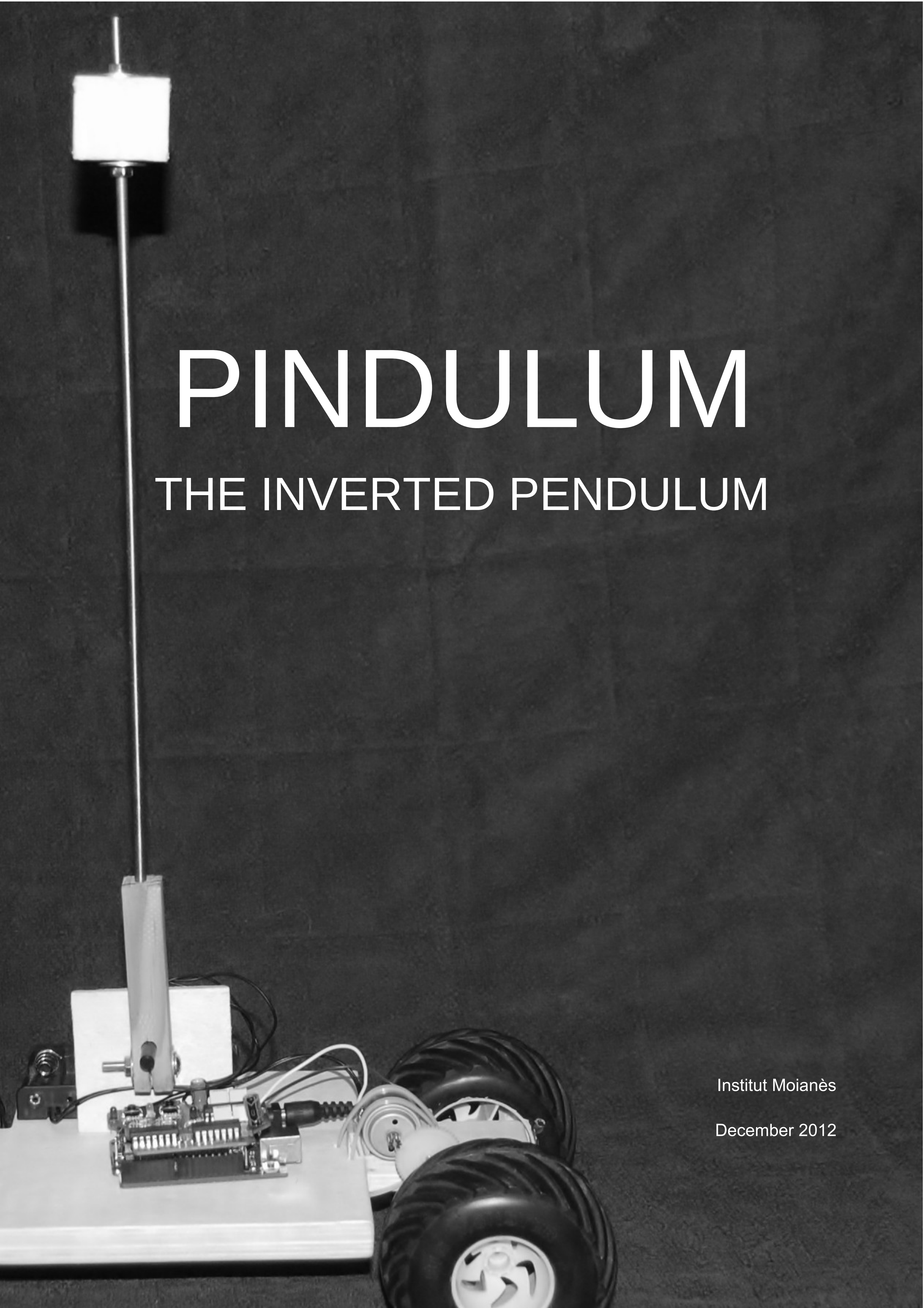

PINDULUM

THE INVERTED PENDULUM

Institut Moianès

December 2012

ACKNOWLEDGMENTS

This Research Project couldn't have been done without the moral and the technical support we have counted on.

First of all we would like to thank very much Àngel Santamaria for his absolutely predisposition. He helped us in everything we asked him, mainly with the electronic issues, and he always received us with a great smile. He also let us use the IRI's laboratory and the professional tools we needed.

Secondly, we are very grateful to our mentor who, from the beginning, gave us advice and awareness.

We also want to thank our family for being moral backers and for supporting our bad mood during the last days. Also our fathers for helping us in some points of the mechanical construction.

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1. INTRODUCTION

“Pindulum” is a research project which aim is to research, learn and apply the basics of an inverted pendulum. Along the pages, we will expose the how-to-build part with some brief explanations to make it more understandable.

The working seems quite easy but there is a principle behind it which is rather complex. Maintaining an inverted pendulum stable has always been a common engineering challenge for researchers. Nowadays, there is a quite wide variety of types of inverted pendulums which involve different bases and different controlling systems. We used a feedback system. This system is the one used to maintain a stick on one's finger.

The inverted pendulum is inherently unstable and has to be constantly balanced to remain upright. We made the potentiometer be the rotation axis to work with one direction: forward and backwards. This way, the programming of the Arduino becomes less complicated. Anyway, when the pendulum falls, as it is attached to the potentiometer axis, the potentiometer rotates and this gives the Arduino a value. The Arduino is programmed to read the incoming value and give the order to the motor to move forward or backwards. When the pendulum falls forward, the center of mass also moves forward, and it happens the same way backwards. The idea is that the base, which in this case is a kind of cart, also moves forward or backward to maintain the center of mass in the middle. The speed the base moves, empowered by the motor, is proportional to the angle the bar is leaned.

Since this is a technological project, we constructed the inverted pendulum itself. On the following pages you will be able to get to know how we proceeded, the problems we had and the final results.

2. MOTIVATIONS

The Research Project is very important for the high school final mark; this means that you have to work on it for lots of hours. Having this in mind, we had to choose the topic we wanted to work on so we went on a brainstorm. The initial decision was to make a pendulum clock, but later we changed our minds.

In this chapter we will explain the evolution of our project theme and our motivations.

2.1. THE CLOCK

As we said before, after the first brainstorm we decided to make a clock. The idea was that we had to design an original clock which worked with a pendulum (like the ones that our grandparents have at their homes) because it combined physics and technology.

We searched on the net and we found a huge range of examples, we searched for interviews and we met with the tutor to talk about how to start: the gears, the material, etc.

Finally, we talked to each other and decided that it was not of our interest. We didn't find it a challenge and we didn't want to spend so many hours doing something that bored us.

2.2. THE SEGWAY

Having left away the idea of the clock, we had to find another project. Then is when Gisela's brother appeared with a great idea for us: making a Segway. We were extremely motivated with that option because it was something interesting, new, useful and environmentally safe and we would have been able to interact with the final construction. It was also a big challenge for us and that made it even more exciting. Academically, it was interesting because it was a technical project just as what we were looking for. It included very different areas that made it be very rich: mechanics, electronics and programming.

A segway is a two-wheeled self-balancing electric vehicle invented by Dean Kamen. Our aim was to build a DIY self-balancing scooter. For this project we found some crucial information: common people who had created one on their own. Some of those men had their websites with the steps, the material, pictures, videos, etc. We spent hours reading, listening, watching and learning (which was sometimes difficult because of the English technical vocabulary). Luckily, since our final Research Project is the basic principle of how a segway works, most of the information we found is now useful. Below, we will explain some of the important knowledge we acquired:

Illustration 1: Four different DIY Segways

Understanding how a Segway works is very simple: when you tilt the main bar forward, the gravity centre is displaced in front of the wheels. The sensors detect that and they send this information to the main computer, which gives the order to the motors to start running in the direction the bar is leaned so that the stick keeps vertical. But, while this process is taking place, the person who is on the Segway doesn't stop tilting the bar. Therefore, this process keeps on and the wheels don't stop running. This is how a Segway moves, either forward or backwards.

One of the most interesting and complicated issues of a self-balancing scooter are the sensors. The sensors are very important as they give you the inclination of the bar regarding the base and the speed of its angle change. For this kind of robot you need an accelerometer and a gyroscope. The combination of these two devices provides you of very precise results because the error of one is cancelled by the other and vice-versa. In short, we could say that the gyroscope tells the short-time reading and the accelerometer the long-time reading.

After having assumed as many information as we could, we managed to get an interview with Angel Santamaria, a man who is working in the Institute of Robotics and Industrial computing of the UPC. We went to Barcelona, visited the installations, watched some of the projects and we finally talked about what we wanted to do. He made us clear that building a Segway was a bit too difficult and expensive for us and that we didn't have enough time. He made us the recommendation of doing an inverted pendulum, which was the basic principle of the Segway. After having thought about his words, we agreed with him.

2.3. THE INVERTED PENDULUM

Angel helped us in structuring our minds. He made us clear what were the following steps we should follow, he recommended us some shops where we could buy the needs and he finally gave us some advices.

Our main motivations for making this project differed a bit on each one of us:

Gisela:

When we were first asked to think about ideas for the research project I decided I wanted to construct something. I, also, wanted to work with Clàudia since we are a hard-working team and we get on very well. The only thing left was to think about a concrete project.

As we have explained, we came up with some ideas. Personally, the idea of building a clock didn't appeal to me: it seemed very easy. But when we were given the idea of the Segway I thought it was a challenge as we knew nothing about it. I cursed technology last year but, actually, it had not much to do with it except for the vocabulary and some principles used. Moreover, the idea of being able to use what we would have built was very attractive. It hasn't result like this at last, but it has not made me lose interest in the project.

So, although we modified the project to an inverted pendulum, the challenge presented and the idea of working with such a good partner made me bet on that idea.

Clàudia:

Although I am following the scientific modality in the high school, I am very interested in technology and constructing an inverted pendulum seemed very interesting to me. I believe that it is very important not to focus on one particular subject but to learn something from each area because you never know where you will find yourself in the future. Making a technological research project was a way to acquire the technological knowledge that I did not have before. It was a challenge for me since I have not done technology at school. In this project, team-working would be indispensable and my workmate would have to help me with my technological weakness.

3. BASIC KNOWLEDGE

In this chapter we will explain some basic knowledge which is indispensable to comprehend the logic of this device and we will give a general idea of how it works.

3.1. THE INVERTED PENDULUM

When we think of a pendulum the image that comes to our mind is a long and straight stick or rope with a weight at the end that swings freely. Then, what is an inverted pendulum? It is exactly the same but, as the word says, upside down.

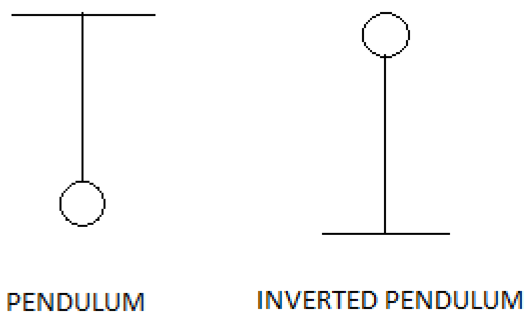

Illustration 2: Schematic view of a pendulum (left) and an inverted pendulum (right)

An inverted pendulum is a very unstable system; it is physically impossible (not mathematically) to keep the pendulum still. To maintain the pendulum in a vertical position it is essential to constantly balance it. To illustrate this, we can imagine the following example:

We all have tried to keep a stick vertical on our hand one time or other. It can clearly be seen that if we don't move, the stick falls. So, what do we do to recover its equilibrium? We have to move in the direction the pendulum is falling. If it moves forward, we will move our hand forward, and the same happens with all the other directions.

Our robot will have the same function as the hand: it will move in the same direction as the pendulum so that it will never fall. However, there will be one highly difference since the pendulum will only be able to move in one dimension while the hand is able to move up, down, left, right, forward and backwards.

There are many devices which use different ways to detect the characteristics (angle, direction and speed) of the bar fall: the light sensors, the accelerometers and gyroscopes and the potentiometer are the most popular. Since we do not need very accurate results and providing the complexity of our project, we thought the best option for us would be the potentiometer system.

3.2. EXPLANATION OF THE PENDULUM'S WORKING

As we said before, an inverted pendulum can't be still. Our aim is to construct a device which is able to sustain its equilibrium for itself. The knowledge required to build an inverted pendulum is too high for us so our project will only consider two directions: forward and backwards.

The system mainly consists of a four-wheeled platform made of wood (similar to a car) and a steel bar with a weight on its top. If the bar falls forward, the wheels of the car will move forward in order to maintain it vertical and if the bar falls backwards, the wheels will move backwards. This is what it is called “feedback system”.

It is very easy to understand the pendulum's working simplified, the way our system transfers the information so that the pendulum stands vertical. Below we will briefly explain it:

The first thing that happens is that the pendulum falls in one direction (only forward or backwards in our particular project). This can be identified in the following picture as the reference. The potentiometer measures the position of the stick and sends this information to the Arduino (controller, (1)) which, since it has been programmed with a certain code, sends the instruction through the motor shield to the motor to move in one direction or other (3). But the Arduino is not able to send this instruction by itself and that is why there stands the motor shield (system, (2)) which allows you to power up the motor and control its direction and speed. When the motor has received the instructions it starts running and its movement is transmitted to the wheels through the gears. Finally, we need batteries which provide all this system of power.

But, actually, the potentiometer keeps sending what would be “wrong” values, and this circle goes over and over. This is why, as shown in the following scheme, there is a point in which the new value of the potentiometer is discounted from the last one (5). This error is sent to the Arduino to correct it and, as we said, it is a vicious circle.

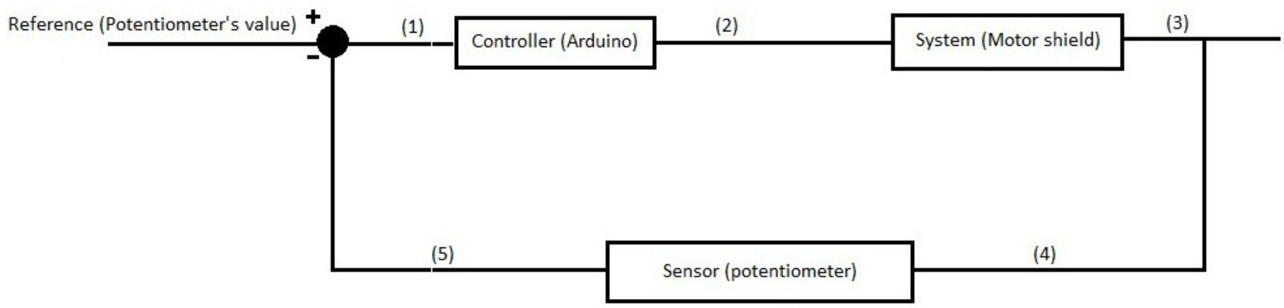

Illustration 3: Control theory scheme

Unless this chain works properly and it is well linked it will not work. This is why it is very important to pay attention and understand all the devices and how they work. We will explain everything about each element in the next chapters.

4. ROBOT'S CONSTRUCTION

4.1 MECHANICAL CONSTRUCTION

Almost all the mechanical part of our project was carried out at the technological workshop from our high school because there we had all the tools we needed. We have to highlight that we tried to construct it with re-used materials.

In this chapter we will focus on each part of the mechanical construction of the pendulum. We will explain the materials we used, where they came from and what is their function. We will include a picture of each element.

4.1.1 BASE

The base of the pendulum is wooden-made and its particular shape is because of the necessity of some space for the wheels. It was important to make these enlargements because it is there where the axis of the wheels will stand.

The particular type of wood used is called plywood. We chose this material because it is not very heavy but it is very resistant since it is made of multiple layers of wood chips. This material is appropriate for the base because it accomplishes its function: it has the power to support the pendulum and the hardware.

We did not have to buy the wood because our parents had some of it at home.

For cutting the base we used an electric saw and after it we used a file in order to sand it and this was the result:

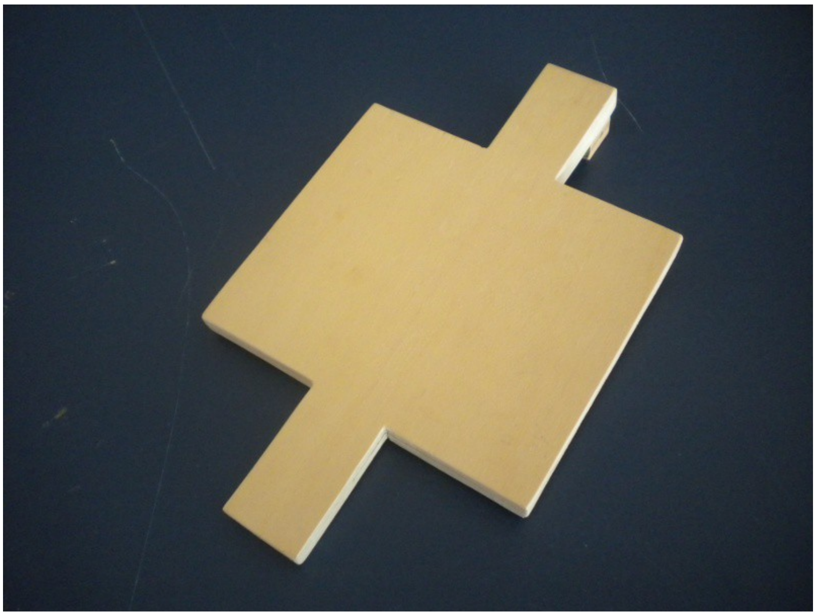

Illustration 4: Cart's base

Under the base we attached four little wood pieces whose function was to hold the wheels-axis. They are 2.3×1.4 cm and we used a hacksaw to cut them and a drill press to made a hold on their center. Since the hold had to be just over the axis' diameter, we polished it with sandpaper.

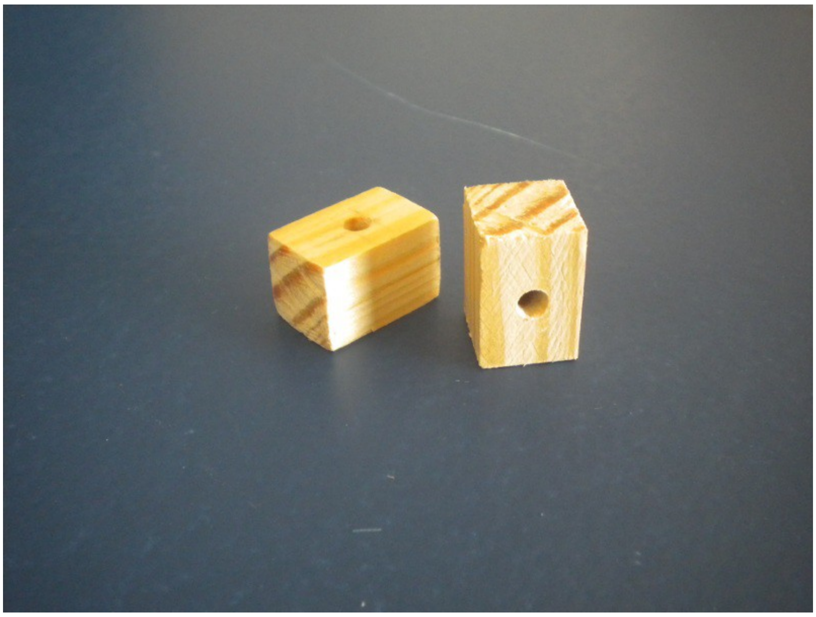

Illustration 5: Axis' wood supports

4.1.2 WHEELS AND AXIS

As this project was to be reused-materials made-of, we took both wheels and axis from a radio-controlled car from our childhood.

The main reason of our choice was because they were big and all-terrain wheels and they would not cause any problems in adhering themselves on any kind of floor. We also had the axis that joined them so that was another advantage because we didn't have to search one that fitted properly.

Below there is picture of them:

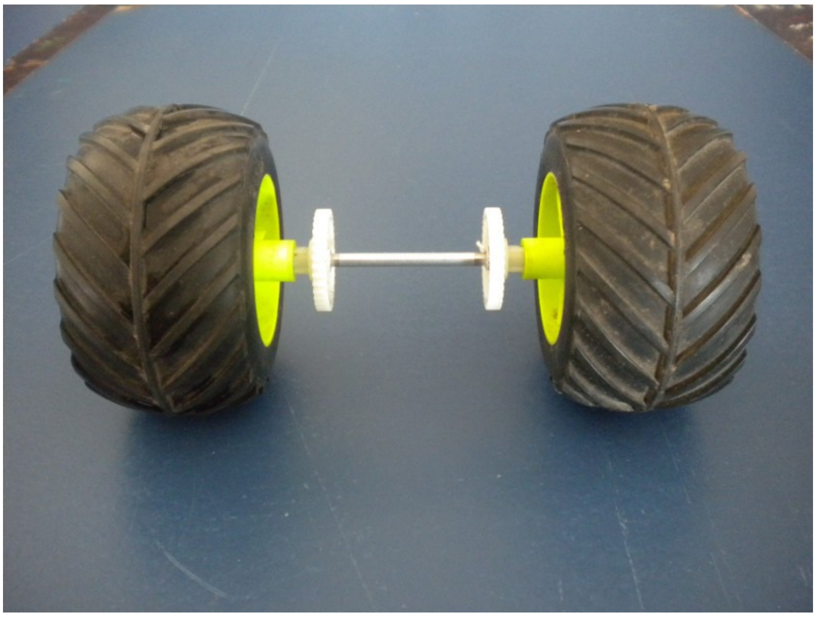

Illustration 6: Cart's wheels joined by the axis

4.1.3 GEARS

We took advantage of the fact that the RC car included some gears to connect the axis and the motors and, as they were the same size and fit perfectly with the axis we had also taken, we needn't buy nor construct them.

The gears are used to transfer the movement of the motor to the wheels' axis. We used three gears: one fitted in the axis, another fitted in the motor's small gear and a last one to connect these two. The picture below shows the composition of these components.

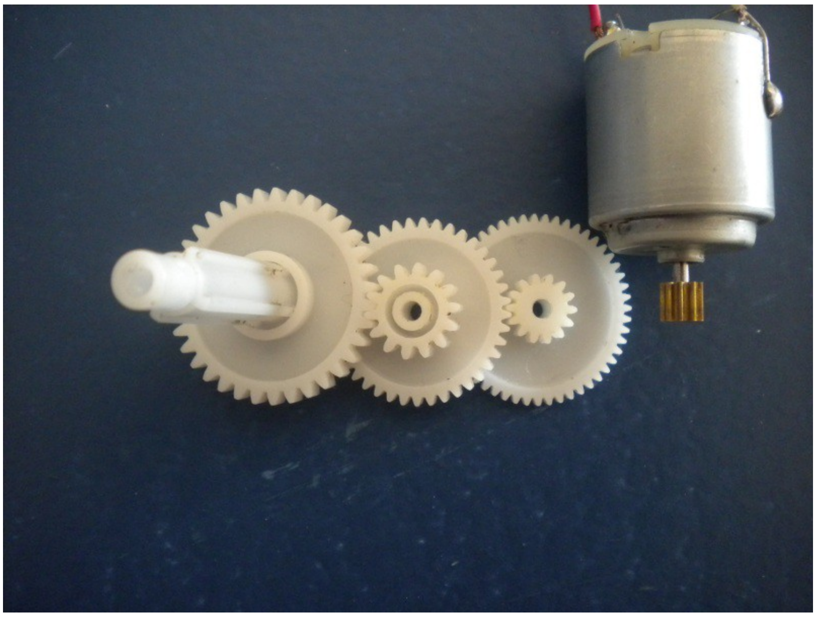

Illustration 7: Gears' composition

4.1.4 THE PENDULUM

We made the pendulum taking into account the weight and the height since it is very important involving programming difficulty. We chose a rib because it is also practical when adding extra weight. The rib goes deep into a piece of wood, which is attached to the potentiometer axis. The rib itself is 35cm high and the whole structure heights 42cm.

Ilustración 8: The pendulum

4.2 HARDWARE

The hardware was one of the most difficult issues since we have not a lot of knowledge about it. This is the reason why a big part of our learning has been through the Internet. Nevertheless, we could not find all the information we wanted so we needed to find a solution by asking experts.

First of all, we'll make clear how the electronic components are connected with each other using the following electronic scheme:

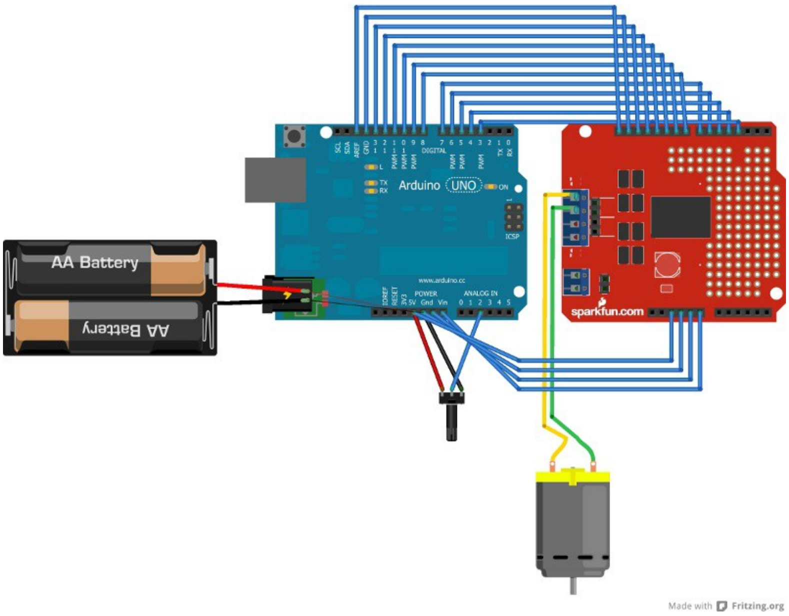

Illustration 9: Electronic scheme

In this chapter we will separately explain each device we needed for our inverted pendulum. We will give a short description of it and we will expose its function within the whole system. Finally, we will add a picture of every piece.

4.2.1 POTENTIOMETER

A potentiometer is an electrical resistor which uses three terminals. Connected to a power source, a ground and a resistive material, it is used to read variables. To make it clear, it is, for example, what adjusts the volume of a loudspeaker.

In our project, we will use the potentiometer to read the values of the pendulum and then turn them into analog values as to be read into the Arduino board.

As shown in the following picture, we had to solder three cables to the potentiometer in order to be able to connect it to the Arduino. We were helped by Clàudia's father.

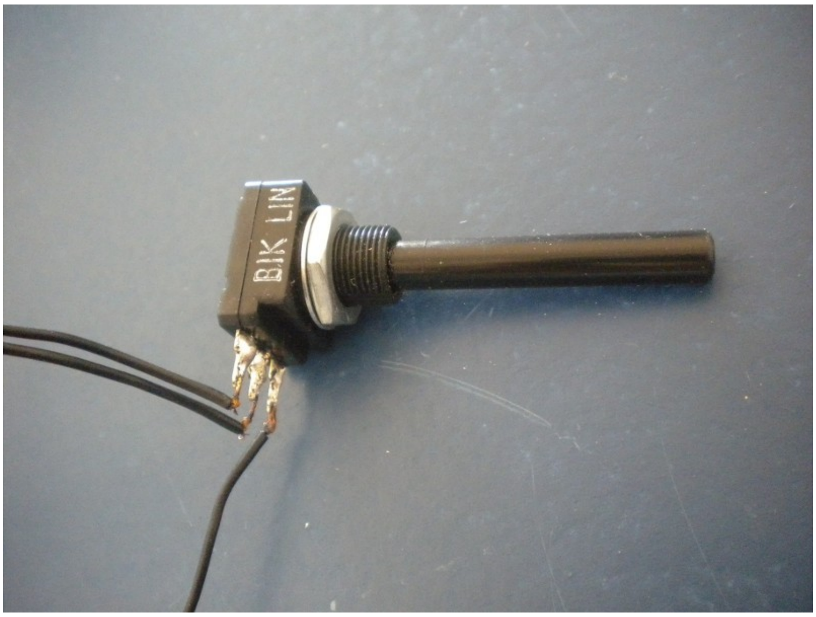

Illustration 10: Potentiometer

4.2.2 ARDUINO

Arduino's webpage tells us that *an Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software*. Reading this and haven't heard much about this device, it seemed quite difficult to achieve our aim of programming it.

Luckily, our mentor kindly explained us the overall idea of its working and uses. Having understood its applications, we started reading from the Arduino website to assemble all the knowledge required to program it.

In this project, the Arduino is programmed to receive the values from the potentiometer and process them to make the motor work proportionally.

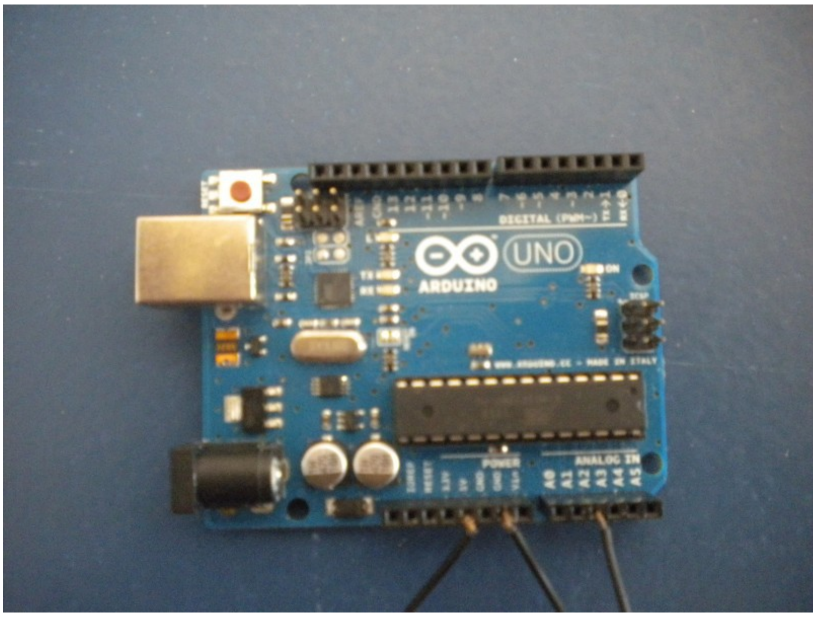

Illustration 11: Arduino UNO

4.2.3 MOTOR

At first, we had the idea to buy a servo and use it as a motor; this requires some modification because the servos are not supposed to roll 360º. We thought we could deal with it; it didn't seem very complicated. But, as we said before, we didn't want to buy a lot of things, and we came up with the idea to take the motor from the radio-controlled car mentioned before. The motor works with direct current.

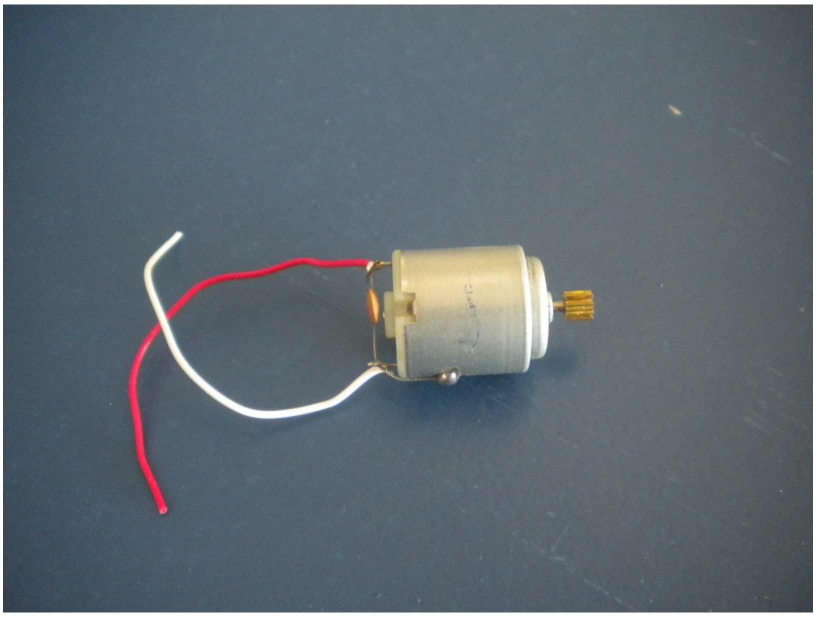

Illustration 12: RC cart's motor

However, the motor cannot be connected directly to the Arduino. There has to be a motor shield which acts as a bridge between both elements or you have to construct an H-bridge. We considered this two options and we finally decided that it would be faster to buy the motor shield directly because constructing the H-bridge would have taken us too much time and it was not a very important part of the project. So we bought this shield and we took use to buy a support for the batteries. But, what we didn't expect was that the motor shield was not assembled. This is how it looked:

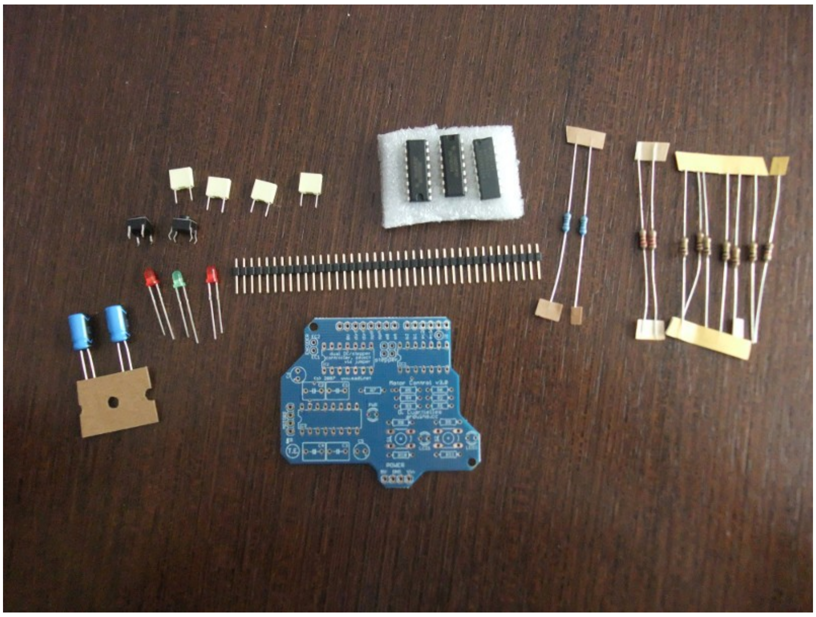

Illustration 13: Motor Shield KIT

Our first task happened to be assembling all these components.

4.2.3.1 MOTOR SHIELD

First of all, it is very important to be very careful while soldering as if one component touches the other, it disables the whole system. It's useful to start with the smallest components.

With the help of a tutorial video, we started putting each one of the six 100K resistors in the R1 to R6 holes and the 1K resistor to the R7 hole. Note that it isn't important to distinguish between the left and the right of the resistors. We soldered these components.

The next step was to solder the 2.2K Ohm and 470 Ohm resistors, two of each type. We soldered the first ones to the R8 and R9 gaps and the other two to the R10 and R11.

We then put the three LEDs in their holes: LED1, LED2 and PWR. Before soldering these elements, we had to watch the long and the short leg were in their correct position. To finish that area of the shield, we assembled the two 6x6-push-buttons.

The 4 100nF capacitor polyester were the following components to solder. They fit in the gaps C1, C2, C3 and C4. Then, we soldered the two 100uF electrolytic capacitor 25Vdc, which were placed in gaps C5 and C6. We also placed the straight single line pinhead connectors which use is to connect the motor shield and the Arduino.

The only things left to solder were the Quad 2-input OR gate, the Quad 2-input NAND gate and the DIL 16. Apparently, they seemed the same, and as in the tutorial there was no mention of a particular order, we soldered them arbitrarily.

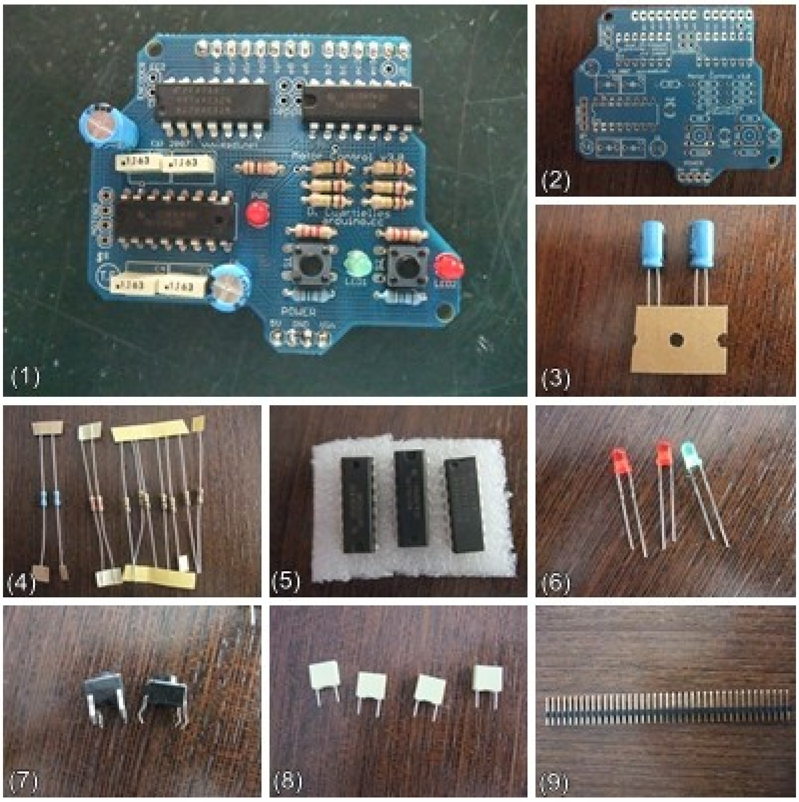

Illustration 14: 1. Motor Shield assembled; 2. Motor Pcb; 3. 100uF electrolytic capacitor 25Vdc; 4. Resistors; 5. Quad 2-input OR gate, Quad 2-input NAND gate and DIL 16; 6. Leds; 7. 6x6-push-buttons; 8. 100nF capacitor polyester; 9. Straight single line pinhead connectors 2,54mm40x1

As we said before, this shield is connected directly to the Arduino through the pinhead connectors. It is connected, first of all, to the 5V, Gnd and Vin gaps. It is also connected to the other side of the Arduino on gaps 3 to 13 digital pins and on Gnd and AREF gaps.

4.2.4 BATTERIES

As we have already said, we bought a support for the batteries. This support has the capacity to hold six 1.5-volted batteries. Using this kind of energy source, we will always be able to change batteries without damaging the structure. There is a cable which connects this support to the Arduino directly.

Illustration 15: Battery support

4.3 PUTTING IT ALL TOGETHER

Once we had constructed every piece of the structure and we had understood and learned how the hardware worked, we were able to put it all together.

We first decided to make the car's platform providing that it is the most basic structure. To do that we had to join the car's base with the wheels. We thought that the best idea would be to make four little wood structures (as explained at the point 4.1.1) that would be pasted on the wood platform and which would hold the wheels-axis.

The following step was to find a method to easily connect the wheels with the motor through the gears. Note that the motor only transfers its movement to one axis, not both. We needed three gears to do so since we had taken them from the RC car and each one of them had a particular shape that fitted with each other. We also had to be careful on how we placed them for they have to be very precise. We took advantage of some other elements already situated: we nailed the middle gear to the base and the one which is connected to the motor to a wood support. We filed that piece of wood to maintain the motor in that exact place. The third one is the piece that links the axis with the wheels.

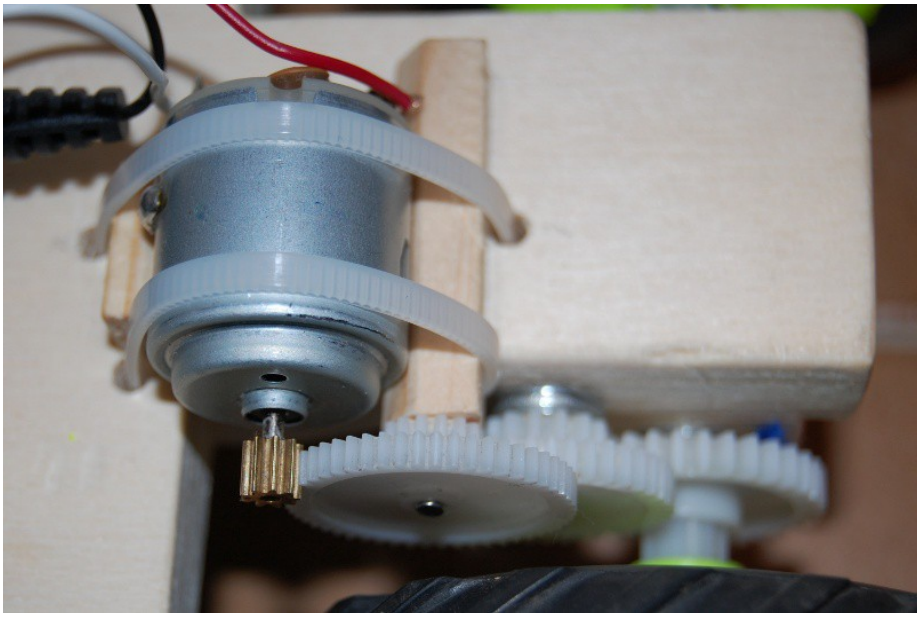

Illustration 16: Gears and motor composition

Once the motor was pieced together with the axis and those with the base, we started thinking about another big issue: the system that combined the pendulum with the potentiometer and with the Arduino. We wanted to locate the pendulum in the middle of the base so that it would be aesthetic. The pendulum had to be fixed at the potentiometer's rotational sensor and we achieved that by making a hole at the end of the pendulum's stick. From that hole to the end of the stick we made a straight cut thus we could strongly fix it to the rotational sensor.

We also needed to make another structure that held the potentiometer and, at the same time, the pendulum. For the reason of being a support we constructed a relatively big structure using the same plywood of the base.

The following picture shows the result of the structure which combines the last-mentioned elements:

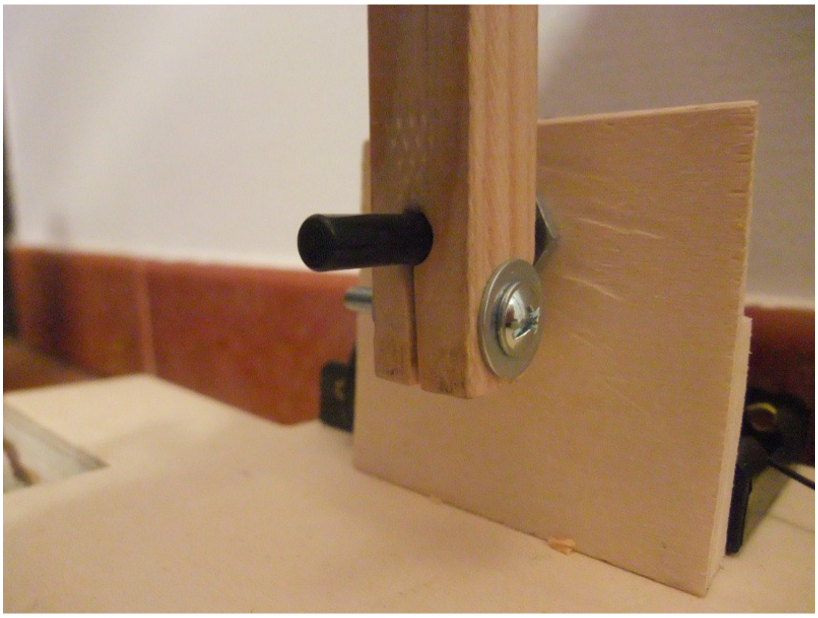

Illustration 17: Combination of the pendulum with the potentiometer

After this we only had to place the battery support and the Arduino with the motor shield on a place where the potentiometer and the batteries cables arrived to the Arduino. It was not very difficult to find a strategical disposition so we quickly screwed them on the base structure.

The last thing we did, but, actually what gives the name to the project, was the pendulum itself. As shown before, we used a piece of wood to connect the pendulum with the potentiometer. But not the whole pendulum is wood-made of; we have used a thin rib. This rib is put into the piece of wood to take advantage of its low weight.

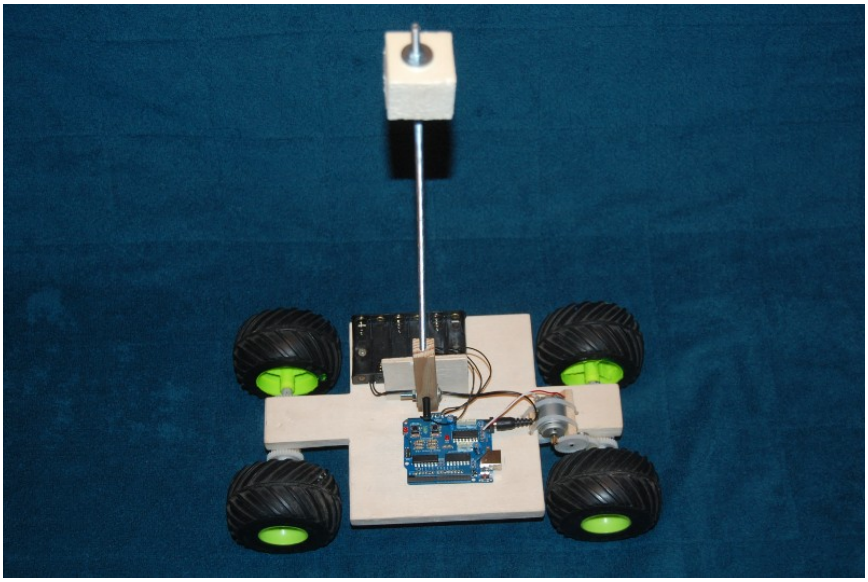

Illustration 18: The inverted pendulum finished

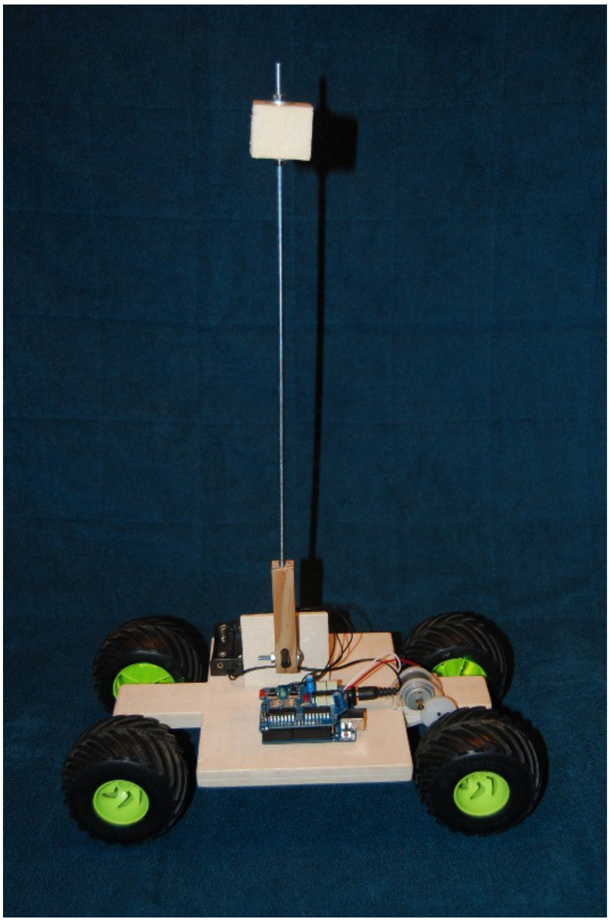

Illustration 19: The inverted pendulum finished (lateral view)

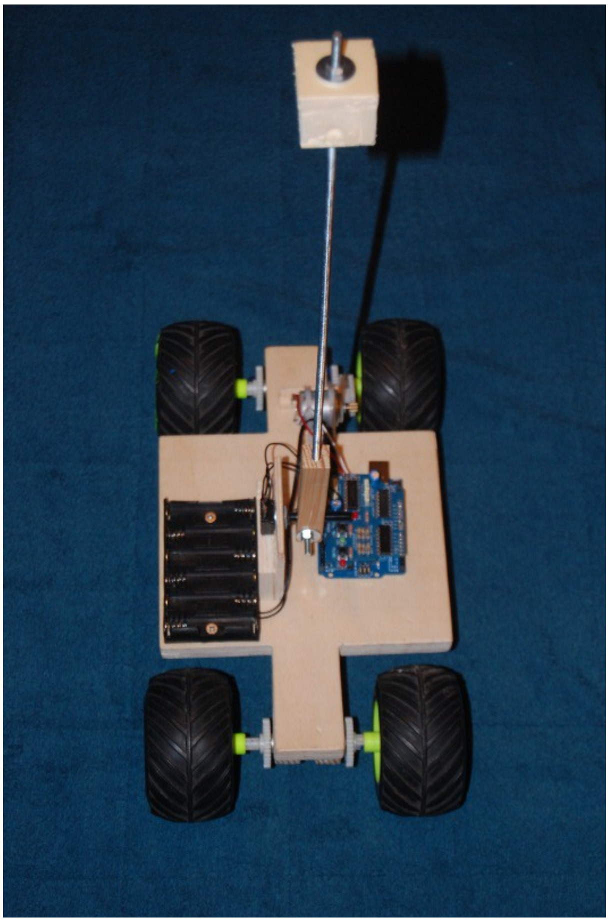

Illustration 20: The inverted pendulum finished (form above)

4.4 PAINTING

When we finished the construction part and as we had decided from the very first start, we went on to paint the Pindulum. It was the easiest part but not the less laborious. We started covering the wheels to paint the tires. The colour we chose was yellow fluorescent as to be seen in the dark. We also painted the pendulum itself, just to give it a little “fashion touch”. The point of being visible in the dark didn't appear in our first aims but, since we wanted to paint some things anyway, we decided to take a fluorescent colour.

4.5 SOFTWARE

Programming an Arduino requires a lot of knowledge we don't have. The time needed to comprehend all this coded language has not been at our disposal but we have written, for the time, the base of what the code needed would be like. It actually works, but we would need a complete PID control to achieve a “stable” pendulum.

```
//INVERTED PENDULUM

#include <PID_v1.h>
//Define Variables we'll be connecting to
double Setpoint, Input, Output;
//Specify the links and initial tuning parameters
PID myPID(&Input, &Output, &Setpoint,5,2,1, DIRECT); // 1

int potPin = A2; // select the input pin for the potentiometer
int pot = 0; // it starts as O but it's not necessary to define it, it doesn't change anything
int dir2B= 12; // Motor direction
int enableM2 = 10; // Motor enabling

void setup () // definine inputs and outputs
{
Serial.begin(9600);
pinMode(potPin, INPUT); // we define the potentiometer input
pinMode(dir2B, OUTPUT); // set the motor pins as outputs:
pinMode(enableM2, OUTPUT); // set the motor pins as outputs:
digitalWrite(enableM2, HIGH);  // set enablePins high so that motor can turn on:
//initialize the variables we're linked to
 Input = analogRead(potPin);
Setpoint = 586;
//turn the PID on
myPID.SetMode(AUTOMATIC);
}

void loop ()
{
pot= analogRead(potPin); // read the value of the potentiometer
Input = pot;
```

1 The values “5,2,1” are linked to the Kp, Ki and Kd and can be modified to try to reach a higher stability.

```
myPID.Compute();
int error=(586-pot); // reference=586, measured=pot
int vel=255;

if (-190 < error && error < 0) // if the value of the potentiometer is between -190 and 0 degrees:
{
        digitalWrite(dir2B, HIGH);
        analogWrite(enableM2,(255-Output));
         Serial.println(255-Output);
}

if (190 > error && error > 0) // if the value of the potentiometer is between 190 and 0 degrees:
{
        digitalWrite(dir2B, LOW);
        analogWrite(enableM2,Output);
        Serial.println(Output);
}

if (error < -190 || error > 190) // if the value of the potentiometer is less than -190 or more than 190 degrees:
{
        digitalWrite(enableM2, LOW);
}
}
```

5. CONCLUSIONS

First of all, we are really impressed on how an apparently simple device can result such a complex thing. We have really learned a lot while doing this project as we had to do it on our own and there was a huge amount of new information. This project has changed our way of thinking though every single thing we see now makes us question how it is built.

After noticing its general difficulty, we also realized that the smaller things happened to be the more laborious to do. The Pindulum required precision since maintaining equilibrium needs very accurate values. For example, we had to make two little wood pieces that held the motor and kept it on its right place but one of them was also where the third gear was nailed. It was a bit difficult to make this composition fit properly and we had to file the wood-piece very carefully in order that it held the motor in the exact place.

Moreover, although apparently seeming the other way around, it happened to be that the longer the stick was and heavier the weight was the more stable the pendulum could stand.

The aesthetic part was also quite important for us. In general, people may tend to go straight and pass over this part of the project. For us, maybe because we are girls, it was always something to consider. It is true, however, that by the end of the delivery time we were less concerned about the aspect and we became more practical.

During this project we came across some problems and difficulties from all the areas that we hadn't expected. The first handicap was with the installation of the Arduino program; we had troubles in both computers. Gisela's laptop did not detect that the Arduino was plugged in and Clàudia's one said that the Arduino did not have enough free bytes to upload the code. Unluckily, we could only solve the problem with Gisela's. After having managed to resolve this issue we found out that we had no idea of programming. Programming the Arduino has really been a challenge for us; it was an unknown world. There were lots of references on the Arduino website but we didn't know any of the names or uses. We needed some help in that aspect to get to know the basic language references but, from that point on, we went on our own to investigate each reference separately. It took a lot of time for us to understand the new language and the way the Arduino works. In spite of this fact, we have to say that we finally managed to program our Arduino properly and that are very satisfied with the final result. It was one of our most difficult aims and, although not being which would be the ideal program, we consider we succeeded.

Maybe one of the less expected problems for us were the little but important details in the written project, for example the pictures, the schemes and the page format. When we got to know that the size (in KB) of the pictures had to be more or less of 200KB we immediately downloaded a program (GIMP) to do so. But it was more complicated than we believed. We had a similar problem with Fritzing, the program used to make electronic schemes, because it did not have in its database all the components of our inverted pendulum and we had to think of a new way of doing them. Finally, we have to say that it was also quite complex to configure the page format of the written project.

The fact of doing the project in English has had both positive and negative aspects. It was positive since all the information was in English. It was not difficult for us to understand the sentences in general but it was quite more complicated to understand specific words like technical terms. This was our main language problem along the project.

Working in pairs has also been a peculiar aspect. Our intention was to do every single thing together. We achieved our aim until the days before the delivery term finished. We were under a lot of pressure and we could not find time to work together. We had a lot of exams and we also do a lot of extracurricular activities. We divided some particular points, not the important ones, to do each of us on our own and then put them together. Although this small self-workings, we are happy about the result of our work. We haven't got angry with each other and we had always agreed in everything.

Also worth-commenting the fact that we changed our project theme, which can be seen as an advantage or a disadvantage. The disadvantage is mainly because we spent several hours reading and trying to understand complex information about the Segway that later we wouldn't use. On the other hand, the inverted pendulum was a kind of Segway simplified so we had already acquired some basic knowledge. We have to admit that by the time we decided to change our project theme we hadn't enough hours to recover the time “wasted” before starting school. It has been hard to combine the project with the school work. We also have to say that the new project was more achievable for us than the first one and also a lot cheaper.

Future work for this project should be to improve the pendulum's structure and stability. It is important to make an accurate analysis of the stick's angle and this could be done by a more precise sensor such as the combination of a gyroscope and an accelerometer. This would provide more exact results. Also, the programming part should be more precise considering the PID control.

It should also be considered constructing an inverted pendulum with only 2 wheels, not four. It would be an interesting project and it would be much more similar to a real Segway. The mainly difference with our project would be the programming, which would be a lot more complicated.

6. BIBLIOGRAPHY

6.1. WEB

1. Arduino Examples

   http://www.ele.uri.edu/courses/ele205/Arduino%20-%20Learning.pdf

2. Arduino Motor Shield tutorial

   http://www.instructables.com/id/Arduino-Motor-Shield-Tutorial/

3. Arduino Playground: Learning; Single Servo example

   http://playground.arduino.cc/Learning/SingleServoExample

4. Arduino: Language Reference

   http://arduino.cc/en/Reference/HomePage

5. Arduino: Learning; Analog input

   http://arduino.cc/en/Tutorial/AnalogInput

6. Arduino: Learning; Blink

   http://arduino.cc/en/Tutorial/Blink

7. Arduino: Learning; Reading a potentiometer (Analog input)

   http://www.arduino.cc/en/Tutorial/Potentiometer

8. Arduino: Motor Control v1.1

   http://www.arduino.cc/en/Main/ArduinoMotorShield

9. Barcelona Cybernetics

   http://www.bcncybernetics.com/

10. Characteristics of plywood

    http://diyguides.dremel.com/characteristics-plywood-20473.html

11. Getting Started w/ Arduino on Windows

    http://arduino.cc/en/Guide/Windows

12. Google Traductor

    http://translate.google.es

13. Libreoffice: Page numbers tutorial

    http://help.libreoffice.org/Writer/Page_Numbers

14. Lucidchart – Diagrames de col·laboració

    https://www.lucidchart.com

15. Oxford Advanced Learner's Dictionary

    http://oald8.oxfordlearnersdictionaries.com/

16. Thesaurus

    http://thesaurus.com/

17. Tutorial: Arduino Motor Shield Kit – BricoGeek.com

    http://www.youtube.com/watch?v=WdQBqqysZZg

18. UPC: Instituts universitaris de recerca

    http://www.upc.edu/recerca/departaments-instituts/instituts-universitaris-de-recerca

19. Wikipedia: Arduino

    http://en.wikipedia.org/wiki/Arduino

20. Wikipedia: Inverted pendulum

    http://en.wikipedia.org/wiki/Inverted_pendulum

21. Wikipedia: Metalworking

    http://en.wikipedia.org/wiki/Metalworking

22. Wikipedia: plywood

    http://en.wikipedia.org/wiki/Plywood

23. Wikipedia: Potentiometer

    http://en.wikipedia.org/wiki/Potentiometer

24. WordReference

http://www.wordreference.com

25. Yorokobu

http://www.yorokobu.es/tibi-y-dabo-robots-para-ayudar-a-viandantes-en-la-ciudad/

6.2. PAPERS

1. SULTAN, KHALIL: “Inverted pendulum. Analysis, Design and Implementation”, *Institute of Industrial Electronics Engineering*: Karachi, 2003.
2. VICENTE ABREU, VICTOR: “Balance-bot”, *Universidade da Madeira*: Funchal, November 2009.

7. INDEX OF IMAGES AND TABLES

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