.

Working principle: A clutch works because of friction between a clutch/pressure plate and a flywheel (see *Figure 5*). In our system, the flywheel connects to the DC motor, and the clutch plate connects to the gearbox.

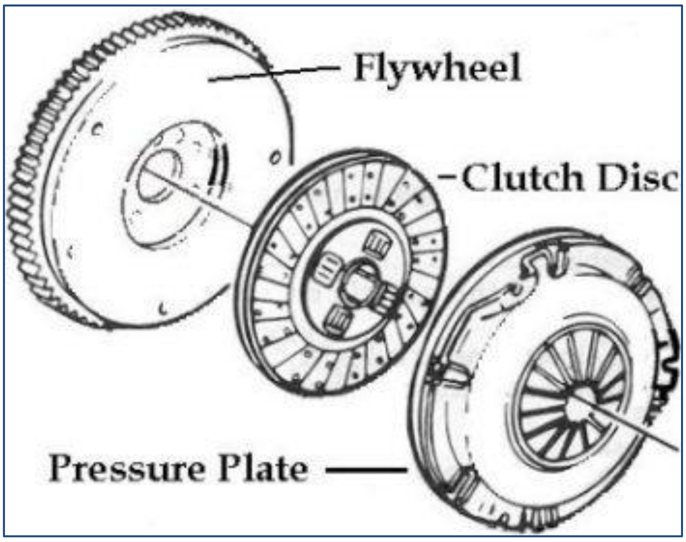


Figure 5: Parts of a clutch. [5]

When the user starts to cut a branch, the springs push the pressure plate against the clutch disc, which in turn presses against the flywheel. This locks the DC motor to the gearbox input shaft, causing them to spin at the same speed.

Design specifications: The clutch that will fit the specifications is a one way drive clutch.

3.5 Bearing.

Function: Two bearings placed in both ends of the rope drum make the function of supporting the rope drum against the cutting force appearing as a result of the operation of the tool. So the bearing constrains relative motion to only the desired motion, and reduces friction between moving parts to spin smoothly and quietly.

Working principle: The concept behind a bearing is that things roll better than they slide. When things slide, the friction between them causes a force that tends to slow them down. But if the two surfaces can roll over each other, the friction is greatly reduced. Bearings reduce friction by providing smooth metal balls or rollers, and a smooth inner and outer metal surface for the balls to roll against. These balls or rollers bear the load. Ball bearings, as the one in the *Figure 6*, are usually found in applications where the load is relatively small.

Figure 6: Example of ball bearing. [6]

Design specifications: Bearings are classified broadly according to the type of operation, the motions allowed, or to the directions of the loads/forces applied to the parts. In our case, a ball bearing that is able to resist a radial force of F_{radial} = 800N as a result of cutting force will be enough for the normal operation of the tool.

3.6 Drum.

Function: The basic function of the drum is to wind the rope in it.

Design: The most important thing while designing the drum is to not have sharp edges in it. Taking into consideration the drum wear, the drum is made of metal strong enough to bear the maximum cutting force at the drum.

3.7 Printed Circuit Board (PCB).

Function: The printed circuit board is going to do important control functions related mainly with the battery and the DC motor:

- Battery management: This control includes the battery level measurement, overtemperature protection of the battery cells, overvoltage or undervoltage level detection in each battery cell, charge and discharge mode detection and a control system to assure, more or less, a constant voltage supply from the battery to the electronic system.

- Charge level indicator: The user will know the approximate battery level simply checking this functionality included in the tool.

- Overcurrent protection: Checking the charging and discharging current, the electronic system will know when the battery charging current or the battery supplying current has a dangerous value (too much current).

- Reverse motor drive: To unlock the clutch.

- USB charging: The tool will be charged with a normal USB charger, just like the one that is normally used to charge a Smartphone. The PCB includes a micro USB female connector socket for this functionality.

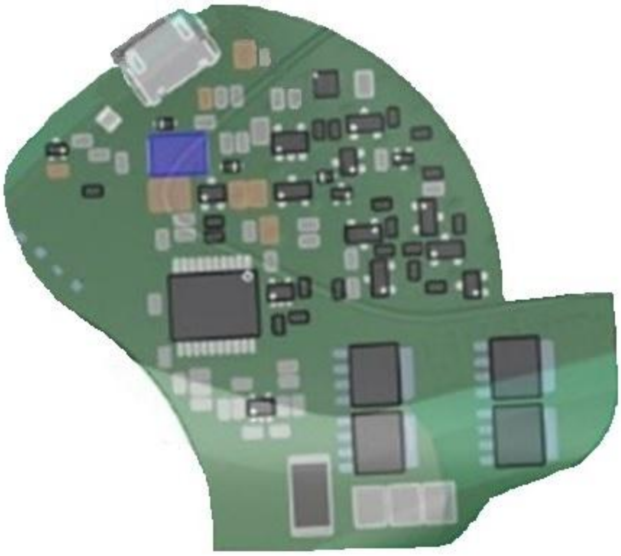


Figure 7: PCB appearance of the powered secateur. [1]

Working principle: To guarantee the normal operation of the battery, it is required to measure minimum three values: temperature and voltage of each cell and charging and discharging current of the battery.

Analyzing the temperature sensor (normally a NTC thermistor) from the battery of the tool, the system is able to detect an unusual high temperature of the battery that, if is not controlled, will seriously damage the battery. Lithium-ion batteries are extremely sensitive to high temperatures. The battery management device will stop the tool system until the battery recovers a normal temperature.

To know the battery level, only measuring the voltage of each cell of the battery (if it has more than one cell) the system can know the existing battery level. This is possible due to the linear voltage value while discharging/charging. To understand this concept better, the *Figure 8* shows the charge stages of a Lithium-ion battery.

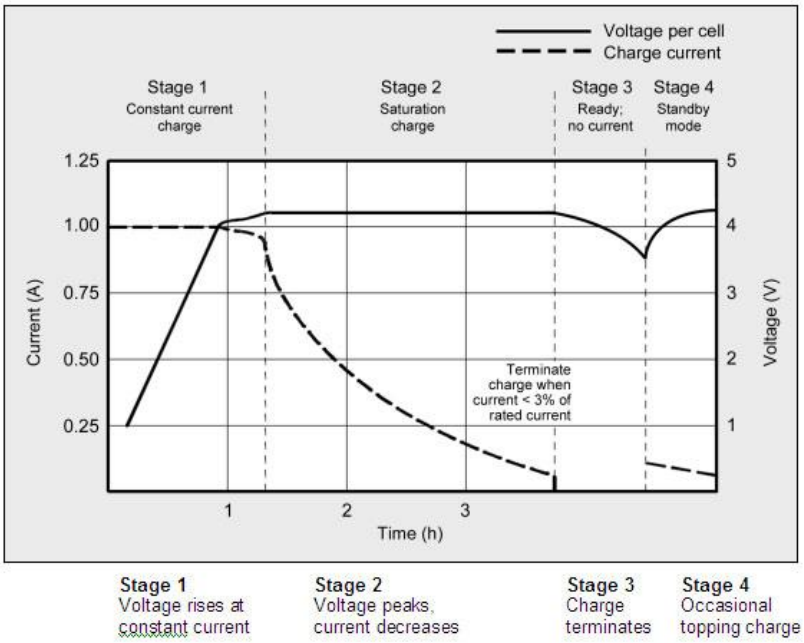


Figure 8: Charge stages of a Lithium-ion battery. [7]

Knowing the cells voltage is also important to protect them from overvoltage or undervoltage, fact that reduce the lifetime of the battery. Also if the battery is fully charged and we continue supplying current from the charger, the battery can be damaged. So the electronic circuit will detect when the supplying has to stop.

Charge and discharge mode detection is needed because the DC motor system will not work while the battery is charging as a safety measure.

To assure a constant voltage supply from the battery to the electronic system, a small CC/CC converter is required due to the big variation of the cell voltage during discharge.

The overcurrent protection is an easy function that can be solved with a simply system that measure the charging and discharging current and that stop current supplying if the current value is bigger than the maximum one.

All the sensors and battery measurements are managed by an integrated circuit. There are a lot of these integrated circuits on the market, like the Texas Instruments bq24160 chip, that are able to manage all these functionalities (*Figure 9*).

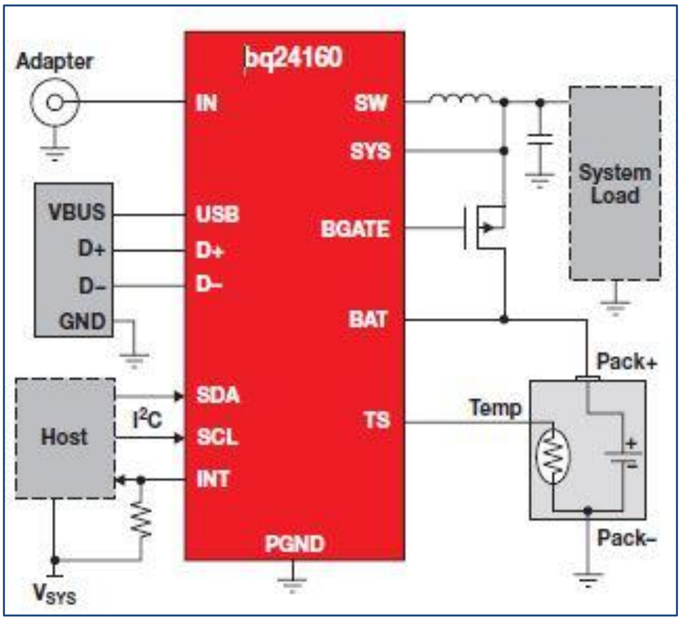


Figure 9: Battery management Integrated Circuit from Texas Instruments. [8]

3.8 Locking button.

Function: Keep the tool closed, keeping the blades together.

Design specifications: The button has to be easy to operate with globes.

3.9 Pivot.

Function: Is the axis of rotation of the blades.

Design specifications: Low friction pivot for the blades and the tool and preferred one removable part only to make blade change easy.

3.10 Blades.

Function: The sharp and the blunt blade will contain the branches and they will cut them.

Design specifications: The sharp blade has to be exchangeable and rust resistant with silver shiny colour and with low friction coated. The blunt blade has to be made of stainless steel and to be fixed in the housing.

3.11 Pivot between metal arm and housing.

Function: Enables relative movement between the force transmitting metal arm and the plastic housing.

3.12 Metal arm.

Function: The metal arm withstand tool force and user's hand force. In the metal arm, the rope is fixed to transmit the movement to the metal arm.

Design specifications: The material of the metal arm has to be stainless steel because of visible area near the blades and very high strength with no-sharp edges around the rope fixing area.

3.13 Rope.

Function: The rope is responsible for transform the kinetic energy of the DC motor in movement of the handles that will help the user in the cutting branches task. The rope, as we already mention, will wind around the drum, generating a force in the metal arm that will move the handles.

Design specifications: The kind of rope that is more appropriate for the system is a high-performance High-Modulus Polyethylene (HMPE) rope, "Dyneema" brand name is preferred to best resist against cutting effects under load (*Figure 10*).

One important design decision is that the rope is located near the pivot. If the rope was located far from the pivot, the torque used to wind the rope would be higher due to the bigger distance from the pivot.

The reason why this decision was made is because, analyzing the satisfaction of some users with the tool, it was more comfortable and logic to them the rope to be near the pivot rather than near the end of the handlers. On this way, the tool was more appropriate to be introduced in the pockets in a safety and easy way. Also, while cutting branches with the powered secateur, the user feel that is easier and safer to cut branches with this distribution of the rope and the opening spring.

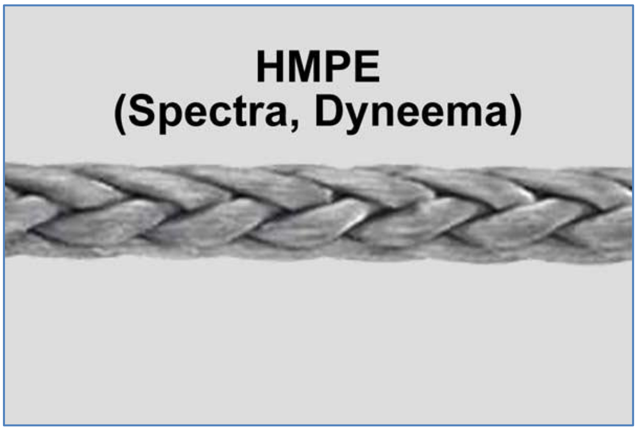


Figure 10: High-Moldulus Polyethylene Dyneema rope. [9]

3.14 Opening spring.

Function: The rope is covered and protected from the outside environment with the spring, which main function is to open the blades once that the branch is cut. This opening spring is also responsible for stable gripping because the force of the spring makes the tool not to fall from the hands of the user while he/she is carrying the tool.

Design specifications: The spring has to have comfortable opening force because the user has to do this force also while cutting branches. The material of the spring has to be stainless steel because it is in continuous contact with the environment.

3.15 Force setting button.

Function: The force at which the DC motor starts running can be set in three different positions:

1) Turn off position: the electric system of the powered secateur is off and the tool works as a normal secateur.
2) Low force limit setting.
3) High force limit setting.

3.16 Lithium-ion Battery.

Function: The battery supplies the electric energy needed to move the DC motor and to make the system works.

As we already saw, the battery will incorporate a temperature sensor and other data output that we have to analyze to understand the battery level and the security state of the device.

Working principle: like any other battery, a rechargeable lithium-ion battery is made of one or more power-generating compartments called cells.

Each cell has essentially three components: a positive electrode (connected to the battery's positive or + terminal), a negative electrode (connected to the negative or − terminal), and a chemical called an electrolyte in between them (*Figure 11*).

The positive electrode is typically made from a chemical compound called lithium-cobalt oxide (LiCoO2) or, in newer batteries, from lithium iron phosphate (LiFePO4). The negative electrode is generally made from carbon (graphite) and the electrolyte varies from one type of battery to another—but isn't too important in understanding the basic idea of how the battery works. *[10]*

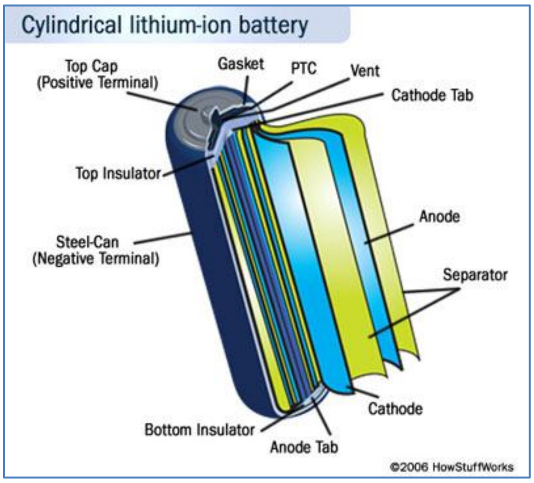


Figure 11: Cylindrical lithium-ion battery. [10]

All lithium-ion batteries work in broadly the same way. When the battery is charging up, the lithium-cobalt oxide, positive electrode gives up some of its lithium ions, which move through the electrolyte to the negative, graphite electrode and remain there. *[10]*

The battery takes in and stores energy during this process. When the battery is discharging, the lithium ions move back across the electrolyte to the positive electrode, producing the energy that powers the battery. In both cases, electrons flow in the opposite direction to the ions around the outer circuit. Electrons do not flow through the electrolyte: it's effectively an insulating barrier, so far as electrons are concerned. *[10]*

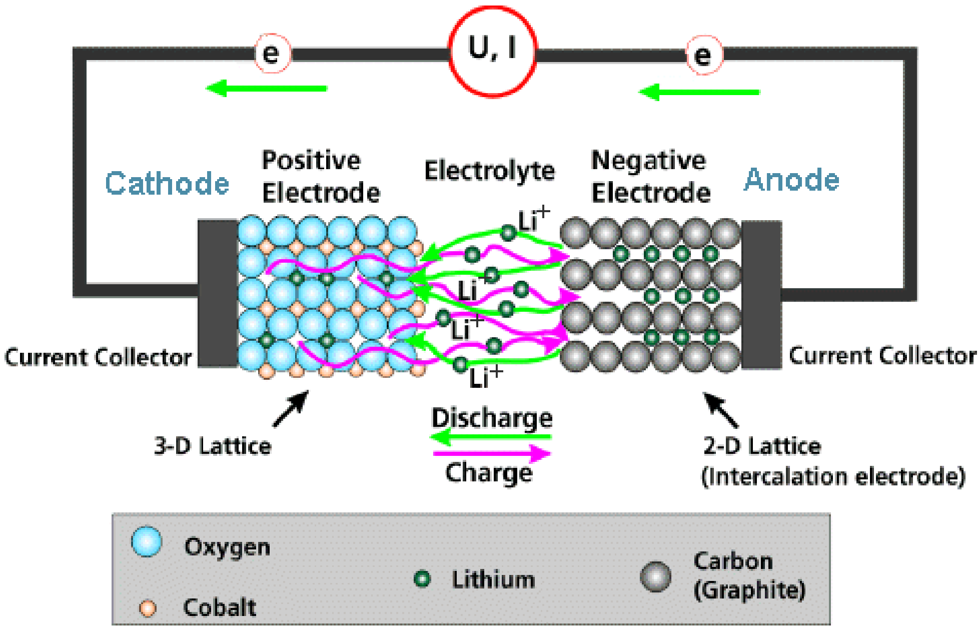


Figure 12: Lithium-ion batteries principle. [11]

The movement of ions (through the electrolyte) and electrons (around the external circuit, in the opposite direction) are interconnected processes, and if either stops so does the other. If ions stop moving through the electrolyte because the battery completely discharges, electrons can't move through the outer circuit either—so you lose your power. Similarly, if you switch off whatever the battery is powering, the flow of electrons stops and so does the flow of ions. *[10]*

The battery essentially stops discharging at a high rate (but it does keep on discharging, at a very slow rate, even with the appliance disconnected).

Unlike simpler batteries, lithium-ion ones have built in electronic controllers that regulate how they charge and discharge. They prevent the overcharging and overheating that can cause lithium-ion batteries to explode in some circumstances.

Design specifications: The appropriate lithium-ion battery for the project has only one cell with a charging voltage of 3.6 V and a capacity between 1.5 and 2 Ah (Ampere-hour).

4. Collect the features and parameters of the powered secateur to be tested and measured during development.

For developing the endurance test of the powered secateur is required to measured important signals and parameters that will ensure the normal process and functionalities of the tool as well as collecting some interesting data about the tool during development.

In this part of the project we will explain which parameters are important to measure and why. Also we will show the best way to measure them and to collect the information for using it later. The list of important parameters is:

4.1 User Force (F_{USER}).

The design decision for this testing process is to apply always the same force with the actuator to the lower handle because all the branches that we are going to use to test the tool are going to have the same diameter. On that way, applying a constant and reasonable force to cut the branches will be enough for the endurance test.

Knowing the constant current applied to the actuator will be enough to know the approximate force exerted by the actuator. So is not required to measure the user force with an external sensor, making the endurance test more simple and robust.

This decision was taken because, to measure the force of the user, we will need to incorporate to the tool handler some strain gauges (some of them subject to tension and others to compression to improve the measuring sensitivity) apart from an accommodation circuit (Wheatstone bridge) to create an appropriate signal to be measured and the use of special adhesives to transfer the punctual force exerted by the actuator to the entire area of the strain gauge.

4.2 Motor Current (I_{MOTOR})

The current that is going through the armature of the DC motor is going to be measured to detect possible overloads that will require a big quantity of current and that can damage the armature of the motor if the current reach the armature ampacity.

The ampacity is defined as the maximum amount of electric current a conductor or device can carry before sustaining immediate or progressive deterioration.

The most robust way of measuring the total current that flows into the DC motor can be shown at the *Figure 13*. This system is based on converting the total current that flows into the DC motor into a voltage signal using a resistor of 1mΩ.

This voltage will be plugged into an analog input of the microcontroller using an operator amplifier in configuration of voltage follower that will make the function of buffer. The analog input of the microcontroller will convert the analog value into a digital 10 bit value to use and analyze inside and outside the microcontroller.

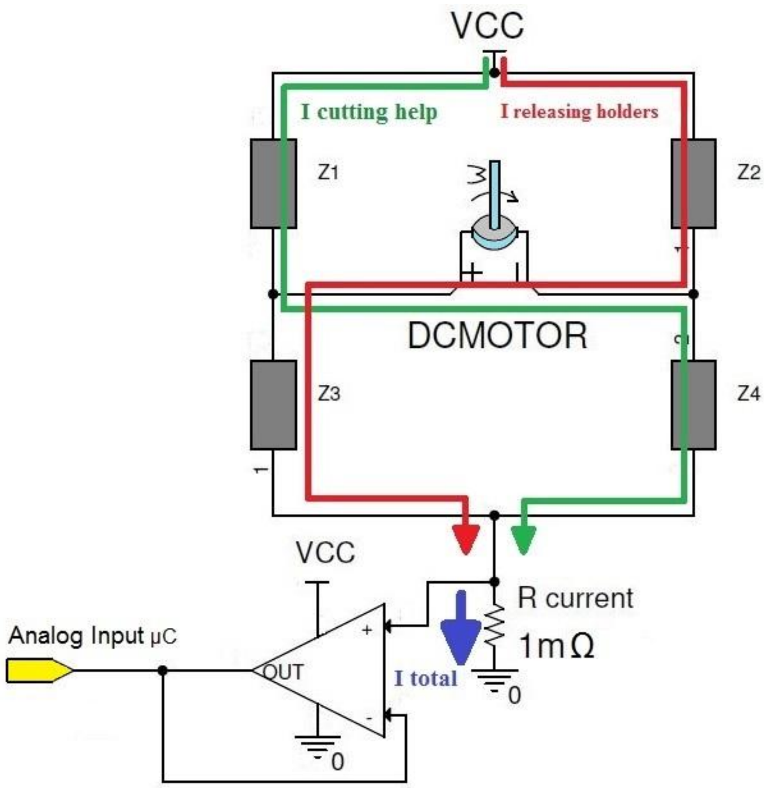


Figure 13: Circuit diagram of measuring system of the current of DC motor.

As we can see at the *Figure 13*, there are two ways of the current flowing through the DC motor. The green color current will activate the motor movement to help the user cutting branches. When the user finishes cutting the branch, the DC motor will invert the direction of the rotation to separate the handlers to its initial state and will unrelease the clutch. The power supply (Vcc) is the Li-ion battery.

The first important thing is to define a maximum current value that, if it is exceed, we will have to control the next values of the motor current and also a maximum time in which the overcurrent is allowed. The values of these two important parameters are:

$$I_{MAX} \simeq 18\ A$$
$$t_{OVERCURRENT\ MAX} \simeq\ 200\ mseg$$

The reason why a punctual overcurrent is allowed is because there is some noise at motor current signal. The main source of motor noise is the commutator brushes, which can bounce as the motor shaft rotates. This bouncing, when coupled with the inductance of the motor coils and motor leads, can lead to a lot of noise on your power line and can even induce noise in nearby lines. This noise is high frequency and can generate a false overcurrent value into the motor current signal that could mean the system stop by overcurrent detection program of the microcontroller.

In the *Figure 14*, we can see a typical measured motor current from an oscilloscope during a normal operation of the powered secateur cutting a branch.

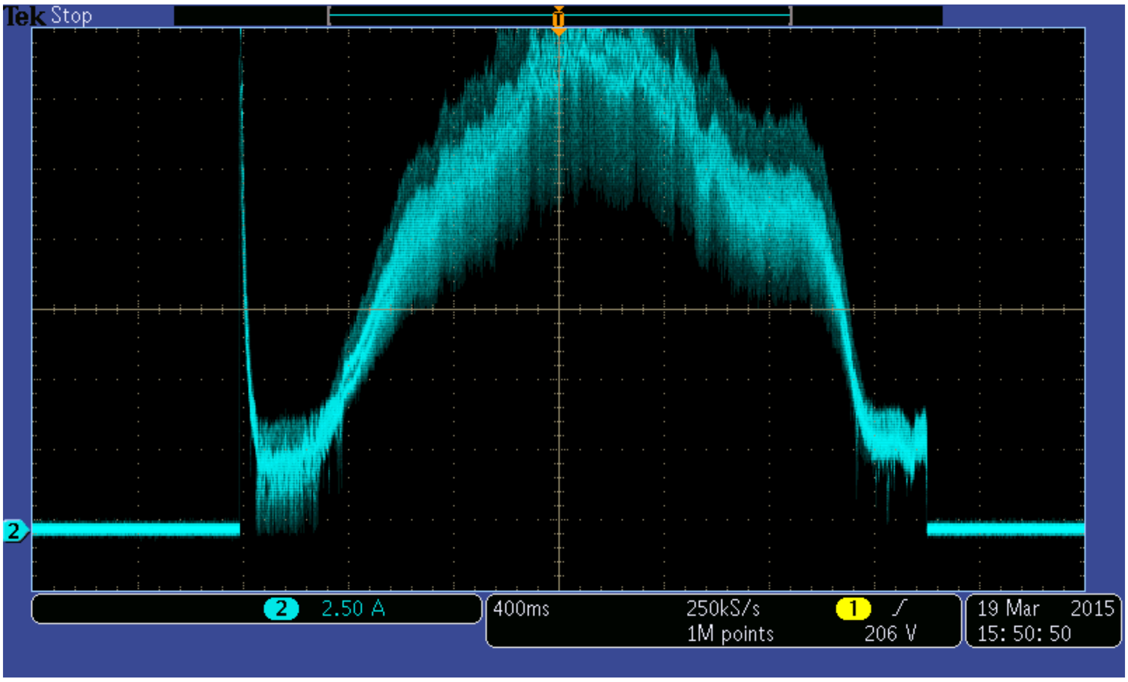


Figure 14: Motor current curve during a normal operation (cutting one branch).

So an easy solution to solve this problem generated by the noise is to count the time since the maximum current value is raised until it returns to have normal values below the maximum. If this time is below 7 milliseconds, the system will continue with the normal operating mode.

In case of a real overcurrent, the system will stop supplying current to the motor. Also, the tool will save the value of an overcurrent counter that will be increased each time the overcurrent is raised. This counter will help during testing to analyze the behavior of the tool.

The current curve versus time of the normal operating mode for cutting a branch can be draw during testing of the tool. The actual motor current is being sent out through the USB socket in real-time. On that way, we can create the graphic representation of motor current versus time easily.

4.3 Battery Temperature ($T_{BATTERY}$).

The operating temperature of the Lithium-ion battery must be controlled, as its performance, health, and safety depends on the temperature. Excessive temperature variations and especially high temperatures can cause a thermal runaway reaction that ignites a fire and consequently cause an explosion of the battery.

Different operating temperatures will also affect the performance of the battery over time and reduce its lifetime and the maximum charge storage of the battery during cycling.

The decided way of controlling the battery temperature is using a Negative Temperature Coefficient (NTC) thermistor as a temperature sensor that is going to be positioned on the surface of the battery. The signal will be transmitted to one of the analog inputs of the microcontroller and subsequently converted from analog to digital by an A/D converter of 10 bits.

The reason why we decided to use a NTC thermistor as temperature sensor is because is a cheap device and its sensibility is enough for the requirements of the testing data that we have to save during the normal use of the powered secateur.

We can see a schematic of the circuit that we use on the *Figure 15*.

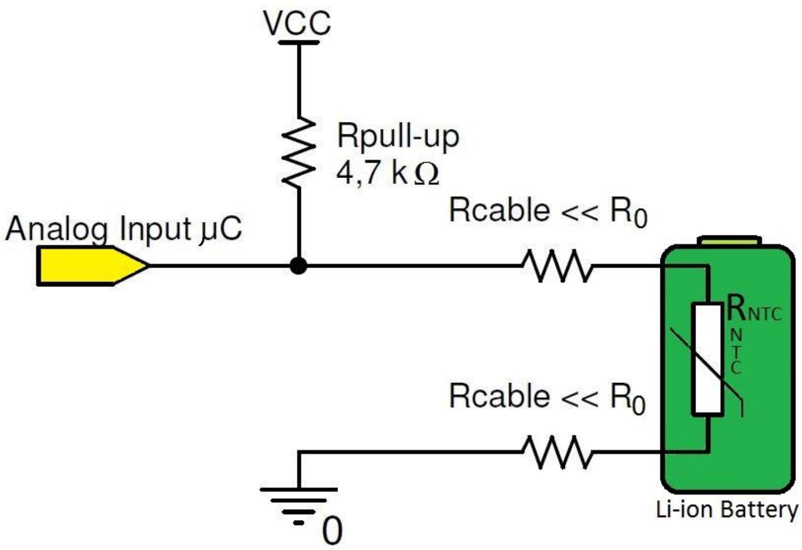


Figure 15: Circuit diagram of measuring system of the battery temperature.

The NTC sensor that was chosen has the following characteristics:

$$T_0 = 25\,°C$$

$$R_0 = 5\ k\Omega$$

$$B = 3984$$

Where T_0 is the reference temperature, R_0 is the resistance of the NTC sensor at temperature T_0 and *B* is the equation parameter between 25 and 100 °C. The equation that relates all the parameters is:

$$R_{NTC} = R_0 * e^{-B*(\frac{1}{T_0}-\frac{1}{T})}$$

As we can see, the relationship between the temperature and the resistance of the sensor is exponential. The equation parameter B will determine the slope of the exponential curve. As we prefer to have bigger resistance difference between close temperature values, we will search for a NTC sensor with an equation parameter B big enough that will produce a more pronounce slope of the exponential curve.

The graphic representation of the resistance of the NTC versus the temperature of the battery is shown at *Figure 16*.

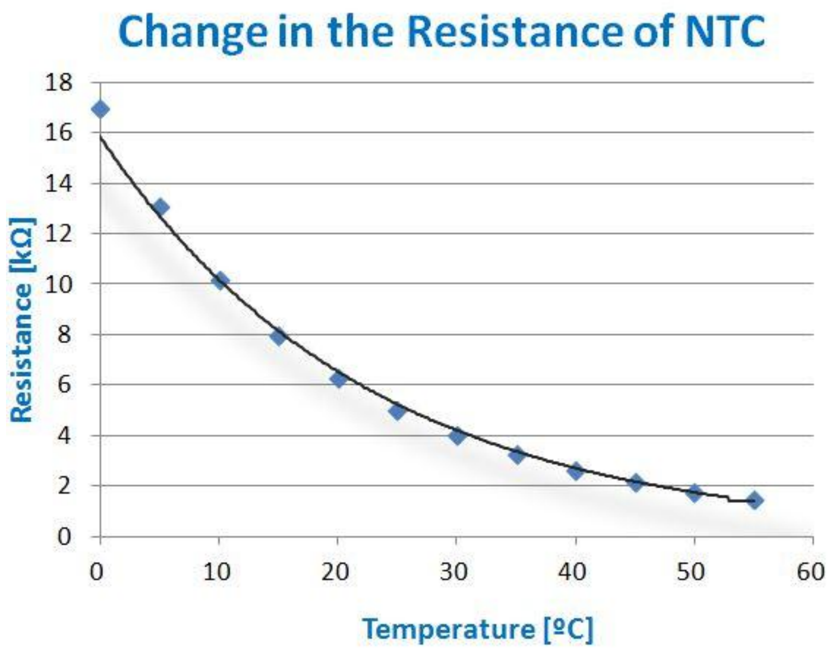


Figure 16: Graphic representation of the change in the NTC resistance with the battery temperature..

The voltage signal that will be plugged on the analog input of the microcontroller will follow so the next equation that we can simulate:

$$V_{Tbattery} = \frac{2 * R_{cable} + R_{NTC}}{2 * R_{cable} + R_{NTC} + R_{pull-up}} * V_{CC}$$

The R_{cable} simulates the equivalent resistance of the wire that we need to use to plug the NTC sensor from the surface of the battery to the analog input of the microcontroller on the PCB board. But, one of the main advantages of using NTC thermistor sensors versus other kind of temperature sensors is that the resistance of the sensor is very high at normal temperature (T_0 = 25 °C). Knowing that, we can skip the effect of the cable resistance because this value is really lower than the resistance of the sensor at normal temperature ($R_{cable} << R_0$). On that way, the new formula to calculate the voltage of the temperature signal is:

$$V_{Tbattery} = \frac{R_{NTC}}{R_{NTC} + R_{pull-up}} * V_{CC}$$

On the *Figure 17* we can see the graphic representation of the final voltage that the microcontroller will analyze versus the temperature of the battery. The resulted curve is the one that we have to save into the microcontroller to understand the temperature that corresponds to each given value of the ADC.

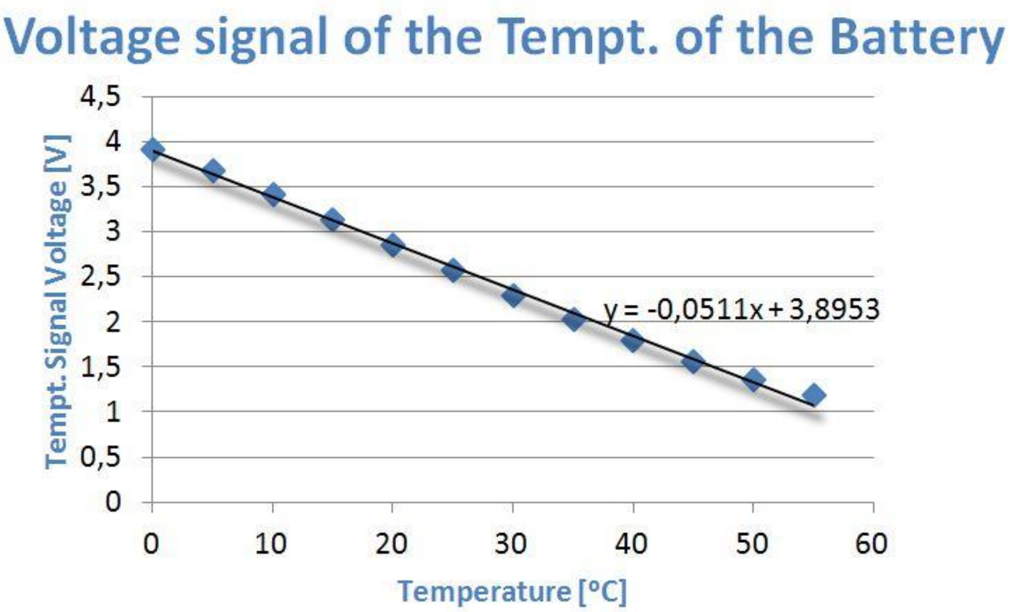


Figure 17: Graphic representation of the voltage signal of the battery temperature variation with regression line included.

The voltage signal becomes more or less lineal. The regression line of the linear behavior of the voltage has been added (y = -0.0511·x + 3.8953). The simulation has been made with power supply equal to 5 V.

Thinking about analyzing the digital given value of the ADC, we can use also this formula that will contain the direct relationship between the digital value and the battery temperature *[14]*:

$$T_{battery} = \frac{1}{\frac{\ln\left(\frac{R_{pull-up}}{R_0 * \left(\frac{1024}{Z_H * 256 + Z_L}\right)}\right)}{B} + \frac{1}{298.15}} - 273.15\ [°C] \quad [14]$$

4.4 Motor Temperature (T_{MOTOR}).

Measuring the temperature at the surface of the housing of the DC motor is required. Motor winding resistance (R_{mt}) is the main cause of heat generation within the motor. The current flows through the motor winding resistance. The motor windings are usually made of copper that, despite being an excellent conductor, it has impurities that will cause the atoms to vibrate at a faster rate as more current flows.

The result is a steady temperature increase in the motor windings. As copper has a positive temperature coefficient, the resistance of the material will increase with the temperature. This can be resumed in an increase in the loss of power:

$$P_{LOSS} = I^2 \cdot R_{mt}$$

If we measure an unusual high temperature at the housing of the DC motor it will mean that the power losses are increasing and that the DC motor will not work as expected.

The motor temperature is going to be measured externally from the PCB of the powered secateur. Just remember that both the motor current and the battery temperature are analyzed and measure within the PCB of the tool. On this case, we are going to interpret the measured signal using an analog input of the Rexroth PLC.

Is really important to consider that this analog input of the PLC could have values between [0 – 10 V] so it will be interesting to use all the range that the analog input offer to us to have a bigger resolution while interpreting the measured signal.

Also, the power supply source for the required energy to measure the motor temperature has to be provided by the PLC voltage supply module through the PWR IN supply terminal with a value of 24 V. Afterwards, this voltage has to be transform in a source of 10 V for supplying energy to the *LM358* operational amplifier and to the *LM35* linear temperature sensor. We will use a simple voltage divider for transforming the voltage of the source because, in our circuit for measuring the temperature of the motor, the voltage divider line is going to be used for high impedance supply inputs of the *LM35* of the operational amplifier *LM358.*

The design decision was to use instead of a NTC sensor with its following signal accommodation circuit (like it happens with the temperature of the battery on the subpart *2.3*) we decide to use an integrated circuit from Texas Instruments called LM35. The reason why to use this integrated circuit instead of a pull-up resistor plus the NTC thermistor is to make the electronic assembly easier because with the motor temperature measuring, the electronic devices used for that propose are outside the tool. They are located in some place between the tool and the Rexroth PLC, but is better to put them the closest possible to the PLC.

On the *Figure 18* there is a schematic representation of the location and the electronic devices needed for transmitting the motor temperature to the analog input of the PLC.

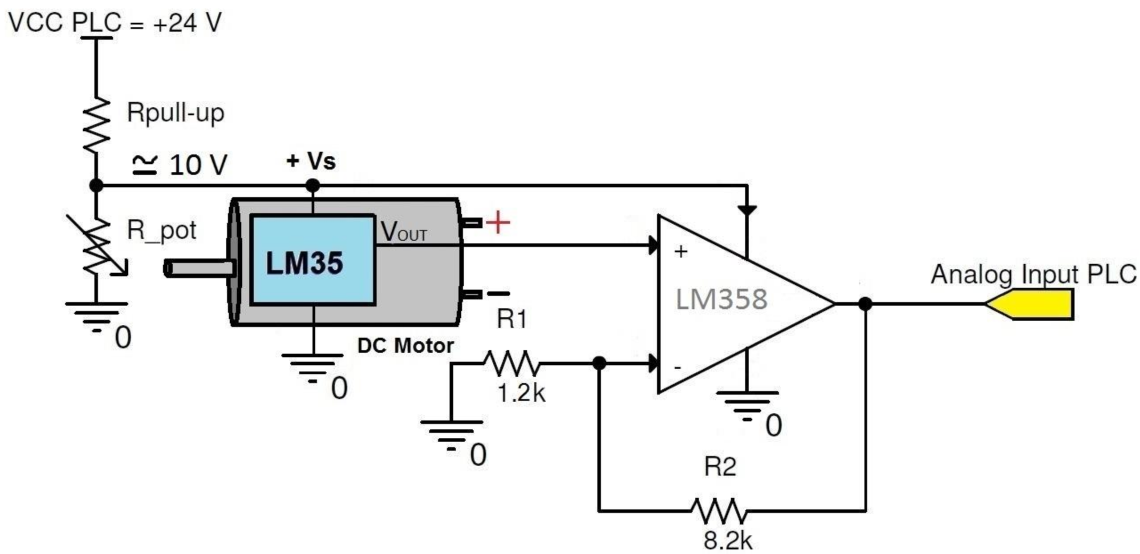


Figure 18: Schematic representation of the electronic circuit needed to plug the motor temperature signal into the PLC.

A brief explanation of the electronic circuit is required to understand the behavior:

The *LM35* National Instruments integrated circuit is a precision integrated-circuit temperature sensor, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. For the normal operation of the integrated circuit it is needed between 4 – 20 V of power supply at the pin $+V_S$. As a basic centigrade temperature sensor configuration, we can measure from +2 °C to +150 °C having a linear output voltage signal with the following expression:

$$V_{OUT} = 0\ mV + 10.0\ mV/°C$$

Analyzing this expression and knowing that the normal range of DC motor housing temperature will be between +2 °C and +125 °C, it can be simply calculate that the maximum and minimum voltage value of the signal V_{OUT} is:

$$V_{\text{OUT}\ LM35}|_{MAX} = 10\ mV * 125\ °C = \ 1{,}25\ V$$

$$V_{\text{OUT}\ LM35}|_{MIN} = 10\ mV * 2\ °C = \ 20\ mV$$

As we already mention, is important to use all the possible range of the analog input of the PLC that goes from 0 V to 10 V to have better accuracy on the motor temperature processing. Understanding this concept, we are going to amplify the signal from the *LM35* integrated circuit till that the maximum value of the sensor is equal (or close) to 10 V. For that purpose, we use a normal operational amplifier single supply type *LM358* in a non-inverting amplifier configuration with gain equal to:

$$\frac{V_{\text{OUT}\ LM358}}{V_{\text{OUT}\ LM35}} = \frac{10\ V}{1{,}25\ V} = \ 8$$

The main equation to control the gain of the non-inverting amplifier configuration is:

$$V_{\text{OUT LM358}} = \left(1 + \frac{R_2}{R_1}\right) * V_+ = \ \left(1 + \frac{R_2}{R_1}\right) * V_{LM35}$$

Following this equation, the value of R_2 and R_1 can be fixed searching for the nearest commercial values that will configure the gain of the circuit on 8. On the *Figure 16* you can see the disposition of the resistance and the value of them corresponds to the following calculation:

$$\left(1 + \frac{R_2}{R_1}\right) = 8\ ;\ \frac{R_2}{R_1} = 7\ \rightarrow \boldsymbol{R_2 = 8.2\ k\Omega}\ \rightarrow\ \boldsymbol{R_1 = 1.2\ k\Omega}$$

The result is that the value of the output of the configuration, $V_{\text{OUT}\ LM358}$, has a value between 10 V and 160 *m*V and now we can take advantage of the voltage range of the analog input of the PLC.

5. Collect the lifetime requirements of the product, trying to find the limit criteria of the product.

The energy that the motor consume from the battery for cutting one branch, as all the branches are going to be of the same size and diameter, is a data that we will calculate using the motor current graphical obtained from a basic test of the tool during a normal operation cutting one branch that we already shown [*Figure 14*]:

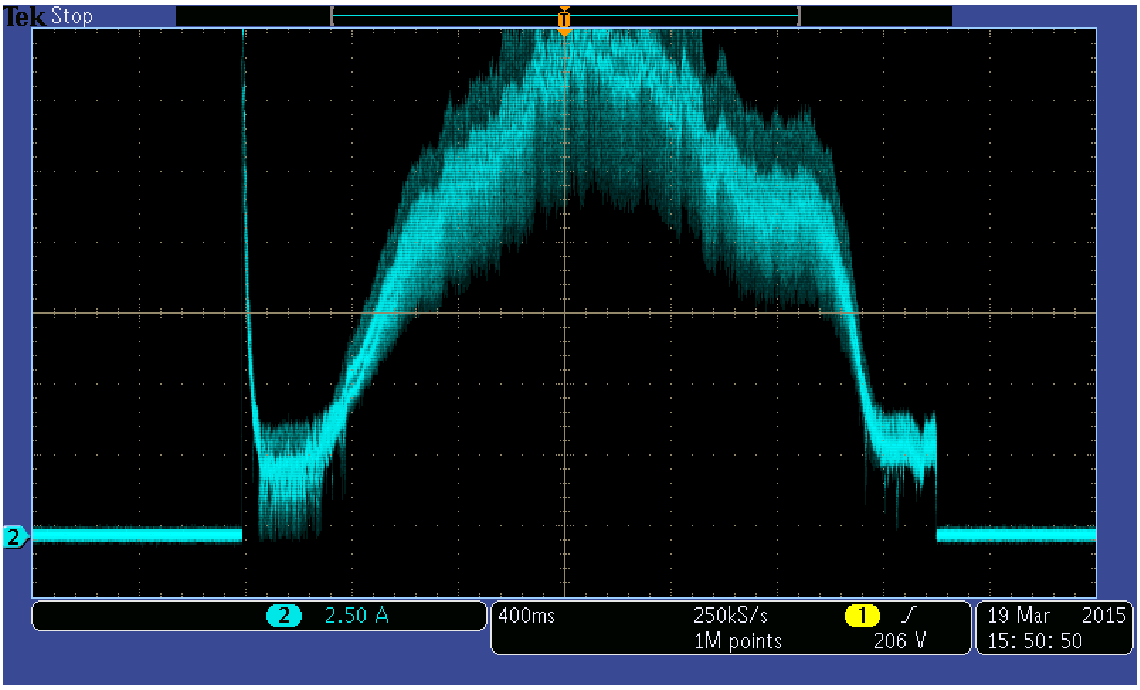


Figure 14: Motor current curve during a normal operation (cutting one branch).

$$Energy_{cutting\ branch} = \int_{T_{INI}}^{T_{END}} [\,V \cdot I(t) \cdot t\,] \cdot dt \cong \int_{T_{INI}}^{T_1} [\,V \cdot (\,I_0 + k_1 \cdot t) \cdot t\,] \cdot dt + \int_{T_1}^{T_{END}} [\,V \cdot (\,I_1 + k_2 \cdot t) \cdot t\,] \cdot dt \quad [1]$$

On the *Equation 1* we can see an approach to the calculation of the energy used cutting a normal branch that is going to be used during the test of the powered secateur. For that approach we used the motor current graphic showed in *Figure 14*. On that figure, we found two main parts of the curve that we can differentiate as it show below in *Figure 15*:

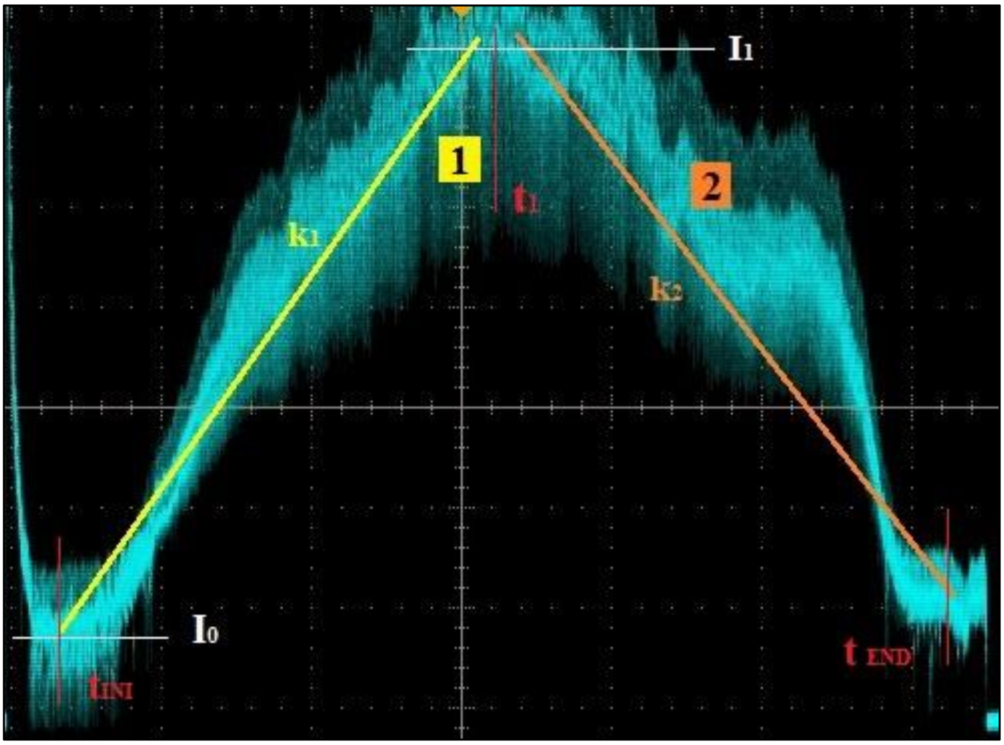


Figure 15: Analysis of the Motor current curve.

This result will allow us to calculate the amount of branches that can be cut in a cell period of the Li-ion battery of the powered secateur considering:

$$k_1 = 12.9\ \mathrm{A/seg}$$

$$k_2 = -13.3\ A/seg$$

$$I_0 = 2\ A$$
$$I_1 = 16.5\ A$$

$$t_{INI} = 0.1\ \mathrm{seg}$$

$$t_1 = 1.28\ seg$$

$$t_{\mathrm{END}} = 2.8\ seg$$

$$Energy_{cutting\ branch} \cong 1.66\ Joules$$

The energy consumed by the electronic PCB circuit is not take into account because is negligible compared to the energy consumed by the DC motor.

So we can take the simplification that the main energy consumed by the tool from the Li-ion battery comes from the DC motor to wind the rope during normal operation of cutting branches and to release the handles once the branch is cut.

First of all, we are going to calculate the total energy that the battery can supply, having as known data:

$$V_{battery|NOMINAL} = 3{,}6\ V$$
$$C_{battery|MIN} = 1{,}5\ Ah$$
$$C_{battery|MAX} = 2\ Ah$$

We should understand the meaning of capacity of the battery. The capacity of a battery is the maximum amount of energy that can be extracted from the battery. We have to take into consideration some things while calculating the real energy of the battery:

- Depth of Discharge (DOD): The total capacity of the battery is not going to be used due to the serious damage to the Li-ion battery if the full energy stored in the battery is used or withdrawn. So the Depth Of Discharge, that should be given by the manufacturer, is the percentage of the total power of the battery that can be withdrawn. In our project, the chosen Li-ion battery has a Depth Of Discharge of 80%.

- Battery level stored: If the battery stored during a long period is a big fraction of the capacity or the complete one, it will lose capacity due to the presence of generally irreversible "side reactions" that consume charge carriers without producing current (internal self-discharge).

- Other important factors: There are some important parameters that will influence in the lifetime of the Li-ion battery that should be mentioned. The temperature of the battery is a critical parameter that can affect seriously to the capacity and lifetime of the battery. As in our project we control the battery temperature in real-time, as we already explained, this parameter is already taken into consideration and we don't have to worry about it for knowing the real lifetime or energy of the Li-ion battery.

  Also if the battery is being discharged very quickly, the current supplied is very high and the amount of energy that can be extracted is reduced, resulting in a decrease in the battery capacity as well. For that reason, the capacity should be given as "C_X", where "x" is the hours that it takes to discharge the battery.

Inside the powered secateur we have an overcurrent protection program that will stop the energy supply if the current demanded by the DC motor is too high, so we don't have to consider the problem during our calculations of the energy inside the battery.

Now that all the important parameters that has to be taken into account, we can proceed to realize the calculation of the real energy stored in the Li-ion battery of the powered secateur:

$$Power = P = \frac{dE}{dt} \approx \frac{\Delta E}{\Delta t} = Energy\ supplied\ (\Delta E) during\ a\ period\ of\ time\ (\Delta t)$$

$$\rightarrow\ P = Voltage \cdot Current = V \cdot I \rightarrow$$
$$\rightarrow Energy\ supplied = \Delta E = P \cdot \Delta t = V \cdot I \cdot \Delta t \ \rightarrow$$
$$\rightarrow [Capacity = C = Current \cdot period\ of\ time = I \cdot \Delta t] \rightarrow$$

$$\boldsymbol{Energy\ supplied = V \cdot I \cdot \Delta t = V \cdot C}$$

$$\rightarrow \boldsymbol{Total\ Energy\ Battery}|_{MAX} = V \cdot C|_{MAX} \cdot DOD(\%) = 3{,}6\,V \cdot 2\,Ah \cdot 80\%$$
$$= 5{,}76\,V \cdot Ah = \boldsymbol{5{,}76\,W \cdot h} = 5{,}76\,\frac{Joule}{s} \cdot h = \boldsymbol{20736\,J} \quad [2]$$

$$\rightarrow \boldsymbol{Total\ Energy\ Battery}|_{MIN} = V \cdot C|_{MIN} \cdot DOD(\%) = 3{,}6\,V \cdot 1{,}5\,Ah \cdot 80\%$$
$$= 4{,}32\,V \cdot Ah = \boldsymbol{4{,}32\,W \cdot h} = 4{,}32\,\frac{Joule}{s} \cdot h = \boldsymbol{15552\,J} \quad [3]$$

To accept these results, we should presuppose that the battery is always near the nominal temperature and that the voltage of the battery is almost constant (in reality it is not, so we are making an approach). As we can see in *Equation 2* and *Equation 3*, there are two values of the total energy for each value of the possible chosen capacity for the battery. These results are approaches that can be accepted in our project due to its simplicity and also because a high accuracy in the result is not required to estimate the number of branches that we are able to cut in a cell period. The real value of the energy that the battery cells are able to supply is the one represented in *Equation 4*:

$$\boldsymbol{Real\ Total\ Energy\ Supplied}\ |_{\boldsymbol{average}} = \frac{\boldsymbol{1}}{\boldsymbol{T}} \cdot \int_{\boldsymbol{0}}^{\boldsymbol{T}} [\,\boldsymbol{V(t) \cdot I(t) \cdot DOD}(\%)\,] \cdot \boldsymbol{dt} \quad [4]$$
$$T = time\ period\ analyzed.$$
$$V(t) = Real\ time\ value\ of\ battery\ cell\ voltage.$$
$$I(t) = Real\ time\ value\ of\ battery\ current\ supplied.$$

To know the amount of branches that the battery cells of the powered secateur is able to cut in a normal user operation (*Equation 4*), we will use the approach energy values that we estimated and the average energy consumed by the tool for cutting one branch:

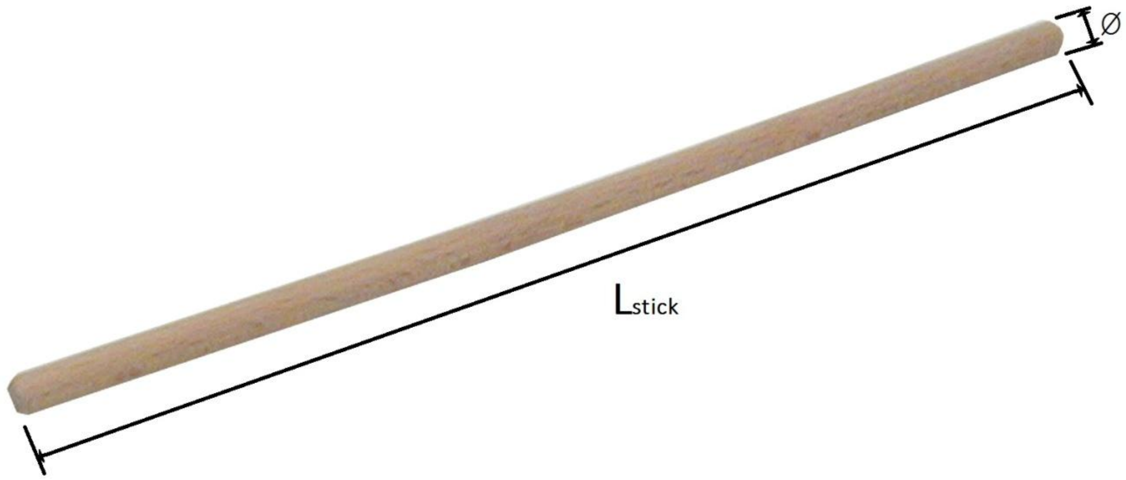
$$\rightarrow \boldsymbol{N^{o}\ branches\ cutted\ per\ battery\ cycle|_{MIN}} = \frac{Total\ Energy\ Battery_{|MIN}}{Energy_{cutting\ branch}} = \boldsymbol{12523\ branches}. [5]$$

$$\rightarrow \boldsymbol{N^{o}\ branches\ cutted\ per\ battery\ cycle|_{MAX}} = \frac{Total\ Energy\ Battery_{|MAX}}{Energy_{cutting\ branch}} = \boldsymbol{9369\ branches}. [6]$$

6. Design proposal for the automation of wood feeding

After several ideas and design proposals for the deposit of the branches for testing the powered secateur, we just choose one final design..

As we mentioned before, there is an important concept to understand and it is that all branches used for testing the tool are going to have the same length and same diameter. Also the surface of the branch is going to be smooth, prepared to slice without problems inside the deposit. The decided parameters for the branches are:



$$\boldsymbol{L_{stick}} = Lenght\ stick = \ \mathbf{1\ meter}$$
$$\boldsymbol{\emptyset_{stick}} = Diameter\ stick = \mathbf{15\ mm}$$

Fixing the length and the diameter of the branches that we are going to use allow us to calculate also the dimensions of the deposit and the system within the deposit.

As there is a high probability for the branch to get stacked during the selection path inside the wood feeding system, two electric vibrators/shakers controlled by the PLC program are included fixed in both walls of the branches feeding deposit that will solve a possible problem during the advance of the branch through the inside of the deposit till it reach the bottom of it.

Inside the deposit, there will be 4 gutters/ramps through where the branches will fall down from the top to the bottom of the deposit. As we want to store around 100 wood sticks for testing the power tool, some calculation should be done:

$$L_{feeding\ ramps|TOTAL} = 100\ sticks \cdot \frac{15\ mm}{1\ stick} = 1500\ mm = 1{,}50\ mm \quad [7]$$

$$L_{feeding\ ramps|1\ ramp} = \frac{1{,}50\ m}{4\ ramps} = 37{,}5\ cm\ (each\ ramp) \quad [8]$$

After making the calculations showed at equations *[7]* and *[8]*, a criterion for deciding the inclination degree of the ramps is going to be explained.

If the 4 ramps containing the branches have a high inclination, the friction between the surface of the ramps and the wood sticks surface will not be enough to avoid them from sliding the mentioned surface. Also, if this inclination is very moderate, the weight of the wood sticks will not be enough to compensate the friction force and the branches will get stack on the channels.

Taking all this considerations into account, there were decide to build the four channels/ramps with an approximated angel of *[9]*:

$$\boldsymbol{\alpha_{ramps} \cong 15}\ ^{o} \qquad [9]$$

On this point of the design decisions, we are ready to decide the total dimensions of the wood sticks deposit. The height (*H*), length (*L*) and width (*W*) of the deposit are calculated below *[10] [11] [12]:*

- $$\boldsymbol{Deposit\ Height = H} = 4 \cdot L_{feeding\ ramps|1\ ramp} \cdot \sin(\boldsymbol{\alpha_{ramps}}) + tolerances_H \cong 4 \cdot 37{,}5\ cm \cdot \sin(15^o) + 4\ cm \approx \boldsymbol{42{,}823\ cm} \qquad [10]$$

- $$\boldsymbol{Deposit\ Lenght = L} = L_{feeding\ ramps|1\ ramp} \cdot \cos(\boldsymbol{\alpha_{ramps}}) + tolerances_L \cong 37{,}5\ cm \cdot \cos(15^o) + 4\ cm \approx \boldsymbol{40{,}2\ cm} \qquad [11]$$

- $$\boldsymbol{Deposit\ Width = W} = L_{stick} + tolerances_W \cong 100\ cm + 4\ cm \approx \boldsymbol{104\ cm} \qquad [12]$$

7. Collect the necessary measuring inputs for the automation and the required measurements from the tool.

Now, we are going to enumerate the required inputs and outputs that will correspond to the sensors and actuators that are required to incorporate to the workspace to be able to control the PLC program of the automation process:

7.1 INPUTS (Sensors).

- **Green Button**: This button will tell the program that the operator has charged the deposit with stick branches. Also, when recovering from an emergency, the use of the green button will mean that the operator has indentified the problem and he already solved.

PLC program name: **Green_Button**

- **Emergency Button**: If the operator realized of a hazard during the normal operation of the test, he/she will pulse this red emergency button.

PLC program name: **Emergency_Button**

- **Step-by-step Yellow Button**: When an emergency occurs, there are several solutions to recover from it. One of these ones is make a *Step-by-step* process that will do the basic program of the test asking for pressing the yellow button each time we want to make progress in the automation program.

PLC program name: **Yellow_Button**

- **Mouth Deposit Branch Detector**: A presence sensor located just at the bottom of the deposit, where a branch is suppose to be elevate and selected to subsequently be cut by the powered secateur.

PLC program name: **DepBranch_Detect**

- **Stepper Movement Arm Detector**: A presence sensor located in the stepper arm that is going to move the branch during the different cuts of the powered secateur per each branch stick will allow us to detect when to start cutting but also when to finish cutting the same branch in smaller pieces.

PLC program name: **ArmBranch_Detect**

- **Griper Detector**: A presence sensor located in the griper that is going to fix the branch during it is being cut, is required to know if the branch that has been moved by the stepper arm has already achieve the griper and later the powered secateur.

PLC program name: **Griper_Detect**

- **Branch at the powered secateur blades detector**: When the branch is already in the blades of the powered secateur, it means that we are ready to cut the branch.

PLC program name: **Secateur_Detect**

- **Power Tool totally close detector**: When we finished cutting a branch, the normal thing is to have the blades together and also the handlers of the powered secateur together.

PLC program name: **SecateurHandlers_Close**

- **Power Tool totally open detector**: When we already have cut the branch, the normal thing will be to have the blades totally open as well as the handlers of the powered secateur.

With this sensor we can guarantee, using as support the *Secateur_Detect* sensor just described previously, that the branch is totally cut. If the signal of the Power Tool totally open detector gives a HIGH signal but the *Secateur_Detect* gives also HIGH signal, this will mean that the branch is not totally cut and we should repeat the cutting process at least one more time.

PLC program name: **SecateurHandlers_Open**

- **Temperature Motor Sensor *[ANALOG]***: As we mentioned at the section 3 of the project, we incorporated a temperature sensor to the housing of the DC Motor. This will add protection to the DC Motor, being complemented with the overcurrent protection of the device.

PLC program name: **Tempt_DC_Motor**

7.2 OUTPUTS (Actuators).

- **Vibrator incorporated in the branches deposit (left)**: A simple vibrator is going to help in case of branches obstruction inside the deposit. If this happen, we will activate the vibrator and it will make the branches move and reorganize, solving the problem commented. This one is going to be located on the left face of the deposit.

PLC program name: **Vibrator_Left**

- **Vibrator incorporated in the branches deposit (right)**: A simple vibrator is going to help in case of branches obstruction inside the deposit. If this happen, we will activate the vibrator and it will make the branches move and reorganize, solving the problem commented. This one is going to be located on the right face of the deposit.

PLC program name: **Vibrator_Right**

- **Branches Elevator**: As we need to select only one branch from the total group of branches that are located inside the deposit each time we want to test the powered secateur, we need an elevator of branches that will select one branch and allow it to go upstairs to the stepper arm that will move the sticks.

PLC program name: **Elevator_Branches**

- **Stepper Robotic Arm (move forward)**: the function of this actuator is going to be to move one step the branch, once it was selected from the rest by the branches elevator, each time we cut a part of the total branch. As we can easily measure, each branch could be cut 4 times. So the stepper robotic arm will move the branch 4 steps before it will be over.

PLC program name: **Stepper_Arm_Forward**

- **Branch gripper**: To fix the branch while is being cut by the powered secateur in order for the branch to not flip from its initial position, we will use a griper with cylindrical form, as the branch, that will be strong enough to resist the reaction forced generated while cutting the branch (not too much force is required for the gripper). Only one signal will be enough to control it, because is going to be pneumatic technology that will recover the initial position if the actuator signal changes from HIGH to LOW.

PLC program name: **Gripper**

7.3 COUNTERS SIGNALS.

- **Cut branches counter**: The working space requires a counter to be able to know the amount of cuts that we have done during the testing program. Consequently, lifetime requirements could be estimated by knowing the maximum number of branches cut, not only in a battery cycle, but also during the whole useful life of the tool.

The operator is going to have a simple screen that will show this number of branches in real time. Consequently, there is going to be an additional output signal that will manage the counter display.

PLC program name: **Cont**

- **Not cut branch detector counter**: It exists a lot of possibilities of a bad behavior of the testing process while cutting a branch. With this counter, we want to amend the situation when we activate the actuator of the powered secateur to cut a branch but the branch is not totally cut.

This may be caused by a thick branch, some problem with the actuator that simulates the human use of the handlers of the device or even by a problem with the blades of the power tool (they are not sharp any more for example).

So each time that we order cutting a branch but we realize that the "branch at the powered secateur blades" detector (**Secateur_Detect**) value is high once that we have detected that the power tool is totally open (**SecateurHandlers_Open**), the program will increase this counter.

PLC program name: **ContDetect**

7.4 BOOLEAN SIGNALS.

The PLC program that will control the workspace is going to include an emergency handler to take into account when the test routine is not going as it should. It is really interesting, not only to have an emergency handler, but also to know which reason has caused the problem or in which part of the workspace the operator should examine to solve the bad behavior of the test routine.

A brief explanation of what each Boolean signal means is required to understand later in which part of the program the emergency handler was activated:

- **BranchStack_Deposit**: After trying to solve the problem of having a branch stacked in the branches deposit activating the shakers incorporated in the walls of the deposit, we should activate this Boolean signal before we start the ***Branch_Handler*** routine.

- **BranchStack_Elevator**: The next step that the branches at the mouth of the branch deposit are going to follow is being selected one by one by the branches elevator. Also, an emergency could appear on this part of the working space.

If this problem happens, the Boolean variable described will be set as TRUE before the program jump into the ***Emergency_Handler***.

- **BranchStack_Arm**: The branch is going to be moved through the grippers by a step-by-step robotic arm selector. As some problems could stack the arm in the arm movement trajectory, the program would locate the problem correctly thanks to this signal.

- **BranchThickness_Alarm**: As it was previously described at *7.3* section, before we consider that the branch after doing the process is not totally cut, the PLC program tries to insist doing the cutting routine till it reach three times of loop.

If after these three attempts, we still detect that the branch is not completely cut, the program is sent to the ***Emergency_Handler***. In a similar way of the cases described on this section of the project, the program will know that there is a problem with the thickness of the branch with this Boolean signal.

8. PLC Program taking into consideration the inappropriate functionality of the workspace

One of the main points of the project was to solve the programming of endurance testing equipment. In this section, a detailed Petri net with all the places and transitions that the workspace needs to make the endurance testing routine for testing the powered secateur is going to be shown.

This representation was chosen for being the best model to understand the program and also for the facility of being translated into the PLC program directly using SFC language inside the Bosch PLC program called *Rexroth IndraWorks*. Getting familiar with the *IndraWorks* program was quite fast taking into account the similarity with other PLC programming programs of other companies like *Unity Pro XL* of the company *Schneider Electric*. This last program was mentioned because was, without question, the PLC program which I used more during all my Electronics and Automation Degree.

As in the Petri net there are several kinds of variables with very different meanings, a short list of contents grouped by color used in the Petri net is listed then:

- Timers: **RED**.

- Inputs/Transitions (section *7.1*): **GREEN**.

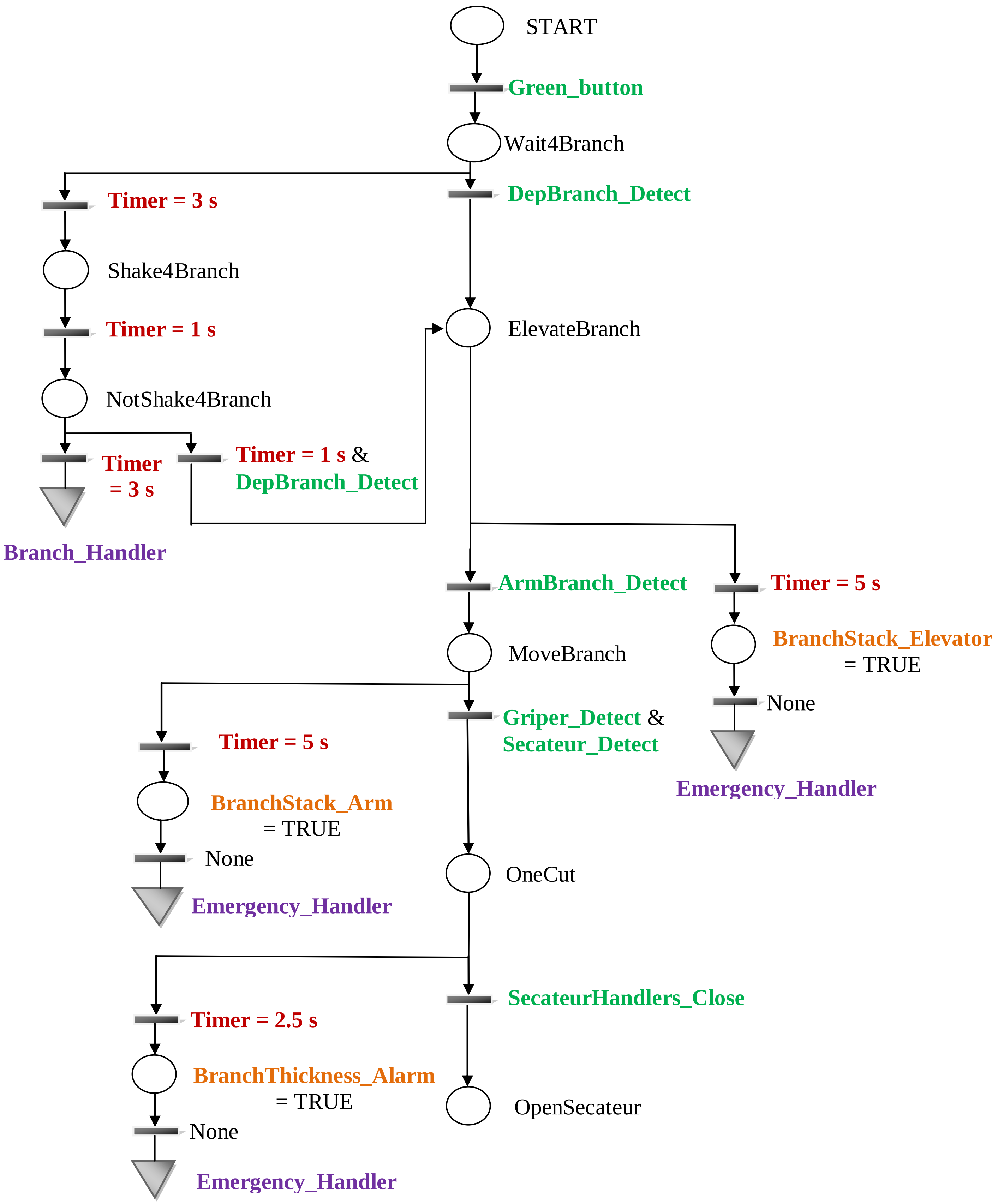
- Places: **BLACK**.

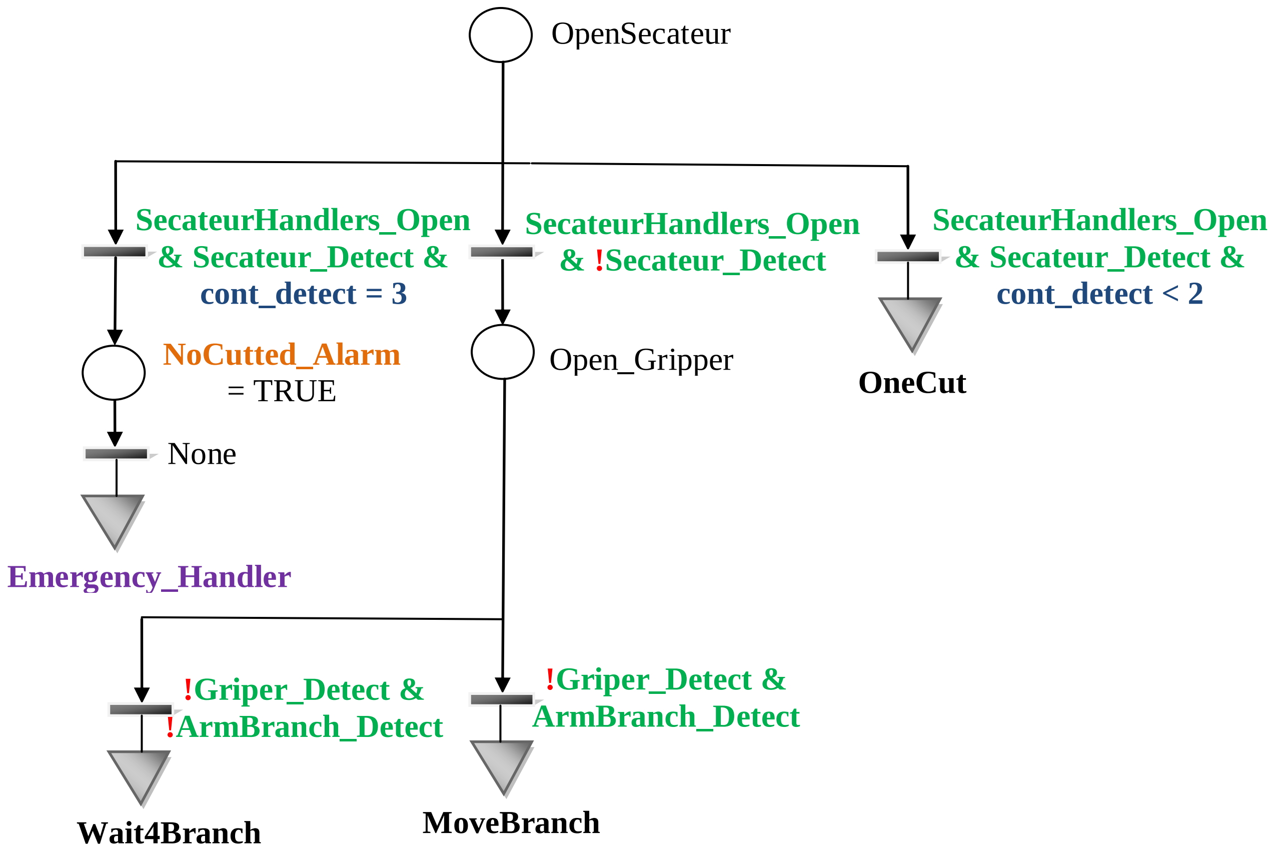
- Boolean signals (section *7.3*): **ORANGE**.

- Jumps of the program to Handlers (Emergency/Branch): **PURPLE**.

- Counters (section *7.2*): **BLUE**.

On the next full two pages of the project, the Petri net is presented:


START
Green_button
Wait4Branch
Timer = 3 s
DepBranch_Detect
Shake4Branch
Timer = 1 s
ElevateBranch
NotShake4Branch
Timer
= 3 s
Timer = 1 s &
DepBranch_Detect
Branch_Handler
ArmBranch_Detect
Timer = 5 s
MoveBranch
BranchStack_Elevator
= TRUE
None
Griper_Detect &
Secateur_Detect
Timer = 5 s
Emergency_Handler
BranchStack_Arm
= TRUE
None
Emergency_Handler
OneCut
SecateurHandlers_Close
Timer = 2.5 s
BranchThickness_Alarm
= TRUE
OpenSecateur
None
Emergency_Handler


OpenSecateur
SecateurHandlers_Open & Secateur_Detect & cont_detect = 3
SecateurHandlers_Open & !Secateur_Detect
SecateurHandlers_Open & Secateur_Detect & cont_detect < 2
NoCutted_Alarm = TRUE
Open_Gripper
OneCut
None
Emergency_Handler
!Griper_Detect & !ArmBranch_Detect
!Griper_Detect & ArmBranch_Detect
Wait4Branch
MoveBranch

9. Summary & Future lines

The main necessities of the project have been achieved. For building an automated workspace you should always include inappropriate functionalities handlers to be able to amend the errors that a real workspace will have and advise the operator for him/her to be able to recognize the problem fast and to solve it.

Thanks to this PLC programming mentality, the workspace will not be damage. We have to take into account that is expensive and delicate system that, if it is damage, will stop the entire test for not little time, resulting in a stop in the test process that will resume in economic losses for the company.

The described system responsible for collecting the important parameters of the devices inside the powered secateur will allow us to not damage the tool. So neither the tool will be damage during the endurance test thanks to the build security system.

Branches are a difficult environment that could be easily stacked in the automated workspace or deposit. For that reason, with this project we achieved to have a robust and secure workspace where to perform the endurance test of the powered secateur.

There are several possible future lines. One of them is the improvement of the communication with the operator. A more complex Supervisory Control And Data Acquisition (*SCADA*) could be build in order to improve the security of the operator. For that purpose, we can incorporate some screens that will display information about where the process is and all the important parameters of the tool.

Also, more parameters of the different parts of the powered secateur could be measured and controlled. On that way, we will be able to improve more the tool to be more competitive on the market.

For example, due to the simplicity of the workspace, the user force is not measured and is always the same one during the automated test (the lower handle actuator always exerts the same force). If we want to build a more real automated testing workspace, we should improve these functionalities.

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