École nationale supérieure d'ingénieurs de Limoges

Systeme d'entrainement

Design of a Dual-Axis Solar Tracking System

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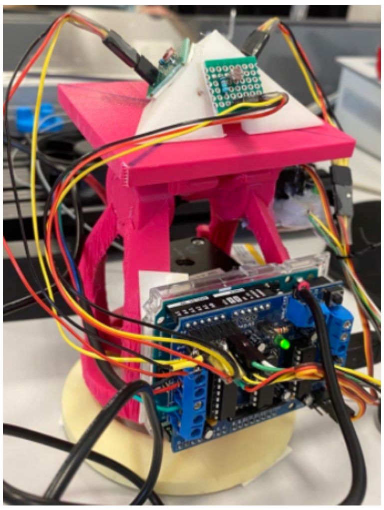

25 janvier 2022

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1 Introduction

Solar energy is rapidly gaining notoriety as an important means of expanding renewable energy resources. As such, it is vital that those in engineering fields understand the technologies associated with this area.

This project includes the design and construction of a microcontroller-based solar panel tracking system using a bipolar stepper motor and a servo motor as actuators. Solar tracking allows more energy to be produced because the solar array is able to remain aligned to the sun.

To make solar energy more viable, the efficiency of solar array systems must be maximized. A feasible approach for maximizing the efficiency of solar array systems is sun tracking. This is a system that controls the movement of a solar array so that it is constantly aligned towards the direction of the sun.

Actually this project came from the course "Additive manufacturing" and it drift from it. In order to present you our work, we will begin with an introduction and the context of this project with the specification. Then we will explain the overall architecture of the system. We will go more in details into the mechanical structure and how it was designed. After that we are going to show you the electronics part of this project and the motorization part. A brief explanation of the algorithm used will be explained. On the top of that we will discuss about one of our work that didn't fitted with this project. Finally, we will conclude on what we did to this system.

1.1 Objectives

If a solar cell is configured so that it faces the sun continually as it moves across the sky from east to west, the most electrical energy possible can be obtained. One way to do this, of course, is by hand. However, keeping a solar cell facing the sun throughout the day is not a very efficient use of a person's time. Going outside to a solar cell every hour, to turn it toward the sun might be possible, but this would still not be an efficient method. A photo sensor is employed to control the solar cell tracking system. For example, if the photo sensor is not aligned with sun rays, then it could turn on the motor until it is once again aligned. If the motor is attached to the frame holding the solar cell, then the solar cell could be moved to face the sun. As long as the photo sensor is in alignment with the sun, nothing happens.

However, when the sun moves across the sky and is not in proper alignment with the photo sensor, then a motor moves the frame until the photo sensor is in the sun once more. This could have the effect of keeping the solar cell facing the sun as it moves across the required human attention. The solar tracker system includes a frame on which a solar cell could be mounted. The frame is to move so that it faces the sun as it travels across the sky during the day. The frame could be driven by an electric motor that turns on and off in response to the movement of the sky.

The Figure 1 shows the implementation of a solar tracker in order to allow the plane parallel to the solar panel to be perpendicular to the rays coming from the sun and therefore maximize their efficiency as much as possible.

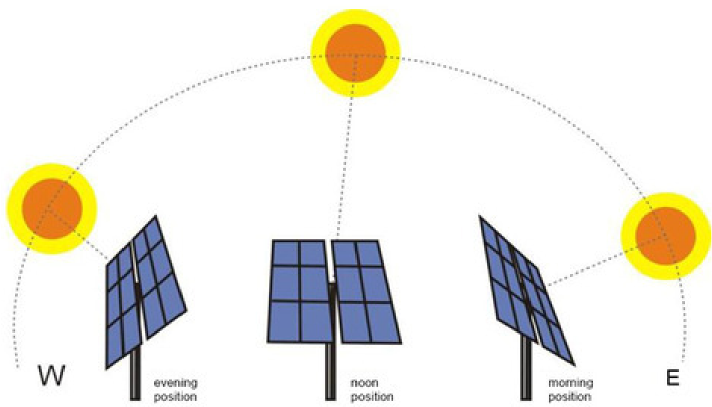


FIGURE 1 – Solar Tracker

1.2 Specifications

Our project is based on the final delivery of another project in the courses "Additive Manufacturing". That project consisted in the conception and fabrication of an heliostat, by a team composed of Ceramic Student, Material Students and use, Mechatronics Students. The rendering was a system (non-actuated) which use plastic additive manufacturing technique for the main parts and ceramics AM for the mirror part. The main specification was :

- Rotational movement around vertical axes at least 270 degs
- Rotational movement around horizontal axes at least 90 degs
- Do not failover
- Restricted volumic area of 120mm diameter and 150mm height.
- Restricted width of the mirror, betweem 5mm and 15mm

On the top of that, we added inside this volumic restricted area, the place for 2 motors.

1.3 Coordinate System

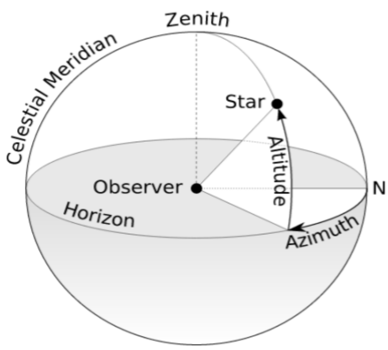
Coordinate system is used for local user to trace the sun path and considered as the fundamental plane. It is expressed in terms of altitude or elevation angle and azimuth angle. This coordinate system divides the sky into the upper hemisphere where objects are visible, and the lower hemisphere where objects cannot be seen since the Earth obstructs vision.

There are **two independent angular coordinates** :

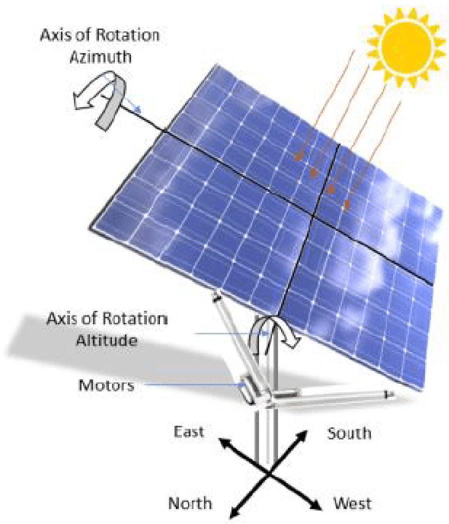
- Altitude(Alt), sometimes referred to as elevation, is the angle between the object to 90 degrees. Alternatively, zenith distance, the distance from directly overhead (the zenith) may be used instead of altitude. The zenith distance is the complement of altitude (90°-altitude).

— Azimuth(Az), that is the angle of the object around the horizon, usually measured from the north increasing towards the east.

This reference system and in particular these angles will be the angles that will control our motors :



(a) Coordinate System



(b) Dual axis active solar tracker

FIGURE 2 – Complete system

1.4 Active Tracking

The type of solar tracker that we are going to implement is the active tracker which measures the light intensity from the sun to determine where the solar modules should be pointing. Light sensors are positioned on the tracker.If the sun is not facing the tracker directly there will be a difference in light intensity on one light sensor compared to another and this difference can be used to determine in which direction the tracker has to tilt in order to be facing the sun.

In particular, we are going to implement a dual-axis active solar tracker which has two degrees of freedom that act as axes of rotation in order to make the system able to track the sun both East to West and North to South direction simultaneously. Two-axis or dual-axis sun trackers, such as the azimuth-elevation and the tilt-roll sun tracking systems, follow the sun in the horizontal and the azimuth elevation sun-tracking system, the solar collector must be free to rotate about the azimuth and the elevation axes. In these systems, the tracking angle about the azimuth axis is the solar azimuth angle and the tracking angle about the elevation axis is the solar elevation angle. Such dual-axis tracker systems track the sun on two axes, such that the sun vector is normal to the apertures to attain near 100 percent of energy collection efficiency.

2 Overall architecture of the system

The architecture of the system relies on the rendering project in Additive Manufacturing courses, and with all the specifications that this project gave us. The shape of the system and the size was strongly restrictive, that was the major constraint of this system. In order to make this system totally operated, we need to define this system in several parts.

2.1 Microcontroller

Our system is based on automatic tracking mechanism instead of an adaptive mechanism or predefined motion. The sensors are the main feedbacks of the system which sends signals to the control system. The backbone of our control system is an Arduino UNO which determines which motor should move in which direction to adjust the system in such a way that the sun light falls orthogonally on the panel.

The Arduino is responsible for all the logical calculations that are required for the system to perform as expected. A 9 Volts battery is used to power the Arduino and the servo, which takes analog input from LDRs and provides power to the motors. Depending upon the position of the sun, the Arduino analyses the signals received from the LDRs. Depending on which of the two LDRs has more light incident on it, its resistance and hence the magnitude of current flowing into the Arduino will vary.

This variation is then translated into the input signals for the motors. The motors, which are connected to the shaft that has the panel mounted on it, are responsible for dual axis movement of the panel.

2.2 Schematics of the system

A complete schema of our system in the following figure is shown :

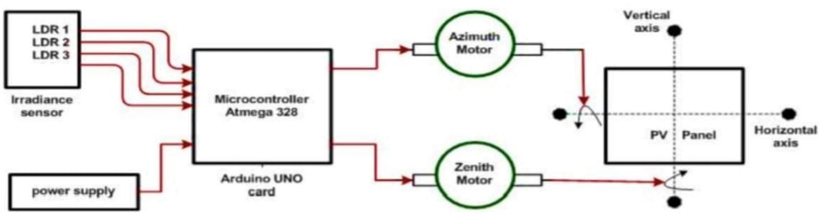


FIGURE 3 – Overall schema of the complete System

From the above illustration we can see that the whole system can be divided into 3 big parts :

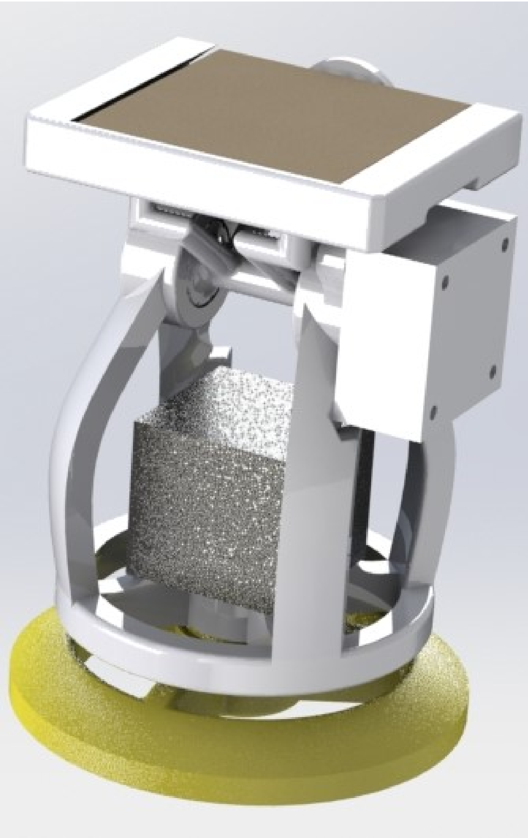
1. **Mechanical structure**
2. **Electronics**
3. **Control Algorithm**

3 Mechanical Structure

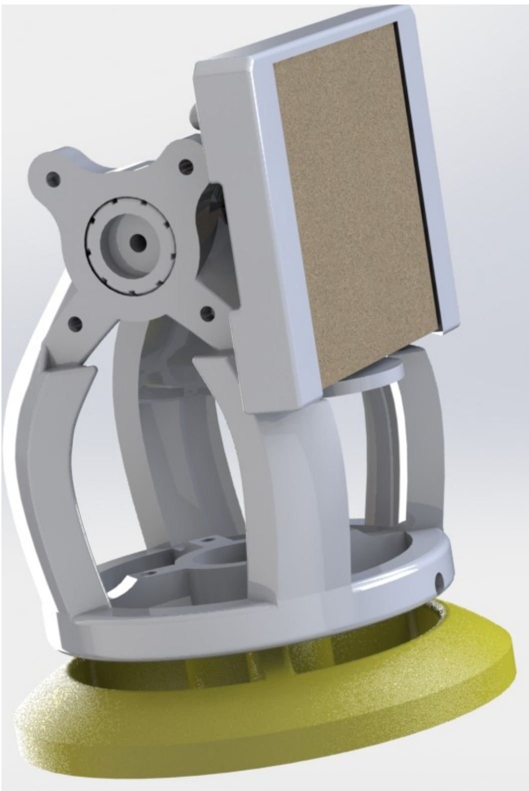
This part took a big part of our time, due to the specification and also to the assembly, that was a long travel to get through. In order to explain clearly what we have done, we will explain firstly the design and CAD of the system, then the printing part and finally the assembly part.

3.1 Design

The heliostat was designing accordingly to the additive manufacturing technology. Indeed, the whole system is printed in only 2 part. And that technological structure can be produced only by the additive manufacturing process. Let's take a look at the complete system on the Figure 4a and the system without motorization Figure 4b



(a) Comprehensive system



(b) Comprehensive system without motorization

FIGURE 4 – Complete system

For our purpose, our system needs two kinematics links. In other words, the system must have 2 degrees of freedom, which are the rotational movement on the Z axis and the rotational movement on the Y axis from the upper part. We call it respectively, azimuth angle and altitude/elevation angle. You can see the limit of the system in the Appendix Figure 27.

3.1.1 Azimuth's pivot

In order to respect the degree of freedom, we did a pivot connection between the lower part (here in yellow) and the upper part (in grey). To have a good placement of the upper part to the lower part, by pivot positioning, we created a long centering as you can see on the Figure 5 and on the Figure 6.

This pivot is holding in position thanks to the motors which is fixed on the upper part from the below with screw. And a coupler is inserted inside the base by warming it. The screws of the coupler need to be adjusted with the holes inside the base, like that we can just replace the motor by unscrewing it from the base/coupler.

An adhesive material like double face duck tape is needed to force the base to stay in position when the motors is turning the upper part.

FIGURE 5 – Base only

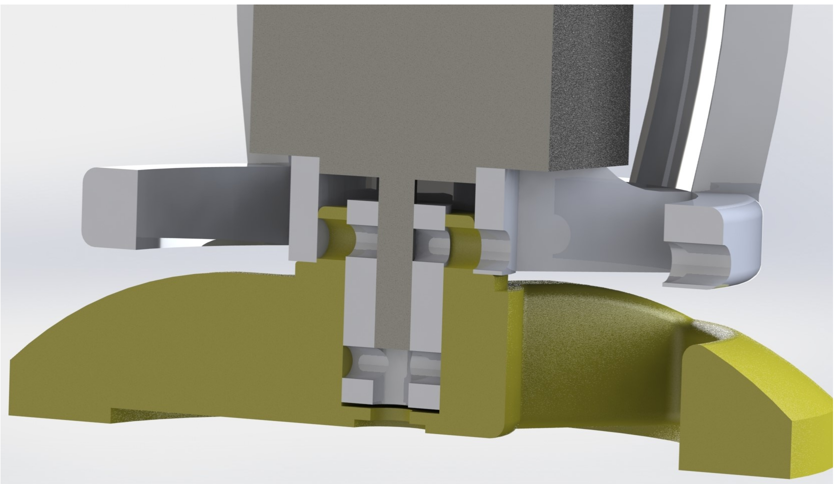


FIGURE 6 – Azimuth linked pivot - Sectional view

3.1.2 Altitude's pivot

This is one of our biggest innovation of our system. Because we used the asset of 3d printing to create our product. As you can see on the Figure 7, we designed the rotational links in one system completely dependant. No need to assembly it. The things is, to create pivot links from several joints, we need a ball joint and a sliding pivot. We could have tried, however, we knew that the 3d printing process engendered a lot of stress inside the materials, that's why we chose to create a double ball joint to have one pivot, because with the stress resulting, the links will be in a good fit.

FIGURE 7 – Upper part, one piece

The sectional view of the pivot joint is on the Figure 8, and the ceramics holding part in the Figure 9. We can also say that the material in contact inside the ball joint is minimized. Every part who has non-necessary material are also optimized. We can see in the Figure 7, that the system has several holes in order to let the steppers motors (or others) drive the joints.

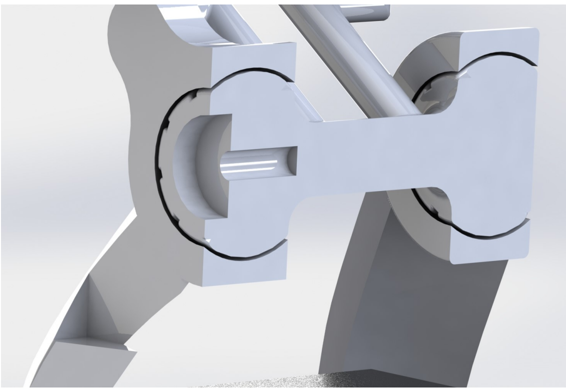


FIGURE 8 – Altitude linked pivot - Sectional view

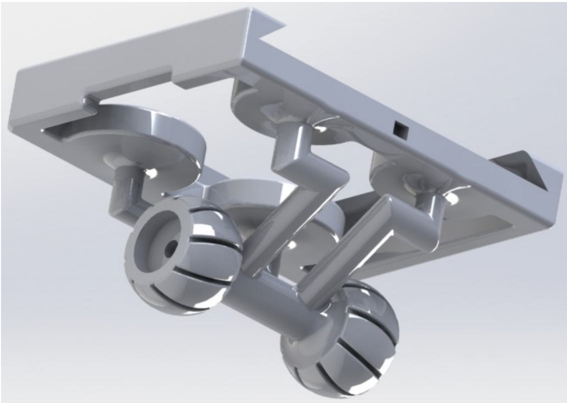
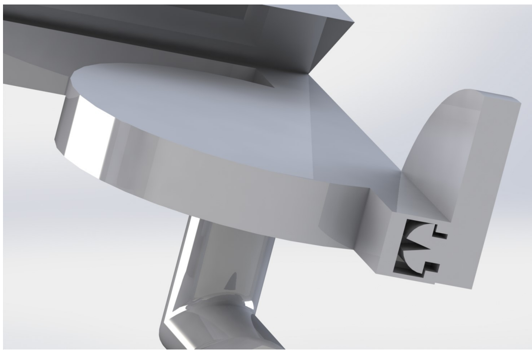


FIGURE 9 – Support for Ceramics part with ball joint

3.1.3 Clips and Ceramic part

In order to not let the ceramics part fall when the plan will be orthogonal to the horizon, we have created a clips, which, when is inserted, need to be break if we want to take it over. It's works with the material deformation. You can see it in the Figure 10a.

Just to let you know how the shape of the mirror is, you can see it on the Figure 10b. The shape is a dovetail shape (queue d'arronde), in order to fit inside the upper saw above.



(a) Clips

(b) Ceramic part

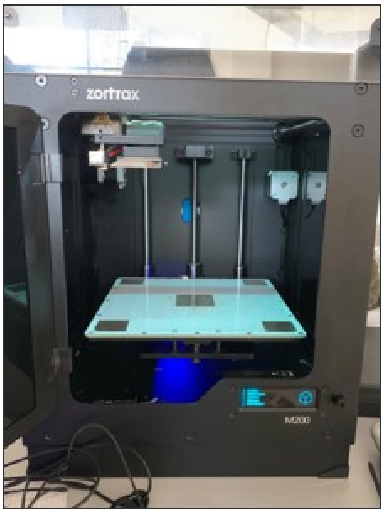
FIGURE 10 – Clips and mirror

3.2 Printing

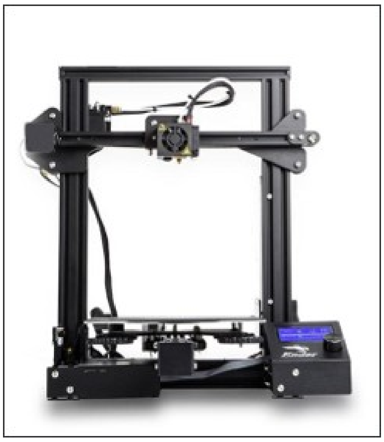
In this section we will explain how our system was printed, but only the plastic part. Even if the ceramic part is very interesting, it is not the goal of this report. Which is how far we are to the final system.

3.2.1 3D Printer

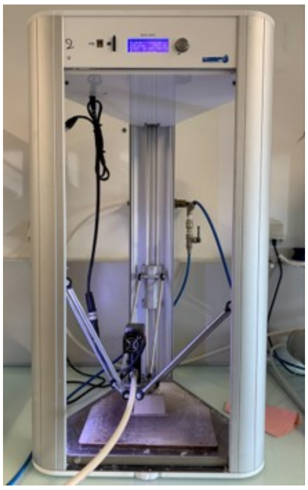
The printers used were *Zortrax M200* that you can see in the Figure 11a at ENSIL-ENSCI. As well as the *Creality Ender 3 Pro* in Figure 11b at Gabriel's place. Moreover, we used the printer *3D WASP* in Figure 11c for the mirror, at EX-ENSCI.



(a) Zortrax M200



(b) Creality Ender 3 Pro



(c) 3D WASP

FIGURE 11 – Printers used

3.2.2 Materials

The final prototype so far is made of *Z-ULTRAT*, the prototype delivered in Additive Manufacturing project was made of *PLA* and *Z-ULTRAT* for the base. The *PLA* is good for prototyping only, because the necessary temperature to degrade it, is about 55 Degree Celsius. So the sum has an advantage in this condition. That's why we used the *Z-ULTRAT*, because it's a mix of *ABS* and *PC*. The Figure 12 and 13 show some results, one has not the desired shape, I let you find which one.

FIGURE 12 – Z-ULTRAT result

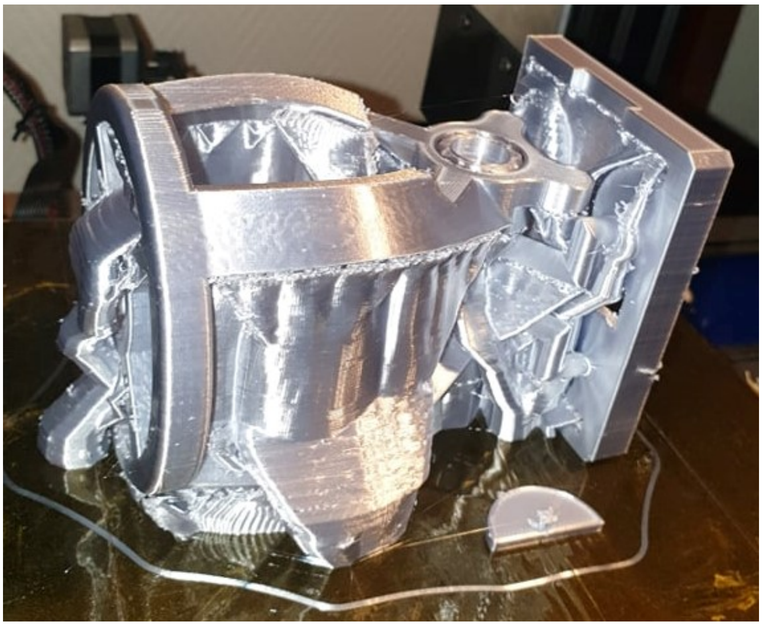


FIGURE 13 – PLA result

We tried some configurations about the printing process and their parameters. As well as the different software or slicer to handle these process. The *Creality Ender 3* is open source, that's means that the code can be generated by every type of slicer, GCODE is used. During the printing on this printer, we used the *CURA* slicer, which have a lot of resources. The *Gyroid* patterns has been used to fil the prints. Which is, a strongly patterns compare to the others. The support was generated by *Tree* support pattern.

In the others hand, on the *Z-SUITE* slicer, which is a proprietary software, we printed with *Honeycomb*. This slicer offers only 3 patterns. However it is also a good and strong pattern. The support was generated by *Line* support pattern.

As you can see on the 2 figures above, the only possible axis of printing was the Z axis of the printer. This is due to the pivot joints integrated inside the print.

3.3 Assembly

The first time we assembly everything, we need to adjust the withdraw of the plastic part and especially the ceramic mirror, which had a withdraw of *16%* on Z axis. The Figure 14 correspond to that point. The system there includes two stepper motors, the plastic system and the mirror part without the metallization (to be a real mirror).

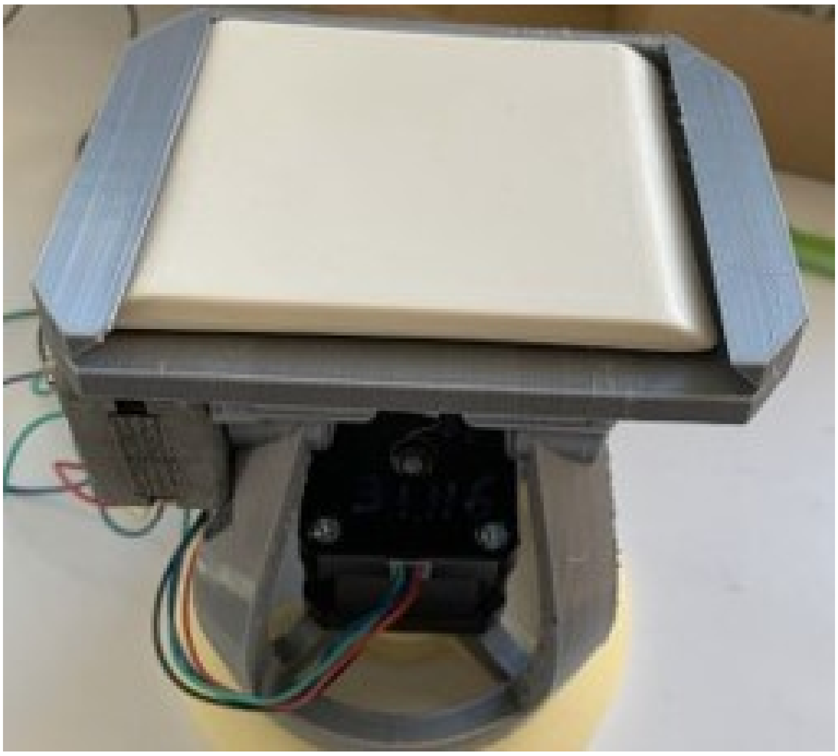


FIGURE 14 – Assembly test

4 Electronics

4.1 Overall electronics

The electrical circuit is mounted on the mechanical structure of the solar panel is shown in the Figure 15 :

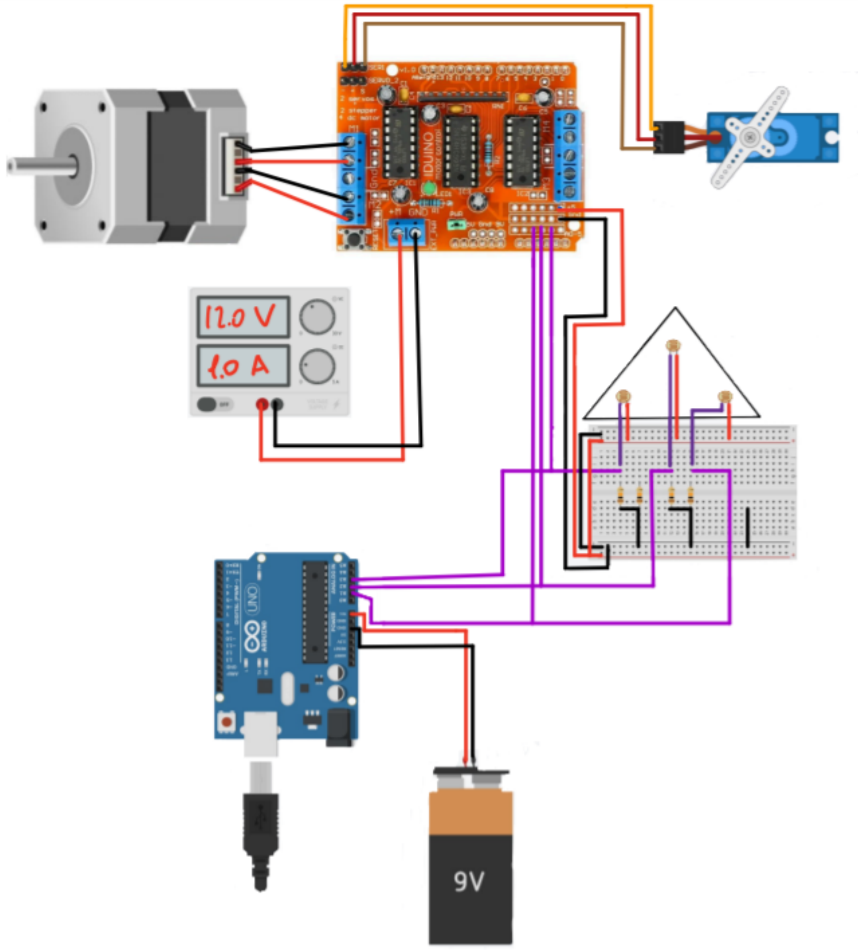


FIGURE 15 – Electronic circuit

4.2 Sensors

Any device that is sensitive to the intensity of light can be used as solar tracking sensors. When the sun is on the left, the sensor on the left receives more light than the one on the left. If the sensors produce voltage with light intensity, the left sensor would produce more voltage than the one on the left. From the result, we can know that the sun is on the left. When the two sensors are outputting the same value, we know that the sun must be at the top, perpendicular to the sensor unit.

4.2.1 LDR

They sense the higher density area of sun light. The solar panel moves to the high light density area through motors. Each LDR is connected to power supply forming a potential divider. Thus, any change in light density is proportional to the change in voltage across the LDR's. We put a pull down resistors inside the LDR, to pull the pin to a logical low value.

LDR is a passive transducer hence we will use potential divider circuit to obtain corresponding voltage value from the resistance of LDR. LDRs resistance is inversely proportional to the intensity of light falling on it i.e. Higher the intensity or brightness of light the Lower the resistance and vice versa. We can see on the Figure 16 the sensors created.

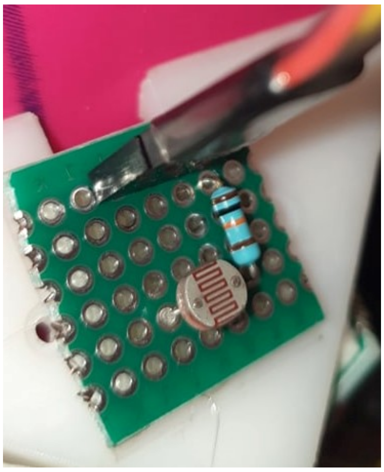


FIGURE 16 – Sensors created

Working Principle

A light dependent resistor works on the principle of photo conductivity. Photo conductivity is an optical phenomenon in which the materials conductivity is increased when light is absorbed by the material.

When light falls i.e. when the photons fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band. These photons in the incident light should have energy greater than the band gap of the semiconductor material to make the electrons jump from the valence band to the conduction band. Hence when light having enough energy strikes on the device, more and more electrons are excited to the conduction band which results in large number of charge carriers. The result of this process is more and more current starts flowing through the device when the circuit is closed and hence it is said that the resistance of the device has been decreased. This is the most common working principle of LDR.

LDR's are light dependent devices whose resistance is decreased when light falls on them and that is increased in the dark. When a light dependent resistor is kept in dark, its resistance is very high. This resistance is called as dark resistance. It can be high as 1012 Ω and if the device is allowed to absorb light its resistance will be decreased drastically. If a constant voltage is applied to it and intensity of light is increased the current starts increasing. Figure below shows resistance vs. illumination curve for a particular LDR.

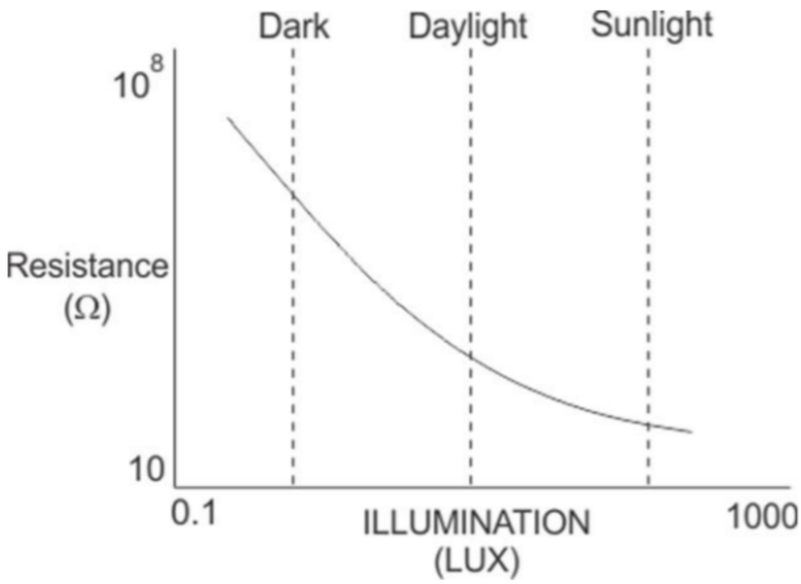


FIGURE 17 – LDR Sensor

4.2.2 Start controller - Push Button - LED

When the power is adding in every motors, the system can directly go away. That's why there is a *push button* which turn on the controller of the Arduino, we can now if the controller is on thanks to the little green LED added on the top.

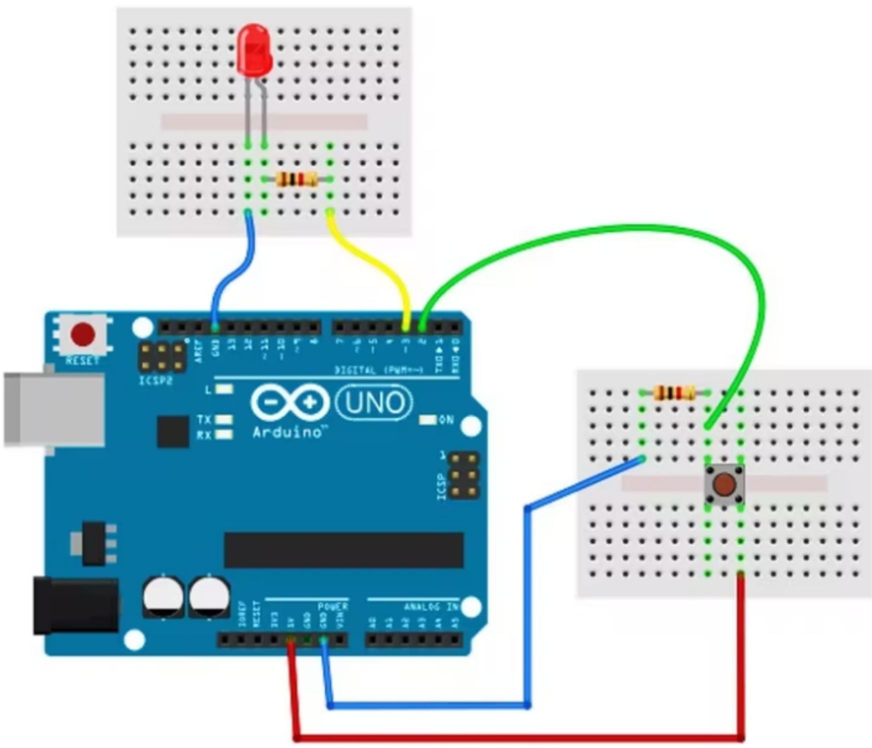


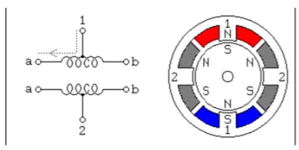
FIGURE 18 – Start controller push button wiring

4.3 Actuators

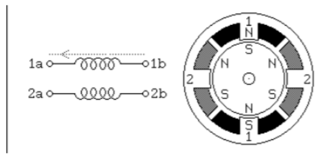
4.3.1 Stepper motor

We used stepper motor *17HS15* for the lower joint.

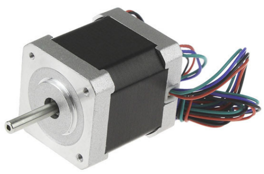
The stepper motor is an electromagnetic device that converts digital pulses into mechanical shaft rotation. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The sequence of the applied pulses is directly related to the direction of motor shafts rotation. The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied. Many advantages are achieved using this kind of motors, such as higher simplicity, since no brushes or contacts are present, low cost, high reliability, high torque at low speeds, and high accuracy of motion. Many systems with stepper motors need to control the acceleration/deceleration when changing the speed.



(a) Unipolar Stepper motor



(b) Stepper motor



(c) Stepper motor

FIGURE 19 – Difference between Unipolar and Bipolar stepper motors

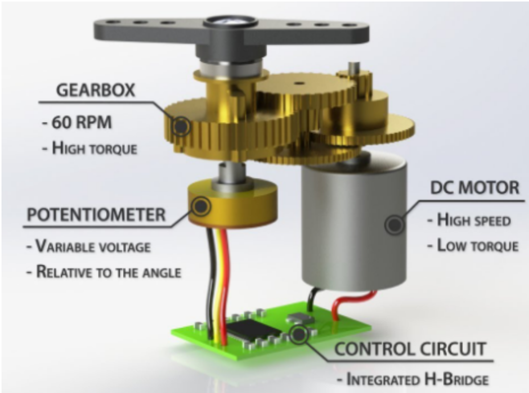
Unipolar vs Bipolar

The two common types of stepper motors are the bipolar motor and the unipolar motor. The bipolar and unipolar motors are similar, except that the unipolar has a center tap on each winding. The bipolar motor needs current to be driven in both directions through the windings, and a full bridge driver is needed .The center tap on the unipolar motor allows a simpler driving circuit, limiting the current flow to one direction. The main drawback with the unipolar motor is the limited capability to energize all windings at any time, resulting in a lower torque compared to the bipolar motor. The unipolar stepper motor can be used as a bipolar motor by disconnecting the center tap. In unipolar there are 5 wires. One common wire and four wires to which power supply has to be given in a serial order to make it drive. Bipolar can have 6 wires and a pair of wires is given supply at a time to drive it in steps. A simple schema of both configurations is represented in the Figure 19a and 19b.

4.3.2 Servo motor

We also used servo motor *Hitec HS-55* for the controlling the upper joint, firstly because of the consumption of the stepper motors remaining inside the lab of ENSIL-ENSCI, which take most than 0.6A to work well, about 1.5A at 12V. And we can see in the datasheet of the motor shield controller that it can deliver a maximum of 1.2A in a peak and 0.6A otherwise. We can also explain our choice about the amount of power needed compares the amount of energy harvested by the system. We will find this study inside the power supply section. Taking this servo motor for the upper part is also useful because of the limit of our system for the upper joint. As we know, lots of servo motor can move with a range of 180 degree, even less. In our case, we only need 120 degree of range, so it's ok for this link.

(a) Kind of servo used



(b) Working principle servo

Figure 20 – Servo's informations

In the Figure 20a, we can see a kind of servo used to control the upper part. And in the Figure 20b, there is the working principle of the servo and the components inside him.

Working principle :

A servo motor is a rotational or translational motor to which power is supplied by a servo amplifier and serves to apply torque or force to a mechanical system, such as an actuator or brake. Servo motors allow for precise control in terms of angular position, acceleration, and velocity. This type of motor is associated with a closed-loop control system. A closed-loop control system considers the current output and alters it to the desired condition. The control action in these systems is based on the output of the motor. It uses a positive feedback system to control the motion and final position of the shaft.

4.4 Power Supply

As said before, we prefer to use one servo motors because he used less current and voltage than the bigger stepper motor. As seen in the beginning of this section, on the Figure 15. We see that there are two main power supplies. One is the 9V battery which power on the Arduino and the Arduino power the servo motor with 5V. And a sector power with 12V and a maximum of 1A for powering the stepper (about 0.6A). In the case that we used double stepper, we will have a power of 24W for the motors ($12V * 2A$) while the servo take only 5V and about 0.3A in load, so we will have a total power consumption of $5V * 0.3A + 12V * 0.5A$ or 7.5W, which is less than before, and pretty good in that case of energy harvesting system. We don't want a system which eat more power than he delivered.

One problem of this system is the power sector, because it has wire that can't be removed. The best way to avoid this problem is, either remove the stepper and put another servo motor (with limit the angle) or instead of moving the upper par with the motor, put the motor inside the basis. Like that the wire will not be a problem anymore. Another best case is to take a little of the energy harvested from the solar panel to go inside the system.

4.5 Summarize electronics used

To summarize, we can see the electric circuit in Figure 15 is made up by the following components :

- Arduino UNO
- L298D - motor shield controller
- 17HS15 - Stepper motor
- HS-55 - Servo motor
- LDR x3
- 10k ΩReistor x3
- 1k Ωresistor
- 1 green LED
- Push button
- 9V Battery
- Wires

The data sheet of the components are supply in the rendering folder.

5 Algorithm

The control of the Dual-Axis Solar tracker is implemented through $C++$ program developed using Arduino IDE and then loaded on an Arduino UNO board.

In this microcontroller program, two main phases are present : first a *setup* function is called in order to initialize all the possible parameters and the objects/variables used to manage all the LDRs sensors and the motors, and the $loopfunction$, that executes repetitively the control task. The Algorithm implemented in order to control the system is shown in the Figure 21 :

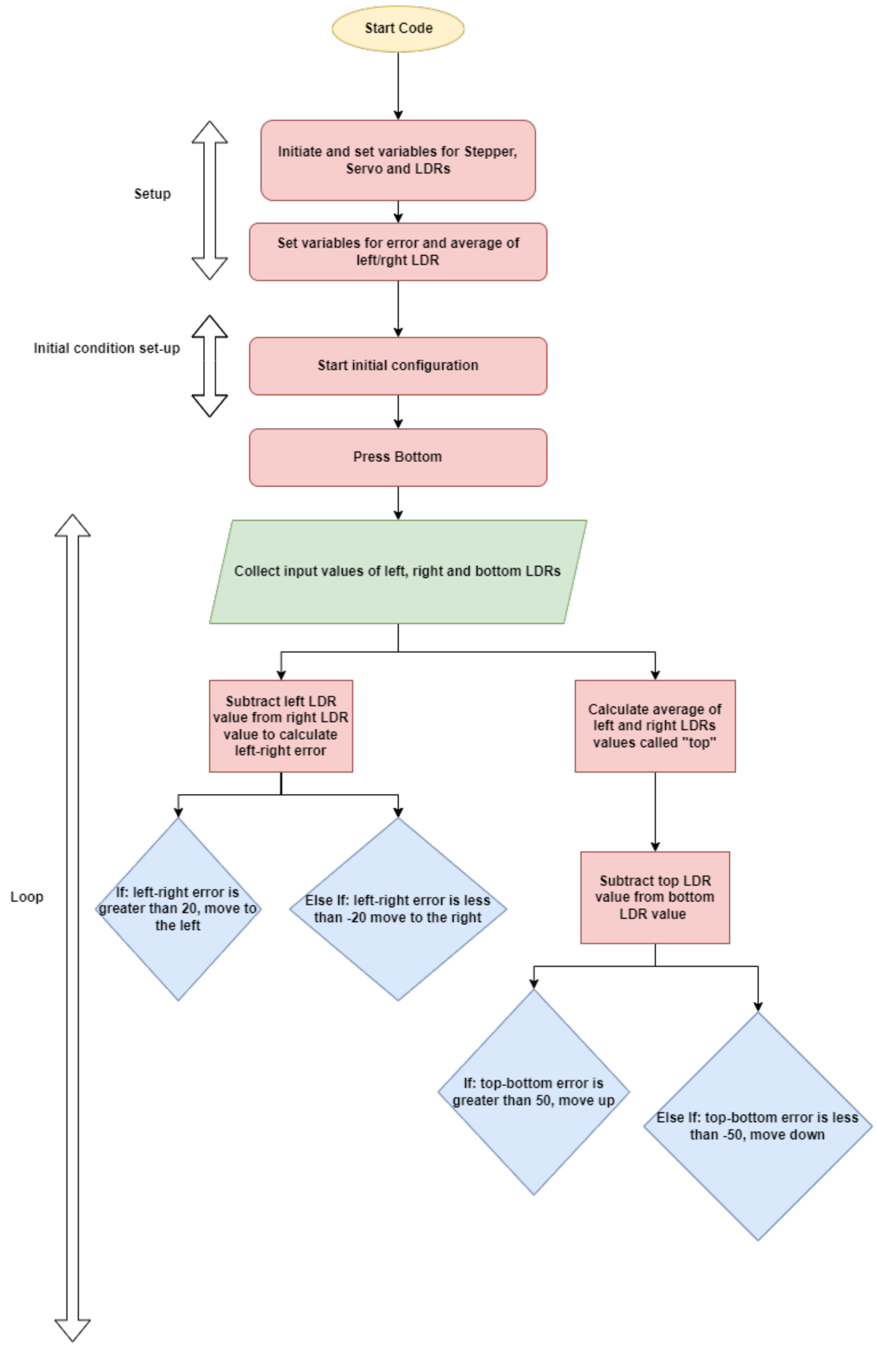


FIGURE 21 – Flow chart of the control law

As we can see, the working principle replied in loop is divided into few steps :

1. **Inizialization of variables for motors and LDRs** : here all variables, physical constraints and I/O ports are initialized in according with the wiring of the electronics schema.
2. **Initial configuration mode** : here the system will take place in the initial condition which is 90 °on the servo axe, with an high value of the button. Once the bottom has been pressed, the controller will begin to work.
3. **Data Acqusition from LDRs and motors** : in this section, we collect all the data from sensors that Arduino converts in to a voltage from 0 to 2054 and from motors in terms of initial position.
4. **Algorithm** : this section is the main part of our Control law implemented in the code which is responsible for understanding how many steps are required and which position motors must go in order to reach the desired position characterized by max intensity of light present in the environment. This is possible by comparing the average between all the combinations of LDRs until they are almost equal taking into account their sensitivity and tolerance.
5. **Motors Control** : in this section, all the results of the computation of the previous section are translated into understanding language for the motors driving them into the right position in terms of numbers of steps **in full step configuration mode**.

6 Miscellaneous

6.1 Half-step configuration control with Matlab

This part is additional to the work done and includes an in-depth analysis of the system reproduced on Simulink and Matlab. Unfortunately, we didn't get to test it due to the component not delivering before the deadline.

In particular, we asked ourselves the question of what happens inside Arduino in detail and we implemented the same type of control at the machine level on the Matlab / Simulink platform by creating the controller ourselves and using Arduino only to acquire data from the sensors and connect the motor pins.

In this way we were able to understand at a basic level the operations to be done to control the motors without having limits in terms of electronics inside the Arduino as it is reproduced on a software.

The complete Simulink schema is shown in the Figure 22 :

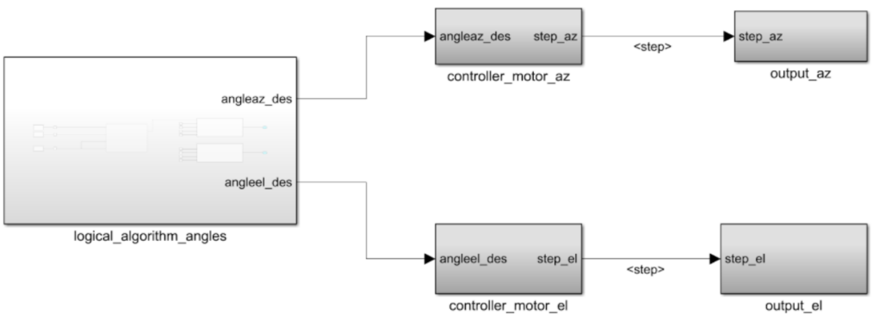


FIGURE 22 – Simulink schema

As we can see there are 4 principle sub-systems :

1. **Acquisition data and Algorithm' computations block** :
2. **Motor controller x 2** :
3. **Output sub-system**

6.1.1 Acquisition data and Algorithm block

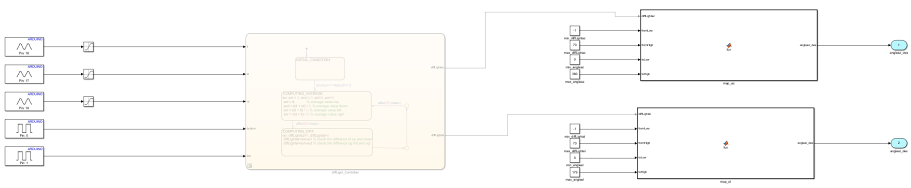


FIGURE 23 – Acquisition and Algorithm block

This main task of this sub-system shown in figure 23, is to acquire all the data input from all LDRs in order to compute the difference between its average inside the Stateflow block shown in figure 23.
This result is then sent to a Matlab function that maps the output of the average between all the LDRs into desired angles.

In the Figure 24 we can see the algorithm implemented on Stateflow :

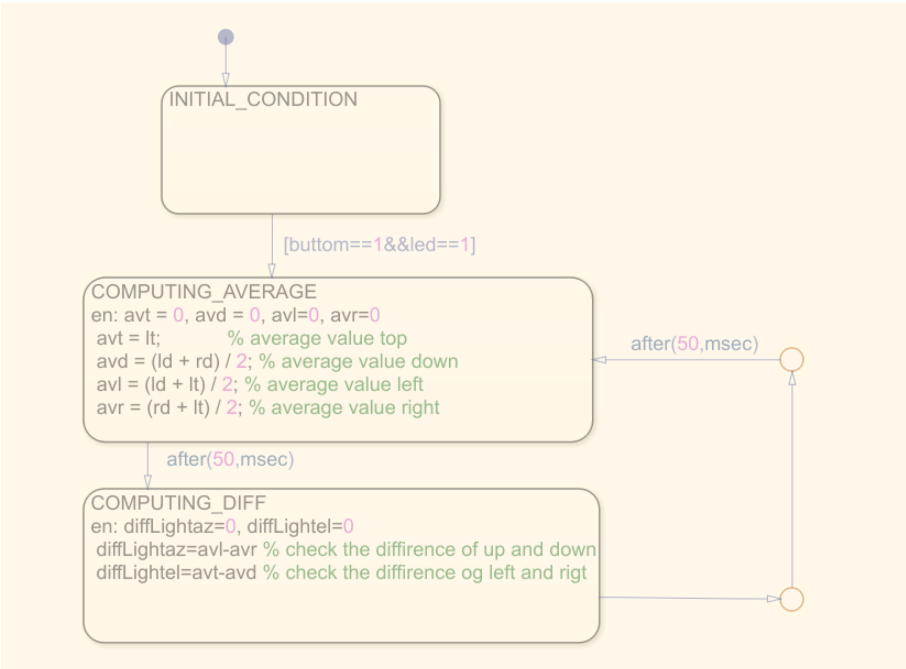


FIGURE 24 – Stateflow

Notice that if the buttom is not pressed then the loop never begin.

6.1.2 Motor Controller

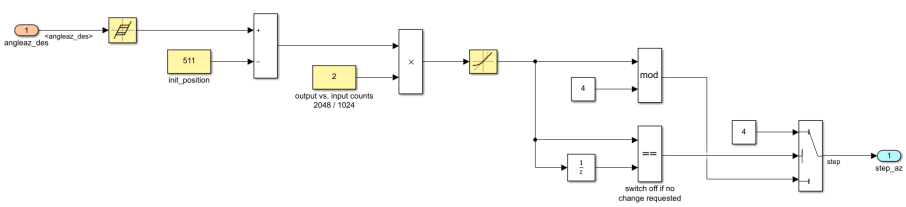


FIGURE 25 – Motor controller block

The main task of this sub-system shown in Figure 25 is to convert the desired angle computed before into required steps to control the motor in the correct way.

6.1.3 Output sub-system

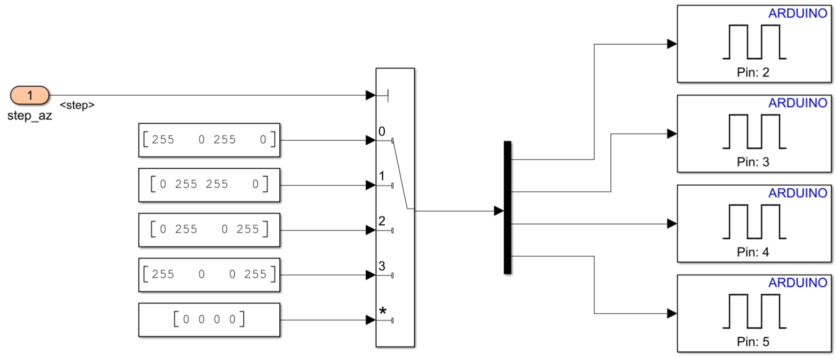


FIGURE 26 – Output sub-system

The main task of this sub-system is to translate the number of steps required to be sent to the motor into a language that can be understood by the Arduino, which will finally transmit the result of the controller to the motors via the digital pins.

6.2 Possible improvement

As we showed the limits of our system are :

— Refreshing period, we don't want our system to be fast and with a quick response, because we need the sun position. And the sun position is changing at a low frequency. Moreover, if we want our system to adjust the position with a faster light, we will have to change the refreshing rate of the control loop

— We could optimise the trajectories of the system by putting some award with a certain trajectory compare to others, for example, move firstly the upper part and after the lower part, not all at the same time.

— As said, improvement about the power supply have to be done, changing the way to couple the stepper motor by putting it inside the base and not inside the upper part.

— We also could need a better wiring and fixing for the servomotor part, because it was done as a prototype.

— The power consumption can be reduced at the maximum point to have a better efficiency at the end of the system

7 Conclusion

To conclude, we can say that this project was a part of a bigger project and the problems of the Additive manufacturing project was transmitted into this project. Like every big project, and we handle it, to have at the end, a functional prototype as we can see in the video. In order to make this project, we made concessions with, for example the upper stepper motor, and in others hand the matlab file that didn't fit with our motor control shield. Above all, we succeed to do what we wanted, we know that it has a lot of improvement to do with this system, but with the time we had to do this project from 0. We are satisfied with this first prototype, that we hope, people could improve it in the next years, firstly thanks to the GitHub that we will exploit for this and secondly thanks to the help of the professors. We learned a lot on team management, 3d printing, project management, electronics and motorization system.

A Dimension and limit for the system

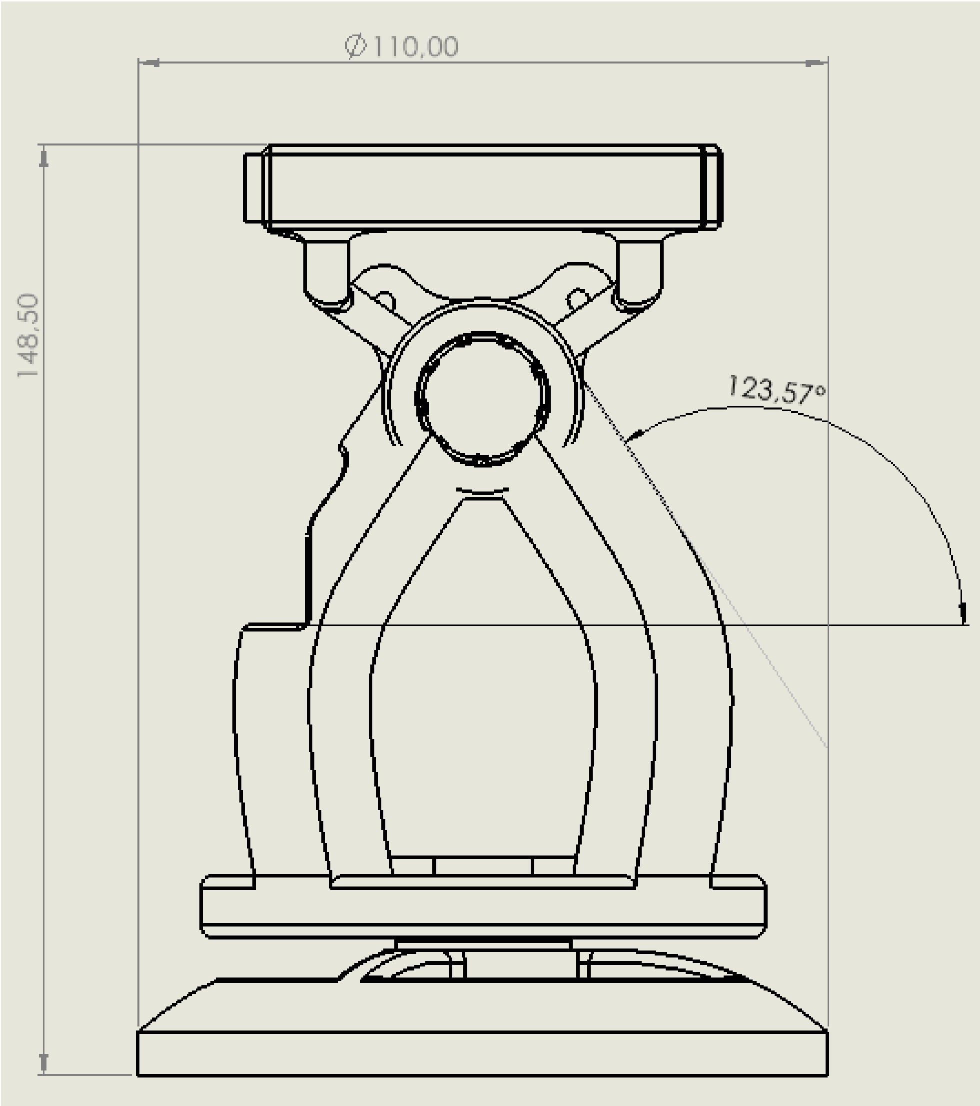


FIGURE 27 – Dimension and limit of the system